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Literature Survey of Available Earthquake Hazard Assessment Studies related to North Eastern Region

CSIR - NORTH EAST INSTITUTE OF SCIENCE AND TECHNOLOGY
ASSAM STATE DISASTER MANAGEMENT AUTHORITY
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PREFACE

The Northeast India region is one of the most active zones in the world; the region is jawed between the two arcs, the Himalayan arc to the north and the Indo-Burmese arc to the east. The region bounded by latitude 22-29^{0}N and longitude 90-98^{0}E, produced two great earthquakes (M> 8.0) and about 20 large earthquakes (7.0>M>8.0) since 1897. The Shillong Plateau was the source area for the 1897 great earthquake M 8.7, and the Assam Syntaxis zone for the 1950 great earthquake M 8.6. Several large earthquakes occurred along the Indo-Burma ranges. Earthquake is only natural disaster, which cannot be predicted till now and may occur at any time and pre-planned strategies for rescue of life and property are not possible and hence causes maximum devastation than other natural disaster. So, earthquake disaster mitigation and responses takes an important role to reduce the destruction of life and property. A mitigation strategy is one of the prime concepts in order to reduce the hazard. This includes land use regulations, seismic construction and retrofit codes, improved engneering practices and simultaneous basic research on earthquake seismology. Effective mitigation will result in the avoidance of many losses that could result from future earthquakes. Additionally, although mitigation measures do provide considerable protection, one of the key features of earthquake disasters is that they produce unanticipated impacts that overwhelm the coping capacities of affected social units. Task force group constituted by Assam State Disaster Management Authority (ASDMA), Dispur, Guwahati, Assam recommended for preparing basic reference document by launching literature survey of available earthquake hazard assessment and mitigation related studies in Northeastern region for finding out what is available and the gaps if any. Pertaining to future research program towards earthquake mitigation aspect, this survey would frame a benchmark for future further research program. Several workers worked on various research topics related to earthquake seismology which delivered the prime input to the earthquake hazard mitigation approach in Northeastern India. However, the studies may lack some of the crucial inputs which still remain unexplored. These inputs are yet to be ascertained. Incidentally, this survey will portray the status of present scenario on earthquake hazard mitigation related studies and the gaps if any available.

MEMBERS OF THE PROJECT

ASDMA, Guwahati		***CSIR NEIST, Jorhat***	
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		Miss Madhusmita Baruah	**Project Fellow**

CHAPTER 1: INTRODUCTION

1.1 Origin of the proposal:

The concern raised by the Honorable President of India with regard to the loss of life and damage to the property caused by the recent earthquake events, occurred in Sumatra and Sikkim region. Major emphasis, has been decided to take up earthquake hazard estimation and its mitigation related studies systematically in the regions where a large earthquake may recur anytime. Northeastern India is one of the highly seismically active zones in the World (Fig. 1). Daily numbers of earthquake occur in Northeastern India (NER) which is not felt mostly. Some of these are felt rigorously too. Recently the people of NER experienced few felt earthquakes.

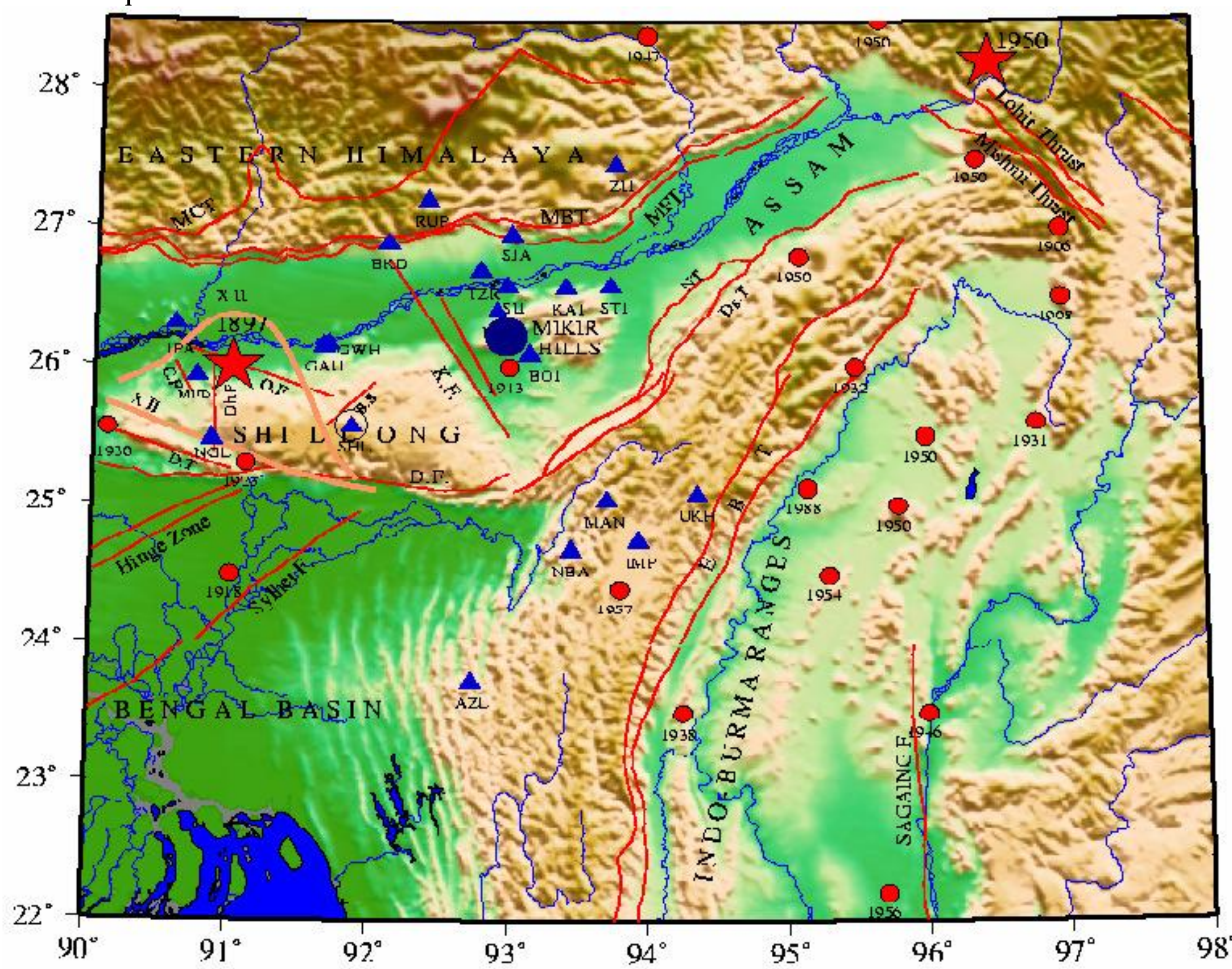

Fig.1 Map showing major tectonic features of northeast India region after (GSI, 2000). Two great earthquakes (M>8.0) are annotated by larger star symbols, and the large earthquakes (8.0>M>7.0) by circles. The digital seismic stations are shown by blue triangles. The hat type maximum intensity zone, isoseismal XII (MM scale), of the 1897 great earthquake is shown (after Oldham, 1899). The existing one is at Shillong indicated by blue triangle encircled. The major tectonic features in the region are indicated; MCT : Main Central Thrust, MBT : Main Boundary Thrust, MFF : Main Frontal Fault, DF : Dauki Fault, DT : Dapsi Thrust, Dh.F : Dudhnoi Fault, OF : Oldham Fault, CF : Chedrang Fault, BS : Barapani Shear Zone, KF : Kopili Fault, NT : Naga Thrust, DsT : Disang Thrust and EBT : Eastern Boundary Thrust.

One of these events (Sikkim eq., 18th Sep, 2011) shook rigorously the entire NER and caused several damage to dwellers with loss of deaths even. Most interestingly there were five felt earthquakes within the span of one and 8 half month's duration after this earthquake. Since the time interval of the felt earthquake was very short, firstly it created a panic among the people of NER and secondly it has created avenues for new scientific study pertaining to earthquake hazard estimation. Simultaneously there is famous quote (Ref. Bilham) "While it is not possible specifically to predict a quake, but if one goes by return period theory, a major quake is definitely due in North-East, taking into account the Assam earthquake of 1950 and Shillong quake in 1897". That is if one considers a gap of 53 years between the Assam and Shillong quakes, there is every possibility of the occurrence of Major earthquake now. The region has experienced some of world's worst quakes, be it the Shillong quake or the Assam one, both measuring around 8.5 and reckoned to be two major quakes in human history, both in terms of intensity and destruction. While not much headway has been made with respect to earthquake hazard and its mitigation related studies in NER, study based on literature survey to be carried out is very much relevant to the present seismicity and seismotectonics scenario which not only identify the areas where most emphasis is needed but also will act as path finder for further planning on R & D features. In this context the National Workshop on Earthquake Risk Mitigation Strategy in the Northeast held in Guwahati on 24th-25th February 2011 discussed the various problems and challenges of earthquake risk management and framed the Roadmap for the same. One of the recommendations of the said roadmap is coordination of earthquake hazard assessment studies. The technical committee formed in Assam, to review & recommend actions regarding Roadmap of earthquake risk mitigation in Northeastern India, decided that proposals from knowledge Institutes of the state of Assam should be collected to make a literature survey of earthquake hazard assessment studies in Northeastern India.

1.2 Project Summary:

The Northeast India region is one of the most active zones in the world; the region is jawed between the two arcs, the Himalayan arc to the north and the Indo-Burmese arc to the east (Fig 1). The region bounded by latitude 22-29^{0}N and longitude 90-98^{0}E, produced two great earthquakes (M> 8.0) and about 20 large earthquakes ($8.0>M\geq 7.0$) since 1897 (Fig.1). The Shillong Plateau was the source area for the 1897 great earthquake M 8.7, and the Assam syntaxis zone for the 1950 great earthquake M 8.6 (Fig.1). Several large earthquakes occurred along the Indo-Burma ranges.

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Task group constituted by Assam State Disaster Management Authority (ASDMA), Dispur, Guwahati, Assam for preparing basic reference document by launching literature survey of available earthquake hazard assessment and mitigation related studies in North-eastern region for finding out what is available and the gaps if any. Pertaining to future research program towards earthquake mitigation aspect, this survey would frame a benchmark for future further research program.

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CHAPTER 2: DATABASE

2.1 Literatures pertinent to Earthquake Hazard Assessment

List of bibliographic references (alphabetic) published in various National and International journals related to earthquake hazard assesment which are the prime inputs to the Seismic Hazard Assesment studies in Northeastern India and its vicinity. A graphical presentation is made alongwith (based on database so far gathered).

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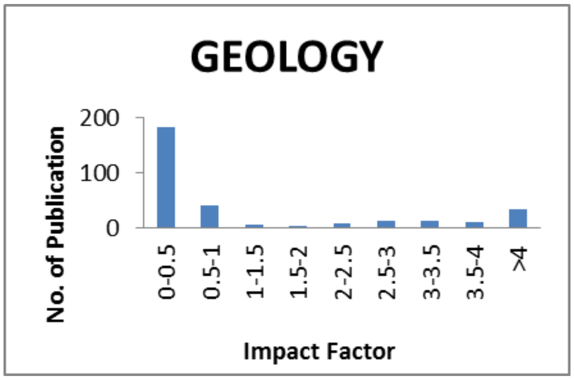
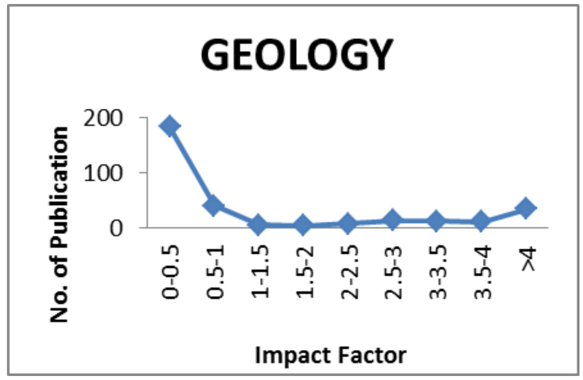
2.2 Impact factor analysis of the literatures

In case of publication pertaining to the subject Geology, Seismology, Geodesy, Seismic Hazard, Earthquake Precursor, Geophysics, Geotechnical, Remote Sensing and Palaeoseismology, it has been observed that there are several papers already been published by various researchers from India and abroad. Most of these are published in SCI Journals only.

Significant contributions are made by numbers of researchers on the Geology, most of which are published in journal having IF<1.0 only and very few are published in the Journal having IF>1.0 (Fig. 1a).

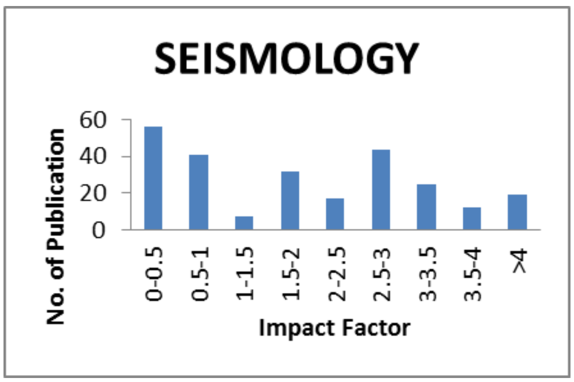


(Fig: 1a)

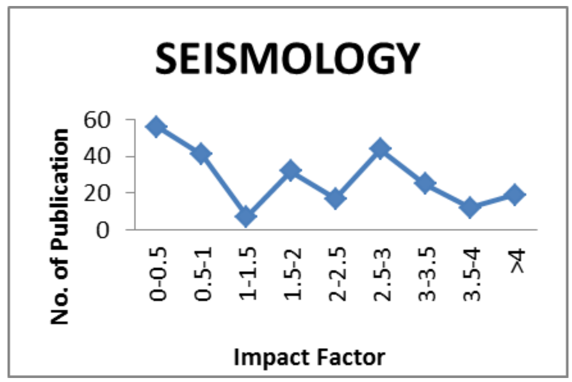


(Fig: 1b)

So far the subject of Seismology is concerned, publications are evenly distributed in almost all the the ranges of impact factor. But only a few publications are found to be published in the range of impact factor 1-1.5 and 3-4. Out of the total number of publications, the highest number of publications are found in low IF journal ie. ~ 0-1.0 while significantly there are some publications placed in the IF range 2.5 - 3.5.

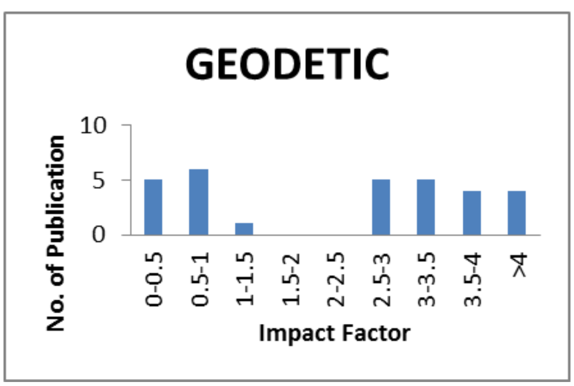


(Fig: 2a)

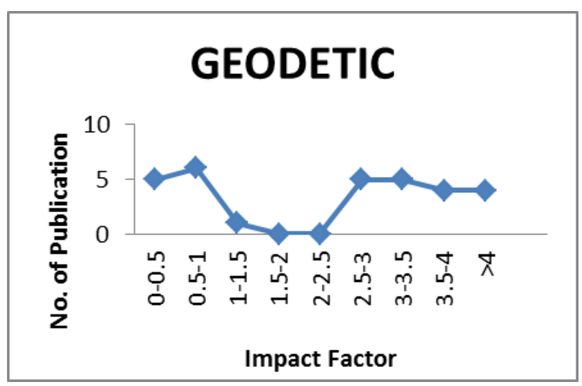


(Fig: 2b)

Regarding the subject of Geodetic, very few research papers are published that to in the range of impact factor 0-1 and 2.5-4. There is a gap in the range 1-2.5 indicating the number of publications to be one or two. Relatively less study reflect further scope in this particular subject.

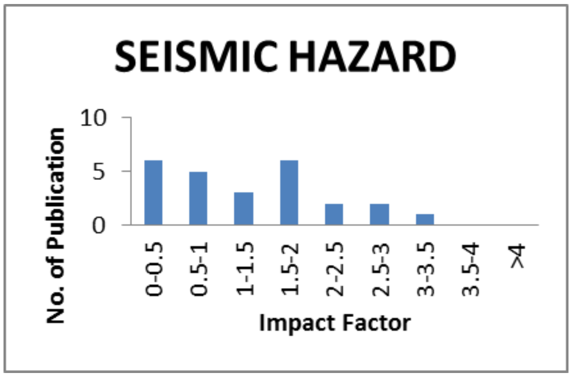


(Fig: 3a)

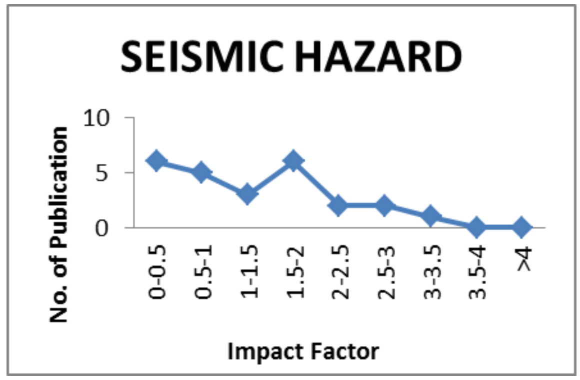


(Fig: 3b)

Very few papers have been published on the subject, Siesmic Hazard. The figure here is showing that out of the published papers mostly are in the range of low impact factor 0-2. A few studies are published in journal having intermediate range impact factor equivalent to 2.5 onwards. There are ample opportunity still exist towards classic work.

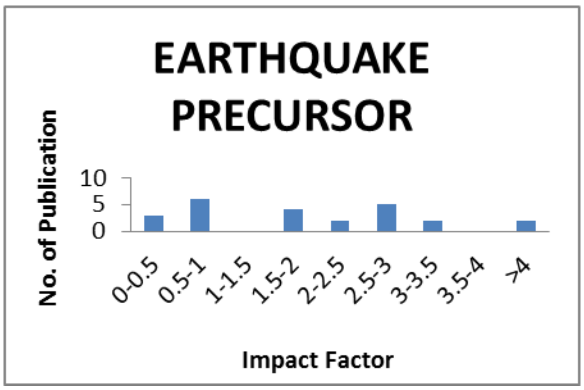


(Fig: 4a)

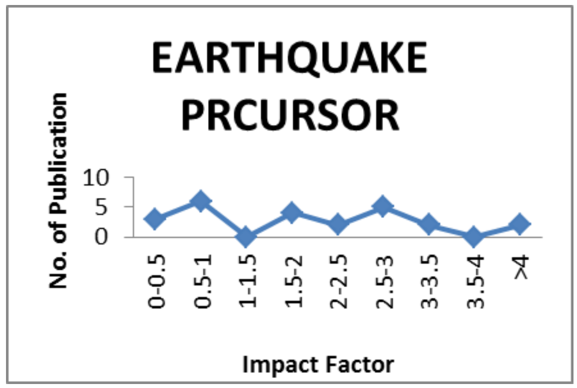


(Fig: 4b)

The number of publications published on the subject, Earthquake Precursor is very few. Out of these publications a few are in the range 0-1 and 1-3.5. Significantly not much precursory related studies are carried out which indicates ample scope of further study.

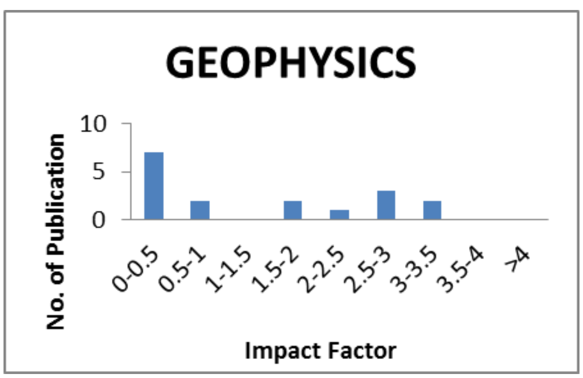


(Fig: 5a)

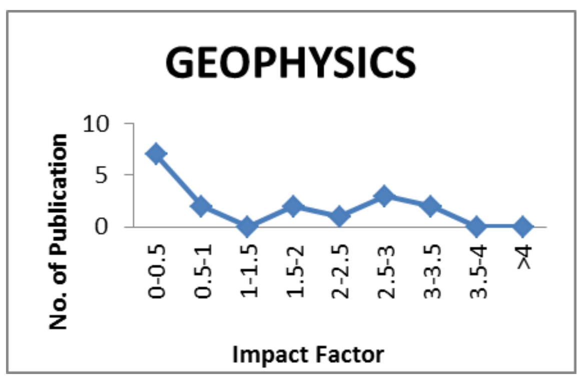


(Fig: 5b)

Publications on Geophysics are very few and most of which are published in the jounals having impact factor ranged between 0-0.5. A few publications are published in intermediate IF journals which are relatively less in numbers. Dearth of geophysical studies as observed from the figure indicates requirement of more geophysical surveys.

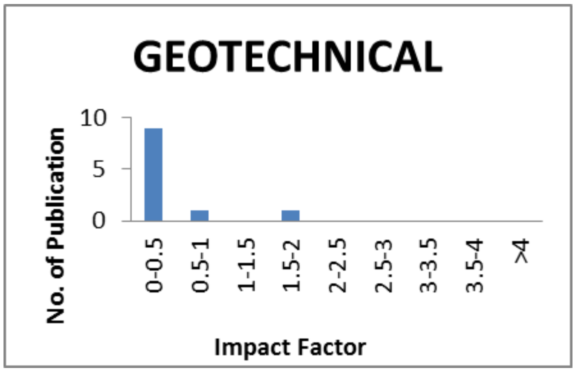


(Fig: 6a)

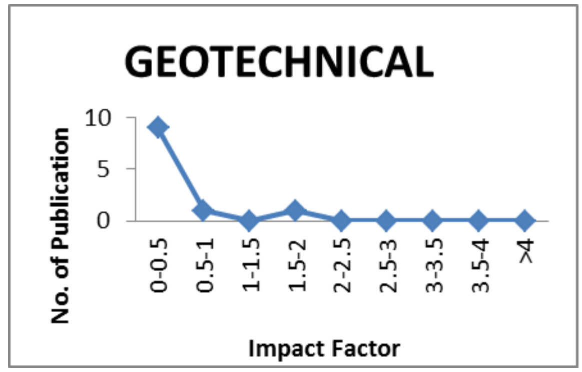


(Fig: 6a)

Less than few publications are published on the subject, Geotechnical which are in the range of impact factor 0-0.5. As such large scope pertains to Geotechnical studies.

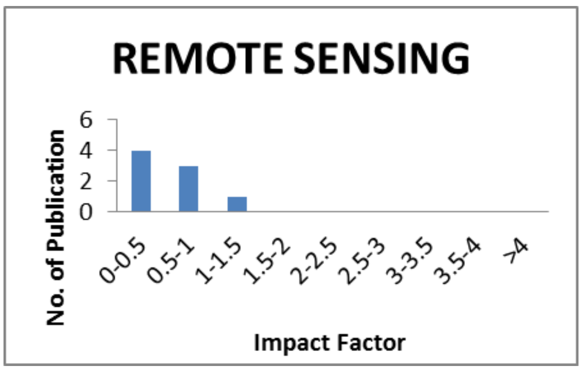


(Fig: 7a)

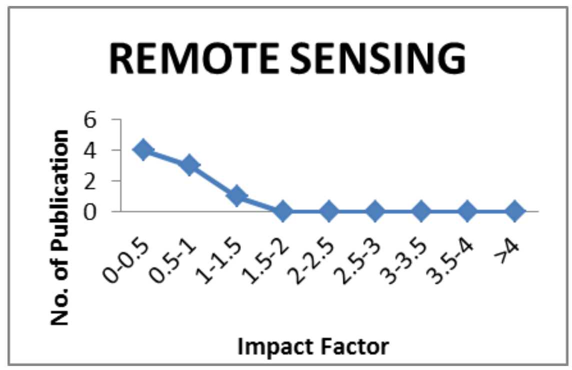


(Fig: 7b)

The figure here is showing that the published papers on Remote Sensing is very less having impact factor in the range 0-1. This indicates that more studies are needed towards this particular subject.

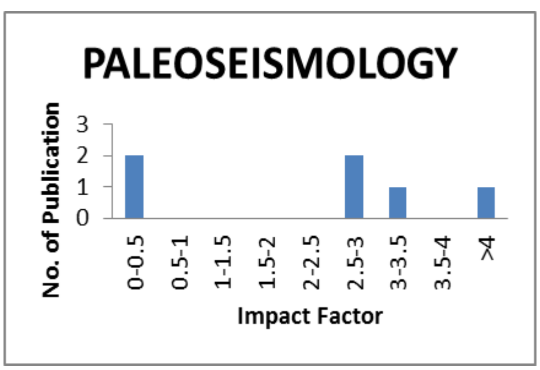


(Fig: 8a)

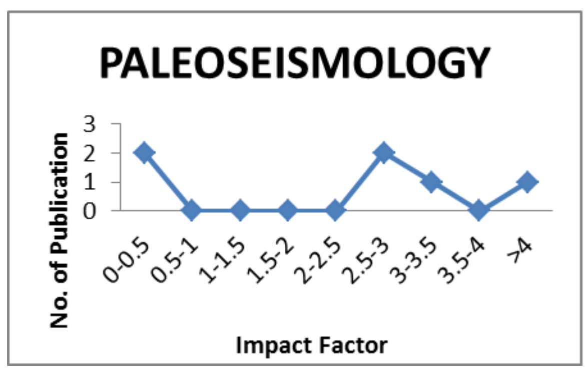


(Fig: 8b)

Very few papers on the subject, Paleoseismology has been published having impact factor in the range 0-0.5 and 2.5-3.5. Also, a small number of papers are seen in the range greater than IF ~4. However towards development of recurrence period, much more indepth studies on palaeoseismology is needed.



(Fig: 9a)



(Fig: 9b)

CHAPTER 3: METHODOLOGY

3.1 Objectives:

- To create high quality database based on literature survey related to earthquake hazard and its mitigation related studies.
- To determine standard benchmark required for Earthquake Hazard Assessment Studies.

3.2 Procedure:

Literature survey had been done based on the collection of literatures from different sources. Collections of literatures are drawn from different institutions like Gauhati University, Indian Institute of Technology-Guwahati, Assam Engineering College-Guwahati, Manipur University and Dibrugarh University locally. Numbers of resource persons are contacted for the necessary reprints they have published. Simultaneously, rigorous search had been made through the Internet to collect the literatures related to the project. With the collection of literatures a list had been made. A part of which had been uploaded in the website. The literatures are further segregated subjectwise. Then impact factor analysis of the literatures had been made and a list of literatures having impact factor greater than 2 had been selected. A list of abstracts of these literatures was made which had been further reviewed. Likewise, a survey on earthquake hazard assessment studies was made in high seismically active zones around the world like USA, TAIWAN, IRAN and JAPAN. Furthermore, critical parameters had been evaluated by comparing the studies carried out in Northeast India and other countries. Henceforth, with these studies an estimation of parameters that needed further research was made.

CHAPTER 4: SURVEY OF LITERATURES IN NE INDIA

4.1 ABSTRACTS OF MOST VALUABLE LITERATURES ON EARTHQUAKE HAZARD ASSESSMENT (Impact Factor>2.0 ; Part 1)

Abstracts of the various research publications on seismological and seismic hazard studies in and around Northeastern India having impact factor above 2.0 are carried out. The prime findings in each of the studies are considered as the inputs to the seismic hazard assesement in the region. These parameters are indicated below.

- **Anomalous behaviour of precursor resistivity in Shillong area, NE India. J.R. Kayal and B. Banerjee.** ***Geophysical Journal (1988) 94, 97-103.***

Abstract:

Daily measurement of apparent resistivity from 1984 May to 1985 October in Shillong Plateau, India, has been carried out for an earthquake-precursor study. The resistivity changes which occur 7 to 10 days before earthquakes do not necessarily satisfy the dilatancy hypothesis, which, of late, has been subjected to criticisms of not being a generalized phenomenological explanation of precursor resistivity variation. Prior to earthquakes, resistivity may increase or decrease or may not even show any change depending on the ori-

entation of measuring electrodes, the elastic nature of the geological formation where observations are made and the direction of tectonic stress.

Key words: Earthquakes, NE India, precursor study, resistivity method.

- **An analysis of the gravity field in Northeastern India. R.K. Verma, Manoj Mukhopadhyay.** ***Tectonophysics,Volume 42, Issues 2–4, 20 October 1977, Pages 283–317.***

Abstract:

Northeastern India comprises several major tectonic units including the Shillong Plateau, the Upper and Lower Brahmaputra (Assam) Valleys, the Northeastern Himalaya, the Naga Hills and the Bengal Basin. The area lies approximately between latitude 23–28°N, and longitude 88–96°E. A revised Bouguer anomaly map of the area with nearly 400 new observations is presented. A Pratt-Hayford isostatic anomaly map using all available information is also given. The whole area shows a large variation in gravity anomalies, Bouguer anomalies show a variation from +40 mGal over the Shillong Plateau to −250 mGal over the northwestern part of the Upper Assam Valley. Isostatic anomalies also show a variation, from +100 mGal over the Shillong Plateau to −125 mGal in the Assam Valley. A study of the Bouguer anomaly map shows that the gravity field is considerably influenced by low-density sediments overlying the Assam Valley as well as the Bengal Basin. A geological correction for these sediments was computed for a few selected profiles for which geological information was available from seismic and bore-hole data along the Upper Assam Valley and the Bengal Basin. The magnitude of the geological correction was found to be of the order of 50 to 100 mGal for the Assam Valley and 40 to 130 mGal for the Bengal Basin. Models for the crust and mantle underlying the Shillong Plateau, the Upper Assam Valley and the Bengal Basin were constructed considering the nature of geologically corrected Bouguer anomalies as well as isostatic anomalies. Gravity data suggest that the crust underlying the Shillong Plateau is probably denser as well as thicker than normal for its elevation. The Assam Valley may overlie a crust which is thicker than normal for its topography, and the crystalline solid crust underlying a large thickness of sediments of Bengal Basin could be denser as well as thinner than the normal continental crust.

Key words: Bouger anomaly; isostatic anomaly; gravity anomaly.

- **A deterministic seismic hazard map of India and adjacent areas. Imtiyaz A. Parvez, Franco Vaccari and Giuliano F. Panza.** ***Geophys. J. Int. (2003) 155, 489–508.***

Abstract:

A seismic hazard map of the territory of India and adjacent areas has been prepared using a deterministic approach based on the computation of synthetic seismograms complete with all main phases. The input data set consists of structural models, seismogenic zones, focal mechanisms and earthquake catalogues. There are few probabilistic hazard maps available for the Indian subcontinent, however, this is the first study aimed at producing a deterministic seismic hazard map for the Indian region using realistic strong ground motion modelling with the knowledge of the physical process of earthquake generation, the level of seismicity and wave propagation in anelastic media. Synthetic seismograms at a frequency of 1 Hz have been generated at a regular grid of $0.2^0 \times 0.2^0$ by the modal summation technique.

The seismic hazard, expressed in terms of maximum displacement (D_{max}), maximum velocity (V_{max}), and design ground acceleration (DGA), has been extracted from the synthetic signals and mapped on a regular grid over the studied territory. The estimated values of the peak ground acceleration are compared with the observed data available for the Himalayan region and are found to be in agreement. Many parts of the Himalayan region have DGA values exceeding 0.6 g. The epicentral areas of the great Assam earthquakes of 1897 and 1950 in northeast India represent the maximum hazard with DGA values reaching 1.2–1.3 g. The peak velocity and displacement in the same region is estimated as 120–177 cm s−1 and 60–90 cm, respectively.

Key words: Design ground acceleration, deterministic modelling, Indian region, seismic hazard, synthetic seismograms.

- **A rupture model for the great earthquake of 1897, northeast India. V.K. Gahalaut and R. Chanaer.** ***Tectonophysics, Volume 204, Issues 1–2, 30 March 1992, Pages 163–174.***

Abstract:

We assume that the unusually deep, extensive and long-lasting floods of 1897 along the section of the Brahmaputra River north of the western Shillong plateau were due to local ground subsidence associated with the great earthquake which occurred on June, 12 of that year in the western part of northeast India. Numerical simulations of ground-level changes due to slip on a buried low-angle thrust fault, dipping due north, then show that the northern limit of the rupture zone of this earthquake should have been along the E-W-flowing Brahmaputra River, about 40 km north of the northern edge of the Shillong plateau and about 70 km south of the Himalayan mountain front. A similar interpretation of a ground tilt observation suggests that the western limit of the 1897 rupture zone was along the western margin of the Shillong plateau. The E-W and N-S dimensions of the rupture zone are estimated to be 170 km and 100 km respectively, so that it enclosed the western half of the Shillong plateau and areas north of it up to the Brahmaputra River. The rupture depth could not be estimated from the available data on ground-level changes, and was constrained at 15 km beneath the southern margin of the Shillong plateau, on other evidence. The above thrust fault should be of the nature of a detachment at midcrustal depth, which arose because the continental crust associated with the Indian Shield terrains of the Shillong plateau and Mikir Hills immediately to the east could not subduct under the continental crust of the Eurasian plate to the north and east. It is tentatively suggested that, although this detachment may extend under the Himalaya, it may not be the detachment on which the great earthquakes of 1905, 1934 and 1950 have occurred in the northwestern, central and eastern Himalaya, respectively. It is also suggested that a distinction should be made between the seismicity of the Himalaya and the seismicity of the Himalayan convergent plate margin (HCPM). An earthquake of the Himalayan seismic belt is also an earthquake of the HCPM, but the converse need not hold true. Since the inferred northern limit of the 1897 rupture zone is about 70 km south of the Himalayan mountain front, it is suggested that this earthquake belongs to the HCPM but not to the Himalayan seismic belt. Thus, conservatively, a seismic gap of about 700 km may exist along the Himalayan seismic belt between the eastern and western limits of the ruptures zones of the great 1934 and 1950 earthquakes respectively.

Key words: Low-angle thrust fault; rupture zone; detachment; rupture model.

- **A seismic hazard map of India and adjacent areas. K.N. Khattri, A.M. Rogers, D.M. Perkins and S.T. Algermissen.** ***Tectonophysics, Volume 108, Issues 1–2, 10 September 1984, Pages 93–108, 111–134.***

Abstract:

We have produced a probabilistic seismic hazard map showing peak ground accelerations in rock for India and neighboring areas having a 10% probability of being exceeded in 50 years. Seismogenic zones were identified on the basis of historical seismicity, seismotectonics and geology of the region. Procedures for reducing the incompleteness of earthquake catalogs were followed before estimating recurrence parameters. An eastern United States acceleration attenuation relationship was employed after it was found that intensity attenuation for the Indian region and the eastern United States was similar. The largest probabilistic accelerations are obtained in the seismotectonic belts of Kirthar, Hindukush, Himalaya, Arakan-Yoma, and the Shillong massif where values of over 70% g have been calculated.

Key words: Seismic hazard; peak ground accelerations; historical seismicity; seismotectonics; geology.

- **A seismotectonic study of the Burma and Andaman arc regions using centroid moment tensor data. M. Ravi Kumar, N. Purnachandra Rao and S.V. Chalam.** ***Tectonophysics, 253 (1996), 155-165.***

Abstract:

The concept of a "mean slip angle" is introduced. This enables a classification of focal mechanisms in any region into predominantly strike-slip, thrust and normal categories. Based on this concept, the Harvard Centroid Moment Tensor (CMT) data, in the Burma and Andaman arc regions from 1977 to 1992, comprising 167 focal mechanism solutions, are examined and categorized. Distinct trends on the surface and in depth sections emerge on examination of these categories. For instance, in the Burmese arc there is a clear segregation along the slab between strike-slip type mechanisms down to a depth of about 90 km and thrust events which occur exclusively below this depth. In addition, a study of P- and T-axis orientations indicates that the stress pattern in the subducted slab is different from that farther east. Whereas the P axes of the thrust and strike-slip mechanisms in the slab show a predominantly NNE trend, commensurate with the direction of motion of the Indian plate with respect to the Eurasian plate, those in the region to the east, show, interestingly, an average E-W-oriented compressive regime. The northern and southern parts of the Andaman are region exhibit distinct tectonic patterns. Whereas in the southern part the disposition of focal mechanisms along the slab and the P- and T-axis orientations indicate active subduction, the mechanisms in the northern part exhibit a peculiar segregation into clusters of thrust, normal and strike-slip types, without conforming to the local trend of the arc. A similar study in the western Aleutian trench region indicates a much simpler subduction pattem.

Key words: Centroid moment tensor; focal mechanisms; strike-slip, thrust and normal categories.

- **Constraints on the structure of the Himalaya from an analysis of gravity anomalies and a flexural model of the lithosphere. H. Lyon-Caen and P. Molnar. J. Geophys. Res. (1983), 88(B10), 8171–8191, Doi:10.1029/JB088iB10p08171.**

Abstract:

The intracontinental subduction of India beneath the Himalaya presents several similarities to that occurring at island arcs. We study one of those similarities by analyzing gravity anomalies across the Himalaya assuming that the topography is supported by the Indian elastic plate, flexed under the weight of both the overthrust mountains and the sediments in the Ganga Basin. We first examine in detail the effects of each of the following parameters on the configuration of the elastic plate and on the gravity anomalies: the flexural rigidity, the position of the northern end of the elastic plate (the amount of underthrusting of such a plate beneath the range), and the density contrasts between the crust and mantle and between the sediments and the crust. A plate with a constant flexural rigidity of about 0.7×1025 N m (between 0.2 and 2.0×1025 N m) allows a good fit to the data from the Lesser Himalaya and the Ganga Basin. Such a plate, however, cannot underthrust the entire Himalaya. Instead, the gravity anomalies show that the Moho steepens from only about 3° beneath the Lesser Himalaya to about 15° beneath the Greater Himalaya. This implies a smaller flexural rigidity beneath the Greater Himalaya (0.1 to 1.0×1023 N m) than beneath the Ganga Basin and the Lesser Himalaya. Even with a thin, weak plate beneath the Greater Himalaya, the weight of the mountains depresses the plate too much unless an additional force or moment is applied to the plate. The application of a bending moment/unit length to the end of the plate of about 0.6×1018 N m is adequate to elevate the Indian plate and to bring the calculated gravity anomalies in agreement with those observed. Both, the smaller flexural rigidity and the bending moment can be understood if we assume that part or all of the Indian crust has been detached from the lower lithosphere that underthrusts the Greater Himalaya. We study the tectonic implications of these results by means of a series of idealized balanced cross sections, from the collision to the present, that reproduce several important features of the geology of the Himalaya and predict an amount of eroded material comparable to that in the Ganga Basin and the Bay of Bengal. These cross sections include high-grade metamorphic rocks near the Main Central Thrust and a steeper dip of it there than in the Lesser Himalaya. They predict rapid uplift only in the Greater Himalaya and at the foot of the Lesser Himalaya.

Key words: Intracontinental subduction; elastic plate; flexural rigidity; density contrasts; bending moment.

- **Crustal structure of Bengal Basin and Shillong Plateau: Extension of Eastern Ghat and Satpura Mobile Belts to Himalayan fronts and seismotectonics. R.P. Rajasekhar and D.C. Mishra.** ***Gondwana Research , Volume 14 (3) Elsevier – Oct 1, 2008.***

Abstract:

Gravity data from the East India and the Bangladesh are processed and compiled together to provide a composite complete Bouguer anomaly map of this region. Modelling of gravity profiles across the East Indian Shield (Chhotanagpur Granite Gneiss Complex, CGGC), the Shillong Plateau and the Bengal basin in Bangladesh, constrained from seismic studies suggest crustal thickness of 37–38 km and thrusted high density rocks in the middle crust under the East Indian Shield reducing to 30–32 km with thick sediments of 12–14 km under Bangladesh. Reduced crustal thickness under Bangladesh is attributed to oceanic type of crust, which is connected to Indian continent along Hinge zone characterized by linear gravity highs connecting east coast of India to the Shillong Plateau. Thrusted high density rocks under the CGGC and the Shillong Plateau are in comparison to those under the Eastern Ghat and the Satpura Mobile belts (EGMB, SMB) respectively suggest the north ward and east ward extensions of these orogenies. Margins of the thrusted block under Shillong Plateau when projected on surface coincide approximately with the south dipping Dauki and the Brahmaputra faults which coincides with central bulge due to lithospheric flexure indicating their surface expositions.

Keywords: Shillong Plateau; lithospheric flexure; Bengal basin; hinge zone; Satpura and Eastern Ghat mobile belts.

- **Crustal structure variations in northeast India from converted phases. M.R. Kumar, P.S. Raju, E.U. Devi, J. Saul and D.S. Ramesh.** ***Geophys. Res. Lett. (2004), 31, L17605, Doi:10.1029/2004GL020576.***

Abstract:

Teleseismic receiver functions from a ten station network deployed in northeast India region sampling the Shillong plateau, Mikir Hills, Himalayan foredeep and the Himalayan convergence zone, are analyzed to obtain the crustal structure in this seismically active but less studied region. The Shillong plateau and Mikir hills, away from the convergent margins, reveal remarkably simple crust with thickness (~35 km) and Poisson's ratio (~0.25), akin to the Indian shield values. A surprisingly thin crust for the uplifted Shillong plateau may be explained invoking presence of an uncompensated crust that popped up in response to tectonic forces. In contrast, crustal signatures from Assam valley suggest a thicker crust and higher Poisson's ratio with evidences for a dipping Moho. Predictably, the crust is much thicker and complicated in the eastern Himalaya further north, with values in excess of 50 km.

Key words: Converted phases; teleseismic receiver function; Poisson's ratio; Indian shield values.

- **Crustal properties in the epicentral tract of the Great 1897 Assam Earthquake, Northeastern India. S. Mukhopadhyay, R. Chander and K.N. Khattri.** ***Tectonophysics (1997), 283, 311-330.***

Abstract:

The velocity structure for the upper and middle crust in the epicentral tract of the Great 1897 Assam Earthquake (western half of the Shillong massif) was estimated using locally recorded microearthquake data. The relatively homogeneous upper crustal layer has P and S wave velocities of 5.9 4- 0.2 and 3.4 4- 0.1 km/s, respectively, with a thickness of 11 to 12 km. The average P and S wave velocities in the middle part of the crust down to a depth of about 26 km were estimated to be 6.3 4- 0.6 and 3.5 4- 0.2 km/s, respectively. The larger scatter in P velocity estimate of the mid-crustal layer was investigated using synthetic examples. Our preference is for the model in which this crustal region is assumed to comprise of a number of thin layers with alternate low and high seismic velocities. From theoretical considerations we confirm that it is possible to estimate the velocity structure for a horizontally layered model using the velocity estimation procedure (a combination of the Wadati, Riznichenko and Bune method) we have used. We also carried out detailed model analysis to

check how effective this velocity estimation procedure is for the type of array data we have. Combining the estimated velocity structure with our earlier work on seismicity of this area we propose that the upper homogeneous crustal layer in the Shillong massif may be moving relatively southward across an intracrustal thrust zone. We suggest that the Great 1897 Assam Earthquake may represent the most recent episode of this relative southward movement of the massif.

Keywords: Shillong massif; velocity; Great 1897 Assam Earthquake; Riznichenko method.

- **Crustal structure and earthquake focal depths beneath Northeastern India and Southern Tibet. Supriyo Mitra, Keith Priestley, Anjan Kr. Bhattacharyya and V.K. Gaur.** ***Geophys. J. Int. (2005) 160, 227-248.***

Abstract:

We use broad-band teleseismic data recorded at eight sites along a north-south profile from Karimganj (24.84^o N, 92.34^o E), south of the eastern Shillong Plateau, to Bomdilla (27.27^o N, 92.41^o E) in the Eastern Lesser Himalaya, to determine the seismic characteristics of the crust in Northeastern India. We also analyse data from the Chinese Digital Seismic Network station at Lhasa and INDEPTH II stations located on the southern Tibetan Plateau north of our profile, to extend the seismic images of the crust further northwards. Although the northeastern Indian and the Tibetan stations do not lie along a linear profile across the Himalaya, the well-recognised uniformity of the Himalaya along strike make this comparison of the two profiles meaningful. Receiver functions calculated from these data show that the crust is thinnest (~ 35-38 km) beneath the Shillong Plateau. Receiver functions at Cherrapunji, on the southern edge of the Shillong Plateau, have a strong azimuthal dependence. Those from northern backazimuth events show that the Moho beneath the southernmost Shillong Plateau is at a depth of ~38 km while receiver functions from southern backazimuth events indicate that the Moho beneath the northern most Bengal Basin is at a depth of ~ 44 km. Receiver functions from sites on the Brahmaputra Valley demonstrate that the Moho is deeper by ~5-7 km than below the Shillong Plateau, a result which agrees with the hypothesis that the Shillong Plateau is supported by shearing stress on two steep faults that cut through the crust. Further north of the eastern Himalayan foredeep, the Moho dips gently northwards, reaching a depth of ~48 km beneath Bomdilla in the Lesser Himalaya, and 88 km below Lhasa in Tibet. Using the crustal velocity models obtained from receiver function inversions, we redetermined focal depths of well-recorded earthquakes across this part of the Indo-Tibetan collision zone and find all of these to occur within the crust. Hence we find no evidence for bimodal depth distribution of earthquakes beneath this region of northeastern India.

Keywords: Crustal structure; earthquake depths; Eastern Himalaya; India; Shillong Plateau; Tibetan Plateau.

- **Deep geoelectric structure over the Lower Brahmaputra valley and Shillong Plateau, NE India using magnetotellurics. S.G. Gokarn, G. Gupta, D. Walia, S.S. Sanabam and Nitu Hazarika.** ***Geophys. J. Int. (2008) 173, 92–104 doi: 10.1111/j.1365-246X.2007.03711.x.***

Abstracts:

Magnetotelluric studies over the Shillong plateau and lower Brahmaputra sediments have delineated the Dauki fault as a NE–SW striking thrust zone with a dip angle of about 30º, along which the low resistivity layer of Bengal sediments and the underlying oceanic crust subduct to the northwest. At present, about 50 km length of these sequences has subducted beneath the Shillong plateau and is traced up to depth of about 40 km. Another thrust zone, sub parallel to the Dauki thrust is observed in the lower Brahmaputra valley, corresponding to the Brahmaputra fault. This is interpreted to be an intracratonic thrust within the Indian plate. These results suggest that a large fraction of the seismicity over the Shillong plateau is associated with the NE–SW striking Dauki thrust, contrary to the earlier belief that this fault zone is relatively aseismic. The present studies also suggest that the Shillong plateau and the adjoining sedimentary layers act as a supracrustal block, not directly participating in the subduction process. However in response to the compressive tectonic forces generated by the Himalayan and Indo-Burman subduction processes the Shillong plateau, together with the Brahmaputra sediments overlying the Indian crust drift eastwards relative to the Bengal sediments along the surface expression of the Dauki fault leading to a dextral strike slip movement. We thus propose that the NE Indian crust responds to the compressive forces differently at different depths, governed by the rheological considerations. At deeper levels the crustal readjustments take place through the subduction along the Dauki and Brahmaputra thrusts where as, at the shallow levels the relative deformability of the supracrustal blocks have a strong influence on the tectonics, leading to the strike slip mechanism along the surface expression of the Dauki fault.

Key words: Magnetotelluric studies; geoelectric structure; thrust zone; intracratonic thrust; aseismic.

- **Deep structure and tectonics of the Burmese Arc: Constraints from earthquake and gravity data. M. Mukhopadhyay and S. DasGupta. *Tectonophysics (1988), 149, 299-322.***

Abstract:

Active subduction of the Indian plate is currently occurring beneath the Burmese arc along an east dipping Benioff zone which extends to a depth of about 180 km. The overriding Burma plate has an appearance of an inland seismic slab that is deflected downwards in the vicinity of the Benioff zone. A crustal seismic zone some 60-80 km east of the Benioff zone correlates to backarc activity. A triangular aseismic wedge in the top part of the crust outlines the Central Belt molasse basin east of the Burmese foldbelt. Fault plane solutions show that the Burmese Benioff zone is characterized by shallow angle thrusting at its upper edge whereas down-tip tensional events dominate its lower edge. Most of the backarc seismicity is accounted for by the Sagaing transform or by the activity of the Shan scarp normal fault zone at the margin of the Asian plate. A gravity anomaly pair with amplitude of 175 mGal coincides with the 1100 km long Burmese arc lying in a north-south direction. The gravity anomalies along a profile in central Burma and in adjacent areas of the Bengal basin are interpreted in terms of plate subduction as well as near-surface mass anomalies. This suggests that sediments below the Central Belt may have an average thickness of the order of 10 km but may be as thick as 15 km at the subduction zone. The oceanic crust underlying deeper parts of the Bengal basin experiences phase transition at about 30 km depth in a Benioff zone environment east of the Burmese fold belt. Several thrust planes are present within the folded

and deformed Cretaceous-Tertiary sediments of the fold belt; these are often associated with ophiolites and basic to ultrabasic rocks. A low density zone, at least 60 km wide, underlies the andesitic volcanic axis in the overriding plate.

Key words: Gravity data; Benioff zone; triangular aseismic wedge; Sagaing transform fault; Shan scarp normal fault; backarc seismicity.

- **Deformation of the subducted Indian lithospheric slab in the Burmese arc. N. Purnachandra Rao and Kalpna.** ***Geophysical Research Letters, Volume 32, Issue 5, March 2005, Doi: 10.1029/2004GL022034.***

Abstract:

Stress inversion of focal mechanism data in the Burmese arc region indicates distinct stress fields above and below 90 km along the subducted Indian lithospheric slab. In the upper part, the σ_1 and σ_3 axes trend NNE and ESE respectively, in conjunction with the ambient stress field of the Indian plate. However, in the lower part of the slab there is no preferred orientation of the σ_1 or σ_2 axes, but a very well defined σ_3 axis is observed, that trends steeply in the down-dip direction. It is inferred that while the upper part is governed by the NNE oriented horizontal plate tectonic forces, the lower part is governed entirely by tensile forces due to gravitational loading on the subducted slab. A model of attempted slab detachment at the base of the lithospheric contact zone is suggested, which is supported by results of high-resolution seismic tomographic studies in this region.

Keywords: Stress inversion; focal mechanism; ambient stress field; high-resolution seismic tomography.

- **Earthquake focal mechanism studies—A review. Kailash Khattri.** ***Earth-Science Reviews, Volume 9, Issue 1, March 1973, Pages 19–63.***

Abstract:

This article reviews the development of the study of the focal mechanism of earthquakes. The representation of focus by point and finite sources are reviewed. The use of initial motion and spectral amplitude of P-waves, the polarization of S-waves and the application of numerical methods in determining optimum solutions are discussed. A survey of the recent advances in the application of surface waves, free oscillations and static dislocations for the determination of focal mechanisms is given. A brief outline of the major results of the interpretation of the focal mechanism solution of earthquakes in terms of regional stress distributions and the geodynamic processes that are currently taking place is also included.

Key words: Focal mechanism; spectral amplitude; polarization.

- **Earthquake focal mechanisms, moment tensors, and the consistency of seismic activity near plate boundaries. C. Frohlich and K. D. Apperson.** ***Tectonics (1992), 11(2), 279–296, Doi:10.1029/91TC02888 (http://dx.doi.org/10.1029/91TC02888).***

Abstract:

Catalogs of moment tensors for more than 8000 earthquakes provide a more objective and complete description of the earthquake source than do focal mechanisms derived from first motions, and therefore moment-tensors provide a valuable resource for tectonic analysis. We here present background information about the properties of moment tensors and examples of moment tensor analysis. We also introduce a new statistic, the seismic consistency Cs, which measures the similarity of earthquakes within a group. Cs is 1.0 if earthquakes are all alike and 0.0 if they cancel one another. Triangle diagrams provide a practical method for defining the fraction of normal, strike-slip and thrust fault components for an earthquake and are a new graphical method for displaying source properties of groups of earthquakes. We apply these methods to the Harvard centroid moment tensor catalog to study the characteristics of shallow earthquakes (<50 km depth) within 200 km of typical ridge-transform and subduction zone plate boundaries. In this way, we have reached four major conclusions. First, even along relatively simple plate boundaries, there is considerable variation in the type and orientation of earthquake mechanisms. Second, along individual plate boundaries, groups of thrust, normal, or strike-slip earthquakes generally have Cs equal to 0.8 or higher. Thus for many types of tectonic analyses it is unnecessary to add moment tensors to study seismic deformation; rather, it is sufficient to add scalar earthquake moments of the individual events. Third, moment tensors for some individual earthquakes are quite different from those produced by slip along a planar fault. However, summing up moment tensors shows that the deformation pattern produced by groups of earthquakes is generally more like fault slip than the pattern of typical earthquakes within the group. Fourth, by dividing the sum of moments by the velocity of plate motion and the length of the boundary, we calculate R_{mom}, the efficiency of seismic moment produced along individual plate boundaries. For the 12.75 years of data available, normal fault earthquakes along spreading ridges produce moment less efficiently than strike-slip earthquakes along transforms. These in turn produce moment less efficiently than thrust earthquakes along subduction zones.

Key words: Moment tensors; focal mechanisms; seismic consistency; Harvard centroid moment tensor catalog; scalar earthquake moments.

- **Earthquake mechanisms and tectonics in the Assam-Burma region. B.K. Rastogi, J. Singh and R.K. Verma. *Tectonophysics, Volume 18, Issues 3–4, July 1973, Pages 355–366.***

Abstract:

Eleven new focal mechanisms from earthquakes in the Assam-Burma region have been determined using P-wave first-motion directions reported in the *Bulletins of the International Seismological Centre (Edinburgh)*. Out of them, eight mechanisms indicate thrust faulting, two normal faultings and one strike-slip faulting. In the thrust type of mechanism solutions, sense of motion on the shallow dipping of the two nodal planes is consistent with underthrusting beneath the arc-like mountain ranges. Seismic slip vectors strike in almost northerly direction along the eastern Himalayas and in almost easterly direction along the Burmese arc. A predominance of thrust faulting is consistent with geological evidences of thrusting and uplift in the Himalayas and the Assam-Burma region.

Key words: Focal mechanisms; thrust faulting; normal faulting; strike-slip faulting; nodal plane.

- **Earthquake mechanisms in the Himalayan, Burmese, and Andaman Regions and continental tectonics in Central Asia. T.J. Fitch.** ***J. Geophys. Res. (1970), 75(14), 2699–2709, Doi:10.1029/JB075i014p02699.***

Abstract:

Focal mechanisms are presented for thirteen earthquakes between Hindu Kush and Sumatra, including four shallow-focus events along the Himalayan mountain front and two events at intermediate depth beneath the Burmese mountains. All mechanisms are based on first-motion P- and S-wave data recorded by long-period instruments. The mechanisms along the Himalayan front confirm the existence of thrust faulting for which there is post-Mesozoic geologic evidence. Additional evidence for thrust faulting in central Asia comes from focal mechanisms based on other seismic data published recently by Russian investigators. The axis of minimum compression (the T axis) at intermediate depths beneath the Burmese mountains is oriented approximately down the dip of the seismic zone, as are T axes at intermediate depths in several other seismic zones. A mechanism solution consistent with strike slip faulting and another consistent with normal faulting were derived from two shallow earthquakes in western China. One shallow earthquake within the Himalayas yielded a normal faulting mechanism, as did one event from the western margin and two events near the northern border of the Andaman Sea. Slip vectors consistent with underthrusting beneath the Himalayas have a nearly uniform north to northeasterly strike. This evidence, as well as the frequency of occurrence of large-magnitude earthquakes, suggests that seismic slip at shallow depths may account for the convergence between the Indian Ocean and the Eurasian plates along the Himalayan mountain front.

Keywords: Asia: Tectonophysics; Earthquakes: Mechanism; Faults: Thrust; Seismology: Seismic Sources; Tectonophysics: Crustal Structure.

- **Earthquake processes of the Himalayan collision zone in eastern Nepal and the southern Tibetan Plateau. T.L. de la Torre, G. Monsalve, A.F. Sheehan, S. Sapkota and F. Wu.** ***Geophys. J. Int. (2007) 171, 718–738 doi: 10.1111/j.1365-246X.2007.03537.x.***

Abstract:

Focal mechanisms determined from moment tensor inversion and first motion polarities of the Himalayan Nepal Tibet Seismic Experiment (HIMNT) coupled with previously published solutions show the Himalayan continental collision zone near eastern Nepal is deforming by a variety of styles of deformation. These styles include strike-slip, thrust and normal faulting in the upper and lower crust, but mostly strike-slip faulting near or below the crust–mantle boundary (Moho). One normal faulting earthquake from this experiment accommodates east–west extension beneath the Main Himalayan Thrust of the Lesser Himalaya while three upper crustal normal events on the southern Tibetan Plateau are consistent with east–west extension of the Tibetan crust. Strike-slip earthquakes near the Himalayan Moho at depths >60 km also absorb this continental collision. Shallow plunging P-axes and shallow plunging EW trending T-axes, proxies for the predominant strain orientations, show active shearing at focal depths 60–90 km beneath the High Himalaya and southern Tibetan Plateau. Beneath the southern Tibetan Plateau the plunge of the P-axes shift from vertical in the upper crust to mostly horizontal near the crust–mantle boundary, indicating that body

forces may play larger role at shallower depths than at deeper depths where plate boundary forces may dominate.

Key words: Focal mechanisms; Tibetan Plateau; earthquake depths; The Himalaya, Nepal; continental collision.

- **Earthquake swarms precursory to moderate to great earthquakes in the northeast India region. H.K. Gupta and H.N. Singh.** ***Tectonophysics, Volume 167, Issues 2–4, 10 October 1989, Pages 285–298.***

Abstract:

The northeast India region has seen ten $M \geqslant 7\frac{1}{2}$ earthquakes since 1897, including two great earthquakes of $M = 8.7$ in 1897 and 1950. The last $M \geqslant 7\frac{1}{2}$ earthquake occurred on August 17, 1952. With the exception of three earthquakes others are found to be associated with periods of background/normal seismicity, precursory swarms, quiescence and mainshocks (and the associated foreshocks and aftershocks). The dataset has been critically examined for completeness considering the current capabilities for defining locations and also considering other parameters. Regression equations relating the mainshock magnitude (*Mm*), the average magnitude of the largest two events in the swarm (*Mp*) and the time interval (*Mp*) between the beginning of the swarm and the mainshock have been developed. These are: $Mm = 1.37Mp - 1.41$ and $Mm = 3log_{10}Tp - 3.27$. It is important to recognize precursory swarms and quiescence in real time; indeed, we believe we have recognized one such sequence in the vicinity of the Arakan Yoma Fold Belt. On the basis of Mp_{-} and Tp_{-} values, the lateral extent of swarm activity and the fact that no event of $M > 6$ has occurred since 1975 in the preparation zone defined by the 1963–1965 swarm, we estimate that an $M \sim 8$ earthquake could occur at any time in the area bounded by 21° and $25\frac{1}{2}$° N and 93° and 96° E. The focal depth of this impending earthquake is estimated to be 100 ± 40 km in view of the focal depths of the other events in the swarm.

Key words: Precursory swarms; background/normal seismicity; quiescence; mainshock; regression equation.

- **Estimation of crustal discontinuities from reflected seismic waves recorded at Shillong and Mikir Hills Plateau, Northeast India. Saurabh Baruah, Dipok K. Bora and Rajib Biswas.** ***Int. J. Earth Sci. (Geol Rundsch) (2011) 100:1283–1292, Doi:10.1007/s00531-010-0541-2.***

Abstract:

In this study, an attempt is made to determine seismic velocity structure of the crust and upper mantle beneath the Shillong-Mikir Hills Plateau in northeast India region. The principle of the technique is to relate seismic travel times with crustal thickness above the Conrad and Moho discontinuities. Broadband digital waveforms of the local earthquakes make a precise detection of the seismic phases possible that are reflected at these discontinuities. The results show that the Conrad discontinuity is at 18–20 (±0.5) km beneath the

Shillong-Mikir Hills Plateau and the Moho discontinuity is at 30 ± 1.0 km beneath the Shillong Plateau and at 35 ± 1.0 km beneath the Mikir Hills.

Keywords: Conrad and Moho discontinuities; Reflected seismic waves; Shillong and Mikir Hills Plateau; Travel time.

- **Evidences for cessation of Indian Plate Subduction in the Burmese Arc Region. N. Purnachandra Rao and M. Ravi Kumar. *Geophysical Research Letters, Volume 26, Issue 20, (/doi/10.1002/grl.v26.20/issuetoc), pages 3149–3152, 15 October 1999.***

Abstract:

The issue of whether subduction is still active in the India-Burma plate boundary zone has been rather controversial. While the presence of an eastward dipping Indian lithospheric slab is undisputed, different opinions have been voiced regarding the continuance of subduction at present. Analysis of the Harvard CMT data in comparison with major subduction zones of the world demonstrates that the Burmese arc is a unique region where there is a subducted slab but the direction of plate motion is nearly perpendicular to the down-dip direction. We propose a major right-lateral shearing of the Indian plate along with its subducted slab past the Burmese plate in the NNE direction.

Key words: Burmese arc; Harvard CMT data; right-lateral shearing.

- **Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere. Wang-Ping Chen and Peter Molnar. *Journal of Geophysical Research, Vol.88, No. B5, Pages 4183- 4214, May 10, 1983.***

Abstract:

We investigate the distribution of focal depths for earthquakes that do not appear to be associated with zones of recent subduction, using both new results from analyses of individual events recorded at teleseismic distances and published data for both microearthquakes and larger events. The deepest events in oceanic regions occur in old lithosphere (>100Ma), and excluding earthquakes in active mountain belts, the deepest crustal events occur in old cratons (tectonic age ≥ 800 Ma). Therefore, the temperature at the source region is likely to be an important factor determining whether deformation occurs seismically or not. From estimates of the temperatures at depths of the deepest events, we conclude that those limiting temperatures are about 250^o–450^oC and 600^o– 800^oC for crustal and mantle materials, respectively. In several regions of recent continental convergence, in addition to shallow crustal seismicity , there is seismic activity in the uppermost mantle. The lower crust, however, is essentially aseismic. We infer that both the upper crustal and the mantle seismic regions correspond to zones of relatively high strength and that they are separated by a zone of lower strength in the lower crust where aseismic, ductile deformation predominates. This simple interpretation is qualitatively in agreement with extrapolated values of brittle and ductile strengths of geologic materials studied under appropriate pressure and temperature conditions in the laboratory. A low-strength zone in the lower crust might allow detachment of crystalline nappes from the underlying mantle (and lower crustal) lithosphere. The apparently greater strength of mantle materials than crustal materials at the same temperature implies that

oceanic lithosphere is much stronger than continental lithosphere, and this difference may account for why plate tectonics works well in oceanic regions but not in continents.

Key words: Intracontinental and intraplate earthquakes; teleseismic; aseismic; nappes.

- **Ground motion estimation at Guwahati city for an *M*$_w$ 8.1 earthquake in the Shillong plateau. S.T.G. Raghu Kanth, S. Sreelatha and Sujit Kumar Dash. *Tectonophysics, Volume 448, Issues 1–4, 25 February 2008, Pages 98–114.***

Abstract:

In this paper, the ground motion at Guwahati city for an 8.1 magnitude earthquake on *Oldham fault* in the Shillong plateau has been estimated by stochastic finite-fault simulation method. The corresponding acceleration time histories on rock level at several sites in the epicentral region have been computed. These results are validated by comparing them with the estimates obtained from Medvedev–Sponheuer–Karnik (MSK) intensity observations of 1897 Shillong earthquake. Using the local soil parameters, the simulated rock level acceleration time history at Guwahati city is further amplified up to the ground surface by nonlinear site response analysis. The results obtained are presented in the form of peak ground acceleration (PGA) contour map. The maximum amplification for PGA over Guwahati city is as high as 2.5. Based on the simulated PGA, the liquefaction susceptibility at several locations in the city has been estimated. The results are presented in the form of contours of factor of safety against liquefaction at different depths below the ground surface. It is observed that over a large part of the Guwahati city, the factor of safety against liquefaction is less than one, indicating that the city is highly vulnerable to liquefaction in the event of this earthquake. The contour maps obtained can be used in identifying vulnerable areas and disaster mitigation.

Key words: Stochastic finite-fault simulation method; MSK intensity scale; peak ground acceleration; liquefaction.

- **Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, Northeast India earthquake: Implications for regional tectonism. C.P. Rajendran, K. Rajendran, B.P. Duarah, S. Baruah and A. Earnest. *Tectonics (2004), 23, TC4009, doi:10.1029/2003TC001605.***

Abstract:

The 1897 Shillong (Assam), northeast India, earthquake is considered to be one of the largest in the modern history. Although Oldham's [1899] classic memoir on this event opened new vistas in observational seismology, many questions on its style of faulting remain unresolved. Most previous studies considered this as a detachment earthquake that occurred on a gently north dipping fault, extending from the Himalayan front. A recent model proposed an alternate geometry governed by high-angle faults to the north and south of the plateau, and it suggested that the 1897 earthquake occurred on a south dipping reverse fault, coinciding with the northern plateau margin. In this paper, we explore the available database, together with the coseismic observations from the region, to further understand the nature of faulting. The geophysical and geological data examined in this paper conform to a south dipping structure, but its location is inferred to be in the Brahmaputra basin, further north of the present plateau front. Our analyses of paleoseismic data suggest a 1200-year interval between

the 1897 event and its predecessor, and we identify the northern boundary fault as a major seismic source. The Shillong Plateau bounded by major faults behaves as an independent tectonic entity, with its own style of faulting, seismic productivity, and hazard potential, distinct from the Himalayan thrust front, a point that provides fresh insight into the regional geodynamics.

Keywords: Earthquake, tectonics, paleoseismology, faulting, seismicity, northeast India.

- **Mapping of b-value beneath the Shillong Plateau. P.K. Khan. *Gondwana Research, Volume 8, Issue 2, April 2005, Pages 271–276.***

Abstract:

The seismic parameter 'b' has been computed over rectangular grid of dimension 0.3° - 0.8° at four depths range: 0-13 km (first layer), 13.1-26 km (second layer), 26.1-39 km (third layer) and 39.1-52 km (fourth layer) beneath the Shillong Plateau area. The four depths were carefully selected based on the crustal structure and distribution of hypocentres. The dimension of each grid was chosen so as to have enough events that can represent the b-value at the respective layer. Finally, two-dimensional mapping was done at these depth-levels considering the respective b-value over each grid. This analysis includes viz., low b-value all through the first layer, and a trend of increasing b-value, which was initially towards north, changes to northwest. Eastern and western parts of the second and third layers document almost moderate b-values, whereas the north-south-oriented central part of layer second is apparently dominated by low b-values, which seems to divide the area broadly into three parallel zones based on b-values. In the deeper part (fourth layer) beneath the Shillong Plateau a moderate b-value that was initially trending towards north becomes high near the northeastern part. This phenomenon may be associated with higher heterogeneity of the medium, and interestingly, this region lies between the lower crust and upper mantle, possibly documents lower degree of seismic coupling, where the Shillong Plateau is being supported by the strong Indian lithosphere at these depths. In addition, minima were noted towards the southern parts of layers first, second and third, which may presumably be related with steeply Bouguer gravity anomaly. It is thus less clear that the occurrence of earthquakes beneath the Shillong Plateau whether is attributed to faults or lineaments at intermediate to deeper level. However, a correlation between high b-values in few parts of each layer and deep-seated minor faults cannot be ruled out.

Key words: Crustal structure; b-value; Bouguer gravity anomaly; seismic coupling; strong Indian lithosphere.

- **Microearthquake activity in some parts of the Himalaya and the tectonic model. J.R Kayal. *Tectonophysics, Volume 339, Issues 3–4, 30 September 2001, Pages 331–351.***

Abstract:

Microearthquake data from temporary/permanent networks in different parts of the Himalaya shed new light on understanding the earthquake generating processes and their relation to tectonic models of the region. The microearthquake activity in Arunachal Pradesh, northeastern Himalaya, is found to be pronounced at the Main Boundary Thrust (MBT) and to its south; the subcrustal earthquakes (depth 50–80 km) occur much below the *plane of detachment* of the tectonic models proposed by and . The MBT is not the seismogenic fault;

the earthquakes are generated by strike–slip movement on deep seated hidden faults, transverse to the MBT. The high seismic activity in the Shillong Plateau, about 200 km south of the MBT in the northeast region, is due to the influence of Himalayan collision tectonics to the north and Burmese arc subduction tectonics to the east. The activity in the Plateau is not directly related to the Himalayan thrust belt or seismic belt. These are mostly crustal earthquakes (depth 10–30 km), and are caused by local active faults/lineaments. In the eastern Himalaya, in the Sikkim and Darjeeling area, the seismic activity is found to be clustered mostly to the north of the MBT. The earthquakes occur at a depth range 0–50 km; the majority of them occur below the detachment plane by thrust-faulting. In the central part, in the Nepal Himalaya, lateral variations of the seismic activity are observed, which represent lateral segmentation of the MBT by transverse tectonic features. In the western Himalaya, however, the tectonic models fit well with the microearthquake data. In the Himachal Pradesh of the western Himalaya, the microearthquakes are mostly recorded in the MBT zone, and the hypocentres (depth 0–20 km) are confined above the plane of detachment or on the Basement Thrust. The earthquakes mostly occur to the south of the Main Central Thrust (MCT), which suggests that the MCT is not seismogenic; it is rather a dormant fault. No single tectonic model explains the Himalayan earthquakes.

Keywords: Microseismicity; b-value; aseismic; seismotectonics; fault-plane solution.

- **Microearthquakes at the main boundary thrust in Eastern Himalaya and the present-day tectonic model. J.R. Kayal, De Reena and P. Chakraborty. *Tectonophysics, Volume 218, Issue 4, 28 February 1993, Pages 375–381.***
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Abstract:

Two microearthquake surveys were carried out at the Main Boundary Thrust (MBT), Eastern Himalaya. Temporal as well as spatial variation in microseismicity was observed. The vertical section of the hypocentres shows subcrustal earthquakes down to a depth of 80 km to the south of the MBT and composite focal mechanisms show strike-slip solutions or transverse tectonics which do not agree with the conceptual tectonic model.

Key words: Microearthquake; MBT; strike-slip solutions; transverse tectonics.

- **Moho geometry and upper mantle images of northeast India. D. S. Ramesh, M. Ravi Kumar, E. Uma Devi, P. Solomon Raju and X. Yuan. *Geophysical Research Letters, Volume 32, Issue 14, 28 July 2005, Doi: 10.1029/2005GL022789.***

Abstract:

Images of the crust and mantle beneath northeast India obtained by 2D migration of 1000 broadband P-receiver functions clearly trace a northward dipping Moho from the Himalayan foredeep reaching depths up to 50 km further north beneath the Himalayan convergence zone. Also, these images reveal presence of largely coherent 410-km and 660-km discontinuities that conform to the IASP91 model. Marginal variations in the depth of the 410-km interface are observed, that appear region specific. The thickness of the mantle transition zone does not deviate significantly from a global average of 250 km. Interestingly, our results reveal consistent presence of a signal from an interface around 300 km. Origin of such a boundary, known as X-discontinuity and unrelated to the Lehmann discontinuity, is dis-

cussed. Possible presence of the X-discontinuity from the Indian region is reported here for the first time.

Key words: Moho geometry; X-discontinuity; Lehmann discontinuity.

- **Occurrence of anomalous seismic activity preceding large to great earthquakes in northeast India region with special reference to 6 August 1988. H.N. Singh, D. Shanker and V.P. Singh. *Physics of the Earth and Planetary Interiors, 148 (2005), 261–284.***

Abstract:

Seismicity database from 1860 to 1985 of northeast India region bounded by the area 20◦–32◦N and 82◦–100◦E have been analyzed for the identification of precursory swarm/anomalous seismic activity preceding large to great earthquakes with M≥7.5. It is observed that with the exception of three earthquakes (1908, 1912 and 1918), the large earthquakes of 1897, 1946, 1947, 1950 and 1951/1952 were preceded by well-developed epoch of swarm/anomalous seismic activity in space and time well before their occurrence. The seismicity is observed to fluctuate in the order of low-high-low ranging from 0–0.5, 01–33 to 0–0.7 events/year prior to these mainshocks during the epochs of normal/background, swarm/anomalous and gap/quiescence respectively. The duration of precursory gap is observed to vary from 11 to 17 years for mainshocks of M 7.5–8.0 and from 23 to 27 years for M 8.7 and this period is dependent on the magnitude of the mainshocks. Using the values of magnitude of mainshock (Mm), average magnitude of swarm (Mp) and the precursory time gap (Tp), the following predictive equations are established for the region: Mm = 1.37Mp − 1.40 and Mm = 3 log Tp − 3.27. All the major earthquakes with mb ≥6.1 occurred during 1963–1988 have been investigated for their association with anomalous seismicity/precursory swarms using the events with cutoff magnitude mb ≥4.5. Eleven such events have occurred in the region during the period except one earthquake of 29 May 1976. All the remaining 10 earthquakes were associated in some forms of anomalous seismicity epochs. Well-defined patterns of anomalous seismicity are observed prior to 1964–1965, 12 August 1976 and 30 December 1984 (mb 5.6). All these mainshocks are preceded by seismicity patterns in the order of low-high-low similar to that observed prior to the mainshocks from 1897 to 1962. The anomalous seismicity epoch is delineated with extremely high annual earthquake frequency, which was preceded and followed by extremely low seismicity epochs of background and gap/quiescence phases. Consequently, seismicity rates during anomalous seismicity epoch have always been above normal (1event/year) whereas it is always below normal during the preceding and the following epochs. A prediction was made using the 1964 swarm based on the Mp and Tp values that a large earthquake with M 8±0.5 with focal depth 100±40 km could occur any time from 1986 to 1990 in an area bound by 21◦–25 5◦N latitudes and 93◦–96◦E longitude in Arakan Yoma fold belt. It is interesting to note that the 6 August 1988 earthquake with magnitude 7.5 and focal depth 115 km had occurred within the delineated zone. In addition, three consecutive swarm activities are identified in a limited area within the Eastern Syntaxis and these were not followed by any mainshock till date and could be potential zone for future earthquake.

Keywords: Anomalous seismic activity; Quiescence; Precursory swarm; Precursory time gap; Seismicity rates.

- **Partial and complete rupture of the Indo-Andaman plate boundary 1847-2004. R. Bilham, E.R. Engdahl, N. Feldl and S.P. Satyabala.** ***Seism. Res. Lett. (2005), 21p.***

Abstract:

We review seismicity along the Nicobar/Andaman plate boundary prior to the Mw=9 earthquake of 26 December 2004, with particular attention to reverse slip in the central and northern parts of the rupture zone 600-1300 km north from the epicenter. Slip is partitioned between convergence and strike-slip motion, which in the northern Andamans is assisted by back-arc spreading. Subduction zone earthquakes prior to the rupture occurred largely to the east, and at deeper depths than the area ruptured in the shallow 2004 megathrust. Large thrust earthquakes in 1847 (Mw>7.5), 1881 (Mw=7.9) and 1941 (Mw=7.7) appear to have occurred on intermediate regions of the down-dip boundary, areas that have been surrounded and probably incorporated into the 2004 rupture. Preliminary reports of 1-4 m of subsidence of the Nicobar islands and 1-2 m uplift of western shorelines of the Andaman islands are consistent with a down-dip fault width of 150-180 km, and a slip of 7-23 m. Based on preliminary reports from the Port Blair tide gage, slip in the Andaman islands, 800 km north of the epicenter, appears to have started no sooner than 36 minutes after the main shock, some 30 minutes after the primary mainshock rupture is inferred to have arrived from the epicenter, but consistent with large aftershocks occurring in this region 85 minutes after the mainshock, and suggestive of slow slip. The delayed slip was not accompanied by shaking except that from aftershocks. GPS measurements in the Andaman islands prior to the earthquake indicate a plate convergence rate of 14 mm/year suggesting that great earthquakes with similar slip to the 2004 event cannot occur more frequently than once every 1000 years. A shorter recurrence interval of 400 years is calculated for the epicentral region where convergence rates are higher. The apparent indifference of the 2004 earthquake to the lowered slip deficits caused by previous major earthquakes, and its release of significant seismic moment without evidence for comparable shaking, has implications for the analysis of historical earthquakes in other plate boundaries.

Key words: Rupture zone; strike-slip motion; reverse slip; down-dip fault; GPS.

- **Plate motion of India and interseismic strain in the Nepal Himalaya from GPS and DORIS measurements. Pierre Bettinelli, Mireille Flouzat, Laurent Bollinger, Jean-Philippe Avouac, Francois Jouanne, Pascal Willis, Gyani Raja Chitrakar.** ***J. Geod.(2006), Doi:10.1007/s00190-006-0030-3.***

Abstract:

We analyse geodetically estimated deformation across the Nepal Himalaya in order to determine the geodetic rate of shortening between Southern Tibet and India, previously proposed to range from 12 to 21mmyr−1. The dataset includes spirit-levelling data along a road going from the Indian to the Tibetan border across Central Nepal, data from the DORIS station on Everest, which has been analysed since 1993, GPS campaign measurements from surveys carried on between 1995 and 2001, as well as data from continuous GPS stations along a transect at the longitude of Kathmandu operated continuously since 1997. The GPS data were processed in International Terrestrial Reference Frame 2000 (ITRF2000), together with the data from 20 International GNSS Service (IGS) stations and then combined using quasi-observation combination analysis (QOCA). Finally, spatially complementary velocities at stations in Southern Tibet, initially determined in ITRF97, were expressed in ITRF2000.

After analysing previous studies by different authors, we determined the pole of rotation of the Indian tectonic plate to be located in ITRF2000 at 51.409±1.560◦ Nand−10.915± 5.556◦E, with an angular velocity of 0.483±0.015◦. Myr−1. Internal deformation of India is found to be small, corresponding to less than about 2mmyr−1 of baseline change between Southern India and the Himalayan piedmont. Based on an elastic dislocation model of interseismic strain and taking into account the uncertainty on India plate motion, the mean convergence rate across Central and Eastern Nepal is estimated to 19 ± 2.5mmyr−1, (at the 67% confidence level). The main Himalayan thrust (MHT) fault was found to be locked from the surface to a depth of about 20km over a width of about 115 km. In these regions, the model parameters are well constrained, thanks to the long and continuous time-series from the permanent GPS as well as DORIS data. Further west, a convergence rate of 13.4 ± 5mmyr−1, as well as a fault zone, locked over 150 km, are proposed. The slight discrepancy between the geologically estimated deformation rate of 21 ± 1.5mmyr−1 and the 19 ± 2.5mmyr−1 geodetic rate in Central and Eastern Nepal, as well as the lower geodetic rate in Western Nepal compared to Eastern Nepal, places bounds on possible temporal variations of the pattern and rate of strain in the period between large earthquakes in this region.

Keywords: GPS; DORIS; Interseismic deformation; Tectonic plate convergence; Himalayas of Nepal.

- **Plateau Pop-up during the 1897 Assam earthquake. R. Bilham and P. England. *Nature(Lond), 410, 806-809, 2001.***

Abstract:

The great Assam earthquake of 12 June 1897 reduced to rubble all masonry buildings within a region of NE India roughly the size of England, and its felt area exceeded that of the 1755 Lisbon Earthquake1. Hitherto it was believed that rupture occurred on a north-dipping Himalayan thrust propagating south of Bhutan 2,3,4,5. We show here that this view is incorrect. The northern edge of the Shillong Plateau rose violently more than 11 m during rupture of a buried, 110-km-long, reverse fault, dipping steeply away from the Himalaya. The stress drop implied by the rupture geometry and the prodigious fault slip of 18±7 m, explains observed epicentral accelerations exceeding 1 g vertically, and surface velocities exceeding 3 m/s1. Our finding represents the first quantitative observation of active deformation of a "pop-up" structure, and confirms that faults bounding such structures can penetrate the whole crust. Plateau uplift in the past 2-5 million years has caused the Indian plate to contract locally by 4±2 mm/year, reducing seismic risk in Bhutan, but increasing it to the large populations of northern Bangladesh.

Key words: Shillong Plateau; rupture geometry; epicentral acceleration.

- **Pop-up tectonics of the Shillong Plateau in the great 1897 earthquake (Ms 8.7): Insights from the gravity in conjunction with the recent seismological results. G.K. Nayak, V.K. Rao, H.V. Rambabu and J.R. Kayal. Tectonics (2008), 27, TC1018, Doi:10.1029/2006TC002027.**

Abstract:

It was reported that a hidden 110-km-long south dipping fault, named Oldham Fault, was responsible for the 1897 great earthquake (Ms 8.7) in the Shillong Plateau by reverse faulting due to ‘pop-up’ tectonics of the plateau in northeast India. Here we report the results of our geophysical investigations, where we critically examine the crustal structure of the plateau on the basis of gravity modeling and attempt to shed light on the hitherto debated hidden Oldham Fault at the northern boundary of the Shillong Plateau. Our gravity model, constrained by broadband seismological data, suggests that the Moho beneath the Shillong Plateau is at a shallower depth of about 35 km when compared to the Bengal basin to the south and the Assam valley to the north, which is about 42 km. Thinning of the crust under the plateau may be a consequence of the ‘pop-up’ mechanism. To examine the possible ‘pop-up’ of the plateau during the great 1897 earthquake, we have estimated the energy released by this earthquake and compared it with the energy required for the ‘pop-up’ of the plateau, using a simplistic rigid model. It is found that the Shillong Plateau between the Oldham Fault and Dauki-Dapsi Thrust would require an energy of 4.5 _ 1019 J, which does match well with the energy released by the great earthquake of Ms = 8.7.

Keywords: Shillong Plateau; pop-up tectonics; Bouguer gravity.

- **Precursory variation of seismicity rate in the Assam area, India. K. Khattri and M. Wyss. *Geology, Vol. 6, No. 11, pp. 685-688, Doi: 10.1130/0091-7613 (1978) 6<685:PVOSRI> 2.0.CO,2.***

Abstract:

The seismicity data from 1825 to the present for the Assam (northeastern India) region show that seismicity rates there deviate from normal before and after major earthquakes. Along this 1,000-km-long section of a plate boundary, all shocks with magnitude M > 6.6 were preceded and sometimes followed by periods of significant seismic quiescence. No major earthquakes occurred without an associated seismic quiescence, and no such quiescence occurred at times other than before or after a major event. The most remarkable periods of quiescence lasted about 28 and 30 yr before the two great (M = 8.7) Assam earthquakes of 1897 and 1950. Other periods of anomalously low seismicity preceded main shocks of magnitudes 6.7 (in 1950 and 1975), 7.8 (in 1869), and 7.7 (in 1947), with durations of 6, 8, 23, and 17 yr, respectively. These durations fit (with approximately the scatter of the original data) a published relation between precursor time and magnitude. Since these changes of seismicity rate were observed at the edges of and within the Assam gap, defined by the 1897 and 1950 great earthquakes, it is likely that a future major or great earthquake in this gap will be preceded by seismic quiescence. Whether a preparatory phase for an earthquake has begun in the Assam gap cannot be stated for certain because of the changing earthquake detection capability in the area and because of poor location accuracy.

Key words: Seismic quiescence; Assam gap; precursor time and magnitude.

- **Seismic activity at the MCT in Sikkim Himalaya. Reena De and J.R.. Kayal. *Tectonophysics, Volume 386, Issues 3–4, 16 August 2004, Pages 243–248.***

Abstract:

A microearthquake survey in the Sikkim Himalaya raised a question whether the north–south segment of the Main Central Thrust (MCT) in this part of the Himalaya is seismically active(?). Fault-plane solution of a cluster of events occurred below this segment of the MCT shows right-lateral strike-slip motion. The seismic observations and the geological

evidences suggest that a NNE–SSW trending strike-slip fault, beneath this segment, caused right lateral movement on the MCT, and is seismically active.

Keywords: Microearthquakes; fault-plane solution; active fault; seismotectonics.

- **Seismicity, earthquake mechanisms and tectonics along the Himalayan mountain range and vicinity. Umesh Chandra.** ***Physics of the Earth and Planetary Interiors, Volume 16, Issue 2, March 1978, Pages 109–131.***

Abstract:

The historical as well as recent seismicity data and the focal mechanism solutions for 48 earthquakes determined from the observations of world-wide standardized stations network (WWSSN) records, were used to investigate the tectonics of the Himalayan mountain system and vicinity. Seismicity maps of the region showing large earthquakes (magnitude 7.0 and above, and damaging earthquakes that caused fatalities) from the earliest time through 1976, and instrumentally located earthquakes for the period January 1963–March 1974 are presented. Eleven of these earthquakes are estimated to be of magnitude 8.0 and above. The earthquake epicenters generally follow the trend of the mountains with greatest concentrations of seismic activity occurring along the Hindu Kush and Pamir mountain ranges, and near the Quetta, Kashmir and Assam syntaxes. Throughout Tibet, however, the distribution of epicenters is rather irregular and no clear trends are apparent. Two aseismic lineaments, one west of the Sulaiman Range and the other in the Assam Valley, are identified. Also, seismic activity in the vicinity of the Counter Thrust (Indus-Tsangpo suture zone) is rather small. Based on the identification of these aseismic lineaments and from a consideration of the geometry and kinematics of the continental collision model, a hypothesis for the origin of the Himalayan syntaxes is presented. Focal mechanism solutions confirm northward underthrusting of the Indian Plate along the Main Boundary Thrust and Main Central Thrust system, and eastward underthrusting along the Burmese Arc. Fault-plane solutions indicate left-lateral motion along the Kirthar-Sulaiman Range, right-lateral motion along the Karakoram Fault, left-lateral motion along the eastern extremity of the Himalayan flank of the Assam syntaxis, and right-lateral motion along the northern part of the Naga Hill flank of the syntaxis. These observations are in agreement with the expected sense of lateral (parallel to the collision boundary) mass movement for the continental collision model. Focal mechanism solutions for three earthquakes in east Afghanistan show NW-SE compression. A near-vertical orientation of the axes of tension in the solutions for two earthquakes in the Hindu Kush region is consistent with the sinking of a remnant slab of oceanic lithosphere. Normal fault-plane solutions showing NW-SE extension for two events near Gatok, Tibet, and for the recent Kinnaur earthquake are interpreted to indicate a possible subsurface northern continuation of the Aravalli Range of Peninsular India, and its involvement in the tectonic framework of the region. Focal mechanism solutions of three earthquakes near the southern edge of the Shillong Plateau suggest block uplift of the plateau as a horst along the Dauki Fault. The solution for one earthquake near the Yunnan Graben shows NE-SW extension.

Key words: Historical seismicity data; recent seismicity data; focal mechanism solution.

- **Seismic moments of major earthquakes and the average rate of slip in Central Asia. Wang-Ping Chen and Peter Molnar.** ***Journal of Geophysical Research, Vol.82, No.20, July 10, 1977.***

Abstract:

Seismic moments for 12 major earthquakes (M ≥ 7.6) in Central Asia From 1911 to 1967 were calculated from long-period Rayleigh and Love wave spectral densities. With fault lengths estimated from geological field observation of surface faulting, intensity distributions, or master event relocations of aftershocks, the calculated moments place bounds on the average slip and fault widths. The following table summarizes the calculated moments, estimated faults lengths, and inferred possible average displacements.

Earthquake Location	Year	M_o, dyn-cm	Length, km	Slip, m
1. Kebin, Kirgizia	1911	4.9×10^{27}	180	2.3
2. Haiyuan, Kansu	1920	3.0×10^{28}	200	10
3. Ku-long, Kansu	1927	4.3×10^{27}	150	2.4
4. Fuh-Yun, Sinkiang	1931	8.5×10^{27}	300	1.9
5. Bihar- Nepal	1934	1.1×10^{28}	130	5.4
6. Eastern Himalaya	1947	9.8×10^{26}	?	?
7. Khait, Tajikistan	1949	2.4×10^{27}	70	3.7
8. Assam, India	1950	4.0×10^{28}	250	6.6
9. South Tibet	1951	4.6×10^{27}	200	?
10. Muya, Siberia	1957	1.4×10^{27}	35	4.5
11. Gobi- Altai, Mongolia	1957	1.3×10^{26}	270	3.2
12. Mogod, Mongolia	1967	3.8×10^{26}	40	1.0

The inferred average displacements on the faults, in general, agree with field observations, if in some cases rupture zones extend to 40 km depth p^P for some other earthquakes in Asia indicate focal depths of 40 km and support the inference of brittle failure to the same depth. The average strain pattern caused by seismic slip shows a nearly north-south horizontal compression (or shortening), a considerable amount of vertical expansion of the crust (uplift and crustal thickening), and some nearly east-west horizontal extension. For different assumptions about recurrence rates of large and small earthquakes the calculated shortening for a layer 40 km thick is about 20 mm/yr. It is tempting to infer that the remainder of 50 mm/yr convergence between India and Eurasia occurs as fault creep. As this rate is inversely proportional to the assumed thickness of the layer, given the uncertainties in the estimates of the moments, all if this convergence could occur as seismic slip without fault creep in a layer 40 but not 100m thick. Similarly, the calculated seismic slip rate seems to be too high for all of the seismic slip to be confined to a thin layer such as the San Andreas fault (~10 km).

Key words: Seismic moment; long-period Rayleigh density; Love wave spectral density.

- **Seismicity and plate deformation below the Andaman arc, northeastern Indian Ocean. Sujit Dasgupta and Manoj Mukhopadhyay. *Tectonophysics, 225 (1993), 529-542.***

Abstract:

The seismic activity originating below the Andaman arc-Sea region is generally discernible into fore- and back-arc seismic zones which are traceable for nearly 1500 km in a N-S direction at the junctures between the Indian, Burma and SE Asia plates. The fore-arc seismicity displays an east-dipping (40–55°) Benioff zone upto about 200 km focal depths. Details of the Benioff zone, in correspondence to the observed gravity field, are discussed in four N-S sectors, which suggest some significant variations in the configuration of the Benioff zone. The back-arc seismicity affects only the top 40–45 km of the lithosphere below the Andaman Sea, where the back-arc spreading ridge splits the volcanic arc. Stress distribution and faulting due to earthquakes below the Andaman-West Sunda arc are studied here using 68 focal mechanism solutions. Their most significant results are: low-angle thrust events occur along the upper edge of the descending Indian plate, downdip tensional events have steeply dipping ($\geqslant 60°$) nodal planes, and normal faulting takes place in most parts of the Benioff zone along moderately dipping (30–45°) planes. Downdip compressional events (high-angle reverse fault, nodal plane dip > 60°) or reverse faulting along moderately dipping (30–45°) nodal planes also occur below the Andaman arc. The compressive earthquakes dominate the shallower level of the subducting slab, and the tensional stress observed locally in north part of the Andaman Sea may be an outcome of the weak coupling between the descending and overriding plates. Generally, a more or less complete sequence of faulting i.e., thrusting below the trench, normal faulting below the fore arc, and strike-slip motion along the inner edges of the fore arc characterize the Andaman-West Sunda arc. In the southern Andaman region, a rather oblique convergence between the Indian Ocean and the SE Asia plates is needed to explain the existence of a somewhat contorted Benioff zone, in which, compressional stress dominates in deeper lithosphère. Oceanward, the Ninetyeast Ridge also impinges on the subduction zone in this region. Left-lateral shear motion along the east margin of the Ninetyeast Ridge is further inferred by the results of focal mechanism solutions.

Key words: Fore-arc seismic zones; back-arc seismic zones; focal mechanism solutions.

- **Seismicity and the nature of plate movement along the Himalayan arc, Northeast India and Arakan-Yoma: A review. R.K. Verma and G.V.R. Krishna Kumar. *Tectonophysics, Volume 134, Issues 1–3, 1 March 1987, Pages 153–175.***

Abstract:

The Himalaya together with Arakan-Yoma form a well defined seismic belt to the north and east of the Indian Peninsula. The Seismicity along this belt is attributed mostly to collision between the Indian and the Eurasian plates. However, the exact nature of activity along the major thrusts and faults is not well understood. The seismicity along the entire Himalaya and Northern Burma has been studied in detail. It has been found that besides the Main Boundary Fault and the Main Central Thrust several transverse features are also very active. Some of these behave like steeply dipping fracture zones. Along the Arakan-Yoma most of the seismicity appears to be due to subduction of the Indian lithosphere to the east. Analysis of focal mechanism solutions for the Himalaya shows that although thrust movements are predominant, normal and strike-slip faulting is taking place along some of the transverse features. In addition to thrusting, strike-slip faulting is also taking place along the Arakan-Yoma. Orientation of *P*-axes for all thrust solutions show a sharp change from predominantly east-west along the Burmese arc to N-S and NE-SW along the Himalaya. The direction further changes to NW-SE along the Baluchistan arc. It appears that the Indian lithosphere is under compression from practically all sides. The present day seismicity of Northeast India and Northern Burma can be explained in terms of a plate tectonics model after Nandy (1976). No simple model appears to be applicable for the entire Himalaya.

Key words: Transverse feature; dipping fracture zone; focal mechanism solution.

- **Seismotectonics of transverse lineaments in the eastern Himalaya and its foredeep. Manoj Mukhopadhyay. *Tectonophysics, Volume 109, Issues 3–4, 10 November 1984, Pages 227–240.***

Abstract:

The Himalayan collision zone and the Burmese subduction zone lie in rather close vicinity across northeast India. Their possible interaction produces complex tectonics and a high level of seismicity in the region. Several prominent transverse lineaments across the eastern Himalaya and its foredeep appear to be seismically active. Quite a few of the active lineaments are regionally extensive, even transgressing the Bengal basin. A focal mechanism study indicates that active lineaments are either normal or strike-slip faults. For the highly active Shillong-Mikir massif (a fragmented portion of the Indian shield) this correlation is less clear, although it appears that some of the activity may be associated with the northeasterly lineaments crossing the massif into the eastern Himalayan foredeep. This presumably results due to drag experienced by the Indian lithosphere near its margins under the Himalayan and Burmese arcs. The Assam Valley, which is the common foredeep for both the arcs, is remarkably aseismic though it is surrounded by active regions. Mainly thrusting mechanisms characterize the earthquakes which originate from the Himalayan and Burmese arcs adjoining the Valley. A model of basement reactivation below the Valley is proposed in order to explain the style of tectonic deformation and current seismicity in the Himalayan and Burmese orogens adjoining the Valley.

Key words: Transverse lineaments; foredeep; aseismic.

- **Seismotectonics of the Himalaya and its vicinity from centroid-moment tensor (CMT) solution of earthquakes. D.D. Singh. *Journal of Geodynamics (2000), 30, 507-537.***

Abstract:

The centroid-moment tensor solutions of more than 300 earthquakes that occurred in the Himalayas and its vicinity regions during the period of 1977±1996 are examined. The resultant seismic moment tensor components of these earthquakes are estimated. The Burmese arc region shows prominent east±west compression and north±south extension with very little vertical extension. Northeast India and Pamir±Hindu Kush regions show prominent vertical extension and east±west compression. The Indian plate is subducting eastward beneath the northeast India and Burmese arc regions. The overriding Burmese arc has overthrust horizontally with the underthrusting Indian plate at a depth of 20±80 km and below 80 km depth, it has merged with the Indian plate making ``Y" shape structure and as a result the aseismic zone has been formed in the region lying between 268N±288N and 91.58E±948E at a depth of 10±50 km. Similarly, the Indian plate is underthrusting in the western side beneath the Pamir±Hindu Kush region and the overriding Eurasian plate has overthrust it to form a ``Y" shape structure at a depth of 10±40 km and below 60 km depth, it has merged with the Indian plate and both the plates are subducting below 60±260 km depth. Further south, the overriding Eurasian plate has come in contact with the Indian plate at a depth of 20±60 km beneath northwest India and Pakistan regions with left lateral strike slip motion.

Key words: CMT solution; aseismic zone; left lateral strike slip motion.

- **Seismotectonics in Northeast India: A stress analysis of focal mechanism solutions of earthquakes and its kinematic implications. Jacques Angelier and Saurabh Baruah. *Geophys. J. Int. (2009) doi: 10.1111/j.1365-246X.2009.04107.x.***

Abstract:

In Northeast India, three major plates interact along two convergent boundaries: the Himalayas and the Indo–Burma Ranges, which meet at the Assam Syntaxis. To clarify this tectonic interaction and the underlying dynamics, we determine the regional seismotectonic stress from the stress inversion of 285 double couple focal mechanism solutions of earthquakes with an average magnitude of 5. We then compare the reconstructed stress regimes with the available information about geodetically determined relative displacements. North–south compression, in a direction consistent with India–Eurasia convergence, prevails in the whole area from the Eastern Himalayas to the Bengal Basin, through the Shillong–Mikir Massif and the Upper Assam Valley. E–W extension in Tibet is related to this N–S India–Eurasia convergence. Not only does the major N–S compression affect the outer segments of the Indo–Burma Ranges, it also extends into the descending slab of Indian lithosphere below these ranges, although stresses at depth are controlled by bending of the slab beneath the Burmese arc. The existence of widespread N–S compression in the Bengal Basin, far away from the Himalayan front, is compatible with the previously proposed convergence between a Shillong–Mikir–Assam Valley block and the Indian craton. E–W compression inside this block supports the hypothesis of a component of eastward extrusion. Stress inversion of focal mechanism solutions in the Indo–Burma Ranges reveals a complex stress pattern. The Burmese arc and its underlying lithosphere experience nearly arcperpendicular extension with ESE–WNW trends in the northernmost, NE-trending segment and ENE–WSW trends in the main N–S arc segment. Such extensional stress, documented from many arcs, is likely a response to pull from and bending of the subducting plate. At the same time, the Indo–Burma Ranges are under compression as a result of oblique convergence between the Sunda and Indian plates. The maximum compressive stress rotates from NE–SW across the inner and northern arc to E–W near the Bengal Basin. This rotation is consistent with the deformation partitioning reflected in the rotation of relative displacement vectors, from a SSW-directed Sunda–Burma motion to a WSW-directed Burma–India motion. As a consequence of this partitioning, the major belt-parallel fault zones show a variety of movements across the main N–S arc segment, from right-lateral slip in the inner ranges to oblique reverse-dextral slip in the outer ranges and pure thrusting in the westernmost foreland belt.

Key words: Stress analysis; focal mechanism solution; geodetic study.

- **Shear wave anisotropy beneath the Tibetan Plateau. Daniel E. Mc Namara and Thomas J. Owens. *Journal of Geophysical Research, Vol. 99, No. B7, Pages 13, 655-13, 665, July 10, 1994.***

Abstract:

Eleven broadband digital seismic stations were deployed across the Central Tibetan Plateau in the first extensive passive-source experiment attempted within the Tibetan Plateau. One year of recording resulted in 186 event-station pairs which we analyze to determine the characteristics of shear wave splitting in the uppermantle beneath the array. Measurements of the fast polarization direction (ϕ) and delay time (δt) for SKS and direct S arrivals reveal sys-

tematic variation along the north-south oriented array. In the north central region of the plateau, very large delay times are observed at three stations, the largest of which is BUDO with δt=2.4 s. However, at TUNL, which is off the northern edge of the plateau and 110 km from BUDO and at sites in the south central plateau, δt decreases by nearly a factor of 3. We also observe a systematic rotation of δ from about 45ф (NE) to 90ф (E-W) from south to north along the array. A previously identified zone of inefficient Sn propagation correlates well with our region of large δt observations. The large delay times suggest that a relatively high number of anisotropic crystals are preferentially aligned within the mantle-lid beneath the north central portion of the Tibetan Plateau. In most cases fast polarization directions appear to be parallel to surface geologic features suggesting as much as 200 km of the upper mantle has been involved in the collisional deformation that has produced the Tibetan Plateau.

Key words: Shear wave anisotropy; polarization direction; delay time.

- **Some observations on the mechanism of earthquakes in the Himalaya and the Burmese arc. Satyajit Biswas and Amit Das Gupta.** ***Tectonophysics, Volume 122, Issues 3–4, 15 February 1986, Pages 325–343.***

Abstract:

Through a closely spaced local network of seismic stations in northwestern and northeastern India, supplemented by worldwide P-wave first-motion data, the fault mechanisms of fourteen recent earthquakes (1975–1977) which occurred near the northern boundary of the Indian plate, extending from the Owen Fracture Zone to Burma through the Himalayas, have been determined and their mechanism style discussed in the light of the concept of Himalayan plate tectonics. The new solutions reveal that thrust-type faulting with predominance of pressure axes acting at right angles to the northern boundary of the Indian plate, is more common. In the eastern sector the occurrence of both normal and thrust-type earthquake faulting points out the complexity of deformation in the region. The mechanism style of normal faulting is best explained in terms of lithospheric bending and the strain-ellipsoid concept. Fault mechanism studies are, by and large, consistent with the northward thrusting of the Indian plate. However, orientations of pressure axes, as obtained from present and earlier mechanism solutions, suggest that the dominant northward driving force of the Indian plate is resolved into differential forces in various directions along the Indian-Burmese plate boundary.

Key words: Owen Fracture Zone; fault mechanism; strain-ellipsoid; thrust-type earthquake.

- **Source parameters of earthquakes and intraplate deformation beneath the Shillong plateau and the Northern Indoburman Ranges.** ***Wang-Ping Chen and Peter Molnar. Journal of Geophysical Research, Vol. 95, No. B8, Pages 12,527- 12,552, August 10, 1990.***

Abstract:

We determined the fault plane solutions and focal depths of 17 earthquakes beneath the Shillong Plateau and the Northern Indoburman Ranges by combining results from the inversion of long-period P and SH waveforms and amplitudes, from polarities of first motions, and from the identification of pP and sP phases on short-period seismograms. Fault plane solutions of 15 earthquakes show mixtures of thrust and strike-slip faulting, but the P axes for these events are nearly horizontal and consistently oriented north-northeast-south-southwest. All of these earthquakes occurred at depths greater than 29km. Beneath the Shillong Plateau, one event occurred at a depth of 52km. The relatively large depths for earthquakes in an intraplate setting suggest that the Indian lithosphere in this area is specially cold. Earthquakes beneath the Northern Indoburman Ranges define a gently east-southeast dipping zone from 30 to 45 km beneath the Bengal basin to 40 to 90 km beneath the ranges. This zone seems to steepen and connect with the zone of intermediate depth seismicity dips eastward beneath Burma. These earthquakes cannot have occurred along the interface between a subducting Indian plate and the overriding Indoburman lithosphere, because the P axes, not the nodal planes, are parallel to the north-south trending seismic zone. Although a couple of the earthquakes might have occurred within the Indoburman lithosphere, most of these seismicity seems to have occurred within the Indian plate, recently and currently being subducted eastward beneath the Indoburman ranges. The consistent north-northeast trend of the P axes implies that the orientation of maximum compressional strain in the Indian plate throughout its northern part is nearly perpendicular to that responsible for roughly north-south trending folds of the Indoburman ranges. Thus, either recently in geologic time (since 1Ma) the orientation of maximum compression changed dramatically, or, more likely, the deformation in the Indoburman ranges is decoupled from that in the underlying Indian plate. Meanwhile, the seemingly identical northward displacement of India and the Indoburman ranges with respect to south China must be accommodated farther east, along the Sagaing and other faults.

Key words: Fault plane solutions; short-period seismograms; compressional strain.

- **Source parameters of the Burma-India border earthquake of July 29, 1970, from body waves. B.K. Rastogi and D.D. Singh.** ***Tectonophysics, Volume 51, Issues 3–4, 20 December 1978, Pages T77–T84.***

Abstract:

The source parameters are determined for the Burma-India border earthquake of July 29, 1970, from body-wave spectra. We obtain seismic moment [$\bar{M}_o(P) = 4.83$, $\bar{M}_o(S) = 3.40$] · 10^{26} dyne cm, source dimension [$\bar{r}(P) = 22.5, -r\ (S) = 27.7$] km, radiated energy [$\bar{E}_R\ (P) = 7.19$, −ER (S) = 1.35]· 10^{20} ergs and the stress drop = 11 bars.

Key words: Body-wave spectra; seismic moment; source dimension; radiated energy.

- **Spectral analysis of body waves for earthquakes and their source parameters in the Himalaya and nearby regions. D.D. Singh, B.K. Rastogi and Harsh K. Gupta.** ***Physics of the Earth and Planetary Interiors, Volume 18, Issue 2, February 1979, Pages 143–152.***

Abstract:

The source characteristics of 33 earthquakes with magnitude m_b between 4.4 and 6.0, which occurred in the Himalayan and nearby regions, are investigated using the records of the Hyderabad seismograph station. The P- and S-wave spectra of these events are interpreted in terms of Brune's seismic source model for estimating the source parameters, i.e., seismic moment, source dimension, stress drop, average dislocation, apparent stress and the radiated energy. Seismic moments, M_0, vary between 0.3×10^{24} and 9.0×10^{26} dyne cm;

source dimensions, r, between 4.3 and 18.6 km; stress-drops, Δσ between 0.3 and 151.6 bar; average dislocations, $\bar{u}$ between 0.6 and 381 cm; apparent stresses, $\eta\bar{\sigma}$ between 0.1 and 73.2 bar. The radiated energy, E_R is estimated by the spectrum integration method and is found to vary between 0.2×10^{18} and 9.3×10^{22} erg. In general, the stress drop and apparent stress are found to be high, indicating high stresses in these regions.

Key words: Spectral analysis; Brune's seismic source model; seismic moment; source dimension; stress drop; average dislocation; apparent stress; radiated energy.

- **Stress buildup in the Himalaya. L. Bollinger, J.P. Avouac, R. Cattin and M.R. Pandey.** ***J. Geophys. Res.(2004), 109, B11405, doi:10.1029/2003JB002911.***

Abstract:

The seismic cycle on a major fault involves long periods of elastic strain and stress accumulation, driven by aseismic ductile deformation at depth, ultimately released by sudden fault slip events. Coseismic slip distributions are generally heterogeneous with most of the energy being released in the rupture of asperities. Since, on the long term, the fault's walls generally do not accumulate any significant permanent deformation, interseismic deformation might be heterogeneous, revealing zones of focused stress buildup. The pattern of current deformation along the Himalayan arc, which is known to produce recurring devastating earthquakes, and where several seismic gaps have long been recognized, might accordingly show significant lateral variations, providing a possible explanation for the uneven microseismic activity along the Himalayan arc. By contrast, the geodetic measurements show a rather uniform pattern of interseismic strain, oriented consistently with long-term geological deformation, as indicated from stretching lineation. We show that the geodetic data and seismicity distribution are reconciled from a model in which microseismicity is interpreted as driven by stress buildup increase in the
interseismic period. The uneven seismicity pattern is shown to reflect the impact of the topography on the stress field, indicating low deviatoric stresses (<35 MPa) and a low friction (<0.3) on the Main Himalayan Thrust. Arc-normal thrusting along the Himalayan front and east-west extension in southern Tibet are quantitatively reconciled by the model.

Keywords: Coseismic; interseismic; microseismicity; geodesy; deviatoric stresses.

- **Strong attenuation of Rayleigh waves in Tibet. Peter Bird and M. Nafi Toksoz.** ***Nature 266, 161 - 163 (10 March 1977), Doi:10.1038/266161a0.***

Abstract:

The Tibetan Plateau, which has an average elevation of 5.0 km over 7×10^5 km^2, is the largest topographic mass above sea-level on the Earth. Because it is covered with Cretaceous limestones[1] its uplift must be Tertiary, and is probably related to the Himalayan continental collision. There is considerable debate concerning its present structure and mode of formation. Various authors have theorised that Tibet was uplifted by underthrusting of a second crustal layer[2–6]; by horizontal compression and thickening[7–9], or by low-density material in the mantle[10]. All that is known with certainty is that it is isostatically compensated[11], and covered with widespread Neogene calc-alkaline volcanic rocks[12]. The study of Rayleigh wave attenuation reported here indicates that the lowermost part of the crust is partially molten, and that uplift has been due to horizontal compression.

Key words: Rayleigh wave; underthrusting; horizontal compression; low-density.

Subduction in the Indo-Burma Region: Is it still active? S. P. Satyabala. *Geophysical Research Letters, Volume 25, Issue 16, pages 3189–3192, 15 August 1998, Doi: 10.1029/98GL02256.*

Abstract:

The Indo-Burma region (which includes longitude 92°–96°E, latitude 20°–26°N) is a subduction zone where the Indian plate underthrusts the South-Eastern Asian plate. But the nature of subduction is complex. I examine here the distribution of the P, T and B axes of 37 earthquakes (the time period 1977–1995, depths 0–153 km and magnitudes m_b 4.8–6.8) with respect to the geometry of the Wadati-Benioif Zone. The analysis shows that the T axes are clustered close to the down-dip direction of the subducting slab implying a predominant down-dip tensional stress regime within the slab, which is typical of intermediate depth seismicity of active subduction zones. These results suggest that the subduction in the Indo-Burma region is possibly active.

Key words: South-Eastern Asian plate; Wadati-Benioif Zone; down-dip tensional stress.

- **Surface wave tomography studies beneath the Indian Subcontinent. D.D. Singh. *Geodynamics, 28(1999), 291-301*.**

Abstract:

The Rayleigh wave group velocities at periods of 5 to 60 s across more than eighty propagation paths of the Indian subcontinent are used to construct estimated Rayleigh wave group velocity distribution maps of the region. Backus and Gilberts'inversion theory is applied for the surface wave tomography studies. High values of Rayleigh wave group velocity are concentrated at periods of 30 to 60 s near the region of the Precambrian shield of central India, the China-East India border, the Pakistan Kashmir border, the Indo-Burmese arc and the west Nepal-Tibet border regions. Low values of group velocity are located at periods of 10 to 20 s in the northernmost part of India beneath the Bangladesh shelf and beneath the northernmost part of the Bay of Bengal Fan and the Arabian Sea, which may be due to the presence of thick sediments in the region. Higher group velocities at periods of 40 to 60 s around the region of the West India-Pakistan border suggest thinning of the Indian lithosphere beneath the region. The nature of the high Rayleigh wave group velocities at periods of 29 to 59 s in the Peninsular shield and the Himalaya indicates the continuation of shield type structure beneath the Himalaya. The nature of the Rayleigh wave group velocities in the Bay of Bengal indicates the continuation of the Ninetyeast Ridge up to the Bangladesh shelf below a depth of 25 km.

Key words: Surface wave tomography; Backus and Gilberts'inversion theory; Rayleigh wave.

- **The Active Tectonics of the Eastem Himalayan Syntaxis and Surrounding Regions. Williame Holt, James F. Ni, Terry C. Wallace and A.J. Haines. *Journal of Geophysical Research, Vol. 96, No. B9, Pages 14,595-14,632, August 10, 1991.***

Abstract:

Source parameters of 53 moderate-sized earthquakes obtained from the joint inversion of regional and teleseismic distance long-period body waves provide the data set for an analysis of the style of deformation and kinematics in the region of the Eastern Himalayan Syntaxis. Focal mechanisms of Eastern Himalayan events show oblique thrust consistent with the N-NE directed movement of the Indian plate as it underthrusts a boundary that strikes at an oblique angle to the direction of convergence. Earthquakes near the Sagaing fault show strike-slip mechanisms with right lateral slip. Earthquakes on its northern splays, however, indicate predominant thrusting evidence that the dextral motion on the Sagaing fault, which accommodates a portion of the lateral motion between India and Southeast Asia, terminates in a zone of thrust faulting at the Eastern Himalayan Syntaxis. Remaining motion between India and Southeast Asia is accommodated in a zone of distributed shear in East Burma and Yunnan, manifested by strike-slip and oblique normal faulting, east-west extension, crustal thinning and clockwise rotation of crustal blocks. We determined strain rates throughout the region with a moment tensor summation using 25 years (modem) and 85 years (modem and historic) of earthquake data. We matched the observed strains with a fifth-order polynomial function, and from this we determined both the velocity field and rotations with respect to a specified region. Velocities calculated relative to South China stationary show that the entire area, extending from 20ºN-36ºN, within deforming Asia (Yunnan, Westem Sichuan and East Tibet), constituted a distributed dextral shear zone with clockwise rotations upto 1.7º/m.y., maximum in the region of the Eastern Syntaxis proper. Integrated strains across this zone, relative to South China stationary show 38 mm/yr±12 mm/yr of north-directed motion at the Himalaya. Remaining plate motion, relative to South China fixed, must be taken up by the underthrusting of India beneath the lesser Himalaya, strike-slip motion on the Sagaing fault and intraplate NE directed shortening within NE India as well as NE directed shortening within the Eastern Syntaxis proper. 10 mm/yr±2 mm/yr of relative right-lateral motion between India and Southeast Asia is absorbed in the region between the Sagaing and Red River faults (94ºE-100ºE). It is the clockwise vorticity (relative to South China) associated with the deformation in Yunnan, East Tibet and Western Sichuan that provides the relative north-directed motion of 38±12 mm/yr at the Himalaya. Not all of the deformation is accommodated in right-lateral shear between India and South China and between East Tibet and South China; velocity gradients exist that are parallel to the trend of the shear zone. Relative to a point within Western Sichuan (32ºN, 100ºE), the velocity field shows that the Yunnan crust is moving S-SE at rates of 8-10 mm/yr. Relative to South China, there is no eastward expulsion of crustal material beyond the eastern margin of the Tibetan plateau.

Key words: Eastern Himalayan Syntaxis; focal mechanisms; oblique thrust; Sagaing fault; strike-slip mechanisms.

- **The b value before the 6th August, 1988 India- Myanmar border region earthquake - A case study. O.P. Sahu and M.M. Saikia. *Tectonophysics, 234(1994), 349-354.***

Abstract:

Smith (1981, 1986) and Wyss et al. (1990) have observed that intermediate- term quiescence is often associated with an increasing b value. This study pertains to the temporal behaviour of the b value before the earthquake of 6th August, 1988, which occurred in the

India- Myanmar border region. The b value in the preparation zone of the earthquake (21º-25.5º N, 93º- 96º E), as identified by Gupta and Singh (1986, 1989), is found to have increased gradually from 1976 to a maximum value of 1.33 during July, 1987, followed by a short- term drop before the occurrence of the earthquake. This quiescence period observed by Gupta and Singh (1986, 1989) for this earthquake is better reflected by the intermediate- term increase in the b-value. A drop in the mean magnitude since 1978 is supported by a CUSUM plot.

Key words: Quiescence; b value; CUSUM plot.

- **The nature of noise wavefield and its applications for site effects studies: A literature review. Sylvette Bonnefoy-Claudet, Fabrice Cotton and Pierre-Yves Bard. *Earth-Science Reviews xx (2006) xxx–xxx.***

Abstract:

The aim of this paper is to discuss the existing scientific literature in order to gather all the available information dealing with the origin and the nature of the ambient seismic noise wavefield. This issue is essential as the use of seismic noise is more and more popular for seismic hazard purposes with a growing number of processing techniques based on the assumption that the noise wavefield is predominantly consisting of fundamental mode Rayleigh waves. This survey reveals an overall agreement about the origin of seismic noise and its frequency dependence. At frequencies higher than 1 Hz, seismic noise systematically exhibits daily and weekly variations linked to human activities, whereas at lower frequencies (between 0.005 and 0.3 Hz) the variation of seismic noise is correlated to natural activities (oceanic, meteorological…). Such a surface origin clearly supports the interpretation of seismic noise wavefield consisting primarily of surface waves. However, the further, very common (though hidden) assumption according which almost all the noise energy would be carried by fundamental mode Rayleigh waves is not supported by the few available data: no "average" number can though be given concerning the actual proportion between surface and body waves, Love and Rayleigh waves (horizontal components), fundamental and higher modes (vertical components), since the few available investigations report a significant variability, which might be related with site conditions and noise source properties.

Keywords: Seismic noise wavefield; microseisms; microtremors; surface waves; seismic hazard.

- **The seismic b-value and its correlation with Bouguer gravity anomaly over the Shillong Plateau area: Tectonic implications. P.K. Khan and Partha Pratim Chakraborty**D:\Project-0273\Project_Bibliography\GPP-0273\ScienceDirect.com - Journal of Asian Earth Sciences - The seismic b-value and its correlation with Bouguer gravity anomaly over the Shillong Plateau area Tectonic implications.htm - aff2***. Journal of Asian Earth Sciences, Volume 29, Issue 1, 15 January 2007, Pages 136–147.***

Abstract:

Clues to the understanding of intra- and inter-plate variations in strength or stress state of the crust can be achieved through different lines of evidence and their mutual relationships. Among these parameters Bouguer gravity anomalies and seismic b-values have been widely accepted over several decades for evaluating the crustal character and stress regime. The present study attempts a multivariate analysis for the Shillong Plateau using the Bouguer gravity anomaly and the earthquake database, and establishes a causal relationship between these parameters. Four seismic zones (Zones I–IV), with widely varying b-values, are delineated and an excellent correlation between the seismic b-value and the Bouguer gravity anomaly has been established for the plateau. Low b-values characterize the southwestern part (Zone IV) and a zone (Zone III) of intermediate b-values separates the eastern and western parts of the plateau (Zones I and II) which have high b-values. Positive Bouguer anomaly values as high as +40 mgal, a steep gradient in the Bouguer anomaly map and low b-values in the southwestern part of the plateau are interpreted as indicating a thinner crustal root, uplifted Moho and higher concentration of stress. In comparison, the negative Bouguer anomaly values, flat regional gradient in the Bouguer anomaly map and intermediate to high b-values in the northern part of the plateau are consistent with a comparatively thicker crustal root and lower concentration of stress, with intermittent dissipation of energy through earthquake shocks. Further, depth wise variation in the b-value for different seismic zones, delineated under this study, allowed an appreciation of intra-plateau variation in crustal thickness from 30 km in its southern part to 38 km in the northern part. The high b-values associated with the depth, coinciding with lower crust, indicate that the Shillong Plateau is supported by a strong lithosphere.

Keywords: Bouguer anomaly, b value, Shillong plateau, stress state, strong lithosphere.

- **The source of the Great Assam Earthquake—An interplate wedge motion. Ari Ben-Menahem, Ezra Aboodi and Rivka Schild.** ***Physics of the Earth and Planetary Interiors, 9 (1974), 265—289.***

Abstract:

The source of the Assam earthquake of Aug. 15, 1950 is revealed from amplitude observations of surface and body waves at Pasadena, Tokyo and Bergen. Seiches' amplitudes in Norway, initial P motions throughout the world, aftershocks and landslides distribution, PP/P ratio at Tokyo, R/L ratio and directivity at Pasadena, are also used. The ensuing fault geometry and kinematics is consistent with the phenomenology of the event and the known geology of the source area. It is found that a progressive strike-slip rupture with velocity 3 km/sec took place on a fault of length 250 km and width 80 km striking 330—337°east of north and dipping 55—60°to ENE. The use of exact surfacewave theory and asymptotic body-wave theory which takes into account finiteness and absorption, rendered an average shear dislocation of 35 m. A three-dimensional theory for the excitation of seiches in lakes by the horizontal acceleration of surface waves was developed. It is confirmed that Love waves near Bergen generated seiches with peak amplitude up to 70 cm depending strongly on the width of the channel. It is believed that the earthquake was caused by a motion of the Asian plate relative to the eastern flank of the Indian plate where the NE Assam block is imparted a tendency of rotation with fracture lines being developed along its periphery. Comparison with other well-studied earthquakes shows that although the magnitude of the Assam event superseded that of all earthquakes since 1950, its potency U_od5 (700,000 m X km^2) was inferior to that of Alaska 1964 (1,560,000 m X km^2) and Chile 1960 (1,020,000 it X km^2).

Key words: Fault geometry and kinematics; strike-slip rupture; three-dimensional theory; Love wave.

- **Timing and return period of major palaeoseismic events in the Shillong Plateau, India. B.S. Sukhija, M.N. Rao, D.V. Reddy, P. Nagabhushanam, Syed Hussain, R.K. Chadha and H.K. Gupta.** ***Tectonophysics*** **,** ***Volume 308 (1)*** *Elsevier* ***– Jul 10, 1999.***

Abstract:

The close temporal occurrence of four great earthquakes in the past century, including the great Assam earthquake of 1897 in the Shillong Plateau, necessitated examination of the palaeoseismicity of the region. The results from such investigation would definitely aid in addressing the problem of the earthquake hazard evaluation more realistically. Our recent palaeoseismological study in the Shillong Plateau has led us to identify and provide geological evidence for large/major earthquakes and estimate the probable recurrence period of such violent earthquakes in parts of the Shillong Plateau and the adjoining Brahmaputra valley. Trenching along the Krishnai River, a tributary of the River Brahmaputra, has unravelled very conspicuous and significant earthquake-induced signatures in the alluvial deposits of the valley. The geological evidence includes: (1) palaeoliquefaction features, like sand dykes and sand blows; (2) deformational features, like tilted beds; (3) fractures and syndepositional deformational features, like flame structures caused by coeval seismic events. Chronological constraints of the past large/major earthquakes are provided from upper and lower radiocarbon age bounds in the case of the palaeoliquefaction features, and the coeval timing of the palaeoseismic events is obtained from the radiocarbon dating of the organic material associated with the deformed horizon as well as buried tree trunks observed wide distances apart. Our palaeoseismic measurements, which are the first from the area, indicate that the Shillong Plateau has been struck by large/major earthquakes around 500±150, 1100±150 and >1500±150 yr BP, in addition to the well-known great seismic event of 1897, thereby the 14 C dates indicate a recurrence period of the order of 500 yr for large earthquakes in the Shillong Plateau.

Keywords: Palaeoseismicity; palaeoliquefaction; deformational features; fractures; syndepositional deformation.

- **3-D seismic structure of the northeast India region and its implications for local and J.R. Kayal.** ***Journal of Asian Earth Sciences (2008), 33, 25–41.***

Abstract:

In this study we attempted to estimate 3-D P-wave velocity structure of northeast India region using the first arrival data of local earthquakes that were recorded by about 77 temporary/permanent local seismic stations. The data set, the published bulletins, include 3494 P-wave travel times and 3064 S–P travel times from 980 local earthquakes that were located with a minimum of six observations. The located earthquakes having a travel-time root mean square (RMS) residual 60.49 s and azimuthal gap 6180_ are selected to compute a 1-D velocity model for the region, which is used as initial model for the subsequent 3-D inversions. Our results demonstrate that the computed 3-D velocity model has significantly improved hypocenter locations of the selected 980 earthquakes by reducing the RMS error (60.06) by about 88% with respect to that by the 1-D velocity model. The reconstructed P-wave velocity (Vp) structure, with relocated events, reveal strong heterogeneity in lateral as well as in vertical direction corresponding to the local and regional geology/tectonics of the region. High Vp is mapped beneath the Shillong Plateau–Mikir hills and in the vicinity of

Indo-Burma ranges at shallower crust (<10 km) suggesting dense crystalline rocks under compressional stress. A prominent NW–SE trending low Vp structure is imaged between the Shillong Plateau and Mikir hills at 20 km depth, which corresponds to the Kopili fault. The Kopili fault system extends down to 30 km depth as evidenced by the low Vp. A high Vp is imaged below the Mikir hills at 40 km depth, which is possibly the stress concentrator for high seismic activity along the Kopili fault, particularly at the fault end. The Bengal basin, south of the Shillong Plateau, is identified as a low Vp zone extending down to a depth of about 20 km, that indicates the thick alluvium sediments.

Keywords: 3-D seismic structure; RMS residual; azimuthal gap.

- **Is shillong region, Northeast India, undergoing a dilatancy stage precursory to a large earthquake? Harsh K. Gupta and V.P. Singh.** ***Tectonophysics, Volume 85, Issues 1–2, 10 May 1982, Pages 31–33.***

Abstract:

Gupta H.K. and Singh V.P., 1982. Is Shillong region, northeast India, undergoing a dilatancy stage precursory to a large earthquake? In: A.L. Hales and Z. Suzuki (Editors), Earthquake Prediction.*Tectonophysics*, 85: 31–33.

- **Mapping the crustal thickness in Shillong–Mikir Hills Plateau and its adjoining region of northeastern India using Moho reflected waves. Dipok K. Bora and Saurabh Baruah.** ***Journal of Asian Earth Sciences, 48 (2012) 83–92.***

Abstract:

In this study we have tried to detect and collect later phases associated with Moho discontinuity and used them to study the lateral variations of the crustal thickness in Shillong–Mikir Hills Plateau and its adjoining region of northeastern India. We use the inversion algorithm by Nakajima et al. (Nakajima, J., Matsuzawa, T., Hasegawa, A. 2002. Moho depth variation in the central part of northeastern Japan estimated from reflected and converted waves. Physics of the Earth and Planetary Interiors, 130, 31–47), having epicentral distance ranging from 60 km to 150 km. Taking the advantage of high quality broadband data now available in northeast India, we have detected 1607 Moho reflected phases (PmP and SmS) from 300 numbers of shallow earthquake events (depth 6 25 km) in Shillong–Mikir Hills Plateau and its adjoining region. Notably for PmP phase, this could be identified within 0.5–2.3 s after the first P-arrival. In case of SmS phase, the arrival times are observed within 1.0–4.2 s after the first S-arrival. We estimated the crustal thickness in the study area using travel time difference between the later phases (PmP and SmS) and the first P and S arrivals. The results shows that the Moho is thinner beneath the Shillong Plateau about 35–38 km and is the deepest beneath the Brahmaputra valley to the north about 39–41 km, deeper by 4–5 km compared to the Shillong Plateau with simultaneous observation of thinnest crust (_33 km) in the western part of the Shillong Plateau in the Garo Hills region.

Keywords: Moho discontinuity; Shillong–Mikir Hills Plateau; inversion algorithm.

- **Evolution of the Himalayan Paleogene foreland basin, influence of its litho-packet on the formation of thrust-related domes and windows in the Eastern Himalayas – A review. S.K. Acharyya.** ***Journal of Asian Earth Sciences, 31 (2007) 1–17.***

Abstract:

Eocene–Oligocene foreland basin was formed in response to the India–Asia collision and ensuing Himalayan orogenesis. The initial collision during late Paleocene to early Eocene was broadly contemporaneous laterally. The Paleogene sediments although discontinuously exposed are remarkably similar in their character and organization. In the Eastern Himalayas it is virtually concealed tectonically, but is exposed close to and beneath the Main Boundary Thrust (MBT) as narrow but laterally extensive thrust slivers of fossiliferous Eocene sediments. Lateral continuity and similar marine fauna in them establish the presence of thicker Eocene sediments beneath MBT further north. Several domes and windows in the Eastern Himalayan frontal belt have evolved with similar geometry. The largest Siang Window exposes duplex antiform of Paleogene sediments and volcanics at the core, which have arched up the MBT roof-thrust. The latter underlies passively domed-up Late Plaeozoic and Proterozoic Himalayan thrust packets. The cores of other windows mainly expose low-grade Proterozoic rocks, with or without the Late Paleozoic rocks. A similar sequence of pre-Tertiary thrust packet is exposed to the south in the frontal belt, which override the Neogene sediments across MBT. A buried basement indenture of the Indian continent continues beneath the Siang Window located at the Eastern Himalayan Syntaxis. The cores of other windows are possibly arched-up by the duplexes of pre-Tertiary and Tertiary sediments during the process of southward movement of the crystalline and foreland sheets.

Keywords: India–Asia collision; Laterally contemporaneous collision; Paleogene foreland basin; Paleogene stratigraphy; Thrust tectonics.

- **Ground motion parameters in Shillong and Mikir Plateau supplemented by mapping of amplification factors in Guwahati City, Northeastern India. Saurabh Baruah, Santanu Baruah, Aditya Kalita and J. R. Kayal.** ***Journal of Asian Earth Sciences, Volume 42, Issue 6, 11 November 2011, Pages 1424–1436.***

Abstract:

Ground motion parameters for Shillong–Mikir Plateau of Northeastern India are examined. Empirical relations are obtained for ground motions as a function of earthquake magnitude, fault type, source depth, velocity characterization of medium and distance. Correlation between ground motion parameters and characteristics of seismogenic zones are established. Simultaneously, new empirical relations are derived for attenuation of ground motion amplitudes. Correlation coefficients of the attenuation relations depend on the site classifications that are identified based on average shear wave velocity and site response factors. The attenuation relation estimated for logarithmic width of Mikir Plateau found to be a little bit higher than that of Shillong Plateau both for soft and hard ground which accounts for geometrical spreading and anelastic attenuation. Simultaneously, validation are made studying the seismic microzonation process related to geomorphological, geological subsurface features for thickly populated Guwahati city of India under threat from scenario earthquake.

Keywords: Ground acceleration; Predominant period; Shaking duration; Response spectra.

- **Geology and tectonic history of the Lohit Valley, Eastern Arunachal Pradesh, India. N.S. Gururajan and B.K. Choudhuri.** ***Journal of Asian Earth Sciences 21 (2003) 731–741.***

Abstract:

The Lohit River section of eastern Arunachal Pradesh comprises four tectonic units. From SW to NE these are: the Lesser Himalayan rocks, the Mishmi Crystallines, the Tidding Suture Zone and the Lohit Plutonic Complex. The Mishmi Thrust underlies the basal Lesser Himalayan unit, while the Mishmi Crystallines are thrust over the Lesser Himalayan unit along the Main Central Thrust. The grade of metamorphism in the Mishmi Crystallines increases up the structural section from chlorite to staurolite–kyanite zones, exhibiting inverted metamorphism. The relationship between deformation and metamorphism shows that the metamorphic peak was syn- to post-tectonic in relation to the main ductile shearing event. Continued deformation, after the metamorphic peak, was accommodated along millimetre scale shear zones, developed throughout the sequence, parallel to the regional schistosity. Movement along these shear zones has resulted in inversion of the metamorphic zones. The rocks of the Tidding Suture represent an ophiolitic me´lange, thrust over the Mishmi Crystallines, which in turn are overthrust by the Lohit Plutonic Complex along the Lohit Thrust. The Lohit Plutonic Complex is subdivided into western and eastern belts separated by the Walong Thrust. The western belt consists of deformed quartz-diorite, diorite, gabbro and trondhjemite, intruded by basic and acid dykes. The eastern belt comprises garnet–sillimanite gneiss, intercalated with crystalline marble bands, followed by a complex zone of leucogranites, aplites and pegmatites, which intrude the early foliated quartz-diorite, soda-rich granite and microdiorite. The rocks of the eastern belt are the northward continuation of the Mogok Gneissic Belt of central Burma. The occurrence of intrusive rocks in the eastern belt suggests that the magmatism related to subduction extended to the east, far from the subduction zone. The peraluminous leucogranites, aplites and pegmatites are the products of crustal melting, induced by crustal thickening related to the intracontinental Walong Thrust. Subsequent to metamorphism and shearing, the whole sequence was folded into an antiform, forming the Eastern Syntaxis, and this deformation steeply tilted the earlier low angle thrusts and foliations. Later compression partitioned into right lateral strike-slip motion, producing a superimposed sub-horizontal lineation observed mostly in the Lohit Plutonic Complex.

Keywords: Lohit Valley; Tectonic history; Mishmi Crystallines.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. B5, PAGES 11,275–11,290, MAY 10, 1996

Mapping the descent of Indian and Eurasian plates beneath the Tibetan Plateau from gravity anomalies

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Abstract. The collision of India with Asia has produced a complicated continental-continental plate boundary involving folding and faulting of variable trends and styles within and along the margins of the Tibetan Plateau. Numerous lines of evidence, including the development of two scales of folding in Tibet, suggest that the lowermost crust is behaving in a ductile fashion. This weak lower crust might then decouple the fundamental plate tectonic motions in the uppermost mantle from the complex pattern of surface faulting. In this study, we use Bouguer gravity anomalies to map out the geometry of Indian and Eurasian plate interactions in the mantle beneath the plateau based on both the inferred geometry of the Moho and lateral variations in lithospheric strength determined from mechanical modeling. In our preferred model, the lithosphere beneath Tibet consists of two distinct units: (1) the underthrust (to the north) Indian plate, which sutures with the Eurasian plate in the upper mantle below the Yarlung-Zangpo Suture or the Gangdese igneous belt, 200-400 km north of the Main Boundary Thrust, and (2) the underthrust (to the south) Eurasian plate. A subducting slab of Indian upper mantle extends about 200 km into the asthenosphere north from the mantle suture and exerts a bending moment of about 3.5×10^{17} N on the Indian plate. Thus the mantle lithosphere appears to be behaving in the simple fashion of converging oceanic plates, while the more buoyant continental crust deforms under high gravitational potential in a complex pattern controlled by its lateral and vertical strength heterogeneity.

Key words: Gravity anomaly; mechanical modeling; Moho.

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The Energy Release in Great Earthquakes

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The conventional magnitude scale M suffers saturation when the rupture dimension of the earthquake exceeds the wavelength of the seismic waves used for the magnitude determination (usually 5–50 km). This saturation leads to an inaccurate estimate of energy released in great earthquakes. To circumvent this problem the strain energy drop W (difference in strain energy before and after an earthquake) in great earthquakes is estimated from the seismic moment M_0. If the stress drop $\Delta\sigma$ is complete, $W = W_0 = (\Delta\sigma/2\mu)M_0 \sim M_0/(2 \times 10^4)$, where μ is the rigidity; if it is partial, W_0 gives the minimum estimate of the strain energy drop. Furthermore, if Orowan's condition, i.e., that frictional stress equal final stress, is met, W_0 represents the seismic wave energy. A new magnitude scale M_w is defined in terms of W_0 through the standard energy-magnitude relation $\log W_0 = 1.5M_w + 11.8$. M_w is as large as 9.5 for the 1960 Chilean earthquake and connects smoothly to M_s (surface wave magnitude) for earthquakes with a rupture dimension of about 100 km or less. The M_w scale does not suffer saturation and is a more adequate magnitude scale for great earthquakes. The seismic energy release curve defined by W_0 is entirely different from that previously estimated from M_s. During the 15-year period from 1950 to 1965 the annual average of W_0 is more than 1 order of magnitude larger than that during the periods from 1920 to 1950 and from 1965 to 1976. The temporal variation of the amplitude of the Chandler wobble correlates very well with the variation of W_0, with a slight indication of the former preceding the latter. In contrast, the number N of moderate to large earthquakes increased very sharply as the Chandler wobble amplitude increased but decreased very sharply during the period from 1945 to 1965, when W_0 was largest. One possible explanation for these correlations is that the increase in the wobble amplitude triggers worldwide seismic activity and accelerates plate motion which eventually leads to great decoupling earthquakes. This decoupling causes the decline of moderate to large earthquake activity. Changes in the rotation rate of the earth may be an important element in this mechanism.

Key words: Strain energy drop; seismic moment; Orowan's condition.

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Tectonophysics 338 (2001) 281–286

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Medium-term forecast of the 1988 north-east India earthquake

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Abstract

Northeast India is seismically one of the most active intra-continental regions in the world. It has been a site of 10 earthquakes of magnitude (M) ≥7.5 during the last 100 years. Gupta and Singh [J. Geol. Soc. India, 28 (1986) 367–406] systematically analysed the time series of earthquakes associated with several main shocks in an area bound by 20°N and 32°N latitude and 87°E and 100°E longitude and concluded: (1) Moderate magnitude to great earthquakes in the north-east India region are found to be preceded, generally, by well defined earthquake swarms and quiescence periods. (2) On the basis of an earthquake swarm and quiescence period, an area bound by 21°N and 25.5°N latitude and 93°E and 96°E longitude is identified to be the site of a possible future earthquake of $M = 8 \pm 0.5$ with a focal depth of 100 ± 40 km. This earthquake should occur any time from now onwards. Should it not occur till the end of 1990, this forecast could be considered as a false alarm. This medium-term earthquake forecast came true with the occurrence of the $M = 7.3$ earthquake on August 6, 1988, within the specified spatial and temporal parameters.

The forecast of this earthquake was based on the concept of precursory swarms and quiescence preceding main-shocks. It is worthwhile noting that in the entire region under study, the August 6, 1988 earthquake was the largest since the August 17, 1952 earthquake of $M = 7.5$. This lends support to the worldwide effort to study and identify spatial and temporal variation of seismicity and recognise patterns that precede major earthquakes.

Keywords: medium term forecast; quiescence; precursory swarm

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. B10, PAGES 8171-8191, OCTOBER 10, 1983

CONSTRAINTS ON THE STRUCTURE OF THE HIMALAYA FROM AN ANALYSIS OF GRAVITY ANOMALIES AND A FLEXURAL MODEL OF THE LITHOSPHERE

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Abstract. The intracontinental subduction of India beneath the Himalaya presents several similarities to that occurring at island arcs. We study one of those similarities by analyzing gravity anomalies across the Himalaya assuming that the topography is supported by the Indian elastic plate, flexed under the weight of both the overthrust mountains and the sediments in the Ganga Basin. We first examine in detail the effects of each of the following parameters on the configuration of the elastic plate and on the gravity anomalies: the flexural rigidity, the position of the northern end of the elastic plate (the amount of underthrusting of such a plate beneath the range), and the density contrasts between the crust and mantle and between the sediments and the crust. A plate with a constant flexural rigidity of about 0.7×10^{25} N m (between 0.2 and 2.0×10^{25} N m) allows a good fit to the data from the Lesser Himalaya and the Ganga Basin. Such a plate, however, cannot underthrust the entire Himalaya. Instead, the gravity anomalies show that the Moho steepens from only about 3° beneath the Lesser Himalaya to about 15° beneath the Greater Himalaya. This implies a smaller flexural rigidity beneath the Greater Himalaya (0.1 to 1.0×10^{23} N m) than beneath the Ganga Basin and the Lesser Himalaya. Even with a thin, weak plate beneath the Greater Himalaya, the weight of the mountains depresses the plate too much unless an additional force or moment is applied to the plate. The application of a bending moment/unit length to the end of the plate of about 0.6×10^{18} N is adequate to elevate the Indian plate and to bring the calculated gravity anomalies in agreement with those observed. Both, the smaller flexural rigidity and the bending moment can be understood if we assume that part or all of the Indian crust has been detached from the lower lithosphere that underthrusts the Greater Himalaya. We study the tectonic implications of these results by means of a series of idealized balanced cross sections, from the collision to the present, that reproduce several important features of the geology of the Himalaya and predict an amount of eroded material comparable to that in the Ganga Basin and the Bay of Bengal. These cross sections include high-grade metamorphic rocks near the Main Central Thrust and a steeper dip of it there than in the Lesser Himalaya. They predict rapid uplift only in the Greater Himalaya and at the foot of the Lesser Himalaya.

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underthrust zone is, of course, an

Key words: Gravity anomaly; flexural model; flexural rigidity; density contrasts.

4.2 ABSTRACTS OF MOST VALUABLE LITERATURES ON EARTHQUAKE HAZARD ASSESSMENT (IF>2.0 part 2)

Review of the various research publications on seismological and seismic hazard studies in and around Northeastern India having impact factor above 2.0 are carried out. The prime findings in each of the studies are considered as the inputs to the seismic hazard assesement in the region. These parameters are indicated below.

- **A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry. Sankar Kumar Nath, Madhav Vyas, Indrajit Pal and Probal Sengupta. J. Geophys. Res., Vol. 110, B01301, doi:10.1029/2004JB003199, 2005.**

Abstract:

In this paper, we present a seismic hazard map of the Indian Himalayan State of Sikkim, lying between Nepal and Bhutan Himalaya, in terms of horizontal peak ground accelerations with 10% exceedance probability over the next 50 years. These figures, the first for the region, were calculated through a stepwise process based on (1) an estimation of the maximum credible earthquake (MCE) from the seismicity of the region and Global Seismic Hazard Assessment Program considerations and (2) four seismotectonic parameters abstracted from accelerograms recorded at nine stations of the Sikkim Strong Motion Array, specifically installed for this study. The latter include (1) the frequency-dependent power law for the shear wave quality factor, QS, (2) the site response function at each station using receiver function analysis and generalized inversion,(3) source parameterization of various events recorded by the array and application of the resulting relationships between M0 and MW, and corner frequency, fc and MW to simulate spectral accelerations due to higher-magnitude events corresponding to the estimated MCE, and (4) abstraction of regional as well as site specific local spectral attenuation laws at different geometrically central frequencies in low-, moderate-, and high-frequency bands.

- **Accretionary tectonics of Burma and the three-dimensional geometry of the Burma subduction zone. James F. Ni, Marco Guzman-Speziale, Michael Bevis, William E. Holt, Terry C. Wallace and William R. Seager. Geology, V. 17, No. 1, p. 68-71.**

Abstract:

The geometry of the Burma Wadati-Benioff zone (WBZ) has been determined by fitting a trend surface parameterized with eight effective degrees of freedom to 184 well-located hypocenters. The dip of this surface, which passes through the middle of the WBZ, varies from about 50° in the north near the eastern Himalayan syntaxis to about 30° in the Bay of Bengal area. The eastern edge of the Indo-Burman ranges closely follows the map projection of the 60 km depth contour of the WBZ. The curvature of the Indo-Burman ranges is controlled by the geometry of the interface between the more steep-

ly dipping part of the Indian plate and the leading edge of the overriding Burma platelet. Shallow earthquakes beneath the Indo-Burman ranges are primarily confined to the underthrusting Indian plate. Their focal mechanisms indicate strike-slip faulting and north-south shortening parallel to the eastern margin of the Indian plate.

- **Active tectonics in Eastern Lunana (NW Bhutan): Implications for the seismic and glacial hazard potential of the Bhutan Himalaya. M.C. Meyer, G. Wiesmayr, M. Brauner, H. Ha¨usler and D. Wangda. Tectonics, Vol. 25, TC3001, Doi:10.1029/2005TC001858, 2006.**

Abstract:

Paleoseismological investigations, brittle fault analysis, and paleostrain calculations combined with the interpretation of satellite imagery and flood wave modeling were used to investigate the seismic and associated glacial hazard potential in Eastern Lunana, a remote area in NW Bhutan. Seismically induced liquefaction features, cracked pebbles, and a surface rupture of about 6.8 km length constrain the occurrence of M > 6 earthquakes within this high altitude periglacial environment, which are the strongest earthquakes ever been reported for the Kingdom of Bhutan. Seismicity occurs along conjugate sets of faults trending NE-SW to NNW-SSE by strike-slip and normal faulting mechanism indicating E-W extension and N-S shortening. The strain field for these conjugate sets of active faults is consistent with widespread observations of young E-W expansion throughout southern Tibet and the north Himalaya. We expect, however, that N-S trending active strike-slip faults may even reach much farther to the south, at least into southern Bhutan. Numerous glacial lakes exist in the investigation area, and today more than 100 x 10^6 m3 of water are stored in moraine-dammed and supraglacial lakes which are crosscut by active faults. Strong earthquakes may trigger glacial lake outburst floods, and the impact of such flash floods may be worst 80 km downstream where the valley is broad and densely populated. Consequently, tectonic models of active deformation have to be closely linked with glacial hazard evaluation and require rethinking and modification.

- **Attenuation character of seismic waves in Sikkim Himalaya. Pinki Hazarika, M. Ravi Kumar and Dinesh Kumar. Geophys. J. Int. (2013), Doi: 10.1093/gji/ggt241.**

Summary:

In this study, we investigate the seismic wave attenuation beneath Sikkim Himalaya using P, S and coda waves from 68 local earthquakes registered by eight broad-band stations of the SIKKIM network. The attenuation quality factor (Q) depends on frequency as well as lapse time and depth. The value of Q varies from (i) 141 to 639 for P waves, (ii) 143 to 1108 for Swaves and (iii) 274 to 1678 for coda waves, at central frequencies of 1.5 Hz and 9 Hz, respectively. The relations that govern the attenuation versus frequency dependence are $Q_\alpha = (96 \pm 0.9)\, f^{(0.94 \pm 0.01)}$, $Q_\beta = (100 \pm 1.4)\, f^{(1.16 \pm 0.01)}$ and $Q_c = (189 \pm 1.5)\, f^{(1.2 \pm 0.01)}$ for P, S and coda waves, respectively. The ratio between Q_β and Q_α is larger than unity, implying larger attenuation of P compared to S waves. Also, the values of Q_c are higher than Q_β. Estimation of the relative contribution of intrinsic (Q_i) and scattering (Q_s) attenuation reveals that the former mechanism is dominant in Sikkim Himalaya. We note that the estimates of Q_c lie in between Q_i and Q_s and are very close to Q_i at lower frequencies. This is in agreement with the theoretical and laboratory experiments.

The strong frequency and depth dependence of the attenuation quality factor suggests a highly heterogeneous crust in the Sikkim Himalaya. Also, the high Q values estimated for this region compared to the other segments of Himalaya can be reconciled in terms of moderate seismic activity, unlike rest of the Himalaya, which is seismically more active.

Keywords: Body waves, Coda waves, Seismic attenuation, Continental margins: convergent.

- **Causative source of Mw 6.9 Sikkim–Nepal border earthquake of September 2011: GPS baseline observations and strain analysis. Rashmi Pradhan, Sanjay K. Prajapati, Sumer Chopra, Ashok Kumar, B.K. Bansal and C.D. Reddy. Journal of Asian Earth Sciences, Volumes 70–71, July 2013, Pages 179–192.**
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Abstract:

The recent earthquake of Mw 6.9 which occurred on September 18, 2011 in Sikkim–Nepal border region (epicenter 27.72°N, 88.06°E, depth 20.7 km, ∼68 km NW of the Capital city Gangtok) is the strongest earthquake in the instrumentally recorded history of the region. The fault plane solution of this earthquake indicates a strike-slip motion. However, the seismological and geological studies carried out so far after the earthquake could not confirm the causative fault plane. In the present study, GPS observations are used to ascertain causative source in the generation of earthquake and its correlation with the observed seismic data of the region. The co-seismic displacements recorded by GPS show maximum displacement of ∼11 mm at Phodong and ∼9 mm at Taplejung station, near the epicenter. A simple rigid cross fault model using GPS baseline observations was employed to figure out the causative fault plane and seismological characteristic of the region. It is inferred that the movement represents the kinematic adjustment of the subsidiary faults as a result of the displacement along the NW–SE principal plane. Strain analysis using GPS baseline inferred that the region southeast of epicenter has undergone large deformation. In addition, a significant part of the measured deformation across the surface fault zone for this earthquake can be attributed to post-seismic creep.

Keywords: GPS baseline; Fault movement; Riedel shear; Strain.

- **Crustal structure across Sikkim, NE Himalaya from new gravity and magnetic data. V.M. Tiwari, M.B.S. Vyghreswara Rao, D.C. Mishra, B. Singh. Earth and Planetary Science Letters, Volume 247, Issues 1–2, 15 July 2006, Pages 61–69.**

Abstract:

The new gravity and magnetic data recorded along a profile in the Sikkim, NE Himalaya are combined with the existing data from Tibet, Bangladesh and India, to delineate the crustal structure in this part of Himalaya. Modelling of gravity data, constrained from seismic results suggests that long wavelength gravity anomalies arise due to variations in the depth of Moho (36 to 74 km), which are caused by flexed lithosphere of effective elastic thickness of ∼ 50 ± 10 km. Simultaneous modelling of magnetic anomalies and short wave-length gravity anomalies reveals that (a) the magnetic anomalies observed over the Lesser Himalaya and the Higher Himalaya Crystalline rocks might be caused by remnant magnetisation with inclination I = − 18° ± 8° and declination D = 147° ± 10°, which is in conformity with the palaeomagnetic results. These magnetic parameters correspond to ~ 35 ± 10 Ma age of magnetic direction and suggest that the rocks might have acquired magnetisation during cooling period of metamorphism, (b) low grade meta-sediments of the Lesser Himalaya extend up to 12 km depth and thins on either sides forming a bowl shaped geometry and (c) relative gravity high in the Bengal basin might be caused by intrusion of the Rajmahal volcanics. Modelling has also provided constraint on the geometry of the north dipping thrusts.

Keywords: Gravity; Isostasy; Effective elastic thickness; Himalaya.

- **Deep geoelectric structure of the Sikkim Himalayas (NE India) using magnetotelluric studies. Prasanta K. Patro and T. Harinarayana. Physics of the Earth and Planetary Interiors, Volume 173, Issues 1–2, March 2009, Pages 171–176.**

Abstract:

Broadband (0.001–1000 s) magnetotelluric soundings were carried out at 18 locations with a station interval of 5–8 km across the Sikkim Himalaya (northern India) along a 120 km long traverse from Siliguri in the south to Yumthang in the north. Magnetotelluric transfer functions were computed after robust processing of single site and remote reference sites. The two-dimensional (2D) model derived from the joint inversion of TE and TM mode data shows distinct electrical signatures of the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). The MFT and MBT zones are expressed by a conductive feature of about 10–40 Ω m indicating, the presence of Siwalik molasse sediments of Gangetic foreland basin. An anomalously high conductive (2–5 Ω m) in the crust in the depth range of 3–15 km is observed to the north of MBT. This may indicate the presence of Siwalik molasse sediments together with lesser Himalayan sediments with trapped fluids in the fault zone. These sediments may act as a lubricant accommodating underthrusting of continental crust. The nature of the low resistivity associated with the Main Himalayan Thrust in the higher Himalayas (north of the MCT) might indicate presence of metamorphic fluids released due to under thrusting of the Indian plate.

Keywords: Sikkim Himalaya; Magnetotellurics; Electrical structure; 2D modeling.

- **Detailed geometry of the subducting Indian Plate beneath the Burma Plate and subcrustal seismicity in the Burma Plate derived from joint hypocenter relocation. Nobuo Hurukawa, Pa Pa Tun and Bunichiro Shibazaki. Earth Planets Space, 64, 333–343, 2012.**

Abstract:

With the aim of delineating the subducting Indian Plate beneath the Burma Plate, we have relocated earthquakes by employing teleseismic P-wave arrival times. We were able to obtain the detailed geometry of the subducting Indian Plate by constructing iso-depth contours for the subduction earthquakes at depths of 30–140 km. The strikes of the contours are oriented approximately N-S, and show an "S" shape in map view. The strike of the slab is N20◦E at 25◦N, but moving southward, the strike rotates counterclockwise to N20◦W at 20◦N, followed by a clockwise rotation to a strike of N10◦E at 17.5◦N, where slab earthquakes no longer occur. The plate boundary north of 20◦N might exist near, or west, of the coast line of Myanmar. The mechanisms of subduction earthquakes are

down-dip extension, and T axes are oriented parallel to the local dip of the slab. Subcrustal seismicity occurs at depths of 20–50 km in the Burma Plate. This activity starts near the 60-km-depth contour of the subduction earthquakes and becomes shallower toward the Sagaing Fault, indicating that this fault is located where the cut-off depth of the seismicity becomes shallower.

Key words: Burma Plate, Indian Plate, subduction, relocation, joint hypocenter determination.

- **Earthquakes beneath the Himalayas and Tibet: Evidence for Strong Lithospheric Mantle. Wang Ping Chen and Zhaohu Yang. Science, Vol.304, 25 June (2004). (IF- 31.027)**

<u>Abstract:</u>

Eleven intracontinental earthquakes, with magnitudes ranging from 4.9 to 6, occurred in the mantle beneath the western Himalayan syntaxis, the western Kunlun Mountains, and southern Tibet (near Xigaze) between 1963 and 1999. High-resolution seismic waveforms show that some focal depths exceeded 100 kilometers, indicating that these earthquakes occurred in the mantle portion of the lithosphere, even though the crust has been thickened there. The occurrence of earthquakes in the mantle beneath continental regions where the subduction of oceanic lithosphere ceased tens of millions years ago indicates that the mantle lithosphere is sufficiently strong to accumulate elastic strain.

- **Earthquake Recurrence and Rupture Dynamics of Himalayan Frontal Thrust, India. Senthi Kumar, Steven G. Wesnousky, Thomas K. Rockwell, Daniel Ragona, Vikram C. Thakur and Gordon G. Seitz. Science, 14 December, 2001, Vol. 294. (IF- 31.027)**

<u>Abstract:</u>

The Black Mango fault is a structural discontinuity that transforms motion between two segments of the active Himalayan Frontal Thrust (HFT) in northwestern India. The Black Mango fault displays evidence of two large surface rupture earthquakes during the past 650 years, subsequent to 1294 A.D. and 1423 A.D., and possibly another rupture at about 260 A.D. Displacement during the last two earthquakes was at minimum 4.6 meters and 2.4 to 4.0 meters, respectively, and possibly larger for the 260 A.D. event. Abandoned terraces of the adjacent Markanda River record uplift due to slip on the underlying HFT of 4.8 ± 0.9 millimeters per year or greater since the mid-Holocene. The uplift rate is equivalent to rates of fault slip and crustal shortening of $9.6_{-3.5}^{+7.0}$ millimeters per year and $8.4_{-3.6}^{+7.3}$ millimeters per year, respectively, when it is assumed that the HFT dips 30° ± 10°.

- **Estimates of interseismic deformation in Northeast India from GPS measurements. Sridevi Jade, Malay Mukul, Anjan Kumar Bhattacharyya, M.S.M. Vijayan, Saigeetha Jaganathan, Ashok Kumar, R.P. Tiwari, Arun Kumar, S. Kalita, S.C. Sahu, A.P. Krishna, S.S. Gupta, M.V.R.L. Murthy and V.K. Gau. Earth and Planetary Science Letters 263 (2007) 221–234.**

Abstract:

Estimates of interseismic deformation in northeastern India based on GPS measurements at eight permanent stations (2003–2006) and six campaign sites (1997–2006) are presented here. The Euler pole of rotation of Indian tectonic plate in ITRF2000 determined from the present data set is located at 51.7± 0.5 °N,−15.1± 1.5 °E with angular velocity of 0.469± 0.01 Myr−1. The results show that there is a statistically insignificant present-day active deformation within the Shillong Plateau and in the foreland spur north of the plateau in the Brahmaputra valley. Convergence rate of the northeastern GPS sites with respect to the IGS station Lhasa along baselines that are normal to the Himalayan arc in this region is 16 ± 0.5 mm/yr. This represents the arc-normal Indo-Eurasian convergence rate across the northeastern boundary, similar to arc-normal convergence rates determined in central Nepal along the Himalayan arc. However, unlike central Nepal, in the Arunachal Himalaya the 16 mm/yr shortening is distributed between the Lesser as well as Higher and Tethyan Himalayas. Baselines between sites on the Indo-Burmese Fold and Thrust Belt (IBFTB) and Shillong Plateau indicate variations in the shortening rate from 1.5 mm/yr on the Tripura–Mizoram salient (TRS) south of the plateau, to 6 mm/yr in the Imphal Recess (IR) to the east and 8 mm/yr in Naga salient (NS) to the northeast. This suggests that the deformation in the IBFTB is segmented into N–S blocks along E–W transverse zones exhibiting dextral slip between NS–IR and sinistral slip between IR and TRS. Baselines between the IBFTB sites also show 10± 0.6 mm/yr convergence pointing to the existence of an active transverse zone between Aizawl and Imphal.

- **Fault interactions and seismic hazard. C.H Scholz and Anupma Gupta. Journal of Geodynamics, Volume 29, Issues 3–5, April 2000, Pages 459–467.**

Abstract:

Faults usually are not isolated features but exist within a population of faults which may interact through their stress fields. This poses two serious problems for seismic hazard analysis. The most severe such problem lies in estimating the likelihood of whether or not a future earthquake will be confined to a single fault (or fault segment) or will jump to adjacent faults and result in a larger earthquake. We review recent results which show that it is possible to determine the degree of fault interaction from geological data alone. We propose that the probability of an earthquake jumping from one fault to another will increase with the degree of stress interaction between the faults, and introduce a simple criterion to estimate the degree of interaction based on separation and overlap of echelon normal fault pairs. This statics based criterion for normal faults agrees qualitatively with the limited dynamic modeling of (Harris, R.A., Day, S.M., 1993. Dynamics of fault interaction: parallel strike-slip faults. Journal of Geophysical Research 98, 4461–4472) of the more complex case of strike slip faults and suggests that a more general criterion may be obtainable. The second problem discussed is the hazard associated with earthquakes being triggered by earlier earthquakes on a different fault. This phenomena produces seis-

mic hazards distinct from that associated with ordinary aftershocks. We point out that with rapid data acquisition and proper preparation, it is feasible to issue a short-term hazard assessment regarding triggered earthquakes shortly after the occurrence of a potentially triggering event.

FAULT PLANE SOLUTIONS OF SHALLOW EARTHQUAKES AND CONTEMPORARY TECTONICS IN ASIA

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The tectonics of Asia are interpreted as a result of convergence of the Indian and Eurasian plates. The Indian shield bends down and underthrusts the Himalayas to the northeast along a shallow dipping fault plane while the Eurasian plate underthrusts the Pamir mountains, and therefore presumably the Indian Plate, to the south. The convergence of the Indian and Eurasian plates appears to cause relatively high stress to be transmitted across a broad area, north and east of the Himalayas, and this stress in turn causes earthquakes and renewed tectonic activity in some of the ancient Paleozoic and Mesozoic fold belts that separate more stable, aseismic blocks in Asia.

- **Focal depths and fault plane solutions of earthquakes and active tectonics of the Himalaya. J. Baranowski, J. Armbruster, L. Seeber and P. Molner. J. Geophys. Res. (1984), 89(B8), 6918-6928. (IF-3.174)**

Abstract:

We have compared synthetic seismograms with long-period body waves for nine earthquakes with epicenters in the Himalayan arc to determine depths of foci and to improve fault plane solutions. Focal depths are shallow (10–20 km). Inferred slip vectors are locally perpendicular to the mountain range; they plunge very gently (~10°) in the eastern sections of the range and more steeply (~25°) in western sections. Assuming India to be a rigid plate, the radially oriented slip vectors imply that southern Tibet extends at about half the rate of underthrusting in the Himalaya and therefore probably at about 5–10 mm/yr. The shallow depths and gentle dips of the fault planes, at least for the events in the eastern half of the range, are consistent with coherent underthrusting of the Indian

plate beneath, at least, the Lesser Himalaya. The steeper dips of fault planes in the western part of the arc might reflect deformation of the overriding thrust plate or simply a steepening of the main underthrusting zone beneath the Greater Himalaya.

- **Great earthquakes, seismicity gaps and potential for earthquake disaster along the Himalayan plate boundary. K.N. Khattri. Tectonophysics (1987), 138, 79-92. (IF-2.684)**

Abstract:

Analysis of the space-time patterns of seismicity in the Himalaya plate boundary has established the existence of three seismic gaps:

1) The “Kashmir gap” lying west of the 1905 Kangra earthquake;
2) The “Central gap”, situated between the 1905 Kangra and the 1934 Bihar earthquakes;
3) The “Assam gap” between the 1897 and 1950 Assam earthquakes.

This study has shown that the above great earthquakes were preceded as well as followed by long periods ($\geqslant$ 19 years) of decreased levels of seismic activity in the epicentral regions. Remarkable decrease in the seismicity following the year 1970 has been observed in the western half of the Central gap as well as in the Assam gap. Local seismic investigation in the Assam gap confirms this feature and the seismicity suggests the existence there of an asperity. The local seismic investigations in Garhwal Himalaya have shown that the small earthquakes are confined to the upper 6–8 km of the crust and may have strike-slip motions. These earthquakes occur in a region where teleseismically recorded events were few.

- **Imaging lithospheric structure of the eastern Himalayan syntaxis: New insights from receiver function analysis. Qiang Xu, Junmeng Zhao, Shunping Pei and Hongbing Liu J. Geophys. Res. Solid Earth, 118, 2323–2332, Doi:10.1002/jgrb.50162.**

Abstract:

We employ the P and S receiver function technique to data from the 44 seismic stations deployed in the eastern Himalayan syntaxis to investigate the crustal thickness, the average Poisson’s ratio, and the depth of the lithosphere-asthenosphere boundary (LAB). The observed crustal thickness exhibits an overall NE-deepening trend, varying from 55 to 75 km. Two anomalous areas lie in the west and east of the Namche Barwa syntaxis characterized by thinner and thicker crust, respectively. The average Poisson’s ratios within the study area are low in the north and moderate elsewhere with some high values in the south, consistent with felsic and intermediate rocks forming the crust. Our migrated images reveal that (1) the LAB of the Tibetan plate exists at relatively shallow depths (~110 km) and exhibits a gap beneath the Namche Barwa syntaxis, which may have formed by the delamination of mantle lithosphere due to local mantle upwelling, and (2) the LAB of

- **Imaging the Indian lithosphere beneath the Eastern Himalayan region. E. Uma Devi, P. Kumar and M. Ravi Kumar. Geophys. J. Int. (2011) 187, 631–641, Doi: 10.1111/j.1365-246X.2011.05185.x.**

Summary:

Lithospheric thickness is an important parameter to understand the nature of collision and subduction between the Indian and Asian tectonic plates. In this study, we apply the S receiver function technique to data from a network of broad-band stations in the northeast India and Eastern Himalayan regions and image the geometry of Indian Plate collision. This analysis reveals clear S-to-p conversions from the Moho and Lithosphere–Asthenosphere boundary (LAB) in the various tectonic units of the study region. The Indian lithosphere is found to be only 90 km thick beneath the Shillong plateau deepening to 135 km on either side suggestive of a lithospheric upwarp related to the plateau uplift. The lithosphere thickens northward, with values reaching ∼180 km beneath the Eastern Himalaya. The trend of the LAB north of the foredeep region indicates that the Indian Plate plunges beneath the Eastern Himalaya. The consistent northward-dipping character of the Indian Plate suggests that the Indian Plate is traceable until it gets subducted beneath Tibet just south of Bangong suture zone. The deepening of the LAB and its correlation with the topographic elevation is in agreement with homogeneous thickening of the lithosphere in response to compressive forces due to the continental collision of India with Asia.

Key words: Seismicity and tectonics; Body waves; Computational seismology; Continental margins: convergent; Dynamics: seismology; Asia.

- **Large and great earthquakes in the Shillong Plateau-Assam valley area of Northeast India region: Pop-up and transverse tectonics. J.R. Kayal, S.S. Arefiev, S. Baruah, D. Hazarika, N. Gogoi, J.L. Gautam, Santanu Baruah, C Dorbath and R. Tatevossian. Tectonophysics (2012), 532-535, 186-192, Doi.10.1016/j.tecto.2012.02.007. (IF-2.684)**

Abstract:

The tectonic model of the Shillong plateau and Assam valley in the northeast India region, the source area for the 1897 great earthquake (Ms ~ 8.7) and for the four (1869, 1923, 1930 and 1943) large earthquakes (M. ≥ 7.0), is examined using the high precision data of a 20-station broadband seismic network. About 300 selected earthquakes M ≥ 3.0 recorded during 2001–2009 are analysed to study the seismicity and fault plane solutions. The dominating thrust/reverse faulting earthquakes in the western plateau may be explained by the proposed pop-up tectonics between two active boundary faults, the Oldham–Brahmaputra fault to the north and the Dapsi–Dauki thrust to the south, though the northern boundary fault is debated. The more intense normal and strike-slip faulting earthquakes in the eastern plateau (Mikir massif) and in the Assam valley, on the other hand, are well explained by transverse tectonics at the long and deep rooted Kopili fault that cuts across the Himalaya and caused the 2009 Bhutan earthquake (Mw 6.3). It is con-

jectured that the complex tectonics of the Shillong plateau and transverse tectonics at the Kopili fault make the region vulnerable for impending large earthquake(s).

Keywords: Shillong plateau, Earthquakes, Fault plane solution Thrust faulting, Strike slip faulting.

- **Low b-value prior to the Indo-Myanmar subduction zone earthquakes and precursory swarm before the May 1995 M 6.3 earthquake. Sangeeta Sharma, Saurabh Baruah, Om Prakash Sahu, Pabon K. Bora and Ranju Duarah. Journal of Asian Earth Sciences (2013), 73, 176-183. (IF-2.379)**

Abstract:

Some 455 events ($m_b \geqslant 4.5$) in the Indo-Myanmar subduction zone are compiled using the ISC/EHB/NEIC catalogues (1964–2011) for a systematic study of seismic precursors, b-value and swarm activity. Temporal variation of b-value is studied using the maximum likelihood method beside CUSUM algorithm. The b-values vary from 0.95 to 1.4 for the deeper (depth ⩾60 km) earthquakes, and from 0.85 to 1.3 for the shallower (depth <60 km) earthquakes. A sudden drop in the b-value, from 1.4 to 0.9, prior to the occurrence of larger earthquake(s) at the deeper depth is observed. It is also noted that the CUSUM gradient reversed before the occurrence of larger earthquakes. We further examined the seismicity pattern for the period 1988–1995 within a radius of 150 km around the epicentre (latitude: 24.96°N; longitude: 95.30°E) of a deeper event M 6.3 of May 6, 1995 in this subduction zone. A precursory swarm during January 1989 to July 1992 and quiescence during August 1992 to April 1995 are identified before this large earthquake. These observations are encouraging to monitor seismic precursors for the deeper events in this subduction zone.

Keywords: b-Value, CUSUM, Swarm, Quiescence, Indo-Myanmar subduction zone.

- **Low seismicity in the Bhutan Himalaya and the stress shadow of the 1897 Shillong Plateau earthquake. V.K. Gahalaut, Shikha Rajput, Bhaskar Kundu. Physics of the Earth and Planetary Interiors, Volume 186, Issues 3–4, June 2011, Pages 97–102.**

Abstract:
The seismicity of the Bhutan Himalaya region is generally low as compared to its adjoining Himalayan segments. The topography in the region is slightly subdued and different from the neighbouring central Nepal region. Low seismicity in the region may possibly be due to the postulated low convergence rate in the Bhutan Himalaya, difference in subsurface structures, or the aseismic nature of the region. We suggest that the lower seismicity in the Bhutan Himalaya may also be due to stress change caused by the great 1897 Shillong Plateau earthquake as the low seismicity region of the Bhutan Himalaya coincides with the stress shadow of the earthquake.

Keywords: Himalaya; Shillong Plateau; Great earthquake; Stress shadow.

- **Long and short wavelengths of Indian Ocean geoid and gravity lows: Mid-to-upper mantle sources, rapid drift and seismicity of Kachchh and Shillong plateau, India.**

D.C. Mishra and M. Ravi Kumar. Journal of Asian Earth Sciences, Volume 60, 22 October 2012, Pages 212–224.

Abstract:

Spectral analysis of the Indian Ocean geoid low provides depth to the large wavelength sources as ~1300, ~700 and 340 km that are supported from the spectral analysis and the modeling of the corresponding large wavelength regional gravity anomaly with negative density contrasts at these levels. The three levels coincide with the sharp changes in the gradient of the seismic velocities related to the olivine–spinel transformation of successively increasing Fe/Mg ratio as depth increases, known as transition zones. The first two segments are supported from continuous wavelet transform analysis of the large wavelength component of the corresponding gravity field. The low density rocks in this section appear to be related to the subducted Indian/Tethyan lithosphere that roll back and drifted southwards after subduction as inferred from tomography experiments. The relatively short wavelength sources of the spectrum of the geoid data at depths of 162 and 85 km suggest sources along the lithosphere – asthenosphere boundary (LAB) under the Indian continent and surrounding oceans, respectively. A low viscosity zone has been envisaged below 660 km discontinuity that may correspond to the low density rocks in this section which is popularly referred to as graveyards of the subducted rocks under geoid lows. The subducted slab is hydrated due to dehydration from metamorphism that causes upwelling in the mid-to-upper mantle which is likely to set in baby plumes. Presence of fluid may transform part of olivine to serpentine further reducing the bulk density of rocks in this section. They would make this region buoyant that appears to be responsible for the Central Indian Ocean Deformation Zone with large scale folding, faulting, seismicity, and high heat flow. The same also appear to be responsible for the rapid drift of the Indian plate.

Short wavelength component of the Indian Ocean geoid low reflects most of the surface/shallow tectonics of the region similar to the gravity anomaly providing an additional data set for this purpose. Kachchh and the Shillong plateau inspite of being in the intra plate region are highly seismogenic that compare almost to the activity along the plate boundaries. Tectonics and residual geoid anomalies of the Indian continent and adjoining regions suggest that the geoid highs of Kachchh and the Shillong plateau along the NW and the NE corners of India are connected to the geoid highs of the plate boundaries through several lineaments and faults that also show geoid highs and trends of seismic activity leading to plate boundaries. Geoid highs indicating high density mafic rocks suggest their connections/extensions to plate boundaries indicating them to be plausibly part of diffused plate boundaries. Besides, both these regions are affected by (i) prominent lithospheric flexure of the Indian plate (ii) large scale mafic intrusions and (iii) interaction of proterozoic mobile belts with effects of present day Himalayan orogeny that make them more vulnerable for seismic activity.

Keywords: Indian Ocean geoid low; Spectral analysis; Mid-to-upper mantle convection; Baby plume; Diffused plate boundary; Low density and low viscosity zones.

- **Occurrence of anomalous seismic activity preceding large to great earthquake in Northeast India region with special reference to 6th August, 1988. H.N. Singh, D. Shanker and V.P. Singh. Physics of the Earth & Planetary Interiors (2005), 148, 261-284. (IF-2.383)**

Abstract:

Seismicity database from 1860 to 1985 of northeast India region bounded by the area 20°-32°N and 82°-100°E have been analyzed for the identification of precursory swarm/anomalous seismic activity preceding large to great earthquakes with $M \geq 7.5$. It is observed that with the exception of three earthquakes (1908, 1912 and 1918), the large earthquakes of 1897, 1946, 1947, 1950 and 1951/1952 were preceded by well-developed epoch of swarm/anomalous seismic activity in space and time well before their occurrence. The seismicity is observed to fluctuate in the order of low-high-low ranging from 0-0.5, 01-33 to 0-0.7 events/year prior to these mainshocks during the epochs of normal/background, swarm/anomalous and gap/quiescence, respectively. The duration of precursory gap is observed to vary from 11 to 17 years for mainshocks of M 7.5-8.0, and from 23 to 27 years for M 8.7 and this period is dependent on the magnitude of the mainshocks. Using the values of magnitude of mainshock (M_m), average magnitude of swarm (M_p) and the precursory time gap (T_p), the following predictive equations are established for the region: M=1.37M-1.40 $M=3\log_{10}T-3.27$ All the major earthquakes with $m_b \geq 6.1$ occurred during 1963-1988 have been investigated for their association with anomalous seismicity/precursory swarms using the events with cutoff magnitude $m_b \geq 4.5$. Eleven such events have occurred in the region during the period except one earthquake of 29 May 1976. All the remaining 10 earthquakes were associated in some forms of anomalous seismicity epochs. Well-defined patterns of anomalous seismicity are observed prior to 1964-1965, 12 August 1976 and 30 December 1984 (m_b 5.6). All these mainshocks are preceded by seismicity patterns in the order of low-high-low similar to that observed prior to the mainshocks from 1897 to 1962. The anomalous seismicity epoch is delineated with extremely high annual earthquake frequency, which was preceded and followed by extremely low seismicity epochs of background and gap/quiescence phases. Consequently, seismicity rates during anomalous seismicity epoch have always been above normal (1 event/year) whereas it is always below normal during the preceding and the following epochs. A prediction was made using the 1964 swarm based on the M_p and T_p values that a large earthquake with M 8 ± 0.5 with focal depth 100 ± 40 km could occur any time from 1986 to 1990 in an area bound by 21°-25 5°N latitudes and 93°-96°E longitude in Arakan Yoma fold belt. It is interesting to note that the 6 August 1988 earthquake with magnitude 7.5 and focal depth 115 km had occurred within the delineated zone. In addition, three consecutive swarm activities are identified in a limited area within the Eastern Syntaxis and these were not followed by any mainshock till date and could be potential zone for future earthquake.

- **P-wave anisotropic tomography in Southeast Tibet: New insight into the lower crustal flow and seismotectonics. Wei Wei, Dapeng Zhao and Jiandong Xu. Physics of the Earth and Planetary Interiors, 222 (2013), 47–57. (IF-2.383)**

Abstract:

We determined the first 3-D P-wave anisotropy tomography beneath Southeast Tibet and adjacent regions using 63,773 P-wave arrivals from 2866 local earthquakes and 55,457 arrivals from 2802 teleseismic events. A remarkable low-velocity layer with a thickness of about 20 km is revealed in the lower crust, which may reflect a mechanically weak zone capable of flow on a geological timescale. Our seismic anisotropy results suggest that the flow direction changes when it encounters the mechanically strong Sichuan

basin. Most of the large earthquakes including the 2008 Wenchuan earthquake (M 8.0) and the 2013 Lushan earthquake (M 7.0) occurred at the margin of the ductile flow in the lower crust, suggesting that the seismogenesis is controlled by the deep dynamic processes. In the upper mantle, the subducting Indian plate is imaged clearly as a high-velocity zone which has reached near the Jinsha River suture. In addition, our results show significant variations of seismic anisotropy with depth, implying that the upper crust and the lithospheric mantle deform separately beneath most parts of the study region.

- **Paleoliquefaction evidence and periodicity of large prehistoric earthquakes in Shillong Plateau India. B.S Sukhija, M.N Rao, D.V Reddy, P. Nagabhushanam, S Hussain, R.K Chadha and H.K Gupta. Earth Planet. Sci. Lett., 167, 269-282. (IF-4.349)**

Abstract:

The tectonic setting and the occurrence of the great Assam earthquake (M=8.7) of 1897 in the Shillong Plateau succeeded by three great earthquakes (1905, 1934 and 1950) in the adjoining Himalayan frontal arc, indicates the vulnerability of the Shillong Plateau to large earthquakes. The lack of seismicity records of the region earlier than 100 years and data on the recurrence of damaging earthquakes led us to investigate the paleoseismicity of the Shillong Plateau. Our paleoseismic investigations in the meizoseismal area of the 1897 earthquake revealed well-preserved liquefaction and deformed syndepositional features at 10 selected sites in the alluvial deposits along two north flowing tributaries of the Brahmaputra river. These features are 14C dated using associated organic samples. As the liquefaction of sediments was an important feature of the 1897 earthquake, we identified this seismic event, and other large/major prehistoric earthquakes through paleoliquefaction and other coseismic structural deformation at the investigated sites. In addition to the 1897 event, we provide geological evidence for at least three large seismic events. Two of them occurred during 1450–1650 and 700–1050 AD, the third predates 600 AD. The analysis of the 14C data suggests a return period of about 400–600 yr for the large earthquakes in the Shillong Plateau. This finding is the first of its kind from the Himalaya and adjoining region.

Keywords: Main Boundary Fault; Shillong Plateau; 1897 Assam India; earthquakes; liquefaction.

- **Paleoseismological evidence of surface faulting along the northeastern Himalayan front, India: Timing, size, and spatial extent of great earthquakes. Senthil Kumar, Steven G. Wesnousky, R. Jayangondaperumal, T. Nakata, Y. Kumahara and Vimal Singh. J. Geophys. Res., Vol. 115, B12422, Doi:10.1029/2009JB006789.**

Abstract:

The ~2500 km long Himalayan arc has experienced three large to great earthquakes of Mw 7.8 to 8.4 during the past century, but none produced surface rupture. Paleoseismic studies have been conducted during the last decade to begin understanding the timing, size, rupture extent, return period, and mechanics of the faulting associated with the occurrence of large surface rupturing earthquakes along the ~2500 km long Himalayan Frontal Thrust (HFT) system of India and Nepal. The previous studies have been limited to about nine sites along the western two-thirds of the HFT extending

through northwest India and along the southern border of Nepal. We present here the results of paleoseismic investigations at three additional sites further to the northeast along the HFT within the Indian states of West Bengal and Assam. The three sites reside between the meizoseismal areas of the 1934 Bihar-Nepal and 1950 Assam earthquakes. The two westernmost of the sites, near the village of Chalsa and near the Nameri Tiger Preserve, show that offsets during the last surface rupture event were at minimum of about 14 m and 12 m, respectively. Limits on the ages of surface rupture at Chalsa (site A) and Nameri (site B),though broad, allow the possibility that the two sites record the same great historical rupture reported in Nepal around A.D. 1100. The correlation between the two sites is supported by the observation that the large displacements as recorded at Chalsa and Nameri would most likely be associated with rupture lengths of hundreds of kilometers or more and are on the same order as reported for a surface rupture earthquake reported in Nepal around A.D. 1100. Assuming the offsets observed at Chalsa and Nameri occurred synchronously with reported offsets in Nepal, the rupture length of the event would approach 700 to 800 km. The easternmost site is located within Harmutty Tea Estate (site C) at the edges of the 1950 Assam earthquake meizoseismal area. Here the most recent event offset is relatively much smaller (<2.5 m), and radiocarbon dating shows it to have occurred after A.D. 1100 (after about A.D. 1270). The location of the site near the edge of the meizoseismal region of the 1950 Assam earthquake and the relatively lesser offset allows speculation that the displacement records the 1950 Mw 8.4 Assam earthquake. Scatter in radiocarbon ages on detrital charcoal has not resulted in a firm bracket on the timing of events observed in the trenches. Nonetheless, the observations collected here, when taken together, suggest that the largest of thrust earthquakes along the Himalayan arc have rupture lengths and displacements of similar scale to the largest that have occurred historically along the world's subduction zones.

Keywords: paleoseismology; thrust fault; Himalaya.

- **Pop-up tectonics of the Shillong Plateau in northeastern India: Insight from numerical simulations. Md. Shofiqul Islam, Ryuichi Shinjo and J.R. Kayal. Gondwana Research, Volume 20, Issues 2–3, September 2011, Pages 395–404.**

Abstract:

The Shillong Plateau in northeastern India represents one of the most seismically active "pop-up" structures within the peninsular shield area. In order to constrain the role of the inferred Oldham Fault in the northern boundary of the plateau, we performed 2-D finite element method (FEM) simulations for convergent displacement caused by northeastward movement of the Indian plate with respect to the Eurasian plate. Various rock properties (density, Poisson's ratio, Young's modulus, cohesion, and angle of internal friction) and the Mohr–Coulomb failure criterion are used to evaluate failure and faulting patterns. Two plane strain models with appropriate boundary conditions were also calculated. The predicted maximum compressive stress (σ_1) shows a preferred orientation that helps explain the tectonic environment and the fault pattern. The best-fit model suggests that a compressive stress regime is dominant in the study area everywhere except for the uppermost part of the crust where extensional stress dominates. With increased progressive convergent displacement, the modeled σ_1 are predicted to rotate counterclockwise around the fault zones. The simulation results suggest that the Oldham Fault does not have a significant role in the development of stress and deformation distribution in the ar-

ea. We also infer that the tectonically induced deformation in both the plateau and the adjoining areas is restricted to mainly within the crust (< 30 km).

Keywords: Shillong Plateau; Pop-up; Numerical simulation; Oldham Fault; Dauki Fault

- **Radial seismic anisotropy as a constraint for upper mantle rheology. Thorsten W. Becker, Bogdan Kustowski and Göran Ekström. Earth and Planetary Science Letters, 267 (2008), 213–227.**

Abstract:

Seismic shear waves that are polarized horizontally (SH) generally travel faster in the upper mantle than those that are polarized vertically (SV), and deformation of rocks under dislocation creep has been invoked to explain such radial anisotropy. Convective flow of the upper mantle may thus be constrained by modeling the textures that progressively form by lattice-preferred orientation (LPO) of intrinsically anisotropic grains. While azimuthal anisotropy has been studied in detail, the radial kind has previously only been considered in semi-quantitative models. Here, we show that radial anisotropy averages as well as radial and azimuthal anomaly-patterns can be explained to a large extent by mantle flow, if lateral viscosity variations are taken into account. We construct a geodynamic reference model which includes LPO formation based on mineral physics and flow computed using laboratory-derived olivine rheology. Previously identified anomalous vSV regions beneath the East Pacific Rise and relatively fast vSH regions within the Pacific basin at ~150 km depth can be linked to mantle upwellings and shearing in the asthenosphere, respectively. Continental anisotropy at shallow (~ 50 km) depth is underpredicted, and these deviations are in quantitative agreement with the expected signature of frozen-in, stochastically-oriented anisotropy from past tectonic episodes. We also consider two end-member models of LPO formation for “wet” and “dry” conditions for the asthenosphere (~ 150 km). Allowing for lateral variations in volatile content, the residual signal can be much reduced, and the inferred volatile patterns underneath the Pacific appear related to plume activity. In deeper layers (~ 250 km), anisotropy indicates that small-scale convection disrupts plate-scale shear underneath old oceanic lithosphere. We suggest that studying deviations from comprehensive geodynamic reference models, or “residual anisotropy”, can provide new insights into the nature and dynamics of the asthenosphere.

Keywords: seismic anisotropy; radial anisotropy; mantle rheology; mantle convection; volatiles; continental formation

- **Revisiting the earthquake sources in the Himalaya: Perspectives on past seismicity. Kusala Rajendran and C.P. Rajendran. Tectonophysics, Volume 504, Issues 1–4, 9 May 2011, Pages 75–88.**

Abstract:

The ~ 2500 km-long Himalaya plate boundary experienced three great earthquakes during the past century, but none of them generated any surface rupture. The segments between the 1905–1934 and the 1897–1950 sources, known as the central and Assam seismic gaps respectively, have long been considered holding potential for future great earthquakes. This paper addresses two issues concerning earthquakes along the Himalaya plate boundary. One, the absence of surface rupture associated with the great earthquakes, vis-à-vis the purported large slip observed from paleoseismological investigations and two, the current understanding of the status of the seismic gaps in the Central Himalaya and Assam, in view of the paleoseismological and historical data being gathered. We suggest that the ruptures of earthquakes nucleating on the basal detachment are likely to be restricted by the crustal ramps and thus generate no surface ruptures, whereas those originating on the faults within the wedges promote upward propagation of rupture and displacement, as observed during the 2005 Kashmir earthquake, that showed a peak offset of 7 m. The occasional reactivation of these thrust systems within the duplex zone may also be responsible for the observed temporal and spatial clustering of earthquakes in the Himalaya. Observations presented in this paper suggest that the last major earthquake in the Central Himalaya occurred during AD 1119–1292, rather than in 1505, as suggested in some previous studies and thus the gap in the plate boundary events is real. As for the Northwestern Himalaya, seismically generated sedimentary features identified in the 1950 source region are generally younger than AD 1400 and evidence for older events is sketchy. The 1897 Shillong earthquake is not a décollement event and its predecessor is probably ~ 1000 years old. Compared to the Central Himalaya, the Assam Gap is a corridor of low seismicity between two tectonically independent seismogenic source zones that cannot be considered as a seismic gap in the conventional sense.

Keywords: Central Himalaya, Earthquakes, Paleoseismology, Seismic gaps, Northeast India.

- **Role of static stress transfer in earthquake occurrence in the Himalaya. I. Sarkar and R. Chander. Journal of Asian Earth Sciences, Volume 22, Issue 1, 2003, Pages 59–65.**

Abstract:

Coulomb failure hypothesis suggests that earthquake interaction can lead to earthquake sequences and clustering. This implies that the phenomenon should be considered a fundamental feature in any description of seismicity and evaluation of the seismic hazard and risk of a region. We translate this idea to the Himalaya and investigate how significantly the past earthquakes of the region may have influenced the present day seismicity and seismic hazard potential along its different segments.

For this, we estimate separately the change in Coulomb failure stress at the source of the most recent moderate magnitude earthquake along the Kumaon Garhwal segment, the March 29, 1999 Chamoli earthquake, due to two possible major sources. These are (i) the process of subduction of the Indian plate beneath the Himalaya and (ii) some selected preceding moderate and small earthquakes in and around the region, during their post seismic phase. Our results indicate that the change due to the former source completely overshadows that due to the latter.

The implication of our calculations is that the plate subduction processes in the Himalaya (i) actively promote large, moderate and small earthquake activity and (ii) also indirectly influence the regional seismicity through the occurrence of the past earthquakes.

Keywords: Static stress transfer; Himalayan seismicity

- **Seismic hazard analysis of India using areal sources. T.G. Sitharam and Sreevalsa Kolathayar. Journal of Asian Earth Sciences, Volume 62, 30 January 2013, Pages 647–653.**

Abstract:

In view of the major advancement made in understanding the seismicity and seismotectonics of the Indian region in recent times, an updated probabilistic seismic hazard map of India covering 6–38^{0}Nand 68–98^{0}E is prepared. This paper presents the results of probabilistic seismic hazard analysis of Indiadone using regional seismic source zones and four well recognized attenuation relations considering variedtectonic provinces in the region. The study area was divided into small grids of size 0.1^{0}x 0.1^0. PeakHorizontal Acceleration (PHA) and spectral accelerations for periods 0.1 s and 1 s have been estimatedand contour maps showing the spatial variation of the same are presented in the paper. The present studyshows that the seismic hazard is moderate in peninsular shield, but the hazard in most parts of North andNortheast India is high.

Keywords: India; Seismic hazard; PSHA; Source zones; Peak Horizontal Acceleration.

- **Seismic hazard assessment and mitigation in India: an overview. Mithila Verma and Brijesh K. Bansal. International Journal of Earth Sciences, July 2013, Volume 102, Issue 5, pp 1203-1218.**

Abstract:

The Indian subcontinent is characterized by various tectonic units viz., Himalayan collision zone in North, Indo-Burmese arc in north-east, failed rift zones in its interior in Peninsular Indian shield and Andaman Sumatra trench in south-east Indian Territory. During the last about 100 years, the country has witnessed four great and several major earthquakes. Soon after the occurrence of the first great earthquake, the Shillong earthquake (M_w: 8.1) in 1897, efforts were started to assess the seismic hazard in the country. The first such attempt was made by Geological Survey of India in 1898 and since then considerable progress has been made. The current seismic zonation map prepared and published by Bureau of Indian Standards, broadly places seismic risk in different parts of the country in four major zones. However, this map is not sufficient for the assessment of area-specific seismic risks, necessitating detailed seismic zoning, that is, microzonation for earthquake disaster mitigation and management. Recently, seismic microzonation studies are being introduced in India, and the first level seismic microzonation has already been completed for selected urban centres including, Jabalpur, Guwahati, Delhi, Bangalore, Ahmadabad, Dehradun, etc. The maps prepared for these cities are being further refined on larger scales as per the requirements, and a plan has also been firmed up for taking up microzonation of 30 selected cities, which lie in seismic zones V and IV and have a population density of half a million. The paper highlights the efforts made in India so far towards seismic hazard assessment as well as the future road map for such studies.

Abstract: Seismic hazard, Indian subcontinent, Seismicity monitoring, Seismic zoning, Microzonation.

- **Seismic Images of Crust and Upper Mantle Beneath Tibet: Evidence for Eurasian Plate Subduction. R. Kind, X. Yuan, J. Saul, D. Nelson, S. V. Sobolev, J. Mechie, W. Zhao, G. Kosarev, J. Ni, U. Achauer and M. Jiang. Science, 8 November 2002, Vol. 298, no. 5596, pp.1219-1221, Doi: 10.1126/science.1078115. (IF-31.027)**

Abstract:

Seismic data from central Tibet have been combined to image the subsurface structure and understand the evolution of the collision of India and Eurasia. The 410- and 660-kilometer mantle discontinuities are sharply defined, implying a lack of a subducting slab beneath the plateau. The discontinuities appear slightly deeper beneath northern Tibet, implying that the average temperature of the mantle above the transition zone is about 300°C hotter in the north than in the south. There is a prominent south-dipping converter in the uppermost mantle beneath northern Tibet that might represent the top of the Eurasian mantle lithosphere underthrusting the northern margin of the plateau.

- **Seismic landscape from Sarpang re-entrant, Bhutan Himalaya foredeep, Assam, India: Constraints from geomorphology and geology. Sujit Dasgupta, Kiron Mazumdar, L.H. Moirangcha, Tanay Dutta Gupta and Basab Mukhopadhyay. Tectonophysics, Volume 592, 19 April 2013, Pages 130–140.**

Abstract:

Geomorphic landscape and late Quaternary geological attributes from the Raidak–Manas interfluve in the Bhutan–Himalayan foothills, Kokrajhar District, Assam led towards documenting the east–west trending, south dipping, 30 km long active Frontal Back Thrust (FBT), well within the foredeep south of the Main Frontal Thrust (MFT). Spectacular north facing 6–50 m high tectonic-scarp generated by the north-propagating emerging thrust front along with a complementary subdued south-facing scarp defines the terrain as a pop-up structure. The entire belt is made up of 5 to 8 km wide six distinct blocks, separated by antecedent rivers/streams. Scarp parallel east–west drainage along with linear lakes characterises the emerging thrust front. Field evidence for a major fault-propagation fold structure along with thrust faulting within the late-Quaternary fluvial sediments is ubiquitous. Clay beds deposited in lakes along the footwall of FBT have formed due to blockade of south flowing rivers by episodic upliftment of the hanging wall block; three such episodes of uplift since 16 k years correspond to three morphogenic earthquakes of magnitude ~ 6.9 rupturing the FBT during late Pleistocene–Holocene. In light of geomorphological and geological studies, neotectonic activity has been modelled as an active south dipping backthrust that originates at shallow crustal depth from south vergent basal Himalayan Decollement in response to the advancing Himalayan wedge.

Keywords: Bhutan Himalaya; Sarpang; Ultapani; Backthrust; Active fault; Foredeep.

- **Seismic signatures of detached lithospheric fragments in the mantle beneath eastern Himalaya and southern Tibet. Arun Singh and M. Ravi Kumar. Earth and Planetary Science Letters, Volume 288, Issues 1–2, 30 October 2009, Pages 279–290.**

Abstract:

In this study, we investigate the mantle transition zone (MTZ) structure beneath eastern Himalaya and southern Tibet using ~ 9000 high quality receiver functions from 96 broadband stations spanning the entire region. The pervasive early arrival times(~ 1.7 s compared to IASP91) of the P-to-s conversions from the 410 km discontinuity are attributed to the high shear wave velocities associated with the subducted Indian (and Asian) lithosphere(s). Global and regional shear wave velocity models obtained from seismic tomography evince such high velocity anomalies both in the uppermost mantle and within the MTZ, in this complex collision environment. In contrast, the conversions from the 660 km discontinuity are either normal or delayed (up to 1 s) providing evidences for a thickened MTZ beneath most of the study region. Although presence of water in the MTZ can result in such a thickening, issues like 1) low amplitudes of the P410s and P660s conversions, 2) small dependence of their amplitudes with frequency, 3) absence of a detectable low velocity layer atop 410 and 4) lack of evidence for a 520 km discontinuity, preclude such an interpretation. Instead, we attribute this thickening to lowered temperatures affected by the possible presence of detached cold and dense lithospheric slabs within the MTZ. Such a detachment might have been facilitated either by convection or gravity removal of the lithosphere thickened due to continued subduction of the Indian plate since the Mesozoic.

Keywords: Eastern Himalaya; detached slabs; mantle transition zone.

- **Seismic Study and Spatial Variation of b-value in Northeast India. Pulama Talukdar. IOSR Journal of Applied Physics (IOSR-JAP)e-ISSN: 2278-4861, Volume 4, Issue 3 (Jul. - Aug. 2013), PP 31-40.**

Abstract:

Study of recent seismicity and b-value estimation by Least Square and Maximum Likelihood Estimation methods in five tectonic blocks of Northeast India demarcates indo Burma Belt, Main Central Thrust, Main Boundary Thrust, Shilling Plateau, Mikir Hills and Kopili Lineament as active seismic source of the region. Spatial variation of b-value is observed by dividing the study area into $1^0 \times 1^0$grids. Higher b-valuecontours depict the highly seismic area with structural heterogeneity, while lower b-value contours indicate theareas under high stress. b-values are observed in the range of 0.437 - 0.908 and mostly concentrated around 0.7, indicating high stress accumulation.
Keywords: Seismicity, b-value, Contour.

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Review Article

Seismicity-based earthquake forecasting techniques: Ten years of progress

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ABSTRACT

Earthquake fault systems interact over a broad spectrum of spatial and temporal scales and, in recent years, studies of the regional seismicity in a variety of regions have produced a number of new techniques for seismicity-based earthquake forecasting. While a wide variety of physical assumptions and statistical approaches are incorporated into the various methodologies, they all endeavor to accurately replicate the statistics and properties of both the historic and instrumental seismic records. As a result, the last ten years have seen significant progress in the field of intermediate- and short-term seismicity-based earthquake forecasting. These include general agreement on the need for prospective testing and successful attempts to standardize both evaluation methods and the appropriate null hypotheses. Here we differentiate the predominant approaches into models based upon techniques for identifying particular physical processes and those that filter, or smooth, the seismicity. Comparison of the methods suggests that while smoothed seismicity models provide improved forecast capability over longer time periods, higher probability gain over shorter time periods is achieved with methods that integrate statistical techniques with our knowledge of the physical process, such as the epidemic-type aftershock sequence (ETAS) model or those related to changes in the *b*-value, for example. In general, while both classes of seismicity-based forecasts are limited by the relatively short time period available for the instrumental catalog, significant advances have been made in our understanding of both the limitations and potential of seismicity-based earthquake forecasting. There is general agreement that both short-term forecasting, on the order of days to weeks, and longer-term forecasting over five-to-ten year periods, is within reach. This recent progress serves to illuminate both the critical nature of the different temporal scales intrinsic to the earthquake process and the importance of high quality seismic data for the accurate quantification of time-dependent earthquake hazard.

- **Seismicity patterns in the Himalayan plate boundary and identification of the areas of high seismic potential. K.N. Khattri and A.K. Tyagi. Tectonophysics (1993), 96, 281-297. (IF-2.684)**

Abstract:

Space-time distribution of earthquakes along the Himalayan plate boundary has been investigated with a view to discerning fluctuations in seismicity rates associated with great earthquakes, the possibilities of epicentre migration and gaps in seismic activity. Data from 1800 to 1976 were considered. This study shows that all great earthquakes (M ⩾ 8.0) were preceded by seismically quiescent periods of at least 19 years. Furthermore, earthquake quiescence has also been recognised to follow the great earthquakes.

Three possible trends of migration of epicentres of great earthquakes have been recognised:

1) The first trend starts from the 1905 Kangra earthquake, the epicentres of subsequent earthquakes migrating eastwards along the plate boundary.
2) The second trend of migration starts from the great Nepal earthquake of 1833 associated with eastward migration.
3) The third trend commences from the great Assam earthquake of 1897 and shows a westward migration of earthquake epicentres. The middle section of the Himalayan convergent plate boundary (80°E to 90°E), in general, displays a relatively low level of seismicity as compared to the adjacent sections.

A remarkable decrease in seismicity following the year 1970 has been observed along a section of the Himalaya which lies to the east of the rupture zone of the great 1905 Kangra earthquake. Since 1970 the seismicity rate has also dropped in the region lying in between the rupture zones of the great Assam earthquakes of 1897 and 1950, as has earlier been reported by Khattri and Wyss (1978). Such decreases in the level of seismicity along active plate boundaries have been demonstrated to be indicative of building up of stresses leading to future great earthquakes (Mogi, 1969; McCann et al., 1979).

- **Seismotectonics and rates of active crustal deformation in the Burmese arc and adjacent regions. M. Radha Krishna and T.D. Sanu. Journal of Geodynamics, Volume 30, Issue 4, 1 November 2000, Pages 401–421.**

<u>Abstract:</u>

The close vicinity of the Burmese subduction zone to the Himalayan collision zone across northeast India produces complex tectonics giving rise to a high level of seismicity. Using the hypocentral data of shallow earthquakes ($h \leq 70$ km) for the period 1897–1995, a large number of focal mechanism solutions and other geophysical data in correlation with major morphotectonic features in the Burmese arc and the adjoining areas, we identified 12 broad seismogenic zones of relatively homogeneous deformation. Crustal deformation rates have been determined for each one of these sources based on summation of moment tensors. The results indicate that along the Kopili–Bomdila fault zone in eastern Himalaya, the deformation is taken up as a compression of 0.12 ± 0.01 mm/yr along N16° and an extension of 0.05 ± 0.004 mm/yr along N104° direction. The deformation velocities show a NS compression of 18.9 ± 2.5 mm/yr and an EW extension of 17.1 ± 2.2 mm/yr in the Shillong Plateau region, while a compression of 5.4 ± 2.8 mm/yr along N33° is observed in the Tripura fold belt and the Bengal basin region. The vertical component in the Shillong Plateau shows crustal thickening of 2.4 ± 0.3 mm/yr. The deformation velocities in Indo–Burman ranges show a compression of 0.19 ± 0.02 mm/yr along N11° and an extension of 0.17 ± 0.01 mm/yr along N101° in the Naga hills region, a compression of 3.3 ± 0.4 mm/yr along N20° and an extension of 3.1 ± 0.36 mm/yr along N110° in the Chin hills region and a compression of 0.21 ± 0.3 mm/yr in N20° and an extension of 0.18 ± 0.03 mm/yr along N110° in the Arakan–Yoma region. The dominance of strike-slip motions with the P axis oriented on an average along N17° indicate that the Burma platelet may be getting dragged along with the Indian plate and the motion of these two together is accommodated along the Sagaing fault. The velocities estimated along Sagaing transform fault in the back-arc region suggest that the deformation is taken up as an extension of 29.5 ± 4.7 mm/yr along N344° and a compression of 12.4 ± 1.9 mm/yr along N74° in the northern part of the fault zone, and a compression of 17.4 ± 2.3 mm/yr along N71° and an extension of 59.8 ± 8.0 mm/yr along N341° in the southern part of the fault zone. The average shear motion of about 13.7 mm/yr is observed along the Sagaing fault. The deformation observed in the southern part of the syntaxis zone along the Mishmi thrust indicate a compression of 0.63 ± 0.08 mm/yr in N58° and an extension of 0.6 ± 0.07 mm/yr in N328° direction. The region of Shan Plateau, west of Red River fault, shows a compression of 17.7 ± 2.6 mm/yr along N36° and an extension of 16.1 ± 2.4 mm/yr along N126°.

Keywords: Global Positioning System; interseismic deformation; plate convergence; Shillong Plateau; Himalayas; Indo-Burman fold and thrust belt (IBFTB).

- **Separation of intrinsic and scattering seismic wave attenuation in Northeast India. Simanchal Padhy and N. Subhadra. Geophys. J. Int. (December, 2013) 195 (3), 1892-1903, Doi: 10.1093/gji/ggt350.**

Summary:

We have analysed the local earthquakes ($2.0 \leq M_L \leq 5.5$) occurred in northeast (NE) India recorded by a temporary seismic network of 10 stations operated by National Geophysical Research Institute (NGRI), Hyderabad to evaluate the relative contributions of scattering loss (Q−1sc) and intrinsic absorption (Q−1i) to total attenuation (Q−1t) using the multiple lapse time window analysis assuming multiple isotropic scattering in a medium of uniformly distributed scatterers. The results show that Q−1i is greater than Q−1sc at high frequencies (f > 3 Hz), while the opposite is observed at low frequencies (f < 3 Hz). The observed frequency dependence of Q−1sc corresponds to the scale length of lithospheric heterogeneity beneath NE India, at least comparable with the wavelength for the lowest frequencies analysed, of about 1 km. The observed Q−1c for the study region obtained with single scattering theory is close to Q−1i at high frequencies, in agreement with theoretical prediction for an idealized case of uniform distribution of scatterers. However, a discrepancy exists between the two at low frequencies, which can be explained by a depth-dependent velocity and attenuation structure. High value of Q−1t is correlated with the geology and tectonic settings of the region characterized by Himalayan and Burman collision zones with a strong lateral heterogeneity. The Q−1i estimates obtained in this study can be used to infer the average temperature of the lower crust with an upper limit estimate of ∼800 °C assuming a lower crustal gabbroic lithology.

Keywords: Seismic attenuation, Wave scattering and diffraction, Wave propagation

- **Source parameters and fmax in Kameng region of Arunachal Lesser Himalaya. Ashwani Kumar, Arjun Kumar, S.C. Gupta, Himanshu Mittal and Rohtash Kumar. Journal of Asian Earth Sciences xxx (2013) xxx–xxx.**

Abstract:

A data set of 79 local events (0.7 6 Mw 6 3.7) occurred during February 2003 to May 2003, collected by a temporary network deployed in Kameng region of Arunachal Lesser

Himalaya have been analyzed to study the source parameters and f_{max}. In this study Brune model that yield a fall-off of two beyond corner frequency along with high frequency diminution factor for frequencies greater than f_{max} represented by a Butterworth high-cut filter (Boore, 1983) has been considered. The software EQK_SRC_PARA (Kumar et al., 2012) has been used to estimate the spectral parameters namely: low frequency displacement spectral levels (Ω_0), corner frequency (f_c) above which spectrum decays with a rate of two, the high cut frequency (f_{max}) above which the spectrum again decays and the rate of decay (N) above f_{max}. These spectral parameters are used to estimate source parameters, viz., seismic moments, source dimensions and stress drops and to develop scaling laws for the region. Seismic moments vary from 1.42×10^{17} - dyne-cm to 4.23×10^{21} dyne-cm; the source radii vary from 88.7 m to 931.5 m. For 28 events, stress drops are less than 1 bar and 51 events have stress drops between 1 bar and 40 bars. A scaling relation, M_0 (dyne-cm) = $2 \times 10^{22} f_c^{-3.34}$ has been derived for earthquakes having seismic moments greater than 1.5×10^{19} dyne-cm. The estimated values of f_{max} values by and large conform to the worldwide observations. Dependence of f_{max} on source sizes, focal depths, epicentral distances and recording sites has been studied on the basis of comparative dependency of f_c and f_{max}. The f_{max} and f_c show almost similar dependency to seismic moments which shows f_{max} is also due to source process and is independent of epicentral distances and focal depths. At different recording sites, the observed values of f_{max} show consistent increase with seismic moment. This reflects that the source is the main controlling factor rather than recording site conditions for the observed variation of f_{max} in the Kameng region.

Keywords: Source parameters, Kameng, Arunachal Lesser Himalaya, fmax.

- **Strange attractor characteristics of earthquakes in Shillong Plateau and adjoining regions. H. N. Srivastava, S. N. Bhattacharya and K. C. Sinha Ray. Geophysical Research Letters,Volume 23, Issue 24, pages 3519–3522, 1 December 1996.**

Abstract:

Strange attractor dimensions were determined for two concentric areas of about 220 km (2°) and 440 km (4°) radii around WWSSN station at Shillong based on earthquake data during the period 1964 to 1992. Existence of deterministic chaos for both the areas was supported by the same fractal dimension of 6.1 and positive value of the largest Lyapunov exponent. The results have provided justification for delineating precursory seismicity patterns based on earthquakes up to epicentral distance of 440 km on different fault systems.

Conspicuous higher value of the strange attractor dimension in Hindukush, Himalaya and northeast India than that in Koyna region in the peninsular India suggests a new criteria for distinction between interplate and intraplate earthquakes. Differences with subduction zone in Pacific vis-à-vis stress drop in great earthquakes ($M \geq 8$) and implications of the chaotic approach in earthquake hazard analysis have also been brought out.

- **Tectonic stress field in the Indian subcontinent. T.N. Gowd, S.V. Srirama Rao and V.K. Gaur. Journal of Geophysical Research: Solid Earth (1978–2012), Volume 97, Issue B8, pages 11879–11888, 30 July 1992.**

Abstract:

A map of maximum horizontal compressive stress orientation in the Indian subcontinent has been prepared using orientations derived from three different stress indicators: borehole elongation breakouts, in situ hydraulic fracturing measurements, and earthquake focal mechanisms. Most part of the subcontinent appears to be characterized by a compressional stress regime (thrust and strike slip faulting) imposed by plate boundary forces although SH_{max} orientations do not, in general, show clear correlation with the direction of motion of the Indian plate. Four provinces are recognized on the basis of regionally consistent orientations. These are the midcontinent stress province, the southern shield, the Bengal basin, and the Assam wedge. Their boundaries have been determined taking into consideration regional tectonics and seismicity. Central and northern India, including the Shillong Plateau stretching up to the great Himalaya, Pakistan, and Nepal are included in a broad "midcontinent" stress province characterized by NNE-ENE oriented SH_{max}. The mean orientation of SH_{max}in this province is N23°E, subparallel to the direction of compression expected to arise from the net resistive forces at the Himalayan collision zone, suggesting that it is largely determined by the tectonic collision processes. Much of southern India (Mysore plateau and the high-grade metamorphic terrain south of the plateau) appears to be part of a second stress province characterized by NW oriented SH_{max}. These appear close to those of the intraplate stress field prevailing in the central Indian Ocean. A third stress province was recognized in the Bengal basin including parts of West Bengal, Tripura, Manipur, and Mizoram in northeastern India and most of Bangladesh. This province extends eastward from the marginal fault in the western margin of the Bengal basin to the Indo-Burma subduction zone and is bounded on the north by the E-W striking Dauki fault. SH_{max} within the sedimentary pile of the Bengal basin is oriented in E-W direction, while P axes of earthquakes within the basement and the crust beneath the basin and within the subducted slab of the Indian plate beneath the Indo-Burman ranges generally trend north - N30°E. SH_{max} orientations within the sedimentary pile of the basin are parallel to the local (approximately E-W) direction of the convergence of Indian and Burmese plates, suggesting a casual relation to the resistive forces at the subduction zone in the Indo-Burma region. Interestingly, the stress field in the basement and the crust beneath the Bengal basin and in the subducted slab is similar to the one prevailing in the midcontinent stress province. Assam wedge stress region occupies the northeastern corner of the Indian plate, including Upper Assam, Arunachal Pradesh, and much of Nagaland. This region subducts beneath a sharply bent continental collision boundary consisting of the northeastern limb of the Himalayan and northern limb of the Indo-Burman fold belts. As a result, the stress field in this province is depth-differentiated and most likely responsible for the absence of consistent SH_{max} directions.

- **Teleseismic P-wave residual Investigations at Shillong, India. H.K. Gupta and V.P. Singh. Tectonophysics (1980), Vol. 66, pp. 19-27. (IF-2.684)**

Abstract:

The northeast India region is seismically very active and it has experienced two large earthquakes of magnitude 8.7 during the last eight decades (1897 and 1950). We have analysed teleseismic P-wave residuals at Shillong, the only reliable seismic station operating in the region, to investigate a possible association of travel-time residual anomaly with earthquake occurrence. The period covered is from October 1964 through March

1976. The total number of events is 9479, including 1767 events with depth >/ 100 km. Six-monthly average residuals have been calculated. The standard deviations are less than 0.10 sec for these data sets. During the period of investigations, no major earthquake took place close to Shillong. The earthquake of June 1, 1969 with a magnitude (Mb) of 5.0, at an epicentral distance of 20 km from Shillong is the only significant event. This earthquake is found to be associated with a travel-time increase with a maximum amplitude of 0.4 sec. It appears that, in general, the P-wave velocity has decreased in the neighbourhood of Shillong since 1969. A quadrant-wise analysis of residuals indicates that the residual anomaly is most prominent in the SE quadrant from Shillong.

- **The Great 1950 Assam Earthquake revisited- Field evidence of liquefaction and search for paleoseismic events. D.V. Reddy, P. Nagabhusanam, Devender Kumar, B.S. Sukhik, P.J. Thomas, Anand K. Pandey, R.N. Sahoo, C.V. Ravi Prasad and K. Datta. Tectonophysics (2009), 474, 463-472. (IF-2.684)**

Abstract:

Extensive field investigations were carried out for the first time in the meizoseismal area of the great 1950 Assam Earthquake aimed at exploring the paleoseismic history of the NE Indian region through documentation of liquefaction features and radiocarbon (14 C) dating. Trenching at more than a dozen locations along the Burhi Dihing River valley and within the alluvial fans adjoining the Brahmaputra and Dibang Rivers resulted in the identification of more than a dozen very prominent liquefaction features (sand dykes, sills, sand blows etc.) as evidences of large to great earthquakes. 14 C dating of the organic material associated with some of the features indicates a paleoseismic record of about 500 yrs archived by the sediments in this region. Compelling geological evidence(s) of the great 1950 earthquake are well constrained by 14 C dating. Out of the two historically reported seismic events (1548 AD and 1697 AD) from this region, 14 C dating could constrain the 1548 AD event though not distinctly. Further studies using combined 14 C and OSL dating may better constrain the seismo-chronology of the study region.

Keywords: Paleoseismology, Liquefaction, 14C dating, Himalaya, 1950-Assam Earthquake, Brahmaputra River, North East India.

- **The motion and active deformation of India. J. Paul, R. Burgmann, V.K. Gaur, R. Bilham, K.M. Larson, M.B., Ananda, S. Jade, M. Mukal, T.S. Anupama, G. Satyal and D. Kumar. Geophysical Research Letters, Vol. 0, No. 0, Pages 0-0, M 0, 2000.**

Abstract:

Measurements of surface displacements using GPS constrain the motion and deformation of India and India-Eurasia plate boundary deformation along the Himalaya. The GPS velocities of plate-interior sites constrain the pole of the angular velocity vector of India with respect to Eurasia to lie at 25.6±1.0ºN 11.1±9.0ºE, approximately 6º west of the NUVEL-1A pole of < 3 Ma plate motion. The angular rotation rate of 0.44 ± 0.03◦ Myr^{-1} is 14% slower than the long-term rate of 0.51º Myr^{-1}. Insignificant velocities be-

tween plate interior sites indicate that the exposed Indian plate is stable to within 7×10^{-9} yr^{-1}. About 20 mm/yr of convergence across the Himalaya rotates counterclockwise by about 45º from NW India (~77ºE) to E Nepal (~92ºE) to remain approximately perpendicular to the Himalayan arc. This rotation of convergence consistent with east-west extension of southern Tibet.

- **The status of central seismic gap: a perspective based on the spatial and temporal aspects of the large Himalayan earthquakes. C.P. Rajendran and Kusala Rajendran. Tectonophysics, Volume 395, Issues 1–2, 6 January 2005, Pages 19–39.**

Abstract:

The central Himalaya, considered as a prominent 'seismic gap', is generally believed to be the most vulnerable segment, due for a great plate boundary earthquake (M>8). Two significant historical earthquakes are known to have occurred in this region, in AD 1505 and 1803. Interpreted by some workers as great earthquakes, occurrences of these events question the validity of central Himalaya being a seismic gap. Here, we analyze the macroseismal data from the Central Himalaya and the Gangetic Plains, and suggest that neither of these earthquakes can be qualified as a plate-boundary-type event, and the size of at least the 1803 does not exceed Mw 7.7. Our studies further indicate that the central Himalayan frontal thrusts may be undergoing a quiescence of >1000 years in terms of generation of great earthquakes. Assuming a steady elastic strain accumulation due to plate convergence, and its simple translation as periodic great earthquakes, such long quiescence may appear intriguing. We suggest that the long-term quiescence and the spatial and temporal clustering that characterize the distribution of large earthquakes in the Himalaya, is a manifestation of the tectonic deformation associated with a highly evolved fold and thrust belt. Our analyses also indicate that the large/moderate earthquakes are mostly concentrated on higher-level thrusts. These structures probably accommodate most of the seismogenic slip in the Himalaya, and the rest of the strain could possibly be expended on passive folding. Consequently, great earthquakes (M>8) are relatively infrequent, as in the case of central Himalaya, apparently leading to long periods of quiescence.

Keywords: Himalaya; Historical seismicity; Earthquake; Tectonics; Fold-thrust-belt.

- **The tectonic stress field and deformation pattern of northeast India, the Bengal basin and the Indo-Burma Ranges: A numerical approach. Md. Shofiqul Islam, Ryuichi Shinjo and J.R. Kayal. Journal of Asian Earth Sciences, Volume 40, Issue 1, 4 January 2011, Pages 121–131.**

Abstract:

We performed numerical simulations to determine the contemporary maximum horizontal compressive stress (σ_{Hmax}) in the northeast India region, the Bengal basin (Bangladesh), and the adjoining Indo-Burma Ranges, with different boundary conditions. The regional tectonic stress was simulated using the finite element method (FEM) under the plane stress condition. Most of the study areas show NE–SW regional stress orientation, which is consistent with other stress indicators, such as earthquake focal mechanism solu-

tions. The E–W trending Dauki fault, which separates the Shillong plateau to the north from the Bengal basin to the south, plays a major role in the stress distribution and regional deformation. This fault alone accommodates ∼25% of the regional surface displacement rate of the study area. The fault pattern of the study area was also simulated using rheological parameters and the Mohr–Coulomb failure criterion. The simulated results reproduce the observed tectonic state of the area, including a strike-slip regime along the Dauki fault, in the southwestern part of the Bengal basin, and in the Tripura fold belt areas. The modeling indicates that the Brahmaputra valley to the north of the Shillong plateau and to the south of the Himalayan frontal thrust exhibits thrust/reverse faulting with a strike-slip component, and in the Indo-Burma Ranges, strike-slip faulting is predominant with a reverse fault component.

Keywords: Shillong plateau; Bengal basin; Dauki fault; Maximum horizontal compressive stress.

4.3 REVIEW ON THE STUDIES PERTAINING TO DAMAGING EARTHQUAKES OF THE REGION

- **The 18 September 2011, North Sikkim Earthquake. Kusala Rajendran, C.P. Rajendran, N. Thulasiraman, Ronia Andrews and Nima Sherpa. Current Science, Vol. 101, No. 11, 10 December 2011.**

The 18 September 2011, magnitude *Mw* 6.9 earthquake close to the Nepal–Sikkim border caused significant damage due to ground shaking and caused several landslides. Observations from the post-earthquake surveys in the affected areas within Sikkim suggest that the poorly engineered, multistoried structures were relatively more impacted. Those located on alluvial terraces were also affected. The morphology ofthe region is prone to landslides and the possibility for their increased intensity during the forthcoming monsoon need to be considered seriously. From the seismotectonic perspective, the mid-crustal focal depth ofthe North Sikkim earthquake reflects the ongoing deformation of the subducting Indian plate.

Keywords: Epicentre, focal depth, post-earthquakesurvey, seismotectonic setting.

- **Causative source of Mw 6.9 Sikkim–Nepal border earthquake of September 2011: GPS baseline observations and strain analysis. Rashmi Pradhan, Sanjay K. Prajapati, Sumer Chopra, Ashok Kumar, B.K. Bansal and C.D. Reddy. Journal of Asian Earth Sciences, Volumes 70–71, July 2013, Pages 179–192.**

Abstract:

The recent earthquake of Mw 6.9 which occurred on September 18, 2011 in Sikkim–Nepal border region (epicenter 27.72°N, 88.06°E, depth 20.7 km, ∼68 km NW of the Capital city Gangtok) is the strongest earthquake in the instrumentally recorded history of the region. The fault plane solution of this earthquake indicates a strike-slip motion. However, the seismological and geological studies carried out so far after the earthquake could not confirm the causative fault plane. In the present study, GPS observations are

used to ascertain causative source in the generation of earthquake and its correlation with the observed seismic data of the region. The co-seismic displacements recorded by GPS show maximum displacement of ∼11 mm at Phodong and ∼9 mm at Taplejung station, near the epicenter. A simple rigid cross fault model using GPS baseline observations was employed to figure out the causative fault plane and seismological characteristic of the region. It is inferred that the movement represents the kinematic adjustment of the subsidiary faults as a result of the displacement along the NW–SE principal plane. Strain analysis using GPS baseline inferred that the region southeast of epicenter has undergone large deformation. In addition, a significant part of the measured deformation across the surface fault zone for this earthquake can be attributed to post-seismic creep.

Keywords: GPS baseline; Fault movement; Riedel shear; Strain.

- **Tectonic implications of the September 2011 Sikkim earthquake and its aftershocks. M. Ravi Kumar, Pinki Hazarika, G. Srihari Prasad, Arun Singh and Satish Saha. Current Science, Vol. 102, No. 5, 10 March 2012.**

This study presents results of the spatial patterns of 292 aftershocks of the *Mw* 6.9 Sikkim earthquake of September 2011, accurately located through analysis of three component waveforms registered by a five station broadband network operated immediately after its occurrence. Refined hypocentral parameters achieved through application of the hypo DD relocation scheme reveal tight clustering of events along a NW–SE trend with focal depths reaching ~60 km.These trends viewed in conjunction with the strike–slip mechanisms of past earthquakes in Sikkim, including the main shock, affirm the predominance of transverse tectonics in this segment of the Himalaya where the Indian plate convergence seems to be accommodated by dextral motion along steeply dipping fault systems.

Keywords: Aftershocks, earthquakes, hypocentral parameters,spatial patterns, transverse tectonics.

- **2011 Sikkim Earthquake: Effects on Building Stocks and Perspective on Growing Seismic Risk. D.C. Rai, G. Mondal, V. Singhal, N. Parool & T. Pradhan. 15 WCEE, Lisboa 2012.**

Summary:

The M6.9 Sikkim Earthquake of Sept. 18, 2011 caused widespread damage in the state and adjoining areas and it exposed the seismic vulnerability of the recently built multi-storied construction. Many building collapses and structural damages were disproportionate to the observed intensity of shaking, primarily due to poor compliance with seismic codes, inferior quality of raw materials and shoddy workmanship. In addition, many unique and inherently poor construction features specific to the affected region significantly added to their structural deficiencies. The event provided ample evidence of growing seismic risk in the region with ever increasing inventory of vulnerable construction. On the other hand, some traditional buildings, like Shing-Khim and Ikra performed well but the preference for such construction is on steady decline. It is, therefore, important that earthquake-resistant construction practices should be promoted and implemented to mitigate the risk and hence, minimize the damage to property and loss of life.

Keywords: Seismic risk, Seismic vulnerability, Himalayan earthquakes.

- **The 2009 Bhutan and Assam felt earthquakes (Mw 6.3 and 5.1) at the Kopili fault in the northeast Himalaya region. J.R. Kayal, Sergei S. Arefiev, Saurabh Baruah, Ruben Tatevossian, Naba Gogoi, Manichandra Sanoujam, J.L. Gautam, Devajit Hazarika and Dipak Borah. Geomatics, Natural Hazards and Risk, Vol. 1, No. 3, September 2010, 273–281.**

Abstract:

Seismotectonics of the two recent earthquakes, one Mw 6.3 in the Bhutan Himalaya on 21 September 2009 and the other Mw 5.1 in the Assam valley on 19 August 2009, are examined here. The recent seismicity and fault plane solutions of these two felt earthquakes suggest that both the events occurred on the Kopili fault zone, a known active fault zone in the Assam valley, about 300 km long and 50 km wide. The fault zone is transverse to the east–west Himalayan trend, and its intense seismicity indicates that it transgresses into the Himalaya. The geologically mapped curvilinear structure of the Main Central Thrust (MCT) in the Himalaya, where the epicentre of the Bhutan earthquake is located, is possibly caused by the transverse Kopili fault beneath the MCT. This intensely active fault zone may be vulnerable to an impending larger earthquake (M47.0) in the region.

- **Surface level ground motion estimation for 1869 Cachar Earthquake (Mw 7.5) at Imphal City. Kumar Pallav, S.T.G Raghukanth and K.D. Singh. Journal of Geophysics and Engineering (7/2010), 7, 321-331, Doi:10.1088/1742-2132/7/3/010.**

Abstract:

In this paper, the seismic susceptibility of Imphal city with respect to ten synthetically generated samples of the historic 1869 Cachar (Mw 7.5) earthquake that occurred in the Kopili fault is presented based on the finite-fault seismological model in conjunction with nonlinear site response analyses. For all the synthetic sample earthquake events, the mean and standard deviation of surface level spectral ground acceleration at peak ground acceleration (PGA) and natural periods of 0.3 and 1 s have been reported in the form of contour maps. These contour maps can serve as guidelines for engineers and planners to identify vulnerable areas for possible seismic disaster mitigation of Imphal city.

- **Low b-value prior to the Indo-Myanmar subduction zone earthquakes and precursory swarm before the May 1995 M 6.3 earthquake. Sangeeta Sharma, Saurabh Baruah, Om Prakash Sahu, Pabon K. Bora and Ranju Duarah. Journal of Asian Earth Sciences (2013), 73, 176-183. (IF-2.379)**

Abstract:

Some 455 events ($m_b \geqslant 4.5$) in the Indo-Myanmar subduction zone are compiled using the ISC/EHB/NEIC catalogues (1964–2011) for a systematic study of seismic precursors, *b*-value and swarm activity. Temporal variation of *b*-value is studied using the maximum likelihood method beside CUSUM algorithm. The *b*-values vary from 0.95 to 1.4 for the deeper (depth $\geqslant$ 60 km) earthquakes, and from 0.85 to 1.3 for the shallower (depth <60 km) earthquakes. A sudden drop in the *b*-value, from 1.4 to 0.9, prior to the occurrence of larger earthquake(s) at the deeper depth is observed. It is also noted that the CUSUM gradient reversed before the occurrence of larger earthquakes. We further examined the seismicity pattern for the period 1988–1995 within a radius of 150 km around the epicentre (latitude: 24.96°N; longitude: 95.30°E) of a deeper event *M* 6.3 of May 6, 1995 in this subduction zone. A precursory swarm during January 1989 to July 1992 and quiescence during August 1992 to April 1995 are identified before this large earthquake. These observations are encouraging to monitor seismic precursors for the deeper events in this subduction zone.

Keywords: *b*-Value, CUSUM, Swarm, Quiescence, Indo-Myanmar subduction zone.

- **Occurrence of anomalous seismic activity preceding large to great earthquake in Northeast India region with special reference to 6^{th} August, 1988. H.N. Singh, D. Shanker and V.P. Singh. Physics of the Earth & Planetary Interiors (2005), 148, 261-284.**

Abstract:

Seismicity database from 1860 to 1985 of northeast India region bounded by the area 20°-32°N and 82°-100°E have been analyzed for the identification of precursory swarm/anomalous seismic activity preceding large to great earthquakes with M ≥ 7.5. It is observed that with the exception of three earthquakes (1908, 1912 and 1918), the large earthquakes of 1897, 1946, 1947, 1950 and 1951/1952 were preceded by well-developed epoch of swarm/anomalous seismic activity in space and time well before their occurrence. The seismicity is observed to fluctuate in the order of low-high-low ranging from 0-0.5, 01-33 to 0-0.7 events/year prior to these mainshocks during the epochs of normal/background, swarm/anomalous and gap/quiescence, respectively. The duration of precursory gap is observed to vary from 11 to 17 years for mainshocks of M 7.5-8.0, and from 23 to 27 years for M 8.7 and this period is dependent on the magnitude of the mainshocks. Using the values of magnitude of mainshock (M_m), average magnitude of swarm (M_p) and the precursory time gap (T_p), the following predictive equations are established for the region: M=1.37M-1.40 M=3log T-3.27 All the major earthquakes with $m_b \geq 6.1$ occurred during 1963-1988 have been investigated for their association with anomalous seismicity/precursory swarms using the events with cutoff magnitude $m_b \geq$ 4.5. Eleven such events have occurred in the region during the period except one earthquake of 29 May 1976. All the remaining 10 earthquakes were associated in some forms of anomalous seismicity epochs. Well-defined patterns of anomalous seismicity are observed prior to 1964-1965, 12 August 1976 and 30 December 1984 (m_b 5.6). All these mainshocks are preceded by seismicity patterns in the order of low-high-low similar to that observed prior to the mainshocks from 1897 to 1962. The anomalous seismicity epoch is delineated with extremely high annual earthquake frequency, which was preceded and followed by extremely low seismicity epochs of background and gap/quiescence

phases. Consequently, seismicity rates during anomalous seismicity epoch have always been above normal (1 event/year) whereas it is always below normal during the preceding and the following epochs. A prediction was made using the 1964 swarm based on the M_p and T_p values that a large earthquake with M 8 ± 0.5 with focal depth 100 ± 40 km could occur any time from 1986 to 1990 in an area bound by 21°-25 5°N latitudes and 93°-96°E longitude in Arakan Yoma fold belt. It is interesting to note that the 6 August 1988 earthquake with magnitude 7.5 and focal depth 115 km had occurred within the delineated zone. In addition, three consecutive swarm activities are identified in a limited area within the Eastern Syntaxis and these were not followed by any mainshock till date and could be potential zone for future earthquake.

- **The b value before the 6th August, 1988 India- Myanmar border region earthquake - A case study. O.P. Sahu and M.M. Saikia. Tectonophysics, 234(1994), 349-354.**

Abstract:

Smith (1981, 1986) and Wyss et al. (1990) have observed that intermediate- term quiescence is often associated with an increasing b value. This study pertains to the temporal behaviour of the b value before the earthquake of 6th August, 1988, which occurred in the India- Myanmar border region. The b value in the preparation zone of the earthquake (21º- 25.5º N, 93º- 96º E), as identified by Gupta and Singh (1986, 1989), is found to have increased gradually from 1976 to a maximum value of 1.33 during July, 1987, followed by a short- term drop before the occurrence of the earthquake. This quiescence period observed by Gupta and Singh (1986, 1989) for this earthquake is better reflected by the intermediate- term increase in the b-value. A drop in the mean magnitude since 1978 is supported by a CUSUM plot.

Key words: Quiescence; b value; CUSUM plot.

4.4 ABSTRACTS OF EARTHQUAKES MAINLY ON TWO GREAT EARTH QUAKES OF 1897 AND 1950 OF NE INDIA

4.4.1 1897 EARTHQUAKE

- **A Homogeneous and complete earthquake catalog for northeast india and the adjoining region. R.B.S. Yadav, P. Bormann, B.K. Rastogi, M.C. Das, and S. Chopra. Seismological Research Letters, Volume 80, Number 4, July/August 2009, 609.**

Introduction:

Earthquake catalogs provide basic parameters such as the occurrence time of earthquakes, their hypocenter coordinates, and magnitudes, often complemented by information about damage or other effects. They are useful for studies in seismotectonics, seismicity, earthquake physics and hazard analysis (Woessner and Wiemer 2005). The data contained in earthquake catalogs are usually based on seismic recordings from spatially, temporally, and often also instrumentally heterogeneous networks of seismometers. Older analog records of usually low resolution in time and amplitude were analyzed manually, in contrast to current high-resolution digital records that are analyzed either interactively or fully automated with the help of software that is often, both for data analysts and users, a "black box" based on different assumptions and models. Therefore, catalog data are usually heterogeneous and sometimes even inconsistent in space and time. Long-term seismic hazard assessment, however, necessitates catalogs that are complete both with respect to the relative frequency of occurrence of events in a wide range of magnitudes and over as long as possible a time span; in addition, magnitudes, which characterize the differences in earthquake "size" or "strength," should be well defined and consistently determined, *i.e.*, unique and homogeneous. Historically measured data usually do not fulfill these requirements. Therefore, one has to select a "size" parameter that is best suited to serve as a general reference magnitude. The latter should grow linearly with the logarithms of either the rupture "size" (*e.g.*, as expressed by the seismic moment M_0, which is proportional to the product of rupture area times average static fault slip) or the "strength" of the earthquake (*e.g.*, as expressed by the released seismic energy E_S). Such a reference magnitude should show no saturation for the largest events (see Kanamori 1983).

- **A rupture model for the great earthquake of 1897, northeast India. V.K. Gahalaut and R. Chanaer.** ***Tectonophysics, Volume 204, Issues 1–2, 30 March 1992, Pages 163–174. (IF=2.433)***

Abstract:

We assume that the unusually deep, extensive and long-lasting floods of 1897 along the section of the Brahmaputra River north of the western Shillong plateau were due to local ground subsidence associated with the great earthquake which occurred on June, 12 of that year in the western part of northeast India. Numerical simulations of ground-level changes due to slip on a buried low-angle thrust fault, dipping due north, then show that the northern limit of the rupture zone of this earthquake should have been along the E-W-flowing Brahmaputra River, about 40 km north of the northern edge of the Shillong plateau and about 70 km south of the Himalayan mountain front. A similar interpretation of a ground tilt observation suggests that the western limit of the 1897 rupture zone was along the western margin of the Shillong plateau. The E-W and N-S dimensions of the rupture zone are estimated to be 170 km and 100 km respectively, so that it enclosed the western half of the Shillong plateau and areas north of it up to the Brahmaputra River. The rupture depth could not be estimated from the available data on ground-level changes, and was constrained at 15 km beneath the southern margin of the Shillong plateau, on other evidence. The above thrust fault should be of the nature of a detachment at midcrustal depth, which arose because the continental crust associated with the Indian Shield terrains of the Shillong plateau and Mikir Hills immediately to the east could not subduct under the continental crust of the Eurasian plate to the north and east. It is tentatively suggested that, although this detachment may extend under the Himalaya, it may not be the detachment on which the great earthquakes of 1905, 1934 and 1950 have occurred in the northwestern, central and eastern Himalaya, respectively. It is also suggested that a distinction should be made between the seismicity of the Himalaya and the seismicity of the Himalayan convergent plate margin (HCPM). An earthquake of the Himalayan seismic belt is also an earthquake of the HCPM, but the converse need not hold true. Since the inferred northern limit of the 1897 rupture zone is about 70 km south of the Himalayan mountain front, it is suggested that this earthquake belongs to the HCPM but not to the Himalayan seismic belt. Thus, conservatively, a seismic gap of about 700 km may ex-

ist along the Himalayan seismic belt between the eastern and western limits of the ruptures zones of the great 1934 and 1950 earthquakes respectively.

Key words: Low-angle thrust fault; rupture zone; detachment; rupture model.

- **Comment on ‘‘Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake’’ by C. P. Rajendran et al. Roger Bilham. Tectonics, Vol. 25, TC2001, Doi:10.1029/2005TC001893, 2006.**

- **Crustal properties in the epicentral tract of the Great 1897 Assam Earthquake, northeastern India. S. Mukhopadhyay, R. Chander and K.N. Khattri. Tectonophysics, 283 (1997) 311-330.**

Abstract:

The velocity structure for the upper and middle crust in the epicentral tract of the Great 1897 Assam Earthquake (western half of the Shillong massif) was estimated using locally recorded microearthquake data. The relatively homogeneous upper crustal layer has P and S wave velocities of 5.9 4- 0.2 and 3.4 4- 0.1 km/s, respectively, with a thickness of 11 to 12 km. The average P and S wave velocities in the middle part of the crust down to a depth of about 26 km were estimated to be 6.3 4- 0.6 and 3.5 4- 0.2 km/s, respectively. The larger scatter in P velocity estimate of the mid-crustal layer was investigated using synthetic examples. Our preference is for the model in which this crustal region is assumed to comprise of a number of thin layers with alternate low and high seismic velocities. From theoretical considerations we confirm that it is possible to estimate the velocity structure for a horizontally layered model using the velocity estimation procedure (a combination of the Wadati, Riznichenko and Bune method) we have used. We also carried out detailed model analysis to check how effective this velocity estimation procedure is for the type of array data we have. Combining the estimated velocity structure with our earlier work on seismicity of this area we propose that the upper homogeneous crustal layer in the Shillong massif may be moving relatively southward across an intracrustal thrust zone. We suggest that the Great 1897 Assam Earthquake may represent the most recent episode of this relative southward movement of the massif.

Keywords: Shillong massif; velocity; Great 1897 Assam Earthquake; Riznichenko method.

- **Ground motion estimation at Guwahati city for an Mw 8.1 earthquake in the Shillong plateau. S.T.G. Raghu Kanth, S. Sreelatha and Sujit Kumar Dash. Tectonophysics, Volume 448, Issues 1–4, 25 February 2008, Pages 98–114.**

Abstract:

In this paper, the ground motion at Guwahati city for an 8.1 magnitude earthquake on Oldham fault in the Shillong plateau has been estimated by stochastic finite-fault simulation method. The corresponding acceleration time histories on rock level at several sites in the epicentral region have been computed. These results are validated by comparing them with the estimates obtained from Medvedev–Sponheuer–Karnik (MSK) intensity observations of 1897 Shillong earthquake. Using the local soil parameters, the simulated

rock level acceleration time history at Guwahati city is further amplified up to the ground surface by nonlinear site response analysis. The results obtained are presented in the form of peak ground acceleration (PGA) contour map. The maximum amplification for PGA over Guwahati city is as high as 2.5. Based on the simulated PGA, the liquefaction susceptibility at several locations in the city has been estimated. The results are presented in the form of contours of factor of safety against liquefaction at different depths below the ground surface. It is observed that over a large part of the Guwahati city, the factor of safety against liquefaction is less than one, indicating that the city is highly vulnerable to liquefaction in the event of this earthquake. The contour maps obtained can be used in identifying vulnerable areas and disaster mitigation.
Key words: Stochastic finite-fault simulation method; MSK intensity scale; peak ground acceleration; liquefaction.

- **Historical Seismologist Tom La Touche and the Great Assam earthquake of 12th June 1897: Letters from the epicenters. Bilham, Roger (2008). Seismological Res. Letters, Vol.79, pp.1-23.**

- **Historical Studies of Earthquakes in India. Roger Bilham. Annals of Geophysics, in press 2004.**

Abstract:

The record of earthquakes in India is patchy prior to 1800 and its improvement is much impeded by its dispersal in a dozen local languages, and several colonial archives. Although geological studies will necessarily complement the historical record, only two earthquakes of the dozens of known historic events have resulted in surface ruptures, and it is likely that geological data in the form of liquefaction features will be needed to extend the historic record beyond the most recent few centuries. Damage from large Himalayan earthquakes recorded in Tibet and in northern India suggests that earthquakes may attain M=8.2. Seismic gaps along two-thirds of the Himalaya that have developed in the past five centuries, when combined with geodetic convergence rates of approximately 1.8m/century, suggests that one or more M=8 earthquakes may be overdue. The mechanisms of recent earthquakes in Peninsular India are consistent with stresses induced in the Indian plate flexed by its collision with Tibet. A region of abnormally high seismicity in western India appears to be caused by local convergence across the Rann of Kachchh and possibly other rift zones of India. Since the plate itself deforms little, this deformation may be related to incipient plate fragmentation in Sindh or over a larger region of NW India.

- **Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake: Implications for regional tectonism. C. P. Rajendran, Kusala Rajendran, B. P. Duarah, S. Baruah and Anil Earnest. Tectonics, Vol. 23, TC4009, Doi:10.1029/2003TC001605, 2004.**

The 1897 Shillong (Assam), northeast India, earthquake is considered to be one of the largest in the modern history. Although Oldham's [1899] classic memoir on this event opened new vistas in observational seismology, many questions on its style of faulting remain unresolved. Most previous studies considered this as a detachment earthquake that occurred on a gently north dipping fault, extending from the Himalayan front. A recent model proposed an alternate geometry governed by high-angle faults to the north and south of the plateau, and it suggested that the 1897 earthquake occurred on a south dipping reverse fault, coinciding with the northern plateau margin. In this paper, we explore the available database, together with the coseismic observations from the region, to further understand the nature of faulting. The geophysical and geological data examined in this paper conform to a south dipping structure, but its location is inferred to be in the Brahmaputra basin, further north of the present plateau front. Our analyses of paleoseismic data suggest a 1200-year interval between the 1897 event and its predecessor, and we identify the northern boundary fault as a major seismic source. The Shillong Plateau bounded by major faults behaves as an independent tectonic entity, with its own style of faulting, seismic productivity, and hazard potential, distinct from the Himalayan thrust front, a point that provides fresh insight into the regional geodynamics.

Keyords: earthquake, tectonics, paleoseismology, faulting, seismicity, northeast India.

- **Intrinsic and scattering attenuation in Chedrang Fault and its vicinity – the rupture area of Great Assam earthquake of 12 June 1897 (M = 8.7). Saurabh Baruah, Devajit Hazarika, Aditya Kalita and Sumana Goswami. Current Science, Vol. 99, No. 6, 25 September 2010.**

The attenuation of seismic waves is one of the basic physical parameters used in seismological studies,which is closely related to the seismicity and tectonicactivity of a particular area. In the present study, attenuation properties of the crust beneath the Chedrang Fault and its vicinity, the rupture area of the great Assam earthquake of 12 June 1897 (M = 8.7) are studied using waveforms recorded by a local seismic network composed of five stations. In total 20 local earthquakes have been analysed to estimate (i) coda wave attenuation quality factor (Qc) applying single scattering model, (ii) total attenuation quality factor (Qd) from direct S-wave applying spectral ratio method and(iii) intrinsic and scattering attenuation quality factors (Qi and Qs) following the Wennerberg's approach. Coda Q (Qc) values are obtained using different coda window lengths (20, 30 and 40 s) for frequency bands centred at 1, 1.5, 2, 3, 4, 6, 8, 12, 16 and 18 Hz. This study indicates that Qc increases with increasing lapse time and that Qc is frequency dependent following the attenuation–frequency relation Qc(20) = 36.29 ± 1.18f 1.45 ± 0.09, Qc(30) = 69.92 ± 1.11f 1.23 ± 0.06 and Qc(40) =117.08 ± 1.08f 1.07 ± 0.05 for 20, 30 and 40 s respectively.This behaviour is usually correlated to the presence of heterogeneity in the crust and to the degree of tectonic complexity underneath the study area. The Qc^{-1} values for this area follow a substantially similar trend of Qc^{-1}decay with frequency as the other tectonically active regions of the world. Finally, from the separation of Qs and Qi values, it is observed that the study area can be characterized by alow scattering attenuation (small scattering Q inverse,Qs^{-1}) and by a relatively high intrinsic attenuation (high intrinsic Q inverse, Qi^{-1}).
Keywords: Chedrang Fault, coda waves, frequencydependence, intrinsic attenuation seismic waves, quality factor.

- **Low seismicity in the Bhutan Himalaya and the stress shadow of the 1897 Shillong Plateau earthquake. V.K. Gahalaut, Shikha Rajput and Bhaskar Kundu. Physics of the Earth and Planetary Interiors, Volume 186, Issues 3–4, June 2011, Pages 97–102.**

Abstract:

The seismicity of the Bhutan Himalaya region is generally low as compared to its adjoining Himalayan segments. The topography in the region is slightly subdued and different from the neighbouring central Nepal region. Low seismicity in the region may possibly be due to the postulated low convergence rate in the Bhutan Himalaya, difference in subsurface structures, or the aseismic nature of the region. We suggest that the lower seismicity in the Bhutan Himalaya may also be due to stress change caused by the great 1897 Shillong Plateau earthquake as the low seismicity region of the Bhutan Himalaya coincides with the stress shadow of the earthquake.
Keywords: Himalaya; Shillong Plateau; Great earthquake; Stress shadow.

- **MSK Isoseismal intensities evaluated for the 1897 Great Assam Earthquake. Ambraseys, N., and R. Bilham. Bull. Seism Soc. Am. 93 (2) 655-673, 2003.**

Abstract:

The great 1897 Assam earthquake of 1897 is the largest known Indian intraplate earthquake ($8<M<8.1$). The earthquake raised the northern edge of the Shillong Plateau by more than 10 m, resulting in the destruction of structures over much of the Plateau and surrounding areas, and causing widespread liquefaction and flooding in the Brahmaputra and Sylhet floodplains. Shaking intensity data for the earthquake are crucial for estimating future earthquake hazards in NE India and Bangladesh since similar earthquakes will no-doubt recur. Yet despite the availability of numerous felt reports, no evaluation of isoseismal contours has been attempted since Oldham's (1898) approximation. We have re-evaluated 365 accounts of the earthquake and quantified 287 on a simplified version of the "MSK 1981" Intensity scale. The reappraised isoseismals are consistent with the geodetic mechanism for the earthquake and are smaller, less regular, and less elliptical than those inferred by Oldham. They suggest that Oldham's intensities were inflated by 1-1.5 intensity units. The revised intensity data provide new quantitative constraints on the attenuation of perceived intensity as a function of distance in northeastern India.

- **Plateau Pop-up during the 1897 Assam Earthquake. Roger Bilham and Philip England. Nature(Lond), 410, 806-809, 2001.**

The great Assam earthquake of 12 June 1897 reduced to rubble all masonry buildings within a region of NE India roughly the size of England, and its felt area exceeded that of the 1755 Lisbon Earthquake1. Hitherto it was believed that rupture occurred on a north-dipping Himalayan thrust propagating south of Bhutan 2,3,4,5. We show here that this view is incorrect. The northern edge of the Shillong Plateau rose violently more than 11 m during rupture of a buried, 110-km-long, reverse fault, dipping steeply away from the Himalaya. The stress drop implied by the rupture geometry and the prodigious fault slip of 18±7 m, explains observed epicentral accelerations exceeding 1 g vertically, and surface velocities exceeding 3 m/s1. Our finding represents the first quantitative observation of active deformation of a "pop-up" structure, and confirms that faults bounding such structures can penetrate the whole crust. Plateau uplift in the past 2-5 million years has caused the Indian plate to contract locally by 4±2 mm/year, reducing seismic risk in Bhutan, but increasing it to the large populations of northern Bangladesh.

- **Pop-up tectonics of the Shillong Plateau in the great 1897 earthquake (M 8.7): Insights from the gravity in conjunction with the recent seismological results. Goutam Kumar Nayak, V. K. Rao, H. V. Rambabu and J. R. Kayal. Tectonics, Vol. 27, TC1018, Doi:10.1029/2006TC002027, 2008.**

It was reported that a hidden 110-km-long south dipping fault, named Oldham Fault, was responsible for the 1897 great earthquake (Ms 8.7) in the Shillong Plateau by reverse faulting due to 'pop-up' tectonics of the plateau in northeast India. Here we report the results of our geophysical investigations, where we critically examine the crustal structure of the plateau on the basis of gravity modeling and attempt to shed light on the hitherto debated hidden Oldham Fault at the northern boundary of the Shillong Plateau. Our gravity model, constrained by broadband seismological data, suggests that the Moho beneath the Shillong Plateau is at a shallower depth of about 35 km when compared to the Bengal basin to the south and the Assam valley to the north, which is about 42 km. Thinning of the crust under the plateau may be a consequence of the 'pop-up' mechanism. To examine the possible 'pop-up' of the plateau during the great 1897 earthquake, we have estimated the energy released by this earthquake and compared it with the energy required for the 'pop-up' of the plateau, using a simplistic rigid model. It is found that the Shillong Plateau between the Oldham Fault and Dauki-Dapsi Thrust would require an energy of 4.5 _ 1019 J, which does match well with the energy released by the great earthquake of Ms = 8.7.

- **Reevaluated Intensities for the Great Assam Earthquake of 12 June 1897, Shillong, India. Nicolas Ambraseys and Roger Bilham. Bulletin of the Seismological Society of America, Vol. 93, No. 2, pp. 655–673, April 2003.**

Abstract:

The great Assam Earthquake of 1897 (8<M<8.1) is the largest known Indian intraplate earthquake. It raised the northern edge of the Shillong Plateau by more than 10 m, resulting in the destruction of structures over much of the plateau and surrounding areas and causing widespread liquefaction and flooding in the Brahmaputra and Sylhet Floodplains. Shaking intensity data for the earthquake are crucial for estimating future earthquake hazards in northeast India and Bangladesh since similar earthquakes will no doubt recur. Yet despite the availability of numerous felt reports, no evaluation of isoseismal contours has been attempted since Oldham's (1899) approximation. We have reevaluated 365 accounts of the earthquake and quantified 287 on a simplified version of the "MSK 1981" intensity scale. The reappraised isoseismals are consistent with the geodetic mechanism for the earthquake and are smaller, less regular, and less elliptical than those inferred by Oldham and suggest that Oldham's intensities were unsuspectingly inflated by 1.5–3 intensity units. The revised intensity data provide new quantitative con-

straints on the attenuation of perceived intensity as a function of distance in northeastern India.

- **Revisiting the 1897 Shillong and 1905 Kangra earthquakes in northern India: Site response, Moho reflections and a triggered earthquake. Susan E. Hough, Roger Bilham, Nicolas Ambraseys and Nicole Feldl. Current Science, Vol. 88, No. 10, 25 May 2005.**

  Re-evaluated intensity distributions for the 1897 *M*w 8.0 Shillong and the 1905 *M*w 7.8 Kangra earthquakes, combined with geodetic constraints on rupture geometries, allow us to compare observed distributions of intensity with theoretically predicted shaking. The difference between predicted and observed shaking is interpreted in terms of the site response of the Ganges and Brahmaputra basins. These comparisons identify regions of enhanced shaking along main rivers, revealing amplifications of 1–2 intensity units, roughly an amplification of 2–4 in acceleration. We also find two unexpected results in our analysis of the Kangra earthquake: (i) The epicentral region is surrounded by a halo of enhanced intensity at 150–200 km radius and (ii) The Dehra Dun region was the locus of a broad region of anomalously high intensities. We interpret the former result as the signal from post-critical Moho reflections and the latter observation as a probable second large earthquake ($M > 7$) at 30–50 km depth triggered within minutes of the 1905 main shock. These results have important consequences from future earthquakes in the Himalaya.

- **Shillong plateau earthquakes in northeast India region: complex tectonic model. J. R. Kayal, S.S. Arefiev, S. Barua, D. Hazarika, N. Gogoi, A. Kumar, S. N. Chowdhury and S. Kalita. Current Science, Vol. 91, No. 1, 10 July 2006.**

  The complex tectonic model of the Shillong plateau (SP), the source area of the 1897 great earthquake in the northeast India region, is examined using the high precision data of a 20-station digital seismic network that is in operation in the SP since 2001. The dominating thrust/strike-slip faulting earthquakes in the western plateau although could be explained by the 'pop-up' tectonic model, the seismological data, however, show that the north dipping Dapsi and the south dipping Brahmaputra faults are the possible boundary faults, not the Dauki and Oldham faults as were proposed in the model. The more intense normal/strike-slip faulting earthquakes in the eastern plateau (Mikir massif), on the other hand, are generated by a long and deep rooted Kopili fault by transverse tectonics, and this could be the more vulnerable source area for an impending large/great earthquake in the region.

  Keywords: Fault-plane solutions, pop-up tectonics, Shillong plateau, strike-slip faulting, waveform inversion.

4.4.2 1950 EARTHQUAKE

- **Apparent Himalayan slip deficit from the summation of seismic moments for Himalayan earthquakes, 1500–2000. Roger Bilham and Nicholas Ambraseys. Current Science, Vol. 88, No. 10, 25 May 2005.**

Re-evaluated estimates of the magnitudes of Himalayan earthquakes since 1500 (ref. 1) permit a measure of the convergence rate between India and Tibet for the past five centuries. Averaged over the entire Himalaya, the calculated rate (<5 mm/yr) is less than one third of the convergence rate observed from GPS measurements in the past decade (18 mm/yr). The missing slip is equivalent to four Mw > 8.5 earthquakes, events that are unlikely to have escaped note in the historical written record. The absence of repeated rupture anywhere in the Himalaya permits several explanations for the missing slip, ranging from the extreme view that large earthquakes are in our future, to less hazardous interpretations, related to flaws in the historical data on Himalayan earthquakes.

- **Catalog of significant earthquakes 2000 B.C. to 1979, including quantitative casualities and damage. Robert A. Ganse and John B. Nelson. Bulletin of the Seismological Society of America, Vol. 72, No. 3, pp. 873-877, June 1982.**

Abstract:

A quantitative file of earthquake casualties and damage has been assembled and is being maintained by World Data Center A. The file now existing is an expansion of a file originally created by the authors to produce the World Map of Significant Earthquakes 1900 to Present.

- **Earthquakes in India and the Himalaya: tectonics, geodesy and history. Roger Bilham. Annals of Geophysics, Vol. 47, N. 2/3, April/June 2004.**

Abstract:

The record of earthquakes in India is patchy prior to 1800 and its improvement is much impeded by its dispersal in a dozen local languages, and several colonial archives. Although geological studies will necessarily complement the historical record, only two earthquakes of the dozens of known historical events have resulted in surface ruptures, and it is likely that geological data in the form of liquefaction features will be needed to extend the historical record beyond the most recent few centuries. Damage from large Himalayan earthquakes recorded in Tibet and in Northern India suggests that earthquakes may attain M = 8.2. Seismic gaps along two-thirds of the Himalaya that have developed in the past five centuries, when combined with geodetic convergence rates of approximately 1.8 m/cy, suggests that one or more M = 8 earthquakes may be overdue. The mechanisms of recent earthquakes in Peninsular India are consistent with stresses induced in the Indian plate flexed by its collision with Tibet. A region of abnormally high seismicity in western India appears to be caused by local convergence across the Rann of Kachchh and possibly other rift zones of India. Since the plate itself deforms little, this deformation may be related to incipient plate fragmentation in Sindh or over a larger region of NW India.

Key words: India, earthquakes, history.

- **Geodetic constraints on the translation and deformation of India: Implications for future great Himalayan earthquakes. Roger Bilham, Frederick Blume, Rebecca Bendick and Vinod K. Gaur. Current Science, Vol. 74, NO.3, 10 February 1998.**

Because the elastic deformation of rock is fundamental to the earthquake process, geodetic surface measurements provide a measure of both the geometrical parameters of earthquake rupture, and a measure of the temporal and spatial development of elastic strain prior to rupture. Yet, despite almost 200 years of geodesy in India, and the occurrence of several great earthquakes, the geodetic contribution to understanding future damaging earthquakes in India remains minor. Global Positioning System (GPS) geodesy promises to remedy the shortcomings of traditional studies. Within the last decade, GPS studies have provided three fundamental constraints concerning the seismogenic framework of the Indian Plate: its overall stability (<0.01 μ strain/year), its velocity of collision with Asia (58 ± 4 mm/year at N44E), and its rate of collision with southern Tibet (20.5 ± 2 *mm/*year). These NE directed motions are superimposed on a secular shift of the Earth's rotation axis. As a net result, India currently moves southward at 8 ± 1 cm/year. In the next few decades we can expect GPS measurements to illuminate the subsurface distribution and rate of development of strain in the Himalaya, the relative contributions of along-arc and arc-normal deformation in the Himalaya and southern Tibet, and perhaps the roles of potential energy, plastic deformation and elastic strain in the earthquake cycle.

- **Heterogeneities of the instrumental seismicity catalog (1904-1980) for strong shallow earthquakes. Omar J. Perez and Christopher H. Scholz. Bulletin of the Seismological Society of America, Vol. 74, No. 2, pp. 669-686, April 1984.**

Abstract:

We analyze the world-wide consistency of teleseismic reporting, completeness of the seismicity record, and homogeneity of magnitude determination for strong shallow earthquakes (magnitude, M ≥ 6; depth, h ≤ 70 km) in the period 1904 to 1980. For earthquakes with magnitude M ≤ 7, we used the catalog given by Abe (1981), which lists the surface-wave magnitude (Ms) of every reported large event that occurred between 1904 and 1980, according to the original formulation of Gutenberg (1945). Under the postulate that the rate of earthquake occurrence for the entire world as a whole is consistent on a time scale of decades, and that since the installation of the World-Wide Standardized Seismograph Network in the early 1960s the earthquake catalog for strong (M ≥ 6) shocks is complete and the seismicity rates are typical of all periods in the century, we find that, for instrumental-related reasons, the Ms of large events prior to 1908 have been systemically overestimated by at least 0.5 magnitude unit, and the Ms of events in the period 1908 to 1948 have been consistently overestimated by 0.2 unit, relative to the Ms assigned to shocks occurring after 1948. When these corrections are taken into account, the catalog of events with Ms ≥ 7.0 is shown to be largely complete (i.e., nearly all the large shallow shocks which occurred in the earth are listed) for most of the world since early in the century. For earthquakes at the magnitude 6 level, we used the International Seismological

Center (ISC) tape and Regional Catalogues of Earthquakes. This file compiles the earthquake data given by Gutenberg and Richter (1954) for the first half of the century, and data from various international agencies after ≈ 1945. We find a highly incomplete seismicity catalog at this magnitude level for the first half of the century, mainly due to numerous increases and decreased in the earthquake detection and reporting capabilities; a more complete but extremely inhomogeneous catalog for the period 1950 to 1963, due to the use of different formulations and criteria to calculate and report the parameter "magnitude" by the various seismological agencies; and a largely complete and homogeneous (in Ms) record since 1964.

- **Investigations on the aftershock sequence of the great Assam earthquake of August 15, 1950. R.K.S. Chouhan, V.K. Gaur and J. Singh.**

Summary:

The strain release curve of the aftershock sequence of the great Assam earthquake of August 15, 1950 exhibits three linear segments. A secondary aftershock sequence has also been reported; the strain release curve in this case is also linear. The b value, using the maximum likelihood method of Utsu, for the sequence is 0.52 ± 0.095. The fault plane solution shows that the fault strikes almost cast-west and dips northward at an angle of 80°; the motion is predominently strike slip (right lateral type). The spatial distribution of aftershocks shows two main centers of activity at the two ends of the probable fault.

- **Magnitudes of great shallow earthquakes from 1904 to 1952. Robert J. Geller and Hiroo Kanamori. Bulletin of the Seismological Society of America, Vol. 67, No. 3, pp. 587-598, June 1977.**

Abstract:

The "revised magnitudes", M, converted from Gutenberg's unified magnitude, m, and listed by Richter (1958) and Duda (1965) are systematically higher than the magnitudes listed by Gutenberg and Richter (1954) in Seismicity of the Earth. This difference is examined on the basis of Gutenberg and Richter's unpublished original worksheets for $eismicity of the Earth. It is concluded that (1) the magnitudes of most shallow "class a" earthquakes in Seismicity of the Earth are essentially equivalent to the 20-sec surface-wave magnitude, Ms; (2) the revised magnitudes, M, of most great shallow (less than 40 km) earthquakes listed in Richter (1958) (also used in Duda, 1955) heavily emphasize body-wave magnitudes, mb, and are given by M = ¼Ms + ¾ (1.59 mb - 3.97). For earthquakes at depths of 40 to 60 km, M is given by M = (1.59 mb - 3.97). M and Ms are thus distinct and should not be confused. Because of the saturation of the surfacewave magnitude scale at Ms ≈ 8.0, use of empirical moment versus magnitude relations for estimating the seismic moment results in large errors. Use of the fault area, S, is suggested for estimating the moment.

- **Magnitudes of great shallow earthquakes from 1953 to 1977. Katsuyuki Abe and Hiroo Kanamori. Tectonophysics, 62 (1980), 191-203.**

Abstract:

The surface-wave magnitudes Ms are determined for 30 great shallow earthquakes that occurred during the period from 1953 to 1977. The determination is based on the amplitude and period data from all available station bulletins, and the same procedure as that employed in Gutenberg and Richter's "Seismicity of the Earth" is used. During this period, the Chilean earthquake of 1960 has the largest Ms, 8.5. The surface-wave magnitudes listed in "Earthquake Data Reports" are found to be higher than Ms on the average. By using the same method as that used by Gutenberg, the broad-band body-wave magnitudes mB are determined for great shallow shocks for the period from 1953 to 1974. mB is based on the amplitudes of P, PP and S waves which are measured on broadband instruments at periods of about 4–20 s. The 1-s body-wave magnitudes listed in "Bulletin of International Seismological Center" and "Earthquake Data Reports" are found to be much smaller than mB on the average. Through the examination of Gutenberg and Richter's original worksheets, the relation between mB and Msis revised to mB = 0.65 Ms + 2.5 which well satisfies the mg and Ms data for Ms between 5.2 and 8.7.

- **Seismic hazard estimation from the isoseismals of three great Indian earthquakes. Ashwani Kumar, Rajiv Jain and S.C. Gupta. 13th World Conference on Earthquake Engineering, Vancouvar, Canada, August 1-6, 2004, Paper no. 2362.**

Summary:

This study is devoted to the construction of anomalous residual intensity maps from isoseismals of three great Indian earthquakes namely, the Kangra earthquake of April 4, 1905 (Ms =8.0), the Bihar–Nepal earthquake of January 15, 1934 (Ms=8.3) and the Assam earthquake of August 15, 1950 (Ms =8.6) for the purpose of delineating areas of anomalous intensities. Computed intensities (Ic) at various localities have been estimated by fitting a simplified model, I c = A+ BΔ+ClogΔ, into the observed intensity data, where, Δ is the average outer radius for each intensity level and A, B and C are constants estimated using regression analysis. The residual intensities (IR) are calculated from the difference between the observed intensity (IOB) and the computed intensity (Ic). The anomalous areas of low and high residual intensities have been correlated with geology, tectonics, subsurface topography and Bouguer gravity anomalies. Four prominent areas of anomalous residual intensities (Ic>2) have been delineated. These areas fall in the Sub Himalaya and the Lesser Himalaya near Dehradun, around Sitamarhi town and Monger-Saharsa ridge in Bihar, and Mikir hills in Assam. These areas are characterized by undulating basement topography and subsurface massif and uplifts in the form of ridges and generally exhibit high Bouguer gravity anomalies. It seems that the basement topography influences the observed anomalous intensities. The expected peak accelerations computed at bed rock level should be modified in these areas of anomalous intensities while making seismic hazard estimation.

- **Seismic moment catalog of large shallow earthquakes, 1900 to 1989. Javier F. Pacheco and Lynn R. Sykes. Bulletin of the Seismological Society of America, Vol. 82 No. 3, pp. 1306-1349, June 1992.**

Summary:

This study is devoted to the construction of anomalous residual intensity maps from isoseismals of three great Indian earthquakes namely, the Kangra earthquake of April 4,

1905 (M_s =8.0), the Bihar–Nepal earthquake of January 15, 1934 (M_s=8.3) and the Assam earthquake of August 15, 1950 (M_s =8.6) for the purpose of delineating areas of anomalous intensities. Computed intensities (I_c) at various localities have been estimated by fitting a simplified model, $I = A + B\Delta + C \log \Delta$, into the observed intensity data, where, Δ is the average outer radius for each intensity level and A, B and C are constants estimated using regression analysis. The residual intensities (I_R) are calculated from the difference between the observed intensity (I_{OB}) and the computed intensity (I_c). The anomalous areas of low and high residual intensities have been correlated with geology, tectonics, subsurface topography and Bouguer gravity anomalies. Four prominent areas of anomalous residual intensities (I_c>2) have been delineated. These areas fall in the Sub Himalaya and the Lesser Himalaya near Dehradun, around Sitamarhi town and Monger-Saharsa ridge in Bihar, and Mikir hills in Assam. These areas are characterized by undulating basement topography and subsurface massif and uplifts in the form of ridges and generally exhibit high Bouguer gravity anomalies. It seems that the basement topography influences the observed anomalous intensities. The expected peak accelerations computed at bed rock level should be modified in these areas of anomalous intensities while making seismic hazard estimation.

- **Seismic moments of major earthquakes and the average rate of slip in Central Asia. W.P. Chen and P. Molnar. J. Geophys. Res., 82, 2945-2969, 1977.**

Abstract:

Seismic moments for 12 major earthquakes (M ≥ 7.6) in central Asia from 1911 to 1967 were calculated from long-period Rayleigh and Love wave spectral densities. With fault lengths estimated from geological field observations of surface faulting, intensity distributions, or master event relocations of aftershocks, the calculated moments place bounds on the average slip and fault widths. The following table summarizes the calculated moments, estimated fault lengths, and inferred possible average displacements.

- **Simulation of Strong Ground Motion During the 1950 Great Assam Earthquake. S.T.G. Raghukanth Pure appl. geophys. 165 (2008) 1761–1787, Doi 10.1007/s00024-008-0403-z.**

Abstract:

In this paper, ground motion during the Independence Day earthquake of August 15, 1950 (Mw 8.6, BEN-MENAHEM et al., 1974) in the northeastern part of India is estimated by seismological approaches. A hybrid simulation technique which combines the low frequency ground motion simulated from an analytical source mechanism model with the stochastically simulated high-frequency components is used for obtaining the acceleration time histories. A series of ground motion simulations are carried out to estimate the peak ground acceleration (PGA) and spectral accelerations at important cities and towns in the epicentral region. One sample PGA distribution in the epicentral region encompassing the epicenter is also obtained. It is found that PGA in the epicentral region has exceeded 1 g during this earthquake. The estimated PGA's are validated to the extent possible using the MMI values. The simulated acceleration time histories can be used for the assessment of important engineering structures in northeastern India.

Key words: Strong ground motion, PGA, stochastic finite fault model, hybrid technique, response spectra.

- **The active tectonics and structure of the Eastern Himalayan Syntaxis and surrounding regions. William Everett Holt (PhD thesis).**

Abstract:

Source parameters of 53 moderate-sized earthquakes, obtained from the joint inversion of regional and teleseismic distance long-period body waves, provide the data set for an analysis of the style of deformation and kinematics in the region of the Eastern Himalayan Syntaxis. Focal mechanisms of Eastern Himalayan events show oblique thrust, consistent with the N-NE directed movement of the Indian plate as it underthrusts a boundary that strikes at an oblique angle to the direction of convergence. Earthquakes near the Sagaing fault show strike-slip mechanisms with right-lateral slip. Earthquakes on its northern splays, however, indicate predominant thrusting, evidence that the dextral motion on the Sagaing fault, which accommodates a portion of the lateral motion between India and southeast Asia, terminates in a zone of thrust faulting at the Eastern Himalayan Syntaxis. Remaining motion between India and southeast Asia is accommodated in a zone of distributed shear in east Burma and Yunnan, manifested by strike-slip and oblique normal faulting, east-west extension, crustal thinning, and clockwise rotation of crustal blocks. We determined strain rates throughout the region with a moment tensor summation using 25 years (modern) and 85 years (modern and historic) of earthquake data. We matched the observed strains with a fifth-order polynomial function, and from this we determined both the velocity field and rotations with respect to a specified region. Velocities calculated relative to south China stationary show that the entire area, extending from 20°N–36°N, within deforming Asia (Yunnan, western Sichuan, and east Tibet), constitutes a distributed dextral shear zone with clockwise rotations up to 1.7°/m.y., maximum in the region of the Eastern Syntaxis proper. Integrated strains across this zone, relative to south China stationary, show 38 mm/yr ± 12mm/yr of north-directed motion at the Himalaya. Remaining plate motion, relative to south China fixed, must be taken up by the underthrusting of India beneath the lesser Himalaya, strike-slip motion on the Sagaing fault, and intraplate NE directed shortening within NE India as well as NE directed shortening within the Eastern Syntaxis proper. 10 mm/yr ± 2 mm/yr of relative right-lateral motion between India and southeast Asia is absorbed in the region between the Sagaing and Red River faults (94°E–100°E). It is the clockwise vorticity (relative to south China) associated with the deformation in Yunnan, east Tibet, and western Sichuan that provides the relative north-directed motion of 38 ± 12 mm/yr at the Himalaya. Not all of the deformation is accommodated in right-lateral shear between India and south China and between east Tibet and south China; velocity gradients exist that are parallel to the trend of the shear zone. Relative to a point within western Sichuan (32°N, 100°E), the velocity field shows that the Yunnan crust is moving S-SE at rates of 8–10 mm/yr. Relative to south China, there is no eastward expulsion of crustal material beyond the eastern margin of the Tibetan plateau.

- **The Assam Earthquake. The Hindu dated August 21, 1950.**

- **The Assam Earthquake of 1950. F. Kingdon-Ward. The Geographical Journal, Vol. 119, No. 2 (June, 1953), pp. 169-182.**

- **The Assam earthquake of 15th August, 1950. M.C. Poddar. Indian Minerals (1950), 4, 167 – 176.**

- **The Earthquake. F. Kingdon-Ward. The Wide World Magazine.**

- **The energy release in great earthquakes. Hiroo Kanamori. J. Geophys. Res. (1977), Vol.82, No. 20.**

Abstract:

The conventional magnitude scale *M* suffers saturation when the rupture dimension of the earthquake exceeds the wavelength of the seismic waves used for the magnitude determination (usually 5–50 km). This saturation leads to an inaccurate estimate of energy released in great earthquakes. To circumvent this problem the strain energy drop *W* (difference in strain energy before and after an earthquake) in great earthquakes is estimated from the seismic moment M_0. If the stress drop $\Delta\sigma$ is complete, $W = W_0 = (\Delta\sigma/2\mu)M_0 \sim M_0/(2\times10^4)$, where μ is the rigidity; if it is partial, W_0 gives the minimum estimate of the strain energy drop. Furthermore, if Orowan's condition, i.e., that frictional stress equal final stress, is met, W_0 represents the seismic wave energy. A new magnitude scale M_w is defined in terms of W_0 through the standard energy-magnitude relation $\log W_0 = 1.5M_w + 11.8$. M_w is as large as 9.5 for the 1960 Chilean earthquake and connects smoothly to M_s (surface wave magnitude) for earthquakes with a rupture dimension of about 100 km or less. The M_w scale does not suffer saturation and is a more adequate magnitude scale for great earthquakes. The seismic energy release curve defined by W_0 is entirely different from that previously estimated from M_s. During the 15-year period from 1950 to 1965 the annual average of W_0 is more than 1 order of magnitude larger than that during the periods from 1920 to 1950 and from 1965 to 1976. The temporal variation of the amplitude of the Chandler wobble correlates very well with the variation of W_0, with a slight indication of the former preceding the latter. In contrast, the number *N* of moderate to large earthquakes increased very sharply as the Chandler wobble amplitude increased but decreased very sharply during the period from 1945 to 1965, when W_0 was largest. One possible explanation for these correlations is that the increase in the wobble amplitude triggers worldwide seismic activity and accelerates plate motion which eventually leads to great decoupling earthquakes. This decoupling causes the decline of moderate to large earthquake activity. Changes in the rotation rate of the earth may be an important element in this mechanism.

- **The great 1950 Assam Earthquake revisited: field evidences of liquefaction and search for paleoseismic events. D.V. Reddy, Pasupuleti Nagabhushanam, Devender Kumar, Balbir S Sukhija, P.J. Thomas, Anand K. Pandey, Radhendra Nath Sahoo, G.V. Ravi Prasad and Koushik Datta. Extended Abstracts: 23rd Himalayan-Karakoram-Tibet Workshop, 2008, India.**

- **The source of great Assam Earthquake-an interplate wedge motion. A. Ben-Menahem, E. Aboodi and R. Schild. Phys. Earth Planet. Interiors (1974), 9, 265-289.**

The source of the Assam earthquake of Aug. 15, 1950 is revealed from amplitude observations of surface and body waves at Pasadena, Tokyo and Bergen. Seiches' amplitudes in Norway, initial P motions throughout the world, aftershocks and landslides distribution, PP/P ratio at Tokyo, R/L ratio and directivity at Pasadena, are also used. The ensuing fault geometry and kinematics is consistent with the phenomenology of the event and the known geology of the source area. It is found that a progressive strike-slip rupture with velocity 3 km/sec took place on a fault of length 250 km and width 80km striking 330—337°east of north and dipping 55—60°to ENE. The use of exact surfacewave theory and asymptotic body-wave theory which takes into account finiteness and absorption, rendered an average shear dislocation of 35 m. A three-dimensional theory for the excitation of seiches in lakes by the horizontal acceleration of surface waveswas developed. It is confirmed that Love waves near Bergen generated seiches with peak amplitude up to 70 cm depending strongly on the width of the channel. It is believed that the earthquake was caused by a motion of the Asian plate relative to the eastern flank of the Indian plate where the NE Assam block is imparted a tendency of rotation with fracture lines being developed along its periphery. Comparison with other well-studied earthquakes shows that although the magnitude of the Assam event superseded that of all earthquakes since 1950, its potency U_0dS (700,000 m X km^2) was inferior to that of Alaska 1964 (1,560,000 m X km^2) and Chile 1960 (1,020,000 m X km^2).

Chapter 4.5 : Abstracts Subject wise-mostly cited

Chapter 4.5.1 : Seismicity and Seismotectonics

Introduction

In true sense the Northeastern India and the adjoining regions is a gold mine for earth science researchers to study various aspects of geology, seismology, seismotectonics etc. The attention of the researchers were first drawn to this region by the Great Assam Earthquake of 1897 (M 8.7) and 1950 (M 8.6) which occurred on 12th June, 1897 and 15th August, 1950 respectively. In addition, dozens of earthquake with magnitude M $\geq$ 7.0 occurred in the region during the last hundred year. With the establishment of various seismic network in the region, the interest of National and Global earth scientists carrying out research on various aspects of seismology/geology increased immensely published their research findings in high Impact Factor Peer review journal. Further, many students carried our Doctoral research as well as M.Tech dissertations. The abstract of the published research paper categorized under 'Seismicity and Seismotectonics' of Northeastern India are listed below.

Abstracts

- **'The Great Assam Earthquake of 15th August 1950'**; ***Current Science; Vol. XIX; No. 9, pp. 265-267, September 1950***

Introduction

On the evening of the 15th August 1950, about forty minutes past seven, an earthquake of catastrophic violence occurred off the north-east border of Assam. The earthquake was recorded by the seismological observatories all over the world as a very great earthquake and various adjectives such as tremendous, very violent, unprecedented, biggest ever recorded, have been used to describe the magnitude of the earthquake. It is one of the biggest ever recorded. Seismologists of the United States of America consider it as one of the five biggest in human history. The magnitude of the shock, as calculated by them, was between 8.25 and 8.5, the highest ever calculated so far being 8.5…………

- **'The Assam Earthquake of 15th August, 1950'; *M.C.Poddar; Indian Minerals; Vol. IV, No. 4, pp. 167-176, October, 1950***

Introduction

One of the biggest earthquakes of the twentieth century was recorded at about 7-40 p.m. (Indian Standard time) on the 15th August, 1950. It caused widespread devastation throughout the Upper Assam, particularly in the frontier tribal districts of the Mishmi and Abor hills and parts of the Lakhimpur and Sibsagar districts. The earthquake shock lasted for a period ranging from 4 minutes to 8 minutes within the severely affected area. It is not known how far this was felt on the Tibetan side, but news from this side of the McMahon Line shows that extensive damage has occurred in the hills, and heavy casualties took place among the hill tribes bordering the North-East Frontier. The shock was felt throughout Eastern India. In badly affected areas, the ground cracked and fissured, water and sands spouted through the fissures, road and railway tracks were broken up and twisted. Many bridges were destroyed and river beds silted up. Damage and casualties subsequently increased considerably, owing to the sudden floods in the Subansiri valley shortly after the quake, due to the bursting of a temporary dam formed by landslips.

It is, however, fortunate that the affected area is generally sparsely populated, and the earthquake occurred just after nightfall when most of the people were awake. Hence the loss of life has been small in comparison with the magnitude of the shock……..

- **'The source of the great Assam earthquake — an interplate wedge motion'; *Ari Ben-Menahem, Ezra Aboodi, Rivka Schild; Physics of the Earth and Planetary Interiors, 01/1974; DOI:10.1016/0031-9201(74)90056-9***

Abstract

The source of the Assam earthquake of Aug. 15, 1950 is revealed from amplitude observations of surface and body waves at Pasadena, Tokyo and Bergen. Seiches' amplitudes in Norway, initial P motions throughout the world, aftershocks and landslides distribution, PP/P ratio at Tokyo, R/L ratio and directivity at Pasadena, are also used. The ensuing fault geometry and kinematics is consistent with the phenomenology of the event and the known geology of the source area. It is found that a progressive strike-slip rupture with velocity 3 km/sec took place on a fault of length 250 km and width 80 km striking 330–337° east of north and dipping 55–60° to ENE. The use of exact surface-wave theory and asymptotic body-wave theory which takes into account finiteness and absorption, rendered an average shear dislocation of 35 m. A three-dimensional theory for the excitation of seiches in lakes by the horizontal acceleration of surface waves was developed. It is confirmed that Love waves near Bergen generated seiches with peak amplitude up to 70 cm depending strongly on the width of the channel. It is believed that the earthquake was caused by a motion of the Asian plate relative to the eastern flank of the Indian plate where the NE Assam block is imparted a tendency of rotation with fracture lines being developed along its periphery. Comparison with other well-studied earthquakes shows that although the magnitude of the Assam event superseded that of all earthquakes since 1950, its potency U0dS (700,000 m × km2) was inferior to that of Alaska 1964 (1,560,000 m × km2) and Chile 1960 (1,020,000 m × km2).

- **'Investigations on the aftershock sequence of the great Assam earthquake of August 15, 1950'; *R. K. S. CHOUHAN , V. K. GAUR and J. SINGH; Received on April 10th, 1974; pp. 245-266***

Summary

The strain release curve of the aftershock sequence of the great Assam earthquake of August 15, 1950 exhibits three linear segments. A secondary aftershock sequence has also been reported; the strain release curve in this case is also linear. The *b* value, using the maximum likelihood method of Utsu, for the sequence is 0.52 ± 0.095. The fault plane solution shows that the fault strikes almost cast-west and dips northward at an angle of 80°; the motion is predominantly strike slip (right lateral type). The spatial distribution of aftershocks shows two main centers of activity at the two ends of the probable fault.

- **'The stress drop and average dislocation of some earthquakes in the Indian subcontinent'; *A.N.Tandon, H.N.Srivastava, Pure and Applied Geophysics; Vol. 112, issues 6, pp. 1051-1057, 1974***

Abstract

The stress drop and average dislocation of some earthquakes in the Indian subcontinent have been determined after deducing the relatioinship between the aftershock area *A*, and the magnitude M_L of the main shock which is given by log A = 0.89 M_L – 2.67 for 5 $\leq$ $M_L \leq 7$.

It has been found that the stress drop is considerably larger for the great Assam earthquake of 15 August, 1950, occurring near the continent-continent boundary of the Indian-Eurasian plates, compared to that of a similar magnitude earthquake in a continent-island are type collission boundary in the Pacific (near Japan). The stress drop in smaller events of comparative magnitude in different regions are, however, of the same order and thus do not bring out the distinguishing features of the source regions in different kinds of plate boundaries.

- **'Seismicity of the north-eastern region (N.E.R.) of India'; *Madan Mohan Saikia, Vit Karnik, Vladimir Schenk, Zdenka Schenkova; Studia Geophysica et Geodaetica; Volume 25, Issue 1, pp. 36-60, 1981***

Abstract

The earthquake pattern in the N.E.R. of India is investigated on the background of tectonic conditions. The epicenter maps and the cross-sections indicate some regularities in the spa-

tial distribution of foci, particularly the existence of a Benioff zone, dipping down to 200 km at an angle of 35^0-40^0 to the East between 25^0 N and 21^0 N. The shallow and intermediate activities in the Indoburmese zone seem to be mutually related as evidenced by the coincidence of periods of quiescence and activity. The origin of the largest of the whole region (15 August, 1950, M=8.6) can be accommodated in the statistics only by assuming a very large preparatory area also encompassing the “extended” Mishmi region. This event seems to be a rather exceptional event with the return period larger than the sample used for investigation, i.e. 54 years. The problem of a gap in the region of the Upper Assam remains open, the lack of activity also be explained also by pure geological reasons, i.e. by the age of the stable geological formation. The maps and the statistics of extremes provide the estimate of probability of occurrence of large events for practical purpose.

- **‘Source parameters of earthquakes in northeast India fromspectra of Rayleigh waves’; *S.K.Upadhyay, V.K.Ahuja; Tectonophysics; Volume 75, Issues 3-4, pp. 297-315, 1 June 1981***

Abstract

A quantitative description of eight earthquakes in northeast India, in terms of seismic moment, dislocation, apparent stress and apparent average strain is sought. The analysis is based on the theory of radiation pattern of surface waves from buried seismic sources proposed by Ben-Menahem and Harkirder (1964). Further, it makes use of the amplitude spectra of digitally recorded Rayleigh waves at the Central Seismological Observatory in Eriangen (GRF), F.R.Germany. The amplitude spectra of Rayleigh waves are corrected for instrument response, path propagation effects and effects of the radiation pattern. Published results on attenuation and focal mechanism solutions are utilized to arrive at reasonable estimates of the quantities under investigation. Comparison of the calculated values is also made with the estimates based on body-wave spectra. It is concluded that the earthquakes in northeast India are of low moment type. The faulting process is supposed to be non-homogeneous, which results in low estimates of seismic source parameters and a characteristic source time function (Upadhyay and duda, 1980). Comparison of source parameter values with known estimates for intraplate earthquake is made. For equal-magnitude earthquakes, intraplate earthquakes are characterized by higher seismic moment. Two of the earthquakes (M_s = 6.3) considered here are compared with the Koyna earthquake of Dec. 10. 1967. Emphasis is laid on development of theoretical models to account for the strain build-up rates in inter-and intraplate earthquakes.

- **‘Local Seismic Activity in the region of the Assam Gap, Northeast India’; *K.Khattri, M.Wyss, V.K.Gaur, S.N.Saha and V.K.Bansal; Bulletin of the Seismological Society of America, Vol. 73, No. 2, pp. 459-469, April 1983***

Abstract

A tripartite array of seismographs was operated for 5.5 months in late 1979 in the Shillong Massif area of northeast India. During this time, 719 local earthquakes were recorded. Of these, 359 were located ($2.4 \leq M_D \leq 5.1$), using for some events additional arrival times from the WWSSN/IMD station Shillong and some portable stations operated by the NGRI/RRL. The area of the Shillong Massif and the Nikir Hills (60 km radius within our array) showed a high seismicity rate of about four earthquakes per week with $M_D \geq 3^{1/}{}_4$. This activity rate contrasted strongly with the Assam Gap where there were practically no earthquake sources detected by our array. A seismic asperity seems to exist in the Kopili valley (between Shillong and Mikir Hills) which may have been the termination of the 1897 rupture, and which could perhaps become the nucleation point for the next great Assam earthquake. Based on these seismicity results and macroseismic data (Seeber and Armbruster, 1981), we estimate the length of the Assam Gap to be about 240 km. Frequency versus magnitude plots revealed *b* values of about 1.5, and suggested that within the array the locations were complete for $M_D \geq 3^{1/}{}_4$. A comparison of local and teleseismic locations and magnitudes could be made only for the largest event which was locatws 300 km outside the array. This comparison suggests that $M_D \sim m_b + 0.5$, and that the epicenter location errors outside the array are of the order of 40 km.

- **'Accretionary tectonics of Burma and the three-dimensional geometry of the Burma subduction zone';** ***James F.Ni, Marco Guzman-Speziale, Michael Bevis, William E.Holt, Terry C.Wallace and William R.Seager; Geology; vol. 17, no. 1; pp. 68-71, 1989; doi:10.1130/009-7613***

Abstract

The geometry of the Burma Wadati-Benioff zone (WBZ) has been determined by fitting a trend surface parameterized with eight effective degrees of freedom to 184 well-located hypocenters. The dip of this surface, which passes through the middle of the WBZ, varies from about 50° in the north near the eastern Himalayan syntaxis to about 30° in the Bay of Bengal area. The eastern edge of the Indo-Burman ranges closely follows the map projection of the 60 km depth contour of the WBZ. The curvature of the Indo-Burman ranges is controlled by the geometry of the interface between the more steeply dipping part of the Indian plate and the leading edge of the overriding Burma platelet. Shallow earthquakes beneath the Indo-Burman ranges are primarily confined to the underthrusting Indian plate. Their focal mechanisms indicate strike-slip faulting and north-south shortening parallel to the eastern margin of the Indian plate.

- **'Source Parameters of Earthquakes and Intraplate Deformation Beneath the Shillong Plateau and the Northern Indoburman Ranges';** ***Wang-Ping Chen, Peter Molnar; Journal of Geophysical Research; Vol. 95, No. B8, pp. 12,527-12,552, August 10, 1990***

Abstract

We determined the fault plane solutions and focal depth of 17 earthquakes beneath the Shillong Plateau and the northern Indoburman ranges by combining results from the inversion of long-period *P* and *SH* waveforms and amplitudes, from polarities of first motions, and from the identification of p^P and s^P phases on short-period seismograms. Fault plane solutions of 15 earthquakes show mixtures of thrust and strike-slip faulting, but the *P* axes for these events are nearly horizontal and consistently oriented north-northeast-south-southwest. All of these earthquakes occurred at depths greater than 29 km. Beneath the Shillong Plateau, one event occurred at a depth of 52 km. The relatively larger depths for earthquakes in an intraplate setting suggest that the Indian lithosphere in this area is especially cold. Earthquakes beneath the northern Indoburman ranges define a a gently east-

southeast dipping zone from 30 to 45 km beneath the Bengal basin to 40 to 90 km beneath the ranges. This zone seems to steepen and connect with the zone of intermediate depth seismicity that dips eastward beneath burma. These earthquakes cannot have occurred along the interface between a subducting Indian plate and the overriding Indoburman lithosphere, because the *P* axes, not the nodal planes, are parallel to the north-south trending seismic zone. Although a couple of the earthquakes might have occurred within the Indoburman lithosphere, most of the seismicity seems to have occurred within the Indian plate, recently and currently being subducted eastward beneath the Indoburman ranges. The consistent north-northeast trend of the *P* axes implies that the orientation of maximum compressional strain in the Indian plate throughout its northeastern part is nearly perpendicular to that responsible for roughly north-south trending folds of the Indoburman ranges. Thus, either recently in geologic time (since 1 Ma) the orientation of maximum compression changed dramatically, or, more likely, the deformation in the Indoburman ranges is decoupled from that in the underlying Indian plate. Meanwhile, the seemingly identical northward displacement of India and the Indoburman ranges with respect to south China must be accommodated farther east, along the Sagaing and other faults.

- **'The active Tectonics of the Eastern Himalayan Syntaxis and Surrounding Regions'; *William E.Holt, James F.Ni, Terry C.Wallace and A.J.Haines; Journal of Geophysical Research, Vol. 96, No. B9, pp. 14,595-14,632, August 10, 1991***

Abstract

Source parameters of 53 moderate-sized earthquakes, obtained from the joint inversion of regional and teleseismic distance long-period body waves, provide the data set for an analysis of the style of deformation and kinematics in the region of the Eastern Himalayan Syntaxis. Focal mechanisms of Eastern Himalayan events show oblique thrust, consistent with the N-NE directed movement of the Indian plate as it underthrusts a boundary that strikes at an oblique angle to the direction of convergence. Earthquakes near the Sagaing fault show strike-slip mechanisms with right-lateral slip. Earthquakes on its northern splays, however, indicate predominant thrusting, evidence that the dextral motion on the Sagaing fault, which accommodates a portion of the lateral motion between India and southeast Asia, terminates in a zone of thrust faulting at the Eastern Himalayan Syntaxis. Remaining motion between India and southeast Asia is accommodated in a zone of distributed shear in east Burma and Yunnan, manifested by strike-slip and oblique normal faulting, east-west extension, crustal thinning, and clockwise rotation of crustal blocks. We determined strain rates throughout the region with a moment tensor summation using 25 years (modern) and 85 years (modem and historic) of earthquake data. We matched the observed strains with a fifth-order polynomial function, and from this we determined both the velocity field and rotations with respect to specified region. Velocities calculated relative to south China stationary show that the entire area, extending from 20^0N- 36^0N, within deforming Asia (Yunnan, western Sichuan, and east Tibet), constitutes a distributed dextral shear zone with clockwise rotations upto 1.7^0m.y., maximum in the region of the Eastern Syntaxes proper. Integrated strains across this zone, relative to south China stationary, show 38 mm/ $\pm$ 12 mm/yr of north directed motion at the Himalaya. Remaining plate motion, relative to south China fixed, must be taken up by the underthrusting of India beneath the lesser Himalaya, strike-slip motion on the Sagaing fault, and interpolate NE directed shortening within NE India as well as NE NE directed shortening within the Eastern Syntaxis proper. 10mm/yr $\pm$ 2mm/yr of relative right-lateral motion be-

tween India and southeast Asia is absorbed in the region between the Sagaing and Red River faults (94^0E- 100^0E). It is the clockwise vorticity (relative to south China) associated with the deformation in Yunnan, east Tibet, and western Sichuan that provides the relative north-directed motion of 38±12mm/yr at the Himalaya. Not all of the deformation is accommodated in right-lateral shear between India and south China and between east Tibet and south China; velocity gradients exist that are parallel to the trend of the shear zone. Relative to a point within western Sichuan (32^0N, 100^0E), the velocity field shows that the Yunnan crust is moving S-SE at rates of 8-10 mm/yr. Relative to south China, there is no eastward expulsion of crustal material beyond the eastern margin of the Tibetan plateau.

- **'A rupture model for the great earthquake of 1897, northeast India'; *V.K.Gahalaut and R.Chander; Techtonophysics, 204, 163-174, 1992***

Abstract

We assume that the unusually deep, extensive and long-lasting floods of 1897 along the section of the Brahmaputra River north of the western Shillong plateau were due to local ground subsidence associated with the great earthquake which occurred on June, 12 of that year in the western part of northeast India. Numerical simulations of ground-level changes due to slip on a buried low-angle thrist fault, dipping due north, then show that the northern limit of the rupture zone of this earthquake should have been along the E-W-flowing Brahmaputra River, about 40 km north of the northern edge of the Shillong plateau and about 70 km south of the Himalayan mountain front. A similar interpretation of a ground tilt observation suggests that the western limit of the 1897 rupture zone was along the western margin of the Shillong plateau. The E-W and N-S dimensions of the rupture zone are estimated to be 170 km and 100 km respectively, so that it enclosed the western half of the Shillong plateau and areas north of it up to the Brahmaputra River. The rupture depth could not be estimated from the available data on ground-level changes, and was constrained at 15 km beneath the southern margin of the Shillong plateau, on other evidence. The above thrust fault should be of the nature of a detachment at midcrustal depth, which arose because the continental crust associated with the Indian Shield terrains of the Shillong plateau and Mikir Hills immediately to the east could not subduct under the continental crust of the Eurasian plate to the north and east. It is tentatively suggested that, although this detachment may extend under the Himalaya, it may not be the detachment on which the great earthquakes of 1905, 1934 and 1950 have occurred in the northwestern, central and eastern Himalaya, respectively. It is also suggested that a distinction should be made between the seismicity of the Himalaya and the seismicity of the Himalayan convergent plate margin (HCPM). An earthquake of the Himalayan seismic belt is also an earthquake of the HCPM, but the converse need not hold true. Since the inferred northern limit of the 1897 rupture zone is about 70 km south of the Himalayan mountain front, it is suggested that this earthquake belongs to the HCPM but not to the Himalayan seismic belt, Thus, conservatively, a seismic gap of about 700 km may exist along the Himalayan seismic belt between the eastern and western limits of the rupture zones of the great 1934 and 1950 earthquakes respectively.

- **'Tectonic stress field in the Indian subcontinent'; *T.N.Gowd, S.V.Sriiama, V.K.Gaur; Journal of Geophysical Research: Solid Earth; Vol. 97, Issue B8, pp. 11879-11888, 30 July 1992; DOI: 10 1029/91B03177***

Abstract

A map of maximum horizontal compressive stress orientation in the Indian subcontinent has been prepared using orientations derived from three different stress indicators: borehole elongation breakouts, in situ hydraulic fracturing measurements, and earthquake focal mechanisms. Most part of the subcontinent appears to be characterized by a compressional stress regime (thrust and strikeslip faulting) imposed by plate boundary forces although $S_{H\max}$ orientations do not, in general, show clear correlation with the direction of motion of the Indian plate. Four provinces are recognized on the basis of regionally consistent orientations. These are the midcontinent stress province, the southern shield, the Bengal basin, and the Assam wedge. Their boundaries have been determined taking into consideration regional tectonics and seismicity. Central and northern India, including the Shillong Plateau stretching up to the great Himalaya, Pakistan, and Nepal are included in a broad "midcontinent" stress province characterized by NNE-ENE oriented $S_{H\max}$. The mean orientation of $S_{H\max}$ in this province is N23°E, subparallel to the direction of compression expected to arise from the net resistive forces at the Himalayan collision zone, suggesting that it is largely determined by the tectonic collision processes. Much of southern India (Mysore plateau and the high-grade metamorphic terrain south of the plateau) appears to be part of a second stress province characterized by NW oriented $S_{H\max}$. These appear close to those of the intraplate stress field prevailing in the central Indian Ocean. A third stress province was recognized in the Bengal basin including parts of West Bengal, Tripura, Manipur, and Mizoram in northeastern India and most of Bangladesh. This province extends eastward from the marginal fault in the western margin of the Bengal basin to the Indo-Burma subduction zone and is bounded on the north by the E-W striking Dauki fault. $S_{H\max}$ within the sedimentary pile of the Bengal basin is oriented in E-W direction, while P axes of earthquakes within the basement and the crust beneath the basin and within the subducted slab of the Indian plate beneath the Indo-Burman ranges generally trend north - N30°E. $S_{H\max}$ orientations within the sedimentary pile of the basin are parallel to the local (approximately E-W) direction of the convergence of Indian and Burmese plates, suggesting a casual relation to the resistive forces at the subduction zone in the Indo-Burma region. Interestingly, the stress field in the basement and the crust beneath the Bengal basin and in the subducted slab is similar to the one prevailing in the midcontinent stress province. Assam wedge stress region occupies the northeastern corner of the Indian plate, including Upper Assam, Arunachal Pradesh, and much of Nagaland. This region subducts beneath a sharply bent continental collision boundary consisting of the northeastern limb of the Himalayan and northern limb of the Indo-Burman fold belts. As a result, the stress field in this province is depth-differentiated and most likely responsible for the absence of consistent $S_{H\max}$ directions.

- **'Fine structure of seismotectonics in western Shillong massif, north east India'; *S.Mukhopadhyay, R.Chander and K.N.Khattri; Proc. Indian Acad. Sci. (Earth Planet, Sci.) Vol. 102, No. 2, June 1993, pp. 383-398***

Abstract

The epicentral tract of the great Assam earthquake of 1897 of magnitude 8.7 was monitored for about 6 months using an array of portable seismographs. The observed seismicity pattern shows several diversely-oriented linear trends, some of which either encompass or parallel known geological faults. A vast majority of the recorded micro-earthquakes had estimated focal depths between 8-14 km. The maximum estimated depth was 45 km. On

the basis of a seismic velocity model for the region reported recently and these depth estimates we suggest that the rupture zone of the great 1897 earthquake had a depth of 11-12 km under the western half of the Shillong massif. Four composite fault planes solutions define the nature of dislocation in three of the seismic zones. Three of them show oblique thrusting while one shows pure dip slip reverse faulting. The fault plane solutions fit into a regional pattern of a belt of earthquake extending in NW-SE direction across the north eastern corner of the Bengal basin. The maximum principal stress axis is approximately NS for all the solutions in conformity with the inferred direction of the Indian-Euro Asian plate convergence in the eastern Himalaya.

Keywords: Shillong massif, seismotectonics, seismicity, 1897 great Assam earthquake, stress pattern

- **'Strange attractor characteristics of earthquakes in Shillong Plateau and adjoining regions'; *H.N.Srivastava, S.N.Bhattacharya, K.C.Sinha Ray; Geophysical Research Letters; Vol. 23, Issue 24, pp. 3519-3522, 1 December 1996; (Article first published online: 7 Dec, 2012), DOI: 10.1029/96GL03232***

Abstract

Strange attractor dimensions were determined for two concentric areas of about 220 km (2°) and 440 km (4°) radii around WWSSN station at Shillong based on earthquake data during the period 1964 to 1992. Existence of deterministic chaos for both the areas was supported by the same fractal dimension of 6.1 and positive value of the largest Lyapunov exponent. The results have provided justification for delineating precursory seismicity patterns based on earthquakes up to epicentral distance of 440 km on different fault systems. Conspicuous higher value of the strange attractor dimension in Hindukush, Himalaya and northeast India than that in Koyna region in the peninsular India suggests a new criteria for distinction between interplate and intraplate earthquakes. Differences with subduction zone in Pacific vis-à-vis stress drop in great earthquakes (M≥8) and implications of the chaotic approach in earthquake hazard analysis have also been brought out.

- **The first and third asymptotic distributions of extremes as applied to the seismic source regions of India and adjacent areas'; *N.Madhava Rao, P.Prasada Rao and K.L.Kaila; Geophysics Journal International (1997) 128, 639-646***

Summary

The seismic source regions are identified on the basis of spatial and temporal distributions of shocks (1900-1989), recurrence relations and the tectonic architecture of the Indian subcontinent and adjoining areas. The probable occurrence of the maximum magnitude earthquake is estimated using the theory of extreme values of Gumbel. The parameters of the first and third asymptotic distributions of extremes and their uncertainty values are computed for the seven identified seismic source regions of India and adjacent areas. The third-type distribution curve is preferable to the first type in all the regions, as revealed by the x^2 test. The results of the third asymptotic distribution indicate the upper bound to earthquake magnitude *w* is equal to 8.94 ± 0.21 for Assam, 8.56 ± 0.29 for Bihar-Nepal, 8.43 ± 0.10 for Kangra, 8.97 ± 0.27 for Hindukush, 7.61 ± 0.24 for Pakistan-Cutch, 7.34 ± 0.12 for Koyna and 8.98 ± 0.27 for Andaman Sea seismic source regions. The predicted most probable largest earthquake magnitude is computed for return periods of 10, 20, 50, 75 and 100 yr in each source region..

Keywords: distribution of extremes, Gumbel probability, mean differences, seismic source regions, shallow focus earthquakes

- **'Crustal properties in the epicentral tract of the Great 1897 Assam Earthquake, northeastern India'; *S.Mukhopadhyay, R.Chander, K.N.Khatti; Tectonophysics 283, pp. 311-330, 1997***

Abstract

The velocity structure for the upper and middle crust in the epicentral tract of the Great 1897 Earthquake (western half of the Shillong massif) was estimated using locally recorded microearthquake data. The relatively homogeneous upper crustal layer has P and S wave velocities of 5.9 ± 0.2 and 3.4 ± 0.1 km/s, respectively, with a thickness of 11 to 12 km. The average P and S wave velocities in the middle part of the crust down to a depth of about 26 km were estimated to be 6.3 ± 0.6 and 3.5 ± 0.2 km/s, respectively. The larger scatter in P velocity estimate of the mid-crustal layer was investigated using synthetic examples. Our preference is for the model in which this crustal region is assumed to comprise of a number of thin layers with alternate low and high seismic velocities. From theoretical considerations we confirm that it is possible to estimate the velocity structure for a horizontally layered model using the velocity estimation procedure (a combination of the Wadati, Riznichenko and Bune method) we have used. We also carried out detailed model analysis to check how effective this velocity estimation procedure is for the type of array data we have. Combining the estimated velocity structure with our earlier work on seismicity of this area we propose that the upper homogeneous crustal layer in the Shillong massif may be moving relatively southward across an intracrustal thrust zone. We suggest that the Great 1897 Assam Earthquake may represent the most recent episode of this relative southward movement of the massif.

Keywords : Shillong massif; velocity; Great 1897 Assam Earthquake; Riznichenko method

- **'Three-dimensional seismic structure beneath Shillong Plateau and Assam Valley, Northeast India'; *J.R.Kayal and Dapeng Zhao; Bulletin of the Seismological Society of America, vol. 88, no. 3, pp. 667-676, June 1998***

Abstract

Northeast India is bounded by the Himalayan arc to the north and the Burmese arc to the east. The Shillong Plateau and Assam Valley lie at the boundary zone of the two arcs. Three microearthquake surveys were conducted in this area from 1984 to 1986. We have applied a tomographic method to about 2800 high-quality *P*- and *S*- wave arrival times from 364 local earthquakes that were recorded in the magnitude range 2.0 to 4.0 by 22 temporary seismic stations during the surveys to determine the 3D velocity structure of the crust and upper mantle in this region. The result reveals significant lateral heterogeneities in the study

area. The tomographic images obtained in this study are compatible with the major tectonic features such as active faults and seismicity trends.

- **'Subduction in the Indo-Burma Region: Is it still active?'; *S.P.Satyabala; Geophysical Research Letters; Vol. 25, issue 16, pp. 3189-3192, 15 August 1998 (First published online: 7 Dec. 2012; DOI:10.1029/98GL02256***

Abstract

The Indo-Burma region (which includes longitude 92°–96°E, latitude 20°–26°N) is a subduction zone where the Indian plate underthrusts the South-Eastern Asian plate. But the nature of subduction is complex. I examine here the distribution of the P, T and B axes of 37 earthquakes (the time period 1977–1995, depths 0–153 km and magnitudes m_b 4.8–6.8) with respect to the geometry of the Wadati-Benioif Zone. The analysis shows that the T axes are clustered close to the down-dip direction of the subducting slab implying a predominant down-dip tensional stress regime within the slab, which is typical of intermediate depth seismicity of active subduction zones. These results suggest that the subduction in the Indo-Burma region is possibly active.

- **'Timing and return period of major palaeoseismic events in the Shillong Plateau, India'; *B.S.Sukhija, M.N.Rao, D. V Reddy, P Nagabhushanam, Syed Hussain, R. K Chadha, H. K Gupta; Tectonophysics, 01/1999; 308 (1); 53-65***

Abstract

The close temporal occurrence of four great earthquakes in the past century, including the great Assam earthquake of 1897 in the Shillong Plateau, necessitated examination of the palaeoseismicity of the region. The results from such investigation would definitely aid in addressing the problem of the earthquake hazard evaluation more realistically. Our recent palaeoseismological study in the Shillong Plateau has led us to identify and provide geological evidence for large/major earthquakes and estimate the probable recurrence period of such violent earthquakes in parts of the Shillong Plateau and the adjoining Brahmaputra valley. Trenching along the Krishnai River, a tributary of the River Brahmaputra, has unravelled very conspicuous and significant earthquake-induced signatures in the alluvial deposits of the valley. The geological evidence includes: (1) palaeoliquefaction features, like sand dykes and sand blows; (2) deformational features, like tilted beds; (3) fractures and syndepositional deformational features, like flame structures caused by coeval seismic events. Chronological constraints of the past large/major earthquakes are provided from upper and lower radiocarbon age bounds in the case of the palaeoliquefaction features, and the coeval timing of the palaeoseismic events is obtained from the radiocarbon dating of the organic material associated with the deformed horizon as well as buried tree trunks observed wide distances apart. Our palaeoseismic measurements, which are the first from the area, indicate that the Shillong Plateau has been struck by large/major earthquakes around 500±150, 1100±150 and >1500±150 yr BP, in addition to the well-known great seismic event of 1897, thereby the 14C dates indicate a recurrence period of the order of 500 yr for large earthquakes in the Shillong Plateau.

- **'Seismotectonics of the Himalaya and its vicinity from centroid-moment tensor (CMT) solution of earthquakes'; *D.D.Singh; Journal of Geodynamics; 30, pp. 507-537, 2000.***

Abstract

The centroid-moment tensor solutions of more than300 earthquakes that occurred in the Himalayas and its vicinity regions during the period of 1977-1996 are examined. The resultant seismic moment tensor components of these earthquakes are estimated. The Burmese arc region shows prominent east-west compression and north-south extension with very little vertical extension. Northeast India and Pamir-Hindu Kush regions show prominent vertical extension and east-west compression. The Indian plate is subducting eastward beneath the northeast India and Burmese arc regions. The overriding Burmese arc has overthrust horizontally with the underthrusting Indian plate at a depth of 20-80 km and below 80 km depth, it has merged with the Indian plate making ""Y"" shape structure and as a result the aseismic zone has been formed in the region lying between 26^0N- 28^0N and 91.5^0E- 94^0E at a depth of 10-50 km. Similarly, the Indian plate is underthrusting in the western side beneath the Pamir-Hindu Kush region and the overriding Eurasian plate has overthrust it to form a "Y" shape structure at a depth of 10-40 km and below 60 km depth, it has merged with the Indian plate and both the plates are subducting below 60-260 km depth. Further south, the overriding Eurasian plate has come in contact with the Indian plate at a depth of 20-60 km beneath northwest India and Pakistan regions with left lateral strike slip motion.

- **'Fault interactions and seismic hazard'; *C.H.Scholz, Anupoma Gupta, Journal of Geodynamics, 29, pp. 459-467, 2000***

Abstract

Faults usually are not isolated features but exist within a population of faults which may interact through their stress fields. This poses two serious problems for a seismic hazard analysis. The most severe such problem lies in estimating the likelihood of whether or not a future earthquake will be confined to a single fault (or fault segment) or will jump to adjacent faults and and result in a larger earthquake. We review recent results which show that it is possible to determine the degree of fault interaction from geological data alone. We propose that the probability of an earthquake jumping from one fault to another will increase with the degree of stress interaction between the faults, and introduce a simple criterion to estimate the degree of interaction based on separation and overlap of echelon normal fault pairs. This statics based criterion for normal faults agrees qualitatively with the limite dynamic modeling of (*Harris, R.A., Day, S.M., 1993. Dynamics of fault interaction: parallel strike-slip faults. Journal of Geophysical Research 98, 4461-4472*) of the more complex case of strike slip faults and suggests that a more general criterion may be obtainable. The second problem discussed is the hazard associated with earthquakes being triggered by earlier earthquakes on a different fault. This phenomena produces seismic hazards distinct from that associated with ordinary aftershocks. We point out that with rapid data acquistion and proper preparation, it is feasible to issue a short-term hazard assessment regarding triggered earthquakes shortly after the occurrence of a potentially triggering event.

- **‘Comment on “Subduction in the Indo-Burma region: Is it still active?”” *by S.P.Satyabala’; Marco Guzman-Speziale, James F.Ni; Geophysical Research Letters, Vol. 27, No. 7, pp. 1065-1066, April 1, 2000***

Abstract

The nature of subduction in the Western Sunda Arc has been, indeed, a puzzle, as Satyabala [1998] (hereafter referred to as SA98) points out. That is why many papers have been written about this arc [e.g., Fitch, 1970; Curray et al., 1979; Lawver and curray, 1981; LeDain et al., 1984; Chen and Molnar, 1990]. We also undertook the problem and published two papers on the subject: Ni et al. [1989] (hereafter NI89) and Guzman-Speziale and Ni, 1993 [1996] (hereafter GU96). A third [Guzman-Speziale and Ni, 1993] also discusses seismotectonic aspects of the area. In this commentary, we would like to refer to critical differences between SA98 and our work, particularly in view that SA98 is probably not aware of the existence of GU96, much less of the conclusion we reached in that paper. Available evidence suggests there is no active subduction along the Burmese Arc at present.

- **‘Seismotectonics and rates of active crustal deformation in the Burmese arc and adjacent regions’; *M.Radha Krishna, T.D.Sanu; Journal of Geodynamics Vol. 30, pp. 401-421, 2000***

Abstract

The close vicinity of the Burmese subduction zone to the Himalayan collision zone across northeast India produces complex tectonics giving rise to a high level of seismicity. Using the hypocentral data of shallow earthquakes (≤70 km) for the period 1897-1995, a large number of focal mechanism solutions and other geophysical data in correlation with major morphotectonic features in the Burmese arc and the adjoining areas, we identified 12 broad seismogenic zones of relatively homogeneous deformation. Crustal deformation rates have been determined for each one of these sources based on summation of moment tensors. The results indicate that along the Kopili±Bomdila fault zone in eastern Himalaya, the deformation is taken up as a compression of 0.12±0.01 mm/yr along N16^0 and an extension of 0:05±004 mm/yr along N104^0 direction. The deformation velocities show a NS compression of 18:9± 2.5 mm/yr and an EW extension of 17:1±2.2 mm/yr in the Shillong Plateau region, while a compression of 5:4±2.8 mm/yr along N33^0 is observed in the Tripura fold belt and the Bengal basin region. The vertical component in the Shillong Plateau shows crustal thickening of 2:4±0:3 mm/yr. The deformation velocities in Indo-Burman ranges show a compression of 0:19±0:02 mm/yr along N11^0 and an extension of 0:17±0:01 mm/yr along N101^0 in the Naga hills region, a compression of 3:3±0:4 mm/yr along N20^0 and an extension of 3:1±0:36 mm/yr along N110^0 in the Chin hills region and a compression of 0:21±0:3 mm/yr in N208 and an extension of 0:18±0:03 mm/yr along N110^0 in the Arakan-Yoma region. The dominance of strike-slip motions with the P axis oriented on an average along N17^0 indicate that the Burma platelet may be getting dragged along with the Indian plate and the motion of these two together is accommodated along the Sagaing fault. The velocities estimated along Sagaing transform fault in the back-arc region suggest that the deformation is taken up as an extension of 29:5±4:7 mm/yr along N344^0 and a compression of 12:4±1:9 mm/yr along N74^0 in the northern part of the fault zone, and a compression of 17:4±2:3 mm/yr along N718 and an extension of 59:8±8:0 mm/

- **‘Tectonics of the Himalaya and southern Tibet from two perspectives; *K.V.Hodges; Geological Society of America Bulletin; vol. 112, no. 3, pp. 324-350, 2000; doi:10.1130/0016-7606***

Abstract

The Himalaya and Tibet provide an unparalleled opportunity to examine the complex ways in which continents respond to collisional orogenesis. This paper is an attempt to synthesize the known geology of the orogenic system, with special attention paid to the tectonic evolution of the Himalaya and southernmost Tibet since India-Eurasia collision at ca. 50 Ma. Two alternative perspectives are developed. The first is largely historical. It includes brief (and necessarily subjective) reviews of the tectonic stratigraphy, the structural geology, and metamorphic geology of the Himalaya. The second focuses on the processes that dictate the behavior of the orogenic system today. It is argued that these processes have not changed substantially over the Miocene-Holocene interval, which suggests that the orogeny has achieved a quasi-steady state. This condition implies a rough balance between plate-tectonic processes that lead to the accumulation of energy in the orogeny and many other processes (e.g., erosion of the Himalayan front and the lateral flow of the middle and lower crust of Tibet) that lead to the dissipation of energy. The tectonics of the Himalaya and Tibet are thus intimately related; the Himalaya might have evolved very differently had the Tibetan Plateau never have formed.

- **‘Microearthquake activity in some parts of the Himalaya and the tectonic model’; *J.R.Kayal; Tectonophysics 339, pp. 331-351,2001***

Abstract

Microearthquake data from temporary/permanent networks in different parts of the Himalaya shed new light on understanding the earthquake generating processes and their relation to tectonic models of the region. The microearthquake activity in Arunachal Pradesh, northeastern Himalaya, is found to be pronounced at the Main Boundary Thrust (MBT) and to its south: the subcrustal earthquakes (depth 50-80 km) occur much below the *plane of detachment* of the tectonic models proposed by Seeber et al. (1981) and Ni and Barazangi (1984). The MBT is not the seismogenic fault: the earthquakes are generated by strike-slip movement on deep seated hidden faults, transverse to the MBT. The high seismic activity in the Shillong Plateau, about 200 km south of the MBT in the northeast region, is due to influence of Himalayan collision tectonics to the north and Burmese arc subduction tectonics to the east. The activity in the Plateau is not directly related to the Himalayan thrust belt or seismic belt. These are mostly crustal earthquakes (depth 10-30 km), and are caused by local active faults/lineaments. In the eastern Himalaya, in the Sikkim and Darjeeling area, the seismic activity is found to be clustered mostly to the north of the MBT. The earthquakes occur at a depth range 0-50 km; the majority of them occur below the detachment plane by thrust-faulting. In the central part, in the Nepal Himalaya, lateral variations of the seismic activity are observed, which represent lateral segmentation of the MBT by transverse tectonic features. In the western Himalaya, however, the tectonic models fit well with the microearthquake data. In the Himachal Pradesh of the western Himalaya, the microearthquakes are mostly recorded in the MBT zone, and the hypocentres (depth 0-20 km) are confined above the plane of detachment or on the Basement Thrust. The earthquakes mostly occur to the south of the Main Central Thrust (MCT), which suggests that the MCT is

not seismogenic; it is rather a dormant fault. No single tectonic model explains the Himalayan earthquakes.

- **Southward extrusion of Tibetan crust and its effect on Himalayan tectonics'; *K.V. Hodges, J.M. Hurtado, and K.X. Whipple; Tectonics, Vol. 20, No. 6, Pages 799-809, December 2001***

Abstract.

The Tibetan Plateau is a storehouse of excess gravitational potential energy accumulated through crustal thickening during India-Asia collision, and the contrast in potential energy between the Plateau and its surroundings strongly influences the modern tectonics of south Asia. The distribution of potential energy anomalies across the region, derived from geopotentiaml models, indicates that the Himalayan front is the optimal location for focused dissipation of excess energy stored in the Plateau. The modem pattern of deformation and erosion in the Himalaya provides an efficient mechanism for such dissipation, and a review of the Neogene geological evolution of southern Tibet and the Himalaya shows that this mechanism has been operational for at least the past 20 million years. This persistence of deformational and erosional style suggests to us that orogens, like other complex systems, can evolve toward "steady state" configurations maintained by the continuous flow of energy. The capacity of orogenic systems to self-organize in to temporally persistent structural and erosional patterns suggests that the tectonic history of a mountain range may depend on local energetics as much as it does on far-field plate interactions.

- **'Oblique Plate Convergence in the Indo-Burma (Myanmar) Subduction Region'; *S.P.Satyabala; Pure and Applied Geophysics; 160, 1611-165, 2003; DOI 10.1007/s00024-003-2378-0***

Abstract

The Indo-Burma (Myanmar) subduction boundary is highly oblique to the direction of relative velocity of the Indian tectonic plate with respect to the Eurasian plate. The area includes features of active subduction zones such as a Wadati-Benioff zone of earthquakes, a magmatic arc, thrust and fold belts. It also has features of oblique subduction such as: an arc-parallel strike-slip fault (Sagaing Fault) that takes up a large fraction of the northward component of motion and a buttress (the Mishmi block) that resists the motion of the fore-arc silver.

In this paper, I have examined the seismicity, slip vectors and principal axes of the focal mechanisms of the earthquakes to look for features of active subduction zones and for evidence of slip partitioning as observed in other subduction zones. The data set consists of Harvard CMT solutions of 89 earthquakes (1977-1999 with $4.8 \leq M_w \leq 7.2$ and depths between 3-140 km). Most of these events are shallow and intermediate depth events occurring within the Indian plate subducting eastward beneath the Indo-Burman ranges. Some shallow events within the fore-arc region have arc-parallel P axes, reflecting buttressing of the fore-arc silver at its leading edge. Some of the shallowest events have nearly E-W oriented P axes which might account for recent folding and thrusting. Examination of earthquake slip vectors in the region show that the slip vector azimuths of earthquakes in the region between 20^0-26^0 N are rotated towards the trench normal, which is an indication of partial partitioning of the oblique convergence. It is seen that all aspects of seismicity, including the paucity of shallow underthrusting earthquakes and the orientation of P axes, are consistent with oblique conver-

gence. The conclusion of this paper are consistent with recent geological studies and interpretations such as the coexistence of eastward subduction, volcanic activity and transcurrent movement through mid-Miocene to Quaternary period.

Keywords: Indo-Burma, Myanmar, subduction, oblique convergence, slip partitioning

- **'MSK Isoseismal intensities evaluated for the 1897 Great Assam Earthquake'; *Ambraseys, N., and R. Bilham; Bull. Seism Soc. Am. 93 (2) 655-673, 2003***

Abstract

The great 1897 Assam earthquake of 1897 is the largest known Indian intraplate earthquake ($8<M<8.1$). The earthquake raised the northern edge of the Shillong Plateau by more than 10 m, resulting in the destruction of structures over much of the Plateau and surrounding areas, and causing widespread liquefaction and flooding in the Brahmaputra and Sylhet floodplains. Shaking intensity data for the earthquake are crucial for estimating future earthquake hazards in NE India and Bangladesh since similar earthquakes will no-doubt recur. Yet despite the availability of numerous felt reports, no evaluation of isoseismal contours has been attempted since Oldham's (1898) approximation. We have re-evaluated 365 accounts of the earthquake and quantified 287 on a simplified version of the "MSK 1981" Intensity scale. The reappraised isoseismals are consistent with the geodetic mechanism for the earthquake and are smaller, less regular, and less elliptical than those inferred by Oldham. They suggest that Oldham's intensities were inflated by 1-1.5 intensity units. The revised intensity data provide new quantitative constraints on the attenuation of perceived intensity as a function of distance in northeastern India.

- **'Seismotectonic Model of the Sikkim Himalaya: Constraint from Microearthquake Surveys'; *Reena De and J.R.Kayal; Bulletin of the Seismological Society of America, Vol. 93, No. 3, pp. 1395-1400, June 2003***

Abstract

The seismotectonic model in the Sikkim Himalaya does not fit well with the proposed steady state or evolutionary models. The main boundary thrust (MBT) is seismogenic and is a mantle-reaching fault. The earthquakes are not confined to shallow depths (<25 km) above the plane of detachment as proposed in the models, the seismic activity continues from surface to the lower crust (0-45 km) to the north of MBT, and earthquakes are produced by a thrust mechanism. The earthquakes to the east of Sikkim, in the Bhutan Himalaya, on the other hand, are produced along a 200-km-long northwest –southeast-trending lineament by transverse tectonics: the seismogenic lineament cuts across the Himalayan major thrusts and extends to the Goalpara wedge in the southeast. The earthquakes occur by strike-slip mechanism in the midcrust, at a depth range of 10-25 km, along this long active lineament.

- **'Reactivation of Himalayan Frontal Fault: Implications'; *K.S. Valdiya; Current Science, Vol. 85, No. 7, 10 October 2003***

Abstract

Youngest of the five terrain-defining faults, the Himalayan Frontal Fault (HFF) is a series of reverse faults that demarcates the boundary of the Siwalik front of the Himalayan province with the alluvial expanse of the Indo-Gangetic Plains. Originated about 1.6 million years ago,

it has truncated and attenuated the Siwalik domain. Over large tracts, it is either concealed under younger sediments or has as yet not reached the ground surface and is therefore a blind fault. The nature of this frontal fault varies along its length. Where the hidden ridges of the Indo-Gangetic basement impinge the Himalaya, the mountain front is ruptured and the HFF is repeatedly reactivated. In the sectors intervening these ridges, it is not expressed on the surface, but the ground of the adjoining Indo-Gangetic Plain is sinking, the rivers are shifting their courses and a large tract of the land is waterlogged and characterized by marshes or ponds and by strong seismicity. The northern part of the Indo-Gangetic Plains in the proximity of the ruptured mountain front is also experiencing buildup of tectonic stress. The HFF traces the frontal line of the detachment plane along which the Indian plate is sliding under the Himalaya and generating earthquakes.

- **'Role of static stress transfer in earthquake occurrence in the Himalaya'; *I.Sarkar, R.Chander; Journal of Asian Earth Sciences 22 , 59-65, 2003***

Abstract

Coulomb failure hypothesis suggests that earthquake interaction can lead to earthquake sequences and clustering. This implies that the phenomenon should be considered a fundamental feature in any description of seismicity and evaluation of the seismic hazard and risk of a region. We translate this idea to the Himalaya and investigate how significantly the past earthquakes of the region may have influenced the present day seismicity and seismic hazard potential along its different segments. For this, we estimate separately the change in Coulomb failure stress at the source of the most recent moderate magnitude earthquake along the Kumaon Garhwal segment, the March 29, 1999 Chamoli earthquake, due to two possible major sources. These are (i) the process of subduction of the Indian plate beneath the Himalaya and (ii) some selected preceding moderate and small earthquakes in and around the region, during their post seismic phase. Our results indicate that the change due to the former source completely overshadows that due to the latter. The implication of our calculations is that the plate subduction processes in the Himalaya (i) actively promote large, moderate and small earthquake activity and (ii) also indirectly influence the regional seismicity through the occurrence of the past earthquakes.

Keywords: Static stress transfer; Himalayan seismicity

- **'Stress buildup in the Himalaya'; *L. Bollinger, J. P. Avouac, R. Cattin, and M. R. Pandey JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, B11405, doi:10.1029/2003JB002911, 2004***

Abstract

[1]The seismic cycle on a major fault involves long periods of elastic strain and stress accumulation, driven by aseismic ductile deformation at depth, ultimately released by sudden fault slip events. Coseismic slip distributions are generally heterogeneous with most of the energy being released in the rupture of asperities. Since, on the long term, the fault's walls generally do not accumulate any significant permanent deformation, interseismic deformation might be heterogeneous, revealing zones of focused stress buildup. The pattern of current deformation along the Himalayan arc, which is known to produce recurring devastating earthquakes, and where several seismic gaps have long been recognized, might accordingly show significant lateral variations, providing a possible explanation for the uneven

microseismic activity along the Himalayan arc. By contrast, the geodetic measurements show a rather uniform pattern of interseismic strain, oriented consistently with long-term geological deformation, as indicated from stretching lineation. We show that the geodetic data and seismicity distribution are reconciled from a model in which microseismicity is interpreted as driven by stress buildup increase in the interseismic period. The uneven seismicity pattern is shown to reflect the impact of the topography on the stress field, indicating low deviatoric stresses (<35 MPa) and a low friction (<0.3) on the Main Himalayan Thrust. Arc-normal thrusting along the Himalayan front and east-west extension in southern Tibet are quantitatively reconciled by the model.

Keywords*:* seismic cycle, interseismic, microseismicity, geodesy, Himalaya,

- **'Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake: Implications for regional tectonism'; *C. P. Rajendran, Kusala Rajendran, B. P. Duarah, S. Baruah, and Anil Earnest; TECTONICS, VOL. 23, TC4009, doi:10.1029/2003TC001605, 2004***

Abstract

[1] The 1897 Shillong (Assam), northeast India, earthquake is considered to be one of the largest in the modern history. Although Oldham's [1899] classic memoir on this event opened new vistas in observational seismology, many questions on its style of faulting remain unresolved. Most previous studies considered this as a detachment earthquake that occurred on a gently north dipping fault, extending from the Himalayan front. A recent model proposed an alternate geometry governed by high-angle faults to the north and south of the plateau, and it suggested that the 1897 earthquake occurred on a south dipping reverse fault, coinciding with the northern plateau margin. In this paper, we explore the available database, together with the coseismic observations from the region, to further understand the nature of faulting. The geophysical and geological data examined in this paper conform to a south dipping structure, but its location is inferred to be in the Brahmaputra basin, further north of the present plateau front. Our analyses of paleoseismic data suggest a 1200-year interval between the 1897 event and its predecessor, and we identify the northern boundary fault as a major seismic source. The Shillong Plateau bounded by major faults behaves as an independent tectonic entity, with its own style of faulting, seismic productivity, and hazard potential, distinct from the Himalayan thrust front, a point that provides fresh insight into the regional geodynamics.

KEYWORDS: earthquake, tectonics, paleoseismology, faulting, seismicity, northeast India.

- **'Structural pattern of eastern Himalayan syntaxis in Namjagbarwa and its formation process'; *Zhang Jinjiang, Ji Jianqing, Zhong Dalai, Ding Lin and HE Shundong; Science in China Ser. D Earth Sciences 2004 Vol. 47, No.2, pp. 138-150; DOI; 10.136002yd0042***

Abstract

The structural pattern of the eastern Himalayan syntaxis in Namjagbarwa consists of two series of structures with different styles. One series compiles the earlier ductile contractional and lateral-slip deformation system, formed by nearly north-south shortening within the syntaxis, left-lateral and right-lateral slipping along its western and eastern boundaries re-

spectively. They were possibly produced by the indentation of the Indian continent into Asian continent after Andia-Asia collision. The peak deformation-metamorphic ages in these structures are 62-60 Ma, ~23 Ma and ~13 Ma. The other series is composed of ductile-brittle normal faults distributing concentrically and dipping towards the outsides of Namjagbarwa Peak. They were probably the collapse structures caused by rapid uplift in a later time and the beginning ages for the normal faulting are about 7.3-6.3 Ma.

- **'Seismic activity at the MCT in Sikkim Himalaya'; *Reena De, J.R.Kayal; Tectonophysics 386 pp. 243-248, 2004***

Abstract

A microearthquake survey in the Sikkim Himalaya raised a question whether the north-south segment of the Main Central Thrust (MCT) in this part of the Himalaya is seismically active (?). Fault-plane solution of a cluster of events occurred below this segment of the MCT shows right-lateral strike-slip motion. The seismic observations and the geological evidences suggest that a NNE-SSW trending strike-slip fault, beneath this segment, caused right lateral movement on the MCT, and is seismically active.

Keywords: Microearthquakes, Fault-plane solution, Active fault, Seismotectonics

- **Earthquakes in India and the Himalaya: tectonics, geodesy and history'; *Roger Bilham; Annals of Geophysics, Vol. 47, N. 2/3, April/June 2004***

Abstract

The record of earthquakes in India is patchy prior to 1800 and its improvement is much impeded by its dispersal in a dozen local languages, and several colonial archives. Although geological studies will necessarily complement the historical record, only two earthquakes of the dozens of known historical events have resulted in surface ruptures, and it is likely that geological data in the form of liquefaction features will be needed to extend the historical record beyond the most recent few centuries. Damage from large Himalayan earthquakes recorded in Tibet and in Northern India suggests that earthquakes may attain $M = 8.2$. Seismic gaps along two-thirds of the Himalaya that have developed in the past five centuries, when combined with geodetic convergence rates of approximately 1.8 m/cy, suggest that one or more $M = 8$ earthquakes may be overdue. The mechanisms of recent earthquakes in Peninsular India are consistent with stresses induced in the Indian plate flexed by its collision with Tibet. A region of abnormally high seismicity in western India appears to be caused by local convergence across the Rann of Kachchh and possibly other rift zones of India. Since the plate itself deforms little, this deformation may be related to incipient plate fragmentation in Sindh or over a larger region of NW India.

Key words: India – earthquakes – history

- **'Seismicity Pattern Changes Prior to Large Earthquakes-An Approach of the RTL Algorithm'; *Qinghua Huang; TAO, Vol. 15, No. 3, pp. 469-491, September, 2004***

Abstract

A statistical method, which is called the Region-Time-Length (RTL) algorithm and takes into account information such as magnitude, occurrence time and place of earthquakes, was applied to earthquake data to investigate seismicity pattern changes prior to large earthquakes. Based on the RTL algorithm and some newly developed parameters such as the *Q*parameter (average of the RTL values over some time window) and *S*-parameter (an index of seismic activation), I quantified both the temporal and spatial characteristics of seismicity pattern changes in various tectonic regions. The results indicated that seismic quiescence anomalies generally started a few years before the occurrence of the earthquakes and lasted from 1 to 2.5 years. The duration of the subsequent stage of seismic activation generally lasted several months. The linear dimension of the quiescence zone reached a few hundred kilometers (several times the rupture dimension of the mainshock), while the activation zone was generally in order of several tens of kilometers (comparable to the rupture dimension). An earthquake is most likely to occur once the relevant source region has passed through the quiescence and activation stages. Close investigation of possible artifacts due to the selection of model parameters and the changes of seismological networks are important in identifying real seismicity changes from man-made ones. Further stochastic testing using random earthquake catalogs was also done and it supports that the anomalies revealed in my works are significant. Besides studying on seismicity changes before large earthquakes, I also performed the first test of the above statistical method for investigating seismicity changes of earthquake swarms. It indicated that an increased RTL parameter would be a new potentially useful index for the risk alarm of earthquake swarms.

- **'Crustal structure variations in northeast India from converted phases'; *M.Ravi Kumar, P.Solomon Raju, E.Uma Devi, J.Saul, D.S.Ramesh; Geophysical Research Letters; Vol. 31, Issue 17, September 2004 (First published online: 10 September 2004); DOI:10.1029/2004GL020576***

Abstract

[1] Teleseismic receiver functions from a ten station network deployed in northeast India region sampling the Shillong plateau, Mikir Hills, Himalayan foredeep and the Himalayan convergence zone, are analyzed to obtain the crustal structure in this seismically active but less studied region. The Shillong plateau and Mikir hills, away from the convergent margins, reveal remarkably simple crust with thickness (~ 35 km) and Poisson's ratio (~ 0.25), akin to the Indian shield values. A surprisingly thin crust for the uplifted Shillong plateau may be explained invoking presence of an uncompensated crust that popped up in response to tectonic features. In contrast, crustal signatures from Assam valley suggest a thicker crust and higher Poisson's ratio with evidence for a dipping Moho. Predictably, the crust is much thicker and complicated in the eastern Himalaya further north, with values in excess of 50 km.

- **'The Eastern Himalayan syntaxis: major tectonic domains, ophiolitic mélanges and geologic evolution'; *Geng Quanru, Pan Guitang, Lailin Zheng, Zhiliang Chen, Richard D.Fisher, Zhiming Sun, Chunsheng Ou, Han Dong, Xiaowei Wang, Sheng Li, Xiongying Lou, Heng Fu; Journal of Asian Earth Sciences, pp. 1-21, 2005***

Abstract

Geologic mapping in the eastern Himalayan syntaxis confirmed the three regional tectonic elements outlined by previous geologic workers. Our studies, however, show that the Indus-Yarlung Tsangpo suture (IYS) is a continuous mélange zone that forms an inverted U in map view around the Namche Barwa antiform. The Namche Barwa and Nyainqentanglha crystalline complexes lie below and above the IYS suture, respectively, and both were parts of the northern Indian plate basement rocks with petrologically and geochronologically correlative protoliths. Both units were deformed, metamorphosed and intruded at the end of the Proterozoic. The Zhibai Formation, the lower part of the Namche Barwa Group, extends along the northwest slope of the Himalaya, and is mainly composed of highly deformed aluminous felsic gneiss containing sporadic boudins of high-pressure granulite in the Namche Barwa antiform. The upper part of the Namche Barwa Group includes a calcareous rock assemblage characterized by marble and diopside-bearing calcsillicate rocks interlayed with felsic gneiss. Petrochemical studies show that the IYS contains lenses of oceanic crustal rocks originated from fore-arc trench, island arc, and back-arc basin environments, which implies they were derived from a SSZ-type (supra-subduction zone) ophiolite. Our field mapping identifies the Jiali-Parlung Tsangpo remnant suture (JPS) that lies north of the Namche Barwa antiform as a possible branch of the Neo-Tethyan oceanic realm. Subduction of the Mesozoic Neo-Tethyan oceanic plate resulted in both Mesozoic and Cenozoic granite intrusions in the northwest-trending Gangdise magmatic belt along the edge of Asia. Uplift and exhumation have been the most recent dominant tectonic processes in the late Cenozoic for the High Himalayan crystalline rocks (Namche Barwa Group) in the core of the Namche Barwa antiform.

- **'Crustal structure and earthquake focal depths beneath northeastern India and southern Tibet'; *Supriyo Mitra, Keith Priestley, Anjan Bhattacharyya and V.K.Gaur; Geophysics, J., Int. (2005) 160, 227-248; doi:10.1111/j-1365-246X.2004.02470.x***

Summary

We use broad-band teleseismic data recorded at eight sites along a north-south profile from Karimganj (24.84^0N, 92.34^0E), south of the eastern Shillong Plateau, to Bomdila (27.27^0N, 92.41^0E) in the eastern Lesser Himalaya, to determine the seismic characteristics of the crust in northeastern India. We also analyse data from the Chinese Digital Seismic Network station at Lhasa and INDEPTHII stations located on the southern Tibetan Plateau north of our profile, to extend the seismic images of the crust further northwards. Although the northeastern Indian stations and the Tibetan stations do not lie along a linear profile across the Himalaya, the well-recognized uniformity of the Himalaya along strike make this comparison of the two profiles meaningful. Receiver functions calculated from these data show that the crust is thinnest (~35-38 km) beneath the Shillong Plateau. Receiver functions at Cherrapunji, on the southern edge of the Shillong Plateau, have a strong azimuthal dependence. Those from northern back azimuth events show that the Moho beneath the southernmost Shillong Plateau is at a depth of ~ 38 km while receiver functions from southern back azimuth events indicate that the Moho beneath the northernmost Bengal Basin is at a depth of ~ 44 km. Receiver functions from sites on the Brahmaputra Valley demonstrate that the Moho is deeper by ~5-7 km than below the Shillong Plateau, a result which agrees with the hypothesis that the Shillong Plateau is supported by shearing stress on two steep faults that cut through the crust. Further north of the eastern Himalayan foredeep, the Moho dips gently northwards, reaching a depth of ~ 48 km beneath Bomdilla in the Lesser Himalaya, and 88 km below Lhasa in Tibet. Using the crustal velocity models obtained from receiver function inversions, we redetermined focal depths of well-recorded earthquakes across this part of the Indo-Tibetan collision zone and find all of these to occur within the crust. Hence we find no evidence for bimodal depth distribution of earthquakes beneath this region of northeastern India.

Keywords: crustal structure, earthquake depths, Eastern Himalaya, India, Shillong Plateau, Tibetan Plateau

- **'A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry';** ***Sankar Kumar Nath, Madhav Vyas, Indrajit Pal, and Probal Sengupta; Journal of Geophysical Research, VOL. 110, B01301, doi:10.1029/2004JB003199, 2005***

Abstract

In this paper, we present a seismic hazard map of the Indian Himalayan State of Sikkim, lying between Nepal and Bhutan Himalaya, in terms of horizontal peak ground accelerations with 10% exceedance probability over the next 50 years. These figures, the first for the region, were calculated through a stepwise process based on (1) an estimation of the maximum credible earthquake (MCE) from the seismicity of the region and Global Seismic Hazard Assessment Program considerations and (2) four seismotectonic parameters abstracted from accelerograms recorded at nine stations of the Sikkim Strong Motion Array, specifically installed for this study. The latter include (1) the frequency-dependent power law for the shear wave quality factor, QS, (2) the site response function at each station using receiver function analysis and generalized inversion, (3) source parameterization of various events recorded by the array and application of the resulting relationships between M0 and MW, and corner frequency, fc and MW to simulate spectral accelerations due to higher-magnitude events corresponding to the estimated MCE, and (4) abstraction of regional as well as site specific local spectral attenuation laws at different geometrically central frequencies in low-, moderate-, and high-frequency bands.

- **'Variation in dip-angle of the Indian plate subducting beneath the Burma plate and its tectonic implications';** ***P.K.Khan; Geosciences Journal, Vol. 9, No. 3, p. 227 − 234, September 2005***

Abstract

The paper presents an analysis of the dip-angle of the Benioff zone trajectory, infers the state of stress of the descending Indian plate and the overriding Burma plate, and proposes three-stage episodic development of the descending Indian lithosphere and the Burma plate along the strike of the Indoburman arc. The first stage accounts for the late Oligocene–early Miocene east–west stretching of back-arc region, which divided the central lowland of Burma into western and eastern troughs along the volcanic line. The dip-angle of Benioff zone trajectory in sector II (ca. 24.0° to 25.5°N), the late Oligocene–early Miocene westward transcurrent displacement of blocks, and the east–west splitting of late Cretaceous–early Eo-

cene ophiolites are evidences of this stretching. The effect of stretching probably lasted through till when post-middle Miocene causing north–northeastward motion of the hanging Indian lithosphere together with the Burma plate through the asthenosphere. This may have been the cause of the westward offset between the main Irrawaddy River and the Chindwin River in the second stage. North–south varying degree of decoupling between the descending Indian plate and overriding plate may account for the interplay between the Indoburman arc and the northward moving Indian plate. The stress state and north–south shallow level seismicity observed in the present study may be evidences for a slow subduction of the Indian plate in the recent or third stage of development.

Key words: back-arc, depth-dip-angle of subducting slab, slow subduction

- **'Relocation of earthquakes in the Northeast Indian region using joint hypocentre determination method'; *Pankaj Mala Bhattacharya, Jose Pujol , R. K. Majumdar and J. R. Kaya ; Current Science, Vol. 89, No. 8, 25 October, 2005***

Abstract

A set of 1941 earthquake events recorded in the northeast region of India during January 1993 – December 1999 was used for relocation by the Joint Hypocentre Determination (JHD) technique. We have utilized both *P*- and *S*-wave arrivals recorded by closely spaced 77 temporary and permanent seismic stations in the region. Results of this analysis show that (a) the average root mean square travel time residual becomes smaller than the corresponding single event locations by the HYPO71; (b) station correction varies from –2.43 to 2.32 s for *P*wave, and from –2.84 to 2.84 s for *S*-wave, indicating large crustal velocity variations in the region; (c) positive station corrections are obtained in the Shillong Plateau, Assam valley and in the Manipur fold belt, and negative station corrections are obtained in the Mikir hills, and (d) lateral variation of the velocity structure inferred from station corrections is comparable with that obtained by 3D velocity inversion using the local earthquake tomography method.

Keywords: Earthquake, joint hypocentre determination, lateral velocity variation, local earthquake tomography, station correction..

- **'Shillong plateau earthquakes in northeast India region: complex tectonic model'; *J. R. Kayal, S. S. Arefiev, S. Barua, D. Hazarika, N. Gogoi, A. Kumar, S. N. Chowdhury and S. Kalita; CURRENT SCIENCE, VOL. 91, NO. 1, 10 JULY 2006***

Abstract

The complex tectonic model of the Shillong plateau (SP), the source area of the 1897 great earthquake in the northeast India region, is examined using the high precision data of a 20-station digital seismic network that is in operation in the SP since 2001. The dominating thrust/strike-slip faulting earthquakes in the western plateau although could be explained by the 'pop-up' tectonic model1, the seismological data, however, show that the north dipping Dapsi and the south dipping Brahmaputra faults are the possible boundary faults, not the Dauki and Oldham faults as were proposed in the model. The more intense normal/strike-slip faulting earthquakes in the eastern plateau (Mikir massif), on the other hand, are generated by a long and deep rooted Kopili fault by transverse tectonics, and this could be the more vulnerable source area for an impending large/great earthquake in the region.

Keywords: Fault-plane solutions, pop-up tectonics, Shillong plateau, strike-slip faulting, waveform inversion.

- **'Crustal structure across Sikkim, NE Himalaya from new gravity and magnetic data'; *V.M.Tiwari, M.B.S. Vyghreswara Rao, D.C. Mishra, B.Singh; Earth and Planetary Science Letters 247 61-69, 2006***

Abstract

The new gravity and magnetic data recorded along a profile in the Sikkim, NE Himalaya are combined with the existing data from Tibet, Bangladesh and India, to delineate the crustal structure in this part of Himalaya. Modelling of gravity data, constrained from seismic results suggests that long wavelength gravity anomalies arise due to variations in the depth of Moho (36 to 74 km), which are caused by flexed lithosphere of effective elastic thickness of ∼50±10 km. Simultaneous modelling of magnetic anomalies and short wave-length gravity anomalies reveals that (a) the magnetic anomalies observed over the Lesser Himalaya and the Higher Himalaya Crystalline rocks might be caused by remnant magnetisation with inclination I=−18°±8° and declination D=147°±10°, which is in conformity with the palaeomagnetic results. These magnetic parameters correspond to ~35±10 Ma age of magnetic direction and suggest that the rocks might have acquired magnetisation during cooling period of metamorphism, (b) low grade meta-sediments of the Lesser Himalaya extend up to 12 km depth and thins on either sides forming a bowl shaped geometry and (c) relative gravity high in the Bengal basin might be caused by intrusion of the Rajmahal volcanics. Modelling has also provided constraint on the geometry of the north dipping thrusts.

Keywords: Gravity; Isostasy; Effective elastic thickness; Himalaya

- **'Cenozoic tectonic evolution of the Himalayan orogeny as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation'; *An Yin; Earth Science Reviews; 76, 1-131, 2006***

Abstract

Despite a long research history over the past 150 years, the geometry, kinematics, and dynamic evolution of the Himalayan orogen remain poorly understood. This is mainly due to continued emphasis on the two-dimensionality of the Himalayan orogenic architecture and extrapolation of geologic relationships from a few well-studied but small areas to the rest of the orogen. Confusion and misconception are also widespread in the Himalayan literature in terms of the geographic, stratigraphic, and structural divisions. To clarify these issues and to provide a new platform for those who are interested in studying the geologic development of this spectacular mountain belt, I systematically review the essential observations relevant to the along-strike variation of the Himalayan geologic framework and its role in Cenozoic Himalayan exhumation, metamorphism and foreland sedimentation. A main focus of my synthesis is to elucidate the emplacement history of the high-grade Greater Himalayan Crystalline Complex (GHC) that occupies the core of the orogen. Because the north-dipping Main Central Thrust (MCT) above and South Tibet Detachment (STD) below bound the GHC in most parts of the Himalaya, it is critical to determine the relationship between them in map and cross-section views. The exposed map pattern in the central Himalaya (i.e., Nepal) indicates that the MCT has a flat-ramp geometry. The thrust flat in the south carries a 2–15-km-thick slab of the GHC over the Lesser Himalayan Sequence (LHS) and creates a large hanging-wall fault-bend fold continuing N100 km south of the MC Tramp zone. In the western Himalayan orogen at the longitude ~778E, the MCT exhibits a major lateral ramp (the Mandi ramp). West of this ramp, the MCT places the low-grade Tethyan Himalayan Sequence (THS) over the low-grade LHS, whereas east of the ramp, the MCT places the high-grade GHC over the low-grade LHS. This along-strike change in stratigraphic juxtaposition and metamorphic grade across the MCT indicates a westward decrease in its slip magnitude, possibly a result of a westward decrease in total crustal shortening along the Himalayan orogen. Everywhere exposed, the STD follows roughly the same stratigraphic horizon at the base of the THS, exhibiting a long (N100 km) hanging-wall flat. This relationship suggests that the STD may have initiated along a preexisting lithologic contact or the subhorizontal brittle–ductile transition zone in the middle crust. Although the STD has the THS in its hanging wall everywhere in the Himalayan orogen, no THS footwall cutoffs have been identified. This has made slip estimates of the STD exceedingly difficult. The southernmost trace of the STD either merges with the MCT (e.g., in Zanskar) or lies within 1–2 km of the MCT frontal trace (e.g., in Bhutan), suggesting that the MCT may join the STD in their up-dip directions to the south. This geometry, largely neglected by the existing models, has important implications for the deformation, exhumation, and sedimentation history of the entire Himalayan orogen.

Keywords: Himalayan orogen; Main Central Thrust; South Tibet Detachment; passive-roof fault; active-roof fault; erosional exhumation

- **'Active tectonics in Eastern Lunana (NW Bhutan): Implications for the seismic and glacial hazard potential of the Bhutan Himalaya'; *M. C. Meyer, G. Wiesmayr, M. Brauner, H. Ha¨usler,and D. Wangda; Tectonics, Vol. 25, TC3001, doi:10.1029/2005TC001858, 2006***

Abstract

Paleoseismological investigations, brittle fault analysis, and paleostrain calculations combined with the interpretation of satellite imagery and flood wave modeling were used to investigate the seismic and associated glacial hazard potential in Eastern Lunana, a remote area in NW Bhutan. Seismically induced liquefaction features, cracked pebbles, and a surface rupture of about 6.8 km length constrain the occurrence of $M \geq 6$ earthquakes within this high altitude periglacial environment, which are the strongest earthquakes ever been reported for the Kingdom of Bhutan. Seismicity occurs along conjugate sets of faults trending NE-SW to NNW-SSE by strike-slip and normal faulting mechanism indicating E-W extension and N-S shortening. The strain field for these conjugate sets of active faults is consistent with widespread observations of young E-W expansion throughout southern Tibet and the north Himalaya. We expect, however, that N-S trending active strike-slip faults may even reach much farther to the south, at least into southern Bhutan. Numerous glacial lakes exist in the investigation area, and today more than 100×10^6 m3 of water are stored in moraine-dammed and supraglacial lakes which are crosscut by active faults. Strong earthquakes may trigger glacial lake outburst floods, and the impact of such flash floods may be worst 80 km downstream where the valley is broad and densely populated. Consequently, tectonic models of active deformation have to be closely linked with glacial hazard evaluation and require rethinking and modification.

- **'Delineation of probable seismic sources in India and neighbourhood by a comprehensive analysis of seismotectonic characteristics of the region'; *I.D.Gupta; Soil Dynamics and Earthquake Engineering, Vol. 26, pp. 766-790, 2006***

Abstract

Identification and delineation of seismogenic sources is one of the most important steps in the seismic hazard analysis. This paper presents a comprehensive description of the various tectonic features and the association of seismicity with them to define the probable seismic sources in India and adjacent areas. The plate boundary areas along the Himalayan and the Indo-Burmese arcs, along with the intervening area of northeast India, are characterized by very high level of seismicity. To consider the spatial variation in the seismicity, these areas are divided into several possible seismic sources. In view of the sporadic nature of seismicity in the interplate area of the peninsular India, it is represented by 21 isolated sources. From a knowledge of the subsurface peninsular features extending up to the Himalaya and the seismicity associated with them, some seismic sources are also delineated transverse to the Himalayan trend in the Indo-Gangetic plains. In all, 81 broad seismic sources are defined by a detailed and critical analysis of the correlation of more than 12,000 past earthquakes with magnitude 4.0 or above the major tectonic features in the Indian region. Due to the use of an up-to-date database on the past seismicity and a very comprehensive analysis of the seismotectonics of the region, the present study is considered to provide a very realistic basis for evaluation of seismic hazard in India.

- **'Are northeast and western Himalayas earthquake dynamics better "organized" than Central Himalayas: An artificial neural network approach'; *S. Sri Lakshmi and R. K. Tiwari; Geofísica Internacional, Vol. 46, Num. 1, pp. 65-75, 2007***

Abstract

The Himalaya covering 20-38° N latitude and 70-98° E longitude, is one of the most seismo-tectonically active and vulnerable regions of the world. Visual inspection of the temporal earthquake frequency pattern of the Himalayas indicates the nature of the tectonic activity prevailing in this region. However, the quantification of this dynamical pattern is essential for constraining a model and characterizing the nature of earthquake dynamics in this region. We examine the temporal evolution of seismicity ($M \geq 4$) of the Central Himalaya (CH), Western Himalaya (WH) and Northeast Himalaya (NEH), for the period of 1960-2003 using artificial neural network (ANN) technique. We use a multilayer feed forward artificial neural network (ANN) model to simulate monthly resolution earthquake frequency time series for all three regions. The ANN is trained using a standard back-propagation algorithm with gradient decent optimization technique and then generalized through cross-validation. The results suggest that earthquake processes in all three regions evolved on a high dimensional chaotic plane akin to "self-organized" dynamical pattern. Earthquake processes of NEH and WH show a higher predictive correlation coefficient (50-55%) compared to the CH (30%), implying that the earthquake dynamics in the NEH and WH are better "organized" than in the CH region. The available tectono-geological observations support the model predictions.

KEY WORDS: Himalaya, neural networks, self-organisation, seismicity.

- **'Using Small, Temporary Seismic Networks for Investigating Tectonic Deformation: Brittle Deformation and Evidence for Strike-Slip Faulting in Bhutan'; *A.A.Velasco, V.L.Gee, C.Rowe, D.Grujic, L.S.Hollister, D.Hernandez, K.C.Miller, T.Tobgay, M.Fort and S.Harder; Seismological Research Letters, Vol. 78, No. 4, July/August 2007***

Abstract

We processed data from a small, five-station temporary seismic network deployed from January 2002 until March 2003 within the Kingdom of Bhutan. We detected, associated, and located approximately 2,100 teleseismic, regional, and local events; approximately 900 were not in the United States Geological Survey (USGS) Earthquake Data Report catalog. We supplemented our data for these 900 events with data from the Global Seismographic Network (GSN) stations in the region. After relocation of these events, we focused on approximately 175 events that occurred near or within the borders of Bhutan. We reviewed each solution, manually timing the P- and S-waves for each event, and inverted for event locations and an average I-D velocity model for the region. We found a high amount of microseismicity throughout southern Bhutan and almost no seismicity under northern Bhutan and southern Tibet. Our results showed that analysis of data from small in-country seismic networks resulted in new scientific findings. In this case, we found that crust under southern Bhutan brittlely deforming, and there was evidence for strike-slip faulting, supporting previous results for the region.

- **'Crust-Mantle Velocity Structure of S Wave and Dynamic process beneath Burma Arc and its Adjacent Regions'; *HU Jia-Fu, HU Yi-Li, XIA Jin-Yu, CHEN Yun , ZHAO Hong, YANG Hai-Yan; Chinese Journal of Geophysics; Vol.51, No.1, pp: 105-114, 2008***

Abstract

The Rayleigh dispersion data of 530 selected paths crossing Burma Arc and its adjacent regions are determined by applying the MF-FTAN (Matched-Filter Frequency-Time Analysis) technique to long period data recorded at SHIO, CHTO, KMI and LSA stations. The periods of the Rayleigh dispersion are in the range of 10.45_105.03 s. On the basis of this, a method of grid dispersion inversion is proposed to extract pure-path dispersion in each 1_ × 1_ grid from mixed-path dispersion. Then the S wave velocity structure to a depth of 200 km is inverted from pure-path dispersion in each grid, and finally the 3-D velocity structure of S wave is reconstructed beneath Burma Arc and its adjacent regions. The result shows that taking Sagain fault as the boundary, the velocity of crust on the west side of the fault is higher than that on the east side of the fault. The lithosphere thickness in the Indo-Burma areas is in the range of 110_130 km and the S wave velocity at the top of upper mantle is 4.3_4.4 km/s beneath the Indo-Burma regions. However there is a lower-velocity column of uprising mantle about 150_200 km wide beneath Yunnan-Burma-Thailand Block on the east side of Burma Arc. The lithosphere thickness is 70_80 km and the velocity of S wave at the top of the upper mantle is 4.1_4.2 km/s in the area. On the other hand, the S wave velocity structure shows an NS (north-south) variation, this feature corresponds well to the distribution of earthquake sources, strikes of the faults and volcanoes.

Key words Burma Arc, S wave velocity, Dynamic process, Plate subduction

- **'Recent seismicity in Northeast India and its adjoining region'; *Kiran K.Singh Thingbaijam, Sankar K.Nath, Abhimanyu Yadav, Abhishek Raj, M.Yanger Walling, William K.Mohanty; J. Seismol 12:107-123, 2008; DOI 10.1007/s10950-007-9074-y***

Abstract

Recent seismicity in the northeast India and its adjoining region exhibits different earthquake mechanisms–predominantly thrust faulting on the eastern boundary, normal faulting in the upper Himalaya, and strike slip in the remaining areas. A homogenized catalogue in moment magnitude, M_w, covering a period from 1906 to 2006 is derived from International Seismological Center (ISC) catalogue, and Global Centroid Moment Tensor (GCMT) database. Owing to significant and stable earthquake recordings as seen from 1964 onwards, the seismicity in the region is analyzed for the period with spatial distribution of magnitude of completeness m_t, b value, a value, and correlation fractal dimension DC. The estimated value of m_t is found to vary between 4.0 & 4.8. The a value is seen to vary from 4.47 to 8.59 while b value ranges from 0.61 to 1.36. Thrust zones are seen to exhibit predominantly lower b value distribution while strike-slip and normal faulting regimes are associated with moderate to higher b value distribution. D_c is found to vary from 0.70 to 1.66. Although the correlation between spatial distribution of b value and D_c is seen predominantly negative, positive correlations can also be observed in some parts of this territory. A major observation is the strikingly negative correlation with low b value in the eastern boundary thrust region implying a possible case of extending asperity. Incidentally, application of box counting method on fault segments of the study region indicates comparatively higher fractal dimension, D, suggesting an inclination towards a planar geometrical coverage in the 2D spatial extent. Finally, four broad seismic source zones are demarcated based on the estimated spatial seismicity patterns in collaboration with the underlying active fault networks. The present work appraises the seismicity scenario in fulfillment of a basic groundwork for seismic hazard assessment in this earthquake province of the country.

Keywords b value . a value . Correlation fractal dimension . Northeast India . Seismicity

- **'Subduction of the Indian lithosphere beneath the Tibetan Plateau and Burma'; *Chang Li, Robert D.van der Hilst, Anne S.Meltzer, E.Robert Engdahl; Earth and Planetary Science Letters; Vo. 274, pp. 157-168, 2008***

Abstract

Subduction of the Indian lithosphere under Eurasia plays an important role in the tectonic evolution of the Tibetan plateau and surrounding regions. To improve our knowledge of pertinent mantle structures through tomographic imaging we combine P-wave arrival time data from temporary arrays in Tibet and stations of the Chinese Seismograph Network with reprocessed data from the International Seismological Centre. The new images reveal considerable atial variations in mantle structure along the collission zone, and the horizontal distance over which presumed (continental) Indian lithosphere slides northward beneath the plateau decreased from west (where it underlies the Himalayas and the entire plateau) to east (where no indication is found for present-day underthrusting beyond the Himalayan Block and Indus-Tsangpo suture). *P*-wavespeed appears low in the shallow mantle beneath much of central and eastern Tibet. These observations suggests that Indian lithosphere underlies only the southwestern part of the plateau and that the central and

northeastern part is underlain by lithosphere of Asian origin. The (continental) parts of the Indian plate that currently underthrust or subduct below the plateau appear generally detached from the (oceanic) slab fragments that subduct longer ago and that have been detected deeper in the mantle, except perhaps in the central part of the collission zone (80-90^{0}E). This suggests that ongoing India-Eurasia collission must increasingly be driven by other forces, such as subduction of the Indian plate further west and east (e.g. beneath Indochina). Our images reveal structures associated with eastward subduction along the Burmese arc southeast of the eastern Himalayan syntaxis. The Tengchong volcanic complex in southwest China is marked by slow wave propagation to -150 km depth, suggesting a casual link to subduction along the Burmese arc; the low velocities beneath the Red River fault region extend to greater depth and may be related to upper mantle processes further southeast.

Keywords: Himalaya syntaxis, Namcha Barwa, Tsangpo, Thermochronology

- **'Crust-Mantle velocity structure of S wave and Dynamic process beneath Burma Arc and its adjacent regions'; *HU Jia-Fu, HU Yi-Li, XIA Jin-Yu, CHEN Yun, ZHAO Hong, YANG Hai-Yan; Chinese Journal of Geophysics, Vol. 51, No. 1, pp. 105-114, 2008***

Abstract

The Rayleigh dispersion data of 530 selected paths crossing Burma Arc and its adjacent regions are determined by applying the MF-FTAN (Matched-Filter Frequency-Time Analysis) technique to long period data recorded at SHIO, CHTO, KMI and LSA stations. The periods of the Rayleigh dispersion are in the range of 10.45~105.03 s. On the basis of this, a method of grid dispersion inversion is proposed to extract pure-path dispersion in each $1^0 \times 1^0$ grid from mixed-path dispersion. Then the S wave velocity structure to a depth of 200 km is inverted from pure-path dispersion in each grid, and finally the 3-D velocity structure of S wave is reconstructed beneath Burma Arc and its adjacent regions. The result shows that taking Sagain fault as the boundary, the velocity of crust on the west side of the fault is higher than that on the east side of the fault. The lithosphere thickness in the Indo-Burma areas is in the range of 110~130 km and the S wave velocity at the top of upper mantle is 4.3~4.4 km/s beneath the Indo-Burma regions. However there is a lower-velocity column of uprising mantle about 150~200 km wide beneath Yunnan-Burma-Thailand Block on the east side of Burma Arc. The lithosphere thickness is 70~80 km and the velocity of S wave at the top of the upper mantle is 4.1~4.2 km/s in the area. On the other hand, the S wave velocity structure shows an NS (north-south) variation, this feature corresponds well to the distribution of earthquake sources, strikes of the faults and volcanoes.

Key words Burma Arc, S wave velocity, Dynamic process, Plate subduction

- **'Growth of the Namche Barwa Syntaxis and associated evolution of the Tsangpo Gorge: Constraints from structural and thermochronological data'; *Diane Seward, Jean-Pierre Burg, Tectonophysics; 451, pp. 282-289, 2008***

Abstract

The eastern syntaxis of the Himalaya, Namcha Barwa, is dominated by a north-plunging antiform which began to decompress/grow at approximately 4 Ma. New fission-track anal-

yses on both apatite and zircon, combined with previous geochronological ages, indicate that the Namche Barwa Dome also extended laterally while growing vertically. Zircon fission-track ages range from 17.6 to 0.2 Ma and have a strong relationship to the main faults of the region, including the Tertiary Tsangpo Suture, with the younger ages inside the fault bounds towards the syntaxis core on the Indian Plate and the older ages away from the fault. Apatite ages reveal that the dome has grown laterally and now impinges over the older faulted margin onto the Asian Plate. The dome is traversed by the Tsangpo which has followed the trace of the Suture for over 1300 km from its source to the entrance of the dome near Daria. As the Tsangpo crosses the dome it departs from the Suture but rejoins it some 60 km northeastwards. We construe that the Suture has been displaced by the growing antiform and as a consequence, the antecedent river has been “”dragged”” in a left-lateral scene along the exhuming north-plunging dome. Restoring the Suture to its position prior to 4 Ma reveals a path of the Tsangpo eastwards across the present southwestern position of the Namcha Barwa indentation. This geometric reconstruction implies that the Tsangpo and the Brahmaputra were always one and the same river. In addition, the Tsangpo was tectonically forced into juxtaposition with a tributary of the Jiali-Parlung which it probably then captured. The capture was due to tectonic forcing, in the last 4 Ma, rather than headward retreat of the paleo-Brahmaputra as has been previously suggested.

- **‘Miocene rise of the Shillong Plateau and the beginning of the end for the Eastern Himalaya’;** ***Marin K.Clark, Roger Bilham; Earth and Planetary Science Letters; Vol. 269, Issues 3-4, pp. 337-351, 30 May 2008***

Abstract

A common feature of convergent plate boundaries is the self-organization of strain, exhumation and topography along discrete, arcuate boundaries. Deviations from this geometry can represent first-order changes in stress applied at a plate boundary that must affect how strain is partitioned within the interior of an orogen. The simplicity of the Himalayan fold and thrust belt seen along its central portion breaks down along the eastern extremity of the arc where the 400 km-long Shillong Plateau has developed. This change in strain partitioning affects nearly 25% of the arc and has not previously been considered to be important to the orogen's development. New low-temperature thermochronometry data suggest this structure initiated in mid to late Miocene time, significantly earlier than was previously estimated from the sedimentary record alone. Development of the Shillong Plateau may be linked to a number of kinematic changes within the Himalayan and Burman collision zones that occur at the same time. These events include the onset of E–W extension in central Tibet, eastward expansion of high topography of the Tibetan Plateau, onset of rotation of crustal fragments in southeastern Tibet, and re-establishment of eastward subduction beneath the Indo-Burman ranges. We suggest that the coincidence of these tectonic events is related to the ‘dismemberment’ of the eastern Himalayan arc, signifying a change in regional stress applied along the India–Eurasia–Burma plate boundaries. Discrepancies between vertical long-term faulting rates and geodetically derived far-field convergence rates suggest that the collisional boundary in the eastern Himalayan system may be poorly coupled due to introduction of oceanic and transitional crust into the eastern plate boundary. The introduction of dense material into the plate boundary late in the orogen's history may explain regional changes in the strain field that affect not only the Himalaya, but also the deformation field more than 1000 km into the Tibetan Plateau.

- **‘Site Amplification, Qs, and Source Parametrization in Guwahati Region from Seismic and Geotechnical Analysis; *S.K.Nath, A.Raj, J.Sharma, K.K.S.Thingbaijam, A.Kumar, D.R.Nandy, M.K.Yadav, S.Dasgupta, K.Majumdar, J.R.Kayal, A.K.Shukala, S.K.Deb, J.Pathak, P.J.Hazarika, D.K. Paul and B.K.Bansal; Seismological Research Letters;; Vol. 79, no. 4, pp. 526-539, July-August 2008; doi: 10.1785/gssrl.79.4.526***

Introduction

As devastating earthquakes continue to inflict widespread destruction to life and property and hinder the development of urban areas, the technical and scientific problems of seismic hazard assessment and risk-related issues warrant urgent attention. In this regard, seismologists play a key role in defining the source parameters of earthquakes and estimating the associated site-specific ground motion amplification commonly termed site response. The relevant analyses are usually performed using either recorded ground motion for a handful of seismic events of moderate to large magnitude or by synthesizing stochastic processes based on the observational data. The hazard projection is aimed at a great earthquake or a maximum earthquake or maximum credible earthquake on probabilistically/deterministically defined terms for a seismic zone under investigation. Seismic sources generally are characterized by well-defined physical parameters such as corner frequency f_c, seismic moment M_0, and stress drop $\Delta\sigma$, derived directly from waveform data, *i.e.*, strong ground motion records for events with significant magnitude. On the other hand, site amplification of ground motion is attributed to either the geomorphological features that produce scattering, focusing, or defocusing of incident energy or thick alluvium-filled terrain that causes reverberations due to trapped energy. The potentially severe consequences of this phenomenon have been demonstrated in the damage patterns of several earthquakes, such as the 1985 Michoacan, Mexico, earthquake (Singh *et al.* 1988), the 1988 Armenian earthquake (Borcherdt *et al.* 1989), and the 1989 Loma Prieta earthquake (Hough *et al.* 1990; Borcherdt and Glassmoyer 1992). Another aspect of ground motion analysis or synthesis is the attenuation of seismic waves along the propagation path connecting the earthquake source and the recording site (observatory). The attenuation may be attributed to degradation in the elastic properties such as shear and compressional moduli and the scattering of seismic waves caused …

- **‘Microearthquake Seismology and Seismotectonics of South Asia’; *J.R.Kayal; Springer, 22 August 2008, 524 pages***

Introduction

This volume is the outcome of about 30 years of research in the field of earthquake seismology in various parts of South Asia. It comprehensively deals with plate tectonics and seismic waves in general and earthquake monitoring by permanent and temporary networks for active fault mapping, aftershocks, swarm and induced seismicity investigations in interpolate collision and subduction zones and in intraplate shield region. Data acquisition as well as data analysis are well presented for clear understanding of interpretation with limitations of the techniques. State-of-the art techniques in earthquake location/relocation, fault plane solution, waveform inversion, seismic tomography, fractals etc. are discussed, and the results are interpreted in terms of seismic source processes in the region. A large quantity of seismic data in the Himalaya from western syntaxis, Pamir-Hindu Kush to western (Garhwal) Himalaya, central (Nepal) Himalaya, eastern (Sikkim and Bhutan) Himalaya to the eastern syntaxis and Arunachal Himalaya are analysed to understand seismotectonics of the Himalayan collision zone. The atypical continental plate (Indian continental plate) subduction beneath the Indo-Burma ranges and typical oceanic plate (Indian Oceanic plate) subduction beneath the Andaman-Sumatra arc in Southeast Asia are also examined with the available data. Temporary and permanent microearthquake network data in the peninsular India shield region and in Bangladesh and Sri Lanka shed light on the intraplate tectonics in Southeast Asia.

- **'Collision of the Ganges-Brahmaputra Delta with the Burma Arc: Implications for earthquake hazard'; *Michael S.Steckler, S.Humayun Akhter, Leonardo Seeber; Earth and Planetary Science Letters; Volume 273, Issues 3-4, pp. 367-378, 15 September 2008***

Abstract

We take a fresh look at the topography, structure and seismicity of the Ganges–Brahmaputra Delta (GBD)–Burma Arc collision zone in order to reevaluate the nature of the accretionary prism and its seismic potential. The GBD, the world's largest delta, has been built from sediments eroded from the Himalayan collision. These sediments prograded the continental margin of the Indian subcontinent by ∼ 400 km, forming a huge sediment pile that is now entering the Burma Arc subduction zone. Subduction of oceanic lithosphere with > 20 km sediment thickness is fueling the growth of an active accretionary prism exposed on land. The prism starts at an apex south of the GBD shelf edge at ∼ 18°N and widens northwards to form a broad triangle that may be up to 300 km wide at its northern limit. The front of the prism is blind, buried by the GBD sediments. Thus, the deformation front extends 100 km west of the surface fold belt beneath the Comilla Tract, which is uplifted by 3–4 m relative to the delta. This accretionary prism has the lowest surface slope of any active subduction zone. The gradient of the prism is only ∼ 0.1°, rising to ∼ 0.5° in the forearc region to the east. This low slope is consistent with the high level of overpressure found in the subsurface, and indicates a very weak detachment. Since its onset, the collision of the GBD and Burma Arc has expanded westward at ∼ 2 cm/yr, and propagated southwards at ∼ 5 cm/yr. Seismic hazard in the GBD is largely unknown. Intermediate-size earthquakes are associated with surface ruptures and fold growth in the external part of the prism. However, the possibility of large subduction ruptures has not been accounted for, and may be higher than generally believed. Although sediment-clogged systems are thought to not be able to sustain the stresses and strain-weakening behavior required for great earthquakes, some of the largest known earthquakes have occurred in heavily-sedimented subduction zones. A large earthquake in 1762 ruptured ∼ 250 km of the southern part of the GBD, suggesting large earthquakes are possible there. A large, but poorly documented earthquake in 1548 damaged population centers at the northern and southern ends of the onshore prism, and is the only known candidate for a rupture of the plate boundary along the subaerial part of the GBD–Burma Arc collision zone.

- **'Tom La Touche and the Great Assam Earthquake of 12 June 1897: Letters from the Epicenter'; *Roger Bilham; Seismological Research Letters, May/June 2008, v. 79, p. 426-437***

Abstract

Richard Dixon Oldham's classic memoir on the great M_w = 8.1 Assam earthquake of 1897 is seminal for its seismological observations, insights, and conclusions (Oldham 1899). Teleseismic arrivals of waves from Shillong led Oldham (1858–1936) to distinguish the three types of seismic waves and eventually to recognize from them the distinctive presence of the Earth's core. Oldham, however, did not feel the earthquake. He had left the Calcutta office of the Geological Survey of India (GSI) in the care of his colleague Thomas Henry Digges La Touche (1856–1938) two weeks previously (see figure 1). Now recently discovered letters written by La Touche from Calcutta and the epicentral region to his wife, Nancy, provide a firsthand, day-by-day account of the post-earthquake investigation and include a seismogram from an instrument that he constructed in the field at a cost of "less than sixpence" from pieces of tin, a suspended boulder, a glass bead, and a bamboo needle that scratched a glass plate (LaTouche papers, 1880–1913). In his memoir Oldham notes that he focused his team of geologists on the physics of the earthquake. Their reports were submitted "under specific instructions to report only on the facts observed, and to refrain from any expressions of opinion as to the conclusions to be drawn, as this could only be profitably done after a review of the whole of the facts, of which only part could become known to each individually." (Oldham 1899, p.257). He deduced from their observations that local accelerations in the earthquake had exceeded 1 g, that velocities had exceeded 3 m/s, that electrical currents in the ground had accompanied aftershocks, that postseismic crustal deformation continued to deform the plateau in the year following the earthquake, and that many of the largest aftershocks lay 15 km beneath the plateau. …

- **'Orogen-parallel, active left-slip faults in the Eastern Himalaya: Implications for the growth mechanism of the Himalayan Arc'; *Dewei Li, An Yin; Earth and Planetry Science Letters; 274, pp. 258-267, 2008***

Abstract

One of the key issues about the evolution of the Himalayan origin is how its map-view curvature has changed with time. Some researchers propose that the arc curvature has decreased due to arc-perpendicular rifting while others suggest that it has increased due to arc-parallel strike-slip faulting. To quantify this problem, we conducted field mapping, geomorphologic analysis of active structures, and dating of Pliocene-Quaternary sedimentary units in southeastern Tibet. This study reveals the existence of a ~100-km wide and >500-km long, east-striking left slip fault zone in the eastern Himalaya. The left-slip faults initiated prior to 3-4 Ma and have a total left-slip rate of 4-8 mm/yr across the fault zone. Although the left-slip rate in the eastern Himalaya is broadly comparable to the right-slip rate across the western Himalaya arc, the distributed and short-segmented geometry of left-slip faulting in the eastern Himalaya contacts sharply to the discrete geometry of right-slip faulting in the western Himalaya. The different geometry may have resulted from an earlier initiation and a greater magnitude of fault motion on the right-slip faults, which implies that asymmetric eastward extrusion of western Tibet across the Himalayan arc was a dominant process in the earlier Himalayan history. This was replaced by orodinal bending since 4 Ma, producing symmetric right-slip and left-slip faulting in the western and eastern Himalaya, respectively.

- **'A GIS based tectonic map of northeastern India'; *Saurabh Baruah, Devajit Hazarika; Current Science, Vol. 17695, No. 2, 25 July 2008***

Northeastern India (NER) and its adjoining areas are one of the most complex tectonic provinces in the world. Various tectonic features with their complicated geotectonic set-up influence the NER to be seismically very active, as it revealed from smaller-magnitude earthquakes that release sizable energy daily. During the last more than 100 years, the region has experienced 20 large ($M \geq 7.0$) and two great earthquakes ($M \geq 8.5$); the two large earthquakes occurred on 12 june 1897 and 15 August 1950. The Eastern Himalayan collision belt to the north consisting of the Main Boundary Thrust (MBT) and Main Central Thrust (MCT); the Indo-Burma subduction zone to the east; the Shillong plateau, the Mikir Hills and the Assam valley-jawed between the Himalayan arc and Burma arc, form the major tectonic domains of NER. In order to obtain a comprehensive idea about geologic and tectonic settings of NER, it is essential to prepare a tectonic map based on geologic field observations.

- **'Simulation of Strong Ground Motion During the 1950 Great Assam Earthquake'; *S.T.G.Raghukanth; Pure and Applied Geophysics, 165 (2008) 1761-1787; DOI 10.1007/s00024-008-0403-z***

Abstract

In this paper, ground motion during the Independence Day earthquake of August 15, 1950 (M_w 8.6, BEN-MENAHEM *et al*., 1974) in the northeastern part of India is estimated by seismological approaches. A hybrid simulation technique which combines the low frequency ground motion simulated from an from an analytical source mechanism model with the stochastically simulated high-frequency components is used for obtaining the acceleration time histories. A series of ground motion simulations are carried out to estimate the peak ground acceleration (PGA) and spectral acceleration at important cities and towns in the epicentral region. One sample PGA distribution in the epicentral region encompassing the epicenter is also obtained. It is found that PGA in the epicentral region has exceeded 1 g during this earthquake. The estimated PGA's are valued to the extent possible using the MMI values. The simulated acceleration time histories can be used for the assessment of important engineering structures in northeastern India.

Keywords: Strong ground motion, PGA, stochastic finite fault model, hybrid technique, response spectra

- **'Recent seismicity in Northeast India and its adjoining region'; *Kiran Kumar Singh Thingbaijam, Sankar Kumar Nath, Abhimanyu Yadav, Abhishek Raj, M.Yanger Walling, William Kumar Mohanty; J. Seismol , 12: 107-123, 2008; DOI 10.1007/s10950-007-9074-y***

Abstract

Recent seismicity in the northeast India and its adjoining region exhibits different earthquake mechanisms – predominantly thrust faulting on the eastern boundary, normal faulting in the upper Himalaya, and strike slip in the remaining areas. A homogenized catalogue in moment magnitude, M_w, covering a period from 1906 to 2006 is derived from International Seismological Centre (ISC) catalogue, and Global Centroid Moment Tensor (GCMT) database. Owing to significant and stable earthquake recording as seen from 1964 onwards, the seismicity in the region is analyzed for the period with spatial distribution of magnitude of completeness m_t *b* value, *a* value, and correlation fractal dimension D_C. The estimated value of m_t is found to vary from 4.47 to 8.59 while *b* value ranges from 0.61 to

1.36. Thrust zones are seen to exhibit predominantly lower *b* value distribution while strike-slip and normal faulting regimes are associated with moderate to higher *b* value distribution. D_C is found to vary from 0.70 to 1.66. Although the correlation between spatial distribution of *b* value and D_C is seen predominantly negative, positive correlation can also be observed in some parts of the territory. A major observation is the strikingly negative correlation with low b value in the eastern boundary thrust region implying a possible case of extending asperity. Incidentally, application of box counting method on fault segment of the study region indicates comparatively higher fractal dimension, D, suggesting an inclination towards a planar geometrical coverage in the 2D spatial extent. Finally, four broad seismic source zones are demarcated based on the estimated spatial seismicity patterns in collaboration with the underlying active fault networks. The present work appraises the seismicity scenario in fulfilment of a basic groundwork for seismic hazard assessment in this earthquake province of the country.

Keywords: b value, a value, Correlation fractal dimension, Northeast India, Seismicity

- **'Coupling Between Seismic Activity and Hydrogeochemistry at the Shillong Plateau, Northeastern India'; *Alasdair Skelton, Lillemor Claesson, Govinda Chakrapani, Chandan Mahanta, Joyanto Routh, Magnus Moorth, Param Khanna; Terrestrial Fluids, Earthquakes and Volcanoes. Pageoph Topical volume, pp. 45-61, 2008***

Abstract

Transient hydrogeochemical anomalies were detected in a granite-hosted aquifer, which is located at a depth of 110 m, north of the Shillong Plateau, Assam, India, where groundwater chemistry is mainly buffered by feldspar alteration to Kaolinite. Their onsets preceded moderate earthquakes on December 9, 2004 (M_w = 5.3) and February 15, 2005 (M_w = 5.0), respectively, 206 and 213 km from the aquifer. The ratio [Na+K]/Si, Na/K and [Na+K]/Ca, conductivity, alkalinity and chloride concentration began increasing 3-5 weeks before the M_w = 5.3 earthquake. By comparison with field, experimental and theoretical studies, we interpret a transient switchover between source aquifers, which induced an influx of groundwater from a second aquifer, where groundwater chemistry was dominantly buffered by the alteration of feldspar to smectite. This could have occurred in response to fracturing of a hydrogeological barrier. The ratio Ba/Sr began decreasing 3-6 days before the M_w = 5.0 earthquake. We interpret a transient switchover to anorthite dissolution caused by exposure of fresh plagioclase to groundwater interaction. This could have been induced by microfracturing, locally within the main aquifer. By comparison with experimental studies of feldspar dissolution, we interpret that hydrogeochemical recovery was facilitated by groundwater interaction and clay mineralization which could have been coupled with fracture sealing. The coincidence in timing of these two hydrogeochemical events with the only two $M_w \geq 5$ earthquakes in the study area argues in favor of cause-and-effect seismic-hydrogeochemical coupling. However, reasons for ambiguity include the lack of similar hydrogeochemical anomalies coupled with smaller seismic events near the monitoring station, the >200 km length scale of inferred seismic-hydrogeochemical coupling, and the potential for far-field effects related to the Great Sumatra-Andaman Island Earthquake of December 26, 2004.

- **‘Litho-tectonic Sequence and their Regional Correlation along the Lohit and Dibang Valleys, Eastern Arunachal Pradesh’; *D.K.Mishra; Journal Geological Society of India; Vol. 73, , pp. 213-219, February 2009***

Abstract

Geological mapping between Lohit and Dibang valleys of eastern Arunachal Pradesh reveals the existence of five thrust bound tectonostratigraphic units. In ascending structural order from SW to NE these are: (1) Sewak Group, (2) Lalpani Group, (3) Mayodiya Group, (4) Tidding Formation and (5) Lohit plutonic complex. This differs from previous mapping, because the three tectonostratigraphic units (Sewak, Lalpani and Mayodia) were grouped under a single unit, referred as the Mishmi crystallines. The low-grade metamorphic of the Sewak Group occur at two different tectonic levels, one as persistent belt in the foothills and the other in the tectonic window beneath the high-grade metamorphic of the Mayodiya thrust sheet in the Higher Himalaya. The Tidding suture is the southeastern extension of the Indus-Tsangpo suture zone.

Keywords: Lohit valley, Dibang valley, Arunachal Pradesh, Himalaya

- **‘Seismic a-value and the Spatial Stress-Level Variation in Northeast India’; *Prosanta Kumar Khan, Manoj Ghosh and V.K.Srivastava; J. Ind. Geophys. Union; Vol.13, No.2, pp.49-62, April, 2009***

Abstract

The present study aims at understanding the variation of stress level vis-à-vis crustal heterogeneity based on seismicity distribution and a-values in the northeast part of India. The study area lies between latitude 24.5° and 27.2°N and longitude 89° and 96°E, and bounded by major thrust sheets of the Himalaya and Indo-Burman Ranges towards north and east. A crustal scale transcurrent Dauki fault demarcates its southern boundary, while the Yamuna lineament and the tail end of the Brahmaputra and Ganga rivers encompass all along the eastern boundary. Regarding seismicity, the area recorded several moderate to large earthquakes during the historical past, and the most damaging well-known 1897 Shillong earthquake was famous for its own kind. In the present study, we have analysed a-values using a comprehensive database recorded by the network jointly run by RRL, Jorhat and NGRI, Hyderabad. A total of 3655 events were used under the present study. Seismicity distribution shows three major clusters of higher concentration over the study area. Contours based on estimated a-values over 240 square grids of dimension 0.6°×0.6° show wide variation. However, the near uniform a-values over specific five zones allowed us for depth probing of a-values. The higher a-values in different layers towards the eastern part are correlated with the reactivation of fractures at lower stress level, whereas the minimum a-values with higher gradient towards the southwestern part of the study area can be associated with higher stress level and linked to the thinner crustal root, and uplifted Moho. The area between the Main Boundary Himalayan Thrust and the Shillong Plateau account higher a-values, and might be indicating brittle failure of the weaker crust at lower stress level around the Tura region. Finally, it may be inferred that the seismicity of the northeast India is due to tectonic adjustment of different geomorphologic features presumably caused by the orogenic processes in the Himalaya and Indo-Burman Ranges.

- **‘Modeling of Strong-Motion Data in Northeastern India: *Q*, Stress Drop, and Site Amplification; *S.T.G.Raghukanth and Surendra Nadh Somala; Bulletin of the Seismological Society of America, Vol. 99, No. 2A, pp. 705-725, April 2009, doi: 10.1785/0120080025***

Abstract

In this article point source seismological model is used to model the available strong-motion accelerograms in northeastern India. Key seismic parameters such as Quality factor (*Q*-value), Kappa factor (k_0), site amplification, and stress drop are derived from the strong-motion data. A total of 111 three-component records coming from seven earthquakes with magnitudes ranging from M_w 5.2 to 7.2 are used in obtaining the source and path parameters. The *Q*-value of the Indo-Burma tectonic domain, which is a subduction zone, is obtained as 431 $f^{0.7}$ .For the Bengal basin-Shillong plateau region the Quality factor is estimated as $224f^{0.93}$. The Kappa factors for vertical and horizontal components are obtained as 0.013 and 0.033 for soft rock type sites. For firm ground sites k_0 is estimated as 0.025 for vertical and 0.041 for horizontal components, respectively. The site amplification functions for soft rock and firm ground conditions are found from the horizontal-to-vertical ratio. The obtained stress drop of the seven events lie between 128 and 282 bars. The source parameters obtained in this study provide a useful framework for working out ground-motion relations in north-eastern India.

- **‘Modelling of sPn phases for reliable estimation of focal depths in northeastern India’; *E.Uma Devi, N.Purnachandra Rao and M.Ravi Kumar; Current Science, Vol. 96, No. 9, 10 May 2009***

Abstract

In North East India, reliable estimation of earthquake focal depths has always been a problem, owing to paucity of permanent regional seismic stations, constraints on good quality data and lack of crustal models in a complex tectonic terrane. The depth estimations by international agencies, mostly based on teleseismic data, vary from very shallow to even 60 km, suggestive of earthquake occurrence in the upper mantle region. However, modelling of sPn phases in earthquake waveforms that are highly sensitive to focal depths indicates that the earthquake locations are probably well within the crustal layer. The current method has the advantage that *dt*, the travel time difference between sPn and Pn, remains constant for a wide range of source-station distances, and hence enables easy identification of the sPn phase, while providing direct and accurate estimate of the focal depth. The approach is also insensitive to location errors and variations in crustal models, a useful feature especially while dealing with sparse data with high location errors. In the present study, earthquakes in the magnitude range 3.0–4.0 recorded by a network of nine broadband stations in NE India have been analysed. Consistent *dt* values at different stations were observed for each event, enabling precise depth estimation mostly within □1 or 2 km. In general, depths of 15–20 km in the Shillong plateau region, >20 km in the Sylhet basin region and shallow <10 km in the eastern Himalayan foothills are confirmed, that correlate well with the local tectonics. Further, we propose that the flat characteristics of the *dt* curve that begin to change for earthquakes below the Moho, can be a potential tool for discriminating between crustal and sub-crustal earthquakes, as well as for delineation of the Moho using dense regional seismic networks in future.

Keywords: Crustal models, earthquakes, focal depth, reliable estimation, sPn phase.

- **'Seismic Vulnerability vis-à-vis Active Faults in the Himalaya - Hindukush Belt'; *D. D. Joshi and A. A. Khan; Journal of South Asia Disaster Studies; Vol. 2 No. 1 June 2009***

Abstract

Himalaya - Hindukush, the world`s youngest mountain belt envelopes the SAARC region all along its northern fringe. These lofty mountain ranges are spread over Afghanistan in the west and Bangladesh in the east across Pakistan, India, Nepal and Bhutan. These mountains are a boon to the socio-economic growth of this region as they control the climate, water resources and monsoon of the region. At the same time being very young in age the Himalaya is still isostatically imbalanced and geodynamically active due to northward push of the Indian Plate towards the Eurasian plate. Due to under-thrusting of the lndian plate beneath the Eurasian plate stresses are generated. When these stresses reach a critical stage, they are released in the form of earthquakes. The magnitude of these earthquakes is governed by the amount of stresses accumulated within the fault zones. The south Asian region has a history of catastrophic earthquakes which have rocked the region time and again. There have been huge losses of life and property in- spite the low population density in the olden times when many of these earthquakes have taken place. A great or major earthquake in the modern times, in this region may create havoc with huge loss of life and property due to high population density and rapidly developing infrastructure. Earthquake vulnerability assessment of an area depends on major geological/geophysical components viz. mapping and characterizing active faults; seismic microzonation; assessment of seismicity induced landslides, and, revisiting seismic history of the area. The paper presents a review of the seismotectonics and earthquake vulnerability of the Hiamlaya-Hindukush belt. The present status with in the SAARC countries as regards to their seismic hazard assessment is also discussed.

Keywords: Himalaya-Hindukush, Seismic vulnerability, Active Fault, Earthquake

- **'Attenuation of coda waves in the Northeastern Region of India'; *Devajit Hazarika, Saurabh Baruah, Naba Kumar Gogoi; J Seismol (2009) 13: 141-160; DOI 10.1007/s10950-008-9132-0***

Abstract

Coda wave attenuation quality factor Qc is estimated in the northeastern region of India using 45 local earthquakes recorded by regional seismic network. The quality factor Qc was estimated using the single backscattering model modified by Sato (J Phys Earth 25: 27-41, 19770, in the frequency range 1-18 Hz. The attenuation and frequency dependence for different paths and the correlation of the results with geotectonics of the region are described in this paper. A total of 3,890 Qc measurements covering 187 varying paths are made for different lapse time window of 20, 30, 40, 50, 60, 70, 80, and 90 s in coda wave. The magnitudes of the analyzed events range from 1.2 to 3.9 and focal depths range between 7 and 38 km. The source-receiver distances of the selected events range between 16 and 270 km. For 30-s duration, the mean values of the estimated Qc vary from 50 $\pm$ 12 (at 1 Hz) to 2,078 $\pm$ 211 (at 18 Hz) for the Arunachal Himalaya, 49 $\pm$ 14 (at 1 Hz) to 2,466 $\pm$ 197 (at 18 Hz) for the Indo-Burman and 45 $\pm$ 13 (at 1 Hz) to 2,069 $\pm$ 198 (at 18 Hz) for Shillong group earthquakes. It is observed that Qc increases with frequency portraying an average attenuation relation Qc + 52.315 $\pm$ 1.07$f^{(1.32\pm0.036)}$ for the region. Moreover, the pattern of Qc^{-1} with frequency is analogous to the estimates obtained in other tectonic areas in the world, except with the observation that the Qc^{-1} is much higher at 1 Hz for the northeastern region. The Qc^{-1} is about $10^{-1.8}$ at 1 Hz and decreases to about $10^{-3.6}$ at 18 Hz indicating clear frequency dependence. Pertaining to the spatial distribution of Qc values, Mikir Hills and western part of Shillong Plateau are characterized by lower attenuation.

Keywords: Qc, Coda waves, Single backscattering, Frequency dependence, Northeastern India

- **The great 1950 Assam Earthquake revisited: Field evidences of liquefaction and search for paleoseismic events'; *D.V.Reddy, P.Nagabhusshanam, Devendra Kumar, B.S.Sukhija, P.J.Thomas, Anand K.Pandey, R.N.Sahoo, G.V.Ravi Prasad, K.Datta; Tectonophysics; 474, 463-472, 2009***

Abstract

Extensive field investigations were carried out for the first time in the meizoseismal area of the great 1950 Assam Earthquake aimed at exploring the paleoseismic history of the NE Indian region through documentation of liquefaction features and radiocarbon (^{14}C) dating. Trenching at more than a dozen locations along the Burhi Dihing River valley and within the alluvial fans adjoining the Brahmaputra and Dibang Rivers resulted in the identification of more than a dozen very prominent liquefaction features (sand dykes, sills, sand blows etc.) as evidences of large to great earthquakes. ^{14}C dating of the organic material associated with some of the features indicates a paleoseismic record of about 500 yrs archived by the sediments in the region. Compelling geological evidence(s) of the great 1950 earthquake are well constrained by ^{14}C dating. Out of the two historically reported seismic events (1548 AD and 1697 AD) from this region. ^{14}C dating could constrain the 1548 AD event through not distinctly. Further studies using combined ^{14}C and OSL dating may better constrain the seismochronology of the study region.

- **'The Tectonic Map of India and Contiguous Areas'; *T.S.Balakrishnan, P.Unnikrishnan and A.V.S.Murthy; Journal Geological Society of India; Vol. 74, pp. 158-170, August 2009***

Abstract

The existing tectonic maps of India produced by the GSI and ONGC are largely based on the geological map of India combined with the topographic maps and the lineations evident in satellite pictures of the earth's surface. Broadly speaking, these consider only features observed on the surface of the earth. The third dimension is not much in evidence. The introduction of 3D-geophysical data into these maps ensured a substantial advance in the study of the crustal structure at depth. The new tectonic map is the result of this integration. Apart from India, the new map covers Pakistan, S.Tibet, Nepal, Myanmar, Sri Lanka, Maldives, the Arabian Sea, Bay of Bengal and the Andaman-Nicobar islands. Geophysical data used largely consists of gravity anomalies. To these are added information from limited magnetic and seismic measurements and topographic data. The result is a depiction of the subsurface as a member of crustal blocks of different orientations and dimensions fused together to form the Indian plate. This paper gives only a description of the results obtained by the analysis and

does not bring into play the details of the data used in the analysis. Such an exercise is proposed to be carried out in a succeeding Memoir.

Keywords: 3D-geophysical data, Tectonic map, India

- **'Seismotectonics in Northeast India: a stress analysis of focal mechanism solutions of earthquakes and its kinematic implications'; *Jacques Angelier, and Saurabh Baruah; Geophys. J. Int., 178, 303-326, 2009***

SUMMARY

In Northeast India, threemajor plates interact along two convergent boundaries: the Himalayas and the Indo–Burma Ranges, which meet at the Assam Syntaxis. To clarify this tectonic interaction and the underlying dynamics, we determine the regional seismotectonic stress from the stress inversion of 285 double couple focal mechanism solutions of earthquakes with an average magnitude of 5. We then compare the reconstructed stress regimes with the available information about geodetically determined relative displacements. North–south compression, in a direction consistent with India–Eurasia convergence, prevails in the whole area from the Eastern Himalayas to the Bengal Basin, through the Shillong–Mikir Massif and the Upper Assam Valley. E–W extension in Tibet is related to this N–S India–Eurasia convergence. Not only does the major N–S compression affect the outer segments of the Indo–Burma Ranges, it also extends into the descending slab of Indian lithosphere below these ranges, although stresses at depth are controlled by bending of the slab beneath the Burmese arc. The existence of widespread N–S compression in the Bengal Basin, far away from the Himalayan front, is compatible with the previously proposed convergence between a Shillong–Mikir–Assam Valley block and the Indian craton. E–W compression inside this block supports the hypothesis of a component of eastward extrusion. Stress inversion of focal mechanism solutions in the Indo–Burma Ranges reveals a complex stress pattern. The Burmese arc and its underlying lithosphere experience nearly arc- perpendicular extension with ESE–WNW trends in the northernmost, NE-trending segment and ENE–WSW trends in the main N–S arc segment. Such extensional stress, documented from many arcs, is likely a response to pull from and bending of the subducting plate. At the same time, the Indo–Burma Ranges are under compression as a result of oblique convergence between the Sunda and Indian plates. The maximum compressive stress rotates from NE–SW across the inner and northern arc to E–W near the Bengal Basin. This rotation is consistent with the deformation partitioning reflected in the rotation of relative displacement vectors, from a SSW-directed Sunda–Burma motion to a WSW-directed Burma–India motion. As a consequence of this partitioning, the major belt-parallel fault zones show a variety of movements across the main N–S arc segment, from right-lateral slip in the inner ranges to oblique reverse-dextral slip in the outer ranges and pure thrusting in the westernmost foreland belt.

Key words: Earthquake dynamics; Seismicity and tectonics; Intra-plate processes; Continental neotectonics; Dynamics: seismototectonics; Asia.

- **'Paleoseismological evidence of surface faulting along the northeastern Himalayan front, India: Timing, size, and spatial extent of great earthquakes'; *Senthil Kumar, Steven G. Wesnousky,R. Jayangondaperumal, T. Nakata, Y. Kumahara, and Vimal Singh; Journal Of Geophysical Research, Vol. 115, 2010, B12422, doi:10.1029/2009JB006789***

Abstract

[1] The ∼2500 km long Himalayan arc has experienced three large to great earthquakes of Mw 7.8 to 8.4 during the past century, but none produced surface rupture. Paleoseismic studies have been conducted during the last decade to begin understanding the timing, size, rupture extent, return period, and mechanics of the faulting associated with the occurrence of large surface rupturing earthquakes along the ∼2500 km long Himalayan Frontal Thrust (HFT) system of India and Nepal. The previous studies have been limited to about nine sites along the western two-thirds of the HFT extending through northwest India and along the southern border of Nepal. We present here the results of paleoseismic investigations at three additional sites further to the northeast along the HFT within the Indian states of West Bengal and Assam. The three sites reside between the meizoseismal areas of the 1934 Bihar-Nepal and 1950 Assam earthquakes. The two westernmost of the sites, near the village of Chalsa and near the Nameri Tiger Preserve, show that offsets during the last surface rupture event were at minimum of about 14 m and 12 m, respectively. Limits on the ages of surface rupture at Chalsa (site A) and Nameri (site B), though broad, allow the possibility that the two sites record the same great historical rupture reported in Nepal around A.D. 1100. The correlation between the two sites is supported by the observation that the large displacements as recorded at Chalsa and Nameri would most likely be associated with rupture lengths of hundreds of kilometers or more and are on the same order as reported for a surface rupture earthquake reported in Nepal around A.D. 1100. Assuming the offsets observed at Chalsa and Nameri occurred synchronously with reported offsets in Nepal, the rupture length of the event would approach 700 to 800 km. The easternmost site is located within Harmutty Tea Estate (site C) at the edges of the 1950 Assam earthquake meizoseismal area. Here the most recent event offset is relatively much smaller (<2.5 m), and radiocarbon dating shows it to have occurred after A.D. 1100 (after about A.D. 1270). The location of the site near the edge of the meizoseismal region of the 1950 Assam earthquake and the relatively lesser offset allows speculation that the displacement records the 1950 Mw 8.4 Assam earthquake. Scatter in radiocarbon ages on detrital charcoal has not resulted in a firm bracket on the timing of events observed in the trenches. Nonetheless, the observations collected here, when taken together, suggest that the largest of thrust earthquakes along the Himalayan arc have rupture lengths and displacements of similar scale to the largest that have occurred historically along the world's subduction zones.

- **'Attenuation of high-frequency seismic waves in northeast India'; *Simanchal Padhy, N. Subhadra; Geophysical Journal International; 181(1), pp. 453-467, 02/2010; DOI;10.1111/j.1365-246X.2010.04502.x***

Abstract

We studied attenuation of S and coda waves, their frequency and lapse time dependencies in northeast India in the frequency range of 1–24 Hz. We adopted theories of both single and multiple scattering to bandpass-filtered seismograms to fit coda envelopes to estimate Q for coda waves (QC) and Q for S-waves (QS) at five central frequencies of 1.5, 3, 6, 12 and 24 Hz. The selected data set consists of 182 seismograms recorded at ten seismic stations within epicentral distance of 22–300 km in the local magnitude range of 2.5–5.2. We found that with the increase in lapse time window from 40 to 60 s, Q0 (QC at 1 Hz) increases from 213 to 278, while the frequency dependent coefficient n decreases from 0.89 to 0.79. Both QC and QS increase with frequency. The average value of QS obtained by using coda normalization method for NE India has the power law form of (96.8 ± 21.5)f(1.03±0.04) in 1–24 Hz. We adopted energy flux model (EFM) and diffusion model for the multiple scattered wave energy in three-dimensions. The results show that the contribution of multiple scattering dominates for longer lapse time close to or larger than mean free time of about 60 s. The estimates of QC are overestimated at longer lapse time by neglecting the effects of multiple scattering. Some discrepancies have been observed between the theoretical predictions and the observations, the difference could be due to the approximation of the uniform medium especially at large hypocentral distances. Increase in QC with lapse time can be explained as the result of the depth dependent attenuation properties and multiple scattering effect.

- **'Himalayan tectonic model and the great earthquakes: an appraisal'; *J.R.Kayal; Geomatics, Natural Hazards and Risk; Vol. 1, No. 1, pp. 51-67, March 2010***

Abstract

The best known conceptual tectonic model of the Himalayan Seismic Belt (HSB) suggests that the Basement Thrust Front (BTF) lies beneath the Main Central Thrust (MCT) with a prominent 'ramp'. The 'ramp' is viewed as a geometrical asperity that accumulates the stress due to the Himalayan collision tectonics, and it has been suggested that the past great earthquakes occurred on the plane of detachment. The plane of detachment is the interface between the Indian shield and the Himalayan sedimentary wedge, also known as the Main Himalayan Thrust (MHT). The recent earthquake data from the local permanent and temporary network and a re-examination of source processes of the great earthquakes in the Himalaya, however, do not support this model for the entire HSB. The four known instrumentally recorded great (M ~8.0-8.7) earthquakes in the foothills of the Himalaya in India, from west to east – the 1905 Kangra, 1934 Bihar, 1897 Shillong and the 1950 Assam earthquakes – occurred by different tectonic processes, and possibly none can be explained as a plane of detachment tectonic processes, and possibly none can be explained as a plane of detachment earthquake: each occurred in its own unique complex tectonic environment. The 1905 as well as the 1934 great event is argued to be a shield earthquake rather than a Himalayan earthquake and it occurred by pop-up tectonics of the Shillong plateau. The 1950 great event is argued to be caused by transform tectonics in the eastern syntaxis zone rather than by thrusting on the plane of detachment.

- **'Geologic correlation of the Himalayan orogen and Indian craton: Part 1. Structural geology, U-Pb zircon geochronology, and tectonic evolution of the Shillong Plateau and its neighboring regions in NE India'; *An Yin, C.S. Dubey, A.A.G. Webb, T.K. Kelty, M. Grove, G.E. Gehrels, and W.P. Burgess; GSA Bulletin; v. 122; no. 3/4; p. 336–359, March/April 2010***

Abstract

The Himalayan orogen has experienced intense Cenozoic deformation and widespread metamorphism, making it difficult to track its initial architecture and the subsequent deformation path during the Cenozoic India-Asia collision. To address this issue, we conducted structural mapping and U-Pb zircon geochronology across the Shillong Plateau, Mikir Hills, and Brahmaputra River Valley of northeastern India, located 30–100 km south of the eastern Himalaya. Our work reveals three episodes of igneous activity at ca. 1600 Ma, ca. 1100 Ma,

and ca. 500 Ma, and three ductile-deformation events at ca. 1100 Ma, 520–500 Ma, and during the Cretaceous. The first two events were contractional, possibly induced by assembly of Rodinia and Eastern Gondwana, while the last event was extensional, possibly related to breakup of Gondwana. Because of its proximity to the Himalaya, the occurrence of 500 Ma contractional deformation in northeastern India implies that any attempt to determine the magnitude of Cenozoic deformation across the Himalayan orogen using Proterozoic strata as marker beds must first remove the effect of early Paleozoic deformation. The lithostratigraphy of the Shillong Plateau established by this study and its correlation to the Himalayan units imply that the Greater Himalayan Crystalline Complex may be a tectonic mixture of Indian crystalline basement, its Proterozoic-Cambrian cover sequence, and an early Paleozoic arc. Although the Shillong Plateau may be regarded as a rigid block in the Cenozoic, our work demonstrates that distributed active left-slip faulting dominates its interior, consistent with earthquake focal mechanisms and global positioning system velocity fields across the region.

- **'Geologic correlation of the Himalayan orogen and Indian craton: Part 2. Structural geology, geochronology, and tectonic evolution of the Eastern Himalaya'; *An Yin, C.S. Dubey, T.K. Kelty, A.A.G. Webb, T.M. Harrison, C.Y. Chou, and Julien Célérier; GSA Bulletin; v. 122; no. 3/4; p. 360–395, March/April 2010***

Abstract

Despite being the largest active collisional orogen on Earth, the growth mechanism of the Himalaya remains uncertain. Current debate has focused on the role of dynamic inter action between tectonics and climate and mass exchanges between the Himalayan and Tibetan crust during Cenozoic India-Asia collision. A major uncertainty in the debate comes from the lack of geologic information on the eastern segment of the Himalayas from 91°E to 97°E, which makes up about one-quarter of the mountain belt. To address this issue, we conducted detailed field mapping, U-Pb zircon age dating, and 40Ar/39Ar thermo chronology along two geologic traverses at longitudes of 92°E and 94°E across the eastern Himalaya. Our dating indicates the region experienced magmatic events at 1745–1760 Ma, 825–878 Ma, 480–520 Ma, and 28–20 Ma. The first three events also occurred in the northeastern Indian craton, while the last is unique to the Himalaya. Correlation of magmatic events and age-equivalent lithologic units suggests that the eastern segment of the Himalaya was constructed in situ by basement-involved thrusting, which is inconsistent with the hypothesis of high-grade Himalaya rocks derived from Tibet via channel flow. The Main Central thrust in the eastern Himalaya forms the roof of a major thrust duplex; its northern part was initiated at ca. 13 Ma, while the southern part was initiated at ca. 10 Ma, as indicated by 40Ar/39Ar thermochronometry. Crustal thickening of the Main Central thrust hanging wall was expressed by discrete ductile thrusting between 12 Ma and 7 Ma, overlapping in time with motion on the Main Central thrust below. Restoration of two possible geologic cross sections from one of our geologic traverses, where one assumes the existence of pre-Cenozoic deformation below the Himalaya and the other assumes fl at-lying strata prior to the India- Asia collision, leads to estimated shortening of 775 km (~76% strain) and 515 km (~70%strain), respectively. We favor the presence of significant basement topography below the eastern Himalaya based on projections of early Paleo zoic structures from the Shillong Plateau (i.e., the Central Shillong thrust) located ~50 km south of our study area. Since northeastern India and possibly the eastern Himalaya both experienced early Paleozoic contraction, the estimat-

ed shortening from this study may have resulted from a combined effect of early Paleozoic and Cenozoic deformation.

- **'Seismotectonic Zones Demarcation in the Shillong Plateau Using the Microearthquakes and Radon Emanation Rate'; *Devesh Walia, Andrew C. Lyngdoh, and Atul Saxena; Acta Geophysica; vol. 58, no. 5, pp. 893-907, 2010; DOI: 10.2478/s11600-010-0015-8***

A b s t r a c t

The Shillong Plateau signifies the intense tectonic processes that the region has experienced during the Tertiary Indo-Tibetan and Indo-Burman collisions. An attempt has been made to study the microearthquake and radon emanation rate to understand and identify the seismotectonic zones. The microearthquake data was recorded along a network of seven temporary seismic stations. The epicentral map prepared using the microearthquake data indicates sparse seismic activity over the Shillong Plateau. The alignment of earthquake epicenters does indicate definite pattern of the activity disposition and hence the active fault zones. The calculated *b*-value over the Shillong Plateau is low which indicates asperity and the fact that the 'stress' is being built-up. Accordingly, along the few identified active crustal structures, time integrated and continuous radon monitoring was made using the LR 115 and Barasol detectors. The sites with anomalous radon concentration are demarcated as active fault zones or sensitive seismotectonic zones and are being monitored continuously using the Barasol detectors. The anomalous radon concentration may not indicate the magnitude of impending earthquake but it certainly can be used to spatially locate the earthquake preparation zones.

Key words: active fault zones, microearthquakes, radon concentration, Shillong Plateau, Dawki Thrust.

- **'Transverse Tectonics in the Sikkim Himalaya: Evidence from Seismicity and Focal-Mechanism Data'; *Pinki Hazarika, M. Ravi Kumar, G. Srijayanthi, P. Solomon Raju, N. Purnachandra Rao, and D. Srinagesh; Bulletin of the Seismological Society of America, Vol. 100, No. 4, pp. 1816-1822, , August 2010, DOI:10.1785/0120090339***

Abstract

In the present study, about 356 local earthquakes in the region of the Sikkim Himalaya have been accurately located and analyzed using 2181 P travel times and 2161 S travel times from a network of 11 broadband seismic stations operated by the National Geophysical Research Institute during January 2006 to November 2007. Further refinement of the hypocentral parameters using the hypoDD relocation program resulted in 198 well-constrained locations. Interestingly, this study reveals several characteristic features that distinguish Sikkim from the rest of the Himalaya. The seismicity distribution is found to be confined mostly between the main boundary thrust (MBT) and the main central thrust (MCT) but not quite associated with either. While the entire Himalayan front is generally characterized by shallow-angle thrust faulting, focal mechanisms in this region are predominantly of strike-slip type in conformity with a right-lateral strike-slip mechanism along the northwest-trending Tista and Gangtok lineaments. The P-axis trends of earthquake focal mechanisms are clearly oriented north-northwest, marking a clear transition from the ambient north-

northeast trending direction of Indian plate motion with respect to the Eurasian plate all along the Himalayan front. Moderate-sized earthquakes occur down to 70 km depth in this region, compared to an average focal depth of 15–20 km in the rest of the Himalaya. Also, a high average crustal P velocity of 6:66 km=sec and a fairly low b value of 0:83 _ 0:04 are obtained indicating the probability of occurrence of a higher magnitude earthquake in the future.Anorth–south section in the Sikkim region shows a relatively flat topography, unlike in the rest of the Himalayan mountain chain and suggestive of lower rates of convergence in the recent geologic past. It is proposed that crustal shortening in the Sikkim Himalaya has been substantially accommodated by transverse tectonics rather than underthrusting in recent times.

- **'The 2009 Bhutan and Assam felt earthquakes (M_w 6.3 and 5.1) at the Kopili fault in the northeast Himalaya region'; *J.R.Kayal, Sergei S.Arefiev, Saurabh Baruah, Ruben Tatevossian, Naba Gogoi, Manichandra Sanoujam, J.L.Gautam, Devajit Hazarika and Dipak Borah; Geomatics, Natural Hazards and Risk, Vol. 1, No. 3,, pp. 273-281, September 2010***

Abstract

Seismotectonics of the two recent earthquakes, one Mw 6.3 in the Bhutan Himalaya on 21 September 2009 and the other Mw 5.1 in the Assam valley on 19 August 2009, are examined here. The recent seismicity and fault plane solutions of these two felt earthquakes suggest that both the events occurred on the Kopili fault zone, a known active fault zone in the Assam valley, about 300 km long and 50 km wide. The fault zone is transverse to the east–west Himalayan trend, and its intense seismicity indicates that it transgresses into the Himalaya. The geologically mapped curvilinear structure of the Main Central Thrust (MCT) in the Himalaya, where the epicentre of the Bhutan earthquake is located, is possibly caused by the transverse Kopili fault beneath the MCT. This intensely active fault zone may be vulnerable to an impending larger earthquake (M7.0) in the region.

- **'Intrinsic and scattering attenuation in Chedrang Fault and its vicinity – the rupture area of Great Assam earthquake of 12 June 1897 (*M* = 8.7)'; *Saurabh Baruah1, Devajit Hazarika, Aditya Kalita and Sumana Goswami; Current Science, VOL. 99, NO. 6, 25 SEPTEMBER 2010***

Abstract

The attenuation of seismic waves is one of the basic physical parameters used in seismological studies, which is closely related to the seismicity and tectonic activity of a particular area. In the present study, attenuation properties of the crust beneath the Chedrang Fault and its vicinity, the rupture area of the great Assam earthquake of 12 June 1897 (M = 8.7) are studied using waveforms recorded by a local seismic network composed of five stations. In total 20 local earthquakes have been analysed to estimate (i) coda wave attenuation quality factor (Q_c) applying single scattering model, (ii) total attenuation quality factor (Q_d) from direct S-wave applying spectral ratio method and (iii) intrinsic and scattering attenuation quality factors (Qi and Qs) following the Wennerberg's approach. Coda Q (Qc) values are obtained using different coda window lengths (20, 30 and 40 s) for frequency bands centred at 1, 1.5, 2, 3, 4, 6, 8, 12, 16 and 18 Hz. This study indicates that Qc increases with increasing lapse time and that Qc is frequency dependent following the attenuation–frequency relation Qc(20) = 36.29 □1.18f 1.45 □□0.09, Qc(30) = 69.92 □□1.11f 1.23 □□0.06 and

*Q*c(40) =117.08 □□1.08*f* 1.07 □□0.05 for 20, 30 and 40 s respectively. This behaviour is usually correlated to the presence of heterogeneity in the crust and to the degree of tectonic complexity underneath the study area. The Qc^{-1} values for this area follow a substantially similar trend of Qc^{-1} decay with frequency as the other tectonically active regions of the world. Finally, from the separation of *Q*s and *Q*i values, it is observed that the study area can be characterized by a low scattering attenuation (small scattering *Q* inverse, Qs^{-1}) and by a relatively high intrinsic attenuation (high intrinsic *Q* inverse, Qi^{-1}).

Keywords: Chedrang Fault, coda waves, frequency dependence, intrinsic attenuation seismic waves, quality factor.

- **'Paleoseismological evidence of surface faulting along the northeastern Himalayan front, India: Timing, size, and spatial extent of great earthquakes; *Senthil Kumar, Steven G. Wesnousky, R. Jayangondaperumal, T. Nakata, Y. Kumahara, and Vimal Singh, Journal of Geophysical Research; Vol. 115, B12422, doi:10.1029/2009JB006789, 2010***

Abstract

The ∼2500 km long Himalayan arc has experienced three large to great earthquakes of Mw 7.8 to 8.4 during the past century, but none produced surface rupture. Paleoseismic studies have been conducted during the last decade to begin understanding the timing, size, rupture extent, return period, and mechanics of the faulting associated with the occurrence of large surface rupturing earthquakes along the ∼2500 km long Himalayan Frontal Thrust (HFT) system of India and Nepal. The previous studies have been limited to about nine sites along the western two-thirds of the HFT extending through northwest India and along the southern border of Nepal. We present here the results of paleoseismic investigations at three additional sites further to the northeast along the HFT within the Indian states of West Bengal and Assam. The three sites reside between the meizoseismal areas of the 1934 Bihar-Nepal and 1950 Assam earthquakes. The two westernmost of the sites, near the village of Chalsa and near the Nameri Tiger Preserve, show that offsets during the last surface rupture event were at minimum of about 14 m and 12 m, respectively. Limits on the ages of surface rupture at Chalsa (site A) and Nameri (site B), though broad, allow the possibility that the two sites record the same great historical rupture reported in Nepal around A.D. 1100. The correlation between the two sites is supported by the observation that the large displacements as recorded at Chalsa and Nameri would most likely be associated with rupture lengths of hundreds of kilometers or more and are on the same order as reported for a surface rupture earthquake reported in Nepal around A.D. 1100. Assuming the offsets observed at Chalsa and Nameri occurred synchronously with reported offsets in Nepal, the rupture length of the event would approach 700 to 800 km. The easternmost site is located within Harmutty Tea Estate (site C) at the edges of the 1950 Assam earthquake meizoseismal area. Here the most recent event offset is relatively much smaller (<2.5 m), and radiocarbon dating shows it to have occurred after A.D. 1100 (after about A.D. 1270). The location of the site near the edge of the meizoseismal region of the 1950 Assam earthquake and the relatively lesser offset allows speculation that the displacement records the 1950 Mw 8.4 Assam earthquake. Scatter in radiocarbon ages on detrital charcoal has not resulted in a firm bracket on the timing of events observed in the trenches. Nonetheless, the observations collected here, when taken together, suggest that the largest of thrust earthquakes along the Himalayan arc have rupture

lengths and displacements of similar scale to the largest that have occurred historically along the world's subduction zones.

- **'Frequency-dependent attenuation of P and S waves in northeast India'; *Simanchai Padhy, N.Subhadra; Geophysical Journal International; 183(2), pp. 1052-1060, 10/2010; DOI:10.1111/j.1365-246X.2010.04783.x*.**

Abstract

We have analysed 202 seismograms recorded at 10 seismic stations in the northeast (NE) India region to infer the frequency-dependent attenuation characteristics of both P and S waves, in the frequency range from 1.5 to 24 Hz and in the distance range from 30 to 100 km. We used extended coda-normalization method to determine the attenuation of P wave (Q−1P) and S wave (Q−1S). The results show that both P and S waves undergo a strong attenuation along ray paths. The values of Q−1P and Q−1S, corresponding to spectral amplitude decays, show strong frequency dependence and are expressed as Q−1P= (0.035 ± 0.014)f−(0.96±0.01) and Q−1S= (0.014 ± 0.006)f−(0.94±0.03), respectively, in 1.5–24 Hz. The ratio Q−1P/Q−1S is found to be larger than unity for the whole frequency range. The high frequency dependence of both P- and S waves indicate the highest attenuation among the world at lower frequencies.

- **'Scattering and anelastic attenuation of seismic energy in Northeast India using the multiple lapse time window analysis'*; S Padhy; AGU Fall Meeting Abstracts 12/2010***

Abstract

We investigated the intrinsic dissipation and scattering properties of the lithosphere beneath the northeast India by using the seismic waves recorded by a network of ten broadband stations in the region with hypocentral distances ranging from 31 to 200 km. First, we determined coda Q from the amplitude decay rate of the S-wave coda envelopes in five frequency bands from 1.5 to 24 Hz based on single scattering theory and QS by means of the coda normalization method. Assuming a frequency dependent power-law of the form , we found a low Q0 (Q0 < 200) and a high frequency dependent parameter n (n ~ 1) for the whole study area, which indicates that the lithosphere beneath NE India is seismically active and heterogeneous. Then we applied the multiple lapse time window (MLTW) analysis in the hypothesis of velocity and scattering coefficients constant with depth. We calculated the variation of integrated spectral energy with hypocentral distance for three consecutive lapse time windows (0-15, 15-30, 30-45 sec), starting from the onset of the S-wave arrival. The spectral energies over an octave bandwidth with central frequencies at 1.5, 3, 6, 12 and 24 Hz were calculated to obtain the frequency dependence of attenuation parameters. The results show that intrinsic absorption dominates over scattering in the attenuation process at high frequencies. However, in the hypothesis of uniform medium, the estimates of scattering attenuations obtained by MLTW analysis are overestimated. So the present results are correct to a first order approximation. To obtain more reliable and unbiased estimates of the attenuation parameters and their frequency dependences by considering the probable influence of crustal-mantel heterogeneities, we analyze the events by using the depth dependent MLTW method.

- **'Ground motion parameters in Shillong and Mikir Plateau supplemented by mapping of amplification factors in Guwahati City, Northeastern India';**

Saurabh Baruah, Santanu Baruah, Aditya Kalita, J.R.Kayal; Journal of Asian Earth Sciences, 42 , pp. 1424-1436, 2011

Abstract

Ground motion parameters for Shillong-Mikir Plateau of Northeastern India are examined. Empirical relations are obtained for ground motion as a function of earthquake magnitude, fault type, source depth, velocity characterization of medium and distance. Correlation between ground motion parameters and characteristics of seismogenic zones are established. Simultaneously, new empirical relations are derived for attenuation of ground motion amplitudes. Correlation coefficients of the attenuation relations depend on the site classification that are identified based on average shear wave velocity and site response factors. The attenuation relation estimated for logarithmic width of the Mikir Plateau found to be a little bit higher than that of Shillong Plateau both for soft and hard ground which accounts for geometrical spreading and anelastic attenuation. Simultaneously, validation are made studying the seismic microzonation process related to geomorphological, geological subsurface features for thickly populated Guwahati city of India under threat from scenario earthquake.

- **'Ground motion parameters in the Shillong–Mikir plateau, northeastern India'; *Saurabh Baruah, Santanu Baruah, Aditya Kalita and J.R. Kayal; Geomatics, Natural Hazards and Risk, 1–15, 2011***

Abstract

Ground motion parameters for the Shillong–Mikir plateau, northeastern India are examined. Empirical relations are obtained for ground motions as a function of earthquake magnitude, fault type, source depth, velocity characterization of medium and distance. A correlation between ground motion parameters and characteristics of seismogenic zones is established. Simultaneously, new empirical relations are derived for the attenuation of ground motion amplitudes. The logarithmic width is found to be independent of earthquake magnitude and distance. The attenuation relations estimated for the logarithmic width of the Mikir plateau are found to be a little bit higher than that of the Shillong plateau both for soft and hard ground, which accounts for geometrical spreading and anelastic attenuation.

- **'Understanding the Tectonic Behaviour of the Shillong Plateau, India using Remote Sensing Data'; *B.P.Duarah and Sarat Phukan; Journal Geological Society of India, Vol. 77, pp. 105-112, February 2011***

Abstract

Shillong Plateau in India is tectonically and geologically interesting entity in the subducted front of Indian Plate below Burmese Plate to the southeast and Tibetan Plate to the north and associated with thrusts and shears along the plate boundaries. Horse-tail geometry in the foothills of the Arunachal Himalaya, east of Jia Bhareli river, associated with south-convex foothill ranges in the eastern Himalaya and exactly similar structural geometry in the eastern part of Shillong Plateau in Meghalaya seems to develop due to resistance received by the plateau in its eastward journey. Wide separation of Karbi Anglong Plateau and Shillong Plateau to the southeast as compared to northwestern part defines the shape of Kopili graben. Low seismic activity in southeastern part of Shillong Plateau might be related to stress released field generated by its clockwise rotation. Satellite derived images and digital elevation data from Landsat ETM$^+$ and SRTM data shows that the central part of Shillong Plateau possesses young topography with strong structural fabrics along with relatively high topography alignment NE-SW following Kolkota-Pabna-Mymansingh high and if extended passes through western part of Arunachal Pradesh in eastern Himalayas. This alignment has been observed in Precambrian gneissic complex west of the Proterozoic intracratonic Shillong basin. The epicentral plot for the period 1918 to 2009 shows their high concentration within the Shillong Plateau aligning along this trend. The active geodynamics of Shillong Plateau is reflected in its seismic activity pattern in relation with the structural fabrics, northward migration of the Brahmaputra in the north front of the Plateau and by shrinking pattern of Chandubi Lake in the Kulsi river catchment, a north-flowing tributary of the Brahmaputra in the north-central part of the plateau.

Keywords: Landsat ETM$^+$, SRTM data, Tectonics, Geodynamics, Shillong plateau, Brahmaputra migration, Himalaya

- **'Estimation of crustal discontinuities from reflected seismic waves recorded at Shillong and Mikir Hills Plateau, Northeast India'; *Saurabh Baruah • Dipok K. Bora • Rajib Biswas; Int J Earth Sci , 2011, 100l 1283-1292; DOI 10.1007/s00531-010-0541-2***

Abstract

In this study, an attempt is made to determine seismic velocity structure of the crust and upper mantle beneath the Shillong-Mikir Hills Plateau in northeast India region. The principle of the technique is to relate seismic travel times with crustal thickness above the Conrad and Moho discontinuities. Broadband digital waveforms of the local earthquakes make a precise detection of the seismic phases possible that are reflected at these discontinuities. The results show that the Conrad discontinuity is at 18–20 (±0.5) km beneath the Shillong-Mikir Hills Plateau and the Moho discontinuity is at 30 ± 1.0 km beneath the Shillong Plateau and at 35 ± 1.0 km beneath the Mikir Hills.

Keywords Conrad and Moho discontinuities, Reflected seismic waves, Shillong and Mikir Hills Plateau ,Travel time

- **'Neotectonic study along mountain front of northeast Himalaya, Arunachal Pradesh, India'; *R. K. Mrinalinee Devi, S. S. Bhakun, P. K. Bora; Environ Earth Sci (2011) 63:751–762; DOI 10.1007/s12665-010-0746-5***

Abstract

To study neotectonics, the structural and morphotectonic aspects are studied along a part of mountain front region of Northeast Himalaya, Arunachal Pradesh, India. Unpaired river terraces are recognized near north of transverse Burai River exit, which is cut by an oblique fault. Across this fault, fluvial terraces are located at heights of 22.7 and 3 m, respectively, on the left and right banks. A water gap is formed along the river channel where the uplifted Middle Siwalik sandstone beds dipping 43_towards ENE direction, thrust over the Quaternary deposit consisting of boulders, cobbles, pebbles and sandy matrix. This river channel incised the bedrock across the intra formational Ramghat Thrust along which the rocks of the Middle Siwalik Formation thrust over the Upper Siwalik Formation. Recent reactivated fault activity is suggested north of the Himalayan Frontal Thrust that forms the youngest deforming front of the Himalaya. The uplifting along the stream channel is noticed

extended for a distance of *130 m and as a result the alluvial river channel became a bedrock river. The relative displacement of rocks is variable along the length of strike–slip faults developed later within the Ramghat Thrust zone. Longitudinal and Channel gradient profiles of Burai River exhibit knick points and increase in river gradient along the tapering ends of the profiles. The study suggests active out-of-sequence neotectonically active thrusting along the mountain front. Neotectonics combined with climatic factor during the Holocene times presents a virgin landscape environment for studying tectonic geomorphology.

Keywords Geomorphic evidence Middle Siwalik Tectonic activity Quaternary Water gap Knick point

- **Morphological signatures of fault lines in an earthquake prone zone of southern Baromura hill, north-east India: a multi source approach for spatial data analysis. A critical review'; *Sunil Kumar De, Sunando Bandyopadhyay; Environ Earth Sci (2011) 63: 437-441; DOI 10.1007/s12665-010-0691-3***

Abstract

In a recent work, Dey et al. (Environ Earth Sci 59:353–361, 2009) presented some new observations on the southern part of one of the anticlinal ridges of Tripura, viz. the Baromura range. The work incorporated a number of irregularities and misinterpretations that need to be addressed to avoid future confusion. The present article critically reviews Dey et al.'s paper to bring out its inaccuracies.

Keywords Chittagong-Tripura Fold Belt , Plunging anticline , Lineament , Spectral signature

- **'Geometry and crustal shortening of the Himalayan fold-thrust belt, eastern and central Bhutan'; *Sean Long, Nadine McQuarrie, Tobgay Tobgay, and Djordje Grujic; GSA Bulletin; July/August 2011; v. 123; no. 7/8; p. 1427–1447; doi: 10.1130/B30203.1***

Abstract

We present a new geologic map of eastern and central Bhutan and four balanced cross sections through the Himalayan fold-thrust belt. Major structural features, from south to north, include: (1) a single thrust sheet of Sub Himalayan rocks above the Main Frontal thrust; (2) the upper Lesser Himalayan duplex system, which repeats horses of the Neo proterozoic–Cambrian(?) Baxa Group below a roof thrust (Shumar thrust) carrying the Paleoproterozoic Daling-Shumar Group; (3) the lower Lesser Himalayan duplex system, which repeats horses of the Daling-Shumar Group and Neoproterozoic–Ordovician(?) Jaishidanda Formation, with the Main Central thrust (MCT) acting as the roof thrust; (4) the structurally lower Greater Himalayan section above the MCT with overlying Tethyan Himalayan rock in stratigraphic contact in central Bhutan and structural contact above the South Tibetan detachment in eastern Bhutan; and (5) the structurally higher Greater Himalayan section above the Kakhtang thrust. Cross sections show 164–267 km shortening in Sub Himalayan and Lesser Himalayan rocks, 97–156 km structural overlap across the MCT, and 31–53 km structural overlap across the Kakhtang thrust, indicating a total of 344–405 km of minimum crustal shortening (70%–75%). Our data show an eastward continuation of Lesser Himalayan duplexing identified in northwest India, Nepal, and Sikkim, which passively folded the overlying Greater Himalayan and Tethyan Himalayan sections. Shortening and percent

shortening estimates across the orogen, although minima, do not show an overall eastward increase, which may suggest that shortening variations are controlled more by the original width and geometry of the margin than by external parameters such as erosion and convergence rates.

- **'When and why the continental crust is subducted: Examples of Hindu Kush and Burma'; *Tetsuzo Seno, Hafiz Ur Rehman; Gondwana Research; 19, 327-333, 2011***

Abstract

The Indian subcontinent has been colliding against Asia along the Himalayas. Hindu Kush and Burma in this collision zone have intermediate-depth seismicities beneath them, with most of the continental crust subducted into a few hundred km depth. The subduction, not collision, in these regions is an enigma long time. We show that the continental lithosphere subducted beneath Hindu Kush and Burma traveled over the Reunion and Kerguelen hotspots from 100 Ma to 126 Ma and is likely to have been metasomatized by upwelling plumes beneath those hotspots. The devolatization of the metasomatized lithosphere impringing on the collision boundary would have provided a high pore fluid pressure ratio at the thrust zones and made the subduction of the continental lithosphere in these regions possible. The subducted lithosphere could give intermediate-depth seismicities by devolatilization embrittlement. Such subduction of hotspot-affected lithosphere without accompanying any oceanic plate would be one candidate for producing ultrahigh-pressure metamorphic rocks by deep subduction of the continental crust.

- **'Peak ground motion predictions in India: an appraisal for rock sites'; *Sankar Kumar Nath, Kiran Kumar Singh Thingbaijam; J Seismol (2011) 15:295-315; DOI 10.1007/s10950-010-9224-5***

Abstract

Proper selection and ranking of Ground Motion Prediction Equations (GMPEs) is critical for successful logic-tree implementation in probabilistic seismic hazard analysis. The present study explores this issue in predicting peak ground accelerations at the rock sites in India. Macroseismic intensity data complemented with limited strong ground-motion recordings are used for the purpose. The findings corroborate the possible conformity between the GMPEs developed for tectonically active shallow crust across the globe. On the other hand, the relevant GMPEs in the intraplate regions cluster into two different groups with the equations of lower ranks catering to higher ground motions. The earthquakes in the subduction zones have significant regional implications. However, affinity in the ground-motion attenuations between the major interface events (Mw > 7.4) in Andaman-Nicobar, japan and Cascadia, respectively, is noted. This can be also observed for the intraslab events in the Hindukush and Taiwan respectively. Overall, we do not observe any significant advantage with the equations developed using the regional data. These findings are expected to be useful in probabilistic seismic hazard analysis across the study region.

Keywords: Ground motion prediction equation, EMS-PGA relation, Peak ground acceleration, India

- **'The tectonic stress field and deformation pattern of northeast India, the Bengal basin and the Indo-Burma Ranges: A numerical approach'; *Md. Shofiqul Islam, Ryuichi Shinjo, J.R.Kayal; Journal of Asian Earth Sciences 40, 121-131, 2011***

Abstract

We performed numerical simulations to determine the contemporary maximum horizontal compressive stress (σ_{Hmax}) in the northeast India region, the Bengal basin (Bangladesh), and the adjoining Indo-Burma Ranges, with different boundary conditions. The regional tectonic stress was simulated using the finite element method (FEM) under the plane stress condition. Most of the study areas show NE-SW regional stress orientation, which is consistent with other stress indicators, such as earthquake focal mechanism solutions. The E-W trending Dauki fault, which separates the Shillong plateau to the north from the Bengal basin to the south, plays a major role in the stress distribution and regional deformation. This fault alone accommodates ~25% of the regional surface displacement rate of the study area. The fault pattern of the study area was also simulated using rheological parameters and the Mohr-Coulomb failure criterion. The simulated results reproduce the observed tectonic state of the area, including a strike-slip regime along the Dauki fault, in the southwestern part of the Bengal basin, and in the Tripura fold belt areas. The modeling indicates that the Brahmaputra valley to the north of the Shillong plateau and to the south of the Himalayan frontal thrust exhibits thrust/reverse faulting with a strike-slip component, and in the Indo-Burma Ranges, strike-slip faulting is predominant with a reverse fault component.

- **'Estimation of Crustal Discontinuities from Reflected Seismic Waves Recorded at Shillong Plateau, Northeast India'; *Dipok K. Bora and Saurabh Baruah; Memoir of the Geological Society of India, No. 77, pp. 161-171, 2011, ISBN:978-81-907636-2-2***

Abstract

In this paper, an attempt is made to determine seismic velocity structure of the crust and upper mantle beneath the Shillong Plateau in northeast India region. The principle of the technique is to relate seismic travel times of direct and reflected phases with crustal thickness above the Conrad and Moho discontinuities. Broadband digital waveforms of the local earthquakes make it possible precise detection of the seismic phases that are reflected at these discontinuities. The results show that the Conrad discontinuity is at 18$\pm$0.5 km and the Moho discontinuity is at 30$\pm$1.o km beneath the Shillong Plateau.

Keywords: Conrad and Moho discontinuities, Reflected seismic waves, Shillong Plateau, Travel time.

- **'Tectonic implication of drainage set-up in the Sub-Himalaya: A case study of Papumpare district, Arunachal Himalaya, India'; *R.K.Mrinalinee Devi, S.S.Bhakuni, Pabon Kumar Bora; Geomorphology, Vol. 127, pp. 14-31, 2011***

Abstract

The Sub-Himalaya, deformed between the Main Boundary Thrust and/ or Bomdila Thrust towards north and Himalayan Frontal Thrust (HFT) towards south, is characterized by the

presence of fault-propagated folds and an imbricate thrust system. Although the HFT, the mountain front is offset for about 10 km sinistrally along a NW-SE trending transverse fault, the Banderdewa Fault, which runs through the Dikrang River valley that seems to have followed a pull-apart basin developed along the Banderdewa Fault. The western part of study area, associated with a major folding, faulting and the development of fault-bounded Quaternary basins with normal faulting along the northern margins, is interpreted to be tectonically more transported towards southeast than the eastern part where no Quaternary basins are developed. The channel forms and landforms have been studied in relation to the neotectonics of the area. The watersheds exhibit their structurally controlled nature, with drainages following tectonic alignments. Rivers/streams experienced compressed meandering, narrowing, widening and deflection of channels. Longitudinal profiles of river stream channels exhibit knick points. Unpaired terraces are observed at higher levels. Factors like the unconsolidated Siwalik rocks, tectonic instability along faults and high rainfall with the advent of the Holocene, led to the development of the present-day drainage set-up. A tectonic model is proposed for development of tectonic geomorphology of the area influenced by ultra-tremor to low magnitude earthquakes in seismically very active northeastern India, as moderate to big earthquakes ($M \geq 6.0$) are scare in this region.

- **Revisiting the earthquake sources in the Himalaya: Perspectives on past seismicity'; *Kusala Rajendran and C. P. Rajendran; Tectonophysics, 2011, DOI:10.1016/j-tecto.2011.03.001***

Abstract

The ~2500 km-long Himalaya plate boundary experienced three great earthquakes during the past century, but none of them generated any surface rupture. The segments between the 1905-1934 and the 1897-1950 sources, known as the central and Assam seismic gaps respectively, have long been considered holding potential for future great earthquakes. This paper addresses two issues concerning earthquakes along the Himalaya plate boundary. One, the absence of surface rupture associated with the great earthquakes, vis-à-vis the purported large slip observed from paleoseismological investigations and two, the current understanding of the status of the seismic gaps in the Central Himalaya and Assam, in view of the paleoseismological and historical data being gathered. We suggest that the ruptures of earthquakes nucleating on the basal detachment are likely to be restricted by the crustal ramps and thus generate no surface ruptures, where as those originating on the faults within the wedges promote upward propagation of rupture and displacement, as observed during the 2005 Kashmir earthquake, that showed a peak offset of 7 m. The occasional reactivation of these thrust systems within the duplex zone may also be responsible for the observed temporal and spatial clustering of earthquakes in the Himalaya. Observations presented in this paper suggest that the last major earthquake in the Central Himalaya occurred during AD 1119-1292, rather than in 1505, as suggested in some previous studies and thus the gap in the plate boundary events is real. As for the Northwestern Himalaya, seismically generated sedimentary features identified in the 1950 source region are generally younger than AD 1400 and evidence for older events is sketchy. The 1897 Shillong earthquake is not a décollement event and its predecessor is probably ~1000 years old. Compared to the Central Himalaya, the Assam Gap is a corridor of low seismicity between two tectonically independent seismogenic source zones that cannot be considered as a seismic gap in the conventional sense.

***Key words**: Central Himalaya, earthquakes, paleoseismology, seismic gaps,Northeast India*

- **'Imaging the Indian lithosphere beneath the Eastern Himalayan region'*; E.Uma Devi, P.Kumar and M.Ravi Kumar; Geophysical Journal International, Vol. 187, pp. 631-641, 2011***

Abstract

Lithospheric thickness is an important parameter to understand the nature of collision and subduction between the Indian and Asian tectonic plates. In this study, we apply the S receiver function technique to data from a network of broad-band stations in the northeast India and Eastern Himalayan regions and image the geometry of Indian Plate collision. This analysis reveals clear S-to-p conversions from the Moho and Lithosphere-Asthenosphere boundary (LAB) in the various tectonic units of the study region. The Indian lithosphere is found to be only 90 km thick beneath the Shillong plateau deepening to 135 km on either side suggestive of a lithospheric upward related to the plateau uplift. The lithosphere thickens northward, with values reaching ~ 180 km beneath the Eastern Himalaya. The trend of the LAB north of the foredeep region indicates that the Indian Plate plunges beneath the Eastern Himalaya. The consistent northward-dipping character of the Indian Plate suggests that the Indian Plate is traceable until it gets subducted beneath Tibet just south of Bangong suture zone. The deepening of the LAB and its correlation with the topographic elevation is in agreement with homogeneous thickening of the lithosphere in response to compressive forces due to the continental collision of India with Asia.

Keywords: Seismicity and tectonics, Body waves, Computational seismology, Continental margins, convergent, Dynamics, seismology, Asia

- **'Low seismicity in the Bhutan Himalaya and the stress shadow of the 1897 Shillong Plateau earthquake'; *V.K.Gahalaut, Shikha Rajput, Bhaskar Kundu; Physics of the Earth and Planetary Interiors; 186, 97-102, 2011***

Abstract

The seismicity of the Bhutan Himalaya region is generally low as compared to its adjoining Himalayan segments. The topography in the region is slightly subdued and different from the neighbouring central Nepal region. Low seismicity in the region may possibly be due to the postulated low convergence rate in the Bhutan Himalaya, difference in subsurface structures, or the aseismic nature of the region. We suggested that the lower seismicity in the Bhutan Himalaya may also be due to stress change caused by the great 1897 Shillong Plateau earthquake as the low seismicity region of the Bhutan Himalaya coincides with the stress shadow of the earthquake.

- **'Potential source zones for Himalayan earthquakes: constraints from spatial–temporal clusters'; *Basab Mukhopadhyay, Anshuman Acharyya, Sujit Dasgupta; Nat Hazards DOI 10.1007/s11069-010-9618-2***

Abstract

The Himalayan fold-thrust belt has been visited by many disastrous earth-quakes (magnitude > 6)time and again. This active collisional orogen bordering Indian subcontinent in the north remains a potential

seismic threat of similar magnitude in the adjoining countries like India, Pakistan, Nepal, Bhutan and China. Though earthquake forecasting is riddled with all conjectures and still not a proven presumption, identifying likely source zones of such disastrous earthquakes would be an important contribution to seismic hazard assessment. In this study, we have worked out spatio-temporal clustering of earthquakes (Mb $\geq$ 4.5;1964–2006) in the Himalayas. 'Point density' spatial statistics has helped in detecting 22 spatial seismicity clusters. Earthquake catalog is then treated with a moving time-distance window technique (inter-event time 35 days and distance 100 ±20 km) to bring out temporal clusters by recognizing several foreshock-main shock-aftershock (FMA) sequences. A total of 53 such temporal sequences identified in the process are confined within the 22 spatial clusters. Though each of these spatio-temporal clusters deserves in-depth analysis, we short-listed only eight such clusters that are dissected by active tectonic discontinuities like MBT/MCT for detail study. Spatio-temporal clusters have been used to constrain the potential source zones. These eight well-defined spatio-temporal clusters demonstrate recurrent moderate to large earthquakes. We assumed that the length of these clusters are indicating the possible maximum rupture lengths and thus empirically estimated the maximum possible magnitudes of eight clusters that can be generated from them (from west to east) as 8.0, 8.3, 8.2, 8.3, 8.2, 8.4, 8.0 and 7.7. Based on comparative study of the eight cluster zones contemplating with their temporal recurrences, historical seismic records, presence of intersecting faults and estimated magnitudes, we have guessed the possibility that Kangra, East Nepal, Garhwal and Kumaun–West Nepal clusters, in decreasing order of earthquake threat, are potential source zones for large earthquakes ($\geq$ 7.7 M) in future.

Keywords Himalayas, Earthquake, Spatio-temporal clusters, Characteristic earthquake, Seismic quiescence, Fault interaction, Rupture

- **'Seismic event of the Dauki Fault in 16th century confirmed by trench investigation at Gabrakhari Village, Haluaghat, Mymensingh, Bangladesh'; *Michio Morino, A.S.M.Maksud Kamal, Dicky Muslim, Reshad Md. Ekram Ali, Mohammad Ashraful Kamal, Md. Zillur Rahman, Fumio Kaneko; Journal of Asian Earth Sciences; Volume 42, Issue 3, pp. 492-498, 10 August 2011,***

Abstract

The Dauki Fault, which is inferred to go through the southern margin of the Shillong Plateau, is an E–W trending reverse one inclined towards the north. The Dauki Fault was believed to be active during the Late Quaternary time by the geomorphic features of the Shillong Plateau, the gravity anomaly data, and uplifted Tertiary and Quaternary deposits on the southern foothills of the Shillong Plateau. However, previous studies did not show any specific evidence that the Dauki Fault is active, since active fault survey such as satellite photo interpretation and trench investigation was not performed hitherto. We carried out CORONA satellite photo interpretation and trench investigation across the Dauki Fault at Gabrakhari Village for the first time. Consequently small fault strands and clear unconformity accompanied with faulting were confirmed in the trench. However, these small fault strands may be secondary ones branched from a main fault which may be concealed under the trench. The time of seismic event, which is inferred from unconformity, is dated back to A.D. 1500–1630. The seismic event during A.D. 1500–1630 may correspond with the 1548 earthquake which is currently a first recorded large earthquake in Bangladesh. Furthermore, sand dikes due to paleo-liquefaction, which reach near the ground surface, were confirmed at the trench. According to radiocarbon age, the sand dikes were formed during the 1897 Ms. 8.0 Great Assam earthquake.

Keywords: Dauki Fault; 1548 Earthquake; Shillong Plateau; Active fault; Trench investigation

- **'Pop-up tectonics of the Shillong Plateau in northeastern India; Insight from numerical simulations'; *Md. Shofiqul Islam, Ryuichi Shinjo, J.R.Kayal; Gondwana Research; Vol. 20, Issues 2-3, pp. 395-404, September 2011***

Abstract

The Shillong Plateau in northeastern India represents one of the most seismically active "pop-up" structures within the peninsular shield area. In order to constrain the role of the inferred Oldham Fault in the northern boundary of the plateau, we performed 2-D finite element method (FEM) simulations for convergent displacement caused by northeastward movement of the Indian plate with respect to the Eurasian plate. Various rock properties (density, Poisson's ratio, Young's modulus, cohesion, and angle of internal friction) and the Mohr–Coulomb failure criterion are used to evaluate failure and faulting patterns. Two plane strain models with appropriate boundary conditions were also calculated. The predicted maximum compressive stress (σ_1) shows a preferred orientation that helps explain the tectonic environment and the fault pattern. The best-fit model suggests that a compressive stress regime is dominant in the study area everywhere except for the uppermost part of the crust where extensional stress dominates. With increased progressive convergent displacement, the modeled σ_1 are predicted to rotate counterclockwise around the fault zones. The simulation results suggest that the Oldham Fault does not have a significant role in the development of stress and deformation distribution in the area. We also infer that the tectonically induced deformation in both the plateau and the adjoining areas is restricted to mainly within the crust (< 30 km).

Keywords : Shillong Plateau; Pop-up; Numerical simulation; Oldham Fault; Dauki Fault

- **'The 18 September 2011, North Sikkim Earthquake'; Kusala Rajendran, *C. P. Rajendran, N. Thulasiraman, Ronia Andrews and Nima Sherpa; Current Science, Vol. 101, No. 11, 10 December, 2011***

Abstract

The 18 September 2011, magnitude *Mw* 6.9 earthquake close to the Nepal–Sikkim border caused significant damage due to ground shaking and caused several landslides. Observations from the post-earthquake surveys in the affected areas within Sikkim suggest that the poorly engineered, multistoried structures were relatively more impacted. Those located on alluvial terraces were also affected. The morphology of the region is prone to landslides and the possibility for their increased intensity during the forthcoming monsoon need to be considered seriously. From the seismotectonic perspective, the mid-crustal focal depth of the North Sikkim earthquake reflects the ongoing deformation of the subducting Indian plate.

Keywords: Epicentre, focal depth, post-earthquake survey, seismotectonic setting.

- **'Seismicity parameters for important urban agglomerations in India'; *S. T. G. Raghukanth; Bull Earthquake Eng, Vol. 9, pp. 1361-1386, 2011; DOI 10.1007/s10518-011-9265-3***

Abstract

India's urban population has increased in the recent times. An earthquake near an urban agglomeration has the potential to cause severe damage. In this article, seismicity parameters for region surrounding important urban agglomerations in India are estimated. A comprehensive earthquake catalogue for the region (6◦E–42◦E latitude and 60◦N–100◦N longitude) including historic and pre-historic events has been compiled from various sources. To estimate the parameters, past earthquake data in a control region of radius 300 km has been assembled to quantify the seismicity around each urban agglomeration. The collected earthquake data is first evaluated for its completeness. From combined (historical and instrumental) data, the seismicity parameters *b*-value, seismic activity rate, λ and maximum expected magnitude (*mmax)* have been obtained from the methodology proposed by Kijko and Graham (1998). The obtained activity rates indicate that region surrounding Guwahati urban agglomeration is the most seismically active region followed by Srinagar, Patna, Amritsar and Chandigarh.

Keywords Seismic hazard · Urban agglomerations · Recurrence relations ·

- **Seismotectonics at the terminal ends of the Himalayan Arc'; *Basab Mukhopadhyay, Anshuman Acharyya, Debkumar Bhattacharyya, Sujit Dasgupta and Prabhas Pande; Geomatics, Natural Hazards and Risk; 1-23, 2011***

Abstract

The Himalayan arc has an arcuate E-W trending geometry with reversal of trend at the terminal ends – Nanga-Parbat (western) syntaxis and Namche-Barwa (eastern) syntaxis. Both ends are characterized by an actively deformed uplifted dome with its flanks bounded by active shear zones faults that cause the majority of the seismicity. Compiled map data and seismo-geological depth sections around these two syntaxial zones have brought out active crustal structure and seismotectonic setup. The Nanga-Parbat syntaxis exhibits upward bending and subsequent thickening of the Indian Plate with the cluster of seismicity along the NNE-SSW trending Raikhot fault/Diamer shear in its western margin and a comparatively less active Rupal-Chichi shear zone of N-S trend with diffused seismicity towards the east. The 2005 Kashmir earthquake is spawned due to interaction of the Main Boundary thrust and the Muzaffrabad fault. The Namche-Barwa syntaxis displaya a fault-bounded up liftment and thickening of the Indian plate where Canyon thrust marks the boundary between the Indian and Eurasian plates. The occurrence of the 1950 Assam earthquake in the vicinity of the eastern syntaxis is attributed to a regional right lateral strike-slip motion on the causative fault plane. The seismicity in the syntaxes is primarily controlled by strike-slip fault shear zones along the flanks of popup antiforms.

- **'Detailed geometry of the subducting Indian Plate beneath the Burma Plate and subcrustal seismicity in the Burma Plate derived from joint hypocenter reloca-**

tion'; ***Nobuo Hurukawa, Pa Pa Tun, and Bunichiro Shibazaki; Earth Planets Space; 64, 333-343, 2012***

Abstract

With the aim of delineating the subducting Indian Plate beneath the Burma Plate, we have relocated earthquakes by employing teleseismic *P*-wave arrival times. We were also able to obtain the detailed geometry of the subducting Indian Plate by constructing iso-depth contous for the subduction earthquakes at depths of 30-140 km. The strikes of the contours are oriented approximately N-S and show an "S" shape in map view. The strike of the slab is N20^{0}E at 25^{0}N, but moving southward, the strike rotates counterclockwise to N20^{0}W at 20^{0}N, followed by a clockwise roatation to a strike of N10^{0}E at 17.5^{0}N, where slab earthquakes no longer occur. The plate boundary north of 20^{0}N might exist near, or west, of the coast line of Myanmar. The mechanisms of subduction earthquakes are down-dip extension, and T axes are oriented parallel to the local dip of the slab. Subcrustal seismicity occurs at depths of 20-50 km in the Burma Plate. This activity starts near the 60-km-depth contours of the subduction earthquakes and becomes shallower towards the Sagaing Fault, indicating that this fault is located where the cut-off depth of the seismicity becomes shallower.

Keywords: Burma Plate, Indian Plate, subduction, relocation, joint hypocenter determination

- **'Tectonic controls on the morphodynamics of the Brahmaputra river system in the upper Assam valley, India'**; ***Siddartha K.Lahiri, Rajiv Sinha; Geomorphology, 2012***

Abstract

The Brahmaputra is one of the largest tropical rivers of the world and is located in an area of high structural instability as evidenced from the presence of a large number of earthquakes in the Himalayan catchment through which it flows. Syntectonic evidence of changes in the morphodynamics is difficult to identify for the large rivers. Nevertheless, we note that the Brahmaputra River has become astonishingly large in planform in a historic timescale. Reconstruction of planform changes over a period of 90 years in the upper reaches of the Assam valley shows that the 240-km-long channel belt is widening all along its course in the region. From the average width of 9.74 km in 1915, the channel belt has widened to the average width of 14.03 km in 2005 (44% widening), and in certain reaches the average widening is as high as 250%. However, the bank line shift is not symmetric along both banks. Further, the planform characteristics of the Brahmaputra River reveal significant spatial and temporal variability to tectenogeomorphic zonation of the river based on the subsurface configuration and channel slope. Further, the tributaries joining the northern and southern banks of the Brahmaputra differ remarkably in terms of river dynamics, and this is attributed to the differences in the tectonic regimes of the Himalaya in the north and the Naga Patkai hills in the south.

- **'Earthquake occurrence processes in the Indo-Burmese wedge and Sagaing fault region'**; ***Bhaskar Kundu, V.K.Gahalaut; Tectonophysics, 524-525, 135-146, 2012***

Abstract

Earthquakes in the Indo-Burmese wedge and Sagaing fault regions occur in response to the partitioning of the India-Sunda motion along these two distinct boundaries. Under the accretionary wedge of the Indo-Burmese arc, majority of the earthquakes occur in depth range of 30-60 km and define an eastward gently dipping seismicity trend surface that coincides with the Indian slab. The dip of the slab steepens in the east direction and earthquakes occur down to a depth of 150 km, though the slab can be traced up to the 660 km discontinuity. Although these features are similar to a subduction zone, the nature of the earthquakes and our analysis of their focal mechanisms suggest that these earthquakes are of intra-slab type which occur on steep plane within the Indian plate and the sense of motion implies a northward relative motion with respect to the Sunda plate. Thus these earthquakes and the stress state do not support active subduction across the Indo-Burmese arc which is also consistent with the relative motion of India-Sunda plates. The absence of inter-plate earthquakes, lack of evidence of the occurrence of great earthquakes in the historical records and non-seismogenic nature of the plate interface under the accretionary wedge suggest that seismic hazards due to earthquakes along the plate boundary may be relatively low. However, major intra-slab earthquakes at shallow and intermediate depths may still cause damage in the sediment filled valley regions of Manipur and Cachar in India and Chittagong and Sylhet regions of Bangladesh. In the Sagaing fault region, earthquakes occur through dextral strike slip motion along the north-south oriented plane and the stress state is consistent with the plate motion across the Sagaing fault.

- **'Tectonic implications of the September 2011 Sikkim earthquake and its aftershocks';** ***M. Ravi Kumar, Pinki Hazarika, G. Srihari Prasad, Arun Singh and Satish Saha; Current Science, Vol. 102, No. 5, 10 March, 2012***

Abstract

This study presents results of the spatial patterns of 292 aftershocks of the *Mw* 6.9 Sikkim earthquake of September 2011, accurately located through analysis of three component waveforms registered by a five station broadband network operated immediately after its occurrence. Refined hypocentral parameters achieved through application of the hypoDD relocation scheme reveal tight clustering of events along a NW–SE trend with focal depths reaching ~60 km. These trends viewed in conjunction with the strike–slip mechanisms of past earthquakes in Sikkim, including the main shock, affirm the predominance of transverse tectonics in this segment of the Himalaya where the Indian plate convergence seems to be accommodated by dextral motion along steeply dipping fault systems.

Keywords: Aftershocks, earthquakes, hypocentral parameters, spatial patterns, transverse tectonics.

- **'Possible influence of subducting ridges on the Himalayan arc and on the ruptures of great and major Himalayan earthquakes';** ***V.K.Gahalaut, Bhaskar Kundu; Gondwana Research, Volume 21, Issue 4, pp. 1080-1088, May 2012***

Abstract

Subduction of bathymetric features, such as ridges, seamounts, fractures etc., on the subducting plate influences the arc morphology and earthquake ruptures. We analyse their effect on the development of the arcuate shape of the Himalayan arc and on the ruptures of great and major Himalayan earthquakes. Besides the two most prominent ridges in the Indian

Ocean, namely the Chagos-Laccadive-Deccan ridge and the 90^0E ridge, which are assumed to extend up to the Himalayan arc, at least three major subsurface ridges have been mapped on the underthrusting Indian plate under the Indo-Gangetic plains. It appears that the subduction of the two most prominent ridges contributed to the development of the arcuate shape of the Himalayan arc. The interaction and subduction of the other subsurface ridges probably influenced the Himalayan arc morphology by causing a localised cusp in the frontal topography. Also, these ridges probably acted as barriers to the ruptures of the major and great Himalayan earthquakes.

- **'The M 6.9 Sikkim (India-Nepal Border) earthquake of 18 September 2011; Durgesh C.Rai, Vaibhav Singhal, Goutam Mondal, Neha Parool, Tripti Pradhan and Keya Mitra; Current Science, Vol. 102, No. 10, 25 May 2012**

Abstract

The *M* 6.9 Sikkim earthquake of 18 September 2011 was a remarkable event in the long history of the Himalayan earthquakes which presented a unique opportunity to reflect on the unacceptable rising trend of the seismic risk in the hilly regions. Many dramatic collapses and damages were disproportionate to the observed intensity of shaking and can be attributed to poor construction material, deficient workmanship and lack of compliance with seismic codes and earthquake-resistant construction practices. Many private and governmental buildings were constructed neglecting the seismic design and detailing requirements necessary in the Zone IV of the Indian seismic code IS 1893. The traditional construction practices prevalent in the area performed rather satisfactorily due to their inherent earthquake-resistant features. Old monastery temple structures of distinctive construction in stone masonry and timber suffered varying degree of damage to masonry walls ranging from minor damages to partial collapse. This event should be regarded as a preview of what is likely to happen in the event of a greater shaking expected for the region and should hasten the community to take necessary steps in identifying seismic vulnerabilities and improving construction practices through an effective intervention.

Keywords: Earthquake effects, Himalayan earthquake, seismic risk.

- **'Long and short wavelengths of Indian Ocean geoid and gravity lows: Mid-to-upper mantle sources, rapid drift and seismicity of Kachchh and Shillong plateau, India'; *D.C.Mishra, M.Ravi Kumar; Journal of Asian Earth Sciences; 60, 212-224, 2012***

Abstract

Spectral analysis of the Indian Ocean geoid low provides depth to the large wavelength sources as _1300, _700 and 340 km that are supported from the spectral analysis and the modeling of the corresponding large wavelength regional gravity anomaly with negative density contrasts at these levels. The three levels coincide with the sharp changes in the gradient of the seismic velocities related to the olivine–spinel transformation of successively increasing Fe/Mg ratio as depth increases, known as transition zones. The first two segments are supported from continuous wavelet transform analysis of the large wavelength component of the corresponding gravity field. The low density rocks in this section appear to be related to the subducted Indian/Tethyan lithosphere that roll back and drifted southwards after subduction as inferred from tomography experiments. The relatively short wavelength

sources of the spectrum of the geoid data at depths of 162 and 85 km suggest sources along the lithosphere – asthenosphere boundary (LAB) under the Indian continent and surrounding oceans, respectively. A low viscosity zone has been envisaged below 660 km discontinuity that may correspond to the low density rocks in this section which is popularly referred to as graveyards of the subducted rocks under geoid lows. The subducted slab is hydrated due to dehydration from metamorphism that causes upwelling in the mid-to-upper mantle˜ which is likely to set in baby plumes. Presence of fluid may transform part of olivine to serpentine further reducing the bulk density of rocks in this section. They would make this region buoyant that appears to be responsible for the Central Indian Ocean Deformation Zone with large scale folding, faulting, seismicity, and high heat flow. The same also appear to be responsible for the rapid drift of the Indian plate. Short wavelength component of the Indian Ocean geoid low reflects most of the surface/shallow tectonics of the region similar to the gravity anomaly providing an additional data set for this purpose. Kachchh and the Shillong plateau inspite of being in the intra plate region are highly seismogenic that compare almost to the activity along the plate boundaries. Tectonics and residual geoid anomalies of the Indian continent and adjoining regions suggest that the geoid highs of Kachchh and the Shillong plateau along the NW and the NE corners of India are connected to the geoid highs of the plate boundaries through several lineaments and faults that also show geoid highs and trends of seismic activity leading to plate boundaries. Geoid highs indicating high density mafic rocks suggest their connections/extensions to plate boundaries indicating them to be plausibly part of diffused plate boundaries. Besides, both these regions are affected by (i) prominent lithospheric flexure of the Indian plate (ii) large scale mafic intrusions and (iii) interaction of proterozoic mobile belts with effects of present day Himalayan orogeny that make them more vulnerable for seismic activity.

- **'Mapping the crustal thickness in Shillong-Mikir Plateau and its adjoining region of northeastern India using Moho reflected waves'; *Dipok K.Bora, Saurabh Baruah; Journal of Asian Earth Sciences, Vol. 48, pp. 83-92, 2012***

Abstract

In this study we have tried to detect and collect later phases associated with Moho discontinuity and used them to study the lateral variations of the crustal thickness in Shillong-Mikir Hills Plateau and its adjoining region of northeastern India. We used the inversion algorithm by Nakajima et al. (Nakajima.J., Matsuzawa, T.Haesgawa, A.2002, Moho depth variation in the central part of northeastern Japan estimated from reflected and converted waves. Physics of the earth and Planetary Interiors, 130, 31-47), having epicentral distance ranging from 60 km to 150 km. Taking the advantage of high quality broadband data now available in northeast India, we have detected 1607 Moho reflected phases (PnP and SnS) from 300 numbers of shallow earthquake events (depth $\leq$ 25 km) in Shillong-Mikir Hills Plateau and its adjoining region. Notably for PnP phase, this could be identified within 0.5-2.3 s after the first P-arrival. In case of SnS phase, the arrival times are observed within 1.0-4.2 s after the first S-arrival. We estimated the crustal thickness in the study area using travel time difference between the later phases (PnP and SnS) and the first P and S arrivals. The results shows that the Moho is thinner beneath the Shillong Plateau about 35-38 km and is the deepest beneath the Brahmaputra valley to the north about 39-41km, deeper by 4-5 km compared to the Shillong Plateau with simultaneous observations of thinner crust (~33 km) in the western part of the Shillong Plateau in the Garo Hills region.

- **'The Dauki Fault at the Shillong Plateau-Bengal Basin Boundary in Northeastern India: 2D Finite Element Modeling'; *Md Shofiqul Islam, Ryuichi Shinjo; Journal of Earth Science, Vol. 23, No. 6, pp. 854-863, December 2012; DOI:10.1007/s12583-012-0297-7***

Abstract

The Dauki fault is a major fault along the southern boundary of the Shillong plateau that may be a source of destructive seismic hazards for the adjoining areas, including northeastern Bangladesh. In this study, we simulated the present stress distribution and the ongoing convergence deformation within the study area using numerical simulation. This simulation attempts to determine the proper dip angle of the Dauki fault from a variety of differently established models but with the same realistic boundary conditions. The simulated stress field helped to predict the type of tectonic environment and the faulting patterns of the study area. The best-fit model can account for the compressive stress regime in the study area, except in the uppermost part of the Shillong plateau, the Bengal basin, and Assam areas where extensional stress regimes exists. In the model, the elements for which Mohr-Coulomb's failure occurs correspond with the observed earthquake data that refer to the Dauki fault as a north-dipping thrust fault.

KEY WORDS: Dauki fault, Bengal basin, tectonic stress, earthquake.

- **'Structural Formation & Seismicity of Kopili Fault Region in North-East India and Estimation of Its Crustal Velocity'; *Kashyap Mahanta, Jyotimoi Das Chowdhury, Atowar UI Islam; International Journal of Modern Engineering Research (IJMER) ISSN: 2249-6645 12/2012; Volume 2(Issue 6):pp 4699-4702.***

Abstract

In the North-East India region, Meghalaya plateau plays a distinct physical characteristic for its high rising granitic rocks and rocks of Gondwana character. The exposed portion of the Indian peninsular shield is evident in Meghalaya plateau and Mikir hills. Here in the plateau we mainly get Archaean gneissic complex, overlain by proterozoic intracratonic sediments of Shillong group. Upper Cretaceous and Carbonatite ultramafic complex are also evident in Kopili Fault region. The Kopili Fault, which extends from western part of Manipur up to the tri-junction of Bhutan, Arunachal Pradesh and Assam, covers a distance of about 400 km. The Kopili fault bisects the Meghalaya Plateau and isolated the Mishmi block from the main part of the plateau. The fault behaviour is studied using Global Positioning System (GPS) techniques to understand the velocity of twelve (12) different points selected on both bank of the Kopili river, since the fault is almost passing through the river. From a field study of four long years, it is observed that the Kopili Fault region is moving in North-East direction at an average velocity of 28.397N(±1.167) mm/yr and 40.227E(±1.184) mm/yr. This paper makes an attempt to understand the physical development or geological character of the region and its crustal velocity studied on various parts of the Kopili Fault area.

- **'Source parameters and f_{max} in Kameng region of Arunachal Lesser Himalaya'; *Ashwani Kumar, Arjun Kumar, S.C.Gupta, Himanshu Mittal, Rohtash Kumar; Journal of Asian Earth Sciences; 2013***

Abstract

A data set of 79 local events ($0.7 \leq M_w \leq 3.7$) occurred during February 2003 to May 2003, collected by a temporary network deployed in Kameng region of Arunachal Lesser Himalaya have been analyzed to study the source parameters and $f_{\max}$. In this study Brune model that yield a fall-off of two beyond corner frequwncy along with high frequency diminution factor for the frequencies greater than $f_{\max}$ represented by a Butterworth high-cut filter (Boore, 1983) has been considered. The software EQK_SRC_PARA (Kumar et al., 2012) has been used to estimate the spectral parameters namely: low frequency displacement spectral level (Ω_0), corner frequency (f_c) above which spectrum decays with a rate of two, the high-cut frequency ($f_{\max}$) above which the spectrum again decays and the rate of decay (N) above $f_{\max}$. These spectral parameters are used to estimate source parameters, viz., seismic moments, source dimensions and stress drops and to develop scaling laws for the region. Seismic moments vary from 1.42 X 10^{17}-dyne-cm to 4.23 X 10^{21} dyne-cm: the source radii vary from 88.7 m to 931.5 m. For 28 events, stress drops are less than 1 bar and 51 events have stress drops between 1 bar and 40 bars. A scaling relation, M_0 (dyne-cm) = 2 X 10^{22} $f_c^{-3.34}$ has been derived for earthquakes having seismic moments greater than 1.5 x 10^{19} dyne-cm. The estimated values of $f_{\max}$ values by and large conform to the worldwide observations. Dependence of $f_{\max}$ on source sizes, focal depths, epicentral distances and recording sites has been studied on the basis of comparative dependency of f_c and $f_{\max}$. The $f_{\max}$ and f_c show almost similar dependency to seismic moments which shows $f_{\max}$ is also due to source process and is independent of epicentral distances and focal depths. At different recording sites, the observed values of $f_{\max}$ show consistent increase with seismic moment. This reflects that the source is the main controlling factor rather than recording site conditions for the observed variations of $f_{\max}$ in the Kameng region.

- **'Imaging lithospheric structure of the eastern Himalayan syntaxis: New insights from receiver function analysis'; *Qiang XU, Jummeng Zhao, Shunping Pei and Hongbing Liu; Journal of Geophysical Research: Solid Earth, Vol. 118, 2323-2332, DOI:10.1002/jgrb.50162, 2013***

Abstract

[I] We employ the P and S receiver function technique to data from the 44 seismic stations deploy in the eastern Himalayan syntaxis to investigate the crustal thickness, the average Poisson's ratio, and the depth of the lithosphere-asthenosphere boundary (LAB). The observed crustal thickness exhibits an overall NE-deepening trend, varying from 55 to 75 km. Two anomalous areas lie in the west and east of the Namche Barwa syntaxis characterize by thinner and thicker crust, respectively. The average Poisson's ratio within the study area are low in the north and moderate elsewhere with some high values in the south, consistent with felsic and intermediate rocks forming the crust. Our migrated images reveal the (1) the LAB of the Tibetan plate exists at relatively shallow depth (~110 km) and exhibits a gap beneath the Namche Barwa syntaxis, which may have formed by the delamination of mantle lithosphere due to local mantle upwelling, and (2) the LAB of the Asian plate is observed at a depth of ~180 km, which implies that the Asian plate has advanced southward to about 30^0N under the Lhasa terrane. Our results provide new insights into the understanding of continental subduction and lithospheric deformation of the eastern Himalaya syntaxis.

- **'Seismic landscape from Sarpang re-entrant, Bhutan Himalaya foredeep, Assam, India: Constraints from geomorphology and geology'; *Sujit Dasgupta,*** *Kiron Mazumdar, L.H.Moirangcha, Tanay Dutta Gupta, Basab Mukhopadhyay';Tectonophysics;592,130-140, 2013*

Abstract

Geomorphic landscape and late Quaternary geological attributes from the Raidak–Manas interfluve in the Bhutan–Himalayan foothills, Kokrajhar District, Assam led towards documenting the east–west trending, south dipping, 30 km long active Frontal Back Thrust (FBT), well within the foredeep south of the Main Frontal Thrust (MFT). Spectacular north facing 6–50 m high tectonic-scarp generated by the north-propagating emerging thrust front along with a complementary subdued south-facing scarp defines the terrain as a pop-up structure. The entire belt is made up of 5 to 8 km wide six distinct blocks, separated by antecedent rivers/streams. Scarp parallel east–west drainage along with linear lakes characterizes the emerging thrust front. Field evidence for a major fault-propagation fold structure along with thrust faulting within the late-Quaternary fluvial sediments is ubiquitous. Clay beds deposited in lakes along the footwall of FBT have formed due to blockade of south flowing rivers by episodic upliftment of the hanging wall block; three such episodes of uplift since 16 k years correspond to three morphogenic earthquakes of magnitude ~6.9 rupturing the FBT during late Pleistocene–Holocene. In light of geomorphological and geological studies, neotectonic activity has been modelled as an active south dipping back thrust that originates at shallow crustal depth from south vergent basal Himalayan Decollement in response to the advancing Himalayan wedge.

- **'Stochastic Finite Fault Modeling of Subduction Zone Earthquakes in Northeastern India'**; ***S.T.G.Raghu Kanth and B.Kavitha; Pure and Applied Geophysics, 170 (2013), pp. 1705-1727; DOI 10.1007/s00024-012-0622-1***

Abstract

In this article, a stochastic finite fault source model is calibrated to estimate ground motion in northeastern India for intermediate depth events originating in the Indo-Burmese tectonic domain. A total of 47 three-component accelerograms from eight events with magnitudes ranging from Mw 4.8–6.4 are used to estimate the input source and site parameters of the finite fault source model. Key seismic parameters such as stress drop (Δ_σ) and site amplification function are determined from the recorded strong motion data. The obtained stress drop of the eight recorded events lies in between 105 and 165 bars.

Key words: Strong ground motion, stochastic seismological model, site amplification, stress drop, subduction zone.

- **'Recent seismic status of Shillong Plateau, Northeast India'**; ***Ananta Panthi, H.N.Singh; Bibechana 9 (2013) 59-62***

Abstract

Seismic status of Shillong Plateau of Northeast India has been studied, considering spatial and temporal pattern of the region and using seismicity data for the period 1808-2008. Cutoff magnitude and b-value has been estimated using earthquake data for the period 1963-2008. Seismic activity is observed to be very feeble along the major faults of Shillong Plateau and strong activity is found to occur slightly away from these faults and confined within middle portion at two locations of the region. The temporal pattern shows that the

region is due for great earthquake. Focal depth distribution of the events shows that all the events are intermediate depth (less than 70 km).

Keywords: b-value, seismicity, faults, focal depth, temporal, spatial

- **'Aseismic plate boundary in the Indo-Burmese wedge, northwest Sunda Arc'; *Vineet K.Gahalaut, Bhaskar Kundu, Sunil Singh Laishram, Joshi Catherine, Arun Kumar, M.Devchandra Singh, R.P.Tiwari, R.K.Chadha, S,K.Samanta, A.Ambikapathy, P.Mahesh, Amit Bansal and M.Narsaiah; Geology; (First published online January 4, 2013, doi:10.1130/G33771.1) v. 41, No. 2, pp. 235-238***

Abstract

Plate motion, crustal deformation, and earthquake occurrence processes in the northwest Sunda Arc, which includes the Indo-Burmese wedge (IBW) in the forearc and the Sagaing fault in the backarc, are very poorly constrained. Plate reconstruction models and geological structures in the region suggest that subduction in the IBW occurred in the geological past, but whether it is still active and how the plate motion between the India and Sunda plates is partitioned between motion in the IBW and Sagaing fault is largely unknown. Recent GPS measurements of crustal deformation and available long-term rates of motion across the Sagaing fault suggest that ∼20 ± 3 mm/yr of the relative plate motion of ∼36 mm/yr between the India and Sunda plates is accommodated at the Sagaing fault through dextral strike-slip motion. We report results from a dense GPS network in the IBW that has operated since 2004. Our analysis of these measurements and the seismicity of the IBW suggest that the steeply dipping Churachandpur-Mao fault in the IBW accommodates the remaining motion of ∼18 ± 2 mm/yr between the India and Sunda plates through dextral strike-slip motion, and this motion occurs predominantly through velocity strengthening frictional behavior, i.e., aseismic slip. The aseismic motion on this plate boundary fault significantly lowers the seismic hazard due to major and great interplate earthquakes along this plate boundary.

- **Grain Scale physical signatures of early Seismio-tectonic occurrences in fault rock: A study in Gajalia fold belt, Tripura (India)'; *Sudip Dey and Sushmita Paul; J. Ind. Geophys. Union, Vol. 17, No. 1, pp. 39-47, January 2013***

Abstract

This paper attempts to assess the microstructural signatures of early seismio-tectonic occurrences which are preserved in fault rocks. For that purpose, some samples were collected from a faulted zone of Gajalia, south Tripura. Digital imaging of the thin sections of those samples was performed for assessing grain scale deformation pattern. It has been observed that the tested samples are characterized by moderate foliations and various shapes of grain particles like round, sub-round, angular and sub-angular. The grain scale deformation patterns in the tested samples clearly show that very complex stress pattern at micro level developed during past seismic events. Fluid flows along the margins of foliations are found which is important for weakening mechanism to initiate seismic slip. From the microstructure of the samples it is assessed that various physical processes like stress development, friction and fluid flow play the key role for brittle deformation of grains during seismo-tectonic events.

- **Intensity map of M*w* 6.9 2011 Sikkim-Nepal border earthquake and its relationships with PGA: distance and magnitude'; *Sanjay K.Prajapati, Ashok Kumar,***

Sumer Chopra, B.K.Bansal; Nat Hazards (2013) 69: 1781-1801; DOI; 10.1007/s11069-013-0776-x

Abstract

We compiled available information of damages and other effects caused by the September 18, 2011, Sikkim-Nepal border earthquake from the print and electronic media, and interpreted them to obtain Modified Mercalli Intensity (MMI) at over 142 locations. These values are used to prepare the intensity map of the Sikkim earthquake. The map reveals several interesting features. Within the meizoseismal area, the most heavily damaged villages are concentrated towards the eastern edge of the inferred fault, consistent with eastern directivity. The intensities are amplified significantly in areas located along rivers, within deltas or on coastal alluvium such as mud flats and salt pans. We have also derived empirical relation between MMI and ground motion parameters using least square regression technique and compare it with the available relationships available for other regions of the world. Further, seismic intensity information available for historical earthquakes which have occurred in NE Himalaya along with present intensity has been utilized for developing attenuation relationship for NE India using two-step regression analyses. The derived attenuation relation is useful for assessing damage of a potential future earthquake (earthquake scenario-based planning purposes) for the northeast Himalaya region.

Keywords: Earthquake, Sikkim, Intensity, Attenuation

- **'State of Tectonic Stress in Northeast India and Adjoining South Asia Region: An Appraisal'; *Santanu Baruah, Saurabh Baruah, and J.R.Kayal; Bulletin of the Seismological Society of America, Vol. 103, No. 2A, pp. 894-910, April 2013; doi:10.1785/0120110354***

Abstract

An attempt is made to map the spatial variation in the tectonic stress pattern in northeast India and its adjoining south Asia region using stress tensor inversion of some 516 fault-plane solutions. The Bhutan Himalaya and the Arunachal Himalaya are mapped with north-south to north-northwest-south-southeast compression. The eastern Himalaya syntaxis zone, on the other hand, shows a clockwise rotation: a north-northeast compression is dominant. To the south, in the interplate part of the region, the Shillong plateau, Assam valley, Bengal basin (Bangladesh), and Tripura fold belt exhibit north-northwest to north-northeast compression. Orthogonal horizontal extension is diminant in southern Tibet, Bhutan, and partly in the syntaxis zone, and the same is also observed in the Shillong plateau and Assam valley area of the interplate region. The Indo-Burma ranges and the Sagaing fault in the in the Myanmar region show a northeast-southwest compression: an orthogonal horizontal northwest-southeast extension is also observed in the Sagaing fault zone. A depth variation of the tectonic stress is observed below the Indo-Burman ranges: it changes from north-south to northeast-southwest in the southern part, and from northeast –southwest to north-northeast-south-southwest in the northern part in the deeper seismogenic zone. The stress inversion results of clusters of events in individual zones, though mostly conformable with the average observations, indicate a variation in the Shillong plateau due to heterogeneity and tectonic complexity.

- **'Seismic landscape from Sarpang re-entrant, Bhutan Himalaya foredeep, Assam, India: Constraints from geomorphology and geology'; *Sujit Dasgupta, Kiron Mazumdar, L.H.Moirangcha, Tanay Dutta Gupta, Basab Mukhopadhyay; Tectonophysics, Volume 592, 19 pages 130-140, April 2013***

Abstract

Geomorphic landscape and late Quaternary geological attributes from the Raidak-Manas interfluve in the Bhutan-Himalayan foothills, Kokrajhar District, Assam led towards documenting the east-west trending, south dipping, 30 km long active Frontal Back Thrust (FBT), well within the foredeep south of the Main Frontal Thrust (MFT). Spectacular north facing 6-50 m high tectonic-scrap generated by the north-propagating emerging thrust front along with a complementary subdued south-facing scrap defines the terrain as a pop-up structure. The entire belt is made up of 5 to 8 km wide six distinct blocks, separated by antecedent rivers/streams. Scrap parallel east-west drainage along with linear lakes characterizes the emerging thrust front. Field evidence for a major fault-propagation fold structure along with thrust faulting within the late-Quaternary fluvial sediments is ubiquitous. Clay beds deposited in lakes along the footwall of FBT have formed due to blockade of south flowing rivers by episodic upliftment of the hanging wall block; three such episodes of uplift since 16 k years correspond to three morphogenic earthquakes of magnitude ~6.9 rupturing the FBT during late Pleistocene-Holocene. In light of geomorphological and geological studies, neotectonic activity has been modelled as an active south dipping backthrust that originates at shallow crustal depth from south vergent basal Himalayan Decollement in respone to the advancing Himalayan wedge.

Keywords: Bhutan Himalaya, Sarpang, Backthrust, Active fault, Foredeep

- **'The plate contact geometry investigation based on earthquake source parameters at the Burma arc subduction zone'; *Zhang LangPing, Shao ZhiGang, MA HongSheng, Wang XingZhou and Li Zhihai; Science China, Earth Sciences, May 2013, Vol. 56, No. 5, pp. 806-817; doi:10.1007/s11430-012-4578-x***

Abstract

Accurately characterizing the three-dimensional geometric contacts between the crust of the Chinese mainland and adjacent regions is important for understanding the dynamics of this part of Asia from the viewpoint of global plate systems. In this paper, a method is introduced to investigate the geometric contacts between the Eurasian and Indian plates at the Burma arc subduction zone using earthquake source parameters based on the Slab1.0 model of Hayes et al. (2009, 2010). The distribution of earthquake focus depths positioned in 166 sections along the Burma Arc subduction zone boundary has been investigated. Linear plane fitting and curved surface fitting has been performed on each section. Three-dimensional geometric contacts and the extent of subduction are defined quantitatively. Finally, the focal depth distribution is outlined for six typical sections along the Burma arc subduction zone, combining focal mechanisms with background knowledge of geologic structure. Possible dynamic interaction patterns are presented and discussed. This paper provides an elementary method for studying the geometric contact of the Chinese mainland crust with adjacent plates and serves as a global reference for dynamic interactions between plates and related geodynamic investigations.

Keywords: Burma arc subduction zone, earthquake source parameters, plate boundary, geometric contact, Slab1.0 model

- **'Largest earthquake in Himalaya: An appraisal'; *H.N.Srivastava, B.K.Bansal, Mithila Verma; Journal Geological Society of India, Volume 82, Issue 1, pp 15-22, July 2013***

Abstract
The largest earthquake (Mw 8.4 to 8.6) in Himalaya reported so far occurred in Assam syntaxial bend in 1950. However, some recent studies have suggested for earthquake of magnitude M_w 9 or more in the Himalayan region. In this paper, we present a detailed analysis of seismological data extending back to 1200 AD, and show that earthquake in Himalayan region may not be expected to be as large as those of subduction zones. Also, there appears to be a lateral variation in the earthquake magnitude, being lesser in the western syntaxial bend when compared close to the eastern syntaxial bend. This is attributed to the difference in the plate boundary scenario; dominance of strike-slip and thrusting along the western syntaxis as against thrusting and remnant subduction along the eastern syntaxis.

- **'Prevailing Stress pattern in the Indo-Myanmar region derived from Focal mechanism data using Multiple Inverse Method and its depth variation'; *Minakshi Devi, Aditya Kalita, Santanu Baruah, Saurabh Baruah; Int. J. Engg. Sc. & Mgmt. Vol. III Issue II Jul-Dec 2013***

Abstract
A multiple inverse method has been used to separate stresses from a set of focal mechanism data of Indo-Myanmar region. Four parameters are determined by the inversion; one for the shape of the stress ellipsoid and three for the direction of principal stress axes. Most prominently, the area is affected by a stress state with a horizontal NE-SW directed maximum compression with low stress ratio which has induced thrust and strike-slip faulting in the region. Study of variation of stress pattern in three different depths ranges (0-45 Km, 45-90 Km and 90-150 Km) in the study region shows rotation of maximum principal stress axis towards North at higher depths.

Keywords: Fault–slip data, stress tensor, parameter space, focal mechanism solution, principal stress axis.

- **'Attenuation character of seismic waves in Sikkim Himalaya'; *Pinki Hazarika, M.Ravi Kumar and Dinesh Kumar; Geophysical Journal International; (2013); DOI: 10.1093/gji/ggt241 (First published online: July 18, 2013)***

Abstract
In this study, we investigate the seismic wave attenuation beneath Sikkim Himalaya using *P*, *S* and coda waves from 68 local earthquakes registered by eight broad-band stations of the SIKKIM network. The attenuation quality factor (*Q*) depends on frequency as well as lapse time and depth. The value of *Q* varies from (i) 141 to 639 for *P* waves, (ii) 143 to 1108 for *S* waves and (iii) 274 to 1678 for coda waves, at central frequencies of 1.5 Hz and 9 Hz, respectively. The relations that govern the attenuation versus frequency dependence are Q_α =

$(96 \pm 0.9)f^{(0.94 \pm 0.01)}$, $Q_\beta = (100 \pm 1.4)f^{(1.16 \pm 0.01)}$ and $Q_c = (189 \pm 1.5)f^{(1.2 \pm 0.01)}$ for *P*, *S* and coda waves, respectively. The ratio between Q_β and Q_α is larger than unity, implying larger attenuation of *P* compared to *S* waves. Also, the values of Q_c are higher than Q_β. Estimation of the relative contribution of intrinsic (Q_i) and scattering (Q_s) attenuation reveals that the former mechanism is dominant in Sikkim Himalaya. We note that the estimates of Q_c lie in between Q_i and Q_s and are very close to Q_i at lower frequencies. This is in agreement with the theoretical and laboratory experiments. The strong frequency and depth dependence of the attenuation quality factor suggests a highly heterogeneous crust in the Sikkim Himalaya. Also, the high *Q* values estimated for this region compared to the other segments of Himalaya can be reconciled in terms of moderate seismic activity, unlike rest of the Himalaya, which is seismically more active.

Keywords Body waves, Coda waves, Seismic attenuation, Continental margins: Convergent

- **'Active Fault Mapping: An Initiative towards Seismic Hazard Assessment in India'; *Mithila Verma and B.K. Bansal; Journal Geological Society of India; Vol. 82, pp. 103-106, August 2013***

Abstract

Identification and characterization of active faults and deciphering their seismic potential are of vital importance in seismic hazard assessment of any region. Seismic vulnerability of India is well known as more than 60% of its area lies in high hazard zones due to the presence of major active faults in its plate boundaries and continental interiors, which produced large earthquakes in the past and have potential to generate major earthquakes in future. The safety of critical establishments, like Power plants, Refinaries and other lifeline structures is a major concern in these areas and calls for a better characterization of these faults to help mitigate the impact of future earthquakes. The paper provides a brief overview of the work carried out in India on active fault research, its limitations and immediate priorities.

- **'The crust below the Indo-Myanmar Ranges of northeast India: A preliminary model in differential isostasy'; *Sanasam Subhamenon Singh;Journal of Himalayan Earth Sciences 46(2) (2013) 1-7***

Abstract

The sediments of the Indo-Myanmar Ranges of northeast India had been deposited in a subsidence basin open up by rifting nearby the Myanmar continental margin. Thickening of the crust in this belt is due to lateral compression of the basin sediments by overriding continental margin of Myanmar. From the viewpoint of the tectonic setting of the region, the variation in the degree of crustal shortening along the ranges, calculated depth to detachment and supported by petro-geochemical evidences, an evolutionary model of the Indo- Myanmar Ranges Basin has been worked out. Calculating the excess thickness of the crust, a model of the crust below the ranges is constructed using principles of differential isostasy. A narrow strip of detached continental landmass, embedded under the sediments, is predicted in this preliminary study.

Keywords: Tectonics; Ophiolites; Thrust; Depth to detachment; Isostasy.

- **'Evidence for Pliocene–Quaternary normal faulting in the hinterland of the Bhutan Himalaya'; *B.A. Adams, K.V. Hodges, M.C. van Soest, and K.X. Whipple; Lithosphere, Vol. 5, No. 4, pp. 438-449, Geological Society of America, 2013 Doi 10.1130/L277.1***

Abstract

In the central Himalaya, past researchers have identified a distinctive transition from the physiographic Lower Himalayan ranges in the south to the Higher Himalayan ranges in the north. Local relief and hill slope gradient, as well as erosion and surface uplift rates, increase abruptly across this transition to the north. In the eastern Himalaya, the same physiographic transition exists, but it is less dramatic. We describe here a previously undocumented steep, north-dipping, brittle structure that is roughly coincident with this physiographic transition in eastern Bhutan—the Lhuentse fault. Low-temperature (U-Th)/He apatite data suggest that the Lhuentse fault has been active since the Pliocene, and (U-Th)/He dates on offset hydrothermal hematite deposits from within the fault zone demonstrate a component of Quaternary slip. Although we identified no definitive evidence of fault kinematics based on fi eld or petrographic analysis of the fault rocks, the disrupted pattern of (U-Th)/He apatite dates suggests normal-sense displacement, contrary to what was expected given previous studies of an analogous transition in the central Himalaya. We regard the existence and activity of the Lhuentse fault as evidence of (1) recent evolution in the tectonic regime of the eastern Himalaya from one of near-exclusive north-south shortening to one in which both transcurrent and normal faulting are increasingly important in the region north of the Himalayan deformation front, or (2) an active duplex south of the physiographic transition in the middle latitudes of Bhutan.

- **'Seismotectonics of Lower Assam, Northeast India, Using the Data of a Dense Microseismic Network'; *A.Serpetsidaki, N.K.Verma, G-A.Tselentis, N.Martakis, K.Polychronopoulou and P.Petrou; Bulletin of the Seismological Society of America, Vol. 103, No. 5, pp. -, October 2013, doi: 10.1785/0120130056***

Abstract

Northeast India has been subjected to extensive compressional forces, mainly in north-south and east-west directions resulting from the convergence of the Indian plate with the Eurasian and Burmese plates, respectively. The area is characterized as one of the most seismically active regions of the world: however, the lower Assam valley's microseismicity has not been monitored and studies intensively by a dense seismic network during the past. During this study, a seismic network of 76 stations was deployed in northeastern India for one year. Hundreds of microearthquakes were recorded. The most accurately located events, moment tensor solutions, and focal mechanisms were used in order to define the seismotectonic and stress regime in the area.

- **'Separation of intrinsic and scattering seismic wave attenuation in Northeast India'; *Simanchal Padhy, N. Subhadra, Geophysical Journal International; 195(3), pp. 1892-1903; 12/2013; DOI:10.1093/gji/ggt350***

Abstract

We have analysed the local earthquakes ($2.0 \leq ML \leq 5.5$) occurred in northeast (NE) India recorded by a temporary seismic network of 10 stations operated by National Geophysi-

cal Research Institute (NGRI), Hyderabad to evaluate the relative contributions of scattering loss ($Q_{sc}^{ - 1}$) and intrinsic absorption ($Q_i^{ - 1}$) to total attenuation ($Q_t^{ - 1}$) using the multiple lapse time window analysis assuming multiple isotropic scattering in a medium of uniformly distributed scatterers. The results show that $Q_i^{ - 1}$ is greater than $Q_{sc}^{ - 1}$ at high frequencies (f > 3 Hz), while the opposite is observed at low frequencies (f < 3 Hz). The observed frequency dependence of $Q_{sc}^{ - 1}$ corresponds to the scale length of lithospheric heterogeneity beneath NE India, at least comparable with the wavelength for the lowest frequencies analysed, of about 1 km. The observed $Q_{{c}}^{ - 1}$ for the study region obtained with single scattering theory is close to $Q_i^{ - 1}$ at high frequencies, in agreement with theoretical prediction for an idealized case of uniform distribution of scatterers. However, a discrepancy exists between the two at low frequencies, which can be explained by a depth-dependent velocity and attenuation structure. High value of $Q_t^{ - 1}$ is correlated with the geology and tectonic settings of the region characterized by Himalayan and Burman collision zones with a strong lateral heterogeneity. The $Q_i^{ - 1}$ estimates obtained in this study can be used to infer the average temperature of the lower crust with an upper limit estimate of ˜800 °C assuming a lower crustal gabbroic lithology.

- **'Separation of intrinsic and scattering seismic wave attenuation in Northeast India'; *Simanchal Padhy and N.Subhadra; Geophys. J. Int. (December, 2013); 195 (3); 1892-1903; doi: 10.1093/gji/ggt350***

Summary

We have analysed the local earthquakes ($2.0 \leq M_L \leq 5.5$) occurred in northeast (NE) India recorded by a temporary seismic network of 10 stations operated by National Geophysical Research Institute (NGRI), Hyderabad to evaluate the relative contributions of scattering loss (Q_{sc}^{-1}) and intrinsic absorption (Q_i^{-1}) to total attenuation (Q_t^{-1}) using the multiple lapse time window analysis assuming multiple isotropic scattering in a medium of uniformly distributed scatters. The results show that Q_i^{-1} is greater than Q_{sc}^{-1} at high frequencies ($f > 3$ Hz), while the opposite is observed at low frequencies($f < 3$ Hz). The observed frequency dependence of Q_{sc}^{-1} corresponds to the scale length of lithospheric heterogeneity bemeath NE India, at least comparable with the wavelength for the lowest frequencies analysed, of about 1 km. The observed Q_c^{-1} for the study region obtained with single scattering theory is close to(Q_i^{-1}) at high frequencies, in agreement with theoretical prediction for an idealized case of uniform distribution of scatters. However, a discrepancy exists between the two at low frequencies, which can be explained by a depth-dependent velocity and attenuation structure. High value of (Q_t^{-1}) is correlated with the geology and tectonic settings of the region characterized by Himalayan and Burman collision zones with a strong lateral heterogeneity. The Q_i^{-1} estimates obtained in this study can be used to infer the average temperature of the lower crust with an upper limit estimate of ~ 800^0 C assuming a lower crustal gabbroic lithology.

Keywords : Seismic attenuation, Wave scattering and diffraction, Wave propagation

- **'The 2011 M_W 6.8 Burma earthquake: fault constraints provided by multiple SAR techniques'; *Wanpeng Feng, Zhenhong Li, John R.Elliot, Yo Fukushima, Trevor Hoey, Andrew Singleton, Robert Cook and Zhonghuai Xu; Geophysical Journal International; 195 (1), pp. 650-660, October 2013; doi:10.1093/gji/ggt254***

Summary

We used two tracks of ALOS PALSAR images to investigate the focal mechanism and slip distribution of the 2011 March 24, M_W 6.8 Burma strike-slip earthquake. Three different SAR techniques, namely conventional interferometry, SAR pixel offsets (SPO) and multiple-aperture InSAR (MAI), were employed to obtain the coseismic surface deformation fields along the ~30 km length of the fault rupture. Along-track measurements from SPO and MAI techniques show a high correlation, and were subsequently used to precisely determine the location and extent of the surface fault trace. The best-fitting fault model geometry derived from an iterative inversion technique suggests that the rupture occurred on a near-vertical sinistral strike-slip fault west of the Nam Ma fault with a strike of 70^0. A maximum slip of 4.2 m occurs at a depth of 2.5 km, with significant slip constrained only to the upper 10 km of the crust.

Keywords: Numerical solutions, Inverse theory, Radar interferometry, Seismicity and tectonics

- **'Seismic treatment for a maximum credible earthquake in Guwahati city area of northeast India region'; *Olga Erteleva, Felix Aptikaev, Saurabh Baruah, Santanu Baruah, Sajal K.Deb, J.R.Kayal; Nat Hazards; Vol. 70, Issue 1, pp. 733-753, 2014***

Abstract

Strong ground motion parameters for the Guwahati city area, the capital city of the state of Assam in northeast India, are examined with the help of data accrued from local as well as worldwide network. Empirical relations are proposed for the ground motion parameters as a function of earthquake magnitude, distance, fault type, source depth and velocity characteristics of medium. Seismotectonics of the study region is examined, and a maximum credible earthquake M_s ~ 8.0 is presumed from the Brahmaputra fault, the nearest source zone in the city area. Such great/major event may cause intensity of the of 9.3 with a probability of 0.95 in the Guwahati city during time interval of 500 years. Further, the design spectrum with 67% confidence level and the synthetic three-component accelerograms are constructed. These results are much relevant and useful for structural engineering to mitigate seismic hazards in the region.

Keywords: Guwahati city, Assam valley, Ground acceleration, Magnitude, Intensity, Attenuation, Response spectrum

- **'Seismotectonics of the great and large earthquakes in Himalaya'; *J.R.Kayal; Special Section: Science of the Himalaya; Current Science, Vol. 10 188 6, No. 2, 25 January 2014***

Abstract

The best known seismotectonic model of the Himalayan Seismic Belt (HSB) suggests that the great and large earthquakes in the Himalaya occur at a shallow depth (10–20 km) by thrust faulting on the Main Himalayan Thrust, i.e. on the plane of detachment. The plane of detachment is the interface between the Indian shield and the Himalayan sedimentary wedge. The recent earthquake data of the permanent and temporary local networks in the Himalaya, however, indicate bimodal seismicity at shallow (0–20 km) as well as greater depths (30–50

km). The source processes of the great and large earthquakes are reexamined in this article (the observations do not support a uniform seismotectonic model for the entire HSB). The four known great earthquakes (*Ms* ~8.0–8.7) in the Himalayan region, from west to east are the 1905 Kangra, 1934 Bihar, 1897 Shillong and the 1950 Assam earthquakes that occurred by different tectonic processes; each occurred in its own unique complex tectonic environment. Most recently, the 1988 strong earthquake (*Ms* 6.6) in the Bihar/Nepal foothill Himalaya and the 2011 strong earthquake (*Mw* 6.9) in the Sikkim Himalaya show that these are not the plane of detachment events; these occurred by strike–slip faulting at mantle depth (~ 50 km). A review of all these significant earthquakes in HSB is presented in this article.

Keywords: Fault plane solutions, plane of detachment, seismotectonics, thrusts, lineaments

- **'The September 2011 Sikkim Himalaya earthquake Mw 6.9: Is it a plane of detachment earthquake?'; *Santanu Baruah, Sowrav Saikia, Saurabh Baruah, Pabon K. Bora, Ruben Tatevossian and J.R.Kayal; Geomatics, Natural Hazards and Risk, 2014; doi:10.1080/19475705.2014.895963***

Abstract

The 18 September 2011 Sikkim Himalaya earthquake of Mw 6.9 (focal depth 50 km, NEIC report) with maximum intensity of VII on MM scale (www.usgs.gov) occurred in the Himalayan seismic belt (HSB), to the north of the main central thrust. Neither this thrust nor the *plane of detachment* envisaged in the HSB model, however, caused this strong devastating earthquake. The Engdahl-Hilst-Buland (EHB) relocated past earthquakes recorded during 1965-2007 and the available global centroid moment tensor solutions are critically examined to identify the source zone and stress regime of the September 2011 earthquake. The depth section plot of these earthquakes shows that a deeper (10-50 km) vertical fault zone caused the main shock in the Sikkim Himalaya. The NW (North-West) and NE (North-East) trending transverse fault zones cutting across the eastern Himalaya are the source zones of the earthquakes. Stress inversion shows that the region is dominated by horizontal NNW-SSE (North of North-West-South of South-East) compressional stress and low angle or near horizontal ENE-WSW (East of North-East-West of South-West) tensional stress; this stress regime is conducive for strike-slip faulting earthquakes in Sikkim Himalaya and its vicinity. The Coulomb stress transfer analysis indicates positive values of Coulomb stress changes ΔS_f for failure in the intersecting deeper fault zone that produced the four immediate felt aftershocks ($M \geq 4.0$)

4.5.2 MAGNITUDE STUDIES

- **On the Bayesian analysis of the earthquake hazard in the North-East Indian peninsula. Imtiyaz A.Parvez. *Natural Hazards, Vol. 40, pp. 397-412, 2007, Doi:10.1007/s11069-006-9002-4.***

Abstract:

The Bayesian extreme-value distribution of earthquake occurrences has been used to estimate the seismic hazard in 12 seismogenic zones of the North-East Indian peninsula. The Bayesian approach has been used very efficiently to combine the prior information on

seismicity obtained from geological data with historical observations in many seismogenic zones of the world. The basic parameters to obtain the prior estimate of seismicity are the seismic moment, slip rate, earthquake recurrence rate and magnitude. These estimates are then updated in terms of Bayes' theorem and historical evaluations of seismicity associated with each zone. From the Bayesian analysis of extreme earthquake occurrences for North-East Indian peninsula, it is found that for T = 5 years, the probability of occurrences of magnitude (M_w = 5.0-5.5) is greater than 0.9 for all zones. For M_w = 6.0, four zones namely Z1 (Central Himalayas), Z5 (Indo-Burma border), Z7 (Burmese arc) and Z8 (Burma region) exhibit high probabilities. Lower probability is shown by some zones namely, Z4, Z12, and rest of the zones Z2, Z3, Z6, Z9, Z10 and Z11 show moderate probabilities.

Keywords: Earthquake occurrences, Bayesian estimators, Extreme values.

- **Probabilistic Assessment of Earthquake Hazards in the North-East Indian Peninsula and Hinukush Regions.** ***Imtiyaz A.Parvez and Avadh Ram. Pure and Applied Geophysics, 149 (1997) pp. 731-746.***

Abstract:

The Himalayan region is one of the most seismic prone areas of the world. The North-East (NE) Indian peninsula and the Hindukush regions mark the zone of collision of the Indian and Eurasaian plates. The probability of the occurrence of great earthquakes with magnitude greater than 7.0 during a specified interval of time has been estimated on the basis of four probabilistic models, namely, Wetbull, Gamma, Lognormal and Exponential for the NE Indian peninsula and Hindukush regions. The model parameters have been estimated by the method of Maximum Likelihood Estimates (MLE) and the Method of Moments (MOM). The cumulative probability is estimated for a period of 40 years from 1964 and is ranging between 0.881 to 0.995 by the year 1995, using all four models for the NE Indian peninsula. The conditional probabilty is also estimated and it is concluded that the NE Indian peninsula would expect a great earthquake at any time in the remaining years of the present century. For the Hindukush region, the cumulative probability has already crossed its highest value, but no earthquake of magnitude greater than 7.0 has occurred after 1974 in this area. It may attribute to the occurrence of frequent shocks of moderate size, as seventeen earthquakes of magnitude greater than 6.0, including four greater than 6.4, have been reported untill 1994 from this region.

Keywords: Earthquake hazards, NE Indian peninsula, probabilistic models.

- **Earthquake hazard in Northeast India – A seismic microzonation approach with typical case studies from Sikkim Himalaya and Guwahati city.** ***Sankar Kumar Nath, Kiran Kumar Singh Thingbaijam and Abhisek Raj. J.Earth Syst. Sci. 117, S2, November 2008, pp. 809-831.***

Abstract:

A comprehensive analytical as well as numerical treatment of seismological, geological, geomorphological and geotechnical concepts has been implemented through microzonation projects in the northeast Indian provinces of Sikkim Himalaya and Guwahati

city, representing cases of contrasting geological backgrounds – a hilly terrain and a predominantly alluvial basin respectively. The estimated maximum earthquakes in the underlying seismic source zones, demarcated in the broad northeast Indian region, implicates scenario earthquakes of *MW* 8.3 and 8.7 to the respective study regions for deterministic seismic hazard assessments. The microzonation approach as undertaken in the present analyses involves multi-criteria seismic hazard evaluation through thematic integration of contributing factors. The geomorphological themes for Sikkim Himalaya include surface geology, soil cover, slope, rock outcrop and landslide integrated to achieve geological hazard distribution. Seismological themes, namely surface consistent peak ground acceleration and predominant frequency were, thereafter, overlaid on and added with the geological hazard distribution to obtain the seismic hazard microzonation map of the Sikkim Himalaya. On the other hand, the microzonation study of Guwahati city accounts for eight themes – geological and geomorphological, basement or bedrock, landuse, landslide, factor of safety for soil stability, shear wave velocity, predominant frequency, and surface consistent peak ground acceleration. The five broad qualitative hazard classifications – ‘low’, ‘moderate’, ‘high’, ‘moderate high’ and ‘very high’ could be applied in both the cases, *albeit* with different implications to peak ground acceleration variations. These developed hazard maps offer better representation of the local specific seismic hazard variation in the terrain.

Keywords: Seismic microzonation, maximum earthquake, Guwahati city, Sikkim Himalaya.

- **Probabilistic seismic hazard analysis and estimation of Spectral Strong Ground Motion on bed rock in North East India. M.L.Sharma and Shipra Malik. *4th International Conference on Earthquake Engineering, Taipei, Taiwan, October 12-13, 2006 (Paper No. 015)***

Abstract:

The present paper consists of the probabilistic seismic hazard analysis for the North East Indian Region, which is one of the most seismically active regions in India. The region has been divided into four major seismogenic sources namely, the regional features in the Himalayas i.e Main boundary Thrust and Main Central Thrust, Eastern Syntaxis, Shillong massif and the north south trending Arakan Yoma seismic belt. The probabilistic seismic hazard estimation is carried out for ten seismogenic zones which are further subdivisions of these four seismogenic sources based on the seismotectonics modeling of the area. The complete as well as the extreme part of the catalogue is used to make maximum likelihood estimates of maximum probable earthquakes for various return periods. The maximum *b*-value estimated is 1.04 for Shillong Plateau (Seismogenic Zone III) while the return periods of magnitude 6.0 have been estimated as about seven years for the Eastern boundary Thrusts (Seismogenic zone VIII and IX), which are part of the Arakan Yoma ranges. The hazard in these individual zones is presented in form of seismic zoning at the bedrock level for 10% and 20% exceedance values of strong ground motion in 50 years. The epistemic errors have been considered using logic tree method by using the spectral attenuation relationship developed for the area as well as those developed for similar tectonic environments elsewhere and adopted for the region. The spectral acceleration at different structural periods is presented for major cities in the region. The PGA value ranges from 0.05_G to 10% exceedance while the PGA value ranges from 0.01_G to 0.04_G for the 20% exceedance in 50 years. The results of the probabilistic seismic hazard analysis in the present study may be used for the seismic microzonation of the area and for earthquake engineering use.

Keywords: Seismic hazard, PSHA, Himalayas, Spectral ground motion.

- **GSHAP revisited for the prediction of Maximum Credible earthquake in the Sikkim region, India. Madhav Vyas, Sankar Kumar Nath, Indrajit Pal, Probal Sengupta and William K.Mohanty.** ***ACTA Geophysica Polonica, Vol. 53, No. 2, pp. 143-152, 2005.***

Abstract:

Global Seismic Hazard Assessment Program (GSHAP) has classified the Indian peninsula into several seismogenic zones. Considering the seismo-tectonic setting of the Sikkim Himalaya, sources 2, 3, 4, 5, 25, 26, 27 and 86 may be critical in contributing to the seismic hazard of the region. These seismogenic zones have been classified as Himalayan source (25, 86), extension of Tibetan plateau (26, 27), Burmese arc subduction zone (4, 5), Shillong plateau (3) and the Indian Shield region (2). The probabilistic seismic hazard assessment of the region necessitated prediction of Maximum Credible Earthquake magnitude for each source with 10% probability of exceedance in 50 years. Considering the widespread damages caused in the state capital of Sikkim due to the recent earthquakes of 1934 (Mw = 8) and 1988 (Mw = 7.2) a 50-year prediction seemed to be reasonable. Gutenberg–Richter (b-value) approach and Gumbel's method of extreme value statistics have been used in the present analysis for the prediction of Maximum Credible Earthquake magnitude, results of both being compa-rable to each other. The maximum credible earthquake magnitude as predicted by both the methods are above 6 except for zone 26, the highest being in the Burmese arc with a magnitude of 8.5 by Gutenberg–Richter approach and a magnitude of 7.7 by Gumbel's method.

Key words: GSHAP, seismogenic zone.

- **A Probable Isoseismal Map due Maximum Credible Earthquake (M=8.7) in NER, India- An Approach towards Risk Mitigation. Saurabh Baruah.** ***12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), 1-6 october, 2008, Goa, India.***

Abstract:

The study estimates the extent of seismic hazard in North East India in correlation to the past great earthquakes. Probable isoseismal maps through deterministic approach are prepared based on the basic information from two major earthquakes of 12th June 1897 (M=8.7) and 6th August 1988 (M=7.3). The study utilizes the database in the form of percentage increase in population and urbanization to the respective seismogenic zones available during the past earthquake besides the estimated peak ground acceleration for NER, India from GSHAP. The study shows that if an earthquake of M=8.7 were to recur today the devastation would be manifold because of abrupt increase in population and urbanization. The new isoseismal map depicts that much larger area covers maximum intensity at present in comparison to the isoseismal map during 1897 earthquake.

Keywords: Great Assam earthquake, isoseismal map.

- **A deterministic seismic hazard map of India and adjacent areas. Imtiyaz A.Parvez, Franco Vaccari and Giuliano F.Panza.** ***Geophys. J. Int. (2003) 155, 489-508.***

Summary:

A seismic hazard map of the territory of India and adjacent areas has been prepared using a deterministic approach based on the computation of synthetic seismograms complete with all main phases. The input data set consists of structural models, seismogenic zones, focal mechanisms and earthquake catalogues. There are few probabilistic hazard maps available for the Indian subcontinent, however, this is the first study aimed at producing a deterministic seismic hazard map for the Indian region using realistic strong ground motion modelling with the knowledge of the physical processes of earthquake generation, the level of seismicity and wave propagation in anelastic media. Synthetic seismograms at a frequency of 1 H_z have been generated at a regular grid of 0.2^0 X 0.2^0 by the modal summation technique. The seismic hazard, expressed in terms of maximum displacement (D_{max}), maximum velocity (V_{max}), and design ground acceleration (DGA), has been extracted from the synthetic signals and mapped on a regular grid over the studies territory. The estimated values of the peak ground acceleration are compared with the observed data available for the Himalayan region and are found to be in agreement. Many parts of the Himalayan region have DGA value exceeding 0.6 g. The epicentral areas of the great Assam earthquake of 1897 and 1950 in northeast India represent the maximum hazard with DGA values reaching 1.2-1.3 g. The peak velocity and the displacement in the same region is estimated as 120-177 cm s^{-1} and 60-90 cm, respectively.

Keywords: Design ground acceleration, deterministic modelling, Indian region, seismic hazard, synthetic seismograms.

- **A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry. Sankar Kumar Nath, Madhav Vyas, Indrajit Pal and Probal Sengupta.** ***Journal of Geophysical Research, Vol. 110, B01301, doi:10.1029/2004JB003199, 2005.***

Abstract:

In this paper, we present a seismic hazard map of the Indian Himalayan State of Sikkim, lying between Nepal and Bhutan Himalaya, in terms of horizontal peak ground accelerations with 10% exceedance probability over the next 50 years. These figures, the first for the region, were calculated through a stepwise process based on (1) an estimation of the maximum credible earthquake (MCE) from the seismicity of the region and Global Seismic Hazard Assessment Program considerations and (2) four seismotectonic parameters abstracted from accelerograms recorded at nine stations of the Sikkim Strong Motion Array, specifically installed for this study. The latter include (1) the frequency-dependent power law for the shear wave quality factor, QS, (2) the site response function at each station using receiver function analysis and generalized inversion, (3) source parameterization of various events recorded by the array and application of the resulting relationships between M0 and MW, and corner frequency, fc and MW to simulate spectral accelerations due to higher-magnitude events corresponding to the estimated MCE, and (4) abstraction of regional as well as site specific local

spectral attenuation laws at different geometrically central frequencies in low-, moderate-, and high-frequency bands.

- **The assessment of seismic hazard in two seismically active regions in Himalayas using deterministic approach. Kapil Mohan, A.Joshi and R.C.Patel. *J.Ind.Geophys. Union (July 2008), Vol. 12, No.3, pp.97-107.***

Abstract:

The long stretch of Himalaya is often visited by many major earthquakes from time to time. The work presented in this paper shows the seismic hazard in the northeast Himalayas and the Uttarakhand Himalayas, India. Seismic hazard estimation in these regions is based on the technique given by Joshi & Patel (1997). In this work, the finite rupture along the lineament has been modeled using the semi empirical technique proposed by Midorikawa (1993) and further modified by Joshi & Midorikawa (2005). The modeling procedure follows the ω2 scaling laws, directivity effects and other strong motion properties. The NE Himalaya has a complex geology. Seismic activities in this region are due to the trijunction of three mountain belts that are Himalayan range, Mishmi Hills and Naga Patkoi range. The huge oil reservoirs and hydroelectric power projects in this area prove its technoeconomic importance and requirement for detailed seismic hazard assessment. The seismic hazard zonation map for magnitude M=6 prepared in this region shows that places like the Tinsukia, North Lakhimpur, Dibrugarh, Ziro, Tezu, Sibsagar, Jorhat, Itanagar, Golaghat, Senapati, Wokha, Imphal and Kohima falls in highly hazardous Zone IV with peak ground acceleration of more than 250 cm/sec2. The places like the Daring, Pasighat, Seppa and Basar, region belongs to Zone III with peak ground accelerations of the order 200–250 cm/sec^2. The region of Uttarakhand Himalaya has witnessed 13 earthquakes of M=6 in last 97 years that indicates the occurrence of one strong earthquake in every 8 years (Rastogi 2000). This region has been visited by two major earthquakes in last one decade. Due to the technoeconomic importance of the region and poor construction practices of building houses, the need for seismic hazard estimation cannot be ruled out in this hilly area. The zonation map prepared for magnitude M ≥ 6.0 in this region using present technique shows that the places like the Munsiari, Dharchula, Lohaghat, Pithoragarh, Almora, Nainital, Uttarkashi and Karanparyag falls in Zone V with peak ground acceleration of more than 400 cm/sec2. The places like Sobla and Gopeshwar lies in Zone IV with peak ground acceleration more than 250 cm/sec2. The zonation maps prepared in this work are also compared with the historical past seismicity map of the respective regions and found that many moderate to major earthquakes falls in the identified hazardous zones.

- **Ground Motion for Scenario Earthquakes at Guwahati City. S.T.G.Raghukanth, J.Dixit, S.K.Dash. *Acta Geod. Geoph. Hung., Vol. 46(3), pp. 326-346* (2011); Doi:10.1556/A Geod.46.2011.3.5.**

Abstract:

In this article, stochastic finite-fault simulation combined with site response analysis is used to understand the spatial distribution of ground motion in Guwahati city due to three damaging earthquakes. The rock level ground motion for the scenario earthquakes is generated based on the stochastic finite-fault methodology. These simulated motions are further amplified up to the surface by equivalent linear site response analyses using the available bore log data at 100 different locations in Guwahati city. A set of twenty simulated rock level time histories for each event, are used to compute the surface level ground motion. Response spectra are computed and the results are presented in the form of contour maps, at selected natural periods. The mean amplification due to local soil deposit is as high as 2.2 at most of the sites in Guwahati city. Based on these simulated motions, an average site correction factor is obtained for soil sites in Guwahati city. The standard error in the simulated response spectra is also reported. The contour maps obtained will be useful in identifying vulnerable places in Guwahati city.

Keywords: Guwahati city; response spectra; seismological model; strong ground motion.

- **Ground motion estimation at Guwahati city for an M_W 8.1 earthquake in the Shillong plateau. S.T.G. Raghu Kanth, S.Sreelatha, Sujit Kumar Dash. *Tectonophysics, 448 (2008) 98-114.***

Abstract:

In this paper, the ground motion at Guwahati city for an 8.1 magnitude earthquake on Oldham fault in the Shillong plateau has been estimated by stochastic finite-fault simulation method. The corresponding acceleration time histories on rock level at several sites in the epicentral region have been computed. These results are validated by comparing them with the estimates obtained from Medvedev–Sponheuer–Karnik (MSK) intensity observations of 1897 Shillong earthquake. Using the local soil parameters, the simulated rock level acceleration time history at Guwahati city is further amplified up to the ground surface by nonlinear site response analysis. The results obtained are presented in the form of peak ground acceleration (PGA) contour map. The maximum amplification for PGA over Guwahati city is as high as 2.5. Based on the simulated PGA, the liquefaction susceptibility at several locations in the city has been estimated. The results are presented in the form of contours of factor of safety against liquefaction at different depths below the ground surface. It is observed that over a large part of the Guwahati city, the factor of safety against liquefaction is less than one, indicating that the city is highly vulnerable to liquefaction in the event of this earthquake. The contour maps obtained can be used in identifying vulnerable areas and disaster mitigation.

- **Probabilistic seismic hazard estimation of Manipur, India. Kumar Pallav, S.T.G.Raghukanth and Konjengbam Darunkumar Singh. *J. OF Geophys. And engineering, 9 (2012) 516-533; doi: 10.1088/1742-2132/9/5/516.***

Abstract:

This paper deals with the estimation of spectral acceleration for Manipur based on probabilistic seismic hazard analysis (PSHA). The 500 km region surrounding Manipur is divided into seven tectonic zones and major faults located in these zones are used to estimate seismic hazard. The earthquake recurrence relations for the seven zones have been estimated from past seismicity data. Ground motion prediction equations proposed by Boore and Atkinson (2008 *Earthq. Spectra* 24 99–138) for shallow active regions and Atkinson and Boore (2003 *Bull. Seismol. Soc. Am.* 93 1703–29) for the Indo-Burma subduction zone are used for estimating ground motion. The uniform hazard response spectra for all the nine constituent districts of Manipur (Senapati, Tamenglong, Churachandpur, Chandel, Imphal east, Imphal

west, Ukhrul, Thoubal and Bishnupur) at 100-, 500- and 2500-year return periods have been computed from PSHA. A contour map of peak ground acceleration over Manipur is also presented for 100-, 500-, and 2500-year return periods with variations of 0.075–0.225, 0.18–0.63 and 0.3–0.1.15 g, respectively, throughout the state. These results may be of use to planners and engineers for site selection, designing earthquake resistant structures and, further, may help the state administration in seismic hazard mitigation.

Keywords: PSHA, seismic hazard, Manipur.

- **Evaluation of seismic soil-liquefaction at Guwahati city. S.T.G. Raghu Kanth, Sujit Kumar Dash.** ***Environ Earth Sci. (2010) 61; 355-368; Doi: 10.1007/s12665-009-0347-3.***

Abstract:

Great earthquakes in the past (e.g. 1869 Cachar earthquake, 1897 great Assam earthquake) have caused large scale damage and ground liquefaction in the Guwahati city. Moreover, seismologists are of opinion that a great earthquake might occur in the unruptured segment of the North-East Himalaya that is near to Guwahati city. In this paper, the liquefaction hazard due to these events have been simulated. The obtained results are in general agreement with the reported damages due to the past earthquakes. The central part of the city (i.e. Dispur, GS road), that has large thickness of soft soil deposit and shallow ground water table, is highly vulnerable to liquefaction.

Keywords: Earthquake, Ground liquefaction, Guwahati city.

- **Deterministic seismic scenarios for North East India. S.T.G.Raghu Kanth, Sujit Kumar Dash.** ***J Seismol, Vol. 14, No. 2, pp. 143-167, 2010; Doi:10.1007/s10950-009-9158-y.***

Abstract:

In this paper, ground motion during six past devastating earthquakes and one possi ble future event in the northeastern part of India is estimated by seismological approaches. Considering uncertainty in the input source parameters, a series of ground motions have been simulated. The peak ground acceleration (PGA) and response spectra at important cities and towns in the epicentral regions of these events are obtained. The PGA distribution over the entire northeastern region of India, encompassing the epicenter, is presented in the form of contours. The obtained results can be used for the seismic analysis and design of structures in this region.

Keywords: Strong ground motion, PGA, Stochastic finite fault model, Northeast India, Response spectra.

- **Deterministic Seismic Scenarios for Imphal City. S.T.G.Raghu Kanth, Konjenbam Darunkumar Singh, Kumar Pallav.** ***Pure and Applied Geophysics, 04/2012, 166(4): 641-672, Doi:10.1007/s00024-009-0460-y.***

Abstract:

In this article, the spatial variation of ground motion in Imphal City has been estimated by the finite-fault seismological model coupled with site response analysis. The important seismic sources around Imphal City have been identified from the fault map and past seismicity data. The rock level acceleration time histories at Imphal City for the 1869 Cachar (M_W 7.5) earthquake and a hypothetical M_W 8.1 event in the Indo-Burma subduction zone have been estimated by a stochastic finite-fault model. Soil investigation data of 122 boreholes have been collected from several construction projects in Imphal City. Site response analysis has been carried out and the surface level ground motion has been determined for Imphal City for these two earthquake events. The results are presented in the form of peak ground acceleration (PGA) contour map. From the present study it has been ascertained that the maximum amplification for PGA over Imphal City is as high as 2.5. The obtained contour maps can serve as guidelines for identifying vulnerable areas and disaster mitigation in Imphal City.

- **Surface level ground motion estimation for 1869 Cachar Earthquake (M_W 7.5) at Imphal City. Kumar Pallav, S.T.G.Raghukanth and K.D. Singh.** ***Journal of Geophysics and Engineering, 07/2010, 7:321-331, Doi:10.1088/1742-2132/7/3/010.***

Abstract:

In this paper, the seismic susceptibility of Imphal city with respect to ten synthetically generated samples of the historic 1869 Cachar (Mw 7.5) earthquake that occurred in the Kopili fault is presented based on the finite-fault seismological model in conjunction with nonlinear site response analyses. For all the synthetic sample earthquake events, the mean and standard deviation of surface level spectral ground acceleration at peak ground acceleration (PGA) and natural periods of 0.3 and 1 s have been reported in the form of contour maps. These contour maps can serve as guidelines for engineers and planners to identify vulnerable areas for possible seismic disaster mitigation of Imphal city.

- **Seismicity parameters for important urban agglomerations in India. S.T.G. Raghukanth.** ***Bull Earthquake Eng., DOI 10.1007/s10518-011-9265-3.***

Abstract:

India's urban population has increased in the recent times. An earthquake near an urban agglomeration has the potential to cause severe damage. In this article, seismicity parameters for region surrounding important urban agglomerations in India are estimated. A comprehensive earthquake catalogue for the region (6◦E–42◦E latitude and 60◦N–100◦N longitude) including historic and pre-historic events has been compiled from various sources. To estimate the parameters, past earthquake data in a control region of radius 300 km has been assembled to quantify the seismicity around each urban agglomeration. The collected earthquake data is first evaluated for its completeness. From combined (historical and instrumental) data, the seismicity parameters *b*-value, seismic activity rate, λ and maximum expected magnitude (*mmax)* have been obtained from the methodology proposed by Kijko and Graham (1998). The obtained activity rates indicate that region surrounding Guwahati urban agglomeration is the most seismically active region followed by Srinagar, Patna, Amritsar and Chandigarh.

Keywords: Seismic hazard, Urban agglomerations, Recurrence relations.

- **A Probabilistic Seismic Hazard Analysis of Northeast India. Sandip Das, Ishwer D. Gupta, and Vinay K. Gupta. *Earthquake Spectra,* Volume 22, No. 1, pages 1–27, February 2006.**

Abstract:

Seismic hazard maps have been prepared for Northeast India based on the uniform hazard response spectra for absolute acceleration at stiff sites. An approach that is free from regionalizing the seismotectonic sources has been proposed for performing the hazard analysis. Also, a new attenuation model for pseudo-spectral velocity scaling has been developed by using 261 recorded accelerograms in Northeast India. In the present study, the entire area of Northeast India has been divided into 0.1° grid size, and the hazard level has been assessed for each node of this grid by considering the seismicity within a 300-km radius around the node. Using the past earthquake data, the seismicity for the area around each node has been evaluated by defining *a* and *b* values of the Gutenberg-Richter recurrence relationship, while accounting for the incompleteness of the earthquake catalogue. To consider the spatial distribution of seismicity around each node, a spatially smoothed probability distribution function of the observed epicentral distances has been used. Uniform hazard contours for pseudo-spectral acceleration as the hazard parameter have been obtained for an exposure time of 100 years and for 50% confidence level at different natural periods for both horizontal and vertical components of ground motion. The trends reflected by these contours are broadly consistent with the major seismotectonic features in the region.

- **Seismic hazard assessment and mitigation in India: an overview. Mithila Verma and Brijesh K. Bansal. *International Journal of Earth Sciences, July 2013, Volume 102, Issue 5, pp 1203-1218.***

Abstract:

The Indian subcontinent is characterized by various tectonic units viz., Himalayan collision zone in North, Indo-Burmese arc in north-east, failed rift zones in its interior in Peninsular Indian shield and Andaman Sumatra trench in south-east Indian Territory. During the last about 100 years, the country has witnessed four great and several major earthquakes. Soon after the occurrence of the first great earthquake, the Shillong earthquake (M_w: 8.1) in 1897, efforts were started to assess the seismic hazard in the country. The first such attempt was made by Geological Survey of India in 1898 and since then considerable progress has been made. The current seismic zonation map prepared and published by Bureau of Indian Standards, broadly places seismic risk in different parts of the country in four major zones. However, this map is not sufficient for the assessment of area-specific seismic risks, necessitating detailed seismic zoning, that is, microzonation for earthquake disaster mitigation and management. Recently, seismic microzonation studies are being introduced in India, and the first level seismic microzonation has already been completed for selected urban centres including, Jabalpur, Guwahati, Delhi, Bangalore, Ahmadabad, Dehradun, etc. The maps prepared for these cities are being further refined on larger scales as per the requirements, and a plan has also been firmed up for taking up microzonation of 30 selected cities, which lie in seismic zones V and IV and have a population density of half a million. The paper highlights the efforts made in India so far towards seismic hazard assessment as well as the future road map for such studies.

- **Seismic Hazard Estimation from the Isoseismals of three Great Indian Earthquakes. Ashwani Kumar, Rajib Jain and S.C.Gupta.** ***13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, August 1-6, 2004; Paper No. 2362.***

Summary:

This study is devoted to the construction of anomalous residual intensity maps from isoseismals of three great Indian earthquakes namely, the Kangra earthquake of April 4, 1905 (Ms =8.0), the Bihar–Nepal earthquake of January 15, 1934 (Ms=8.3) and the Assam earthquake of August 15, 1950 (Ms =8.6) for the purpose of delineating areas of anomalous intensities. Computed intensities (Ic) at various localities have been estimated by fitting a simplified model, $I = A + B\Delta + C \log \Delta c$, into the observed intensity data, where, Δ is the average outer radius for each intensity level and A, B and C are constants estimated using regression analysis. The residual intensities (IR) are calculated from the difference between the observed intensity (IOB) and the computed intensity (Ic). The anomalous areas of low and high residual intensities have been correlated with geology, tectonics, subsurface topography and Bouguer gravity anomalies. Four prominent areas of anomalous residual intensities (Ic>2) have been delineated. These areas fall in the Sub Himalaya and the Lesser Himalaya near Dehradun, around Sitamarhi town and Monger-Saharsa ridge in Bihar, and Mikir hills in Assam. These areas are characterized by undulating basement topography and subsurface massif and uplifts in the form of ridges and generally exhibit high Bouguer gravity anomalies. It seems that the basement topography influences the observed anomalous intensities. The expected peak accelerations computed at bed rock level should be modified in these areas of anomalous intensities while making seismic hazard estimation.

- **Seismic treatment for a maximal credible earthquake in Guwahati city area of northeast India region. Olga Erteleva, Felix Aptikaev, Saurabh Baruah, Santanu Baruah, Sajal K.Deb, J.R.Kayal.** ***Nat Hazards; Doi:10.1007/s1 1069-013-0843-3.***

Abstract:

Strong ground motion parameters for the Guwahati city area, the capital city of the state of Assam in northeast India, are examined with the help of data accrued from local as well as worldwide network. Empirical relations are proposed for the ground motion parameters as a function of earthquake magnitude, distance, fault type, source depth and velocity characteristics of medium. Seismotectonics of the study region is examined, and a maximum credible earthquake M_S ~ 8.0 is presumed from the Brahmaputra fault, the nearest source zone in the city area. Such great/major event may cause intensity of the of 9.3 with a probability of 0.95 in the Guwahati city during the interval of 500 years. Further, the design spectrum with 67% confidence level and the synthetic three-component accelerograms are constructed. These results are much relevant and useful for structural engineering to mitigate seismic hazards in the region.

Keywords: Guwahati city, Assam valley, Ground acceleration, Magnitude, Intensity, Attenuation, Response spectrum.

- **Seismic hazard analysis of India using areal sources. T.G.Sitharam and Sreevalsa Kolathayar. Journal of Asian Earth Sciences, 62 (2013) 647-653.**

Abstract:

In view of the major advancement made in understanding the seismicity and seismotectonics of the Indian region in recent times, an updated probabilistic seismic hazard map of India covering 6–38^{0}N and 68–98^{0}E is prepared. This paper presents the results of probabilistic seismic hazard analysis of India done using regional seismic source zones and four well recognized attenuation relations considering varied tectonic provinces in the region. The study area was divided into small grids of size 0.1^0 x 0.1^0. Peak Horizontal Acceleration (PHA) and spectral accelerations for periods 0.1 s and 1 s have been estimated and contour maps showing the spatial variation of the same are presented in the paper. The present study shows that the seismic hazard is moderate in peninsular shield, but the hazard in most parts of North and Northeast India is high.

- **Probabilistic seismic hazard analysis of Tripura and Mizoram states. Arjun Sil, T.G.Sitharam, Sreevalsa Kolathayar.** ***Nat. Hazards (2013) 68:1089-1108, Doi:10.1007/s11069-013-0678-y***.

Abstract:

A probabilistic seismic hazard analysis for the states of Tripura and Mizoram in North East India is presented in this paper to evaluate the ground motion at bedrock level. Analyses were performed considering the available earthquake catalogs collected from different sources since 1731–2010 within a distance of 500 km from the political boundaries of the states. Earthquake data were declustered to remove the foreshocks and aftershocks in time and space window and then statistical analysis was carried out for data completeness. Based on seismicity, tectonic features and fault rupture mechanism, this region was divided into six major seismogenic zones and subsequently seismicity parameters (a and b) were calculated using Gutenberg–Richter (G–R) relationship. Faults data were extracted from SEISAT (Seismotectonic atlas of India, Geological Survey of India, New Delhi, 2000) published by Geological Survey of India and also from satellite images. The study area was divided into small grids of size 0.05^0×0.05^0(approximately 5 km × 5 km), and the hazard parameters (rock level peak horizontal acceleration and spectral accelerations) were calculated at the center of each of these grid cells considering all the seismic sources within a radius of 500 km. Probabilistic seismic hazard analyses were carried out for Tripura and Mizoram states using the predictive ground motion equations given by Atkinson and Boore (Bull Seismol Soc Am 93:1703–1729, 2003) and Gupta (Soil Dyn Earthq Eng 30:368–377, 2010) for subduction belt. Attenuation relations were validated with the observed PGA values. Results are presented in the form of hazard curve, peak ground acceleration (PGA) and uniform hazard spectra for Agartala and Aizawl city (respective capital cities of Tripura and Mizoram states). Spatial variation of PGA at bedrock level with 2 and 10 % probability of exceedance in 50 years has been presented in the paper.

Keywords**:** Seismicity, Faults, Ground motion, PSHA, Hazard curves, Spectral acceleration.

- **Assessment of Liquefaction Potential of Guwahati City: A Case Study.Binu Sharma, P.J.Hazarika.** ***Geotechnical and Geological Engineering, October 2013, volume 31, issue 5, pp. 1437-1452.***

Abstract:

The liquefaction potential of saturated cohesionless deposits in Guwahati city, Assam, was evaluated. The critical cyclic stress ratio required to cause liquefaction and the cyclic stress ratio induced by an earthquake were obtained using the simplified empirical method developed by Seed and Idriss (J soil Mech Found Eng ASCE 97(SM9):1249–1273, 1971, Ground motions and soil liquefaction during earthquakes. Earthquake Engineering Research Institute, Berkeley, CA, 1982) and Seed et al. (J Geotech Eng ASCE 109(3):458–483, 1983, J Geotech Eng ASCE 111(12):1425–1445, 1985) and the Idriss and Boulanger (2004) method. Critical cyclic stress ratio was based on the empirical relationship between standard penetration resistance and cyclic stress ratio. The liquefaction potential was evaluated by determining factor of safety against liquefaction with depth for areas in the city. A soil database from 200 boreholes covering an area of 262 km^2 was used for the purpose. A design peak ground acceleration of 0.36 g was used since Guwahati falls in zone V according to the seismic zoning map of India. The results show that 48 sites in Guwahati are vulnerable to liquefaction according to the Seed and Idriss method and 49 sites are vulnerable to liquefaction according to the Idriss and Boulanger method. Results are presented as maps showing zones of levels of risk of liquefaction.

- **Evaluation of liquefaction potential of Guwahati: Gateway city to Northeastern India. R.Ayothiraman, S.T.G.Raghu Kanth, S.Sreelatha.** ***Nat Hazards (2012) 63, 449-460, Doi:10.1007/s11069-012-0158-9.***

Abstract:

Guwahati city is a major city in the northeastern region of India, which is growing rapidly in every aspect, particularly the major infrastructures like sports complex, educational institutions, flyovers, multiplex halls, etc. Two great earthquakes struck this region in 1897 and 1950, and large-scale liquefaction was reported in and around the Guwahati city. However, a detailed microzonation study for liquefaction is not available so far and is taken up accordingly. The liquefaction potential of the Guwahati city is estimated using hundred boreholes data located at different places of city with a design peak ground acceleration of 0.36 g. The results are presented in the form of factor of safety contours at several depths below the ground surface. These contour maps indicate that most of the sites in Guwahati city area are susceptible to liquefaction and hence this aspect has to be considered in earthquake-resistant design of foundation/structures in Guwahati city.

- **Deterministic seismic hazard macrozonation of India. Sreevalsa Kolathayar, T.G. Sitharam and K.S. Vipin.** ***J. Earth Syst. Sci.*** **121, No. 5, October 2012, pp. 1351–1364.**

Abstract:

Earthquakes are known to have occurred in Indian subcontinent from ancient times. This paper presents the results of seismic hazard analysis of India (6◦–38◦N and 68◦–98◦E) based on the deterministic approach using latest seismicity data (up to 2010). The hazard analysis was done using two different source models (linear sources and point sources) and 12 well recognized attenuation relations considering varied tectonic provinces in the region. The earthquake data obtained from different sources were homogenized and declustered and a total of 27,146 earthquakes of moment magnitude 4 and above were listed in the study area.

The sesismotectonic map of the study area was prepared by considering the faults, lineaments and the shear zones which are associated with earthquakes of magnitude 4 and above. A new program was developed in MATLAB for smoothing of the point sources. For assessing the seismic hazard, the study area was divided into small grids of size 0.1◦ × 0.1◦ (approximately 10 × 10 km), and the hazard parameters were calculated at the center of each of these grid cells by considering all the seismic sources within a radius of 300 to 400 km. Rock level peak horizontal acceleration (PHA) and spectral accelerations for periods 0.1 and 1 s have been calculated for all the grid points with a deterministic approach using a code written in MATLAB. Epistemic uncertainty in hazard definition has been tackled within a logic-tree framework considering two types of sources and three attenuation models for each grid point. The hazard evaluation without logic tree approach also has been done for comparison of the results. The contour maps showing the spatial variation of hazard values are presented in the paper.

Keywords: India; seismic hazard; deterministic approach; ground motion; peak horizontal acceleration.

- **Seismic hazard assessment in the Jia Bhareli river catchment in eastern Himalaya from SRTM-derived basin parameters, India. B.P.Duarah and Sarat Phukan. *Nat Hazards (2011) 59:367-381, Doi:10.1007/s11069-011-9761-4.***

Abstract:

SRTM (Shuttle Radar Topographic Mission), Landsat ETM + satellite image analysis along with earthquake data in the Jia Bhareli river catchment, an eastern Himalayan tributary of the Brahmaputra indicates neotectonic activities in the region. We have envisaged from the study that the western part of the river catchment (*western tectonic domain*) is highly tectonically active as indicated by earthquake data, and SRTM DEM-derived longitudinal profiles, valley profiles, valley asymmetry, hypsometric integral values. On the other hand, the eastern part of the catchment has no sign of such active tectonics (*eastern tectonic domain*) except the south convex fan-shaped zone further east with linear ridges paralleling the convex shape deforming the Miocene-Pleistocene Siwalik sediments and the Quaternary piedmont deposits in the Himalayan foothills. The catchment seems tilting to the east due to the ongoing tectonic activities propagating the deformational activities, generating folded structures, to the east and yielding earthquakes due to rigid deformation in the western part of the catchment. From the study, seismic risk in the south-central part of eastern Himalayas around Bomdila in the state of Arunachal Pradesh appears to be high.

Keywords: Seismic hazard, Jia Bhareli river, Eastern Himalayas, SRTM, Morphometry.

- **An initial model of seismic microzonation of Sikkim Himalaya through thematic mapping and GIS integration of geological and strong motion features. Sankar Kumar Nath. *Journal of Asian Earth Sciences, 25 (2005) 329-343.***

Abstract:

Seismic microzonation and hazard mapping was undertaken in the Sikkim Himalaya with local site conditions and strong ground motion attributes incorporated into a geographic information system. A strong motion network in Sikkim consisting of 9 digital accelerographs recorded more than 100 events during 1998-2002, of which 72 events are se-

lected with signal-to-noise ratios $\geq$3 for the estimation of site response (SR), peak ground acceleration (PGA) and resonance frequency (RF) at all stations. With these data and inputs from IRS-IC LISS III digital data, topo-sheets, geographic boundary of the State of Sikkim, surface geological maps, soil taxonomy map at !:50,000 scale and seismic refraction profiles, the seismological and geological thematic maps, namely, SR, PGA, RF, lithology, soil class, slope, drainage, and landslide layers were generated. The geological and seismological layers are assigned normalized weights and feature ranks following a pair wise comparison hierarchical approach and lateral integrated through GIS to create the microzonation map of the region. The overall SR, PGA and resonance frequency show an increasing trend in a NW-SE direction, peaking at Singtam in the lesser Himalaya. Six major hazard zones are demarcated with different percentages of probability index values in the geological, seismological hazard and microzonation maps. The maximum risk is attached to a probability greater than 78% in the Singtam and adjoining area. These maps offer generally better spatial representation of seismic hazard including site-specific analysis as a first level microzonation attempt.

Keywords: Seismic hazard, Peak ground acceleration, Resonance frequency, GIS integration, Microzonation.

- **Selection of ground motion for performing incremental dynamic analysis of existing reinforced concrete buildings in India. M.M. Maniyar and R.K. Khare. *Current Science, Vol. 100, No. 5, 10 March 2011.***

Abstract:

In this article, a suite of 20 ground motion time histories has been selected from all available recorded Indian earthquake events based on a detailed statistical study performed on various ground motion parameters like peak ground acceleration, peak ground velocity, peak ground displacement, acceleration RMS, velocity RMS, displacement RMS, Arias intensity, characteristic intensity, spectral acceleration, acceleration spectrum intensity and significant duration. Statistical analysis has been performed by scaling the time histories to uniform values of various parameters considered, singly and in combination. Minimum, maximum and median values, standard deviations, and lognormal deviations have been calculated. The selected set of earthquakes in this article effectively captures the variability in response to the randomness of input motion. It represents different rates of energy input to the structures as well as different effective durations. At the same time inelastic response of single degree of freedom system shows less lognormal dispersion when scaled to median spectral acceleration for a narrow band of time-period surrounding the fundamental period, indicating converged response. Median spectral acceleration for period range significant to population of structures under consideration has been proposed as an efficient intensity measure.

4.5.3 GEOPHYSICAL/GEODETIC

- **The potential of satellite gravity and gravity gradiometry in deciphering structural setting of the Himalayan Collision Zone. V.M. Tiwari, B. Singh, K. Arora and S. Kumar. *Current Science, Vol., 99, No. 12, 25 December 2010.***

Abstract:

During the last decade, three dedicated satellite gravity missions(CHAMP, GRACE and GOCE) have greatly improved the knowledge of the static and dynamic gravity field of the earth. Bougher gravity anomalies (BGA) derived from global gravity models (e.g. EGM2008), which consist of GRACE satellite observations and terrestrial gravity data, are analysed to demonstrate through selected applications, their potential use in studying large scale geological features of the Himalaya, where little or no terrestrial data are available. A constrained 3D lithospheric density model over a part of the Eastern Himalayan region is constructed from modelling of BGA and utilized to calculate forward responses of selected gravity gradient (GG) tensors, highlighting certain aspects of the structural features of the Himalayan Collision Zone (HCZ). In addition, GG are also computed directly from BGA by Fourier transformation to study the additional information content they may provide. This exercise may demonstrate the extra advantages of modelling gravity gradiometry measurements, which is of high contemporary relevance in view of the fact that satellite gravity gradient data from the ongoing GOCE mission will be available shortly. We find that structural features like Main Boundary Thrust, Main Central Thrust are sharply reflected in GG and combined interpretation of BGA and GG can better resolve the locations and possibly the depth extent of the density anomalies . BGA is also utilized to constrain crustal thickness variation and used along with topography to estimate variation of effective elastic thickness across the Eastern Himalayan Region.

Keywords: Gravity and Gradiometry, GRACE, GOCE,Himalaya, Isostasy.

- **Specific Gravity Field and Deep Crustal Structure of the Himalayas East Structural Knot. Teng Ji-Wen, Wang Qian-Shen, Wang Guang-Jie, Xu Ya, Zhang Xue-Mei.** ***Chinese Journal of Geophysics, Vol.49, No.4, 2006, pp: 932-940.***

Abstract:

More than half of the ‘Himalayas east structural knot’ area (92_E_97_E, 26_N_30_N) that straddles boundaries between China, India and Burma has no ground gravity measuring point yet. Here it is hard to research directly the gravity field characteristic and the deep crustal structure. In this paper, the satellite gravity anomaly data are employed as pseudo free air gravity anomaly to calculate Bouguer gravity anomaly. The calculated Bouguer gravity anomaly exhibits well mirror correlation with the topography altitude of this area. Three profiles of deep crustal structure according to above calculation are obtained. In the Tibetan Plateau the crust thickness is more than 70km, in the orogenic belt of Himalayan Mountains it is about 55km, in the Brahmaputra basin valley it is 33 to 35km, and in the Naga Mountain it is 40 to 45km. The ‘east structural knot’ is composed of high-density matter, moves northward after collision and extrusion by the Indian plate, and then inserts into the eastern margin of the Tibetan Plateau. This dynamic process results in violent tectonic movement of southeast and northeast edges of the Tibetan Plateau, induces a series of earthquakes frequently, and accumulates a large amount of mineral resources.

Key words: Himalayas, East structural knot, Gravity field, Deep crustal structure, Wedge insertion.

- **Integrated interpretation of seismic, gravity, magnetic and magneto-telluric data in geologically complex thrust belt areas of Manabum, Arunachal Pradesh. G.K.**

Ghose, S.K. Basha, M.Salim and V.K. Kulshreshth. ***J.Ind.Geophys. Union (January 2010), V 14, No. 1, pp. 1-14.***

Abstract:

Subsurface heterogeneity delineation in the geologically complex and logistically hostile terrain of the Assam-Arakan basin near fore deep of Himalayan foot hills is one of the key factors for hydrocarbon exploration among the Geoscientists. The area of study primarily falls close to the foot hills of Himalaya i.e fore deep region in the North-East and partly in Belt of Schuppen (thrust belt) to the south-east, facing the Upper Assam foreland shelf in India. In such a complex mountainous and thrusted terrain, the seismic method has its own limitation to map the deeper geological basement configuration, because energy transmission is very meager and most part of the energies engrossed at boulder-sandstone formation. To overcome this problem it is always recommended to utilize some passive geophysical methods to supplement some value added constraints information to seismic data. Oil India Limited (OIL) decided to acquire ground Gravity-Magnetic (GM) as well as Magneto-Telluric (MT) data acquisition simultaneously in the fringe of Seismic lines where few profiles fall on the vicinity area to map the deeper subsurface information and also to make out the potentially hydrocarbon prospect zone. Additional quantitative spectral analysis technique has been use to map the top sedimentary layer and basement structure. This paper describes the correlation between GM,MT and seismic data to map the different sedimentary layers and the basement configuration.

- **Integrated Interpretation of Gravity, Magnetic & Seismic data for delineation of Basement Configuration in Sadiya Block, Upper assam, India. G.K.Ghose, S.K.Basha, V.K.Kulshreshth.** ***8th Biennial International Conference & Exposition on Petroleum Geophysics, Hyderabad 2010.***

Summary:

Gravity and magnetic data were collected jointly by National Geophysical Research Institute (NGRI), Hyderabad and Oil India Limited (OIL) during 2005 - 2008 in OIL's NELP-V Sadiya Block. Gravity was collected using Lacoste and Romberg Gravimeter (Model G) with an accuracy of 0.01 mGal. The magnetic data was collected using Scintrex Magnetometer (maintained for Base Station) and Geometrics Magnetometer (used for field data acquisition) with an accuracy of 0.01 nTesla at spacing of 0.05 km to 1.0 km interval. The main objective of this interpretation was to establish depth to magnetic basement, basement configuration and basement related structural elements. The results of this interpretation strengthen the seismic interpretation. The combined use of gravity, magnetic and seismic data helped in understanding and resolving the geological features and constraining the basement depth during seismic interpretation. The integrated interpretation of these data derived the basement depth, basement configuration, sediment thickness etc. These results have been further refined with 2.5-D/3-D modeling and generated a three dimensional basement configuration map. A number of positive structural features were identified which may provide leads for future hydrocarbon exploration. The computed density model suggests a fault controlled undulating sub surface with maximum basement depth of approximately 6 km in the south-eastern corner and the minimum depth of 4 to 4.5 km in the north-western and north-eastern part of the study area. The results thus obtained in the integrated interpretation of Gravity, Magnetic and Seismic data of Sadiya Block in Upper Assam in north eastern part of India are presented in this paper.

Keywords: Block, Basement, Integrated Interpretation, Gravity, Magnetic, Seismic.

- **Deep geoelectric structures of the Sikkim Himalayas (NE India) using magnetotelluric studies. Prasanta K.Patro and T.Harinarayana.** ***Physics of the Earth and Planetary Interiors, v 173, (2009) pp. 171-176.***

Abstract:

Broadband (0.001–1000 s) magnetotelluric soundings were carried out at 18 locations with a station interval of 5–8km across the Sikkim Himalaya (northern India) along a 120km long traverse from Siliguri in the south to Yumthang in the north. Magnetotelluric transfer functions were computed after robust processing of single site and remote reference sites. The two-dimensional (2D) model derived from the joint inversion of TE and TM mode data shows distinct electrical signatures of the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). The MFT and MBT zones are expressed by a conductive feature of about 10–40_m indicating, the presence of Siwalik molasse sediments of Gangetic foreland basin. An anomalously high conductive (2–5_m) in the crust in the depth range of 3–15 km is observed to the north of MBT. This may indicate the presence of Siwalik molasse sediments together with lesser Himalayan sediments with trapped fluids in the fault zone. These sediments may act as a lubricant accommodating underthrusting of continental crust. The nature of the low resistivity associated with the Main Himalayan Thrust in the higher Himalayas (north of the MCT) might indicate presence of metamorphic fluids released due to under thrusting of the Indian plate.

- **Long and short wavelengths of Indian Ocean geoid and gravity lows: Mid-to-upper mantle sources, rapid drift and seismicity of Kachchh and Shillong plateau, India. D.C.Mishra and M.Ravi Kumar.** ***Journal of Asian Earth Sciences, v 60, (2012), pp. 212-224.***

Abstract:

Spectral analysis of the Indian Ocean geoid low provides depth to the large wavelength sources as _1300, _700 and 340 km that are supported from the spectral analysis and the modeling of the corresponding large wavelength regional gravity anomaly with negative density contrasts at these levels. The three levels coincide with the sharp changes in the gradient of the seismic velocities related to the olivine–spinel transformation of successively increasing Fe/Mg ratio as depth increases, known as transition zones. The first two segments are supported from continuous wavelet transform analysis of the large wavelength component of the corresponding gravity field. The low density rocks in this section appear to be related to the subducted Indian/Tethyan lithosphere that roll back and drifted southwards after subduction as inferred from tomography experiments. The relatively short wavelength sources of the spectrum of the geoid data at depths of 162 and 85 km suggest sources along the lithosphere – asthenosphere boundary (LAB) under the Indian continent and surrounding oceans, respectively. A low viscosity zone has been envisaged below 660 km discontinuity that may correspond to the low density rocks in this section which is popularly referred to as graveyards of the subducted rocks under geoid lows. The subducted slab is hydrated due to dehydration from metamorphism that causes upwelling in the mid-to-upper mantle˜ which is likely to set in baby plumes. Presence of fluid may transform part of olivine to serpentine further reducing the bulk density of rocks in this section. They would make this region buoyant

that appears to be responsible for the Central Indian Ocean Deformation Zone with large scale folding, faulting, seismicity, and high heat flow. The same also appear to be responsible for the rapid drift of the Indian plate. Short wavelength component of the Indian Ocean geoid low reflects most of the surface/shallow tectonics of the region similar to the gravity anomaly providing an additional data set for this purpose. Kachchh and the Shillong plateau inspite of being in the intra plate region are highly seismogenic that compare almost to the activity along the plate boundaries. Tectonics and residual geoid anomalies of the Indian continent and adjoining regions suggest that the geoid highs of Kachchh and the Shillong plateau along the NW and the NE corners of India are connected to the geoid highs of the plate boundaries through several lineaments and faults that also show geoid highs and trends of seismic activity leading to plate boundaries. Geoid highs indicating high density mafic rocks suggest their connections/extensions to plate boundaries indicating them to be plausibly part of diffused plate boundaries. Besides, both these regions are affected by (i) prominent lithospheric flexure of the Indian plate (ii) large scale mafic intrusions and (iii) interaction of proterozoic mobile belts with effects of present day Himalayan orogeny that make them more vulnerable for seismic activity.

- **Structural Study of Meghalaya Plateau through Aeromagnetic Data. Rajendra Sharma, H.C. Gouda, R.K. Singh and B.V. Nagaraju.** ***Journal Geological Society of India, v 79. January 2012, pp. 11-29.***

Abstract:

The study of aeromagnetic data over parts of Assam-Meghalaya has delineated major discontinuities representing faults/ fractures/ contacts/ shears and magnetic body axes, which helped in understanding the regional and structural setup of the area. The known Barapani and Dapsi Thrusts, Dudhnai Fault and three strong magnetic anomalies with reverse magnetisation have been delineated. The quantitative analysis of aeromagnetic data brought out the depths of magnetic interfaces and the magnetic picture of different layers, which also helped in understanding the regional and structural setup. The contact modeling across few profile sections showed the depths to the top of contacts and the map of magnetic-basement-depth-model revealed the undulations of the basement. Magnetic body axes of several magnetic anomalies and also several magnetic discontinuities representative of faults/ fractures/ contacts/ shears system in the area along with five potential blocks for mineral prospecting are the main outcome of this exercise. The seismotectonic activity associated with the magnetic features has also been studied to understand the structural setup.

Keywords: Structural study, Aeromagnetic data, Meghalaya.

- **Deep geoelectric structure over the Lower Brahmaputra valley and Shillong plateau, NE India using magnetotellurics. S.G. Gokarn, G. Gupta, D. Walia, S.S. Sanabamand and Nitu Hazarika.** ***Geophysics. J. Int. (2008), v. 173, 92-104.***

Summary:

Magnetotelluric studies over the Shillong plateau and lower Brahmaputra sediments have delineated the Dauki fault as a NE-SW striking thrust zone with a dip angle of about 30^0 along which the low resistivity layer of Bengal sediments and the underlying oceanic crust subduct to the northwest. At present, about 50 km length of these sequences has subducted beneath the Shillong plateau and is traced upto depth of 40 km. Another thrust zone, sub par-

allel to Dauki fault is observed in the lower Brahmaputra valley, corresponding to the Brahmaputra fault. This is interpreted to be an intracratonic thrust within the Indian plate. These results suggest that a large fraction of the seismicity over the Shillong plateau is associated with the NE-SW striking Dauki thrust, contrary to the earlier belief that this fault zone is relatively aseismic. The present studies also suggest that the Shillong plateau and the adjoining sedimentary layers act as a supercrustal block, not directly participating in the subduction process. However in response to the compressive tectonic forces generated by the Himalayan and Indo-Burman subduction processes the Shillong plateau, together with the Brahmaputra sediments overlying the Indian crust drift eastward relative to the Bengal sediments along the surface expression of the Dauki fault leading to a dextral strike slip movement. We thus propose that the NE Indian crust responds to the compressive forces differently at different depths, governed by the rheological considerations. At deeper levels the crustal readjustments take place through the subduction along the Dauki and Brahmaputra thrusts whereas, shallow levels the relative deformability of the super crustal blocks have a strong influence on the tectonics, leading to the strike slip mechanism along the surface expression of the Dauki fault.

Keywords: Magnetotelluric; Seismicity and tectonics; Crustal structure; Asia.

- **An analysis of the gravity field in Northeastern India. R.K. Verma and Manoj Mukhapadhyay.** ***Tectonophysics, 01/1977, Doi:10.1016/0040-1951(77)90171-8.***

Abstract:

Northeastern India comprises several major tectonic units including the Shillong Plateau, the Upper and Lower Brahmaputra (Assam) Valleys, the Northeastern Himalaya, the Naga Hills and the Bengal Basin. The area lies approximately between latitude 23–28°N, and longitude 88–96°E. A revised Bouguer anomaly map of the area with nearly 400 new observations is presented. A Pratt-Hayford isostatic anomaly map using all available information is also given.The whole area shows a large variation in gravity anomalies, Bouguer anomalies show a variation from +40 mGal over the Shillong Plateau to −250 mGal over the northwestern part of the Upper Assam Valley. Isostatic anomalies also show a variation, from +100 mGal over the Shillong Plateau to −125 mGal in the Assam Valley. A study of the Bouguer anomaly map shows that the gravity field is considerably influenced by low-density sediments overlying the Assam Valley as well as the Bengal Basin. A geological correction for these sediments was computed for a few selected profiles for which geological information was available from seismic and bore-hole data along the Upper Assam Valley and the Bengal Basin. The magnitude of the geological correction was found to be of the order of 50 to 100 mGal for the Assam Valley and 40 to 130 mGal for the Bengal Basin.Models for the crust and mantle underlying the Shillong Plateau, the Upper Assam Valley and the Bengal Basin were constructed considering the nature of geologically corrected Bouguer anomalies as well as isostatic anomalies. Gravity data suggest that the crust underlying the Shillong Plateau is probably denser as well as thicker than normal for its elevation. The Assam Valley may overlie a crust which is thicker than normal for its topography, and the crystalline solid crust underlying a large thickness of sediments of Bengal Basin could be denser as well as thinner than the normal continental crust.

- **The seismic b value and its correlation with Bouguer gravity anomaly over the Shillong plateau area: Tectonic implications. P.K. Khan and Partha Pratim Chakraborty.** ***Journal of Asian Earth Sciences, 29 (2007) 136-147.***

Abstract:

Clues to the understanding of intra-and intra-plate variations in strength or stress state of the crust can be achieved through different lines of evidence and their mutual relationships. Among these parameters Bouguer gravity anomalies and seismic *b*-values have been widely accepted over several decades for evaluating the crustal character and stress regime. The present study attempts a multivariate analysis for the Shillong plateau using the Bouguer gravity anomaly and the earthquake database, and establishes a casual relationship between these parameters. Four seismic zones (Zone I-IV), with widely varying *b*-values, are delineated and an excellent correlation between the seismic *b*-value and the Bouguer gravity anomaly has been established for the plateau. Low *b*-values characterize the south-western part (Zone IV) and a zone (Zone III) of intermediate *b*-values separates the eastern and western parts of the plateau (Zones I and II) which have high *b*-values. Positive Bouguer anomaly values as high as + 40 mgal, a steep gradient in the Bouguer anomaly map and low *b*-values in the southwestern part of the plateau are interpreted as indicating a thinner crustal root, uplifted Moho and higher concentration of stress. In comparison, the negative Bouguer anomaly values, flat regional gradient in the Bouguer anomaly map and intermediate to high *b*-values in the northern part of the plateau are consistent with a comparatively thicker crustal root and lower concentration of stress, with intermittent dissipation of energy through earthquake shocks. Further, depth wise variation in the *b*-value for different seismic zones, delineated under this study, allowed an appreciation of intra-plateau variation in crustal thickness from ~30km in its southern part to ~38km in the northern part. The high *b*-values associated with the depth, coinciding with lower crust, indicate that the Shillong plateau is supported by a strong lithosphere.

Keywords: Shillong plateau; Bouguer anomaly; *b*-value; Stress state; Strong lithosphere

- **Effects on atmospherics at 6 KHz and 9 KHz recorded at Tripura during the India-Pakistan Border earthquake. S.S. De, B.K. De, B. Bandyopadhyay, S. Paul, D.K. Halder, A. Bhowmick, S. Barui and R. Ali.** ***Nat. Hazards Earth Syst. Sci., 10, 843-855, 2010.***

Abstract:

The outcome of the results of some analyses of electromagnetic emissions recorded by VLF receivers at 6 kHz and 9 kHz over Agartala, Tripura, the North-Eastern state of India (Lat. 23^0 N, Long. 91.4^0 E) during the large earthquake at Muzaffarabad (Lat. 34.53^0N, Long. 73.58^0 E) at Kashmir under Pakistan have been presented here. Spiky variations in integrated field intensity of atmospherics (IFIA) at 6 and 9 kHz have been observed 10 days prior (from midnight of 28 September 2005) to the day of occurrence of the earthquake on 8 October 2005 and the effect continued, decayed gradually and eventually ceased on 16 October 2005. The spikes distinctly superimposed on the ambient level with mutual separation of 2–5 min. Occurrence number of spikes per hour and total duration of their occurrence have been found remarkably high on the day of occurrence of the earthquake. The spike heights are higher at 6 kHz than at 9 kHz. The results have been explained on the basis of generation of electromagnetic radiation associated with fracture of rocks, their subsequent penetration into the Earth's

atmosphere and finally their propagation between Earth-ionosphere waveguide. The present observation shows that VLF anomaly is well-confined between 6 and 9 kHz.

- **Optimization of spread configuration for seismic data acquisition through numerical modeling in tectonically complex areas: a case study from Badarpur anticline, Cachar, India. Somaditya Dutta and S.M.chatterjee.** ***Journal of Apllied Geophysics, V 40, Issue 4, December 1998, pp. 205-222.***

Abstract:

Cachar area, a part of the Assam–Arakan frontal fold belt in the eastern part of India is characterized by a series of narrow anticlines which are dissected by a number of faults including thrusts, and broad synclines. Out of several exposed structures, Badarpur anticline is most important because of its major share of hydrocarbon strikes in Cachar. However, the seismic image of this area so far has been extremely poor for deciding locations for exploratory drilling. The problems in obtaining a good seismic image in this area include proper spread configuration including far and near offsets to capture reflected signals from the complex subsurface, variation of charge-sizes and depths along a line, large variation in statics due to rapid changes in elevation and near surface properties. The presence of coherent noise due to scattering and proper migration are major processing problems. This paper deals with the problem of spread configuration. For areas of complex subsurface, spread configuration obtained through field experiment at one spot may be quite different from other spots, requiring a large number of costly experiments. In this work, therefore, we used numerical modeling to derive an optimum spread configuration. For this, we chose a line passing through four wells on Badarpur anticline, and prepared a depth model using available seismic, surface geological and well data. Continuous synthetic common shot records were generated through oblique incidence ray tracing and were processed to obtain stacks with various spread configurations. Comparison of these stacks of synthetic data shows that end-on shooting configuration is inadequate for acquiring a good seismic image of the complex subsurface. From the present study it is evident that a split–spread configuration with near and far offsets of 50 m and 2400 m, respectively, can bring out optimum seismic images in Badarpur and other anticlines in this area.

- **Deep structure and tectonics of the Burmese arc: constraints from earthquake and gravity data. Manoj Mukhopadhyay and Sujit Dasgupta.** ***Tectonophysics, 149 (1988), 299-322.***

Abstract:

Active subduction of the Indian plate is currently occurring beneath the Burmese arc along an east dipping Benioff zone which extends to a depth of about 180 km. The overriding Burma plate has an appearance of an inland seismic slab that is deflected downwards in the vicinity of the Benioff zone. A crustal seismic zone some 60-80 km east of the Benioff zone correlates to backarc activity. A triangular seismic wedge in the top part of the crust outlines the Central Belt molasse basin east of the Burmese fold belt. Fault plane solutions shows that the Burmese Benioff zone is characterized by shallow angle thrusting at its upper wedge whereas, down-tip tensional events dominate its lower edge. Most of the backarc seismicity is accounted for by the Sagaing transform or by the activity of the Sun Scrap normal fault zone at the margin of the Asian plate. A gravity anomaly pair with amplitude of 175 mGal coincides with the 1100-km long Burmese arc lying in a north-south direction. The gravity

anomalies along a profile in Central Burma in adjacent areas of the Bengal basin are interpreted in terms of plate subduction as well as near surface mass anomalies. This suggests that the sediments below the Central belt may have an average thickness of the order of 10km but may be as thick as 15 km at the subduction zone. The Oceanic crust underlying deeper parts of the Bengal basin experiences plate transition at about 30 km depth in a Benioff zone environment east of the Burmese fold belt. Several thrust planes are present within the folded and deformed Createceous-Tertiary sediments of the fold belt; these are often associated with ophiolites and basics to ultrabasic rocks. A low density zone, at least 60 km wide, underlies the andesitic volcanic axis in the overriding plate.

4.5.4 SEISMIC HAZARD ASSESSMENT

- **On the Bayesian analysis of the earthquake hazard in the North-East Indian peninsula. Imtiyaz A.Parvez.** ***Natural Hazards, vol. 40, pp. 397-412, 2007, Doi:10.1007/s11069-006-9002-4.***

Abstract:

The Bayesian extreme-value distribution of earthquake occurrences has been used to estimate the seismic hazard in 12 seismogenic zones of the North-East Indian peninsula. The Bayesian approach has been used very efficiently to combine the prior information on seismicity obtained from geological data with historical observations in many seismogenic zones of the world. The basic parameters to obtain the prior estimate of seismicity are the seismic moment, slip rate, earthquake recurrence rate and magnitude. These estimates are then updated in terms of Bayes' theorem and historical evaluations of seismicity associated with each zone. From the Bayesian analysis of extreme earthquake occurrences for North-East Indian peninsula, it is found that for T = 5 years, the probability of occurrences of magnitude (M_w = 5.0-5.5) is greater than 0.9 for all zones. For M_w = 6.0, four zones namely Z1 (Central Himalayas), Z5 (Indo-Burma border), Z7 (Burmese arc) and Z8 (Burma region) exhibit high probabilities. Lower probability is shown by some zones namely, Z4, Z12, and rest of the zones Z2, Z3, Z6, Z9, Z10 and Z11 show moderate probabilities.

Keywords: Earthquake occurrences, Bayesian estimators, Extreme values.

- **Probabilistic Assessment of Earthquake Hazards in the North-East Indian Peninsula and Hinukush Regions. Imtiyaz A.Parvez and Avadh Ram.** ***Pure and Applied Geophysics, 149 (1997) pp. 731-746.***

Abstract:

The Himalayan region is one of the most seismic prone areas of the world. The North-East (NE) Indian peninsula and the Hindukush regions mark the zone of collision of the Indian and Eurasaian plates. The probability of the occurrence of great earthquakes with magnitude greater than 7.0 during a specified interval of time has been estimated on the basis of four probabilistic models, namely, Wetbull, Gamma, Lognormal and Exponential for the NE Indian peninsula and Hindukush regions. The model parameters have been estimated by the method of Maximum Likelihood Estimates (MLE) and the Method of Moments (MOM).

The cumulative probability is estimated for a period of 40 years from 1964 and is ranging between 0.881 to 0.995 by the year 1995, using all four models for the NE Indian peninsula. The conditional probabilty is also estimated and it is concluded that the NE Indian peninsula would expect a great earthquake at any time in the remaining years of the present century. For the Hindukush region, the cumulative probability has already crossed its highest value, but no earthquake of magnitude greater than 7.0 has occurred after 1974 in this area. It may attribute to the occurrence of frequent shocks of moderate size, as seventeen earthquakes of magnitude greater than 6.0, including four greater than 6.4, have been reported untill 1994 from this region.

Keywords: Earthquake hazards, NE Indian peninsula, probabilistic models.

- **Earthquake hazard in Northeast India – A seismic microzonation approach with typical case studies from Sikkim Himalaya and Guwahati city. Sankar Kumar Nath, Kiran Kumar Singh Thingbaijam and Abhisek Raj.** ***J.Earth Syst. Sci., 117, S2, November 2008, pp. 809-831.***

Abstract:

A comprehensive analytical as well as numerical treatment of seismological, geological, geomorphological and geotechnical concepts has been implemented through microzonation projects in the northeast Indian provinces of Sikkim Himalaya and Guwahati city, representing cases of contrasting geological backgrounds – a hilly terrain and a predominantly alluvial basin respectively. The estimated maximum earthquakes in the underlying seismic source zones, demarcated in the broad northeast Indian region, implicates scenario earthquakes of *MW* 8.3 and 8.7 to the respective study regions for deterministic seismic hazard assessments. The microzonation approach as undertaken in the present analyses involves multi-criteria seismic hazard evaluation through thematic integration of contributing factors. The geomorphological themes for Sikkim Himalaya include surface geology, soil cover, slope, rock outcrop and landslide integrated to achieve geological hazard distribution. Seismological themes, namely surface consistent peak ground acceleration and predominant frequency were, thereafter, overlaid on and added with the geological hazard distribution to obtain the seismic hazard microzonation map of the Sikkim Himalaya. On the other hand, the microzonation study of Guwahati city accounts for eight themes – geological and geomorphological, basement or bedrock, landuse, landslide, factor of safety for soil stability, shear wave velocity, predominant frequency, and surface consistent peak ground acceleration. The five broad qualitative hazard classifications – ‘low’, ‘moderate’, ‘high’, ‘moderate high’ and ‘very high’ could be applied in both the cases, *albeit* with different implications to peak ground acceleration variations. These developed hazard maps offer better representation of the local specific seismic hazard variation in the terrain.

Keywords: Seismic microzonation, maximum earthquake, Guwahati city, Sikkim Himalaya.

- **Probabilistic seismic hazard analysis and estimation of Spectral Strong Ground Motion on bed rock in North East India. M.L. Sharma and Shipra Malik.** ***4th International Conference on Earthquake Engineering, Taipei, Taiwan, October 12-13, 2006 (Paper No. 015).***

Abstract:

The present paper consists of the probabilistic seismic hazard analysis for the North East Indian Region, which is one of the most seismically active regions in India. The region has been divided into four major seismogenic sources namely, the regional features in the Himalayas i.e Main boundary Thrust and Main Central Thrust, Eastern Syntaxis, Shillong massif and the north south trending Arakan Yoma seismic belt. The probabilistic seismic hazard estimation is carried out for ten seismogenic zones which are further subdivisions of these four seismogenic sources based on the seismotectonics modeling of the area. The complete as well as the extreme part of the catalogue is used to make maximum likelihood estimates of maximum probable earthquakes for various return periods. The maximum *b*-value estimated is 1.04 for Shillong Plateau (Seismogenic Zone III) while the return periods of magnitude 6.0 have been estimated as about seven years for the Eastern boundary Thrusts (Seismogenic zone VIII and IX), which are part of the Arakan Yoma ranges. The hazard in these individual zones is presented in form of seismic zoning at the bedrock level for 10% and 20% exceedance values of strong ground motion in 50 years. The epistemic errors have been considered using logic tree method by using the spectral attenuation relationship developed for the area as well as those developed for similar tectonic environments elsewhere and adopted for the region. The spectral acceleration at different structural periods is presented for major cities in the region. The PGA value ranges from 0.05_G to 10% exceedance while the PGA value ranges from 0.01_G to 0.04_G for the 20% exceedance in 50 years. The results of the probabilistic seismic hazard analysis in the present study may be used for the seismic microzonation of the area and for earthquake engineering use.

Keywords: Seismic hazard, PSHA, Himalayas, Spectral ground motion.

- **GSHAP revisited for the prediction of Maximum Credible earthquake in the Sikkim region, India. Madhav Vyas, Sankar Kumar Nath, Indrajit Pal, Probal Sengupta and William K.Mohanty.** ***ACTA Geophysica Polonica, Vol. 53, No. 2, pp. 143-152, 2005.***

Abstract:

Global Seismic Hazard Assessment Program (GSHAP) has classified the Indian peninsula into several seismogenic zones. Considering the seismo-tectonic setting of the Sikkim Himalaya, sources 2, 3, 4, 5, 25, 26, 27 and 86 may be critical in contributing to the seismic hazard of the region. These seismogenic zones have been classified as Himalayan source (25, 86), extension of Tibetan plateau (26, 27), Burmese arc subduction zone (4, 5), Shillong plateau (3) and the Indian Shield region (2). The probabilistic seismic hazard assessment of the region necessitated prediction of Maximum Credible Earthquake magnitude for each source with 10% probability of exceedance in 50 years. Considering the widespread damages caused in the state capital of Sikkim due to the recent earthquakes of 1934 (Mw = 8) and 1988 (Mw = 7.2) a 50-year prediction seemed to be reasonable. Gutenberg–Richter (*b*-value) approach and Gumbel's method of extreme value statistics have been used in the present analysis for the predic-tion of Maximum Credible Earthquake magnitude, results of both being comparable to each other. The maximum credible earthquake magnitude as predicted by both the methods are above 6 except for zone 26, the highest being in the Burmese arc with a magnitude of 8.5 by Gutenberg–Richter approach and a magnitude of 7.7 by Gumbel's method
Keywords: GSHAP, seismogenic zone.

- **A Probable Isoseismal Map due Maximum Credible Earthquake (M=8.7) in NER, India; an Approach towards Risk Mitigation. Saurabh Baruah. *12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), 1-6 october, 2008, Goa, India.***

Abstract:

The study estimates the extent of seismic hazard in North East India in correlation to the past great earthquakes. Probable isoseismal maps through deterministic approach are prepared based on the basic information from two major earthquakes of 12th June 1897 (M=8.7) and 6th August 1988 (M=7.3). The study utilizes the database in the form of percentage increase in population and urbanization to the respective seismogenic zones available during the past earthquake besides the estimated peak ground acceleration for NER, India from GSHAP. The study shows that if an earthquake of M=8.7 were to recur today the devastation would be manifold because of abrupt increase in population and urbanization. The new isoseismal map depicts that much larger area covers maximum intensity at present in comparison to the isoseismal map during 1897 earthquake.

Keywords: Great Assam earthquake, isoseismal map.

- **A deterministic seismic hazard map of India and adjacent areas. Imtiyaz A.Parvez, Franco Vaccari and Giuliano F.Panza. *Geophys. J. Int. (2003) 155, 489-508.***

Summary:

A seismic hazard map of the territory of India and adjacent areas has been prepared using a deterministic approach based on the computation of synthetic seismograms complete with all main phases. The input data set consists of structural models, seismogenic zones, focal mechanisms and earthquake catalogues. There are few probabilistic hazard maps available for the Indian subcontinent, however, this is the first study aimed at producing a deterministic seismic hazard map for the Indian region using realistic strong ground motion modelling with the knowledge of the physical processes of earthquake generation, the level of seismicity and wave propagation in anelastic media. Synthetic seismograms at a frequency of 1 H_z have been generated at a regular grid of 0.2^0 X 0.2^0 by the modal summation technique. The seismic hazard, expressed in terms of maximum displacement (D_{max}), maximum velocity (V_{max}), and design ground acceleration (DGA), has been extracted from the synthetic signals and mapped on a regular grid over the studies territory. The estimated values of the peak ground acceleration are compared with the observed data available for the Himalayan region and are found to be in agreement. Many parts of the Himalayan region have DGA value exceeding 0.6 g. The epicentral areas of the great Assam earthquake of 1897 and 1950 in northeast India represent the maximum hazard with DGA values reaching 1.2-1.3 g. The peak velocity and the displacement in the same region is estimated as 120-177 cm s^{-1} and 60-90 cm, respectively.

Keywords: Design ground acceleration, deterministic modelling, Indian region, seismic hazard, synthetic seismograms.

- **A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry. Sankar Kumar Nath, Madhav Vyas, Indrajit Pal, and Probal**

Sengupta. *Journal of Geophysical Research, Vol. 110, B01301, doi:10.1029/2004JB003199, 2005.*

Abstract:

In this paper, we present a seismic hazard map of the Indian Himalayan State of Sikkim, lying between Nepal and Bhutan Himalaya, in terms of horizontal peak ground accelerations with 10% exceedance probability over the next 50 years. These figures, the first for the region, were calculated through a stepwise process based on (1) an estimation of the maximum credible earthquake (MCE) from the seismicity of the region and Global Seismic Hazard Assessment Program considerations and (2) four seismotectonic parameters abstracted from accelerograms recorded at nine stations of the Sikkim Strong Motion Array, specifically installed for this study. The latter include (1) the frequency-dependent power law for the shear wave quality factor, QS, (2) the site response function at each station using receiver function analysis and generalized inversion, (3) source parameterization of various events recorded by the array and application of the resulting relationships between M0 and MW, and corner frequency, fc and MW to simulate spectral accelerations due to higher-magnitude events corresponding to the estimated MCE, and (4) abstraction of regional as well as site specific local spectral attenuation laws at different geometrically central frequencies in low-, moderate-, and high-frequency bands.

- **The assessment of seismic hazard in two seismically active regions in Himalayas using deterministic approach. Kapil Mohan, A.Joshi and R.C.Patel.** ***J.Ind.Geophys. Union (July 2008), Vol.12, No.3, pp.97-107.***

Abstract:

The long stretch of Himalaya is often visited by many major earthquakes from time to time. The work presented in this paper shows the seismic hazard in the northeast Himalayas and the Uttarakhand Himalayas, India. Seismic hazard estimation in these regions is based on the technique given by Joshi & Patel (1997). In this work, the finite rupture along the lineament has been modeled using the semi empirical technique proposed by Midorikawa (1993) and further modified by Joshi & Midorikawa (2005). The modeling procedure follows the ω2 scaling laws, directivity effects and other strong motion properties. The NE Himalaya has a complex geology. Seismic activities in this region are due to the trijunction of three mountain belts that are Himalayan range, Mishmi Hills and Naga Patkoi range. The huge oil reservoirs and hydroelectric power projects in this area prove its technoeconomic importance and requirement for detailed seismic hazard assessment. The seismic hazard zonation map for magnitude M=6 prepared in this region shows that places like the Tinsukia, North Lakhimpur, Dibrugarh, Ziro, Tezu, Sibsagar, Jorhat, Itanagar, Golaghat, Senapati, Wokha, Imphal and Kohima falls in highly hazardous Zone IV with peak ground acceleration of more than 250 cm/sec2. The places like the Daring, Pasighat, Seppa and Basar, region belongs to Zone III with peak ground accelerations of the order 200–250 cm/sec^2. The region of Uttarakhand Himalaya has witnessed 13 earthquakes of M=6 in last 97 years that indicates the occurrence of one strong earthquake in every 8 years (Rastogi 2000). This region has been visited by two major earthquakes in last one decade. Due to the technoeconomic importance of the region and poor construction practices of building houses, the need for seismic hazard estimation cannot be ruled out in this hilly area. The zonation map prepared for magnitude M $\geq$ 6.0 in this region using present technique shows that the places like the Munsiari, Dharchula, Lohaghat, Pithoragarh, Almora, Nainital, Uttarkashi and Karanparyag falls in Zone V with peak ground acceleration of more than 400 cm/sec2. The places like Sobla and Gopeshwar lies in Zone IV with peak ground acceleration more than 250 cm/sec2. The zonation maps prepared in this work are also compared with the historical past seismicity map of the respective regions and found that many moderate to major earthquakes falls in the identified hazardous zones.

- **Ground Motion for Scenario Earthquakes at Guwahati City. S.T.G.Raghukanth, J.Dixit, S.K.Dash.** ***Acta Geod. Geoph. Hung., Vol. 46(3), pp. 326-346*** **(2011).**

Abstract:

In this article, stochastic finite-fault simulation combined with site response analysis is used to understand the spatial distribution of ground motion in Guwahati city due to three damaging earthquakes. The rock level ground motion for the scenario earthquakes is generated based on the stochastic finite-fault methodology. These simulated motions are further amplified up to the surface by equivalent linear site response analyses using the available bore log data at 100 different locations in Guwahati city. A set of twenty simulated rock level time histories for each event, are used to compute the surface level ground motion. Response spectra are computed and the results are presented in the form of contour maps, at selected natural periods. The mean amplification due to local soil deposit is as high as 2.2 at most of the sites in Guwahati city. Based on these simulated motions, an average site correction factor is obtained for soil sites in Guwahati city. The standard error in the simulated response spectra is also reported. The contour maps obtained will be useful in identifying vulnerable places in Guwahati city.

Keywords: Guwahati city; response spectra; seismological model; strong ground motion.

- **Ground motion estimation at Guwahati city for an M_W 8.1 earthquake in the Shillong plateau. S.T.G.Raghu Kanth, S.Sreelatha, Sujit Kumar Dash.** ***Tectonophysics, 448 (2008) 98-114.***

Abstract:

In this paper, the ground motion at Guwahati city for an 8.1 magnitude earthquake on Oldham fault in the Shillong plateau has been estimated by stochastic finite-fault simulation method. The corresponding acceleration time histories on rock level at several sites in the epicentral region have been computed. These results are validated by comparing them with the estimates obtained from Medvedev–Sponheuer–Karnik (MSK) intensity observations of 1897 Shillong earthquake. Using the local soil parameters, the simulated rock level acceleration time history at Guwahati city is further amplified up to the ground surface by nonlinear site response analysis. The results obtained are presented in the form of peak ground acceleration (PGA) contour map. The maximum amplification for PGA over Guwahati city is as high as 2.5. Based on the simulated PGA, the liquefaction susceptibility at several locations in the city has been estimated. The results are presented in the form of contours of factor of safety against liquefaction at different depths below the ground surface. It is observed that over a large part of the Guwahati city, the factor of safety against liquefaction is less than one, indicating that the city is highly vulnerable to liquefaction in the event of this earthquake. The contour maps obtained can be used in identifying vulnerable areas and disaster mitigation.

- **Probabilistic seismic hazard estimation of Manipur, India.** ***Kumar Pallav, S.T.G. Raghukanth and Konjengbam Darunkumar Singh. Journal of Geophysics and Engineering, 9 (2012) 516-533; doi: 10.1088/1742-2132/9/5/516.***

Abstract:

This paper deals with the estimation of spectral acceleration for Manipur based on probabilistic seismic hazard analysis (PSHA). The 500 km region surrounding Manipur is divided into seven tectonic zones and major faults located in these zones are used to estimate seismic hazard. The earthquake recurrence relations for the seven zones have been estimated from past seismicity data. Ground motion prediction equations proposed by Boore and Atkinson (2008 *Earthq. Spectra* **24** 99–138) for shallow active regions and Atkinson and Boore (2003 *Bull. Seismol. Soc. Am.* **93** 1703–29) for the Indo-Burma subduction zone are used for estimating ground motion. The uniform hazard response spectra for all the nine constituent districts of Manipur (Senapati, Tamenglong, Churachandpur, Chandel, Imphal east, Imphal west, Ukhrul, Thoubal and Bishnupur) at 100-, 500- and 2500-year return periods have been computed from PSHA. A contour map of peak ground acceleration over Manipur is also presented for 100-, 500-, and 2500-year return periods with variations of 0.075–0.225, 0.18–0.63 and 0.3–0.1.15 g, respectively, throughout the state. These results may be of use to planners and engineers for site selection, designing earthquake resistant structures and, further, may help the state administration in seismic hazard mitigation.

Keywords: PSHA, seismic hazard, Manipur.

- **Evaluation of seismic soil-liquefaction at Guwahati city. S.T.G.Raghu Kanth, Sujit Kumar Dash.** ***Environ Earth Sci. (2010) 61; 355-368; Doi: 10.1007/s12665-009-0347-3.***

Abstract:

Great earthquakes in the past (e.g. 1869 Cachar earthquake, 1897 great Assam earthquake) have caused large scale damage and ground liquefaction in the Guwahati city. Moreover, seismologists are of opinion that a great earthquake might occur in the unruptured segment of the North-East Himalaya that is near to Guwahati city. In this paper, the liquefaction hazard due to these events have been simulated. The obtained results are in general agreement with the reported damages due to the past earthquakes. The central part of the city (i.e. Dispur, GS road), that has large thickness of soft soil deposit and shallow ground water table, is highly vulnerable to liquefaction.

Keywords: Earthquake, Ground liquefaction, Guwahati city.

- **Deterministic seismic scenarios for North East India. S.T.G.Raghu Kanth, Sujit Kumar Dash.** ***J Seismol, Vol. 14, No. 2, pp. 143-167, 2010; Doi:10.1007/s10950-009-9158-y.***

Abstract:

In this paper, ground motion during six past devastating earthquakes and one possible future event in the northeastern part of India is estimated by seismological approaches. Considering uncertainty in the input source parameters, a series of ground motions have been simulated. The peak ground acceleration (PGA) and response spectra at important cities and

towns in the epicentral regions of these events are obtained. The PGA distribution over the entire northeastern region of India, encompassing the epicenter, is presented in the form of contours. The obtained results can be used for the seismic analysis and design of structures in this region.

Keywords: Strong ground motion, PGA, Stochastic finite fault model, Northeast India, Response spectra.

- **Deterministic Seismic Scenarios for Imphal City. S.T.G.Raghu Kanth, Konjenbam Darunkumar Singh and Kumar Pallav.** ***Pure and Applied Geophysics, 04/2012, 166(4): 641-672, Doi:10.1007/s00024-009-0460-y.***

Abstract:

In this article, the spatial variation of ground motion in Imphal City has been estimated by the finite-fault seismological model coupled with site response analysis. The important seismic sources around Imphal City have been identified from the fault map and past seismicity data. The rock level acceleration time histories at Imphal City for the 1869 Cachar (M_W 7.5) earthquake and a hypothetical M_W 8.1 event in the Indo-Burma subduction zone have been estimated by a stochastic finite-fault model. Soil investigation data of 122 boreholes have been collected from several construction projects in Imphal City. Site response analysis has been carried out and the surface level ground motion has been determined for Imphal City for these two earthquake events. The results are presented in the form of peak ground acceleration (PGA) contour map. From the present study it has been ascertained that the maximum amplification for PGA over Imphal City is as high as 2.5. The obtained contour maps can serve as guidelines for identifying vulnerable areas and disaster mitigation in Imphal City.

- **Surface level ground motion estimation for 1869 Cachar Earthquake (M_W 7.5) at Imphal City. Kumar Pallav, S.T.G.Raghukanth, K.D.Singh.** ***Journal of Geophysics and Engineering,07/2010; 7:321-331. DOI:10.1088/1742-2132/7/3/010.***

Abstract:

In this paper, the seismic susceptibility of Imphal city with respect to ten synthetically generated samples of the historic 1869 Cachar (Mw 7.5) earthquake that occurred in the Kopili fault is presented based on the finite-fault seismological model in conjunction with nonlinear site response analyses. For all the synthetic sample earthquake events, the mean and standard deviation of surface level spectral ground acceleration at peak ground acceleration (PGA) and natural periods of 0.3 and 1 s have been reported in the form of contour maps. These contour maps can serve as guidelines for engineers and planners to identify vulnerable areas for possible seismic disaster mitigation of Imphal city.

- **Seismicity parameters for important urban agglomerations in India. S. T. G. Raghukanth.** ***Bull Earthquake Eng., DOI 10.1007/s10518-011-9265-3.***

Abstract :

India's urban population has increased in the recent times. An earthquake near an urban agglomeration has the potential to cause severe damage. In this article, seismicity parameters for region surrounding important urban agglomerations in India are estimated. A comprehensive earthquake catalogue for the region (6◦E–42◦E latitude and 60◦N–100◦N longitude) including historic and pre-historic events has been compiled from various sources. To estimate the parameters, past earthquake data in a control region of radius 300 km has been assembled to quantify the seismicity around each urban agglomeration. The collected earthquake data is first evaluated for its completeness. From combined (historical and instrumental) data, the seismicity parameters *b*-value, seismic activity rate, λ and maximum expected magnitude (*mmax)* have been obtained from the methodology proposed by Kijko and Graham (1998). The obtained activity rates indicate that region surrounding Guwahati urban agglomeration is the most seismically active region followed by Srinagar, Patna, Amritsar and Chandigarh.

Keywords: Seismic hazard · Urban agglomerations · Recurrence relations

- **A Probabilistic Seismic Hazard Analysis of Northeast India. Sandip Das, Ishwer D. Gupta, and Vinay K. Gupta. *Earthquake Spectra,* Volume 22, No. 1, pages 1–27, February 2006.**

Abstract:

Seismic hazard maps have been prepared for Northeast India based on the uniform hazard response spectra for absolute acceleration at stiff sites. An approach that is free from regionalizing the seismotectonic sources has been proposed for performing the hazard analysis. Also, a new attenuation model for pseudo-spectral velocity scaling has been developed by using 261 recorded accelerograms in Northeast India. In the present study, the entire area of Northeast India has been divided into 0.1° grid size, and the hazard level has been assessed for each node of this grid by considering the seismicity within a 300-km radius around the node. Using the past earthquake data, the seismicity for the area around each node has been evaluated by defining *a* and *b* values of the Gutenberg-Richter recurrence relationship, while accounting for the incompleteness of the earthquake catalogue. To consider the spatial distribution of seismicity around each node, a spatially smoothed probability distribution function of the observed epicentral distances has been used. Uniform hazard contours for pseudo-spectral acceleration as the hazard parameter have been obtained for an exposure time of 100 years and for 50% confidence level at different natural periods for both horizontal and vertical components of ground motion. The trends reflected by these contours are broadly consistent with the major seismotectonic features in the region.

- **Seismic hazard assessment and mitigation in India: an overview. Mithila Verma, Brijesh K. Bansal. *International Journal of Earth Sciences, July 2013, Volume 102, Issue 5, pp 1203-1218.***

Abstract:

The Indian subcontinent is characterized by various tectonic units viz., Himalayan collision zone in North, Indo-Burmese arc in north-east, failed rift zones in its interior in Peninsular Indian shield and Andaman Sumatra trench in south-east Indian Territory. During the last about 100 years, the country has witnessed four great and several major earthquakes. Soon after the occurrence of the first great earthquake, the Shillong earthquake (M_w: 8.1) in 1897, efforts were started to assess the seismic hazard in the country. The first such attempt was made by Geological Survey of India in 1898 and since then considerable progress has been

made. The current seismic zonation map prepared and published by Bureau of Indian Standards, broadly places seismic risk in different parts of the country in four major zones. However, this map is not sufficient for the assessment of area-specific seismic risks, necessitating detailed seismic zoning, that is, microzonation for earthquake disaster mitigation and management. Recently, seismic microzonation studies are being introduced in India, and the first level seismic microzonation has already been completed for selected urban centres including, Jabalpur, Guwahati, Delhi, Bangalore, Ahmadabad, Dehradun, etc. The maps prepared for these cities are being further refined on larger scales as per the requirements, and a plan has also been firmed up for taking up microzonation of 30 selected cities, which lie in seismic zones V and IV and have a population density of half a million. The paper highlights the efforts made in India so far towards seismic hazard assessment as well as the future road map for such studies.

- **Seismic Hazard Estimation from the Isoseismals of three Great Indian Earthquakes'; Ashwani Kumar, Rajib Jain and S.C.Gupta.** ***13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, August 1-6, 2004, Paper No. 2362.***

Summary:

This study is devoted to the construction of anomalous residual intensity maps from isoseismals of three great Indian earthquakes namely, the Kangra earthquake of April 4, 1905 (Ms =8.0), the Bihar–Nepal earthquake of January 15, 1934 (Ms=8.3) and the Assam earthquake of August 15, 1950 (Ms =8.6) for the purpose of delineating areas of anomalous intensities. Computed intensities (Ic) at various localities have been estimated by fitting a simplified model, $I = A + B\Delta + C \log \Delta c$, into the observed intensity data, where, Δ is the average outer radius for each intensity level and A, B and C are constants estimated using regression analysis. The residual intensities (IR) are calculated from the difference between the observed intensity (IOB) and the computed intensity (Ic). The anomalous areas of low and high residual intensities have been correlated with geology, tectonics, subsurface topography and Bouguer gravity anomalies. Four prominent areas of anomalous residual intensities (Ic>2) have been delineated. These areas fall in the Sub Himalaya and the Lesser Himalaya near Dehradun, around Sitamarhi town and Monger-Saharsa ridge in Bihar, and Mikir hills in Assam. These areas are characterized by undulating basement topography and subsurface massif and uplifts in the form of ridges and generally exhibit high Bouguer gravity anomalies. It seems that the basement topography influences the observed anomalous intensities. The expected peak accelerations computed at bed rock level should be modified in these areas of anomalous intensities while making seismic hazard estimation.

- **Seismic treatment for a maximal credible earthquake in Guwahati city area of northeast India region. Olga Erteleva, Felix Aptikaev, Saurabh Baruah, Santanu Baruah, Sajal K.Deb, J.R.Kayal.** ***Nat Hazards, Doi:10.1007/s1 1069-013-0843-3.***

Abstract:

Strong ground motion parameters for the Guwahati city area, the capital city of the state of Assam in northeast India, are examined with the help of data accrued from local as well as worldwide network. Empirical relations are proposed for the ground motion parameters as a function of earthquake magnitude, distance, fault type, source depth and velocity characteristics of medium. Seismotectonics of the study region is examined, and a maximum credible

earthquake M_S ~ 8.0 is presumed from the Brahmaputra fault, the nearest source zone in the city area. Such great/major event may cause intensity of the of 9.3 with a probability of 0.95 in the Guwahati city during the interval of 500 years. Further, the design spectrum with 67% confidence level and the synthetic three-component accelerograms are constructed. These results are much relevant and useful for structural engineering to mitigate seismic hazards in the region.

Keywords: Guwahati city, Assam valley, Ground acceleration, Magnitude, Intensity, Attenuation, Response spectrum.

- **Seismic hazard analysis of India using areal sources. T.G.Sitharam, Sreevalsa Kolathayar. Journal of Asian Earth Sciences, 62 (2013) 647-653.**

Abstract:

In view of the major advancement made in understanding the seismicity and seismotectonics of the Indian region in recent times, an updated probabilistic seismic hazard map of India covering 6–38^{0}N and 68–98^{0}E is prepared. This paper presents the results of probabilistic seismic hazard analysis of India done using regional seismic source zones and four well recognized attenuation relations considering varied tectonic provinces in the region. The study area was divided into small grids of size 0.1^0 x 0.1^0. Peak Horizontal Acceleration (PHA) and spectral accelerations for periods 0.1 s and 1 s have been estimated and contour maps showing the spatial variation of the same are presented in the paper. The present study shows that the seismic hazard is moderate in peninsular shield, but the hazard in most parts of North and Northeast India is high.

- **Probabilistic seismic hazard analysis of Tripura and Mizoram states. Arjun Sil, T.G.Sitharam, Sreevalsa Kolathayar.** ***Nat. Hazards (2013) 68:1089-1108, DOI:10.1007/s11069-013-0678-y.***

Abstract :

A probabilistic seismic hazard analysis for the states of Tripura and Mizoram in North East India is presented in this paper to evaluate the ground motion at bedrock level. Analyses were performed considering the available earthquake catalogs collected from different sources since 1731–2010 within a distance of 500 km from the political boundaries of the states. Earthquake data were declustered to remove the foreshocks and aftershocks in time and space window and then statistical analysis was carried out for data completeness. Based on seismicity, tectonic features and fault rupture mechanism, this region was divided into six major seismogenic zones and subsequently seismicity parameters (a and b) were calculated using Gutenberg–Richter (G–R) relationship. Faults data were extracted from SEISAT (Seismotectonic atlas of India, Geological Survey of India, New Delhi, 2000) published by Geological Survey of India and also from satellite images. The study area was divided into small grids of size 0.05_ 9 0.05_ (approximately 5 km 9 5 km), and the hazard parameters (rock level peak horizontal acceleration and spectral accelerations) were calculated at the center of each of these grid cells considering all the seismic sources within a radius of 500 km. Probabilistic seismic hazard analyses were carried out for Tripura and Mizoram states using the predictive ground motion equations given by Atkinson and Boore (Bull Seismol Soc Am 93:1703–1729, 2003) and Gupta (Soil Dyn Earthq Eng 30:368–377, 2010) for subduction belt. Attenuation relations were validated with the observed PGA values. Re-

sults are presented in the form of hazard curve, peak ground acceleration (PGA) and uniform hazard spectra for Agartala and Aizawl city (respective capital cities of Tripura and Mizoram states). Spatial variation of PGA at bedrock level with 2 and 10 % probability of exceedance in 50 years has been presented in the paper.

Keywords: Seismicity, Faults, Ground motion, PSHA, Hazard curves, Spectral acceleration.

- **Assessment of Liquefaction Potential of Guwahati City: A Case Study. Binu Sharma, P.J.Hazarika.** ***Geotechnical and Geological Engineering, October 2013, volume 31, issue 5, pp. 1437-1452.***

Abstract:

The liquefaction potential of saturated cohesionless deposits in Guwahati city, Assam, was evaluated. The critical cyclic stress ratio required to cause liquefaction and the cyclic stress ratio induced by an earthquake were obtained using the simplified empirical method developed by Seed and Idriss (J soil Mech Found Eng ASCE 97(SM9):1249–1273, 1971, Ground motions and soil liquefaction during earthquakes. Earthquake Engineering Research Institute, Berkeley, CA, 1982) and Seed et al. (J Geotech Eng ASCE 109(3):458–483, 1983, J Geotech Eng ASCE 111(12):1425–1445, 1985) and the Idriss and Boulanger (2004) method. Critical cyclic stress ratio was based on the empirical relationship between standard penetration resistance and cyclic stress ratio. The liquefaction potential was evaluated by determining factor of safety against liquefaction with depth for areas in the city. A soil database from 200 boreholes covering an area of 262 km^2 was used for the purpose. A design peak ground acceleration of 0.36 g was used since Guwahati falls in zone V according to the seismic zoning map of India. The results show that 48 sites in Guwahati are vulnerable to liquefaction according to the Seed and Idriss method and 49 sites are vulnerable to liquefaction according to the Idriss and Boulanger method. Results are presented as maps showing zones of levels of risk of liquefaction.

- **Evaluation of liquefaction potential of Guwahati: Gateway city to Northeastern India. R. Ayothiraman, S.T.G. Raghu Kanth, S. Sreelatha.** ***Nat Hazards (2012) 63:449-460, Doi:10.1007/s11069-012-0158-9.***

Abstract:

Guwahati city is a major city in the northeastern region of India, which is growing rapidly in every aspect, particularly the major infrastructures like sports complex, educational institutions, flyovers, multiplex halls, etc. Two great earthquakes struck this region in 1897 and 1950, and large-scale liquefaction was reported in and around the Guwahati city. However, a detailed microzonation study for liquefaction is not available so far and is taken up accordingly. The liquefaction potential of the Guwahati city is estimated using hundred boreholes data located at different places of city with a design peak ground acceleration of 0.36 g. The results are presented in the form of factor of safety contours at several depths below the ground surface. These contour maps indicate that most of the sites in Guwahati city area are susceptible to liquefaction and hence this aspect has to be considered in earthquake-resistant design of foundation/structures in Guwahati city.

- **Deterministic seismic hazard macrozonation of India. Sreevalsa Kolathayar, T.G. Sitharam and K.S. Vipin.** ***J. Earth Syst. Sci.*** **121, No. 5, October 2012, pp. 1351–1364.**

Abstract:

Earthquakes are known to have occurred in Indian subcontinent from ancient times. This paper presents the results of seismic hazard analysis of India (6°–38°N and 68°–98°E) based on the deterministic approach using latest seismicity data (up to 2010). The hazard analysis was done using two different source models (linear sources and point sources) and 12 well recognized attenuation relations considering varied tectonic provinces in the region. The earthquake data obtained from different sources were homogenized and declustered and a total of 27,146 earthquakes of moment magnitude 4 and above were listed in the study area. The sesismotectonic map of the study area was prepared by considering the faults, lineaments and the shear zones which are associated with earthquakes of magnitude 4 and above. A new program was developed in MATLAB for smoothing of the point sources. For assessing the seismic hazard, the study area was divided into small grids of size $0.1^\circ \times 0.1^\circ$ (approximately 10×10 km), and the hazard parameters were calculated at the center of each of these grid cells by considering all the seismic sources within a radius of 300 to 400 km. Rock level peak horizontal acceleration (PHA) and spectral accelerations for periods 0.1 and 1 s have been calculated for all the grid points with a deterministic approach using a code written in MATLAB. Epistemic uncertainty in hazard definition has been tackled within a logic-tree framework considering two types of sources and three attenuation models for each grid point. The hazard evaluation without logic tree approach also has been done for comparison of the results. The contour maps showing the spatial variation of hazard values are presented in the paper.

Keywords: India; seismic hazard; deterministic approach; ground motion; peak horizontal acceleration.

- **Seismic hazard assessment in the Jia Bhareli river catchment in eastern Himalaya from SRTM-derived basin parameters, India. B.P.Duarah, Sarat Phukan.** ***Nat Hazards (2011) 59:367-381; Doi:10.1007/s11069-011-9761-4.***

Abstract:

SRTM (Shuttle Radar Topographic Mission), Landsat ETM + satellite image analysis along with earthquake data in the Jia Bhareli river catchment, an eastern Himalayan tributary of the Brahmaputra indicates neotectonic activities in the region. We have envisaged from the study that the western part of the river catchment (*western tectonic domain*) is highly tectonically active as indicated by earthquake data, and SRTM DEM-derived longitudinal profiles, valley profiles, valley asymmetry, hypsometric integral values. On the other hand, the eastern part of the catchment has no sign of such active tectonics (*eastern tectonic domain*) except the south convex fan-shaped zone further east with linear ridges paralleling the convex shape deforming the Miocene-Pleistocene Siwalik sediments and the Quaternary piedmont deposits in the Himalayan foothills. The catchment seems tilting to the east due to the ongoing tectonic activities propagating the deformational activities, generating folded structures, to the east and yielding earthquakes due to rigid deformation in the western part of the catchment. From the study, seismic risk in the south-central part of eastern Himalayas around Bomdila in the state of Arunachal Pradesh appears to be high.

Keywords: Seismic hazard, Jia Bhareli river, Eastern Himalayas, SRTM, Morphometry.

- **An initial model of seismic microzonation of Sikkim Himalaya through thematic mapping and GIS integration of geological and strong motion features. Sankar Kumar Nath.** ***Journal of Asian Earth Sciences, 25 (2005) 329-343.***

Abstract:

Seismic microzonation and hazard mapping was undertaken in the Sikkim Himalaya with local site conditions and strong ground motion attributes incorporated into a geographic information system. A strong motion network in Sikkim consisting of 9 digital accelerographs recorded more than 100 events during 1998-2002, of which 72 events are selected with signal-to-noise ratios ≥3 for the estimation of site response (SR), peak ground acceleration (PGA) and resonance frequency (RF) at all stations. With these data and inputs from IRS-IC LISS III digital data, topo-sheets, geographic boundary of the State of Sikkim, surface geological maps, soil taxonomy map at !:50,000 scale and seismic refraction profiles, the seismological and geological thematic maps, namely, SR, PGA, RF, lithology, soil class, slope, drainage, and landslide layers were generated. The geological and seismological layers are assigned normalized weights and feature ranks following a pair wise comparison hierarchical approach and lateral integrated through GIS to create the microzonation map of the region. The overall SR, PGA and resonance frequency show an increasing trend in a NW-SE direction, peaking at Singtam in the lesser Himalaya. Six major hazard zones are demarcated with different percentages of probability index values in the geological, seismological hazard and microzonation maps. The maximum risk is attached to a probability greater than 78% in the Singtam and adjoining area. These maps offer generally better spatial representation of seismic hazard including site-specific analysis as a first level microzonation attempt.
Keywords: Seismic hazard, Peak ground acceleration, Resonance frequency, GIS integration, Microzonation.

- **Selection of ground motion for performing incremental dynamic analysis of existing reinforced concrete buildings in India. M.M. Maniyar and R.K. Khare.** ***Current Science, Vol. 100, No. 5, 10 March 2011.***

Abstract:

In this article, a suite of 20 ground motion time histories has been selected from all available recorded Indian earthquake events based on a detailed statistical study performed on various ground motion parameters like peak ground acceleration, peak ground velocity, peak ground displacement, acceleration RMS, velocity RMS, displacement RMS, Arias intensity, characteristic intensity, spectral acceleration, acceleration spectrum intensity and significant duration. Statistical analysis has been performed by scaling the time histories to uniform values of various parameters considered, singly and in combination. Minimum, maximum and median values, standard deviations, and lognormal deviations have been calculated. The selected set of earthquakes in this article effectively captures the variability in response to the randomness of input motion. It represents different rates of energy input to the structures as well as different effective durations. At the same time inelastic response of single degree of freedom system shows less lognormal dispersion when scaled to median spectral acceleration for a narrow band of time-period surrounding the fundamental period, indicating

converged response. Median spectral acceleration for period range significant to population of structures under consideration has been proposed as an efficient intensity measure.

4.5.5 SEISMIC PRECURSOR STUDIES

- **Precursory variation of Seismicity rate in the Assam area, India. K.Khattri and M.Wyss.** ***Geology, November 1978, Vol. 6, pp. 685-688.***

Abstract:

The seismicity data from 1825 to the present for the Assam (northeastern India) region show that seismicity rates there deviate from normal before and after major earthquakes. Along this 1,000-km-long section of a plate boundary, all shocks with magnitude $M > 6.6$ were preceded and sometimes followed by periods of significant seismic quiscence. No major earthquakes occurred without an associated seismic quiscence, and no such quiscence occurred at times other than before or after a major event. The most remarkable periods of quiscence lasted about 28 and 30 yr before the two great ($M = 8.7$) Assam earthquakes of 1897 and 1950. Other periods of anomalously low seismicity preceded main shocks of magnitude 6.7 (in 1950 and 1975), 7.8 (in 1869), and 7.7 (in 1947), with durations of 6, 8, 23 and 17 yr, respectively. These durations fit (with approximately the scatter of the original data) a published relation between precursor time and magnitude.

Since these changes of seismicity rate were observed at the edges of and within the Assam gap, defined by the 1897 and 1950 great earthquakes, it is likely that a future major or great earthquake in this gap will be preceded by seismic quiscence. Whether a preparatory phase for an earthquake has begun in the Assam gap cannot be stated for certain because of the changing earthquake-detection capability in the area and because of poor location accuracy.

- **Anomalous behaviour of precursor resistivity in Shillong area, NE India. J. R. Kayal and B. Banerjee.** ***Geophysical Journal (1988) 94, 97-103.***

Summary:

Daily measurement of apparent resistivity from 1984 May to 1985 October in Shillong Plateau, India, has been carried out for an earthquake-precursor study. The resistivity changes which occur 7 to 10 days before earthquakes do not necessarily satisfy the dilatancy hypothesis, which, of late, has been subjected to criticisms of not being a generalized phenomenological explanation of precursor resistivity variation. Prior to earthquakes, resistivity may increase or decrease or may not even show any change depending on the orientation of measuring electrodes, the elastic nature of the geological formation where observations are made and the direction of tectonic stress.

Key words: Earthquakes, NE India, precursor study, resistivity method.

- **Earthquake swarms precursory to moderate to great earthquakes in the northeast India region. H.K. Gupta and H.N. Singh.** ***Tectonophysics, Vol. 167, Issues 2-4, 10 October 1989, pages 285-298.***

Abstract:

The northeast India region has seen ten ***M* ≥ 7$^1/_2$** earthquakes since 1897, including two great earthquakes of *M* = 8.7 in 1897 and 1950. The last ***M* ≥ 7$^1/_2$ earthquake occurred on August 17, 1952.** With the exception of three earthquakes others are found to be associated with periods of background/normal seismicity, precursory swarms, quiscence and mainshocks (and the associated foreshocks and aftershocks). The dataset has been critically examined for completeness considering the current capabilities for defining locations and also considering other parameters. Regression equations relating the mainshock magnitude (M_m) , the average magnitude of the largest two events in the swarm (M_p) and the time interval (T_p) between the beginning of the swarm and the mainshock have been developed.
These are: $M_m = 1.37 M_p - 1.41$ and $M_m = 3\log_{10} T_p - 3.27$
It is important to recognize precursory swarms and quiscence in real time, indeed, we belief we have recognizes one such sequence in the vicinity of the Arakan Yoma Fold Belt. On the basis of M_p- and T_p- values, the lateral extent of swarm activity and the fact that no event of $M > 6$ has occurred since 1975 in the preparation zone defined by the 1963-1965 swarm, we estimate that an *M* ~8 earthquake could occur at any time in the area bounded by 21^0 and $25^1/_2{}^0$ N and 93^0 and 96^0 E. The focal depth of this impending earthquake is estimated to be 100 + 40km in view of the focal depths of the other

- **Patterns preceding major earthquakes in north-east India. Harsh K.Gupta. *Current Science, Vol. 64, Nos. 11 & 12, 10 & 25 June 1993.***

Abstract:

Major earthquakes in north-east India are generally preceded by precursory earthquake swarms and quiescences. Developing regression equations relating the mainshock magnitude (M_m), the average magnitude of the largest two events in the swarm (M_p) and the time interval (T_p) between the onset of the swarm and the occurrence of the mainshock, Gupta and Singh in 1986 made a medium-term forecast of a *M* ~8 magnitude earthquake in the vicinity of the India-Murma border. This forecast has come true. However, the mainshock was not preceded by any short-term seismicity pattern precursor.

- **The b-value before the 6th August, 1988 India-Myanmar Border Region Earthquake-a case study. O.P. Sahu, M.M. Saikia. *Tectonophysics, Vol. 234, Issue 4, 15 july 1994, pages 349-354.***

Abstract:

Smith (1981, 1986) and Wyss et al.(1990) have observed that intermediate-term quiscence is often associated with an increasing b value. This study pertains to the temporal behaviour of the b value before the earthquake of 6th August, 1988, which occurred in the India-Myanmar border region. The b value in the preparation zone of the earthquake (21^0-25.5^0N, 93^0-96^0E), as identified by Gupta and Singh (1986, 1989), is gound to have increased gradually from 1976 to a maximum value of 1.33 during July, 1987, followed by a short-term drop before the occurrence of the earthquake. The quiscence period observed by Gupta and Singh (1986, 1989) for this earthquake is better reflected by the intermediate-term increase in the b-value. A drop in the mean magnitude since 1978 is supported by a CUSUM plot.

- **Medium-term forecast of the 1988 north-east India earthquake. Harsha K. Gupta. *Tectonophysics, 338 (2001), pp. 281-286.***

Abstract:

Northeast india is seismically one of the most active intra-continental regions in the world. It has been a site of 10 earthquakes of magnitude (M) $\geq$7.5 during the last 100 years. Gupta and Singh [J.Geol.Soc.India. 28 (1986) 367-406] systematically analysed the series of earthquakes associated with several main shocks in and area bound by 20^0N and 32^0N latitude and 87^0E and 100^0E longitude and concluded: (1) Moderate magnitude to great earthquakes in the north-east India region are found to be preceded, generally, by well defined earthquakes swarms and quiescene periods, (2) On the basis of an earthquake swarms and quiescene period, an area bounded by 21^0N and 25.5^0N latitude and 93^0E and 96^0E longitude is identified to be the site of a possible future earthquake of M = 8 $\pm$ 0.5 with a focal depth of 100 $\pm$ 40 km. This earthquake should occur any time from now onwards. Should it not occur till the end of 1990, this forecast could be considered as as a false alarm. This medium-term earthquake forecast came true with the occurrence of M = 7.3 earthquake on August 6, 1988, within the specified spatial and temporal parameters.

The forecast of the earthquake was based on the concept of precursory swarms and quiescene preceeding main-shock. It is worthwhile noting that the entire region under study, the August 6, 1988 earthquake was the largest since the August 17, 1952 earthquake of M = 7.5. This lends support to the worldwide effort to study and identift spatial and temporal variation of seismicity and recognise patterns that precede major earthquakes.

- **Fractal dimension and b-value mapping in northeast India. Pankaj Mala Bhattacharya, R. K. Majumdar and J. R. Kayal. *Current Science, Vol. 82, No. 12, 25 June 2002.***

Abstract:

The statistical characteristics of seismicity, fractal dimension and *b*-values are mapped in the NE India region using permanent microearthquake network data and teleseismic data. The maps revealed the seismogenic structures and the crustal heterogeneities, which are useful for earthquake risk evaluation.

- **Mapping the b-value and its Correlation with the Fractal Dimension in the Northeast Region of India. Pankaj Mala Bhattacharya and J.R.Kayal. *Journal Geological Society of India, Vol. 62, Dec. 2003, pp. 680-695.***

Abstract:

The Northeast region of India, one of the most tectonically complex and high seismicity prone regions in the world, is examined with the power law distribution and fractal dimension of seismicity. About 1250 earthquakes (M 2.0 – 5.0) recorded by the permanent stations /telemetric networks in the region during the period 1993-96 are analysed in this study. The Gutenberg-Richter power law distribution, b-value, is estimated by least square fit and maximum likelihood methods in the five selected tectonic blocks of the region. The b-value (0.5-0.9) obtained for the earthquakes (2.5 $\leq$ M $\leq$ 5.0) by both the methods are comparable, and it varies with space and depth. The spatial variation of b-value and the activity level (‘a’ constant in the power law relation) are mapped. The maps imaged the higher frequency of earthquake occurrence as well as the higher activity level of the seismogenic structures in the region. The fractal dimension (D) of spatial distribution of earthquakes in the selected tectonic blocks are calculated using the correlation Integral. The estimated D values vary from 1.20 to 1.80.

Keywords: Seismicity, b-value, Fractal dimensions, Northeastern India.

- **Prediction of Seismicity Cycles in the Himalayas using Artificial Neutral Network. Mukat L. Sharma and Manoj K. Arora.** ***Acta Geophysica Polonica, Vol. 53, No. 3, pp. 299-305, 2005.***

Abstract:

In this paper, cyclic behaviour of seismicity cycles in the Himalayas has been exploited to predict the future earthquake activity using Artificial Neural Network (ANN). The Himalayan region has been divided into six seismogenic zones. A feed forward multi-layer ANN has been used to evaluate the seismicity fluctuation in the time series containing data from historical times to 1998 for each zone. The most widely used Back Propagation Algorithm (BPA) is applied to train the neural net-work. BPA iteratively minimises an error function over the network outputs and a set of target outputs taken from the training data set. The results show that the probability of occurrence of moderate to great earth-quake in next 50 years is relatively lower in the Hindukush-Pamirs zone. Since the intense release of energy will take place in the Kashmir-Himachal Pradesh zone, between 2030 to 2055, the probability of occurrence of moderate to great earth-quake is higher. The accumulation of energy stage is still going on in the India -Western Nepal Border zone, and there will be an increase in seismic activity after 2030 for the next 50 years. The hazard parameters could not be estimated for the Nepal-India-Sikkim Border zone because of lesser number of data to capture cyclic behaviour. In NE India, intense release and remnant release will take place up to 2030 due to which there will be an increase in the probability of occurrence of moderate to great earthquake in this zone. In Burma-Andaman Nicobar, the energy accumulation stage for the next cycle has started in 1990 and will continue till 2020.

Key words: Artificial neural network, seismic hazard, Himalayas, seismogenic zones.

- **Occurrence of anomalous seismic activity preceding large to great earthquakes in northeast India region with special reference to 6 August 1988. H.N. Singh, D. Shankar and V.P. Singh.** ***Physics of the Earth and Planetary Interiors, 148 (2005), 261-284.***

Abstract:

Seismicity database from 1860 to 1985 of northeast India region bounded by the area 20◦–32◦N and 82◦–100◦E have been analyzed for the identification of precursory swarm/anomalous seismic activity preceding large to great earthquakes with $M \geq 7.5$. It is observed that with the exception of three earthquakes (1908, 1912 and 1918), the large earthquakes of 1897, 1946, 1947, 1950 and 1951/1952 were preceded by well-developed epoch of swarm/anomalous seismic activity in space and time well before their occurrence. The seismicity is observed to fluctuate in the order of low-high-low ranging from 0–0.5, 01–33 to 0–0.7 events/year prior to these main shocks during the epochs of normal/background, swarm/anomalous and gap/quiescence, respectively. The duration of precursory gap is observed to vary from 11 to 17 years for main shocks of M 7.5–8.0, and from 23 to 27 years for

M 8.7 and this period is dependent on the magnitude of the main shocks. Using the values of magnitude of main shock (Mm), average magnitude of swarm (M_p) and the precursory time gap (T_p), the following predictive equations are established for the region:

$M_m = 1.37M_p - 1.40$

$M_m = 3 \log T_p - 3.27$

All the major earthquakes with $m_b \geq 6.1$ occurred during 1963–1988 have been investigated for their association with anomalous seismicity/precursory swarms using the events with cutoff magnitude $m_b \geq 4.5$. Eleven such events have occurred in the region during the period except one earthquake of 29 May 1976. All the remaining 10 earthquakes were associated in some forms of anomalous seismicity epochs. Well-defined patterns of anomalous seismicity are observed prior to 1964–1965, 12 August 1976 and 30 December 1984 (m_b 5.6). All these mains hocks are preceded by seismicity patterns in the order of low-high-low similar to that observed prior to the main shocks from 1897 to 1962. The anomalous seismicity epoch is delineated with extremely high annual earthquake frequency, which was preceded and followed by extremely low seismicity epochs of background and gap/quiescence phases. Consequently, seismicity rates during anomalous seismicity epoch have always been above normal (1event/year) whereas it is always below normal during the preceding and the following epochs. A prediction was made using the 1964 swarm based on the M_p and T_p values that a large earthquake with M 8±0.5 with focal depth 100±40 km could occur any time from 1986 to 1990 in an area bound by 21◦–25 5◦N latitudes and 93◦–96◦E longitude in Arakan Yoma fold belt. It is interesting to note that the 6 August 1988 earthquake with magnitude 7.5 and focal depth 115 km had occurred within the delineated zone. In addition, three consecutive swarm activities are identified in a limited area within the Eastern Syntaxis and these were not followed by any main shock till date and could be potential zone for future earthquake.

Keywords: Anomalous seismic activity; Quiescence; Precursory swarm; Precursory time gap; Seismicity rates.

- **The seismic b value and its correlation with Bouguer gravity anomaly over the Shillong plateau area: Tectonic implications. P.K.Khan, Partha Pratim Chakraborty.** ***Journal of Asian Earth Sciences, 29 (2007) 136-147.***

Abstract:

Clues to the understanding of intra-and intra-plate variations in strength or stress state of the crust can be achieved through different lines of evidence and their mutual relationships. Among these parameters Bouguer gravity anomalies and seismic *b*-values have been widely accepted over several decades for evaluating the crustal character and stress regime. The present study attempts a multivariate analysis for the Shillong plateau using the Bouguer gravity anomaly and the earthquake database, and establishes a casual relationship between these parameters. Four seismic zones (Zone I-IV), with widely varying *b*-values, are delineated and an excellent correlation between the seismic *b*-value and the Bouguer gravity anomaly has been established for the plateau. Low *b*-values characterize the south-western part (Zone IV) and a zone (Zone III) of intermediate *b*-values separates the eastern and western parts of the plateau (Zones I and II) which have high *b*-values. Positive Bouguer anomaly values as high as + 40 mgal, a steep gradient in the Bouguer anomaly map and low *b*-values in the southwestern part of the plateau are interpreted as indicating a thinner crustal root, uplifted Moho and higher concentration of stress. In comparison, the negative Bouguer anomaly values, flat regional gradient in the Bouguer anomaly map and intermediate to high *b*-values in the northern part of the plateau are consistent with a comparatively thicker crustal root and lower concentration of stress, with intermittent dissipation of energy through earthquake shocks. Further, depth wise variation in the *b*-value for different seismic zones, delineated under this study, allowed an appreciation of intra-plateau variation in crustal thickness from ~30km in its southern part to ~38km in the northern part. The high *b*-values associated with the depth, coinciding with lower crust, indicate that the Shillong plateau is supported by a strong lithosphere.

Keywords: Shillong plateau; Bouguer anomaly; *b*-value; Stress state; Strong lithosphere.

- **Geomorphological, Fractal Dimension and b – value mapping in Northeast India. Pradip Kumar Pal. *J.Ind.Geophysics. Union, Vol. 12, No. 1, pp. 41-54 (January 2008).***

Abstract:

Satellite based Geomorphological mapping is an essential tool for natural hazard estimation in Northeast India. The geomorphological mapping of the study region (26-27^{0}N, 91-95^{0}E) was carried out with the help of IRS-1D LISS imagery of March 5, 2003on 1:250,000 scales by visible interpretation technique. The individual satellite imagery has been studied and compared with the Survey of India (SOI) topographical sheets on 1:50,000 scale to demarcate geomorphic features. The geomorphological maps of the study region refers to, (i) flood plain, (ii) younger alluvial plain, (iii) older alluvial plain, (iv) upper piedmont, (v) lower piedmont, (vi) valley fill area, (vii) structural hills of Tertiary group, (viii) structural hills of Shillong group, (ix) denudational hills of Tertiary group, (x) denudational hills of Shillong group, (xi) denudational hills of Gneissic group, (xii) pediment surface. The statistical characteristics of sedimentary and drainage parameters, fractal dimension and *b-values* are mapped in the study region. The maps revealed that the fractal dimension of the drainage parameters are comparable with the seismogenic structures and are very appropriate for earthquake risk evaluation.

- **Earthquake Prediction through Animal Behavior: A Review. Neeti Bhargava, V.K. Katiyar, M.L. Sharma and P. Pradhan. *Indian Journal of Biomechanics, Special Issue (NCBM 7-8 March, 2009).***

Abstract:

This paper presents a review of the work done in earthquake prediction using abnormal animal behavior. The earthquake prediction can be done using the abnormal behavior of animals preceding earthquake occurrence in seismically active region because of their relatively more capability than humans of perceiving certain kind of geophysical stimuli which may precede earthquake. The international work specially carried out specially in China, Japan, USA has been summarized. Further, the data requirement for the earthquake prediction in the Indian context has been discussed.

Keywords: Earthquake, Unusual animal behavior, Seismic waves at low frequency, Sound of seismic waves ground electric field, animal physiology.

- **Measurement of indoor concentrations of radon and thoron in Mizoram, India. P.C. Rohmingliana, Lalmuanpuia Vanchhawng, R.K. Thapa, B.K. Sahoo, R. Mishra, B. Zoliana and Y.S. Mayya.** ***Sci/Vis 10(4), 148-152, October-December, 2010, ISSN (print) 0975-6175, ISSN (online) 2229-6026.***

Abstract:

Radon, thoron and their progenies as a natural radiation hazards to human health is well known. These gases are present in the environment and their level of concentration depends upon geographical and geological conditions, meteorological factors, etc. The indoor radon/thoron concentration is also influenced by building materials, ventilating system and soil gas diffusion. Measurement of radon/thoron concentration in Mizoram is reported in this paper covering three districts, namely Aizawl, Kolasib and Champhai. In this study, we used solid-state nuclear track detectors to obtain the time integrated concentration levels of indoor radon/thoron. The study was conducted by measuring the cumulative exposure for a period of about 90 days each in 149 houses during rainy season (May-August). Houses were selected on the basis of geological characteristics of the area and the construction types in order to determine variation of concentrations of radon and thoron due to these factors. Among the three districts, Champhai District had the highest radon/thoron concentrations, while Kolasib District had the maximum thoron concentration. Among the different types of houses, concrete building had the average maximum concentration of radon followed by Assam type building with G.I. Sheet walls while the contribution due to asbestos walls of Assam type building was found to be lowest.
Key words: Construction types of buildings; Mizoram; radon; solid state nuclear track detectors; thoron; twin cup dosimeter.

- **Radon Monitoring in Soil Gas and Ground Water for Earthquake Prediction Studies in North West Himalay as, India. Surinder Singh, Arvind Kumar, Bikramjit Singh Bajwa, Sandeep Mahajan, Vinod Kumar, and Sunil Dhar.** ***Terr. Atmos. Ocean. Sci., Vol. 21, No. 4, 685-695, August 2010.***

Abstract:

Continuous monitoring of soil gas radon at Sarol and the daily monitoring of radon concentration in water at Banikhet is carried out in Chamba valley of North West Himalayas, India “a well known seismic zone” to study the correlation of radon anomalies in relation to seismic activities of the region. Radon monitoring in soil gas was carried out by using Barasol probe manufactured by Algade France and the radon content in water was recorded using RAD7 radon monitoring system of Durridge Company, USA. The effect of meteorological parameters viz. temperature and pressure on soil gas radon emission has been studied. Correlation coefficient has been calculated between radon in soil gas, soil temperature and soil pressure. The radon anomalies observed in the region have been correlated with the seismic events in the magnitude range 2.2 to 5.0 recorded by Wadia Institute of Himalayan Geology Dehradun in NW Himalayan. Empirical equations between earthquake magnitude, epicentral distance and precursor time were examined, and respective constants were determined.

Key words: Radon, NW Himalayas, Barasol probe, RAD7, Earthquake precursor.

- **Earthquake Source Zones in Northeast India: Seismic Tomography, Fractal Dimension and b Value Mapping. Pankaj M. Bhattacharryya, J.R. Kayal, Saurabh Baruah and S.S. Arefiev.** ***Pure and Applied Geophysics, 167 (2010), 999-1012.***

Abstract:

We have imaged earthquake source zones beneath the northeast India region by seismic tomography, fractal dimension and b value mapping. 3D P-wave velocity (Vp) structure is imaged by the Local Earthquake Tomography (LET) method. High precision P-wave (3,494) and S-wave (3,064) travel times of 980 selected earthquakes, md C 2.5, are used. The events were recorded by 77 temporary/permanent seismic stations in the region during 1993–1999. By the LET method simultaneous inversion is made for precise location of the events as well as for 3D seismic imaging of the velocity structure. Fractal dimension and seismic b value has been estimated using the 980 LET relocated epicenters. A prominent northwest–southeast low Vp structure is imaged between the Shillong Plateau and Mikir hills; that reflects the Kopili fault. At the fault end, a high-Vp structure is imaged at a depth of 40 km; this is inferred to be the source zone for high seismic activity along this fault. A similar high Vp seismic source zone is imaged beneath the Shillong Plateau at 30 km depth. Both of the source zones have high fractal dimension, from 1.80 to 1.90, indicating that most of the earthquake associated fractures are approaching a 2D space. The spatial fractal dimension variation map has revealed the seismogenic structures and the crustal heterogeneities in the region. The seismic b value in northeast India is found to vary from 0.6 to 1.0. Higher b value contours are obtained along the Kopili fault (~1.0), and in the Shillong Plateau (~0.9) The correlation coefficient between the fractal dimension and b value is found to be 0.79, indicating that the correlation is positive and significant. To the south of Shillong Plateau, a low Vp structure is interpreted as thick (~20 km) sediments in the Bengal basin, with almost no seismic activity in the basin.

Key words: Microearthquake, fault plane solutions, seismotectonics, seismic tomography, fractal dimension, b value.

- **A possible link between radon anomaly and earthquake. I. Laskar, P. Phukon, A.K. Goswami, G. Chetry and U.C. Roy.** ***Geochemical Journal, Vol. 45, pp. 439 to 446, 2011.***

Abstract:

Radon in soil gas had been measured at 39 locations, distributed along three prominent lineaments in the Guwahati city, Assam, India; using solid state nuclear track detectors. The most suitable site is selected from these locations, for continuous radon monitoring by an Alpha-GUARD PQ 2000 on the basis of high average radon concentration, no rock structure in the background and low ground water level even in the rainy season in summer. Influences of ambient temperature, atmospheric air pressure and relative humidity on temporal variation of radon concentration are investigated applying multiple regression method and an equation is derived. Using this equation, radon anomaly peaks are selected and a possible link between these and the observed earthquakes (data collected from USGS and Regional Research Laboratory, Jorhat, Assam, India) have been suggested.

Keywords: soil gas, lineaments, meteorological parameters, multiple regressions, Guwahati.

- **Time-predictable model applicability for earthquake occurrence in northeast India and vicinity. A. Panthi, D. Shankar, H.N. Singh, A.Kumar and H. Paudyal. *Natural Hazards and Earth System Sciences, 11, 993-1002, 2011.***

Abstract:

Northeast India and its vicinity is one of the seismically most active regions in the world, where a few large and several moderate earthquakes have occurred in the past. In this study region of northeast Indiahas been considered for an earthquake generation model using earthquake data as reported by earthquake catalogues National Geophysical data Centre, National Earthquake Information Centre, United States Geological Survey and from book prepared by Gupta et al. (1986) for the period 1906-2008. The events having a surface wave magnitude of $M_s \geq 5.5$ were considered for statistical analysis. In this region, nineteen seismogeneic sources were identified by the observation of clustering of earthquakes. It is observed that the time interval between the two consecutive mainshocks depends upon the preceding mainshock magnitude (M_p) and not on the following mainshock (M_f). This result corroborates the validity of time-predictable model in northeast India and its adjoining regions. A linear relation between the logarithim of repeat time *(T)* of two consecutive events and the magnitude of the preceding mainshock is established in the form LogT = c M_p + a, where "c" is a positive slope of line and "a" is function of minimum magnitude of the earthquake considered. The values of the parameters "c" and "a" are estimated to be 0.21 and 0.35 in northeast India and its adjoining regions. The less value of c than the average implies that the earthquake occurrence in this region is different from those of plate boundaries. The result derived can be used for long term seismic hazard estimation in the delineated seismogenic regions.

- **Seismic b-Value and the Assessment of Ambient Stress in Northeast India. Prosanta Kumar Khan, Manoj Ghosh, Partha Pratim Chakraborty and Debdeep Mukherjee. *Pure and Applied Geophysics, 168 (2011), 1693-1706, Doi:10.1007/s00024-010-019-x.***

Abstract:

Seismicity data of northeast India, recorded between 1986 and 1999 by a local network, are analyzed for estimation of *b*-values. Based on the obtained values, viz. low ($b <$ 0.5), moderate ($0.5 < b \leq 0.7$) and high ($b > 0.7$), the study area is classified into different seismic-domains. An assessment of stress level is also carried out in identifying seismic-domains. Seismic activities, though mostly confined in some sectors, are presumablt triggered by mutual interaction of the Shillong plateau, Mikr Hills, Indo-Burman Ranges and the easternmost part of the Himalayas, and the contributions from deep-seated fractures cannot be ignored. The results resembles the seismic character of a foreland setting adjacent to a convergent margin. The b-values estimated for 240 square grids of dimension 0.6^0 x 0.6^0 over five seismic domains indicate wide variation. An analysis of cumulative seismic moment release (M_O) in different layers also indicates an anomaly in reference to the total seismic-energy budget of five zones. The lower b-value and higher M_O recorded at relatively lower depth (~30km) towards the southwest of the study area might be associated with upward bulging of a strong lithosphere. The bulging is perhaps regionally compensated by the downward flexing of the descending Indian lithosphere beneath the Upper Assam area; fea-

tures unequivocally observed in any foreland setup. Towards the north and east of the study area, random variation of in both *b*-value and M_O along the converging zone suggests a varied tectonic environment with active interaction between the tectonic elements in these areas.

Keywords: *b* value, Seismic Moment Energy, Strong lithosphere, foreland, deep-seated fracture.

- **Low b-value prior to the Indo-Myanmar subduction zone earthquakes and precursory swarm before the May 1995 M 6.3 earthquake. Sangeeta Sharma, Saurabh Baruah, Om Prakash Sahu, Pabon K.Bora, Ranju Duarah. *Journal of Asian Earth Sciences, 73 (2013), pp. 176-183.***

Abstract:

Some 455 events (mb $\geq$ 4.5) in the Indo-Myanmar subduction zone are compiled using the ISC/EHB/NEIC catalogues (1964–2011) for a systematic study of seismic precursors, b-value and swarm activity. Temporal variation of b-value is studied using the maximum likelihood method beside CUSUM algorithm. The b-values vary from 0.95 to 1.4 for the deeper (depth $\geq$ 60 km) earthquakes, and from 0.85 to 1.3 for the shallower (depth <60 km) earthquakes. A sudden drop in the b-value, from 1.4 to 0.9, prior to the occurrence of larger earthquake(s) at the deeper depth is observed. It is also noted that the CUSUM gradient reversed before the occurrence of larger earthquakes. We further examined the seismicity pattern for the period 1988–1995 within a radius of 150 km around the epicentre (latitude: 24.96^0N; longitude: 95.30^0E) of a deeper event M 6.3 of May 6, 1995 in this subduction zone. A precursory swarm during January 1989 to July 1992 and quiescence during August 1992 to April 1995 are identified before this large earthquake. These observations are encouraging to monitor seismic precursors for the deeper events in this subduction zone.

- **Long range correlation in earthquake precursory signals. H. Chaudhuri, C. Barman, A.N.S. Iyengar, D. Ghose, P. Sen, and B. Sinha. *European Physical Journal, Special Topics, 222, pp. 827-838, 2013, Doi:10.1140/epjst/e2013-01886-y.***

Abstract:

Research on earthquake prediction has drawn serious attention of the geophysicist, geologist and investigators in different fields of science across the globe for many decades. Researchers around the world are actively working on recording pre-earthquake changes in non-seismic parameters through a variety of methods that include anomalous changes in geochemical parameters of the Earth's crust, geophysical properties of the lithosphere as well as ionosphere etc. Several works also have been done in India to detect earthquake precursor signals using geochemical and geophysical methods. However, very few works have been done so far in India in this field through the application of nonlinear techniques to the recorded geophysical and geochemical precursory signals for earthquakes. The present paper deals with a short review of the early works on geochemical precursors that have been carried out in India as yet. With a view to detect earthquake precursor signals by means of gas-geochemical method we developed a network of seismo-geochemical monitoring observatories in India in hot springs and mud volcano crater. In the last few years we detected several geochemical anomalies and those were observed prior to some major earthquakes that occurred within a radius of 1500km from the test sites. In the present paper we have applied nonlinear techniques to the long term, real-term and natural data set of radon 222 and associ-

ated gamma originated out of the terrestrial degassing process of the earth. The results reveal a clear signature of the long range correlation present in the geochemical time series. This approach appears to be a potential tool to explore intrinsic information hidden within the earthquake precursory signals.

- **Radon and thoron anomalies along Mat fault in Mizoram, India. Hari Prasad Jaishi, Sanjay Singh, Raghavendra Prasad Tiwari and Ramesh Chandra Tiwari. *J. Earth Syst. Sci. 122, No. 6, December 2013, pp. 1507-1513.***

Abstract:

In this study, radon and thoron concentrations in soil gas has been monitored using LR-115(II) solid state nuclear track detectors since 15th July 2011 to February 2012. The study was carried out along Mat fault in Serchip district, Mizoram, India at two different sites, Mat Bridge ($23^0 18^{'}$N, $92^0 48^{'}$E) and Tuichang ($23^0 13^{'}$N, $92^0 56^{'}$E). The results obtained have been correlated to the seismic events that occurred within 800km from the measuring sites over the mentioned period of time. Anomalous behavior in the radon concentrations have been observed prior to some earthquakes. Interestingly, some thoron anomalies were also recorded.

Keywords: Radon; thoron; LR-115(II) detectors; correlation; seismic events.

- **A statistical study on precursory effects of earthquakes observed through the atmospheric vertical electric field in northeast India. Abhijit Choudhury, Anirban Guha, Barin Kumar De, Rakesh Roy. *Annals of Geophysics, Vol. 56, No. 3 (2013).***

Abstract:

The study of anomalous variations in the near-surface atmospheric vertical electric field (VEF) that have the form of bay-like depressions in strength have been used as precursors of earthquakes in various studies. We present here the first statistical report from an earthquake-prone zone in northeast India from July 2009 to July 2012. The 10 days that were meteorologically fair and with earthquake occurrences were selected for the present analysis. The average VEF bay durations and depths were ca. 50 min to 70 min, with the corresponding magnitudes of 500 Vm^{-1} to 800 Vm^{-1}. Anomalous variation in VEF before 7 to 12 hour of the impending earthquake has been observed. There was a 31% probability that a VEF bay would show as an earthquake precursor. The positive correlation coefficient was 0.72 between the VEF bay depth and the ratio of earthquake magnitude to depth, while the negative correlation coefficient of 0.82 was calculated between VEF bay duration and the ratio of earthquake magnitude to depth. There was moderate correlation for distance of the earthquake epicenter to the observation point with both VEF bay depth and VEF bay duration. The correlation of the time difference of VEF variations and earthquakes with VEF bay depth was good, whereas the correlation of the time difference of VEF variations and earthquakes with VEF bay duration was too low to be considered.
Keywords: Vertical Electric Field; Earthquake; Negative Bay Anomaly; Lithosphere-Atmosphere-Ionosphere Coupling.

- **Seismic Study and Spatial Variation of b-value in Northeast India. Pulama Talukdar. *IOSR Journal of Applied Physics, Volume 4, Issue 3 (Jul. - Aug. 2013), PP 31-40.***

Abstract:

Study of recent seismicity and b-value estimation by Least Square and Maximum Likelihood Estimation methods in five tectonic blocks of Northeast India demarcates indo Burma Belt, Main Central Thrust, Main Boundary Thrust, Shilling Plateau, Mikir Hills and Kopili Lineament as active seismic source of the region. Spatial variation of b-value is observed by dividing the study area into $1^0 \times 1^0$ grids. Higher b-valuecontours depict the highly seismic area with structural heterogeneity, while lower b-value contours indicate theareas under high stress. b-values are observed in the range of 0.437 - 0.908 and mostly concentrated around 0.7, indicating high stress accumulation.

Keywords: Seismicity, b-value, Contour.

- **Earthquake forerunner as probable precursor – an example from north burma subduction zone. Sujit Dasgupta, Basab Mukhopadhay, Manoj Mukhopadhyay.** ***Journal of the Geological Society of India, August 2013, 80(3), Doi:10.1007/s 12594-012-0157-1.***

Abstract:

The Burmese Arc seismic activity is not uniform for its ∼ 1100 km length; only the Northern Burmese Arc (NBA) is intensely active. Six large earthquakes in the magnitude range 6.1–7.4 have originated from the NBA Benioff zone between 1954–2011, within an area of 200 × 300 km2 where the Indian plate subducts eastward to depths beyond 200 km below the Burma plate. An analysis on seismogenesis of this interplate region suggests that while the subducting lithosphere is characterized by profuse seismicity, seismicity in the overriding plate is rather few. Large earthquakes occurring in the overriding plate are associated with the backarc Shan-Sagaing Fault (SSF) further east. The forecasting performance of the Benioff zone earthquakes in NBA as forerunner is analysed here by: (i) spatial earthquake clustering, (ii) seismic cycles and their temporal quiescence and (iii) the characteristic temporal b-value changes. Three such clusters (C1–C3) are identified from NBA Benioff Zones I & II that are capable of generating earthquakes in the magnitude ranges of 7.38 to 7.93. Seismic cycles evidenced for the Zone I displayed distinct quiescence (Q1, Q2 and Q3) prior to the 6th August 1988 (M 6.6) earthquake. Similar cycles were used to forecast an earthquake (Dasgupta et al. 2010) to come from the Zone I (cluster C1); which, actually struck on 4 February 2011 (M 6.3). The preparatory activity for an event has already been set in the Zone II and we speculate its occurrence as a large event (M > 6.0) possibly within the year 2012, somewhere close to cluster C3. Temporal analysis of b-value indicates a rise before an ensuing large earthquake.

- **A statistical study on precursory effects of earthquakes observed through the atmospheric vertical electric field in northeast India. Abhijit Choudhury, Anirban Guha, Barin Kumar De, Rakesh Roy.** ***Annals of Geophysics, Vol. 56, No. 3, 2013, R033, Doi:10.4401/ag-6235.***

Abstract:

The study of anomalous variations in the near-surface atmospheric vertical electric field (VEF) that have the form of bay-like depressions in strength have been used as precursors of earthquakes in various studies. We present here the first statistical report from an earthquake-prone zone in northeast India from July 2009 to July 2012. The 10 days that were meteorologically fair and with earthquake occurrences were selected for the present analysis. The average VEF bay durations and depths were ca. 50 min to 70 min, with the corresponding magnitudes of 500 Vm-1 to 800Vm-1. Anomalous variation in VEF before 7 to 12 hour of the impending earthquake has been observed. There was a 31% probability that a VEFbay would show as an earthquake precursor. The positive correlation coefficient was 0.72 between the VEF bay depth and the ratio of earthquake magnitude to depth, while the negative correlation coefficient of 0.82 was calculated between VEF bay duration and the ratio of earthquake magnitude to depth. There was moderate correlation for distance of the earthquake epicenter to the observation point with both VEF bay depth and VEF bay duration. The correlation of the time difference of VEF variations and earthquakes with VEF bay depth was good, whereas the correlation of the time difference of VEF variations and earthquakes with VEF bay duration was too low to be considered.

- **Earthquake forecasting: a possible solution considering the GPS ionospheric delay. M. De Agostino and M. Piras.** ***Nat. Hazards Earth Syst. Sci., 11, 3263–3273, 2011.***

Abstract:

The recent earthquakes in L'Aquila (Italy) and in Japan have dramatically emphasized the problem of natural disasters and their correct forecasting. One of the aims of the research community is to find a possible and reliable forecasting method, considering all the available technologies and tools. Starting from the recently developed research concerning this topic and considering that the number of GPS reference stations around the world is continuously increasing, this study is an attempt to investigate whether it is possible to use GPS data in order to enhance earthquake forecasting. In some cases, ionospheric activity level increases just before to an earthquake event and shows a different behavior 5–10 days before the event, when the seismic event has a magnitude greater than 4–4.5 degrees. Considering the GPS data from the reference stations located around the L'Aquila area (Italy), an analysis of the daily variations of the ionospheric signal delay has been carried out in order to evaluate a possible correlation between seismic events and unexpected variations of ionospheric activities. Many different scenarios have been tested, in particular considering the elevation angles, the visibility lengths and the time of day (morning, afternoon or night) of the satellites. In this paper, the contribution of the ionospheric impact has been shown: a realistic correlation between ionospheric delay and earthquake can be seen about one week before the seismic event.

- **Statistical Tests for Pre-earthquake Ionospheric Anomaly. Yuh-Ing Chen, Jann-Yenq Liu, Yi-Ben Tsai and Chun-Shu Chen.** ***TAO, Vol. 15, No. 3, pp. 385-396, September, 2004.***

Abstract:

The anomalous depression depression of the maximum plasma frequency in the ionosphere (foF2) appears significantly within 1-5 days before the M $\geq$ 5.0 earthquakes in the Taiwan area during 1994-1999 (Liu etal. 2003). In this paper, we propose two statistical tests against the foF2 anomaly as a candidate for precursor of earthquakes based on criteria including the success rate, alarm rate, probability gain, and R score. One statistical test is conducted

to investigate the significance of the observed foF2 anomalies related to the recorded M $\geq$ 5.0 earthquakes in the Taiwan area during 1994-1999. The other statistical test is designed to compare the foF2 anomaly based method with competitive alternatives for predicting the earthquakes under study. The involved alternatives are a naïve prediction based on a coin-tossing experiment and a simple prediction method constructed from the current M $\geq$ 5.0 earthquakes catalogue during 1994-1999. The simulation results indicates that, contrast to possible foF2 anomalies, the observed foF2 anomalies are significantly earthquake related. Moreover, comparing with the alternative prediction under study, the foF2 anomaly remains valid for temporal alarming of the M $\geq$ 5.0 earthquakes in the Taiwan area during 1994-1999.

- **On the existence of earthquake precursors. Frank Evison. *Annali Di Geofisica, Vol. 42, N. 5, October 1999.***

Abstract:

Earthquake prediction based on precursors can aim to provide fully qualified, time-varying, synoptic forecasts, which do not depart from physical and geological principles, and are amenable to formal testing. These features are in contrast to the traditional occultist or soothsayer style of prediction. The recently-advanced, pre-emptive hypothesis that earthquakes are intrinsically unpredictable, and precursors non-existent, is also amenable to testing: it is refuted by the well-known relations between mainshocks and aftershocks. These relations shows that a set of aftershocks is to a high degree predictable from the mainshock, so that, as a matter of principle, the mainshock is precursor to its aftershocks. This result is compatible with the power-law property of seismicity, on which the unpredictability hypothesis is based. Empirical research on most precursors is difficult because of the scarcity of the data, and is still largely at the anecdotal stage. Additional difficulties at the experiment stage are exemplified by the failure of the Tokai Parkfield experiments to advance the study of precursors as planned. A comparative abundance of data is available on seismicity anomalies, and research on this type of precursor is progressing towards the operational stage.

Keywords: earthquake prediction - precursors.

- **Precursor-Like Anomalies prior to the 2008 Wenchuan Earthquake: A Critical-but-Constructive Review. Tengfei Ma and Zhongliang Wu. *International Journal of Geophysics, Vol. 2012, Article ID 583097, 13 pages, doi:10.1155/2012/583097.***

Abstract:

Results published since the last three years on the observations of the precursor-like anomalies before the May 12, 2008 Wenchuan, M 8.0 earthquake are collected and analyzed. These retrospective case studies would have provided heuristic clues about the preparation process of this inland great earthquake and the predictability of this destructive event if the standards for the rigorous test of earthquake forecast schemes were strictly observed. At least in some of these studies, however, several issues still need to be further examined to confirm or falsify the connection of the reported observations with the Wenchuan earthquake. Some of the problems are due to the inevitable limitation of observational infrastructure at the recent time, but some of the problems are due to the lack of communication about the test of earthquake forecast schemes. For the interdisciplinary studies on earthquake forecast reminding of the latter issue seems of special importance for promoting the works and cooperation in this field.

- **Identification of seismic precursors before large earthquakes: Decelerating and accelerating seismic patterns. Panayotis Papadimitriou. *Journal of Geophysical Research, Vol. 113, B04306, doi:10.1029/2007/jb005112, 2008.***

Abstract:

A useful way of understanding both seismotectonic processes and earthquake prediction research is to conceive seismic patterns as a function of space and time. The present work investigates seismic precursors before the occurrence of an earthquake. It does so by means of a methodology designed to study spatiotemporal characteristics of seismicity in a selected area. This methodology is based on two phenomena: the decelerating moment release (DMR) and the accelerating moment release (AMR), as they occur within a period ranging from several months to a few years before the oncoming event. The combination of these two seismic sequences leads to the proposed decelerating-accelerating moment release (DAMR) earthquake sequence, which appears as thelast stage of loading in the earthquake cycle. This seismic activity appears as a foreshock sequence and can be supported by the stress accumulation model (SAM). The DAMR earthquake sequence continues a double seismic precursor identified in space and time before the occurrence of an earthquake and can be used to improve seismic hazard assessment research. In this study, the developed methodology is applied to the data of the 1989 Loma Prieta (California), the 1995 Kobe (Japan), and the 2013 Lefkada (Greece) earthquakes. The last pair of this study focuses on the application of the methodology to the Ionian Sea (western Greece) and forecasts two earthquakes in that area.

- **The 1999 Chi-Chi, Taiwan, earthquake as a typical example of seismic activation and quiescence. Chien-Chih Chen, John B. Rundle, James R. Holliday, Kazuyoshi Z, Nanjo, Donald L. Turcotte, Shian-Chi Li and Kristy F. Tiampo. *Geophysical Research Letters, Vol. 32, L22315, Doi:10.1029/2005GLo23991, 2005.***

Abstract:

The pattern Informatics algorithim, which has recently shown promising performance for earthquake forecasting in Southern California, has been used to detect the locations where precursory seismic activity occurred preceding the 1999 Chi-Chi, Taiwan, earthquake. Using the Pattern Informatics method as presented in this paper, the epicenter of the Chi-Chi main shock was found to exhibit signatures of anomalous activity related to the seismic activation and quiescence in the Taiwan region over a time span of about 6 years before the main shock. A strategy of making intermediate-term earthquake hazard assessment by means of Pattern Informatics is therefore proposed on the basis of retrospective analysis of the Chi-Chi earthquake.

- **Predicting the 1975 Haicheng Earthquake', Kelin Wang, Qi-Fu Chen, Shihong Sun and Andong Wang. *Bulletin of the Seismological Society of America, Vol. 96, No. 3, pp. 757-795, June 2006, doi:10.1785/0120050191.***

Abstract:

The publicized four-stage (long term, middle-term, short-term, and imminent) prediction of the *M* 7.3 1975 Haicheng, China, earthquake once generated worldwide facination. Yet the prediction process has remained mysterious because of lack of reports on real-time documentation and details of how warnings were issued. In the present work, study of

classified chinese documents and interviews of key witnesses have allowed us to reconstruct this important history. Our findings indicate that there were two official middle-term predictions but no official short-term prediction. On the day of the earthquake, a county government issued a specific evacuation order, and actual actions taken by provincial scientists and government officials also effectively constituted an imminent prediction. These efforts saved thousands of lives, but the local construction style and time of earthquake also contributed to minimizing fatalities. Evacuation was extremely uneven across the disaster region, and critical decisions were often made at very local levels. The most important precursor was a foreshock sequence, but other anomales such as geodetic deformation, changes in ground water level, color, and chemistry, and peculiar animal behavior also played a role.

- **Precursory seismic changes associated with the M_w 7.4 1999 August 17 Izmit (Turkey) earthquake. Q. Huang , A.O.Oncel and G.A.Sobolev. *Geophysics. J. Int. (2002) 151, 235-242.***

Summary:

We investigated precursory seismicity in and around the epicentral zone of the M_w = 7.4 1999 August 17 Izmit (Turkey) earthquake, by applying a statistical method-the RTL Region-Time-Length) algorithim-to earthquake catalogues derived from that for the period 1981-1999 of Kandilli Observatory and Earthquake Research Institute (KOERI). The derived catalogues are complete for events $M_D \geq 3$ in most of western Turkey. After declustering aftershocks, we investigated the seismicity patterns preceding the Izmit event at local (Izmit tectonic zone) and national (Turkey) scales. The RTL parameter indicates that a period of seismic quiescence started at the end of 1995 and reached a minimum in December 1996. An activation phase lasting about three months followed. The mainshock in Izmit and vicinity did not occur when the seismicity retrurned to its background level, but occurred with a delay of nearly 2.5 yr. We present a new parameter to quantify the spatial distribution of seismic quiescence. The results from both catalogues indicate that a significant quiescence anomaly appeared in 1996 around the epicenter of the Izmit earthquake. The primary characeteristics of the seismicity patterns prior to the Izmit earthquake are similar to those obtained for larhe events in Russia and Japan. The variation of seismicity patterns revealed by the RTL algorithim may offer better understanding of the physical nature of seismo-tectonics and provide useful information for seismic hazard estimation.The varying characteristics of the Izmit and other events may reflect the difference between seismo-tectonics In Turkey and in other regions such as Russia and Japan.

Key words: Izmit earthquake, quiscence, seismicity, seismo-tectonics, statistical method.

- **Seismicity-based earthquake forecasting techniques: ten years of progress. Kristy F. Tiampo and Robert Shcherbakov. *Tectonophysics, 2012.***

Abstract:

Earthquake fault systems interact over a broad spectrum of spatial and temporal scales and, in recent years syudies of the regional seismicity in a variety of regions have produced a number of new techniques for seismicity-based earthquake forecasting. While a wide variety of physical assumptions and statistical approaches are incorporated into the various

methodologies, they all endeavorto accurately replicate the statistics and properties of both the historic and Instrumental seismic records. As a result, the last ten years have seen significant progress in the field of intermediate-and short-term seismicity-based earthquake forecasting. These include general agreement on the need for prospective testing and successful attempts to standize both evaluation methods. And the appropriate null hypothesis. Here we differentiate the predominant approaches into models based upon techniques for identifying particular physical processes and those that filter, or smooth, the seismicity. Comparison of the methods suggests that while smoothed seismicity models provide improved forecast capability over longer time periods, higher probability gain over shorter time period is achieved with methods that integreat statistical techniques with our knowldege of the physical process, such as the epidemic-type aftershock sequence (ETAS) model or those related to changes in the b-value, for example. In general, while both classes of seismicity-based forecasts are limited by the relatively short time period available for the instrumental catalogue. Significant advances have been made in our understanding of both the limitations and potential of seismicity-based earthquake forecasting. There is general agreement that both short-term forecasting, on the order of days to week, and longer term forecasting over five-to-ten year periods, is within reach. The recent progress serves to illuminate both the critical nature of the different temporal scales intrinsic to the earthquake process and the importance of high quality seismic data for the accurate quantification of time-dependent earthquake hazard.

- **Seismicity Gap near Oaxaca, Southern Mexico as a Probable Precursor. Masakazu Ohtake, Tosimatu Matumoto and Gary V. Latham. *Pageoph, Vol. 115 (1977).***

Summary:

An area of significant seismic quiescence is found near Oaxaca, southern Mexico. The anomalous area may be in the site of a future large earthquake as many cases so far reported were. This conjecture is justified by study of past seismicity changes in the Oaxaca rewgion. An interval of reduced seismicity, followed by a renewal of activity, preceded both the recent large events of 1965 and 1968. Those past earthquakes have ruptured the eastern and western portions of the present seismicity gap, respectively, so that the central part remaining is considered to be of the highest risk of the pending earthquake.

The most probable estimates are: $7^{1/2} \pm ^{1/4}$ for the magnitude $\phi = 16.5^0 \pm 0.5^0$N, $\lambda = 96.5^0 \pm$ 0.5W for the epicenter location. A firm prediction of the occurrence time is not attempted. However, a resumption of seismic activity in the Oaxaca region may precede a main shock.

Kew words: Seismicity; Earthquake Prediction.

- **A new algorithm for the detection of seismic quiescence: introduction of the RTM algorithm, a modified RTL algorithm. Toshiyasu Nagao, Akihiro Takeuchi and Kenji Nakamura. *Earth Planets Space, 63, 315-324, 2011.***

Abstract:

There are a number of reports on seismic quiescence phenomena before large earthquakes. The RTL algorithm is a weighted coefficient statistical method that takes into account the magnitude, occurrence time, and place of earthquake when seismicity pattern changes before large earthquakes are being investigated. However, we consider the original

RTL algorithm to be over weighted on distance. In this paper, we introduce a modified RTL algorithm, called the RTM algorithm, and apply it to three large earthquakes in Japan, namely, the Hyogoken Nanbu earthquake in 1995 (*M*JMA 7.3), the Noto Hanto earthquake in 2007 (*M*JMA 6.9), and the Iwate-Miyagi Nairiku earthquake in 2008 (*M*JMA 7.2), as test cases. Because this algorithm uses several parameters to characterize the weighted coefficients, multi-parameter sets have to be prepared for the tests. The results show that the RTM algorithm is more sensitive than the RTL algorithm to seismic quiescence phenomena. This paper represents the first step in a series of future analyses of seismic quiescence phenomena using the RTM algorithm. At this moment, whole surveyed parameters are empirically selected for use in the method. We have to consider the physical meaning of the “best fit” parameter, such as the relation of _CFS, among others, in future analyses.

Key words: Seismicity, seismic quiescence, RTM, RTL, precursor.

- **Seismic quiescence patterns as possible precursors of great earthquakes in Mexico. Adolfo H. Rudolf-Navarro, Alejandro Muñoz-Diosdado and Fernando Angulo-Brown. *International Journal of the Physical Sciences, Vol. 5 (6), pp. 651-670, June 2010.***

Abstract:

A catalog of shallow Mexican earthquakes (depth _ 60 Km) is presented for a region bounded by north latitude and west longitude, covering the period from January, 1806 to December, 2010, which is incomplete in this period for a wide range of magnitudes, but is complete for different ranges of magnitude in short intervals of time. The catalog is probably complete for since 1860 and for since 1846, but for earthquakes of magnitude greater than or equal to 4.3 the catalog is complete since 1969. Using the data of this master catalog, we show that there is evidence that the last earthquakes of magnitude that occurred in Mexico from 1975 to 2009 were preceded by an unusual seismic quiescence. We use the method of space-time plots and cumulative seismicity plots.

Key words: Seismic quiescence, cumulative seismicity, Mexican earthquakes.

- **Seismic quiescence before the M7, 1988, Spitak earthquake, Armenia. MaxWyss and Artak H. Martirosyan. *Geophys. J. Int. (1998) 134, 329–340.***

Summary:

A detailed analysis of the 35 yr of seismicity between 1962 and 1997 using a gridding technique shows that the M7, Spitak earthquake of 1988 December 7 was preceded by a quiescence anomaly that started at approximately 1984±0.5, and lasted about 5±0.5 yr, up to the main shock. This quiescence anomaly had a radius of about 20±3 km, estimated from circular areas with 75 per cent rate decrease, centred at the point of maximum significance of the anomaly. The quiescence was clearly present in the aftershock volume during the 5 yr before the 1988 main shock, but its statistically strongest expression was located 30 km NW of the epicentre. This anomaly fulfills the association rules between precursory quiescence anomalies and main shocks, even for a tight definition, and is therefore proposed as a case of precursory quiescence. The largest value of the standard deviate Z, found by random selection of

samples by gridding, was Z=14 for a time window of Tw=3 yr, using a sample size of N=300 events. This makes this anomaly the strongest observed so far, and it is the first documented in an environment of continental collision. There are no false alarms exceeding in significance the precursor. The Armenian earthquake catalogue used for this study had 4600 earthquakes with MµMmin=2.2 in the area bounded by 39.5° to 42°N/42.5° to 47°E. From the point of view of homogeneous reporting this is the best catalogue we have analysed so far. The limits of the data used and the density of the grid are dictated by the data, and have no influence on the results. The choice of free parameters does not influence the results significantly within the following limits: 100≤ N≤500, 2 ≤Tw ≤ 7, 2.2Mmin ≤ 2.8.

Key words: Armenia, earthquake prediction, seismic quiescence, seismicity patterns.

- **Seismic Quiiescence before the Urakawa-Oki Earthquake. D.W.A. Taylor, J.A. Snoke, I.S. Sacks and T. Takanami.** ***Bulletin of the Seismological Society of India, Vol. 81, 4, pp. 1255-1271, August, 1991.***

Abstract:

There were significant changes in seismicity preceding a large earthquake, the Urakawa-Oki earthquake of 21 March 1982. This event, a M_{JMA} = 7.1 thrust fault, crustal earthquake, is the largest from a data set of 35,000 earthquakes beneath the southern corner of Hokkaido Island (Japan) during the period July 1976 through December 1986. There was a quiescence for the 2 years preceding the main shock, surrounding, but not including, the immediate epicenter, and only for magnitude ≥ 3.0. During the same time span, there was an increase in the number of small (magnitude ≤ 2.4) events restricted to the general focal region of the main shock. The magnitude dependence of the precursory seismicity pattern is a departure from self-similarity, one of the currently prevalent assumptions in earthquake source models. These seismicity anomalies can be seen using conventional methods such as cumulative number versus time for selected magnitudes in a bounded geographical region. However, such displays requires a priori knowledge of assumptions about the prospective target region and magnitude range. For this anomaly, there was no reason to target the epicentral region in advance, and the usual assumption that quiescence should be most evident at small magnitudes was not appropriate here. We have developed an efficient, objective procedure for alerting one to the possible existence of a developing anomaly and then analyzing its spatial bounds and itd magnitude dependence. This procedure has potential value as a general monitoring tool.

- **Relationship between accelerating seismicity and quiescence, two precursors to large earthquakes. Amaud Mignam and Rita Di Giovambattista.** ***Geophysical Researcl Letters, Vol. 35, I5306, Doi:10.1029/2008GL035024, 2008.***

Abstract:

The Non-Critical Precursory Accelerating Seismicity Theory (PAST) has been proposed recently to explain the formation of accelerating seismicity (increase of the *a*-value) observed before large earthquakes. In particular, it predicts that precursory accelerating seismicity should occur in the same spatiotemporal window as quiescence. In this first combined study we start by determining the spatiotemporal extent of quiescence observed prior to the 1997 M_W = 6.0 Umbria-Marche earthquake, Italy, using the RTL (Region-Time-Length) algorithm. We then so that background events located in that spatiotemporal window foem a clear

acceleration, as expected by the Non-Critical PAST. This result is a step forward in the understanding of precursory seismicity by relating two of the principal patterns that can precede large earthquakes.

- **Seismicity Pattern Changes Prior to Large Earthquakes -An Approach of the RTL Algorithm. Qinghua Huang.** ***TAO, Vol. 15, No. 3, 469-491, September 2004.***

Abstract:

A statistical method, which is called the Region-Time-Length (RTL) algorithm and takes into account information such as magnitude, occurrence time and place of earthquakes, was applied to earthquake data to investigate seismicity pattern changes prior to large earthquakes. Based on the RTL algorithm and some newly developed parameters such as the *Q* parameter (average of the RTL values over some time window) and *S*-parameter (an index of seismic activation), I quantified both the temporal and spatial characteristics of seismicity pattern changes in various tectonic regions. The results indicated that seismic quiescence anomalies generally started a few years before the occurrence of the earthquakes and lasted from 1 to 2.5 years. The duration of the subsequent stage of seismic activation generally lasted several months. The linear dimension of the quiescence zone reached a few hundred kilometers (several times the rupture dimension of the mainshock), while the activation zone was generally in order of several tens of kilometers (comparable to the rupture dimension). An earthquake is most likely to occur once the relevant source region has passed through the quiescence and activation stages. Close investigation of possible artifacts due to the selection of model parameters and the changes of seismological networks are important in identifying real seismicity changes from man-made ones. Further stochastic testing using random earthquake catalogs was also done and it supports that the anomalies revealed in my works are significant. Besides studying on seismicity changes before large earthquakes, I also performed the first test of the above statistical method for investigating seismicity changes of earthquake swarms. It indicated that an increased RTL parameter would be a new potentially useful index for the risk alarm of earthquake swarms.

- **Medium-Term Earthquake Forecast Using Gravity Monitoring Data: Evidence from the Yutian and Wenchuan Earthquakes in China. Yiqing Zhu and F. Benjamin Zhan.** ***International Journal of Geophysics, Volume 2012, 6 pages, Doi:10.1155/2012/307517.***

Abstract:

Gravity changes derived from regional gravity monitoring data in China from 1998 to 2005 exhibited noticeable variations before the occurrence of two large earthquakes in 2008 in China—the 2008 Yutian (Xinjiang) Ms = 7.3 earthquake and the 2008 Wenchuan (Sichuan) Ms = 8.0 earthquake. Based on these gravity variations, a group of researchers at the Second Crust Monitoring and Application Center of China Earthquake Administration made a suggestion in December of 2006 that the possibility for the Yutian (Xinjiang) and Wenchuan (Sichuan) areas to experience a large earthquake in either 2007 or 2008 was high. We review the gravity monitoring data and methods upon which the researchers reached these medium-term earthquake forecasts. Experience related to the medium-term forecasts of the Yutian and Wenchuan earthquakes suggests that gravity changes derived from regional

gravity monitoring data could potentially be a useful medium-term precursor of large earthquakes, but significant additional research is needed to validate and evaluate this hypothesis.

- **Seismicity changes associated with the 2000 earthquake swarm in the Izu Island region. Qinghua Huang.** ***Journal of Asian Earth Sciences, 26 (2006) 509-517.***

Abstract:

A statistical method taking into account the information of magnitude, occurrence time and location of earthquakes was applied to the earthquake data (1977-2000) of the Japan Meterological Agency (JMA) to investigate seismicity changes in the Izu Island region. The analysis indicated that a quiescence anomaly started about 15 years before the occurrence of the largest swarm in the summer of 2000 in the Izu Island region. Close investigations of the possible artifacts due to the selection of model parameters and the improvement of the seismological network lead to the conclusion that the above quiescence anomaly is unlikely a man-made change. The further stochastic test using 1000 random earthquake catalogues supports the idea that the above anomaly is significant. The spatial distribution of the seismic quiescence, which is quantified by a newly developed *Q*-parameter, revealed a clear anomalous region around the epicentral area of the above earthquake swarm. The seismicity revealed by the normalized parameter tends to increase just before the swarm. As the first test of the above statistical method for investigating seismicity changes of earthquake swarms, this study indicates that the increased *RTL* parameter would be a new potentially used index for the risk alarm of earthquake swarm.

Keywords: Earthquake swarms, Seismicity changes; Seismic quiescence; Accelerated seismicity; Iza Island region.

- **GSHAP revisted for the Prediction of Maximum Credible Earthquake in the Sikkim region, India. Madhav Vyas, Sankar Kumar Nath, Indrajit Pal, Probal Sengupta and William K. Mohanty.** ***Acta Geophysica Polonica, Vol. 53, No. 2, pp. 143-152, 2005.***

Abstract:

Global Seismic Hazard Assessment Program (GSHAP) has classified the Indian peninsula into several seismogenic zones. Considering the seismo-tectonic setting of the Sikkim Himalaya, sources 2, 3, 4, 5, 25, 26, 27 and 86 may be critical in contributing to the seismic hazard of the region. These seismogenic zones have been classified as Himalayan source (25, 86), extension of Tibetan plateau (26, 27), Burmese arc subduction zone (4, 5), Shillong plateau (3) and the Indian Shield region (2). The probabilistic seismic hazard assessment of the region necessitated prediction of Maximum Credible Earthquake magnitude for each source with 10% probability of exceedance in 50 years. Considering the widespread damages caused in the state capital of Sikkim due to the recent earthquakes of 1934 (Mw = 8) and 1988 (Mw = 7.2) a 50-year prediction seemed to be reasonable. Gutenberg–Richter (*b*-value) approach and Gumbel's method of extreme value statistics have been used in the present analysis for the predic-tion of Maximum Credible Earthquake magnitude, results of both being compa-rable to each other. The maximum credible earthquake magnitude as predicted by both the methods are above 6 except for zone 26, the

highest being in the Burmese arc with a magnitude of 8.5 by Gutenberg–Richter approach and a magnitude of 7.7 by Gumbel's method.

Keywords: GSHAP, seismogenic zone.

- **Evolution mechanisms of an earthquake swarm under the Hida Mountains, central Japan, in 1998. H. Aoyama,1 M. Takeo, and S. Ide. *Journal of Geophysical Research, Vol. 107, No. B8, 10.1029/2001JB000540, 2002.***

Abstract:

An earthquake swarm occurred under the Hida Mountains in central Japan in 1998. The focal area, which expanded from south to north, was distributed above the low-velocity and high-attenuation zone, which lies under the main range. During the swarm, there was a migration of focal areas with time delays. In this paper, we investigate the spatiotemporal distribution of earthquakes in the swarm and discuss the phenomenon that must have controlled the seismicity. Understanding the complicated spatial pattern of seismicity, we investigate the dependency of the occurrence of earthquakes on the static stress changes caused by preceding earthquakes. Our findings show that, for each of 18 major earthquakes (magnitudes 4.0 or higher), the estimated distribution of the resulting Coulomb failure stress corresponds to the expansion of focal areas and the distribution of the seismically quiescent region. However, the detailed structure of seismicity cannot be explained only by the static stress changes. We discuss two additional factors which may control delayed fractures: flow of underground water for the seismicity around the southernmost focal cluster and stress corrosion process for the leaps of seismicities. The results of this study suggest that the 1998 Hida swarm was strongly affected by the disturbances of a static stress field that was created by the swarm itself, although the magnitudes of static stress change are small. The seismic activity was initiated by swarm-type seismicity around the southernmost cluster and then expanded northward gradually due to the increase in static stress.

Keywords: earthquake swarm, earthquake triggering, Coulomb failure stress.

- **Spatial-Temporal Variation of Seismicity and Spectrum of the 1980 Earthquake Swarm near the Izu Peninsula, Japan. Mizuho Ishida. *Bulletin of the Seismological Society of America, Vol. 74, No. 1, pp. 199-221, February 1984.***

Abstract:

The spatial-temporal variation of seismicity of the 1980 earthquake swarm off the east coast of the Izu Peninsula, Japan, was investigated. Hypocentral distribution, focal mechanism, wave forms, and spectra of seismic waves were studied. The hypocenters were relocated by using the master event method. The forerunning earthquakes which started about one week before the largest shock (main shock), the 1980 Izu-Hanto-Toho-Oki earthquake (M = 6.7), occurred within the quiescent area of the earthquake activity for the preceding one year. The swarm area migrated toward the south with time and triggered the main shock in June 1980. The fault dimension and geometry were estimated from the aftershock area: the fault length and width are 14 km and 8 km; the strike and dip angles of the fault are N15°W and 65 ° to N75°E. Locations of the events in an earlier earthquake swarm (1978) were also examined by using difference in the *S-P* time at five selected stations distributed around the

epicentral area. The 1978 swarm events were found to have clustered within a very small area of 8 x 1 km 2 located about 2 km to the west of the 1980 swarm area. The earthquakes which occurred after the main shock of the 1980 swarm were classified into two groups, aftershocks and swarm events, according to the location of epicenters, wave forms, and spectra of S waves. The peak frequencies of spectra were distributed around 5 to 8 Hz for the aftershocks and around 10 to 15 Hz for the swarm events. Most of the aftershocks, characterized by low frequency content, occurred to the south of the main shock within 2 weeks after the main shock. The number of aftershocks decayed following the modified Omori's formula with p = 1.5 _ 0.3. The swarm activity, on the other hand, continued intermittently for about I month after the main shock. The 1980 seismic activity is interpreted as a complex of a foreshock-main shock-aftershock sequence and swarm activity. The direction of the longer axis of the swarm area coincided with the direction of the maximum pressure axis of the main shock. The trend of the aftershock zone coincided with the strike of the fault planes of the main shock and aftershocks. This feature strongly suggests that tension cracks trending in the maximum stress direction opened prior to the occurrence of the main shock. The opening of cracks may be accounted for by increasing of interstitial pore pressure associated with increase in regional stress.

- **Earthquake Prediction: The interaction of public policy and science. Lucile M.Jones.** ***Proc. Natl. Acad. Sci. USA, vol. 93, pp. 3721-3725, April 1996.***

Abstract:

Earthquake prediction research has searched for both informational phenomena, those that provide information about earthquake hazards useful to the public, and casual phenomena, causally related to the physical processes governing failure on a fault, to improve our understanding of those processes. Neither information nor casual phenomena are subset of the other. I propose a classification of potential earthquake predictors of information, casual, and predictive phenomena, where predictors are casual phenomena that provide more accurate assessments of the earthquake hazard than can be gotten from assuming a random distribution. Achieving higher, more accurate probabilities than a random distribution requires much more information about the precursor than just that is casually related to the earthquake.

- **Values of b and p: Their variations and relation to physical processes for earthquakes in Japan and Romania. B. Enescu, D. Enescu, K. Ito.** ***Rom. Journ. Phys., Vol. 56, Nos. 3–4, P. 590–608, Bucharest, 2011.***

Abstract:

This work reviews some results obtained for the variations of the seismicity parameters *b* and *p* in different seismogenic and tectonic regions in Japan. We bring as well new evidence that the time and space changes in seismicity parameters are correlating well with the crustal structure and/or some parameters of the earthquake process. Moreover, we also analyze the variation of b-value as a function of depth for the Vrancea (Romania) region, of intermediate-depth seismicity. In the first part of the paper we show that several seismicity precursors (clear *b*-value changes, quiescence and clustering) occurred about two years before the 1995 Kobe earthquake and they correlate well with other geophysical premonitory phenomena of the major event. The precursory phenomena occurred in a relatively large area, which corresponds probably with the preparation zone of the future event. In the second part, we analyze the *b* and *p* value spatial and temporal distribution for the aftershocks of the 2000

Tottori earthquake. The results indicate significant correlations between the spatio-temporal pattern of *b* and *p* and the stress distribution after the main shock, as well as the crustal structure. The swarm-like seismic sequences occurred in 1989, 1990 and 1997 showed significant precursory *b* and *p* values. In the third part of the paper we analyze the seismicity during the 1998 Hida Mountain earthquake swarm. The double-difference-relocated events are analyzed for their frequency magnitude distribution and stress changes. While again the *b*-value is significantly different in south comparing with the north part of the epicentral area, the physical interpretation is difficult and complex. The changes in the Coulomb failure stress (ΔCFF) can explain the *b*-value distribution features, but the crustal structure may be also important. The seismicity distribution and migration, in relation with ΔCFF is also discussed. In the last part of the paper, we find that the b-value is higher in the upper part (60 km - 120 km) of the Vrancea subducting slab and decreases in the lower part (130 km – 220 km). We discuss this change in relation to stress variations within the subducting slab. We refer as well to other world-wide studies.

Key words: *magnitude-frequency distribution, Omori law, seismicity, earthquake statistics, Coulomb stress changes, double-difference earthquake relocation.*

- **Seismicity Pattern Changes Prior to Large Earthquakes -An Approach of the RTL Algorithm. Qinghua Huang.** ***TAO, Vol. 15, No. 3, 469-491, September 2004.***

Abstract:

A statistical method, which is called the Region-Time-Length (RTL) algorithm and takes into account information such as magnitude, occurrence time and place of earthquakes, was applied to earthquake data to investigate seismicity pattern changes prior to large earthquakes. Based on the RTL algorithm and some newly developed parameters such as the *Q* parameter (average of the RTL values over some time window) and *S*-parameter (an index of seismic activation), I quantified both the temporal and spatial characteristics of seismicity pattern changes in various tectonic regions. The results indicated that seismic quiescence anomalies generally started a few years before the occurrence of the earthquakes and lasted from 1 to 2.5 years. The duration of the subsequent stage of seismic activation generally lasted several months. The linear dimension of the quiescence zone reached a few hundred kilometers (several times the rupture dimension of the main shock), while the activation zone was generally in order of several tens of kilometers (comparable to the rupture dimension). An earthquake is most likely to occur once the relevant source region has passed through the quiescence and activation stages. Close investigation of possible artifacts due to the selection of model parameters and the changes of seismological networks are important in identifying real seismicity changes from man-made ones. Further stochastic testing using random earthquake catalogs was also done and it supports that the anomalies revealed in my works are significant. Besides studying on seismicity changes before large earthquakes, I also performed the first test of the above statistical method for investigating seismicity changes of earthquake swarms. It indicated that an increased RTL parameter would be a new potentially useful index for the risk alarm of earthquake swarms.

- **Evidence for Mogi doughnut behavior in seismicity preceding small earthquakes in southern California. Peter M. Shearer and Guoqing Lin.** ***Journal of Geophysical Research, Vol. 114, B01318,doi:10.1029/2008JB005982, 2009.***

Abstract:

We examine the average space-time behavior of seismicity preceding *M* 2-5 earthquakes in southern California from 1981 to 2005 using a high- resolution catalog and identify regions of enhanced activity in a 1-day period preceding larger earthquakes at distances comparable to their predicted source radii. The difference in precursory behavior between large and small earthquakes is subtle but statistically significant when averaged over many earthquakes, and it has similarities to the "Mogi doughnut" seismicity pattern observed to occur prior to some *M* 6 and larger earthquakes. These results indicate that many standard earthquake triggering models do not account for all of the processes involved in earthquake occurrence.

- **Changes of Mean Magnitude of Parkfield Seismicity: A part of the Precursory Process?Max Wyss.** ***Geophysical Research Letters, Vol. 17, No. 12, pp. 2429-2432, December 1990.***

Abstract:

The average magnitude of earthquakes produced along the Parkfield segment of the San Andreas fault was decreased significantly between late 1986 and late 1988 along with the seismic quiescence [Wyss et al., 1990a]. The change corresponds to an increase of the b-value from 1.1 to 1,4. During the last year (1989) however, the average magnitude produced was approximately normal again. This same phenomena had been identified before several other main shocks. Therefore it may be interpreted as a precursor to the predicted Parkfield main shock.

- **Precursors to the Kalapana M = 7.2 Earthquake. Max Wyss.** ***Journal of Geophysical Research, Vol 86, No. B 5, pages 3881-3900, May 10, 1981.***

Abstract:

The Kalapana, Hawaii earthquake of November 1975 had a rupture length of 40 to 50 km and was located on the south flank of the active volcano Kilauea. The source mechanism was dip slip normal faulting on a plane dipping ~20 degrees to the SE, with the greatest principal stress oriented in that direction and accumulated by volcanic intrusions into Kilauea's rifts. The source area of the 1978 earthquake was subject to intensive geological and geophysical research for many years before this earthquake because of its proximity to the volcano. We studied the distribution of epicenters for small earthquakes from 1962 to 1975. Seven seismographs located within 3 km of the aftershock area had been in operation for 3 to 10 years before the main shock, and geodetic triangulations and trilaterations in the source area had been carried out repeatedly since 1914. We found that precursory changes occurred throughout most of the rupture area but in two distinctly different patterns. In the larger outer anomalous area the seismicity rate was decreased by 50% during the 3.8 years before the main shock; in addition, several geodetic lines indicated anomalous strain release during this time. Within two inner areas the seismicity remained high, then increased shortly before the main shock. In one of the inner areas a P wave travel time delay of 0.2 s could be detected, which began about 3.5 years before the main shock. Within the other inner anomalous area geodetic strain was accumulating until the first half of 1975 when 3.5x10 -4 strain (35 bars), was released aseismic ally. By contrast, the outer anomalous volume was experiencing strain

softening from 1970/1971 on. We interpret these observations as indicating that strain softening by fault creep in the outer anomalous area transferred stress into two major asperities (locked portions of the fault). A velocity decrease and foreshocks were observed in one asperity and high stress accumulation in the other, implying that dilatancy of the crust probably occurred. Our model is qualitatively supported by the independent evidence of strong motion records which show that the Kalapana earthquake was a complex multiple rupture. We conclude that the Kalapana earthquake was preceded by a preparatory process which lasted 3.8 +0.3 years and which had dimensions of 45 x 10 km covering approximately the aftershock area.

- **Rethinking Earthquake Prediction. Lynn R. Sykes, Bruce E. Shaw and Christopher H. Scholz.** ***Pure and Applied Geophysics, 155 (1999) 207-232.***

Abstract:

We re-examine and summarize what is now possible in predicting earthquakes, what might be accomplished (and hence might be possible in the next few decades) and what types of prediction appear to be inherently impossible based on our understanding of earthquakes as complex phenomena. We take predictions to involve a variety of time scales from seconds to a few decades. Earthquake warnings and their possible societal uses differ for those time scales. Earthquake prediction should not be equated solely with short-term prediction-those with time scales of hours to weeks-nor should it be assumed that only-short term warnings either are or might be useful to society. A variety of "consumers" or stakeholders are likely to take different mitigation measures in response to each type of prediction. A series of recent articles in scientific literature and the media claim that earthquakes cannot be predicted and that exceedingly high accuracy is needed for predictions to be of societal value. We dispute a number of their key assumptions and conclusions, including their claim that earthquakes represent a self-organized critical (SOC) phenomenon, implying a system maintained on the edge of chaotic behavior of all times. We think this is correct but only in an understanding way, that is on global or continental scales. The stresses in the region surrounding the rupture zones of individual large earthquakes are reduced below a SOC state at the times of those events and remain so for long periods. As stresses are slowly re-established by tectonic loading, a region approaches a SOC state during the last part of the cycle of large earthquakes. The presence of that state can be regarded as a long-term precursor rather than as an impediment to prediction. We examine other natural processes such as volcanic eruptions, severe storms and climate change that, like earthquakes, are also example of complex processes, each with its own predictable, possible predictable and inherently unpredictable elements. That a natural system is complex does not mean that predictions are not possible for some spatial, temporal and size regimes. Long-term, and perhaps Intermediate-term, predictions for large earthquakes appear to be possible for very active fault segments. Predicting large events more than one cycle into the future appears to be inherently difficult, if not impossible since much of of the nonlinearity in the earthquake processes occurs at or near the time of large events. Progress in earthquake science and prediction over the next few decades will require increased monitoring in several active areas.

- **Developing a Prototype Earthquake Early Warning System in the Beijing Capital Region. Hanshu Peng, Zhongliang Wu, Yih-Min Wu, Shuming Yu, Dongning Zhang and Wenhui Huang.** ***Seismological Research Letters Volume 82, Number 3 May/June 2011.***

Introduction:

The Beijing capital region (36°N–42°N, 113.5°E–120°E) is located in northern China and includes Beijing City, Tianjin City, and Hebei Province. This region of critical economic and cultural importance is threatened by large earthquakes. Historical earthquake records show that this region has been struck by many strong-to-great earthquakes (see Figure 1), with magnitudes up to M 8 (the 1679 Sanhe-Pinggu earthquake). In the 20th century, the 1976 M 7.8 Tangshan earthquake caused more than 240,000 fatalities and uncountable economic losses. Developing an earthquake early warning system (EEWS) in this region is therefore of great importance and necessity. This necessity was dramatically highlighted by the disastrous Wenchuan earthquake in 2008. After the Wenchuan earthquake, a news media report that Japanese seismologists could "predict" an earthquake several seconds before its occurrence caused a lot of discussion in China. This was actually a misunderstanding of the EEWS performance during the Iwate- Miyagi Nairiku earthquake on 14 June 2008, about one month after the Wenchuan earthquake, but the importance of EEWS in earthquake disaster mitigation has become more and more evident. Accordingly, the China Earthquake Administration (CEA) was motivated to configure a nationwide EEWS.

CHAPTER 5: SURVEY ON EARTHQUAKE HAZARD ASSESSMENT STUDIES MADE IN HIGHLY SEISMICALLY ACTIVE ZONES in USA, TAIWAN, IRAN AND JAPAN

5.1 USA

5.1.1 Abstracts

- **A Monte Carlo approach to seismic hazard analysis. John E. Ebel and Alan L. Kafka.** ***Bulletin of the Seismological Society of America August 1999 vol. 89 no. 4 854-866.***

Abstract:

We have developed a Monte Carlo methodology for the estimation of seismic hazard at a site or across an area. This method uses a multitudinous resampling of an earthquake catalog, perhaps supplemented by parametric models, to construct synthetic earthquake catalogs and then to find earthquake ground motions from which the hazard values are found. Large earthquakes extrapolated from a Gutenberg-Richter recurrence relation and characteristic earthquakes can be included in the analysis. For the ground motion attenuation with distance, the method can use either a set of observed ground motion observations from which estimates are randomly selected, a table of ground motion values as a function of epicentral distance and magnitude, or a parametric ground motion attenuation relation. The method has been tested for sites in New England using an earthquake catalog for the northeastern United States and southeastern Canada, and it yields reasonable

ground motions at standard seismic hazard values. This is true both when published ground motion attenuation relations and when a dataset of observed peak acceleration observations are used to compute the ground motion attenuation with distance. The hazard values depend to some extent on the duration of the synthetic catalog and the specific ground motion attenuation used, and the uncertainty in the ground motions increases with decreasing hazard probability. The program gives peak accelerations that are comparable to those of the 1996 U.S. national seismic hazard maps. The method can be adapted to compute seismic hazard for cases where there are temporal or spatial variations in earthquake occurrence rates or source parameters.

- **A Test of Various Site-Effect Parameterizations in Probabilistic Seismic Hazard Analyses of Southern California. Edward H. Field and Mark D. Petersen. *Bulletin of the Seismological Society of America, December 2000, vol. 90, no. 6B S222-S244.***

Abstract:

We evaluate the implications of several attenuation relationships, including three customized for southern California, in terms of accounting for site effects in probabilistic seismic hazard studies. The analysis is carried out at 43 sites along a profile spanning the Los Angeles basin with respect to peak acceleration, and 0.3-, 1.0-, and 3.0-sec response spectral acceleration values that have a 10% chance of being exceeded in 50 years. The variability among currently viable attenuation relationships (espistemic uncertainty) is an approximate factor of 2. Biases between several commonly used attenuation relationships and southern California strong-motion data imply hazard differences that exceed 10%. However, correcting each relationship for the southern California bias does not necessarily bring hazard estimates into better agreement. A detailed subclassification of site types (beyond rock versus soil) is found to be both justified by data and to make important distinctions in terms of hazard levels. A basin depth effect is also shown to be important, implying a difference of up to a factor of 2 in ground motion between the deepest and shallowest parts of the Los Angeles basin. In fact, for peak acceleration, the basin-depth effect is even more influential than the surface site condition. Questions remain, however, whether basin depth is a proxy for some other site attribute such as distance from the basin edge. The reduction in prediction error (sigma) produced by applying detailed site and/or basin-depth corrections does not have an important influence on the hazard. In fact, the sigma reduction is less than epistemic uncertainties on sigma itself. Due to data limitations, it is impossible to determine which attenuation relationship is best. However, our results do indicate which site conditions seem most influential. This information should prove useful to those developing or updating attenuation relationships and to those attempting to make more refined estimates of hazard in the near future.

- **A technical note on seismic microzonation in the Central United States. Zhenming Wang.**

Abstract:

Microzonation is an effort to evaluate and map potential hazards found in an area, urban area in particular, that could be induced by strong ground shaking during an earthquake. These hazards include: ground motion amplification, liquefaction, and slope failure. The microzonation maps, depicting ground-motion amplification, liquefaction, and landslide potentials, can be produced if the ground motion on bedrock (input) and the site conditions are known. These maps, in combination with ground-motion hazard maps (on bedrock), can be used to develop a variety of hazard mitigation strategies such as seismic risk assessment, emergency response and preparedness, and land-use planning. However, these maps have certain limitations that result from the nature of regional mapping, data limitations, generalization, and computer modeling. These microzonations show that when strong ground shaking occurs, damage is more likely to occur, or be more severe, in the higher hazard areas. The zones shown on the hazard maps should not serve as a substitute for site-specific evaluations.

- **A Time-Dependent Probabilistic Seismic- Hazard Model for California. Chris H. Cramer, Mark D. Petersen, Tianqing Cao, Tousson R. Toppozada and Michael Reichle.** ***Bulletin of the Seismological Society of America February 2000 vol. 90 no. 1 1-21.***

Abstract:

For the purpose of sensitivity testing and illuminating nonconsensus components of time-dependent models, the California Department of Conservation, Division of Mines and Geology (CDMG) has assembled a timedependent version of its statewide probabilistic seismic hazard (PSH) model for California. The model incorporates available consensus information from within the earth-science community, except for a few faults or fault segments where consensus information is not available. For these latter faults, published information has been incorporated into the model. As in the 1996 CDMG/U.S. Geological Survey (USGS) model, the time-dependent models incorporate three multisegment ruptures: a 1906, an 1857, and a southern San Andreas earthquake. Sensitivity tests are presented to show the effect on hazard and expected damage estimates of (1) intrinsic (aleatory) sigma, (2) multisegment (cascade) vs. independent segment (no cascade) ruptures, and (3) timedependence vs. time-independence. Results indicate that (1) differences in hazard and expected damage estimates between time-dependent and independent models increase with decreasing intrinsic sigma, (2) differences in hazard and expected damage estimates between full cascading and not cascading are insensitive to intrinsic sigma, (3) differences in hazard increase with increasing return period (decreasing probability of occurrence), and (4) differences in moment-rate budgets increase with decreasing intrinsic sigma and with the degree of cascading, but are within the expected uncertainty in PSH time-dependent modeling and do not always significantly affect hazard and expected damage estimates.

- **Analytical Seismic Fragility Curves for Typical Bridges in the Central and Southeastern United States. Bryant G. Nielson and Reginald Des Roches.**

Abstract:

Seismic fragility curves for classes of highway bridges are essential for risk assessment of highway transportation networks exposed to seismic hazards. This study develops seismic fragility curves for nine classes of bridges (common three-span, zero-skew bridges with non-integral abutments) common to the central and southeastern United States. The methodology adopted uses 3-D analytical models and nonlinear time-history analyses. An important aspect of the selected methodology is that it considers the contribution of multiple bridge components. The results show that multispan steel girder bridges are the most vulnerable of the considered bridge classes while single-span bridges tend to be the least vulnerable. A comparison of the proposed fragility curves with those currently found in HAZUS-MH shows a strong agreement for the multispan simply supported steel girder bridge class. However, for other simply supported bridge classes (concrete girder, slab), the proposed fragility curves suggest a lower vulnerability level than presented in HAZUS-MH.

- **Comparison of the Historical Record of Earthquake Hazard with Seismic- Hazard models for New Zealand and the Continental United States. Mark Stirling and Mark Petersen.** ***Bulletin of the Seismological Society of America December 2006 vol. 96 no. 6 1978-1994.***

  <u>Abstract:</u>

We compare the historical record of earthquake hazard experienced at 78 towns and cities (sites) distributed across New Zealand and the continental United States with the hazard estimated from the national probabilistic seismic-hazard (PSH) models for the two countries. The two PSH models are constructed with similar methodologies and data. Our comparisons show a tendency for the PSH models to slightly exceed the historical hazard in New Zealand and westernmost continental United States interplate regions, but show lower hazard than that of the historical record in the continental United States intraplate region. Factors such as non- Poissonian behavior, parameterization of active fault data in the PSH calculations, and uncertainties in estimation of ground-motion levels from historical felt intensity data for the interplate regions may have led to the higher-than-historical levels of hazard at the interplate sites. In contrast, the less-than-historical hazard for the remaining continental United States (intraplate) sites may be largely due to site conditions not having been considered at the intraplate sites, and uncertainties in correlating ground-motion levels to historical felt intensities. The study also highlights the importance of evaluating PSH models at more than one region, because the conclusions reached on the basis of a solely interplate or intraplate study would be very different.

- **Comparison of recent probabilistic seismic hazard maps for southern California. Mark W. Stirling and Steven G. Wesnousky.** ***Bulletin of the Seismological Society of America June 1998 vol. 88 no. 3 855-861.***

  <u>Abstract:</u>

Probabilistic seismic hazard (PSH) maps for southern California produced from the models of Ward (1994), the Working Group on California Earthquake Probabilities (1995), and the U.S. Geological Survey and California Division of Mines and Geology

(Frankel *et al.*, 1996, Petersen *et al.*, 1996) show the peak ground accelerations predicted with each model to occur at 10% probability in 50 years, and the probability that 0.2 *g* will occur in 30 years, for "rock" site conditions. Differences among the maps range up to 0.4 *g* and 50%, respectively. We examine the locations and magnitudes of the differences as a basis to define the issues and avenues of research that may lead to blackberries confident estimates of PSH in the future. Our analysis shows three major factors that contribute to the observed differences between the maps. They are the size of maximum magnitude assigned to a fault given, that the proportion of predicted earthquakes are distributed off the major faults, and the use of geodetic strain data to predict earthquake rates.

- **Contemporary Tectonics and Seismicity of the Western United States with Emphasis on the Intermountain Seismic Belt. Robert B. Smith and Marc L. Sbar. *Geological Society of America Bulletin* 1974, 85, no.8, 1205-1218, Doi: 10.1130/0016-7606(1974)85<1205:CTASOT>2.0.CO,2.**

Abstract:

The Intermountain seismic belt, a north-trending zone of seismicity in the western United States, is interpreted as a boundary between subplates of the North American plate. The seismic activity closely follows the boundary between the Great Basin and the Colorado Plateau-Middle Rocky Mountains and extends northwestward into the Northern Rocky Mountains. Seismicity is characterized by shallow focal depths, most less than 15 km, and by earthquake swarms that are coincident in some cases with geothermal features and areas of high heat flow. A secondary zone of earthquakes extends from southwestern Utah along the southern margin of the Great Basin. The Northern Rocky Mountains are separated from the Great Basin and the Snake River Plain by an east-trending seismic zone in Idaho. Together, these patterns of seismicity outline the Great Basin and Northern Rocky Mountain subplates. The contemporary motions of t he subplates with respect to one another and with respect to the North American plate are inferred from fault-plane solutions of earthquakes around their borders. The Northern Rocky Mountain and Great Basin subplates are moving relatively west with respect to the stable part of the North American plate. The Idaho seismic zone exhibits northsouth extension, the same as that postulated for the Snake River Plain. The overall motions of the subplates of the Intermountain West may be explained as a response to a mantle plume that tracked beneath the Snake River Plain anc that is now beneath Yellowstone Park. On the basis of a comparison of the calculated and observed rates of the motion for the Yellowstone plume with respect to that for the North American plate, we conclude that the Yellowstone plume has remained stationary relative to the Hawaiian plume. Deformation along the southern and western margins of the Great Basin is dominated by northwest-southeast extension and appears to be primarily related to the relative motion between the Pacific and North American plates.

- **Consistency of Precariously Balanced Rocks with Probabilistic Seismic Hazard Estimates in Southern California. Matthew D. Purvance and James N. Brune, Norman A. Abrahamson John G. Anderson. *Bulletin of the Seismological Society of America, December 2008, vol. 98, no. 6, 2629-2640.***

Abstract:

The overturning fragility of a freestanding block such as a precariously balanced rock (PBR) has been parameterized as a function of a vector of ground-motion intensity measures. Methodologies are outlined to estimate the failure probabilities of such objects given their residence times. For deterministic seismic hazard analyses (DSHAs), a PBR is exposed to the scenario earthquakes that occur during its exposure time providing an estimate of the probability that the PBR survives the ensemble of events. For probabilistic seismic hazard analyses (PSHAs), the PBR overturning fragility is multiplied by the ground-motion occurrence rate from a vector-valued probabilistic seismic hazard analysis (VPSHA), yielding the marginal overturning rate for each ground-motion bin. Summing the marginal rates over all ground-motion bins produces the total overturning rate. For time independent Poisson-based PSHA estimates, the probability of block failure can be easily calculated as a function of exposure time. This latter method is used to test VPSHA estimates similar to the 2002 U.S. Geological Survey (USGS) National Seismic Hazard Maps via PBR residence times. PBR overturning fragilities are estimated at sites in southern California near the San Andreas fault, between the San Jacinto and Elsinore faults, and near the White Wolf fault. The resulting failure probabilities for several of the PBRs are very high, suggesting that they are inconsistent with the 2002 USGS ground motions. An investigation of the hazard calculated with zero aleatory variability in the ground-motion prediction equations (GMPEs) suggests that the median ground motions or the earthquake rupture rates are too high at certain PBR sites.

- **Deaggregation of probabilistic ground motions in the central and eastern United States. Stephen Harmsen, David Perkins and Arthur Frankel. *Bulletin of the Seismological Society of America, February 1999, vol. 89, no. 1 1-13.***

Abstract:

Probabilistic seismic hazard analysis (PSHA) is a technique for estimating the annual rate of exceedance of a specified ground motion at a site due to known and suspected earthquake sources. The relative contributions of the various sources to the total seismic hazard are determined as a function of their occurrence rates and their ground-motion potential. The separation of the exceedance contributions into bins whose base dimensions are magnitude and distance is called *deaggregation*. We have deaggregated the hazard analyses for the new USGS national probabilistic ground-motion hazard maps (Frankel *et al.*, 1996). For points on a 0.2° grid in the central and eastern United States (CEUS), we show color maps of the geographical variation of mean and modal magnitudes ($\bar{M}$, $\check{M}$) and distances ($\bar{D}$, $\check{D}$) for ground motions having a 2% chance of exceedance in 50 years. These maps are displayed for peak horizontal acceleration and for spectral response accelerations of 0.2, 0.3, and 1.0 sec. We tabulate $\bar{M}$, $\bar{D}$, $\check{M}$, and $\check{D}$ for 49 CEUS cities for 0.2- and 1.0-sec response. Thus, these maps and tables are PSHA-derived estimates of the potential earthquakes that dominate seismic hazard at short and intermediate periods in the CEUS. The contribution to hazard of the New Madrid and Charleston sources dominates over much of the CEUS; for 0.2-sec response, over 40% of the area; for 1.0-sec response, over 80% of the area. For 0.2-sec response, $\bar{D}$ ranges from 20 to 200 km, for 1.0 sec, 30 to 600 km. For sites influenced by New Madrid or Charleston, $\bar{D}$ is less than the distance

to these sources, and $\bar{M}$ is less than the characteristic magnitude of these sources, because averaging takes into account the effect of smaller magnitude and closer sources. On the other hand, $\check{D}$ is directly the distance to New Madrid or Charleston and $\check{M}$ for 0.2- and 1.0-sec response corresponds to the dominating source over much of the CEUS. For some cities in the North Atlantic states, short-period seismic hazard is apt to be controlled by local seismicity, whereas intermediate period (1.0 sec) hazard is commonly controlled by regional seismicity, such as that of the Charlevoix seismic zone.

- **Development of seismic hazard maps for the proposed 2005 edition of the National Building Code of Canada. John Adams and Gail Atkinson. *Canadian Journal of Civil Engineering*, 2003, 30(2): 255-271, 10.1139/l02-070.**

  <u>Abstract:</u>

A new seismic hazard model, the fourth national model for Canada, has been devised by the Geological Survey of Canada to update Canada's current (1985) seismic hazard maps. The model incorporates new knowledge from recent earthquakes (both Canadian and foreign), new strong ground motion relations to describe how shaking varies with magnitude and distance, the newly recognized hazard from Cascadia subduction earthquakes, and a more systematic approach to reference site conditions. Other new innovations are hazard computation at the 2% in 50 year probability level, the use of the median ground motions, the presentation of results as uniform hazard spectra, and the explicit incorporation of uncertainty via a logic-tree approach. These new results provide a more reliable basis for characterizing seismic hazard across Canada and have been approved by the Canadian National Committee on Earthquake Engineering (CANCEE) as the basis of the seismic loads in the proposed 2005 edition of the National Building Code of Canada.

Key words: seismic hazard, earthquake, probability, uniform hazard spectrum, maps, Cascadia subduction, strong ground motions, uncertainty, CANCEE, National Building Code of Canada.

- **Development of a seismic source model for probabilistic seismic hazard assessment of nuclear power plant sites in Switzerland: the view from PEGASOS Expert Group 4 (EG1d). Stefan Wiemer Mariano García-Fernández & Jean-Pierre Burg. *Swiss J. Geosci. 102 (2009) 189–209.***

  <u>Abstract:</u>

We present a seismogenic source model for site-specific probabilistic seismic hazard assessment at the sites of Swiss nuclear power plants. Our model is one of four developed in the framework of the PEGASOS project; it contains a logic tree with nine levels of decision-making. The two primary sources of input used in the areal zonation developed by us are the historical and instrumental seismicity record and large-scale geological/rheological units. From this, we develop a zonation of six macrozones, refined in a series of seven decision steps up to a maximum of 13 zones. Within zones, activity rates are either assumed homogeneous or smoothed using a Gaussian kernel with width of 5 or 15 km. To estimate recurrence rate, we assume a double truncated Gutenberg-Richter law, and consider five models of recurrence parameters with different degrees of freedom.

Models are weighted in the logic tree using a weighted Akaike score. The maximum magnitude is estimated following the EPRI apporach. We perform extensive sensitivity analyses in rate and hazard space in order to assess the role of declustering, the completeness model, quarry contamination, border properties, stationarity, regional b-value and magnitude-dependent hypocentral depth.

Key words: PEGASOS, Switzerland, probabilistic seismic hazard, seismic source model.

- **Earthquakes, Quaternary Faults, and Seismic Hazard in California. Steven G. Wesnousky.** ***Journal of Geophysical Research, Vol. 91, No. B12, Pages 12,587-12,631, November 10, 1986.***

<u>*Abstract:*</u>

Data describing the locations, slip rates, and lengths of Quaternary faults are the primary basis in this work for constructing maps that characterize seismic hazard in California. The expected seismic moment Moe and the strength of ground shaking resulting from the entire rupture of each mapped fault (or fault segment) are estimated using empirical relations between seismic moments M_o, rupture length, source to site distance, and strong ground motions. Assuming a fault model. Whereby the repeat time T of earthquakes on each fault equal M_o^e/M_o^g (where the moment M_o^g is proportional to fault slip rate), it is observed that the moment-frequency distribution of earthquakes predicted from the geologic data agrees well with the distribution determined from a 150-year historical record. The agreement is consistent with the argument that the geologic record of Quaternary fault offsets contains information sufficient to predict the average spatial and size distribution of earthquakes through time in California. The estimates of T for each fault are the foundation for constructing maps that depicts the average return period of ≥0.lg peak horizontal ground accelerations, and the horizontal components of peak acceleration, peak velocity, and the pseudo velocity response (at 1-period and 5% damping) expected to occur at the level of 0.1 probability during a 50-year period of time. A map is also formulated to show the probability that ≥0. lg horizontal ground accelerations will occur during the next 50 years. The maps serve to illustrate the potential value of Quaternary fault studies for assessing seismic hazard. Interpretation of available slip rates indicates that the largest and most frequent occurrence of potentially destructive strong ground motions are associated principally with the San Andreas, San Jacinto, Calaveras, Hayward, and Ventura Basin fault zones. Other regions of similarly high hazard may yet remain unrecognized. This inadequacy results primarily from an incomplete data set. Numerous faults, for example, are mapped along the coastal region of northern California and within the Modoc Plateau, but relatively few studies relating to fault slip rate are reported. A similar problem exists for other stretches of coastal California where marine reflection studies provide evidence of active faulting offshore yet yield little or no information of fault slip rate. Geological and geophysical field studies can work to remove these deficiencies. A concerted effort to locate and define rates of activity on all faults in California is the most promising means to further quantify present levels of seismic hazard in California.

- **Effects of uncertainty in seismicity on estimates of seismic hazard for the east coast of the United States. Robin K. Mcguire.** ***Bulletin of the Seismological Society of America, June 1977, vol. 67, no. 3, 827-848.***

  Abstract:

  The lack of knowledge of the cause of earthquakes in the Eastern United States and the short length of seismic history lead to decisional and statistical uncertainties concerning the seismicity of the East. The effect of these uncertainties on the calculated seismic hazard for the east coast is assessed by deriving probability distributions on the important parameters. The available earthquake catalog for the Eastern United States is adequate to establish activity rates for seismic sources but not maximum possible sizes of events. Thus it is not justifiable on a statistical basis to assume that events larger than those observed historically in areas of the East will not occur in the future. The Modified Mercalli intensities associated with an annual probability of 10^{-4} of being equaled or exceeded range from VIII to IX for selected sites from Florida to Maine; these intensities are generally insensitive to the manner in which seismic sources are drawn to represent seismicity, except for those sites which lie within an important seismic source under one hypothesis and outside all seismic sources under a different hypothesis. Several disadvantages of using a strictly deterministic procedure to determine design intensities are disclosed by this study. Specifically, design intensities established deterministically are sensitive to seismic source geometry and to the largest event observed historically in each source. The risks associated with these design intensities vary by more than a factor of ten for the sites on the east coast examined here.

- **Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada. John Adams and Stephen Halchuk.** ***Geological survey of Canada, open file 4459.***

  Abstract:

  We summarize the methods being used for the new seismic hazard maps of Canada and estimate median ground motion on firm soil sites for a probability of exceedence of 2% in 50 years. Spectral acceleration at 0.2, 0.5, 1.0 and 2.0 second periods and peak acceleration will form the basis of the seismic provisions of the 2005 National Building Code of Canada. We tabulate values for more than 650 localities to be listed in the next Code and include maps of seismic hazard for Canada. The four spectral parameters will allow the construction of approximate uniform hazard spectra for each listed locality, and hence improve earthquake-resistant design. For comparison to NBCC 1995, selected 10% in 50 year hazard values are also given.

- **Geographic Deaggregation of Seismic Hazard in the United States. Stephen Harmsen and Arthur Frankel.** ***Bulletin of the Seismological Society of America, February 2001, vol. 91, no. 1, 13-26.***

Abstract:

The seismic hazard calculations for the 1996 national seismic hazard maps have been geographically deaggregated to assist in the understanding of the relative contributions of sources. These deaggregations are exhibited as maps with vertical bars whose heights are proportional to the contribution that each geographical cell makes to the ground-motion exceedance hazard. Bar colors correspond to average source magnitudes. We also extend the deaggregation analysis reported in Harmsen *et al.* (1999) to the western conterminous United States. In contrast to the central and eastern United States (CEUS); the influence of specific faults or characteristic events can be clearly identified. Geographic deaggregation for 0.2-sec and 1.0-sec pseudo spectral acceleration (SA) is performed for 10% probability of exceedance (PE) in 50 yr (475-yr mean return period) and 2% PE in 50 yr (2475-yr mean return period) for four western U.S. cities, Los Angeles, Salt Lake City, San Francisco, and Seattle, and for three central and eastern U.S. cities, Atlanta, Boston, and Saint Louis. In general, as the PE is lowered, the sources of hazard closer to the site dominate. Larger, more distant earthquakes contribute more significantly to hazard for 1.0-sec SA than for 0.2-sec SA. Additional maps of geographically deaggregated seismic hazard are available on the Internet for 120 cities in the conterminous United States (*http://geohazards.cr.usgs.gov/eq/*) for 1-sec SA and for 0.2-sec SA with a 2% PE in 50 yr. Examination of these maps of hazard contributions enables the investigator to determine the distance and azimuth to predominant sources, and their magnitudes. This information can be used to generate scenario earthquakes and corresponding time histories for seismic design and retrofit. Where fault density is lower than deaggregation cell dimensions, we can identify specific faults that contribute significantly to the seismic hazard at a given site. Detailed fault information enables investigators to include rupture information such as source directivity, radiation pattern, and basin-edge effects into their scenario earthquakes used in engineering analyses.

- **History of Modern Earthquake Hazard Mapping and Assessment in California Using a Deterministic or Scenario Approach. Lalliana Mualchin.** ***Pure Appl. Geophys. 168 (2011), 383–407-2010 Birkha¨user / Springer Basel AG DOI 10.1007/s00024-010-0121-1.***

Abstract:

Modern earthquake ground motion hazard mapping in California began following the 1971 San Fernando earthquake in the Los Angeles metropolitan area of southern California. Earthquake hazard assessment followed a traditional approach, later called Deterministic Seismic Hazard Analysis (DSHA) in order to distinguish it from the newer Probabilistic Seismic Hazard Analysis (PSHA). In DSHA, seismic hazard in the event of the Maximum Credible Earthquake (MCE) magnitude from each of the known seismogenic faults within and near the state are assessed. The likely occurrence of the MCE has been assumed qualitatively by using late Quaternary and younger faults that are presumed to be seismogenic, but not when or within what time intervals MCE may occur. MCE is the largest or upper-bound potential earthquake in moment magnitude, and it supersedes and automatically considers all other possible earthquakes on that fault. That moment magnitude is used for estimating ground motions by applying it to empirical attenuation relationships, and for calculating ground motions as in neo-DSHA (ZUCCOLO et al., 2008).

The first deterministic California earthquake hazard map was published in 1974 by the California Division of Mines and Geology (CDMG) which has been called the California Geological Survey (CGS) since 2002, using the best available fault information and ground motion attenuation relationships at that time. The California Department of Transportation (Caltrans) later assumed responsibility for printing the refined and updated peak acceleration contour maps which were heavily utilized by geologists, seismologists, and engineers for many years. Some engineers involved in the siting process of large important projects, for example, dams and nuclear power plants, continued to challenge the map(s). The second edition map was completed in 1985 incorporating more faults, improving MCE's estimation method, and using new ground motion attenuation relationships from the latest published results at that time. CDMG eventually published the second edition map in 1992 following the Governor's Board of Inquiry on the 1989 Loma Prieta earthquake and at the demand of Caltrans. The third edition map was published by Caltrans in 1996 utilizing GIS technology to manage data that includes a simplified three-dimension geometry of faults and to facilitate efficient corrections and revisions of data and the map. The spatial relationship of fault hazards with highways, bridges or any other attribute can be efficiently managed and analyzed now in GIS at Caltrans. There has been great confidence in using DSHA in bridge engineering and other applications in California, and it can be confidently applied in any other earthquake-prone region. Earthquake hazards defined by DSHA are: (1) transparent and stable with robust MCE moment magnitudes; (2) flexible in their application to design considerations; (3) can easily incorporate advances in ground motion simulations; and (4) economical. DSHA and neo-DSHA have the same approach and applicability. The accuracy of DSHA has proven to be quite reasonable for practical applications within engineering design and always done with professional judgment. In the final analysis, DSHA is a reality- check for public safety and PSHA results. Although PSHA has been acclaimed as a better approach for seismic hazard assessment, it is DSHA, not PSHA, that has actually been used in seismic hazard assessment for building and bridge engineering, particularly in California.

- **Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard estimates. Robert T. R. Youngs and Kevin J. Coppersmith. *Bulletin of the Seismological Society of America, Vol. 75, No. 4, pp. 939-964, August 1985.***

Abstract:

Increasingly, fault slip rates are being used to constrain earthquake recurrence relationships for site-specific probabilistic seismic hazard (ground motion) assessments. This paper shows the sensitivity of seismic hazard assessments to variations in recurrence models and parameters that incorporate fault slip rates. Two models are considered to describe the partitioning of the slip rate or seismic moment rate into various magnitude earthquakes: an exponential magnitude distribution and a characteristic earthquake distribution. Assuming an exponential distribution, the activity rate, N(m°), is constrained by the upper bound magnitude, m u, the b-value for the region and the fault slip rate, S. For a given S, variations in m u and b-value have significant effects on recurrence and computed hazard, depending on whether the assumption is made that the seismicity rate is constant or the moment rate is constant. There is increasing evidence that the characteristic earthquake model is more appropriate for individual faults than the exponential magni-

tude distribution. Based on seismicity data from areas having repeated large earthquakes, a generalized recurrence density function is developed, and the resulting recurrence relationship requires only m u, b-value, and S, A comparison of the recurrence relationships from this model with the historical seismicity and paleoseismicity data on the Wasatch and San Andreas faults shows a good match. The computed hazard based on the characteristic earthquake model differs from that obtained for the exponential model as a function of the fault-to-site distance and the acceleration level. One check on the recurrence models using slip rate is to compare over large regions activity rates based on seismicity data and slip rate data. Such a comparison in the western Transverse Ranges shows a reasonable match for both the exponential and characteristic earthquake models in the moderate-to-large magnitude range.

- **Information-Theoretic Selection of Ground-Motion Prediction Equations for Seismic Hazard Analysis: An Applicability Study Using Californian Data. Elise Delavaud, Frank Scherbaum, Nicolas Kuehn and Carsten Riggelsen.** ***Bulletin of the Seismological Society of America, Vol. 99, No. 6, pp. 3248–3263, December 2009, Doi: 10.1785/0120090055.***

  <u>Abstract:</u>

  Considering the increasing number and complexity of ground-motion prediction equations available for seismic hazard assessment, there is a definite need for an efficient, quantitative, and robust method to select and rank these models for a particular region of interest. In a recent article, Scherbaum et al. (2009) have suggested an information-theoretic approach for this purpose that overcomes several shortcomings of earlier attempts at using data-driven ground-motion prediction equation selection procedures. The results of their theoretical study provides evidence that in addition to observed response spectra, macroseismic intensity data might be useful for model selection and ranking. We present here an applicability study for this approach using response spectra and macroseismic intensities from eight Californian earthquakes. A total of 17 ground-motion prediction equations, from different regions, for response spectra, combined with the equation of Atkinson and Kaka (2007) for macroseismic intensities are tested for their relative performance. The resulting data driven rankings show that the models that best estimate ground motion in California are, as one would expect, Californian and western U.S. models, while some European models also perform fairly well. Moreover, the model performance appears to be strongly dependent on both distance and frequency. The relative information of intensity versus response spectral data is also explored. The strong correlation we obtain between intensity-based rankings and spectral-based ones demonstrates the great potential of macroseismic intensities data for model selection in the context of seismic hazard assessment.

- **Introduction to special section: Stress transfer, earthquake triggering, and time-dependent seismic hazard. Sandy Steacy, Joan Gomberg and Massimo Cocco.** ***Journal of Geophysical Research, Vol. 110, B05S01, doi:10.1029/2005JB003692, 2005.***

Abstract:

In this introduction, we review much of the recent work related to stress transfer, earthquake triggering, and time-dependent seismic hazard in order to provide context for the special section on these subjects. Considerable advances have been made in the past decade, and we focus on our understanding of stress transfer at various temporal and spatial scales, review recent studies of the role of fluids in earthquake triggering, describe evidence for the connection between volcanism and earthquake triggering, examine observational evidence for triggering at all scales, and finally discuss the link between earthquake triggering and time-dependent seismic hazard. We conclude by speculating on future areas of research in the next decade.

- **Integrated Seismic-Hazard Analysis of the Wasatch Front, Utah. Wu-Lung Chang and Robert B. Smith.** ***Bulletin of the Seismological Society of America, Vol. 92, No. 5, pp. 1904–1922, June 2002.***

Abstract:

We examined the combined effects of different sources that influence earthquake hazard of the populated Wasatch Front, Utah. We first evaluated the fault stress interaction of the two largest historic earthquakes of the Intermountain Seismic Belt (ISB): the 1959 Hebgen Lake, Montana (*M*s 7.5) and the 1983 Borah Peak, Idaho (*M*s 7.3) earthquakes, which experienced multisegment, normal-faulting ruptures. Estimates of the static-stress change for these events revealed an increase in Coulomb failure stress in areas of extended aftershocks. These observations suggested that fault-stress analysis is applicable in evaluating the spatial distribution of aftershocks after large, normal-faulting earthquakes in the same extensional-stress regime of the eastern Basin–Range, including the Wasatch Front, Utah, which encompasses the 370-km-long Wasatch Fault and surrounding faults. On the basis of this result, we applied the modeling technique to the historically seismically quiescent Wasatch Fault and examined the relation between the pattern of stress change and the space– time distribution of paleoearthquakes. Ages and locations of the Wasatch Fault paleoseismic data imply 17 single-segment or 11 multisegment ruptures in the past 5.6 kyr. We prefer the multisegment model because almost all of the large, historical, normal-faulting earthquakes in the ISB were multisegment. Fitting the along-fault displacements by an analytic half-ellipse function provides a first-order distribution of the displacement over an entire rupture length and allows new estimates of fault slip rates and seismic moment. With these data, we also estimated the occurrence rate of *M*w ! 6.6 Wasatch paleoearthquakes and showed that the rate was about three times higher than that inferred by the historical seismicity. This result, along with new information from a "megatrench" on the Wasatch Fault near Salt Lake City, that revealed no scarp-forming earthquakes between ca. 9.0 and 15.5 ka, suggests that large Wasatch Fault events in the past 5.6 kyr may be clustered. The recurrence rate of large earthquakes estimated by the geodetic-measured strain, on the other hand, is three to four times higher than that estimated by the long-term fault-slip rate. This difference, together with the observation of a low regional strain rate from historical seismicity, suggests that cumulative, aseismic deformation may be significant on the Wasatch Fault. We also examined a major consideration for along-strike segmentation, namely, how stress "contagion" could affect the probability of failure of adjacent faults. Including paleoearthquake-derived fault-slip rates,

global positioning system derived geodetic moment rates, and the effect of stress contagion in the earthquake-hazard estimation for a specific location in the Salt Lake Valley revealed an increase in the annual frequency of peak ground acceleration! 0.25*g* by a factor of 1.4, 4.0, and 5.4, respectively, compared with that derived from historical seismicity only.

- **Mitigation of seismic and meteorological hazards to marine oil terminals and other pier and wharf structures in California. M. L. Eskijian. *Springer Science+Business Media B.V. 2006.***

Abstract:

For the past 12 years, the California State Lands Commission has been involved in the operational monitoring, structural inspection and requalification of 45 marine oil terminals along California's coast, which have an average age of about 50 years and plans to keep these structures in service for another 20–40 years. Having seen the port and harbor damage from the 1995 Kobe and 1999 Izmit earthquakes, the potential for a major disruption in petroleum product production is real. Losing the daily gasoline production for a period of weeks or months as a result of a moderate earthquake or tsunami could significantly affect the economic well being of California and much of the western United States. In addition, a major oil spill resulting from such an event could cause the closure of a major port for days or even weeks. Such a closure would further affect the economy of California and the United States. Most of these facilities were designed to primitive seismic standards and for vessels much smaller than those currently moored. Many of these structures have never had a comprehensive underwater inspection. Wind and current forces on large tank ships can cause mooring lines to break or cause serious structural damage to supporting structures. In California, non-regulatory progress has been made in the following areas: (i) underwater and above water inspections or audits; (ii) mooring analyses and structural/environmental monitoring in high velocity current areas; (iii) seismic analyses and structural rehabilitation with updated seismic hazard data; and (iv) accelerometers on marine structures. In addition, standards have been developed and are proposed to be regulatory by early 2004. The new standards include most of the items listed above, but also extend into many other areas. Along with the proposed regulations come many issues that raise economic and political questions. These issues are not unique to marine oil terminals and are applicable to other pier and wharf structures in harbors.

Keywords Marine structures, Seismic requalification, Mooring analyses.

- **Modelling Seismic Hazard in Earthquake Loss Models with Spatially Distributed Exposure. Helen Crowley and Julian J. Bommer. *Bulletin of Earthquake Engineering (2006) 4:249–273 © Springer 2006.***

Abstract:

The prediction of possible future losses from earthquakes, which in many cases affect structures that are spatially distributed over a wide area, is of importance to national authorities, local governments, and the insurance and reinsurance industries. Generally, it is necessary to estimate the effects of many, or even all, potential earthquake scenarios that could impact upon these urban areas. In such cases, the purpose of the loss calculations is to estimate the annual frequency of exceedance (or the return period) of different levels of loss due to earthquakes: so-called loss exceedance curves. An attractive option for generating loss exceedance curves is to perform independent probabilistic seismic hazard assessment calculations at several locations simultaneously and to combine the losses at each site for each annual frequency of exceedance. An alternative method involves the use of multiple earthquake scenarios to generate ground motions at all sites of interest, defined through Monte–Carlo simulations based on the seismicity model. The latter procedure is conceptually sounder but considerably more time-consuming. Both procedures are applied to a case study loss model and the loss exceedance curves and average annual losses are compared to ascertain the influence of using a more theoretically robust, though computationally intensive, procedure to represent the seismic hazard in loss modeling.

Key words: average annual loss, earthquake loss modeling, ground-motion variability, scenario earthquakes, seismic hazard, spatial correlation.

- **Model Uncertainties of the 2002 Update of California Seismic Hazard Maps. Tianqing Cao, Mark D. Petersen and Arthur D. Frankel.** ***Bulletin of the Seismological Society of America December 2005 vol. 95 no. 6 2040-2057.***

  Abstract:

In this article we present and explore the source and ground-motion model uncertainty and parametric sensitivity for the 2002 update of the California probabilistic seismic hazard maps. Our approach is to implement a Monte Carlo simulation that allows for independent sampling from fault to fault in each simulation. The source-distance dependent characteristics of the uncertainty maps of seismic hazard are explained by the fundamental uncertainty patterns from four basic test cases, in which the uncertainties from one-fault and two-fault systems are studied in detail. The California coefficient of variation (COV, ratio of the standard deviation to the mean) map for peak ground acceleration (10% of exceedance in 50 years) shows lower values (0.1–0.15) along the San Andreas fault system and other class A faults than along class B faults (0.2–0.3). High COV values (0.4–0.6) are found around the Garlock, Anacapa-Dume, and Palos Verdes faults in southern California and around the Maacama fault and Cascadia subduction zone in northern California.

- **Mutually consistent seismic-hazard source model for southern California. Edward H. Field, David D. Jackson and James F. Dolan.** ***Bulletin of the Seismological Society of America June 1999 vol. 89 no. 3 559-578.***

  Abstract:

A previous attempt to integrate geological, geodetic, and observed seismicity data into a probabilistic-hazard source model predicted a rate of magnitude 6 to 7 earthquakes significantly greater than that observed historically. One explanation was that the discrepancy, or apparent earthquake deficit, is an artifact of the upper magnitude limit built into the model. This was controversial, however, because removing the discrepancy required earthquakes larger than are seen in the geological record and larger than implied from empirical relationships between fault dimension and magnitude. Although several articles have addressed this issue, an alternative, integrated source model without an apparent deficit has not yet appeared. We present a simple geologically based approach for constructing such a model that agrees well with the historical record and does not invoke any unsubstantiated phenomena. The following factors are found to be influential: the *b*-value and minimum magnitude applied to Gutenberg-Richter seismicity; the percentage of moment released in characteristic earthquakes; a round-off error in the moment-magnitude definition; bias due to historical catalog incompleteness; careful adherence to the conservation of seismic moment rate; uncertainty in magnitude estimates obtained from empirical regressions; allowing multisegment ruptures (cascades); and the time dependence of recurrence rates. The previous apparent deficit is shown to have resulted from a combination of these factors. None alone caused the problem nor solves it. The model presented here is relatively robust with respect to these factors.

- **Paleoseismic Targets, Seismic Hazard, and Urban Areas in the Central and Eastern United States. Russell L. Wheeler. *Bulletin of the Seismological Society of America, June 2008, vol. 98, no. 3, 1572-1580.***

  <u>Abstract:</u>

  Published geologic information from the central and eastern United States identifies 83 faults, groups of sand blows, named seismic zones, and other geological features as known or suspected products of Quaternary tectonic faulting. About one fifth of the features are known to contain faulted Quaternary materials or seismically induced liquefaction phenomena, but the origin and associated seismic hazard of most of the other features remain uncertain. Most of the features are in or near large urban areas. The largest cluster of features is in the Boston–Washington urban corridor (2005 estimated population: 50 million). The proximity of most features to populous areas identifies paleoseismic targets with potential to impact urban-hazard estimates.

- **Politics of Hazard Mitigation. Carla S. Prater and Michael K. Lindell. *Natural Hazards Review, May 2000, 73.***

  <u>Abstract:</u>

  The formulation, adoption, and implementation of mitigation measures is an intensely political process that hazards professionals need to understand if they are to be effective in reducing community hazard vulnerability. We describe the process by which either focusing events such as disasters, or policy entrepreneurs such as involved professionals, can frame hazard mitigation as a salient issue on the community agenda. In addition, we discuss the demands of policy formulation, particularly the importance of mobilizing a constituency for hazard mitigation among affected stakeholders in the community. Finally, we conclude by showing how a widely used model of policy implementation reveals critical features that community hazard mitigation policies must have if they are to be implemented successfully by administrative bureaucracies.

- **Preliminary seismic hazard assessment for Los Angeles, Ventura and Orange counties, California, affected by the 17 January 1994 Northridge earthquake. Mark D. Petersen, Chris H. Cramer, William A. Bryant, Michael S. Reichle and Tousson R. Toppozada.** ***Bulletin of the Seismological Society of America February 1996 vol. 86 no. 1B S247-S261.***

  <u>Abstract:</u>

  The seismic ground motion hazard is assessed for a 10% probability of exceedance in 50 years for the three counties (Los Angeles, Ventura, and Orange) impacted by the 1994 Northridge earthquake (*Mw* 6.7). The earthquake source model of the Southern California Earthquake Center has been modified with additional slip-rate information for mapped faults and blind thrusts and incorporated into seismic hazard maps that will be used for making regional hazard and risk mitigation decisions by state and local government agencies. Peak horizontal ground acceleration (pga) and 5% damped spectral acceleration (SA) (0.3 and 1 sec) were calculated with three equally weighted attenuation relationships of Boore *et al.* (1993), Campbell and Bozorgnia (1994), and Sadigh (written comm., 1994). The results of this assessment indicate high hazard over the entire tri-county area with ground motions exceeding 0.4 *g* (pga), 1.0 *g* (0.3-sec SA), and 0.5 *g* (1-sec SA) nearly everywhere. A Monte Carlo uncertainty analysis is described for two sites located in Los Angeles and Northridge. This analysis yields 95% confidence limits for peak ground acceleration at the two sites that range between ±0.1 and ±0.2 *g*. Our calculations indicate that the uncertainty in the magnitude-rupture length relations, magnitude distribution, moment-magnitude relation, attenuation relation, and slip-rate contribute most to the hazard uncertainty at these sites and that the highest uncertainties in the mapped ground motion are associated with the strongest anticipated ground motions.

- **Probabilistic estimates of maximum acceleration and velocity in rock in the contiguous United States. S. T. Algermissen, D. M. Perkins, P. C. Thenhaus, S. L. Hanson and B. L. Bender.** ***Open-File Report 82-1033 1982, United States Department of the Interior Geological Survey*.**

  <u>Abstract:</u>

  Maximum horizontal accelerations and velocities caused by earthquakes are mapped for exposure times of 10, 50 and 250 years at the 90-percent probability level of nonexceedance for the contiguous United States. In many areas these new maps differ significantly from the 1976 probabilistic acceleration map by Algermissen and Perkins because of the increase in detail, resulting from greater emphasis on the geologic basis for seismic source zones. This new emphasis is possible because of extensive data recently acquired on Holocene and Quaternary faulting in the western United States and new interpretations of geologic structures controlling the seismicity pattern in the central and eastern United States. Earthquakes are modeled in source zones as fault ruptures (for large shocks), as a combination of fault ruptures and point sources, and as point sources (for small shocks). The importance of fault modeling techniques is demonstrated by examples in the Mississippi Valley. The effect of parameter variability, particularly in the central and eastern United States is discussed. The seismic source zones used in the de-

velopment of the maps are more clearly defined and are generally smaller than the seismic source zones used in the Algermissen and Perkins (1976) probabilistic acceleration map. As a result, many areas of high seismic hazard are more clearly defined on these maps than in the 1976 map, although in large areas of the country well defined geologic control for the seismic source zones is still lacking. The six probabilistic ground motion maps presented are multi-purpose maps useful in building code applications, land use planning, insurance analysis and disaster mitigation planning. As fault slip and related geological data become available, the further refinement of probabilistic ground motion maps through the use of time dependent models for earthquake occurrence will become feasible.

- **Probabilistic Seismic-Hazard Assessment Including Site Effects for Evansville, Indiana, and the Surrounding Region. Jennifer S. Haase, Yoon Seok Choi, Tim Bowling and Robert L. Nowack. *Bulletin of the Seismological Society of America, June 2011, vol. 101, no. 3, 1039-1054.***

  Abstract:

  Evansville, Indiana, is one of the closest large urban areas to both the New Madrid Seismic Zone, where large earthquakes occurred in 1811–1812, and the Wabash Valley Seismic Zone, where there is evidence of several large prehistoric earthquakes in the last 14,000 yr. For this reason, Evansville has been targeted as a priority region for urban seismic-hazard assessment. The probabilistic seismic-hazard methodology used for the Evansville region incorporates new information from recent surficial geologic mapping efforts, as well as information on the depth and properties of near-surface soils and their associated uncertainties. The probabilistic seismic-hazard calculation applied here follows the method used for the 2008 United States Geological Survey (USGS) national seismic-hazard maps, with modifications to incorporate estimates of local site conditions and their uncertainties, in a completely probabilistic manner. The resulting analysis shows strong local variations of acceleration with 2% probability of exceedance in 50 yr, which are clearly correlated with variations in the thickness of unconsolidated soils above bedrock. Spectral accelerations at 0.2-s period range from 0.6 to 1.5*g*, values that are much greater than those of the USGS national seismic-hazard map, which assume B/C site conditions with an average shear-wave velocity of 760 m/s in the top 30 m. The presence of an ancient bedrock valley underlying the current Ohio River flood plain strongly affects the spatial pattern of accelerations. For 1.0-s spectral acceleration, ground motions are significantly amplified due to deeper soils within this structure, to a level comparable to that predicted by the national seismic-hazard maps with D site conditions assumed. For PGA and 0.2-s spectral acceleration, ground motions are significantly amplified outside this structure, above the levels predicted by the national seismic-hazard maps with uniform D site conditions assumed.

- **Probabilistic Seismic Hazard - Maps of Alaska. Robert L. Wessonl, Arthur D. Frankel, Charles S. Mueller and Stephen C. Harmsen.*Open-File Report 99-36 USGS.***

Abstract:

Probabilistic seismic hazard maps have been prepared for Alaska portraying ground motion values (peak ground acceleration and spectral amplitude at periods of 0.2,0.3 and 1.0 seconds) at probabilities of exceedance of 2% and 10% in 50 years. Preparation of these maps followed the same general strategy as that followed for the U.S.G.S. seismic hazard maps of the contiguous United States, combining hazard derived from spatially-smoothed historic seismicity with hazard from fault-specific sources. Preparation of the Alaska maps presented particular challenges in characterizing the hazard from the aaska- Aleutian megathrust. In the maps of the contiguous United States the rate of seismicity for recognized active faults was determined from slip rates estimated from geologic data. This approach is not appropriate for the megathrust because it has been demonstrated that a sigmhcant fraction of the subduction occurs aseismically. The characteristic earthquake hypothesis, based on recurrence rates determined from geologic data, is appealing for the portion of the megathrust that ruptured in the 1964 Alaskan earthquake, but is shown to be inappropriate for the western portion of the megathrust by the recent large earthquakes in the region which did not follow the characteristic model. Consequently the hazard from the western portion was estimated based on a truncated Gutenberg and Richter model derived from historic seismicity, and the hazard for the 1964 zone was estimated from a combination of a Gutenberg and Richter model derived from historic seismicity and the characteristic earthquake hypothesis with recurrence rates estimated from geologic data. Owmg to geologic complexity and limited data, hazard models of the easternmost portion of the megathrust in the vicinity of Yakataga are the least satisfactorily constrained. Hazard is estimated for the recognized crustal faults of the Denali, Fairweather-Queen Charlotte and Castle Mountain fault systems based on available geologic slip rates. Hazard from other sources is estimated from spatially smoothed historic seismicity. Disaggregations of the hazard for Anchorage, Fairbanks and Juneau reveal the dominant sources of the hazard at each location.

- **Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts. R.J. Budnitz (Chairman), G. Apostolakis, D.M. Boore, L.S. Cluff, K.J. Coppersmith, C.A. Cornell, P.A. Morris. *NUREG/CR-6372, UCRL-ID- 122160, Vol. 2.***

Abstract:

Probabilistic Seismic Hazard Analysis (PSI-A) is a methodology that estimates the likelihood that various levels of earthquake-caused ground motion will be exceeded at a given location in a given future time period. Due to large uncertainties in all the geosciences data and in their modeling, multiple model interpretations are often possible. This leads to disagreement among experts, which in the past has led to disagreement on the selection of ground motion for design at a given site. In order to review the present state-of-the-art and improve on the overall stability of the PSI-A process, the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE); and the Electric Power Research Institute (EPRI) co-sponsored a project to provide methodological guidance on how to perform a PSHA. The project has been carried Out by a seven-member Senior Seismic Hazard Analysis Committee (SSHAC) supported by a large number other ex-

perts. The SSHAC reviewed past studies, including the Lawrence Livermore National Laboratory and the EPRI landmark PSHA studies of the 1980's and examined ways to improve on the present state-of-the-art. The Committee's most important conclusion. is that differences in PSHA results are due to procedural rather than technical differences. Thus, in addition to providing a detailed documentation on state-of-threat elements of a PSHA, this report provides a series of procedural recommendations. The role of experts is analyzed in detail. Two entities are formally defined-the Technical Integrator (TI) and the Technical Facilitator Integrator (TFI)-to account for the various levels of complexity in the technical issues and different levels of effort needed in a given study.

- **Seismic Hazard Assessment: Issues and Alternatives. Zhenming Wang. *Pure Appl. Geophys. 168 (2011), 11–25, 2010, Springer Basel AG, DOI 10.1007/s00024-010-0148-3.***

  Abstract:

  Seismic hazard and risk are two very important concepts in engineering design and other policy considerations. Although seismic hazard and risk have often been used interchangeably, they are fundamentally different. Furthermore, seismic risk is more important in engineering design and other policy considerations. Seismic hazard assessment is an effort by earth scientists to quantify seismic hazard and its associated uncertainty in time and space and to provide seismic hazard estimates for seismic risk assessment and other applications. Although seismic hazard assessment is more a scientific issue, it deserves special attention because of its significant implication to society. Two approaches, probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA), are commonly used for seismic hazard assessment. Although PSHA has been proclaimed as the best approach for seismic hazard assessment, it is scientifically flawed (i.e., the physics and mathematics that PSHA is based on are not valid). Use of PSHA could lead to either unsafe or overly conservative engineering design or public policy, each of which has dire consequences to society. On the other hand, DSHA is a viable approach for seismic hazard assessment even though it has been labeled as unreliable. The biggest drawback of DSHA is that the temporal characteristics (i.e., earthquake frequency of occurrence and the associated uncertainty) are often neglected. An alternative, seismic hazard analysis (SHA), utilizes earthquake science and statistics directly and provides a seismic hazard estimate that can be readily used for seismic risk assessment and other applications.

- **Seismic hazard and risk assessment in the intraplate environment: The New Madrid seismic zone of the central United States. Zhenming Wang. *The Geological Society of America, Special Paper 425, 2007.***

  Abstract:

  Although the causes of large intraplate earthquakes are still not fully understood, they pose certain hazard and risk to societies. Estimating hazard and risk in these regions is diffi cult because of lack of earthquake records. The New Madrid seismic zone is one such region where large and rare intraplate earthquakes (M = 7.0 or greater) pose signifi cant hazard and risk. Many different defi nitions of hazard and risk have been used, and the resulting estimates differ dramatically. In this paper, seismic hazard is defi ned as the natural phenomenon generated by earthquakes, such as ground motion, and is quantifi ed by two parameters: a level of hazard and its occurrence frequency or mean recurrence interval; seismic risk is defi ned as the probability of occurrence of a specifi c level of seismic hazard over a certain time and is quantifi ed by three parameters: probability, a level of hazard, and exposure time. Probabilistic seismic hazard analysis (PSHA), a commonly used method for estimating seismic hazard and risk, derives a relationship between a ground motion parameter and its return period (hazard curve). The return period is not an independent temporal parameter but a mathematical extrapolation of the recurrence interval of earthquakes and the uncertainty of ground motion. Therefore, it is diffi cult to understand and use PSHA. A new method is proposed and applied here for estimating seismic hazard in the New Madrid seismic zone. This method provides hazard estimates that are consistent with the state of our knowledge and can be easily applied to other intraplate regions.

Keywords: New Madrid seismic zone, seismic hazard, seismic risk, probabilistic seismic hazard analysis, seismic hazard assessment.

- **Seismic hazard estimate from background seismicity in southern California. Tianqing Cao, Mark D. Petersen and Michael S. Reichle. *Bulletin of the Seismological Society of America, October 1996, vol. 86, no. 5, 1372-1381.***

  <u>Abstract:</u>

  We analyzed the historical seismicity in southern California to develop a rational approach for calculating the seismic hazard from background seismicity of magnitude 6.5 or smaller. The basic assumption for the approach is that future earthquakes will be clustered spatially near locations of historical mainshocks of magnitudes equal to or greater than 4. We analyzed the declustered California seismicity catalog to compute the rate of earthquakes on a grid and then smoothed these rates to account for the spatial distribution of future earthquakes. To find a suitable spatial smoothing function, we studied the distance (*r*) correlation for southern California earthquakes and found that they follow a 1/*r* power-law relation, where μ increases with magnitude. This result suggests that larger events are more clustered in space than smaller earthquakes. Assuming the seismicity follows the Gutenberg-Richter distribution, we calculated peak ground accelerations (PGA) for 10% probability of exceedance in 50 yr. PGA estimates range between 0.25 and 0.35 *g* across much of southern California. These ground-motion levels are generally less than half the levels of hazard that are obtained using the entire seismic source model that also includes geologic and geodetic data. We also calculated the overall uncertainty for the hazard map using a Monte Carlo method and found that the coefficient of variation is about 0.24 ± 0.01 for much of the region.

- **Seismic hazards in Southern California: Probable earthquakes, 1994 to 2024. D.D. Jackson, K. Aki, C.A. Cornell, J.H., Dieterich, T.L. Henyey, M. Mahdyiar, D. Schwartz, and S.N. Ward, D. Agnew, G. Davis, J. Davis, J. Dolan, P. Flores, M. Forrest, E. Hauksson, T. Heaton, G. Huftile, I. M. Idriss, K., Jackson, P. Jennings, L. Jones, Y. Kagan, E. Lehmer, K. McNally, J. McRaney, B. Minster, S. Park, M. Petersen, M. Reichle, T. Rockwell, S. Salyards, J. Savage, K. Sieh, J. Suppe, P. Ward,**

R. Weldon, S. Wesnousky, and R. Yeats. ***Bulletin of the Seismological Society of America, April 1995, vol. 85, no. 2, 379-439.***

Abstract:

We combine geodetic, geologic and seismic information to estimate frequencies of damaging earthquakes in three types of seismotectonic zone. Type A zones contain faults for which paleoseismic data suffice to estimate conditional probabilities. Type B zones contain faults with insufficient data for conditional probability analysis. Type C zones contain diverse or hidden faults. Each zone is assumed to have randomly distributed earthquakes plus characteristic earthquakes on specific faults. Our "cascade" model allows for multiple-segment earthquakes. Within each zone, distributed earthquakes are assumed uniform in time and space, with a truncated Gutenberg-Richter magnitude distribution. Thus, seismic hazard is defined by the characteristic earthquake rate, the rate of all distributed events, and the limiting (characteristic) magnitude. Limiting magnitudes are determined from fault lengths, while earthquake rates are determined by observed seismicity and seismic moment rate. We present a preferred seismic hazard model with lognormal recurrence and an alternate Poissonian model. The models predict 80 to 90% probability of an $m \geqq 7$ earthquake within southern California before 2024. The 17 January 1994 Northridge earthquake occurred within the 13% of southern California's area having the highest moment rate density. The probability of 0.2 g or greater shaking before 2024 exceeds 60% in the Ventura and San Bernardino areas, and 50% throughout the Transverse Ranges between Santa Barbara and San Bernardino. The predicted seismicity exceeds that observed historically. This may imply that (1) we underestimate the maximum magnitudes, (2) significant strain may be released aseismically, or (3) seismicity may have been anomalously low since 1850.

- **Seismic Hazard Estimation in Northern Algeria. Mohamed Hamdache.** ***Natural Hazards*** **18, 119–144, 1998.**

Abstract:

In the present study, the seismic hazard in northern Algeria is estimated using both physical strain energy release and Gumbel's extreme values approaches. For six of the most industrial and populated cities in Algeria, seismic hazard is assessed and examined in greater detail. Gumbel's extreme values approach has been used to estimate seismic hazard in terms of magnitude and P.G.A at each point of an equispaced grid all over the north of Algeria. An average attenuation relationship for PGA has been provided using known relations which have been established in regions with similar attenuation characteristics. The results are presented mainly in the form of graphs and contour maps of magnitudes (respectively PGA) with a 60% probability of not being exceeded in the next 100 and 200 years. Globally, they give main features of northern Algeria in terms of zoning (as well as in terms of magnitude and in terms of PGA). They corroborate the ones obtained through other works, especially in the basin areas (Mitidja, Cheliff, Soumam and Constantine Basin).

Key words: probabilistic seismic hazard, seismic energy release, Northern Algeria.

- **Seismic Hazard Evaluation. Paul Somerville.** ***12WCEE 2000, 2833.***

  Abstract:

  This paper reviews concepts and trends in seismic hazard characterization that have emerged in the past decade, and identifies trends and concepts that are anticipated during the coming decade. New methods have been developed for characterizing potential earthquake sources that use geological and geodetic data in conjunction with historical seismicity data. Scaling relationships among earthquake source parameters have been developed to provide a more detailed representation of the earthquake source for ground motion prediction. Improved empirical ground motion models have been derived from a strong motion data set that has grown markedly over the past decade. However, these empirical models have a large degree of uncertainty because the magnitude - distance - soil category parameterization of these models often oversimplifies reality. This reflects the fact that other conditions that are known to have an important influence on strong ground motions, such as near fault rupture directivity effects, crustal waveguide effects, and basin response effects, are not treated as parameters of these simple models. Numerical ground motion models based on seismological theory that include these additional effects have been developed and extensively validated against recorded ground motions, and used to estimate the ground motions of past earthquakes and predict the ground motions of future scenario earthquakes. The probabilistic approach to characterizing the ground motion that a given site will experience in the future is very compatible with current trends in earthquake engineering and the development of building codes. Performance based design requires a more comprehensive representation of ground motions than has conventionally been used. Ground motions estimates are needed at multiple annual probability levels, and may need to be specified not only by response spectra but also by suites of strong motion time histories for input into time-domain non-linear analyses of structures.

- **Seismic hazard maps for Puget Sound, Washington. S.M. Ihnen and D.M. Hadley.** ***Bulletin of the Seismological Society of America August 1987 vol. 77 no. 4 1091-1109.***

  Abstract:

  A set of maps have been constructed which estimate the hazard of seismic ground shaking in the Puget Sound, Washington, area as measured by the peak ground acceleration (PGA). The average PGA in this region for which there is a 5 per cent chance of exceedence in 50 yr is approximately 30 per cent of *g*. PGAs on the map vary from a low of 20 per cent of *g* to a maximum of near 60 per cent of *g*. The effects of local seismicity patterns, type of soil, and subsurface geology are all included, and all contribute significantly to the variation of expected PGA across Puget Sound. The predicted PGAs are slightly larger than or comparable to the PGAs experienced in magnitude 6.5 and 7.2 earthquakes in this century, and the average PGA is consistent with work by previous investigators. The hazard estimates are controlled by earthquakes in the magnitude 4.5 to 7.0 range and are largely independent of the rate of occurrence of earthquakes outside of that range.

- **Seismic Response of Multiple Span Steel Bridge in Centra and Southeastern United States. I: As Built. Reginald Des Roches, M.ASCE, Eunsoo Choi, Roberto T. Leon, M.ASCE, Shirley J. Dyke, M.ASCE4 and Mark Aschheim, M.ASCE.** ***Doi: 10.1061/~ASCE!1084-0702~2004!9:5~464!***

  Abstract:

  The seismic response of typical multispan simply supported (MSSS) and multispan continuous steel girder bridges in the central and southeastern United States is evaluated. Nonlinear time history analyses are conducted using synthetic ground motion for three cities for 475 and 2,475-year return period earthquakes (10 and 2% probability of exceedance in 50 years). The results indicate that the seismic response for the 475-year return period earthquake would lead to an essentially linear response in typical bridges. However, the seismic response for a 2,475-year return period earthquake resulted in significant demands on nonductile columns, fixed and expansion bearings, and abutments. In particular, pounding between decks in the MSSS bridge would result in significant damage to steel bearings and would lead to the toppling of rocker bearings, which may result in unseating of the bridge deck.

- **Seismic strain rates in the Central and Eastern United States. John G. Anderson.** ***Bulletin of the Seismological Society of America February 1986 vol. 76 no. 1 273-290.***

  Abstract:

  Seismic strain rates for the entire Central and Eastern United States are estimated from historical seismicity and from several seismicity models. Typical strain rates are estimated to be the on the order of 10^{-12} to 10^{-11} per year, except near historical sites of large earthquakes where higher rates pertain. Uncertainties in strain rates are large. Deformation caused by strain rates less than 10^{10}/yr is very small compared to average denudation rates. Denudation and deposition may control the rate of earthquake occurrence in some parts of the Central and Eastern United States by modifying the vertical stress due to load. A simple quantitative model predicts the earthquake occurrence rate in the Appalachian Mountains from an estimate of the regional denudation rate.

- **Simulations of Seismic Hazard for the Pacific Northwest of the United States from Earthquakes Associated with the Cascadia Subduction Zone. Mark D. Petersen, Chris H. Cramer and Arthur D. Frankel.** ***Pure appl. geophys. 159 (2002) 2147–2168 0033 – 4553/02/092147 – 22, 1.50+0.20/0.***

  Abstract:

  We investigate the impact of different rupture and attenuation models for the Cascadia subduction zone by simulating seismic hazard models for the Pacific Northwest of the U.S. at 2% probability of exceedance in 50 years. We calculate the sensitivity of hazard (probabilistic ground motions) to the source parameters and the attenuation relations for both intraslab and interface earthquakes and present these in the framework of the standard USGS hazard model that includes crustal earthquakes. Our results indicate that allowing the deep intraslab earthquakes to occur anywhere along the subduction zone increases the peak ground acceleration hazard near Portland, Oregon by about 20%. Alternative attenuation relations for deep earthquakes can result in ground motions that differ by a factor of two. The hazard uncertainty for the plate interface and intraslab earthquakes is analyzed through a Monte-Carlo logic tree approach and indicates a seismic hazard exceeding 1 g (0.2 s spectral acceleration) consistent with the U.S. National Seismic Hazard Maps in western Washington, Oregon, and California and an overall coefficient of variation that ranges from 0.1 to 0.4. Sensitivity studies indicate that the paleoseismic chronology and the magnitude of great plate interface earthquakes contribute significantly to the hazard uncertainty estimates for this region. Paleoseismic data indicate that the mean earthquake recurrence interval for great earthquakes is about 500 years and that it has been 300 years since the last great earthquake. We calculate the probability of such a great earthquake along the Cascadia plate interface to be about 14% when considering a time-dependent model and about 10% when considering a time independent Poisson model during the next 50-year interval

Key words: Seismic hazard, uncertainty, Cascadia.

- **Slow Deformation and Lower Seismic Hazard at the New Madrid Seismic Zone. Andrew Newman, Seth Stein, John Weber, Joseph Engeln, Ailin Mao, Timothy Dixon.** ***Science, 30 July 1999, Vol. 285 no. 5428 p. 663, Doi: 10.1126/science.285.5428.663d.***

  Abstract:

  Global Positioning System (GPS) measurements across the New Madrid seismic zone (NMSZ) in the central United States show little, if any, motion. These data are consistent with platewide continuous GPS data away from the NMSZ, which show no motion within uncertainties. Both these data and the frequency magnitude relation for seismicity imply that had the largest shocks in the series of earthquakes that occurred in 1811 and 1812 been magnitude 8, their recurrence interval should well exceed 2500 years, longer than has been assumed. Alternatively, the largest 1811 and 1812 earthquakes and those in the paleoseismic record may have been much smaller than typically assumed. Hence, the hazard posed by great earthquakes in the NMSZ appears to be overestimated.

- **Soil-Column Depth-Dependent Seismic Site Coefficients and Hazard Maps for the Upper Mississippi Embayment. Youssef M.A. Hashash, Chi-Chin Tsai, Camilo Phillips and Duhee Park.** ***Bulletin of the Seismological Society of America August 2008 vol. 98 no. 4 2004-2021.***

  Abstract:

  The presence of deep unconsolidated deposits in the Upper Mississippi Embayment (UME) has an important impact on surface motions and has been the subject of several studies including a study by two of us, who integrated probabilistic seismic hazard analysis (PSHA) with nonlinear site effects (NL). This study extends the PSHA–NL procedure to (1) incorporate a finite-fault model capable of generating near-source motions instead of using point source models only, (2) better approximate the range of available attenuation relations for the Central and Eastern United States (CEUS), (3) examine the hazard at very high levels of shaking, and (4) propagate generated rock motions through randomized soil profile properties to achieve a more consistent probabilistic procedure. The extended PSHA–NL procedure is used to develop updated depth-dependent site coefficients for the UME, which generally provides a lower hazard at short periods but a higher hazard at longer periods than current approaches. Proposed probabilistic seismic hazard maps, at selected spectral accelerations, that incorporate the proposed site effects are also presented for the UME and are systematically compared with seismic hazard maps proposed by others.

- **Statistical uncertainties in seismic hazard evaluations in the United States. Robin K. Mcguire and Kaye M. Shedlock.** ***Bulletin of the Seismological Society of America August 1981 vol. 71 no. 4 1287-1308.***

  Abstract:

  Efficient and accurate methods of estimating the sensitivity of seismic hazard calculations to statistical uncertainties in models and parameters are demonstrated. These models require knowledge of the earthquake magnitude and distance that contribute most to the probability of exceedence of a chosen acceleration level; the methods estimate sensitivities using point-source seismic-hazard approximations for which closed-form solutions are available. An additional result is that the use of Bayesian estimates for seismicity and ground motion parameters in the hazard analysis produces unbiased Bayesian estimates of the seismic ground motion hazard, due to the almost linear relationship between ground motion amplitudes at a given probability level, and parameter uncertainties. Application of these methods to the San Francisco, California, Bay area indicates a coefficient of variation (cov) of the 500-yr acceleration of about 0.4 at sites close to major faults, and a cov of about 0.2 at sites 50 km to the east of the major east bay faults. These cov's result from statistical uncertainty in the depth of energy release, the activity rate and Richter *b* value for each fault, and the mean acceleration-attenuation relationship. A similar analysis in the central Mississippi Valley area indicates a cov in 500-yr acceleration of 0.4 near the major faults, with a value of about 0.3 at distances greater than 50 km. The sources of statistical uncertainty in this region are the depth of energy release as well as its location, the activity rate and Richter *b* value for each fault, and the mean acceleration-attenuation function.

- **The calculation of expected loss using probabilistic seismic hazard. Tianqing Cao, Mark D. Petersen, Chris H. Cramer, Tousson R. Toppozada, Michael S. Reichle and James F. Davis.** ***Bulletin of the Seismological Society of America August 1999 vol. 89 no. 4 867-876.***

  Abstract:

  The formulas for the estimation of expected loss from probabilistic seismic hazard are presented systematically by using the basics of calculating expected values and the concept of distributing the total loss between the insurer and the insured. The conversion from acceleration to intensity and then to loss factor (the ratio of damage value to the property value) is applied in the calculation. The seismic hazard used in the loss calculation is for four locations in California. These locations are representative of high and low hazards in California and of the two most populated areas in northern and southern California. The calculated loss values show a strong dependence on the hazard and the soil conditions. The deaggregation of total loss with respect to intensity, acceleration, and loss factor shows that a greater portion of the total loss in the high-hazard region is from large intensities and accelerations compared with the low-hazard region. The deaggregation with respect to loss factor reveals that most of the loss is from loss factors below 15-20%, even for the high-hazard regions. This result has a significant impact on the amount of the loss that is greater than the deductible. The calculation of loss to the insurer shows that a mere 5% deductible reduces the loss to the insurer by 40-50% for a high-hazard region and by more than that for a low-hazard region. Underinsurance and inflation have the effect of increasing the loss to the insurer but are less significant than the effect of deductible in reducing the loss to the insurer. These calculations suggest that updating the relation converting ground motion to loss factor is critical. In addition, the correction for soil condition needs to be calibrated with more recent strong-motion and earthquake damage data.

- **The Earthquake Potential of the New Madrid Seismic Zone. Martitia P. Tuttle, Eugene S. Schweig, John D. Sims, Robert H. Lafferty, Lorraine W. Wolf, and Marion L. Haynes. *Bulletin of the Seismological Society of America, Vol. 92, No. 6, pp. 2080–2089, August 2002.***

Abstract:

The fault system responsible for New Madrid seismicity has generated temporally clustered very large earthquakes in A.D. 900 _ 100 years and A.D. 1450 _ 150 years as well as in 1811–1812. Given the uncertainties in dating liquefaction features, the time between the past three New Madrid events may be as short as 200 years and as long as 800 years, with an average of 500 years. This advance in understanding the Late Holocene history of the New Madrid seismic zone and thus, the contemporary tectonic behavior of the associated fault system was made through studies of hundreds of earthquake-induced liquefaction features at more than 250 sites across the New Madrid region. We have found evidence that prehistoric sand blows, like those that formed during the 1811–1812 earthquakes, are probably compound structures resulting from multiple earthquakes closely clustered in time or earthquake sequences. From the spatial distribution and size of sand blows and their sedimentary units, we infer the source zones and estimate the magnitudes of earthquakes within each sequence and thereby characterize the detailed behavior of the fault system. It appears that fault rupture was complex and that the central branch of the seismic zone produced very large earthquakes during the A.D. 900 and A.D. 1450 events as well as in 1811–1812. On the basis of a minimum recurrence rate of 200 years, we are now entering the period during which the next 1811–1812-type event could occur

- **The Influence of Maximum Magnitude on Seismic-Hazard Estimates in the Central and Eastern United States. Charles S. Mueller. *Bulletin of the Seismological Society of Americ, April 2010, Vol. 100, No. 2, 699-711.***

Abstract:

I analyze the sensitivity of seismic-hazard estimates in the central and eastern United States (CEUS) to maximum magnitude (*m* max) by exercising the U.S. Geological Survey (USGS) probabilistic hazard model with several *m* max alternatives. Seismicity-based sources control the hazard in most of the CEUS, but data seldom provide an objective basis for estimating *m* max. The USGS uses preferred *m* max values of moment magnitude 7.0 and 7.5 for the CEUS craton and extended margin, respectively, derived from data in stable continental regions worldwide. Other approaches, for example analysis of local seismicity or judgment about a source's seismogenic potential, often lead to much smaller *m* max. Alternative models span the *m* max ranges from the 1980s Electric Power Research Institute/Seismicity Owners Group (EPRI/SOG) analysis. Results are presented as hazard ratios relative to the USGS national seismic hazard maps. One alternative model specifies *m* max equal to moment magnitude 5.0 and 5.5 for the craton and margin, respectively, similar to EPRI/SOG for some sources. For 2% probability of exceedance in 50 years (about 0.0004 annual probability), the strong *m* max truncation produces hazard ratios equal to 0.35–0.60 for 0.2- sec spectral acceleration, and 0.15–0.35 for 1.0-sec spectral acceleration. Hazard-controlling earthquakes interact with *m* max in complex ways. There is a relatively weak dependence on probability level: hazard ratios increase 0–15% for 0.002 annual exceedance probability and decrease 5–25% for 0.00001 annual exceedance probability. Although differences at some sites are tempered when faults are added, *m* max clearly accounts for some of the discrepancies that are seen in comparisons between USGS-based and EPRI/SOG-based hazard results.

- **Topographic Slope as a Proxy for Seismic Site Conditions and Amplification-Review Article. David J. Wald and Trevor I. Allen. *Bulletin of the Seismological Society of America, Vol. 97, No. 5, pp. 1379–1395, October 2007, doi: 10.1785/0120060267.***

Abstract:

We describe a technique to derive first-order site-condition maps directly from topographic data. For calibration, we use global 30 arc sec topographic data and VS 30 measurements (here VS 30 refers to the average shear-velocity down to 30 m) aggregated from several studies in the United States, as well as in Taiwan, Italy, and Australia. VS 30 values are correlated against topographic slope to develop two sets of parameters for deriving VS 30: one for active tectonic regions where topographic relief is high, and one for stable shields where topography is more subdued. By taking the gradient of the topography and choosing ranges of slope that maximize the correlation with shallow shear-velocity observations, we can recover, to first order, many of the spatially varying features of site-condition maps developed for California. Our site-condition map for the low-relief Mississippi Embayment also predicts the bulk of the VS 30 observations in that region despite rather low slope ranges. We find that maps derived from the slope of the topography are often well correlated with other independently derived, regional-scale site-condition maps, but the latter maps vary in quality and continuity, and subsequently, also in their ability to match observed VS 30 measurements contained therein. Alternatively, the slope-based method provides a simple approach to uniform site-condition mapping. After validating this approach in regions with numerous VS 30 observations, we subse-

quent estimate and map site conditions for the entire continental United States using the respective slope correlations.

- **Triggered Earthquakes and the 1811–1812 New Madrid, Central United States, Earthquake Sequence. Susan E. Hough.** ***Bulletin of the Seismological Society of America, 91, 6, pp. 1574–1581, December 2001.***

  Abstract:

  The 1811–1812 New Madrid, central United States, earthquake sequence included at least three events with magnitudes estimated at well above *M* 7.0. I discuss evidence that the sequence also produced at least three substantial triggered events well outside the New Madrid Seismic Zone, most likely in the vicinity of Cincinnati, Ohio. The largest of these events is estimated to have a magnitude in the low to mid*M*5 range. Events of this size are large enough to cause damage, especially in regions with low levels of preparedness. Remotely triggered earthquakes have been observed in tectonically active regions in recent years, but not previously in stable continental regions. The results of this study suggest, however, that potentially damaging triggered earthquakes may be common following large mainshocks in stable continental regions. Thus, in areas of low seismic activity such as central/ eastern North America, the hazard associated with localized source zones might be more far reaching than previously recognized. The results also provide additional evidence that intraplate crust is critically stressed, such that small stress changes are especially effective at triggering earthquakes.

- **Understanding Seismic Hazard and Risk Assessment: An example in the New Madrid Seismic Zone of the Central United States. Zhenming Wang.** ***Proceedings of the 8th U.S. National Conference on Earthquake Engineering, Paper No. 416, April 18-22, 2006, San Francisco, California, USA.***

  Abstract:

  Seismic hazard and risk are fundamentally different concepts. Seismic hazard describes phenomena generated by earthquakes that have potential to cause harm, but seismic risk is the likelihood (chance) of experiencing a specified level of seismic hazard in a given time exposure. Seismic hazard occurs naturally and can be evaluated from instrumental, historical, and geological observations. Seismic risk depends not only on the hazard and exposure, but also on models (i.e., time-independent [Poisson] and time-dependent ones) used to describe the occurrence of earthquakes. High seismic hazard does not necessarily mean high seismic risk, and vice versa. Probabilistic seismic hazard analysis (PSHA) is a commonly used method to derive seismic hazard curve – a relationship between a ground motion parameter and its return period. The so-called return period in PSHA is a modification of the recurrence intervals of earthquakes using the probabilities of ground motions. The return period is not an independent temporal parameter, but it has been inappropriately treated as the mean recurrence interval of an independent event (ground motion) and used in seismic risk analysis. In the New Madrid Seismic Zone of the central United States, the mean recurrence interval of large earthquakes (~M7.5) is about 500 years, and the risk posed by such events or their ground motions (consequences) is about 10 percent probability of exceedance (PE) in 50 years. However, PSHA could predict

ground motions with a range of return periods, up to 106 to 108 years, for the same earthquakes. In other words, use of PSHA could derive a range of risk estimates for a single earthquake. Thus, the use of PSHA for seismic risk analysis is not appropriate and confusing. An alternative method, seismic hazard assessment (SHA), is presented in this paper. SHA is comparable to flood and wind hazard analyses and can be used for risk analysis in a similar way.

5.2 Taiwan

5.2.1 Abstracts

- **A Catalog of Taiwan Earthquakes (1900–2006) with Homogenized Mw Magnitudes. Kuei-Pao Chen,Yi-Ben Tsai.** ***Bulletin of the Seismological Society of America February 2008 vol. 98 no. 1, 483-489, doi: 10.1785/0120070136.***

  <u>Abstract:</u>

  Taiwan has a relatively complete catalog of earthquakes since the first seismograph was installed in 1897. However, due to changes in seismographic characteristics, network coverage, and observational practice, the definition and procedure for magnitude determination were different during different time periods. Recognizing a complete catalog of earthquakes with consistent magnitudes is essential for delineating seismicity patterns and assessing seismic hazards for Taiwan; efforts have been made to convert the original magnitudes of earthquakes in Taiwan based on various magnitude scales to a common ML or MS magnitude scale. Unfortunately, the ML or MS magnitude scales chosen for previous studies all are subject to a fundamental limitation of saturation toward large earthquakes. Besides, these studies are nearly two decades old. In order to avoid this limitation and to follow the current trend, we have chosen in this study to convert original magnitudes of various scales to a common Mw scale. In this study we used two independent methods for magnitude conversion. In the first method we converted the original magnitudes to Mw through empirical relations between these magnitudes and Mw. This magnitude is called the old Mw. In the second method we used the best-fitting a- and b-values to convert the original magnitudes to Mw. This magnitude is called the new Mw. The converted Mw magnitudes from both methods have resulted in significant improvements over the original magnitudes and are in good agreement with each other. Nevertheless, by examining the log10N versus Mw plots, we found better linearity and tighter overlap among different time periods for the new Mw than for the old Mw. Thus, we chose the new Mw as the unified magnitude for the catalog of Taiwan earthquakes. Finally, a list of 899 earthquakes from 1900 to 2006 with Mw≥5.5 is presented (see the earthquake lists available in the electronic supplement to this article). The list is considered complete for the whole period from 1900 to 2006.

- **Effects of Realistic Surface Topography on Seismic Ground Motion in the Yangminshan Region of Taiwan Based Upon the Spectral-Element Method and LIDAR DTM. Shiann-Jong Lee and Yu-Chang Chan, Dimitri Komatitsch, Bor-Shouh Huang, Jeroen Tromp.** ***Bulletin of the Seismological Society of America April 2009 vol. 99 no. 2A 681-693, doi: 10.1785/0120080264.***

Abstract:

We combine light detection and ranging (LiDAR) digital terrain model (DTM) data and an improved mesh implementation to investigate the effects of highresolution surface topography on seismic ground motion based upon the spectral-element method. In general, topography increases the amplitude of shaking at mountain tops and ridges, whereas valleys usually have reduced ground motion, as has been observed in both records from past earthquakes and numerical simulations. However, the effects of realistic topography on ground motion have not often been clearly characterized in numerical simulations, especially the seismic response of the true ground surface. Here, we use LiDAR DTM data, which provide two-meter resolution at the free surface, and a spectral-element method to simulate three-dimensional (3D) seismic-wave propagation in the Yangminshan region in Taiwan, incorporating the effects of realistic topography. A smoothed topographic map is employed beneath the model surface in order to decrease mesh distortions due to steep ground surfaces. Numerical simulations show that seismic shaking in mountainous areas is strongly affected by topography and source frequency content. The amplification of ground motion mainly occurs at the tops of hills and ridges whilst the valleys and flat-topped hills experience lower levels of ground shaking. Interaction between small-scale topographic features and high-frequency surface waves can produce unusually strong shaking. We demonstrate that topographic variations can change peak ground acceleration (PGA) values by ±50% in mountainous areas, and the relative change in PGA between a valley and a ridge can be as high as a factor of 2 compared to a flat surface response. This suggests that high-resolution, realistic topographic features should be taken into account in seismic hazard analysis, especially for densely populated mountainous areas.

- **Ground-Motion Attenuation Relationships for Subduction-Zone Earthquakes in Northeastern Taiwan. Po-Shen Lin, Chyi-Tyi Lee.** ***Bulletin of the Seismological Society of America February 2008 vol. 98 no. 1 220-240, doi: 10.1785/0120060002.***

Abstract:

Subduction zone earthquakes have not been taken into special consideration in most previous probabilistic seismic hazard analyses (PSHA) in Taiwan. However, they may be critical to properly analyze the earthquake hazard in metropolitan Taipei, so they need to be studied. Strong-motion data from subduction zone earthquakes, of both interface and intraslab types, obtained by the TSMIP and SMART arrays in northeastern Taiwan, are used to establish the attenuation equations for peak ground acceleration (PGA) and response spectral acceleration (SA). The resultant PGA and SA attenuation equations include two site classes and two earthquake source types. The ground-motion values predicted by these attenuation equations are higher than those obtained from the crustal earthquake attenuation equations previously used in Taiwan but are lower than those predicted by the attenuation equations for worldwide subduction zone earthquakes.

- **Interseismic Deformation and Earthquake Hazard along the Southernmost Longitudinal Valley Fault, Eastern Taiwan. Ray Y. Chuang, M. Meghan Miller, Yue-Gau Chen, Horng-Yue Chen, J. Bruce H. Shyu, Shui-Beih Yu, Charles M. Rubin, Kerry**

Sieh and Ling-Ho Chung. ***Bulletin of the Seismological Society of America August 2012 vol. 102 no. 4, 1569-1582, doi: 10.1785/0120110262.***

Abstract:

About half of the 8 cm/yr of oblique convergence across the active convergent plate boundaries of Taiwan occurs in eastern Taiwan, across the Longitudinal Valley. Significant shortening and left-lateral slip occurs across the Longitudinal Valley fault there, both as shallow fault creep and as seismogenic fault slip. The southernmost Longitudinal Valley fault comprises an eastern Peinan strand and a western Luyeh strand. We derive an interseismic block model for these two strands using data from a small-aperture Global Positioning System (GPS) campaign and leveling. The model provides estimates of fault slip rates and quantifies slip partitioning between the two strands. A 45 mm/yr dip-slip rate on the northern Peinan strand diminishes southward, whereas the left-lateral component increases. In contrast, nearly pure dip-slip motion of about 20 mm/yr on the southern Luyeh strand diminishes northward to about 8 mm/yr and picks up a component of left-lateral motion of about 15 mm/yr before it dies out altogether at its northern terminus. The Luyeh and the northern Peinan strands record near-surface creep, but the southern Peinan strand appears locked. The potential earthquake magnitude for the two strands may be as high as Mw 6.5. We anticipate seismic rupture mainly on the locked portion of the Peinan strand.

- **Phase Velocity Variation at Periods of 0.5–3 Seconds in the Taipei Basin of Taiwan from Correlation of Ambient Seismic Noise. Yu-Chih Huang, Huajian Yao, Bor-Shouh Huang, Robert D. Van der Hilst, Kuo-Liang Wen, Win-Gee Huang, Chi-Hsuan Chen.** ***Bulletin of the Seismological Society of America October 2010 vol. 100 no. 5A, 2250-2263, doi: 10.1785/0120090319.***

Abstract:

Improving seismic hazard mitigation of the densely populated metropolitan area of and around the capital of Taiwan requires detailed knowledge of the 3D crustal structure of Taipei basin. The high levels of ambient noise and the low levels of regional seismicity of this region complicate investigations of crustal structure with traditional seismic exploration or earthquake tomography methods. We investigate the shallow crust in the metropolitan region using surface wave array tomography with time domain empirical Green's function (TDEGF) inferred from correlation of ambient seismic noise. Analysis of the TDEGF amplitudes suggests that the dominant sources of ambient seismic noise are the coastlines and shallow continental shelf of the Taiwan Strait, northwest of the study region. Our study demonstrates that ambient seismic noise tomography is feasible at periods of 0.5–3 s, which is much shorter than the 10–30 s used in most other studies, and which opens new opportunities for high resolution studies of near-surface heterogeneity. The lateral variation in Rayleigh wave phase velocity correlates well with surface geology and suggests that faults play an important role in the regional tectonic setting. High phase velocities mark the Tatun volcanic area, the Kuanyin Mountain dominated by Quaternary igneous rock, and the Miocene Western Foothills south of the Taipei fault. Low phase velocities characterize regions are along western and southeastern edges of the Taipei basin and the Pleistocene Linkou tableland. Main faults in the region are either

marked by low phase velocities or define transitions between regions of high- and low velocity anomalies.

- **Probability for Simulating Future Earthquakes with Mw ≥6.0 in Taiwan for Seismic Hazard for the Earthquake Catalog from 1900 to 2008. Kuei-Pao Chen, Yi-Ben Tsai, Wen-Yen Chang, Chin-Tung Cheng. *Bulletin of the Seismological Society of America October 2012 vol. 102 no. 5, 2252-2256, doi: 10.1785/0120110253.***

  Abstract:

  In this study, we use extreme value theory based on Gumbel-equation derivations to estimate the Gutenberg–Richter a and b parameters for Taiwan. Data are from the augmented, homogenized (in terms of moment magnitude), historic catalog for Taiwan. The island is divided into grids of 0.2° latitude by 0.2° longitude, and Gumbel type 1 statistical analysis is applied. The values of a and b are then used to determine the probability of large earthquakes (Mw≥6.0) occurring at each grid. The results show two relatively high probability paths for large earthquakes, one extending from Hsinchu southward to Taichung, Chiayi, and Tainan in western Taiwan and the other from Ilan southward to Hualian and Taitung in eastern Taiwan, both of which are characterized by low b-values. It indicates that future earthquakes can be expected along these paths characterized by low b-values. Additionally, maximum peak ground acceleration and maximum peak ground velocity (determined from respective attenuation laws and a gridding regimen of 0.1° latitude by 0.1° longitude for Taiwan) follow similar paths to that of the low b values.

- **Source-Scaling Relationship for M 4.6–8.9 Earthquakes, Specifically for Earthquakes in the Collision Zone of Taiwan. Yin-Tung Yen and Kuo-Fong Ma. *Bulletin of the Seismological Society of America April 2011 vol. 101 no. 2, 464-481, doi: 10.1785/0120100046.***

  Abstract:

  We investigated the source scaling of earthquakes (Mw 4.6–8.9), mostly from the Taiwan orogenic belt, and made a global compilation of source parameters to examine the scaling self-similarity. Finite-fault slip models (12 dip-slip and 7 strike-slip) using mainly dense strong-motion data and teleseismic data from Taiwan were utilized. Seven additional earthquakes (M>7) were included for further examination of scaling of large events. We determined the effective length and width for the scaling study was $M_0 \sim L$ and $M_0 \sim L$ for the events less than and larger than the seismic moment of 10^{20} Nm , respectively, regardless of the fault types, suggesting a nonself similar scaling for small to moderate events and a self-similar scaling for large events. Although the events showed variation in stress drops, with the exception of three events with high stress drops, most of the events had stress drops of 10–100 bars. The observed bilinear relation is well explained by the derived magnitude–area equation of Shaw (2009) when we considered only events with stress drops of 10–100 bars and a seismogenic thickness of 35 km. The bilinear feature of the regressed magnitude–area scaling holds for ruptured areas up to about 1000 km^2 for our seismogenic thickness of 35 km. For the events having rupture areas larger than that, the average slip becomes proportional to the rupture length. The distinct high stress drop

events from blind faults in the western foothill of Taiwan yield local high peak ground accelerations (PGAs) when compared to the Next Generation Attenuation model. Regardless of the relative small magnitudes of these events, the high PGAs give the region higher seismic hazard potential and thus require special attention for seismic hazard mitigation.

- **Structures Associated with the Northern End of the 1999 Chi-Chi Earthquake Rupture, Central Taiwan: Implications for Seismic-Hazard Assessment. Yuan-Hsi Lee, Shih-Ting Lu, Tung-Sheng Shih, Meng-Long Hsieh and Wei-Yu Wu.** ***Bulletin of the Seismological Society of America April 2005 vol. 95 no. 2 471-485, doi: 10.1785/0120020170.***

  Abstract:

  The surface rupture of the 1999 Chi-Chi earthquake (Mw 7.6) trends more than 100 km in a north–south direction. Surface deformation at the northern end stops abruptly at an area between the Tachia River and the Taan River where a broad pop-up structure with east to northeast strike can be found that has a trend different from the north–south-striking main thrust. We combine the absolute elevation data before and after the Chi-Chi earthquake to obtain the regional vertical displacement and the magnitude of the pop-up structure. The greatest uplift could reach as high as 15–16 m. Using deformation magnitude and the area-balancing method we measure the depth of the detachment to show the subsurface geometry of the Chelungpu fault at its northern end. This shows that the geometry of the Chelungpu fault controls termination of the surface rupture and the depth of the detachment controls the amount of deformation.

- **Taiwan's medical response to the 921 'Chi-Chi' earthquake. N. Colgrave.** ***Disater & Military Surgery Eur J Trauma Emerg Surg (2011) 37:13–18, Doi: 10.1007/s00068-010-0026-9.***

  Abstract:

  The objective of this study was to identify and review literature relevant to the medical response to the 921 earthquake in order to analyse Taiwan's immediate and long-term management of the medical issues arising from the disaster. Methods Pubmed and Google Scholar searches were conducted in June 2008 to identify papers relevant to the topic. These were reviewed and the findings of each collated to develop a critical review of Taiwan's response to the earthquake. Pubmed and Google Scholar searches were conducted again in March 2010 to verify the currency of the literature reviewed. Results A total of 14 papers were identified and reviewed. Many concluded that while disaster response efforts were initiated quickly, the inexperience of the authorities, the timing and location of the earthquake, and the associated destruction of vital infrastructure, meant much of the initial rescue planning and coordination was improvised. This resulted in poor response times by emergency teams, inefficient mobilisation of military and medical resources, poor cooperation between authorities and a failure to fully utilise international assistance when it arrived. Conclusion Taiwan was unprepared for a disaster of the magnitude of the 921 earthquake. The government has since taken initiatives to ensure Taiwan is better prepared for any future large scale disaster, including the establishment of the National Institute for Disaster Management. There is a paucity of literature on the medical response to the disaster. Only one new paper of relevance to the topic has been listed on Pubmed or Google Scholar in recent years.

Keywords: 921 earthquake Chi-Chi Disaster response Taiwan.

- **A seismic landslide hazard analysis with topographic effect, a case study in the 99 Peaks region, Central Taiwan. Wen-Fei Peng, Chein-Lee Wang, Shih-Tsu Chen, Shing-Tsz Lee.** ***Environ Geol (2009) 57:537–549 DOI 10.1007/s00254-008-1323-z.***

Abstract:

It has been known that ground motion amplitude will be amplified at mountaintops; however, such topographic effects are not included in conventional landslide hazard models. In this study, a modified procedure that considers the topographic effects is proposed to analyze the seismic landslide hazard. The topographic effect is estimated by back analysis. First, a 3D dynamic numerical model with irregular topography is constructed. The theoretical topographic amplification factors are derived from the dynamic numerical model. The ground motion record is regarded as the reference motion in the plane area. By combining the topographic amplification factors with the reference motions, the amplified acceleration time history and amplified seismic intensity parameters are obtained. Newmark's displacement model is chosen to perform the seismic landslide hazard analysis. By combining the regression equation and the seismic parameter of peak ground acceleration and Arias intensity, the Newmark's displacement distribution is generated. Subsequently, the calculated Newmark's displacement maps are transformed to the hazard maps. The landslide hazard maps of the 99 Peaks region, Central Taiwan are evaluated. The actual landslide inventory maps triggered by the 21 September 1999, Chi-Chi earthquake are compared with the calculated hazard maps. Relative to the conventional procedure, the results show that the proposed procedures, which include the topographic effect can obtain a better result for seismic landslide hazard analysis.

Keywords: Landslides Seismic hazards, Newmark's method, Topographic effect, The 99 Peaks region, Earthquakes.

- **Influence of ground-motion correlation on probabilistic assessments of seismic hazard and loss: sensitivity analysis. Vladimir Sokolov and FriedemannWenzel.** ***Bull Earthquake Eng (2011) 9:1339–1360 DOI 10.1007/s10518-011-9264-4.***

Abstract:

Recent studies have shown that the proper treatment of ground-motion variability and, particularly, the correlation of ground motion are essential for the estimation of the seismic hazard, damage and loss for distributed portfolios. In this work we compared the effects of variations in the between-earthquake correlation and in the site-to-site correlation on probabilistic estimations of seismic damage and loss for the extended objects (hypothetical portfolio) and critical elements (e.g. bridges) of a network. Taiwan Island has been chosen as a test case for this study because of relatively high seismicity and previous experience in earthquake hazard modelling. The hazard and loss estimations were performed using Monte Carlo approach on the basis of stochastic catalogues and random ground-motion fields. We showed that the influence of correlation on parameters of seismic hazard, characteristics of loss distribution and the probability of damage depend, on one hand, on level of hazard and probability level of interest (return period) and, on the other hand, the relative influence of each type of correlation is not equal.

Keywords: Probabilistic seismic hazard and loss estimation · Ground-motion correlation.

- **A web-based decision support system for slopeland hazard warning. Yu Fan-Chieh, Chen Chien-Yuan, Lin Sheng-Chi, Lin Yu-Ching, Wu Shang-Yu and Cheung Kei-Wai.** ***Environ Monit Assess (2007) 127:419–428 DOI 10.1007/s10661-006-9291-9.***

  Abstract:

A WebGIS decision support system for slopeland hazard warning based on real-time monitored rainfall is introduced herein. This paper presents its framework, database, processes of setting up the threshold line for debris flow triggering and the calculation algorithm implemented in the system. The web-based GIS via the Microsoft Internet Explorer is designed for analysis of areas prone to debris flows outburst and landslides during torrential rain. Its function is to provide suggestions to commander for immediate response to the possibility of slopeland hazards, and determine if pre-evacuation is necessary. The defining characteristics of the internet-based decision support system is not to automatically show the dangerous areas but acts as part of the decision process via information collection to help experts judge the prone debris flow creeks and the tendency of landslides initiation. The combination with real-time rainfall estimation by the QPESUMS radar system is suggested for further enhancement.

Keywords: Landslide, Debris flow, Decision support system, Real-time monitoring, WebGIS.

- **Performance-based assessment of earthquake-induced catastrophic landslide hazard in liquefiable soils. Aurelian Catalin Trandafir and Kyoji Sassa.** ***Geotechnical and Geological Engineering (2006) 24: 1627–1639 Springer 2006, Doi: 10.1007/s10706-005-4896-2.***

  Abstract:

This paper outlines a methodology for evaluating the likelihood of catastrophic landslide occurrence on gentle slopes in liquefiable soils during earthquake. The approach is based on a modified Newmark sliding block model of assessing the earthquake-induced undrained landslide displacements for conditions of no shear stress reversals on the sliding surface. By employing the shear resistance-displacement relationship from undrained monotonic ring shear tests, the simulation model incorporates the sensitivity of computed displacements to variations in yield acceleration. The proposed approach involves an examination of undrained seismic slope performance under various horizontal seismic waveforms scaled to different specific values of the peak earthquake acceleration. An example problem illustrates how the proposed methodology may be used to demarcate, based on the magnitude of permanent seismic displacement, the levels of low, moderate

and high risk of catastrophic landslide on a gentle slope in a saturated cohesionless soil susceptible to liquefaction during earthquake.

Key words: catastrophic landslide hazard, earthquakes, liquefiable soil, seismic displacements, slopes.

- **Overview of Taiwan Earthquake Loss Estimation System. Chin-Hsun Yeh, Chin-Hsiung Loh and Keh-Chyuan Tsai.** ***Natural Hazards (2006) 37:23–37 Springer 2006 DOI 10.1007/s11069-005-4654-z.***

Abstract:

The National Science Council (NSC) of Taiwan started the HAZ-Taiwan project in 1998 to promote researches on seismic hazard analysis, structural damage assessment, and socio-economic loss estimation. The associated application software, ''Taiwan Earthquake Loss Estimation System (TELES)'', integrates various inventory data and analysis modules to fulfill three objectives. First, it helps to obtain reliable estimates of seismic hazards and losses soon after occurrence of large earthquakes. Second, it helps to simulate earthquake scenarios and to provide useful estimates for local governments or public services to propose their seismic disaster mitigation plans. Third, it helps to provide catastrophic risk management tools, such as proposing the seismic insurance policy for residential buildings. This paper focuses on the development and application of analysis modules used in early loss estimation system. These modules include assessments of ground motion intensity, soil liquefaction potential, building damage and casualty.

Key words: seismic hazard analysis, damage assessment, casualty assessment, early seismic loss estimation.

- **Early Estimation of Seismic Hazard for Strong Earthquakes in Taiwan. Wen-Yu Jean, Yu-Wen Chang, Kuo-Liang Wen and Chin-Hsiung Loh.** ***Natural Hazards (2006) 37:39–53 Springer 2006 DOI 10.1007/s11069-005-4655-y.***

Abstract:

A shakemap system providing rapid estimates of strong ground shaking could be useful for emergency response providers in a damaging earthquake. A hybrid procedure, which combines site-dependent ground motion prediction models and the limited observations of the Real-Time Digital stream output system (RTD system operated by Central Weather Bureau, CWB), was set up to provide a high-resolution shakemap in a near-real-time manner after damaging earthquakes in Taiwan. One of the main factors that affect the result of ground motion prediction analysis is the existence of site effects. The purpose of this paper is to investigate the local site effects and their influence in the ground shaking and then establish an early estimation procedure of potential hazard for damaging earthquakes. Based on the attenuation law, the site effects of each TSMIP station are discussed in terms of a bias function that is site and intensity-level dependent function. The standard deviation of the site-dependent ground motion prediction model can be significantly reduced. The nonlinear behavior of ground soil is automatically taken into account in the intensity-level dependent bias function. Both the PGA and the spectral acceleration are studied in this study. Based on the RTD data, event correctors are calculated and applied to precisely estimate the shakemap of damaging earthquakes for emergency response.

Key words: shakemap, damaging earthquake, earthquake emergency response, attenuation law, site effects.

- **Study on the Fragility of Building Structures in Taiwan. Wen Liao, Chin-Hsiuung Loh and Keh-Chyuan Tsai.** ***Natural Hazards (2006) 37:55–69 Springer 2006 DOI 10.1007/s11069-005-4656-x.***

Abstract:

This paper describes procedures of damage assessment for building structures in Taiwan Earthquake Loss Estimation System (TELES), and focuses on evaluation of parameters used in the building damage assessment. The objective of this paper is to define the building classification and provide the fragility functions of the general building structures in Taiwan by using the available data. The organization of this paper is as follows. First, the types of the building structures in Taiwan are reviewed and a classification based on the available data to be implemented in TELES is proposed. Second, the description of failure mechanisms and criteria in different damage states adopted in this research are summarized. Third, the theoretical methodology of the fragility analysis for the proposed building classes and examples for some typical building structures are presented. Parameters for describing the fragility functions for each class are also generated and shown in the paper.

Key words: fragility analysis, capacity curve, building structure

- **Characteristics analysis for the flash flood-induced debris flows. Chen Chien-Yuan, Chen Lien-Kuang, Yu Fan-Chieh, Lin Sheng-Chi, Lin Yu-Ching, Lee Chou-Lung, Wang Yu-Ting, Cheung Kei-Wai.** ***Nat Hazards (2008) 47:245–261 DOI 10.1007/s11069-008-9217-7.***

Abstract:

Typhoon Haitang caused landfall on Taiwan during 15–21 July, 2005 and brought 2,279 mm of maximum cumulative rain with a maximum intensity of 176 mm/h. The torrential rain was mainly distributed from the central mountain range to southern Taiwan and triggered 222 slopeland-related hazards. Among the hazard events, there were 17 debris flows, 157 cases of traffic cut-off, three large-magnitude deep-seated landslides, and 10 villages isolated in the off-track mountainous areas. The debris flows initiated in southern Taiwan were associated with torrential rain, short channel length (\2 km), and small basin area (\3 km2), and were speculated to be induced by flash flood. These flash flood-induced debris flows have a higher rainfall intensity-duration threshold for initiation than in other areas. The deep-seated landslides, isolated villages due to traffic cut-off in off-track mountain areas, and recurrent hazards in areas affected by the ML 7.6 Chi-Chi earthquake in 1999 are characteristics of slopeland hazards in Taiwan in recent years. One of the most urgently needed mitigation strategies in response to slopeland hazards is

the plan for enhancing self-rescue disaster resistance in off-track mountainous villages in Taiwan.

Keywords Debris flow Landslide Flash flood Hazard mitigation.

- **Regional economic impact analysis of earthquakes in northern Taiwan and its implications for disaster reduction policies. H. C. Lin, Y. L. Kuo, D. Shaw, M. C. Chang, T. M. Kao.** ***Nat Hazards (2012) 61:603–620 DOI 10.1007/s11069-011-0049-5.***

Abstract:

The direct damage caused by earthquakes, such as impaired buildings, may interfere with normal business operations and disrupt the function of the industrial chain. Such economic impacts can be evaluated using the input–output analysis developed by Leontief. In this paper, two scenario earthquakes in northern Taiwan both with a return period of 475 years—the Hsinchu Hsincheng and the Yilan Nan-ao earthquakes—are simulated. The results show that the economic impact caused by the Hsincheng earthquake is greater than that resulting from the Nan-ao earthquake, which should be the major scenario considered for the disaster reduction plan. The industries affected the most are the manufacturing, food services and entertainment, storage and retail trade, and public and construction industries. The Nan-ao earthquake causes relatively more losses in the food services and entertainment industries. Most of the repercussion effects of these industries are in the central and southern parts of Taiwan. The loss to the manufacturing sector and its repercussion effects are enormous. Therefore, the government should make it a first priority to encourage the manufacturing sector to implement earthquake mitigations, such as a seismic retrofit, or to provide a seismic evaluation, which can enable firms to engage in mitigation voluntarily. The measure needed to reduce the loss in agriculture is that the government can purchase agricultural products in central and southern Taiwan following the disaster and offer them to survivors in northern Taiwan.

Keyword: Regional economic impact, Multi-regional input–output table, TELES, Scenario earthquake, Seismic retrofit.

- **The distribution of annual maximum earthquake magnitude around Taiwan and its application in the estimation of catastrophic earthquake recurrence probability. Jui-Pin Wang, Chung-Han Chan, Yih-Min Wu.** ***Nat Hazards (2011) 59:553–570 DOI 10.1007/s11069-011-9776-x.***

Abstract:

The annual maximum earthquake magnitudes around Taiwan from 1900 to 2009 are presented in this paper. Using the distribution of the AMEM, a probabilistic framework to estimate the recurrence probability of a large-size earthquake is also proposed and an illustration was made in this paper. The mean value of the 110-AMEM is 6.433, and the coefficient of variation is around 10%. The results of two goodness-of-fit tests show that the Gamma and lognormal distributions are relatively suitable to represent the AMEM around Taiwan among five common probability distributions. Using the proposed approach, the recurrence probability is 4% for an earthquake with magnitude greater than

7.5 in a 1-year period around Taiwan. More site-specifically, the probability is around 5% in Central Taiwan for such an earthquake to occur in a 50-year period.

Keyword: Annual maximum earthquake magnitude, Goodness-of-fit test, Lognormal distribution, Gamma distribution.

- **Modeling and assessment of bridge structure for seismic hazard prevention. Jeng-Wen Lin, Cheng-Wu Chen, Shang-Heng Chung.** ***Nat Hazards (2012) 61:1115–1126, Doi: 10.1007/s11069-011-9969-3.***

  Abstract:

  This study uses data from Mao-Luo-Hsi Bridge to model the bridge structure and a set of developed alarm and action values to formulate guidelines for bridge maintenance and seismic hazard prevention. The bridge model is improved by incorporating onsite ambient vibration measurement to perform modal analyses. Dynamic analyses of the bridge are implemented using the established 3D model subjected to uniform loading and seismic force, with or without consideration of soil interaction with the structure. The maximum displacements for different sections of the bridge are compared, and statistical regression analyses are used to explore their correlation. Information for bridge safety assessment is proposed, which can mitigate loss of property and lives due to bridge failure. Regression analyses of the maximum displacements between abutments D and E of the considered bridge in the axial, horizontal, and vertical directions under various seismic intensities are conducted, giving R2 values of 0.9462, 0.9352, and 0.9010, respectively. The developed maintenance guidelines are reliable since all parameters from regression analyses have a 95% confidence interval excluding the zero value. The bridge alarm value and action value are determined for this bridge site at earthquake intensity scales of 4 and 5, respectively.

  Keyword: Assessment, Bridge maintenance, Seismic hazard, Statistical regression, Structural modeling.

- **PGA distributions and seismic hazard evaluations in three cities in Taiwan. Jui-Pin Wang, Su-Chin Chang, Yih-Min Wu, Yun Xu.** ***Nat Hazards (2012) 64:1373–1390, Doi: 10.1007/s11069-012-0298-y.***

  Abstract:

  This study first presents the series of peak ground acceleration (PGA) in the three major cities in Taiwan. The PGAs are back-calculated from an earthquake catalog with the use of ground motion models. The maximums of the 84th percentile (mean ? one standard deviation) PGA since 1900 are 1.03, 0.36, and 0.10 g, in Taipei, Taichung, and Kaohsiung, respectively. Statistical goodness-of-fit testing shows that the series of PGA follow a double-lognormal distribution. Using the verified probability distribution, a probabilistic analysis was developed in this paper, and used to evaluate probability-based seismic hazard. Accordingly, given a PGA equal to 0.5 g, the annual exceedance probabilities are 0.56, 0.46, and 0.23 % in Taipei, Taichung, and Kaohsiung, respectively; for PGA equal to 1.0 g, the probabilities become 0.18, 0.14, and 0.09 %. As a result, this analysis indicates the city in South Taiwan is associated with relatively lower seismic hazard, compared with those in Central and North Taiwan.

Keyword: Probability-based seismic hazard, Double-lognormal distribution, three major cities in Taiwan.

- **Improved stress release model: Application to the study of earthquake prediction in Taiwan area. Zhu Shou-biao, Shi Yao-lin.** ***Acta Seismologica Sinica March 2002, Vol. 15 No.2 (171-178).***

  Abstract:

  Stress release model used to be applied to seismicity study of large historical earthquakes in a space of large scale. In this paper, we improve the stress release model, and discuss whether the stress release model is still applicable or not in the case of smaller spatio-temporal scale and weaker earthquakes. As an example of testing the model, we have analyzed the M'e_6 earthquakes in recent about 100 years. The result shows that the stress release model is still. The earthquake conditional probability intensity in Taiwan area is calculated with the improved stress release model. We see that accuracy of earthquake occurrence time predicted by the improved stress release model is higher than that by Poisson model in the test of retrospect earthquake prediction.
  Key word: improved stress release model, conditional probability intensity, Poisson model, Taiwan area.

- **Potential rupture surface model and its application on probabilistic seismic hazard analysis. Xu Guang-yin, Gao Meng-tan.** ***Acta Seismologica Sinica, May 2007, Vol.20 No.3 (302~311), doi: 10.1007/s11589-007-0302-x.***

  Abstract:

  Potential sources are simplified as point sources or linear sources in current probabilistic seismic hazard analysis (PSHA) methods. Focus size of large earthquakes is considerable, and fault rupture attitudes may have great influence upon the seismic hazard of a site which is near the source. Under this circumstance, it is unreasonable to use the simplified potential source models in the PSHA, so a potential rupture surface model is proposed in this paper. Adopting this model, we analyze the seismic hazard near the Chelungpu fault that generated the Chi-Chi (Jiji) earthquake with magnitude 7.6 and the following conclusions are reached. 1 This model is reasonable on the base of focal mechanism, especially for sites near potential earthquakes with large magnitude; 2 The attitudes of potential rupture surfaces have great influence on the results of probabilistic seismic hazard analysis and seismic zoning.

  Key words: potential seismic source; fault rupture attitude; potential rupture surface; probabilistic seismic hazard Analysis; seismic zoning

- **Non-Structural Mitigation Programs For Sediment-Related Disasters after the Chi-chi Earthquake in Taiwan. Chen Su-Chin, Huang Bo-Tsung.** ***J. Mt. Sci. (2010) 7: 291–300, Doi: 10.1007/s11629-010-2021-3.***

Abstract:

Following the Chichi Earthquake (ML=7.3) in 1999, sediment-related disasters, such as landslides and debris flows, have become more frequent in Taiwan. Because engineering structures cannot be fully and rapidly emplaced, the government has initiated non-structural hazard mitigation programs. Initially, community debris flow evacuation drills were promoted in 2000. Typhoon Toraji caused numerous debris flow events in July 2001, and some communities evacuated according to the drills, significantly reducing the numbers of possible casualties. Based on that result, the government expanded the program for evacuation drills Secondly, the early warning system created after the Chichi Earthquake will prevent many potential futures casualties. Rainfall threshold values for debris flow warnings in different areas are determined from information received from local weather stations and modified for local geomorphologic situations. Realtime information is gradually being integrated to create a debris flow disaster warning system, the goal of which is to provide warnings to zones in which debris flows are likely. The warning system was launched in 2005 and has two levels of alarms: yellow and red. The final, red alarm triggers enforced evacuation. Overall, the decrease in casualties from debris flows during the decade after the Chichi Earthquake is not the result of a decrease in number or severity of sediment related disasters, but is more directly related to the gradually improved early warning and evacuation system. However, the compound hazards resulting from Typhoon Morakot in 2009 remind us of the ongoing need for improving the existing mitigation system.

Keywords: Warning system; evacuation and shelter; rainfall threshold value for debris flow; ChiChi Earthquake

- **Effect of near-fault earthquake on bridges: lessons learned from Chi-Chi earthquake. Chin-Hsiung Loh, Wen-I Liao, Juin-Fu Chai.** ***Earthquake Engineering and Engineering Vibration, June 2002, Vol.1, No.1.***

Abstract:

The objective of this paper is to describe the lessons learned and actions that have been taken related to the seismic design of bridge structures after the Chi-Chi, Taiwan earthquake. Much variable near-fault ground motion data was collected from the rupture of Chelungpu fault during the Chi-Chi earthquake, allowing the seismic response of bridge structures subjected to these near-fault ground motions to be carefully examined. To study the near-fault ground motion effect on bridge seismic design codes, a two-level seismic design of bridge structures was developed and implemented. This design code reflects the near-fault factors in the seismic design forces. Finally, a risk assessment methodology, based on bridge vulnerability, is als developed to assist in decisions for reducing seismic risk due to failure of bridges.

Keywords: Chi-Chi earthquake; near-fault; bridge seismic design; risk assessment

- **Development of seismic force requirements for buildings in Taiwan. Juin-Fu Chai, Tsung-Jen Teng and Keh-Chyuan Tsai** ***Earthq Eng & Eng Vib (September 2009) 8, 3, 349-358 DOI: 10.1007/s11803-009-9077-5.***

  <u>Abstract:</u>

  This paper describes static and dynamic procedures to calculate seismic demand specifi ed by the current seismic design code for buildings in Taiwan, which was issued in 2005. For design levels with a return period of 475 years, the design spectral response acceleration can be developed for general sites, near-fault sites and Taipei Basin. In addition, in order to prevent building collapse during extremely large earthquakes and yielding of structural components and elements during frequent small earthquakes, the required seismic demands at the maximum considered earthquake level (MCE, 2%/50 years) and operational level are also included in the new seismic design code. For dynamic analysis procedures, both the response spectrum method and time history method are specifi ed in the new seismic design code. Finally, procedures to generate spectrum compatible ground motions for time history analysis are illustrated in this paper.

  Keywords: building code; seismic force requirement; design spectrum; spectrum compatible design ground motion; site effect; near-fault; basin effect

- **Development of shallow seismic landslide potential map based on Newmark's displacement: the case study of Chi-Chi earthquake, Taiwan. Kuo-Lung Wang and Meei-Ling Lin.** ***Environ Earth Sci (2010) 60:775–785 DOI 10.1007/s12665-009-0215-1.***

  <u>Abstract:</u>

  With the development of the geographic information system (GIS), the analysis of regional slope stability under seismic loading has evolved rapidly in recent years. In many studies, the Newmark's method is used for the computation of displacements triggered by an earthquake on a single slope, while for regional analysis, the infinite slope theory is frequently used due to its simplicity when large amount of computations are required. In this research, the infinite slope theory was examined considering various seismic conditions, material properties, and slope geometry to verify the suitability of the method when applied to regional analysis and development of potential shallow landslide maps. The landslide cases induced by Chi-Chi earthquake in central Taiwan were used in this study for verification. It was found that the infinite slope theory is valid for regional analysis when used with discretion. Based on the calculated Newmark's displacement and combining the GIS technique, procedures for the potential map development are established in this study.

  Keyword: Landslide, Earthquake, Infinite slope, Newmark's displacement, Potential map.

- **Inversion of local S-wave velocity structures from average H/V ratios, and their use for the estimation of site-effects. Donat Fäh, Fortunat Kind & Domenico Giardini.** ***Journal of Seismology 7: 449–467, 2003.***

Abstract:

H/V spectral ratios from microtremors are used to retrieve the S-velocity structure from a single ambient vibration record, by using its relation to the ellipticity of the fundamental mode Rayleigh wave and the amplitude of observed H/V ratio. Constraints are needed in order to restrict the possible range of solutions, and the inversion is applied to sites where the thickness of the unconsolidated sediments is approximately known from borehole information. Within the uncertainty, the inverted structures agree well with the results from other S-wave measuring techniques such as downhole and cross-hole measurements, and the analysis of ambient vibrations measured on an array. The influence of the inversion uncertainty on site-amplification estimates for earthquakes is then investigated. For all inverted models, site response is computed for a large number of events, which allows to define the uncertainty by the apriori unknown source position and mechanism of a future earthquake. In most cases the variability between the results obtained for the different models is much smaller than the variability introduced by the unknown source position. The accuracy with which S-wave velocity structures can be retrieved from observed H/V ratios is therefore sufficient for an application of the method in seismic hazard analysis for a specific site.

Key words: site effects, microtremors, S-wave velocity, seismic ambient vibrations, seismic hazard assessment, inversion for structure.

- **Relationships between Strong Ground Motion Peak Values and Seismic Loss during the 1999 Chi-Chi, Taiwan Earthquake. Yih-Min Wu, Nai-Chi Hsiao and Ta-Liang Teng.** ***Natural Hazards 32: 357–373, 2004.***

Abstract:

A better real-time assessment of earthquake effects (i.e. seismic intensity estimation) is crucial for hazard mitigation. Especially during the aftermath of a disastrous event, significant reduction of loss can usually be realized through timely execution of emergency response measures. These effects include strong-ground shaking, ground failure, and their impact on man-made structures. The descriptive Modified Mercalli intensity scale, though still in common use in many poorly instrumented areas of the world, is out of date in areas of extensive strong-motion instrumentation. It is desirable to place the earthquake intensity scale on a more quantitative basis based on the actual recorded ground-motion shaking and carefully compiled damage records. In this paper, we investigated the relationships between earthquake loss, intensity and strong motion peak values, mainly based on the Chi-Chi earthquake. Both the strong-motion peak values and the earthquake loss are related. From the results, we found that peak ground acceleration (PGA) and peak acceleration response spectra at 1 s period (1 s Sa) values are two parameters that give slightly higher correlation coefficients than other parameters for earthquake loss analysis. For intensity estimations, the peak ground velocity (PGV) values and 1 s Sa values are better parameters in the high range and PGA is not stable for smaller earthquakes. Although PGV values give a slightly lower correlation coefficient and larger standard deviation in seismic loss analysis during the Chi-Chi earthquake, it nevertheless gives more reliable instrumental intensity over a broad magnitude range. 1 s Sa is a good parameter for both seismic losses and intensity evaluation. We thus conclude that PGV and 1 s Sa are relatively more stable in damage assessment and, at least in the high end, in intensity estimation. We shall incorporate these findings in our real-time earthquake rapid reporting and early warning systems.

Key words: seismic hazard mitigation, seismic damage assessment, peak ground motion, earthquake rapid reporting system.

- **Seismic Hazard Assessment for the Taiwan Region on the Basis of Recent Strong-Motion Data and Prognostic Zonation of Future Earthquakes. Vladimir Sokolov, Arkaday Ovcharenko, Chin-Hsiung Loh and Kuo-Liang Wen. *Natural Hazards 33: 319–363, 2004.***

<u>Abstract:</u>

The paper describes an integrated approach to seismic hazard assessment, which was applied to the Taiwan region. First, empirical models for ground motion estimation in the region were obtained on the basis of records from recent (1993-1999) earthquakes. The database includes strong-motion data collected during the recent Chi-Chi earthquake (M = 7.6, 21 September 1999) and large (M = 6.8) aftershocks. The ground-motion database was also used for evaluation of generalised site amplification functions for typical soil classes (B, C and D). Second, the theoretical seismic catalogue (2001–2050) for the Taiwan region had been calculated using the 4D-model (location, depth, time) for dynamic deformation of the Earth' crust and 5D-model (location, depth, time, magnitude) for seismic process. The models were developed on the basis of available geophysical and geodynamic data that include regional seismic catalogue. Third, the region and site and time dependent seismic analysis, which is based on schemes of probable earthquake zones evaluated from the theoretical catalogue, regional ground motion models, and local site response characteristics, has been performed. The seismic hazard maps are compiled in terms of Peak Ground Acceleration (PGA) and Response Spectra (RS) amplitudes. The maps show distribution of amplitudes that will not be exceeded with certain probability in condition of typical soil classes during all possible earthquakes that may occur in the region during time period of 2003–2025. The approach allows introduction of a new parameter that describes the dependency of seismic hazard on time, the so-called "period of maximum hazard". The parameter shows the period, during which every considered site will be subjected by the maximum value of ground motion characteristic (PGA or RS).

Key words: future earthquake zonation, ground-motion models, integrated approach, time dependent seismic hazard.

- **Integrated Community-Based Disaster Management Program in Taiwan: A Case Study of Shang-An Village. Liang-Chun Chen, Yi-Chng Liu and Kuei-Chi Chan. *Natural Hazards (2006) 37:209–223 Springer 2006 DOI 10.1007/s11069-005-4669-5.***

<u>Abstract:</u>

Taiwan has long made efforts to increase community emergency response capability, due to its vulnerability to earthquakes, typhoons, landslides and debris flows. Not until recent

major natural disasters, such as the 1999 Chi–Chi Earthquake, Typhoon Toraji and Typhoon Nari, has the government reformed its policy toward empowering the community to take actions in hazard mitigation, emergency preparedness and emergency response. A new initiatve, Integrated Community-Based Disaster Management Program (ICBDM), was launched in 2001 by the Executive Yuan to achieve the goal of strengthening community resistance. The paper, taking Shang-An Village as an example, describes Taiwan's new community-based disaster management program. Through a participatory process, community residents have learned how to analyze vulnerable conditions, discover problems, develop solutions and establish an organization to implement disaster management tasks. Further, basic response training courses and a disaster scenario were held in order to improve their emergency response capability. Based on the case study, a phased process, including initiation, assessment, planning and practice, is generalized.

Key words: community-based disaster management, empowerment, participatory process, resistance.

- **Near Real-Time Seismic Damage Assessment of the Rapid Reporting System. Yih-Min Wu1, Nai-Chi Hsiao, Ta-Liang Teng and Tzay-Chyn Shin.** ***Tao, Vol. 13, No. 3, 313-324, September 2002.***

Abstract:

Having the ability of near real-time damage assessment would benefit earthquake emergency response operations in Taiwan greatly. Thus, we established an empirical method of assessing the near real-time damage using the rapid reporting system in Taiwan. Relationships between peak ground velocity and damage rates (fatality rate, total and partial household collapsing rates) during the 1999 Chi-Chi earthquake were determined in this study. The distribution of the peak ground velocity can be mapped within minutes of post-initiation of a strong earthquake by the rapid reporting system of the Taiwan Central Weather Bureau (Wu et al. 2001). By correlating peak ground velocity with damage rates gathered by the rapid reporting system, a near real-time damage assessment can be issued, in addition to the epicenter, magnitude and intensity.

Key words: Seismic damage rate, Seismic rapid reporting system, Peak ground acceleration, Peak ground velocity.

- **Development of a national earthquake risk assessment model for Taiwan. *Chin-Hsiung Loh, R.Scott Lawson and Weimin Dong.***

Abstract:

This paper summarizes the development of an earthquake risk assessment methodology for Taiwan. This earthquake loss model is the first model of its kind in Taiwan. The frame work of this model includes five basic components: ground shaking/failure, building damage, lifeline damage, economic losses, and social losses. Through this program the implementation of earthquake loss assessment and integrated GIS technology provide emergency planners and government officials with a variety of earthquake scenarios. It

will also facilitate the rapid transfer of information between the academic/research community and the end user.

- **New ground motion data and concepts in seismic hazard analysis. John G. Anderson, James N. Brune, Rasool Anooshehpoor and Shean-Der Ni.** ***1278 Current Science, Vol. 79, No. 9, 10 November 2000.***

  Abstract:

  The strong motion data from the Izmit, Turkey and Chi-Chi, Taiwan earthquakes have pointed out uncertainties in current strong motion attenuation curves for large earthquakes. Although the near-source strong motion data from these two well-recorded large earthquakes were well below the estimated values by the ground motion models, they were consistent with constraints estimated from precarious rock methodology. This discrepancy could be a result of inadequate ground motion data for large earthquakes and possible flaws with a number of statistical parameter assumptions that were necessary for extrapolation from existing database, which is dominated by small earthquake data. This review article discusses several important issues that have the potential to cause major impact on seismic hazard analysis. They are: (i) partitioning of uncertainties into aleatory and epistemic contributions, (ii) quantification of precarious rock observations and use of the data to constrain and improve ground motion models, (iii) continuing to deploy strong motion instruments near major faults since only more strong motion data will definitively resolve the issues of what is normal behaviour, and (iv) understanding through modelling and observations, the physical phenomena that affect strong motion, including the effect of total fault offset, surface rupture and type of faulting.

- **Active faulting and earthquake hazard: The case study of the Chihshang Fault, Taiwan. Jacques Angeliera, Hao-Tsu Chub, Jian-Cheng Leec and Jyr-Ching Huc.** ***Journal of Geodynamics 29 (2000) 151±185.***

  Abstract:

  The Longitudinal Valley Fault Zone of eastern Taiwan is the present-day plate boundary between the Philippine Sea Plate and the South China block of Eurasia. Repeated surveys of active deformation were carried out at ®ve sites along its most active segment, the Chihshang Fault. Annual surveys during the period 1990±1997 reveal a rather constant slip velocity of 2.2 cm/yr in a N408W direction, involving both a thrust component with horizontal shortening of nearly 1.7 cm/yr and a left-lateral component of nearly 1.4 cm/yr. The fault trends N188E and dips 39±458 to the east. The vertical displacement velocity is about 1.3 cm/yr and the actual oblique o€ set of the fault increases at a rate of 2.6 cm/yr. Comparison with GPS data suggests that some additional deformation occurs on the edge of the Valley. Active faulting of the Chihshang Fault and of the entire Longitudinal Valley Fault Zone accounts for 24% and 37% (respectively) of the total shortening across the Taiwan collision in the N548W direction of relative motion between the Philippine Sea Plate and the South China shelf. This distribution of relative displacements illustrates the major role played by this boundary, as a zone of mechanical weakness where tectonic partitioning occurs. Permanent surveying of the displacement on the Chihshang

Fault has the potential to detect signi®cant decrease in slip rates, and hence to predict forthcoming locking stages, which would increase earthquake hazard.

- **Neotectonics and seismic hazard assessment in Hengchun Peninsula, Southern Taiwan. Claudio Vita-Finzi and Jiun-Chuan Lin.** ***C. R. Geoscience 337 (2005) 1194–1199.***

Abstract:

Neotectonic data may indicate whether stored elastic energy will be dissipated or released destructively. The Hengchun Peninsula of Taiwan is the southern extremity of the Central Range of Taiwan and thus an emergent part of the accretionary wedge resulting from subduction of Eurasia beneath the Philippine Sea plate at the Manila Trench. Radiocarbon dating of fossil shorelines on the peninsula shows that it has been uplifted at an average rate of 3.8 mm/yr during the Holocene. About 1/3 of the uplift is due to deformation along the Hengchun reverse fault but, in contrast with the Chelungpu and other low angle reverse faults west of the Central Range, it accommodates strain principally by aseismic creep.

Keywords: Taiwan; Seismicity; Neotectonics; 14C Dating; Geodesy

- **Hanging wall deformation and its effect to buildings and structures a learned from the Chelungpu faulting in the 1999 chi-chi, Taiwan earthquake. C. T. Lee, Keith I. Kelson, and K. H. Kang.** ***International Workshop on Annual Commemoration of Chi-Chi Earthquake September 18-20, 2000, Taipei.***

Abstract:

The 1999 Chi-Chi, Taiwan earthquake provides an excellent opportunity to characterize the ground deformation associated with thrust faulting at the surface, especially the deformation within the near-field hangingwall and its effects on buildings and other structures. The surface faulting along the Chelungpu fault produced by the earthquake extends north-south about 96 km, and has a maximum horizontal slip of about 10 m and a maximum scarp height about 8 m. Ground deformation occurred predominant on the hangingwall, ranged in width from several meters to several tens of meters. In a few cases, the deformation zone was several hundred meters wide, and it was even wider in Tsuolan area. In the deformation zone, there are secondary faults, branch faults, open cracks and/or tilted ground, which damaged existing buildings and structures. Along the length of the Chelungpu fault rupture, hangingwall deformation may be classified into 9 different styles. This includes: (1) Thrusting, (2) Monoclinal folding, (3) Warping, (4) Thrusting and warping, (5) Thrusting and graben formation, (6) Warping and normal faulting, (7) Thrusting and back-kinking, (8) Thrusting and backthrusting, and (9) Thrusting with multiple bending axes. Simple thrusting and monoclinal folding generally represent narrower deformation; whereas more complex zones of deformation tend to be wider. An important lesson from the Chi-Chi earthquake is that the deformation of the near-field hangingwall may be highly destructive. This knowledge was not fully recognized in the previous engineering site selection and design. For a critical facility, like a nuclear

power plant or a high dam, sitting and construction on the hangingwall deformation zone should be avoided.

- **Study on probabilistic seismic hazard maps on Taiwan after Chi-Chi earthquake. Chin-Tung Cheng, Shian-Jin Chiou, Chyi-Tyi Lee, Yi-Ben Tsai. *Journal of GeoEngineering Vol.2, No.1, pp.19-28, April 2007, 19.***

  Abstract:

  Probabilistic seismic hazard maps are widely used for engineering design, land use planning, and disaster mitigation etc. This study conducted a review of readily available information on tectonic setting, geology, and seismicity, and the attenuation of peak ground acceleration (PGA) of Taiwan for completing the revised probabilistic seismic hazard maps by the state-of-the-art probabilistic seismic hazard analysis (PSHA) method. The mainshocks from the earthquake catalog of 1900 to 1999 were used to evaluate the earthquake recurrence rate for regional sources and subduction - intraslab sources from Truncated-Exponential model. The fault-slip rates for estimating the earthquake recurrence rates of faults and subduction interface sources by Characteristic- Earthquake model were adopted. The revised PSHA in this study takes into consideration the fact that subduction plate sources induce higher ground-motion levels than crustal sources, and active faults induce the hanging-wall effect in attenuation relationships. After considering the fault activity and hanging wall effects in our revised PSHA, it was found that the peak ground acceleration (PGA) levels of near-field in Taiwan always exceed 0.4 g in a 475-year return period. This situation is clearly obvious in central Taiwan, the Miaoli - Taichung region, Chyiayi - Tainan region and eastern longitudinal valley.

  Key words: probabilistic seismic hazard, fault, ground motion.

- **Modern Seismic Observations in the Tatun Volcano Region of Northern Taiwan: Seismic/Volcanic Hazard Adjacent to the Taipei Metropolitan Area. Kwang-Hee Kim, Chien-Hsin Chang, Kuo-Fong Ma, Jer-Ming Chiu and Kou-Cheng Chen. *Tao, Vol. 16, No. 3, August 2005.***

  Abstract:

  The Tatun volcano group is located adjacent to the Taipei metropolitan area in northern Taiwan and was a result of episodic volcanisms between 2.8 and 0.2 Ma. Earthquake data collected over the last 30 years are analyzed to explore seismicity patterns and their associated mechanisms of faulting in the area. Using a Joint Hypocenter Determination (JHD) method, a few sequences of relocated earthquake hypocenters are tightly clustered; these seemed to be blurry in the original catalog locations. Numerous earthquakes, previously unnoticed and not reported in the CWB catalog, have been identified from careful examination of the continuous recordings of a nearby broadband seismic station. These newly identified earthquakes show similarities in waveforms and arrival time differences between direct P- and S-waves indicating that their hypocenter locations are very close to each other and their source mechanisms are similar. A relatively high b-value of 1.22 is obtained from the analysis of crustal earthquakes (depth < 30 km) in the region, which may suggest that clustered local seismicity in the Tatun volcanic region probably resulted

from subsurface hydrothermal or volcano-related activities. Focal mechanism solutions determined in this study are dominated by normal faulting. Thus, these earthquake clusters are most probably associated with hydrothermal/magmatic activities in a back-arc extensional environment.

Key words: Seismic/Volcanic Hazard, Tatun Volcano Group, Taipei metropolitan area, Joint Hypocenter Determination, Waveform Similarity, Earthquake Swarm, B-value.

5.3 Iran

5.3.1 Abstracts

- **A comparative seismic hazard study for Azerbaijan Province in Iran. B. Rowshandel, S. Nemat-Nasser and R. B. Corotis.** ***Bulletin of the Seismological Society of America, February 1981, vol. 71, no. 1, 335-362.***

Abstract:

Different seismic source models are used to estimate regional seismic hazard. Commonly used point, line, and area seismic sources are considered in addition to a new method which is obtained by modifying the line source model to take into account the uncertainty associated with the exact location of the line (i.e., fault). The results are presented in terms of cumulative functions of peak ground acceleration for major sites in the Azerbaijan Province of northwest Iran. Iso-acceleration maps for two different return periods are also developed for each seismic source model and a comparison is made among the results of the models. The point source model is shown to be unrealistic when used to model large shocks (Ms > 6.5), which correspond to long ruptures. The model cannot incorporate the fault length, thus ignoring possible spatial migration of seismicity along the fault. In addition, the actual attenuation of ground motion departs considerably from that associated with point source assumption. The conventional line source model, while providing a good representation of vertical strike-slip faults, cannot accurately model the seismicity in other cases, such as reverse faults in general, and thrust (low angle reverse) faults in particular. Epicenters for these latter cases do not lie along a line, as they do in case of vertical strike-slip faults. The area source model is used for those cases where the distribution of earthquake epicenters in a region does not follow any identifiable geological fault pattern. The spatial migration of seismicity along an active fault during a given exposure time is of vital importance in seismic hazard analysis. An analysis based on an area source model corresponds to assuming this migration will be equal in all directions. The theory of plate tectonics, however, suggests an elongated narrow zone corresponding to each fault. A fault line model is developed which exhibits less sensitivity of near-field ground motion to precise fault location than the line source model. This model is referred to as the strip source model. According to this model, the seismicity on a fault is spatially distributed in a long and narrow zone along the margins of the corresponding plates or microplates, and decreases with distance from the fault on either side. It is believed that this kind of modeling closely represents the seismicity corresponding to interplate earthquakes, especially when the type of faulting is thrust. Uncertainties due to the location and orientation of faults will be considerable, particularly for the buried faults, and these uncertainties can be incorporated in the strip source model.

- **Historical and modern seismicity of Pakistan, Afghanistan, northwestern India, and southeastern Iran. R.C. Quittmeyer and K.H. Jacob. *Bulletin of the Seismological Society of America, June 1979, vol. 69, no. 3, 773-823.***

Abstract:

Both historical (noninstrumental) and modern (instrumental) data are compiled and critically reviewed to document the seismicity of Pakistan, Afghanistan, northwestern India, southeastern Iran, and neighboring areas. Earthquakes occurring between 1914 and 1965 are systematically relocated and magnitudes are determined for these events when possible. For some of the larger earthquakes, in both historical and modern times, the orientation and length of the rupture zone, and an approximate value of the seismic moment, are estimated. The usefulness of the documented seismicity to locate the sites of future large earthquakes in this part of the world is limited. The restricted historical record, the occurrence of earthquakes over wide zones (i.e., less confined than at oceanic subduction zones), and the long recurrence intervals combine to make the identification of seismic gaps, with a significant potential for rupture in large earthquakes, a difficult procedure. Seismicity variations prior to the great earthquake in the Makran region alone the southern coast of Pakistan, in 1945, appear to be consistent with patterns identified before large earthquakes else-where in the world. Recent patterns of seismicity farther west along the Makran coast may be consistent with those for a zone in preparation for a large future earthquake; however, this observation is based on a limited amount of data.

- **Incorporation of crustal deformation to seismic hazard analysis. Dimitri Papastamatiou. *Bulletin of the Seismological Society of America, August 1980, vol. 70, no. 4, 1321-1335.***

Abstract:

The incorporation of the crustal deformation to the input parameters of the traditional probabilistic seismic hazard analysis is discussed on the basis of a relationship between the rate of crustal deformation and the seismicity parameters. The formulation is in terms of the seismic moment, which is defined as a function of the crustal deformation at the earthquake source, and a three dimensional representation of seismogenic sources. The relationship between tectonic and seismicity parameters is presented in a graphical form, and its implications are discussed on the hazard of a seismic dislocation at a site on an earthquake fault. This hazard is directly related to the seismic slip part of crustal deformation. The introduction of the crustal deformation to the seismic hazard evaluation reduces the uncertainty associated with the long-term seismic behavior and elucidates the notion of the limiting size of an earthquake. Nevertheless, considerable uncertainty remains pertaining to the long-term stability of the seismic parameters. This uncertainty should be considered in the development of seismic criteria. The use of regional values of crustal deformation and present seismicity data is discussed for the San Andreas Fault in southern California and the Zagros Active Belt in southern Iran. In these determinations, it is necessary to differentiate between seismic slip and creep. This differentiation is particularly difficult in cases like the Zagros where seismic deformation has no direct surface manifestations.

- **Microearthquake survey of Tehran region, Iran. A. Hedayati, J.L. Brander and M. Berberian. *Bulletin of the Seismological Society of America, October 1976, vol. 66, no. 5, 1713-1725.***

  <u>Abstract:</u>

  A short microearthquake survey of part of north central Iran around the city of Tehran made late in 1974, showed that earthquakes occurred at the rate of 21.37 events per day. Epicentral locations for 37 events, using a geometric ray path technique, show the observed activity to be concentrated in three principal groups: two associated with the known major fault on the south flank of the Alborz mountain, while the third constitutes a previously unrecognized lineation passing very close to the city of Tehran. The cumulative number versus magnitude relation was obtained from the study of 198 well-recorded events. The slope of the linear portion of the relation (b value), −0.79, agrees well with the value of −0.86 determined from the USCGS records of larger earthquakes between 1961 and 1973. Composite fault-plane solutions were made for each of the three principal groups, showing predominantly strike-slip movement with a thrust component on the south of the Alborz and thrusting on the new lineation. The seismic intensity risk curve calculated for the area shows that the city of Tehran can expect ground movement of MM intensity VII every 12 years, and intensity IX every 350 years.

- **Patterns of historical earthquake rupture in the Iranian Plateau. Manuel Berberian and Robert S. Yeats. *Bulletin of the Seismological Society of America, February 1999, vol. 89, no. 1, 120-139.***

  <u>Abstract:</u>

  The Iranian plateau accommodates the 35 mm/yr convergence rate between the Eurasian and Arabian plates by strike-slip and reverse faults with relatively low slip rates in a zone 1000 km across. Although these faults have only locally been the subject of paleoseismological studies, a rich historical and archeological record spans several thousand years, long enough to establish recurrence intervals of 1000 to 5000 yr on individual fault segments. Several clusters of earthquakes provide evidence of interaction among reverse and strike-slip faults, probably due to adjacent faults being loaded by individual earthquakes. The Dasht-e-Bayaz sequence of 1936 to 1997 includes earthquakes on left-lateral, right-lateral, and reverse faults. The Neyshabur sequence of four earthquakes between 1209 and 1405 respected the segment boundary between the Neyshabur and Binalud reverse fault systems. The two pairs of earthquakes may have ruptured different faults in each segment, similar to the 1971 and 1994 San Fernando, California, earthquakes. The 1978 Tabas reversefault earthquake was preceded by the 1968 Ferdows earthquake part of the Dasht-e-Baya sequence. The North Tabriz fault system ruptured from southeast to northwest in three earthquakes from 1721 to 1786; a previous cluster may have struck this region in 855 to 958. The Mosha fault north of Tehran ruptured in three earthquakes in 958, 1665, and 1830. Five large earthquakes struck the Tehran region from 743 to 1177, but only two that large have struck the area since 1177. Other earthquakes occurred in pairs in the Talesh Mountains near the Caspian Sea (1863, 1896), the Iran-Turkey border (1840, 1843), and the Nayband-Gowk fault system (both in 1981).

Other historical events did not occur as parts of sequences. The historic seismi moment release in Iran accounts for only a small part of the plate convergence rate, which may be due to aseismic slip or to the Iranian historical record, long as it is, being too short to sample long-term deformation across the plateau. No historic earthquakes of $M \geqq 8$ have struck Iran. However, several long, straight strike-slip faults (Doruneh, West Neh, East Neh, and Nayband) have not sustained large historical earthquakes, raising the possibility that these long faults could produce earthquakes of $M \geqq 8$, thereby removing at least part of the apparent slip deficit. An increased understanding of Iran's seismic hazard could be obtained by an extensive paleoseismology program and space-geodetic arrays, supplementing the abundant historical and archaeological record.

- **Seismic Hazard Assessment of Metropolitan Tehran, Iran. G. Ghodrati Amiri, R. Motamed and H. Rabet Es-Haghi.** ***Journal of earthquake engineering Volume 07, Issue 03, July 2003, 347.***

  Abstract:

  This paper presents a probabilistic seismic hazard assessment of Tehran, the capital of Iran. Two maps have been prepared to indicate the earthquake hazard of Tehran and its vicinity in the form of iso-acceleration contour lines. They display the probabilistic estimate of Peak Ground Acceleration (PGA) over bedrock for the return periods of 475 and 950 years. Tehran is a densely populated metropolitan in which more than 10 million people live. Many destructive earthquakes happened in Iran in the last centuries. It comes from historical references that at least 6 times, Tehran has been destroyed by catastrophic earthquakes. The oldest one happened in the 4th century BC. A collected catalogue, containing both historical and instrumental events and covering the period from the 4th century BC to 1999 is then used. Seismic sources are modelled and recurrence relationship is established. For this purpose the method proposed by Kijko [2000] was employed considering uncertainty in magnitude and incomplete earthquake catalogue. The calculations were performed using the logic tree method and three weighted attenuation relationships; Ramazi [1999], 0.4, Ambraseys and Bommer [1991], 0.35, and Sarma and Srbulov [1996], 0.25. Seismic hazard assessment is then carried out for 12×11 grid points using SEISRISK III. Finally, two seismic hazard maps of the studied area based on Peak Ground Acceleration (PGA) over bedrock for 10% probability of exceedance in two life cycles of 50 and 100 years are presented. The results showed that the PGA ranges from 0.27(g) to 0.46(g) for a return period of 475 years and from 0.33(g) to 0.55(g) for a return period of 950 years. Since population is very dense in Tehran and vulnerability of buildings is high, the risk of future earthquakes will be very significant.

  Keywords: Seismic hazard assessment; historical earthquakes; seismicity parameters; Tehran; Iran.

- **Towards a reliable seismic microzonation in Tehran, Iran. H. Hamzehloo, F. Vaccari and G.F. Panza.** ***Science Direct*** **Elsevier,** ***Engineering Geology, 93 (2007), 1–16.***

Abstract:

A hybrid method for the calculation of realistic synthetic seismograms in laterally heterogeneous, anelastic media has been used to model the ground motion in Tehran city. The synthetic records compare reasonably well with the observed ground motion due to the 2004 Firozabad Kojor earthquake located 60 km north of Tehran. The ratio between the response spectrum for the signals calculated along a laterally varying structure, Sa(2D), and that for the signals at the bedrock regional reference structure, Sa(1D), shows a high amplification of seismic waves in Tehran. The procedure can be readily implemented for the entire Tehran city, which experienced large historical earthquakes in the past, simply by extending the analysis, made so far, in space and to different scenario earthquakes, consistent with the local and regional tectonics.

Keywords: Synthetic seismograms; Ground motion; Tehran.

- **Seismic Hazard Assessment of Gilan Province including Manjil in Iran. G.Ghodrati Amiri1 and S.A. Razavian Amrei.** ***The 14thWorld Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China.***

Abstract:

Manjil is an important city in Gilan province in Iran. It has experienced one of the largest earthquakes in Iran on 21 June 1990 with magnitude of Ms = 7.7 Richter that caused many destructions and human casualties. With respect to historical earthquakes in the region of Gilan province and existing active faults like Manjil-Rudbar and also according to the distribution of earthquakes, this region has high seismic potential. With respect to the mentioned reasons, current study has been performed as seismic hazard analysis of Gilan province with different risk levels. It is needed to provide horizontal Peak Ground Acceleration (PGA) maps with different risk levels for different parts of the region. A category of historical and instrumental seismic data since the 4th century BC up to 2005 has been used and seismic sources in the radius of 200 km of the region have been modeled. In order to assess the seismicity parameters, with respect to the lack of proper seismic data and uncertainty of magnitudes in different times, the Kijko [2000] method has been used. In order to determine the PGA over bedrock three different attenuation relationships of Ramazi [1999], Ambaseys et al. [1996] and also Sarma and Srbulov [1996] relationships have been used. These three relationships have been mixed by using logic tree method with weighted coefficients of 0.4, 0.35 and 0.25 respectively and final results have been produced. The probabilistic hazard analysis of earthquakes has been performed for a 50*50 mesh which covers the region, by SEISRISK III [1987] for occurrence probability of 2% and 10% in 50 years.

Keywords: Seismic Hazard Assessment, Seismicity Parameter, PGA, Gilan, Iran.

- **Seismic Hazard and Seismic Design requirements for the Arabian Peninsula Region. V. Pascucci, M.W. Free and Z.A. Lubkowski.** ***The 14th World Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China.***

Abstract:

This paper presents the results of a regional seismic hazard assessment undertaken for the Arabian Peninsulr region. This area includes a number of major regional tectonic features including the Zagros and Makran regions to the north and east, the Dead Sea and Red Sea to the west and the Gulf of Aden and Owen Fracture Zone to the south and southeast, with the stable continental Arabian Plate in the centre of the region. An earthquake catalogue has been compiled and critically reviewed for this region and seismic source zones and their associated magnitude recurrence parameters defined. Attenuation relationships have been selected based on the tectonic character of the source zones. The uncertainty in each element of the hazard assessment has been included in the assessment using logic tree methodology. The seismic hazard results are presented in the form of peak ground motions and uniform hazard response spectra for selected cities in the region. The paper also discusses how these results compare with design values typically used for seismic design purposes in the region.

Keywords: seismic hazard, ground motion, Arabia, United Arab Emirates.

- **Seismicity patterns associated with the September 10th, 2008 Qeshm earthquake, South Iran. Mohammad Reza Sorbi, Faramarz Nilfouroushan and Ahmad Zamani.** ***Int J Earth Sci (Geol Rundsch) (2012), 101, 2215–2223, Doi: 10.1007/s00531-012-0771-6.***

Abstract:

The b value of the Gutenberg-Richter relation and the standard deviate, Z, were calculated to investigate the temporal and spatial variations in seismicity patterns associated with the September 10th, 2008 (Mw = 6.1) Qeshm earthquake. The temporal variations of b value illustrate a distinct dramatic drop preceding the Qeshm earthquake, and the spatial changes in b value highlight a zone with an abnormally low b value around the epicenter of this event. The cumulative number and Z value as a function of time show a precursory seismic quiescence preceding the 2008 Qeshm earthquake that observed for 1 year in a circle with R = 50 km around its epicenter. The spatial distribution map of the standard deviate, Z, also exhibits an obvious precursory seismic quiescence region before the 2008 Qeshm event around the epicenter of this event. Interestingly, the precursory seismic quiescence region is approximately consistent with low b value anomaly region, and both have E–W to NE–SW trend. These two precursory anomalies took place in relatively large regions, which were possibly relevant to the preparation zone of the 2008 Qeshm event.

Keywords: Seismicity patterns, b value, Z value, Qeshm earthquake, Earthquake precursors.

- **Falling rock hazard index: a case study from the Marun Dam and power plant, south-western Iran. Mehran Koleini and Jan Louis Van Rooy.** ***Springer-Verlag 2010.***

Abstract:

Rock fall phenomena are a major hazard during construction in mountainous regions. At the Marun Dam site, rock falls occur almost every day on the downstream side. The left flank power plant and access roadways as well as the right flank roadways are susceptible to rock falls from the 100 m high cliffs with slopes of 70–90. The cause is a combination of the orientation of the bedding planes and joint sets and the active tectonic setting of thearea. The paper reports the use of RocFall and Dips software to simulate the conditions in order to define the potential risk of rock falls at the Marun Dam site, which could affect workers as well as structures. In the light of the Falling Rock Hazard Index obtained, preventative and remedial measures are suggested.

Keywords: Marun dam, Rock fall hazard, Protection system and Power plant Roadway.

- **Slope stability modelling and landslide hazard zonation at the Seymareh dam and power plant project, west of Iran. Mehran Koleini, Jan Louis Van Rooy and Adam Bumby.** ***Bull Eng Geol Environ (2012), 71, 691–701, Doi: 10.1007/s10064-012-0437-4.***

Abstract:

The Zagros Mountains Range is an important structural unit in south western Iran and accommodates significant portion of the 2.5 cm/year convergence between Arabia and Eurasia. This structural unit includes folds thrusts, strike-slip faults and salt diapirs. There is evidenc of past failures in the area, probably some 11,000 year ago. In the order of 30 million cubic metres of rock debri was moved from the Kabir Kuh Anticline as well as roc failures from the Ravandi Anticline. Investigations indicate 4.5 m of landslide/rock fall debris underlying abou 28 m of lake deposits and 5.5 m of recent river alluviu upstream of the Seymareh Dam area. The direction of th Seymareh River bed was displaced by about 1,000 m to th northeast, forming a sharp river meander near the entranc to the gorge of the Ravandi Anticline where the Seymare Dam is being constructed. The paper reports the rock slop instability modelling, kinematic analysis of slope faces an landslide hazard zoning undertaken.

Keywords: Seymareh dam, Rock slope, Kinematic analysis, Instability modeling, Landslide hazard zonation.

- **Saving lives in earthquakes: successes and failures in seismic protection since 1960. Robin Spence.** ***Bull Earthquake Eng (2007) 5, 139–251, Doi: 10.1007/s10518-006-9028-8.***

Abstract:

This paper will look at what we have and have not achieved in reducing the risk to human life from earthquakes in the last 50 years. It will review how success has been achieved in a few parts of the world, and consider what needs to be done by the scientific and engineering community globally to assist in the future task of bringing earthquake risks under control. The first part of the talk will re-examine what we know about the casualties from

earthquakes in the last 50 years. Almost 80% of about 1million deaths turn out to have been caused by just ten great earthquakes, together affecting a tiny proportion of the territory at risk from heavy ground shaking. The disparity between richer and poorer countries is also evident, not only in fatality rates, but also in their rates of change. But the existing casualty database turns out to be a very poor basis for observing such differences, not only because of the small number of lethal events, but also because of the very limited data on causes of death, types and causes of injury. These have been examined in detail in only a few, recent events. All that can be said with certainty is that a few wealthier earthquake-prone countries or regions have made impressive progress in reducing the risk of death from earthquakes, while most of the rest of the world has achieved comparatively little, and in some areas the problem has become much worse. The second part of the paper looks in more detail at what has been achieved country by country. Based on a new expert-group survey of key individuals involved in earthquake risk mitigation, it will examine what are perceived to be the successes and failures of risk mitigation in each country or group of countries. This survey will be used to highlight the achievements of those countries which have successfully tackled their earthquake risk; it will examine the processes of earthquake risk mitigation, from campaigning to retrofitting, and it will consider to what extent the achievement is the result of affluence, scientific and technical activity, political advocacy, public awareness, or the experience of destructive events. It will ask to what extent the approaches pioneered by the global leaders can be adopted by the rest. The final section of the talk will argue that it can be useful to view earthquake protection activity as a public health matter to be advanced in a manner similar to globally successful disease-controlmeasures: it will be argued that the key components of such programmes—building in protection; harnessing new technology and creating a safety culture—must be the key components of earthquake protection strategies also. It will consider the contribution which the scientific and engineering community can make to bringing down today's unacceptably high global earthquake risk. It will be suggested that this role is wider than commonly understood and needs to include:

Building-in protection:

- Improving and simplifying information available for designers and self-builders of homes and infrastructure.
- Devising and running "building for safety" programmes to support local builders. Harnessing new technologies.
- Developing and testing cost-effective techniques for new construction and retrofit.

Creating a safety culture:

- Involvement in raising public awareness.
- Political advocacy to support new legislation and other actions.
- Prioritising action on public buildings, especially schools and hospitals.

Examples of some of these actions will be given. International collaboration is essential to ensure that the resources and expertise available in the richer countries is shared with those most in need of help. And perhaps the most important single task for the engineering community is to counter the widespread fatalistic attitude that future earthquakes are bound to be at least as destructive as those of the past.

Keywords: Earthquakes, Building damage, Casualties, Mitigation.

- **Multivariate rule-based seismicity map of Iran: a data-driven model. Ahmad Zamani, Ashkan Sami and Marziyeh Khalili.** ***Bull Earthquake Eng (2012) 10, 1667–1683, Doi: 10.1007/s10518-012-9386-3.***

Abstract:

The seismic hazard map or delineation of regions with high earthquake hazard is important to plan risk mitigation strategies. Identifying areas of high seismic hazard can lead city planners to enforce better construction standards and predict areas vulnerable to slope instability. Conventional seismic hazard maps are based on limited factors like ground acceleration, ground velocity, etc. This paper presents a new class of data-driven multivariate rule–based model to create online as well as offline interactive seismic hazard map that is flexible and readily automated. A multivariate rule-based seismicity map (MRBSM) is defined as the map of regions with a future high hazard of earthquakes. The classification and regression tree method is used to extract rules that predict regions with high hazard of earthquakes with mb ≥ 4.5 in Iran. The rules generated for our MRBSM of Iran are based on a large number of geological and geophysical parameters The MRBSM indicates that the province of Bandar Abbas, a major population center in the South of Iran has a high hazard of earthquakes with mb ≥ 4.5. In addition, our method allows identification of the most important parameters associated with earthquakes. Our analysis shows that the isostatic anomaly has the strongest correlation with earthquakes while magnetic intensity, regional Bouger anomaly, Bouger anomaly, and gravity anomaly also correlate well. Despite widespread application of a- and b-values of the Gutenberg-Richter formula, these parameters do not correlate well with earthquake hazards in the area.

Keywords: Data mining, Decision tree, Neotectonics, Seismotectonics, Earthquake hazard prediction, Iran.

- **An empirical spectral ground-motion model for Iran. H. Ghasemi, M. Zare, Y. Fukushima and K. Koketsu.** ***J Seismol (2009) 13:499–515 DOI 10.1007/s10950-008-9143-x.***

Abstract:

A new ground-motion prediction equation for 5%-damped horizontal spectral acceleration applicable to Iran is presented. On the basis of analysis of variance (ANOVA), selected West-Eurasian records are added to an existing dataset of Iranian accelerometric data to yield a ground-motion prediction equation applicable at wider ranges of magnitude and distance. The advantages of using this model rather than those proposed previously for Iran are discussed by considering the distribution of residuals against the explanatory variables, magnitude and distance. The applicability of the proposed model, as well as those of several other models developed for shallow crustal environments, is also investigated by means of statistical tools. The results reveal the overall suitability of the

new model as well as the validity of models developed using mainly Eurasian strong-motion records.

Keywords: Spectral attenuation relation, Seismic hazard analysis and Iran.

- **Pattern recognition of major asperities using local recurrence time in Alborz Mountains, Northern Iran. Khalil Motaghi, Khaled Hessami and Mohammad Tatar.** ***J Seismol (2010) 14:787–802 DOI 10.1007/s10950-010-9201-z.***

<u>Abstract:</u>

In this study, seismic data recorded during the period 01/01/1996 to 09/01/2009 has been used to evaluate the seismic hazard potential along the Alborz region, Northern Iran. The technique of mapping local recurrence time, TL, is used to map major asperities, which are considered as the areas with maximum hazard. We calculated TL from a and b values which are in turn derived from the frequency–magnitude relation constants within a radius of 30 km about every corner point of a 10-km spacing grid. Since b value is inversely related to applied stress, the areas with lowest b values and/or shortest TL are interpreted to locate the asperities or the areas of maximum seismic hazard. To test this method, we computed TL map using seismic catalogues before and after the 2004 Baladeh earthquake of Mw 6.2. The local recurrence time map before the earthquake shows anomalously short TL in the epicentral region of the Baladeh earthquake a decade before its occurrence. The TL map after the earthquake indicates that this large event has redistributed the applied stress in the Alborz region. The microseismicity of the region after the Baladeh earthquake, however, suggests that there are two anomalies in TL map positioned in Alborz. The places where these anomalies are observed can be considered as the areas with maximum seismic hazard for future large earthquake in the Alborz region.

Keywords: b Value, Local recurrence time, Asperity, Alborz Mountains, Microseismicity.

- **Time independent seismic hazard analysis in Alborz and surrounding area. Mohammad Ashtari Jafari.** ***Nat Hazards, (2007), 42, 237–252, Doi: 10.1007/s11069-006-9097-7.***

<u>Abstract:</u>

The Bayesian probability estimation seems to have efficiencies that make it suitable for calculating different parameters of seismicity. Generally this method is able to combine prior information on seismicity while at the same time including statistical uncertainty associated with the estimation of the parameters used to quantify seismicity, in addition to the probabilistic uncertainties associated with the inherent randomness of earthquake occurrence. In this article a time-independent Bayesian approach, which yields the probability that a certain cut-off magnitude will be exceeded at certain time intervals is examined for the region of Alborz, Iran, in order to consider the following consequences for the city of Tehran. This area is located within the Alpine-Himalayan active mountain belt. Many active faults affect the Alborz, most of which are parallel to the range and accommodate the present day oblique convergence across it. Tehran, the capital of Iran, with millions of

inhabitants is located near the foothills of the southern Central Alborz. This region has been affected several times by historical and recent earthquakes that confirm the importance of seismic hazard assessment through it. As the first step in this study an updated earthquake catalog is compiled for the Alborz Then, by assuming a Poisson distribution for the number of earthquakes which occur at a certain time interval, the probabilistic earthquake occurrence is computed by the Bayesian approach. The highest probabilities are found for zone AA and the lowest probabilities for zones KD and CA, meanwhile the overall probability is high.

Keywords: Alborz, Seismicity, Bayesian probability, Seismic hazard, Probability of exceedance.

- **Resource allocation for regional earthquake risk mitigation: a case study of Tehran, Iran. Pantea Vaziri, Rachel A. Davidson, Linda K. Nozick and Mahmood Hosseini.** ***Nat Hazards (2010), 53, 527–546, Doi: 10.1007/s11069-009-9446-4.***

  Abstract:

  This paper presents a new optimization model to help cities in seismically active developing countries decide (1) How much to spend on pre-earthquake mitigation versus waiting until after an event and paying for reconstruction or simply not rebuilding damaged buildings? (2) Which buildings to mitigate and how? and (3) Which buildings to reconstruct and how? It extends previously developed optimization models to consider the particular issues that arise in such countries. First, the model allows for the possibility that some damaged buildings will not be reconstructed immediately and keeps track of any lost building inventory. Second, buildings can be mitigated to, or when damaged, reconstructed to, any appropriate structural type and seismic design level. Finally, the model objectives include minimizing the chance of an extremely high death toll in any one earthquake and minimizing the average annual death toll across earthquakes. The model is illustrated through a case study analysis for Tehran, Iran.

  Keywords Earthquake, Mitigation, Resource allocation, Developing country, Optimization.

- **A probabilistic tsunami hazard assessment for the Makran subduction zone at the north western Indian Ocean. Mohammad Heidarzadeh and Andrzej Kijko.** ***Nat Hazards (2011), 56, 577–593 DOI 10.1007/s11069-010-9574-x.***

  Abstract:

  A probabilistic tsunami hazard assessment is performed for the Makran subduction zone (MSZ) at the northwestern Indian Ocean employing a combination of probability evaluation of offshore earthquake occurrence and numerical modeling of resulting tsunamis. In our method, we extend the Kijko and Sellevoll's (1992) probabilistic analysis from earthquakes to tsunamis. The results suggest that the southern coasts of Iran and Pakistan, as well as Muscat, Oman are the most vulnerable areas among those studied. The probability of having tsunami waves exceeding 5 m over a 50-year period in these coasts is estimated as 17.5%. For moderate tsunamis, this probability is estimated as high as 45%. We recommend the application of this method as a fresh approach for doing probabilistic hazard assessment for tsunamis. Finally, we emphasize that given the lack of sufficient information on the mechanism of large earthquake generation in the MSZ, and inadequate data on Makran's paleo and historical earthquakes, this study can be regarded as the first generation of PTHA for this region and more studies should be done in the future.

Keywords: Probabilistic tsunami hazard assessment (PTHA), Seismic hazard analysis, Numerical modeling, Makran subduction zone (MSZ), Indian Ocean.

- **Experimental vulnerability curves for the residential buildings of Iran. Babak Omidvar, Behrouz Gatmiri and Sahar Derakhshan.** ***Nat Hazards (2012) 60:345–365 DOI 10.1007/s11069-011-0019-y.***

Abstract:

Iran is one of the most seismically active countries of the world located on the Alpine-Himalayan earthquake belt. More than 180,000 people were killed due to earthquakes in Iran during the last five decades. Considering the fact that most Iranians live in masonry and non-engineered houses, having a comprehensive program for decreasing the vulnerability of society holds considerable importance. For this reason, loss estimation should be done before an earthquake strikes to prepare proper information for designing and selection of emergency plans and the retrofitting strategies prior to occurrence of earthquake. The loss estimation process consists of two principal steps of hazard analysis and vulnerability assessment. After identifying the earthquake hazard, the first step is to evaluate the vulnerability of residential buildings and lifelines and also the social and economic impacts of the earthquake scenarios. Among these, residential buildings have specific importance, because their destruction will disturb the daily life and result in casualties. Consequently, the vulnerability assessment of the buildings in Iran is important to identify the weak points in the built environment structure. The aim of this research is to prepare vulnerability curves for the residential buildings of Iran to provide a proper base for estimating probable damage features by future earthquakes. The estimation may contribute fundamentally for better seismic performance of Iranian societies. After a brief review of the vulnerability assessment methods in Iran and other countries, through the use of the European Macroseismic method, a model for evaluating the vulnerability of the Iranian buildings is proposed. This method allows the vulnerability assessment for numerous sets of buildings by defining the vulnerability curves for each building type based on the damage observations of previous earthquakes. For defining the vulnerability curves, a building typology classification is presented in this article, which is representative of Iranian building characteristics. The hazard is described in terms of the macroseismic intensity and the EMS-98 damage grades have been considered for classifying the physical damage to the buildings. The calculated vulnerability indexes and vulnerability curves show that for engineered houses there is not any notable difference between the vulnerability of Iranian and Risk-UE building types. For the non-engineered houses, the vulnerability index of brick and steel structures is less than the corresponding values of the other unreinforced masonry buildings of Iran. The vulnerability index of unreinforced and masonry buildings of Iran are larger than the values of the similar types in Risk-UE and so the Iranian buildings are more vulnerable in this regard.

Keywords: Vulnerability assessment, Residential buildings, Iranian building typology, Seismic risk analysis.

- **Ground motion studies for microzonation in Iran. Ali Shafiee, Mohsen Kamalian, Mohammad Kazem Jafari and Hossein Hamzehloo.** ***Nat Hazards (2011), 59,481–505, Doi: 10.1007/s11069-011-9772-1.***

Abstract:

An important step in effectively reducing seismic risk and the vulnerability of a city located in an earthquake prone area is to conduct a ground motion microzonation study for the desired return period. The International Institute of Earthquake Engineering and Seismology (IIEES) initiated a number of seismic microzonation projects for Iran. This paper presents the steps followed by IIEES in ground motion microzonation. IIEES performs both probabilistic and deterministic seismic hazard analysis. IIEES uses his own fault map for seismotectonic studies and develops modulus and damping curves for the soils in the study area. The experience of ground motion microzonation shows that in almost all cases, the estimated 475-year peak ground acceleration (PGA) values are higher than the PGA proposed by the Iranian seismic code. Although ground motion microzonation in Iran has some shortcomings, IIEES is making new improvement. This includes development in deterministic seismic hazard analysis, two-dimensional and threedimensional modelling of basin and topographical effects, using microtremor measurements to find shear-wave velocity profiles in high-density urban areas and providing maps for spectral acceleration in the study area.

Keywords: Microzonation, Seismic hazard analysis, Site response analysis, Peak ground acceleration.

- **A new empirical estimator of coseismic landslide displacement for Zagros Mountain region (Iran). Ali M. Rajabi, Mohammad R. Mahdavifar, M. Khamehchiyan and V. Del Gaudio.** ***Nat Hazards (2011), 59, 1189–1203, Doi: 10.1007/s11069-011-9829-1.***

Abstract:

Earthquake-induced landslides are responsible worldwide for significant socioeconomic losses and historically have a prominent position in the list of natural hazards affecting the Iran plateau. As a step toward the development of tools for the assessment and the management of this kind of hazard at regional scale, an empirical estimator of coseismic displacements along potential sliding surfaces was obtained through a regression analysis for the Zagros region, a mountainous Iranian region subjected to earthquake-induced landslides. This estimator, based on the Newmark's model, allows to evaluate the expected permanent displacement (named ''Newmark displacement'') induced by seismic shaking of defined energy on potential sliding surface characterized by a given critical acceleration. To produce regression models for Newmark displacement estimators, a data set was constructed for different critical acceleration values on the basis of 108 accelerometric recordings from 80 Iranian earthquakes with moment magnitudes between 3.6 and 7. The empirical estimator has a general form, proposed by Jibson (Eng Geol

91:209–218, 2007), relating Newmark displacement to Arias intensity (as parameter representing the energy of the seismic forces) and to critical acceleration (as parameter representing the dynamic shear resistance of the sliding mass). As an example of application, this relation was employed to provide a basic document for earthquake-induced landslide hazard assessment at regional scale, according to a method proposed by Del Gaudio et al. (Bull Seismol Soc Am 93:557–569, 2003), applied to the whole Iranian territory, including Zagros region. This method consists in evaluating the shear resistance required to slopes to limit the occurrence of seismically induced failures, on the basis of the Newmark's model. The obtained results show that the exposure to landslide seismic induction is maximum in the Alborz Mountains region, where critical accelerations up to ~0.1 g are required to limit the probability of seismic triggering of coherent type landslides within 10% in 50 years.

Keywords: Newmark displacement, Zagros, Iran, Earthquake-induced landslides, Critical acceleration, Arias intensity.

- **A survey of challenges in reducing the impact of geological hazards associated with earthquakes in Iran. Kambod Amini Hosseini and Mohammad Reza Ghayamghamian.** ***Nat Hazards (2012), 62, 901–926, Doi: 10.1007/s11069-012-0123-7.***

Abstract:

Most of the recent earthquakes in Iran were associated with some types of geological hazards that were the cause of additional damage and casualties in the earthquake- affected areas. In order to reduce the impacts of geo-hazards, several policies and plans were prepared, approved, and implemented by the Iranian government during the last two decades. However, such activities have not yet resulted in risk reduction to an acceptable level; since they are not formulated based on local conditions and are not linked to location-specific comprehensive plans. In this paper, after introducing some of the impacts of geo-hazards associated with recent earthquakes in Iran, the country trends in development of relevant risk reduction plans and policies are introduced, evaluated, and compared with some other countries having similar challenges. Strategies toward risk mitigation in the country are addressed, and a number of indices for the assessment of the geo-hazard risk reduction plans and activities are introduced. Finally, a conceptual model for the evaluation of the preparedness level against geo-hazards is proposed and discussed.

Keywords: Earthquake, Landslide, Rockfall, Liquefaction, Subsidence, Risk mitigation plans.

- **Seismic hazard assessment of the city of Hamedan and its vicinity, west of Iran. Mohammad Hossein Ghobadi and Davood Fereidooni.** ***Nat Hazards (2012), 63, 1025–1038 Doi: 10.1007/s11069-012-0203-8.***

Abstract:

This article presents the results of deterministic and probabilistic seismic hazard analyses (DSHA and PSHA) of the city of Hamedan and its neighboring regions. This historical city is one of the developing cities located in the west of Iran. For this reason, the DSHA and PSHA approaches have been used for the assessment of seismic hazards and earthquake risk evaluation. To this purpose, analyses have been carried out considering the historic and instrumented earthquakes, geologic and seismotectonic parameters of the region covering a radius of 100 km, keeping Hamedan as the center. Therefore, in this research, we studied the main faults and fault zones in the study area and calculated the length and distance of faults from the center of Hamedan. In the next step, we measured the maximum credible earthquake (MCE) and peak ground acceleration (PGA) using both DSHA and PSHA approaches and utilized the various equations introduced by different researchers for this purpose. The results of DSHA approach show that the MCE-evaluated value is 7.2 Richter, which might be created by Nahavand fault activities in this region. The PGA value of 0.56 g will be obtained from Keshin fault. The results of PSHA approach show that the MCE-evaluated value is 7.6 Richter for a 0.64 probability in a 50-year period. The PGA value of 0.45 g will be obtained from Keshin fault. Seismic hazard parameters have been evaluated considering the available earthquake data using Gutenberg–Richter relationship method. The ‘a’ and ‘b’ parameters were estimated 5.53 and 0.68, respectively.

Keywords: Hamedan, Fault, Earthquake, DSHA, PSHA.

- **An effective procedure for seismic hazard analysis including nonlinear soil response. Saman Yaghmaei-Sabegh and Roya Motallebzade.** ***Nat Hazards, (2012), 64, 1731–1752 Doi: 10.1007/s11069-012-0332-0.***

Abstract:

This paper presents probabilistic seismic hazard analysis (PSHA) of Tehran, Iran, accounting the effect of nonlinear soil response. It is well-known that soil nonlinearity and its accurate prediction could play important role in seismic hazard study. For this purpose, two different approaches have been carried out for predicting the hazard curves by (1) applying site modifications to the ground motion prediction equation based on generic site classes and use of constant coefficients (2) using a close-form solution that modifies the hazard results at the rock level. Also, efficiency of the Monte Carlo method in modeling of amplification function for the six selected sites in the study area was examined. Results showed important effect of nonlinear soil response mainly for frequencies lower than 8 Hz, which should be considered properly in hazard estimation. As an interesting subject, influence of soil plasticity index (PI) on hazard estimation of clayey sites including the nonlinear soil response was evaluated.

Keywords: Probabilistic seismic hazard analysis, Soil nonlinearity, Surface response Spectra, Amplification function, Hazard estimation, Tehran

- **A uniform catalog of earthquakes for seismic hazard assessment in Iran. Noorbakhsh Mirzaei, Meng-Tan Gaoo, Yun-Tai Chen and Xjian Wangi.** ***Acta Seismologica Sinica, Nov.1997, Vol. 10, No. 6 (713~726).***

Abstract:

The assessment of seismicity is strongly dependent on the recorded events as data base. A uniform catalog of earthquakes in Iran and neighbouring regions is provided to use for seismic hazard assessment of the country. Since the recurrence time of maximum credible earthquake can not be estimated directly from mb, empirical relationships for different seismotectonic provinces arc established to convert mb to Ms, which is a suitable magnitude scale for our purpose. It emerges from completeness study of the catalog that many small and moderate earthquakes are missed out, specially in the historical and early instrumental time-periods.

Key words: seismicity, uniform catalog, seismic hazard, empirical relationships, completeness.

- **Delineation of potential seismic sources for seismic zoning of Iran. Noorbakhsh Mirzaei, Mengtan Gao1 & Yun-tai Chen.** ***Journal of Seismology, 3, 17–30, 1999.***

  Abstract:

  A total of 235 potential seismic sources in Iran and neighboring regions are delineated based on available geological, geophysical, tectonic and earthquake data for seismic hazard assessment of the country. In practice, two key assumptions are considered; first, the assumption of earthquake repeatedness, implying that major earthquakes occur preferentially near the sites of previous earthquakes; second, the assumption of tectonic analogy, which implies that structures of analogous tectonic setting are capable of generating same size earthquakes. A two-step procedure is applied for delineation of seismic sources: first, demarcation of seismotectonic provinces; second, determination of potential seismic sources. Preferentially, potential seismic sources are modeled as area sources, in which the configuration of each source zone is controlled, mainly, by the extent of active faults, the mechanism of earthquake faultings and the seismogenic part of the crust.

  Key words: potential seismic source, seismic hazard assessment, seismogenic zone, seismotectonic province, tectonic analogy.

- **Sensitivity of seismic hazard evaluations to uncertainties determined from seismic source characterization. Behrooz Tavakoli.** ***Journal of Seismology, 6, 525–545, 2002.***

  Abstract:

  The sensitivity and overall uncertainty in peak ground acceleration (PGA) estimates have been calculated for the city of Tabriz, northwestern Iran by using a specific randomized blocks design. Eight seismic hazard models and parameters with randomly selected uncertainties at two levels have been considered and then a linear model between predicted PGA at a given probability level and the uncertainties has been performed. The input models and parameters are those related to the attenuation, magnitude rupture-length and recurrence relationships with their uncertainties. Application of this procedure to the studied area indicates that effects of the simultaneous variation of all eight input models and parameters on the sensitivity of the seismic hazard can be investigated with a decreasing number of computations for all possible combinations at a fixed annual probability. The results show that the choice of a mathematical model of the source mechanism, attenuation relationships and the definition of seismic parameters are most critical in estimating the sensitivity of seismic hazard evaluation, in particular at low levels of probability of exceedance. The overall uncertainty in the expected PGA for an annual probability of 0.0021 (10% exceedence in 50 yr) is expressed by a coefficient of variation (CV) of about 34% at 68% confidence level for a distance of about 5km from the field of the major faults. The CV will decrease with increasing site-source distance and remains constant, CV = 15%, for distances larger than 15 km. Finally, treating alternative models on the overall uncertainty are investigated by additional outliers in input decision.

Key words: North Tabriz Fault, northwestern Iran, Poisson model, randomized blocks design, renewal model, Sensitivity, seismic hazard, uncertainty.

- **Scenarios of Seismic Risk in the United Arab Emirates, an Approximate Estimate. Max Wyss and Azm S. Al-Homoud.** ***Natural Hazards 32, 375–393, 2004.***

Abstract:

We estimate the losses due to 10 scenario earthquakes in 150 settlements of the United Arab Emirates (UAE). For southern Iran, we use four source zones and the maximum magnitudes in them as determined by GSHAP ($7.2 \leq M \leq 8.1$). For six local scenario earthquakes, we use the range $5.5 \leq M \leq 6.5$, place the sources mainly on mapped faults and vary the distance to major cities from 10 to 60 km. In the test case of the Masafi earthquake (M5, 11 March 2002), the method and data bank we use yield the correct results, suggesting that our approach to the problem is valid for the UAE. The sources in Iran are expected to cause only minor damage, except for an M8.1 earthquake in theMakran region. For such an event we expect some deaths, several hundred injured and a loss of 3– 6% of the value to the building stock in the northeastern UAE, including Oman. The losses for local scenarios with epicenters in the unpopulated areas of the UAE and for scenarios with $M < 5.8$ are estimated to be minor. Because the two major mapped faults run through several of the large cities, scenarios with short epicentral distances from cities have to be considered. Scenarios with M6 near cities lead to estimates of about 1000 ± 500 deaths, and several thousand injured. Most buildings are expected to be damaged to a moderate degree and the loss to buildings is estimated around 1/4 of their value. If the magnitude should reach 6.5, the losses to humans and to building value could be staggering. These estimates are approximate because: (1) there exists no local seismograph network that could map active faults by locating microseismicity; (2) there exist no historically old buildings that could serve as tests for effects due to strong ground motion in the past; (3) there exist no microzonation of the subsurface properties in this region of unconsolidated building ground; (4) there exists no detailed inventory of building fragility. Nevertheless, our conclusion that there exists a substantial seismic risk in the UAE is reliable, because our method yields accurate results in the cases of earthquakes with known losses during the last several decades in the Middle East.

- **Earthquake Hazard Zonation of Eastern Arabia. Jamal A. Abdalla and Azm Al-Homoud.** ***13th World Conference on Earthquake Engineering Vancouver, B.C., Canada, August 1-6, 2004, Paper No. 1008.***

Abstract:

This paper presents seismic hazard assessment and seismic zoning of United Arab Emirates and its vicinity based on the probabilistic approach. The studied area lies between 50°E - 60°E and 20°N - 30°N and spans several Gulf countries. First, the geology and tectonics of the area and its surroundings is reviewed. An updated catalogue, containing both historical and instrumental events, is used. Seismic source regions are modeled and relationships between earthquake magnitude and earthquake frequency is established. An attenuation relation for Zagros is used. Seismic hazard assessment was carried out for 25 km interval grid points. Seismic hazard maps of the studied area based on probable Peak Ground Acceleration (PGA) for 10% probability of exceedance for time-spans of 50 and 100 years is shown. Peak ground acceleration for selected cities and seismic zone map for a 475-year return period are shown.

- **Preliminary Seismic Microzonation of Bam. F. Askari, A. Azadi, M. Davoodi, M.R. Ghayamghamian, E. Haghshenas, H. Hamzehloo, M.K. Jafari, M. Kamalian, M. Keshavarz, O. Ravanfar, A. Shafiee, and A. Sohrabi-Bidar.** ***JSEE: Special Issue on Bam Earthquake.***

Abstract:

After the devastating earthquake of 26 December 2003 in Bam, a discipline was followed to prepare a preliminary site effect microzonation map for the city. Seismic hazard studies for two return periods, geological studies accompanied by geophysical surveys and aftershock and microtremor measurements were carried out to provide site classification and PGA distribution maps. The results of this study show tha reasonable agreements exist between the 2475 years PGA distribution map and the damage distribution map for the recent earthquake. The 475 years PGA Microzonation maps could also be used as a preliminary useful hint in reconstruction and urban planning of the totally destroyed city.

Keywords: Bam; Seismic Microzonation; Site effect; Micro tremor; Shear wave velocity; Peak ground acceleration; Urban planning.

- **Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s. David M. Boore and Gail M. Atkinson, M.EERI.** ***Doi: 10.1193/1.283043.***

Abstract:

This paper contains ground-motion prediction equations (GMPEs) for average horizontal-component ground motions as a function of earthquake magnitude, distance from source to site, local average shear-wave velocity, and fault type. Our equations are for peak ground acceleration (PGA), peak ground velocity (PGV), and 5%-damped pseudo-absolute-acceleration spectra (PSA) at periods between 0.01 s and 10 s. They were derived by empirical regression of an extensive strong-motion database compiled by the "PEER NGA" (Pacific Earthquake Engineering Research Center's Next Generation At-

tenuation) project. For periods less than 1 s, the analysis used 1,574 records from 58 mainshocks in the distance range from 0 km to 400 km (the number of available data decreased as period increased). The primary predictor variables are moment magnitude (M), closest horizontal distance to the surface projection of the fault plane RJB, and the time-averaged shear-wave velocity from the surface to 30 m VS30. The equations are applicable for M=5–8, RJB200 km, and VS30=180–1300 m/ s.

- **Active faulting and natural hazards in Armenia, eastern Turkey and Northwestern Iran. Arkady S. Karakhaniana, Vladimir G. Trifonovb, Herve Philipc, Ara Avagyana, Khaled Hessamid, Farshad Jamalie, M. Salih Bayraktutanf, H. Bagdassariana, S. Arakeliana, V. Davtiana, A. Adilkhanyana. *Tectonophysics, 380 (2004), 189– 219.***

Abstract:

Active fault zones of Armenia, SE Turkey and NW Iran present a diverse set of interrelated natural hazards. Three regional case studies in this cross-border zone are examined to show how earthquakes interact with other hazards to increase the risk of natural disaster. In northern Armenia, a combination of several natural and man-made phenomena (earthquakes, landslides and unstable dams with toxic wastes) along the Pambak-Sevan-Sunik fault (PSSF) zone lowers from 0.4 to 0.2–0.3g the maximum permissible level (MPL) of seismic hazard that may induce disastrous destruction and loss of life in the adjacent Vanadzor depression. In the Ararat depression, a large active fault-bounded pull-apart basin at the junction of borders of Armenia, Turkey, Iran and Azerbaijan, an earthquake in 1840 was accompanied by an eruption of Ararat Volcano, lahars, landslides, floods, soil subsidence and liquefaction. The case study demonstrates that natural hazards that are secondary with respect to earthquakes may considerably increase the damage and the casualties and increase the risk associated with the seismic impact. The North Tabriz–Gailatu fault system poses a high seismic hazard to the border areas of NW Iran, eastern Turkey, Nakhichevan (Azerbaijan) and southern Armenia. Right-lateral strike–slip motions along the North Tabriz fault have given rise to strong earthquakes, which threaten the city of Tabriz with its population of 1.2 million. The examples illustrate how the concentration of natural hazards in active fault zones increases the risk associated with strong earthquakes in Armenia, eastern Turkey and NW Iran. This generally occurs across the junctions of international borders. Hence, the transboundary character of active faults requires transboundary cooperation in the study and mitigation of the natural risk.

Keywords: Active faults; Earthquakes; Paleoseismicity; Holocene volcanism; Landslides.

- **A geologic contribution to the evaluation of the seismic potential of the Kahrizak fault (Tehran, Iran). P.M. De Martini, K. Hessami, D. Pantosti, G. D'Addezio, H. Alinaghi, M. Ghafory-Ashtiani. *Tectonophysics, 287 (1998), 187- I99.***

Abstract:

In this paper we present the results of preliminary geomorphic and trenching investigations along the Kahrizak fault. This fault is located south of the highly populated metropolis of Tehran and represents one of the main structures in the area containing important

seismic potential. The Kahrizak fault has a very clear expression at the surface where it forms a prominent 35-km-long, 15-m-high scarp on Holocene alluvial deposits. The fault strikes N70”-80”W and dips to the north. Movement is prevalently right-lateral with the northern side of the fault up. Trench excavations exposed a sequence of weathered, massive, alluvial deposits which are dated, by means of radiometric methods, to the Holocene. In the trenches the sequence is intensely deformed by north-dipping, high- and low-angle faults within a 30-m-wide zone. On the basis of stratigraphic and structural relations, some evidence for individual Holocene earthquakes is found; however, we were not able to reconstruct the seismic history of the fault nor to evaluate the size of deformation produced by each event. Because of the possible -10 m offset of ancient linear hydraulic artifacts, that cross the fault, we hypothesize that the most recent event may have occurred in historical times (more recent than 5000 yr B.P.) and it may be one of those reported in this area by the current catalogues of seismicity. Based on these preliminary investigations we estimate an elapsed time between 5000 and 800 years, a maximum slip per event d,,,, of -10 m, a minimum Holocene vertical slip rate of –I mm/yr versus a horizontal slip rate of -3.5 mm/yr, a maximum of -3000 years for the average recurrence time, and an expected M, = 7.0 to 7.4. These can be considered as a first-hand reference for the activity on this fault.

Keywords: Iran; paleoseismology; geomorphology; seismic hazard assessment.

- **Shear-wave velocity characteristics of geological units throughout Tehran City, Iran. A. Shafiee and A. Azadi.** ***Journal of Asian Earth Sciences xxx (2006) xxx–xxx.***

Abstract:

One simple way of accounting for site conditions in calculating seismic hazards is to use the shear-wave velocity (Vs) in the shallow subsurface to classify materials. We used the average shear-wave velocity to a depth of 30 m ðV sð30ÞÞ to develop site categories for Tehran. This parameter can further be used for modifying a calculated ground motion to account for site conditions. The National Earthquake Hazard Reduction Program (NEHRP) classification was used to group sites into different classes. Our classification was based on V sð30Þ values measured in 188 seismic profiles and on the assumption of similar values for similar geological materials. For each geological unit, characteristics of shear-wave velocity distribution including histograms of shear-wave velocity and variation of Vs versus depth were calculated and shown. This study reveals that the V sð30Þ of the mountainous zones fall into categories A and B of NEHRP site classification. But, in the Tehran Plain, the northern alluvium tends to have V sð30Þ values which fall into range of category C of the NEHRP site classification, whereas, those in the southern alluvium would be categorized as NEHRP D.

Keywords: Tehran; Geological units; Shear-wave velocity; NEHRP classification.

- **Region-Specific Key Seismic Parameters for Earthquakes in Northern Iran by Dariush Motazedian.** ***Bulletin of the Seismological Society of America, Vol. 96, No. 4A, pp. 1383–1395, August 2006, Doi: 10.1785/0120050162.***

Abstract:

Strong-motion accelerograms recorded within northern Iran are used to examine the propagation characteristics of shear wave, including geometric spreading behavior, Q-value, j0, and horizontal-to-vertical (H/V) ratio. These region-specific key seismic parameters are estimated from 259 three-component records of 22 earthquakes with magnitude ranging from M 4.9 toM7.4 in northern Iran. The geometric spreading follows a trilinear behavior with a strong postcritical reflection from the Moho. The first and second hinges of the trilinear behavior are at 75 and 150 km, respectively. The associated Q-value, based on the vertical component is Q 87 f 1.46. j0 value for vertical and horizontal components are 0.03 and 0.05, respectively. Because of lack of station-specific site information, the H/V ratio is considered to be a rough estimation of generic site amplification. The obtained region-specific parameters are used to estimate the average stress drop based on three stochastic modeling approaches. Stochastic point-source modeling suggests a Brune stress drop of 125 bars, whereas stochastic finite-fault modeling based on static and dynamic corner frequency approaches suggests a stress drop of 68 bars.

- **Use of Remote Sensing Data and GIS Tools for Seismic Hazard Assessment for Shallow Oilfields and its Impact on the Settlements at Masjed-i-Soleiman Area, Zagros Mountains, Iran. Hojjat Ollah Safari, Saied Pirasteh, Biswajeet Pradhan and Ladan Khedri Gharibvand.** ***Remote Sensing, ISSN 2072-4292 2010, 2, 1364-1377; doi:10.3390/rs2051364.***

Abstract:

Masjed-i-Soleiman (MIS) is situated in the northern part of the Dezful embayment, which is in the Zagros fold–thrust belt with high seismic activities. MIS faces a shallow buried anticline, formed by the shallowest oilfield with a thick gas cap. The cap rocks of this oilfield are highly fractured, which has resulted in leakages from the gas cap. In this paper, we have used remote sensing techniques and image interpretation for the identification of the Niayesh, Lahbari, Andika and MIS fault zones in the studied area. Further, the study exploited seismic potential mapping using the remote sensing techniques. The relationships between the structural controls and localized gas leakage are assessed within the GIS environment. Additionally, field observation data corroborated that the leakages (and seepages) are smashed within the intersection of Niayesh and MIS fault zone, which belongs to the high fractured hinge zone of the MIS anticline. As a result, the reactivation of these active faults may cause large earthquakes with a maximum magnitude of between 6.23 < Ms < 7.05 (Richter scale) and maximum horizontal acceleration 0.26 < a < 0.55 g. Finally, the authors concluded that this anticipated earthquake may cause large scale fracturing of cap rocks, releasing a large volume of H_2S gas from the uppermost layer of the reservoir.

Keywords: seismic hazard assessment; remote sensing; GIS; Zagros Mountain.

- **Determining the long-term slip rate along the Mosha Fault, Central Alborz, Iran. Implications in terms of seismic activity. J-F. Ritz1, S. Balescu, S. Soleymani, M. Abbassi, H. Nazari, K. Feghhi, E. Shabanian, H. Tabassi, Y. Farbod and M. Lamothe, J-L.** ***Fourth International Conference of Earthquake Engineering and Seismology, 12-14, May 2003, Tehran, Islamic Republic of Iran.***

  Abstract:

  The Mosha fault is one of the major active fault in Central Alborz as shown by its strong historical seismicity and its obvious morphological signature. Situated at the vicinity of Tehran city, this ~150 km long ~N100°E trending fault represents an important potential seismic source that threatens the Iranian metropolis. In the framework of an Iranian-French joint research program devoted to seismic hazard assessment in the Tehran region, we undertook a morphotectonic (determination of the cumulative displacements and the ages of offset morphologic markers) and paleoseismic (determination of the ages and magnitudes of ancient events) study along the Mosha fault. Our objectives are the estimation of the long-term slip rate (Upper Pleistocene-Holocene) and the mean recurrence interval of earthquakes along the different segments of the fault. Our investigations within the Tar Lake valley, along the eastern part of the fault – potentially the site of the 1665 (VII, 6.5) historical earthquake - allows us to calculate a preliminary 2 ± 0.1 mm/yr minimum left lateral slip rate. If we assume a characteristic coseismic average displacement comprised between 0.35 m (Mw 6.5) and 1.2 m (Mw 7.1) – calculated from Wells & Coppersmith's functions (1994) and taking the moment magnitudes attributed to the 1665 and 1830 earthquakes (e.g. Berberian & Yeats, 2001) – the mean maximum recurrence intervals along this segment of the Mosha fault are comprised between 160 and 620 yrs.

- **Scenarios of Seismic Risk in the United Arab Emirates, an Approximate Estimate. Max Wyss and Azm S. Al-Homoud.** ***Natural Hazards 32, 375–393, 2004.***

  Abstract:

  We estimate the losses due to 10 scenario earthquakes in 150 settlements of the United Arab Emirates (UAE). For southern Iran, we use four source zones and the maximum magnitudes in them as determined by GSHAP ($7.2 \leq M \leq 8.1$). For six local scenario earthquakes, we use the range $5.5 \leq M \leq 6.5$, place the sources mainly on mapped faults and vary the distance to major cities from 10 to 60 km. In the test case of the Masafi earthquake (M5, 11 March 2002), the method and data bank we use yield the correct results, suggesting that our approach to the problem is valid for the UAE. The sources in Iran are expected to cause only minor damage, except for an M8.1 earthquake in the Makran region. For such an event we expect some deaths, several hundred injured and a loss of 3– 6% of the value to the building stock in the northeastern UAE, including Oman. The losses for local scenarios with epicenters in the unpopulated areas of the UAE and for scenarios with $M < 5.8$ are estimated to be minor. Because the two major mapped faults run through several of the large cities, scenarios with short epicentral distances from cities have to be considered. Scenarios with M6 near cities lead to estimates of about 1000 ± 500 deaths, and several thousand injured. Most buildings are expected to be damaged to a moderate degree and the loss to buildings is estimated around 1/4 of their value. If the magnitude should reach 6.5, the losses to humans and to building value

could be staggering. These estimates are approximate because: (1) there exists no local seismograph network that could map active faults by locating microseismicity; (2) there exist no historically old buildings that could serve as tests for effects due to strong ground motion in the past; (3) there exist no microzonation of the subsurface properties in this region of unconsolidated building ground; (4) there exists no detailed inventory of building fragility. Nevertheless, our conclusion that there exists a substantial seismic risk in the UAE is reliable, because our method yields accurate results in the cases of earthquakes with known losses during the last several decades in the Middle East.

5.4 Japan

5.4.1 Abstracts

- **A hybrid recurrence model and its implication on seismic hazard results. Shen-Chyun Wu, C. Allin Cornell and Steven R. Winterstein.** ***Bulletin of the Seismological Society of America, February 1995, vol. 85, no. 11-16.***

Abstract:

To account for the effects of the characteristic earthquakes on an individual fault (segment), a renewal hybrid model is proposed for seismic hazard analysis and studied in depth. This model incorporates a renewal-time, characteristic-magnitude model for larger earthquakes with the conventional exponential-time, exponential-magnitude model for smaller earthquakes. Properties of important temporal and magnitude parameters are studied. The exact and the approximate ("first-event") hazards estimated by this model are discussed. The approximate results are found sufficiently accurate for most engineering applications. These approximations can be obtained by making minor modifications to existing hazard analysis programs designed for traditional Poisson models. Hazard estimates of this model and other more complicated hybrid models, e.g., time- and slip-predictable models, are compared. For reasonable parameter values, the characteristic events are found to be the major contributor to seismic hazards in most cases, unless the source-site distance is very small. This effect is even stronger with a large elapsed time in a nonmemoryless interarrival time distribution. Based on previous findings of small values of the coefficients of variation in time and low correlations between the interarrival times and magnitudes among characteristic earthquakes, the proposed renewal hybrid model will produce hazard estimates close to those of more complicated non-Poissonian models.

- **A New Attenuation Relation for Strong Ground Motion in Japan Based on Recorded Data. Tatsuo Kanno, Akira Narita and Nobuyuki Morikawa, Hiroyuki Fujiwara and Yoshimitsu Fukushima.** ***Bulletin of the Seismological Society of America, June 2006, vol. 96, no. 3, 879-897, Doi: 10.1785/0120050138.***

Abstract:

Following the 1995 Hyogo-ken Nanbu Kobe. Earthquake, the Japanese government, in an effort to prevent future earthquake disasters, installed networks consisting of a large

number of strong-motion observation stations. Further, national seismic hazard maps were made available to the public on an Internet website in March 2005 by the Headquarters for Earthquake Research Promotion. However, these maps indicate only the local seismic intensity for Japan, as empirically converted from predicted peak velocity in consolidated soils. For various applications, other strong-motion indexes such as the response spectral acceleration are required. In this study, a database of whole Japanese strong ground motion records between 1963 and 2003 is established in order to identify a new standard attenuation relation for Japan, for response acceleration as well as peak value. It is usually very difficult to determine a suitable model form due to the large variability of strong-motion data and correlation among the model variables, because the strong coupling of variables in an attenuation model, and the statistical power of the data is often not large enough to determine the necessity of these parameters. Therefore, in this study, our model has only three variables: earthquake magnitude, shortest distance to the seismic fault plane, and focal depth. To improve predictions given by the model, site correction terms are adopted and additional terms for correcting regional anomalous seismic intensity with respect to the base model are determined. The good fit between the model and observed strong-motion records suggests that the new model is reasonably robust.

- **Assessment of Site Effects on Seismic Motion in Ashigara Valley, Japan. Tomiichi Uetake and Kazuyoshi Kudo.** ***Bulletin of the Seismological Society of America, December 2005, vol. 95, no. 6, 2297-2317, Doi: 10.1785/0120040065.***

Abstract:

We compared site amplifications at rock sites and sediment sites of Ashigara Valley, Japan, using ground-motion data from five remote (>700 km) large (>M 7) events. The use of remote large events is advantageous to estimating site factors because the source and path effects are considered to be common with a sufficient accuracy and the ground motions will cover a wide-frequency band. Ground motions at both sediment and rock sites were coherent in frequencies lower than 0.1 Hz. This means that the wavelength in these frequencies is longer than the size of the valley (12 km long and 5 km wide). Site amplification factors were determined by taking spectral ratios with reference to one rock outcrop site. The amplification factors of sediment sites deviated 2–10 times with respect to the rock site in the frequency range higher than 0.1 Hz, in which significant peaks at about 1–2 Hz were found at most sites. These dominant amplifications in sedimentary basin are most essential for assessing earthquake hazard in the region. For sediment sites, the peak frequencies of spectral ratios to the rock sites were stable for different events and coincided with those of horizontal to vertical spectral ratios for the Swave portion and those of relative site factors estimated separately by the generalized inversion method using local small-events data in the frequency range higher than 2 Hz. Although spectral ratios for frequencies lower than about 1 Hz should be affected by 3D basin structure, 1D S-wave responses represent the amplification of ground motion in the sediment sites for frequencies higher than 2 Hz.

- **Can Strong-Motion Observations be used to Constrain Probabilistic Seismic-Hazard Estimates? Beauval, P.Y. Bard, S. Hainzl and P. Guéguen.** ***Bulletin of the Seismological Society of America, April 2008, vol. 98, no. 2, 509-520*****, Doi: *10.1785/0120070006*C.**

Abstract:

Because of the new regulatory requirements that hazards have to be estimated in probabilistic terms, the number of probabilistic hazard studies conducted has recently been increasing. The present study aims at defining the possibilities and limits for comparing predictions from these studies and observations. Comparison tests based directly on the rate of ground-motion occurrences are favored over the rate of earthquake occurrences. Based on the properties of Poisson processes, the minimum time window ensuring reliable occurrence rate estimates at a site is computed and evaluated. For example, for ground motions with a 475-yr return period at a site, a minimal 12,000-yr observation time window is required for estimating the rate with a 20% uncertainty (coefficient of variation: standard deviation divided by the mean). These values are not dependent on the seismicity level of the regions under study. An analysis of recorded ground motions at the stations of the permanent French accelerometer network shows that at best, the occurrence rates can be estimated with an accuracy of 30% for very low acceleration levels (0.0001–0.001g for the station STET). The same analysis, carried out at two stations with longer recording histories and located in higher seismicity regions (Greece and California), provides ground-motion levels up to 0.1g. Therefore, the question posed is can the results of a comparison test at low acceleration levels be generalized to higher acceleration levels, even if using a ground-motion prediction equation uniformly valid for a wide range of accelerations?

- **Integration of geological and seismological data for the analysis of seismic hazard: A case study of Japan. S.G. Wesnousky, C.H. Scholz, K. Shimazaki and T. Matuda.** ***Bulletin of the Seismological Society of America, April 1984, vol. 74, no. 2, 687-708.***

Abstract:

Seismic hazard analyses are associated with large uncertainties when historical data are insufficient to define secular rates of seismicity. Such uncertainties may be decreased with geological data in areas where seismicity is shallow and produced by Quaternary faulting. To illustrate, we examine intraplate Japan. Large intraplate earthquakes in Japan characteristically produce surface ruptures along mappable Quaternary faults and show a systematic relation between seismic moment, M0 and rupture length I (log M0 = 23.5 + 1.94 × log I). It is observed that, within the bounds placed by geologically assessed slip rates, the mean regional moment release rate M0 resulting from slip on mapped Quaternary faults is in accord with estimates of M0 determined with the 400-yr record of seismicity. Recent work also shows that when the repeat time T of earthquakes on Quaternary faults in southwest Japan is assumed to equal M0/M0 (where M0 is estimated for rupture extended over the entire fault length and M0 is the geologically assessed moment release rate of each fault), the moment frequency distribution of earthquakes predicted from the geologic record is virtually identical to that seen with the 400-yr record of seismicity. These observations indicate that the geologic record of Quaternary fault offsets contains sufficient information to predict both the spatial and size distribution of

intraplate earthquakes in Japan. A contour map of the average recurrence time of ground shaking of JMA intensity ≧V is thus computed using an empirical relation between seismic moment and the areal distribution of seismic intensity and assuming that the repeat time T of earthquakes on each Quaternary fault equals M0/M0 . The map demonstrates how Quaternary fault data may be used to assess long-term seismic hazard in areas of active faulting where historical records of seismicity are relativel short or absent. Another shortcoming of conventional seismic hazard analysis is that hazard is not considered a function of the time since each fault in a region last ruptured. A simple procedure is used to demonstrate how the time-dependent nature of the earthquake cycle affects the evaluation of seismic hazard. The distribution of seismic shaking characteristic of large interplate earthquakes offshore of Japan is estimated from published isoseismal maps. The observed average repeat times of ruptures along specific segments of the plate boundaries then provide the basis to make probabilistic estimates of the next expected time of seismic shaking due to plate boundary earthquakes. When data are too few to document the average repeat times of rupture, the estimates of probability are calculated with data relating to the relative coseismic slip during past earthquakes and the rate of interseismic strain accumulation, interpreted within the framework of the time predictable model of earthquake occurrence. Results are displayed as maps of instantaneous seismic hazard: the probability that seismic shaking will occur conditional to knowledge of where in time each fault in a region presently resides with respect to the earthquake cycle.

- **Possibility of Biases in the Estimation of Earthquake Recurrence and Seismic Hazard from Geologic Data. Steven G. Wesnousky.** ***Bulletin of the Seismological Society of America, October 2010, vol. 100, no. 5A, 2287-2292, Doi: 10.1785/0120090370.***

Abstract:

Aseismic deformation is an integral part of the earthquake process and may lead to systematic biases in the estimation of earthquake size, recurrence, and attendant strong ground motions in seismic hazard analyses founded on the geologic description of the locations, lengths, and slip rates of active faults. Observations are reviewed and presented to suggest that large earthquakes systematically rupture to increasingly greater depths below the seismogenic layer and that the portion of slip on faults accommodated by aseismic processes may be inversely related to the length of rupture expected to occur on them. If so, the expected seismic moment per unit area of earthquakes on mapped faults may be systematically overestimated as a function of rupture length when derived from regressions of seismic moment and aftershock area, and estimates of seismic moment rate derived from geologic measures of fault offset might be systematically overestimated as an inverse function of the length of rupture expected to recur on a fault.

- **Probabilistic Characterization of Spatially Correlated Response Spectra for Earthquakes in Japan. Katsuichiro Goda and Gail M. Atkinson.** ***Bulletin of the Seismological Society of America, October 2009, vol. 99, no. 5, 3003-3020, Doi: 10.1785/0120090007.***

Abstract:

Seismic hazard and risk assessments of spatially distributed infrastructural systems require seismic demand models that capture random but correlated simultaneous seismic effects at multiple sites. This study characterizes spatially correlated ground-motion parameters probabilistically using comprehensive databases of the K-NET and KiK-net strong-motion networks in Japan by developing a ground-motion prediction equation and then investigating the correlation structure of regression residuals from the prediction equation. Analysis results indicate that (1) interevent residuals of ground-motion parameters at different vibration periods are more strongly correlated than intraevent and total residuals with zero separation distance; and (2) intraevent spatial correlation coefficients can be described as a simple exponential decay function that is independent of the way the event-based intraevent standard deviation is calculated, of the earthquake type, and of the vibration period. The developed overall correlation model of spatially correlated ground-motion parameters may be used for seismic hazard and risk assessments in a subduction environment.

- **Reply to "Comment on 'Test of Seismic Hazard Map from 500 Years of Recorded Intensity Data in Japan by Masatoshi Miyazawa and Jim Mori" by Céline Beauval, Pierre-Yves Bard, and John Douglas. Masatoshi Miyazawa and Jim Mori.** ***Bulletin of the Seismological Society of America, December 2010, vol. 100, no. 6, 3332-3334, Doi: 10.1785/0120100158.***

Miyazawa and Mori (2009) focused on obtaining the recorded maximum seismic intensity in Japan over the last 500 years and made comparisons to the corresponding Japanese probabilistic seismic hazard map (PSHM) by the Headquarters for Earthquake Research Promotion (2005). The comments by Beauval et al. (2010) state that this comparison is not correct. In this reply, we try to further justify the validity of the comparison by clarifying that (1) many stations over Japan are used to test the PSHMs on average and (2) the PSHM assumes both a time-dependent model and a time-independent model for the probability of earthquake occurrences. The present PSHMs in Japan use both time-dependent and time-independent models. It is well-known that large earthquakes with magnitude larger than 7 repeatedly occur in subduction zones at intervals on the order of 100 years or less and with similar mechanisms. Also the recurrences of onshore earthquakes on major active faults have been investigated geologically, though their uncertainties are much larger compared to the subduction zone earthquakes. The recurrences of these earthquakes are modeled in the PSHM as a Brownian passage time distribution (Fujiwara et al., 2006), and Miyazawa and Mori (2009, p. 3124) say that the "present PSHM is a time-dependent hazard map." For some onshore earthquakes with unclear return periods and earthquakes with nonspecified source faults, the occurrence probability is modeled as a Poisson process, which is time independent. For details, see National Research Institute for Earth Science and Disaster Prevention (2009) and the Japan Seismic Hazard Information Station Web site (National Research Institute for Earth Science and Disaster Prevention [NIED], 2010).

- **Seismic Demand Estimation of Inelastic SDOF Systems for Earthquakes in Japan. Katsuichiro Goda and Gail M. Atkinson.** ***Bulletin of the Seismological Society of America, December 2009, vol. 99, no. 6, 3284-3299, Doi: 10.1785/0120090107.***

<u>Abstract:</u>

An accurate estimation of the maximum inelastic displacement of a structure under seismic excitations is essential to quantitative seismic risk assessment. The seismic performance of existing structures can be evaluated by utilizing inelastic single-degree-of-freedom (SDOF) systems and carrying out nonlinear dynamic analysis. This article develops a probabilistic model of the peak ductility demand of inelastic SDOF systems with various hysteretic characteristics using comprehensive sets of strong ground-motion records observed in Japan. The use of a large database facilitates the systematic investigation of the effects of earthquake type, record selection criteria, seismological parameters, and seismic region on the inelastic seismic demand. Nonlinear dynamic analysis of inelastic SDOF systems is carried out for statistical analysis and probabilistic modeling of the peak inelastic seismic demand. Analysis results indicate that the inelastic seismic demand depends on earthquake type, selection criteria, and seismological parameters to some degree. The most notable differences in inelastic seismic demands are observed for interface records at short vibration periods in comparison with crustal and inslab records; the differences can be explained by different response spectral shapes of the datasets. The inelastic seismic demand for the California crustal records is greater than that for the Japanese crustal records at short vibration periods, whereas the demands are comparable at long vibration periods. The peak ductility demand can be modeled as a Frechet variate, and empirical equations for calculating its statistics are developed, which achieve simplicity an sufficiency in probabilistic seismic risk analysis.

- **Seismic hazard assessment through semi stochastic simulation. F. Alejandro Nava and Victor H. Espindola.** ***Bulletin of the Seismological Society of America, April 1993, vol. 83, no. 2, 450-468.***

Abstract:

A method for the evaluation of seismic hazard for a seismogenic region from catalog seismicity data is presented. This method includes consideration of causal processes involved in elastic energy accumulation that result in the concept of seismic gaps and deals in a stochastic way with random effects that cannot be treated deterministically. The usually scarce information contained in catalogs for any particular seismogenic region corresponding to a seismic gap is used to calibrate a model that describes the distribution of magnitudes as a function of the elastic energy stored in it. Afterwards, distributions of recurrence times for earthquakes of various magnitudes can be obtained from results of long simulations using the calibrated model. The method is applied to the Acapulco-San Marcos, Mexico, region, which is considered as the possible site of a $M \approx 7.5$ (or larger) earthquake in the near future. For this region, given that the most recent “gap-filling” $M = 7.5$ earthquake occurred there in July 1957, the probabilities of an $M \geqq 7.3$ event occurring before 1992, 1995, and 2000 are <0.001, <0.001, and 0.011, respectively; those of a not-so-large but still danagerous $M \geqq 7.3$ event during the mentioned intervals are 0.012, 0.054, and 0.145, respectively.

- **Space-Time Correlations of Seismotectonic Parameters: Examples from Japan and from Turkey Preceding the İzmit Earthquake. Ali Osman Oncel and Thomas H. Wilson.** ***Bulletin of the Seismological Society of America, February 2002, vol. 92, no. 1, 339-349, Doi: 10.1785/0120000844.***

Abstract:

Analysis of the correlation between fractal attributes of complex seismotectonic variables may offer insights into seismic hazard assessment. The Gutenberg-Richter, moment-magnitude, and moment-source area relations yield a direct fractal relationship among the Gutenberg-Richter bvalue, occurrence rate, and the characteristic linear dimension of the fault plane (square root of fault surface area). In contrast, temporal variation in the correlation dimension of epicenters (DC) is found, in several studies, to correlate negatively with the b-value in different regions of the world. Spatial variations between the b-value and DC also tend to oppose each other. In Japan, negative correlations are also observed in the regional scale comparisons of the capacity dimension (Do) of active fault systems and the bvalue. However, at local scales, the relationship yields both positive and negative correlation. The occurrence of positive or negative correlation appears to be controlled by different modes of failure within the active fault complex. Spatial variations between the b-value and DC along the Northern Anatolian Fault Zone (NAFZ) suggest that, on average from 1900 to 1992, earthquake magnitudes were higher and epicenters more scattered within the central NAFZ than in its eastern and western segments. Temporal analysis reveals that the relationship between the b-value and DC are nonstationary. Temporal correlations are generally negative. A period of positive correlation is observed between 1976 and 1988. During the last 3 yr of this period (1985-1988), both the b-value and DC rose significantly, suggesting that stress release occurs through increased levels of low-magnitude and increasingly scattered seismicity. This dispersed pattern of seismicity, in combination with higher slip rates in the central NAFZ, may be one that did not adequately relieve stress along the main fault zone. This change in behavior and the tendency during the last century for the seismicity to migrate westward along the NAFZ may point to an increased risk of larger magnitude events such as the İzmit earthquake.

- **Test of Seismic Hazard Map from 500 Years of Recorded Intensity Data in Japan. Masatoshi Miyazawa and Jim Mori. *Bulletin of the Seismological Society of America, December 2009, vol. 99, no. 6, 3140-3149, Doi: 10.1785/0120080262.***

Abstract:

Maximum seismic intensity maps for Japan are constructed using the recorded intensity data from 1498 to 2007 and are used to test the probabilistic seismic hazard map (PSHM) by the Headquarters for Earthquake Research Promotion, Japan. The historical intensity maps are compared with the hazard maps of probable maximum seismic intensity for a 475-yr return period, assuming a Poisson distribution (10% in 50 yrs). We look at cases that include all events, only subduction zone earthquakes, and all events excluding subduction zone earthquakes. The megathrust earthquakes in the subduction zones produce large bands of high intensities along the Pacific coast side, while onshore crustal earthquakes create a patchy distribution of large intensities over all of Japan. The maximum recorded intensity map for the past 500 yrs and the maximum predicted intensity map for the return period 500yr from the PSHM are very similar for the cases including all events and the subduction zone earthquakes, while there is poor correlation for the

third category that includes mostly onshore crustal earthquakes. If we consider only the amount of area, not the specific locations, the recorded intensity map and the PSHM (using the maximum case) have a high degree of correlation for Japanese Meteorological Agency (JMA) intensity higher than 4 for all of the cases. Statistically, the present hazard maps for Japan seem to agree with the past intensity distributions and can be regarded as appropriate hazard maps, even though there may be strong dependencies on uncertain model parameters for the PSHMs.

- **Tsunami hazard probability in Japan. T. Rikitake and I. Aida.** ***Bulletin of the Seismological Society of America, June 1988, vol. 78, no. 3, 1268-1278.***

Abstract:

An analysis of future tsunami hazard on the coast of the Japanese Islands is made in terms of probability for a coastal site being hit by a tsunami, of which the wave height exceeds a certain level during a period from 2000 to 2010. Tsunami wave height at a site on the Pacific coast is estimated mostly based on numerical experiment, in which a typical fault model of the tsunamigenerating earthquake is assumed. Meanwhile, probability of the tsunami-generating earthquake occurring during 2000 to 2010 is evaluated either from historical data of earthquake occurrence or from near-shore crustal strain accumulation. Combining the wave height estimate with the probability evaluation of tsunami occurrence, probabilities of a site being hit by a tsunami, of which the wave height exceeds certain levels, are evaluated on the Pacific coast. It seems that the probability for a violent tsunami, of which the wave height exceeds 5 m, is highest along the Pacific coast in central Japan, reaching a value of 41 per cent. On the other hand, a probability value as high as 69 per cent is found for a moderately large tsunami having a wave height of 1 m or so along the Shikoku and Kyushu coasts. A crude probability evaluation is also made for tsunamis on the Japan Sea coast, where tsunami activity is substantially lower than that of the Pacific coast. T he probability for a violent tsunami seems to amount to only 1 per cent or so for a 10-yr period. Similar probabilities for tsunamis excited by a distant source off Peru, Chile, Kamchatka, and Aleutian-Alaska are also evaluated. In this case, probabilities of tsunami wave height exceeding 1 and 3 m are, respectively, evaluated as 19 and 15 per cent on the Pacific coast, such probabilities being not quite negligible.

- **Probabilistic Seismic Hazard Assessment for Japan. George Ch. Koravos, Theodoros M. Tsapanos and M. Bejaichund.** ***Pure appl. geophys., 163 (2006), 137–151, 0033–4553/06/010137–15, Doi: 10.1007/s00024-005-0003-0.***

Abstract:

A probabilistic seismic hazard assessment was performed for the Japanese islands and surrounding areas. Seismic hazard parameters characteristic of the seismic history of the regions were obtained. The probability of occurrence of a large M ‡ 7 earthquake within a 10- and 50-year period was also calculated. Regions of very high levels of hazard occur where the Pacific, Phillipine and Eurasian Plates meet. High probabilities of occurrence of a large M ‡ 7 earthquake within a 10- and 50-year period occur within the region where the Pacific Plate subducts with the Eurasian Plate.
Key words: Seismic hazard, probabilistic occurrence, Japan

- **Seismic Hazard Evaluation Using Markov Chains: Application to the Japan Area. F. Alejandro Nava, Claudia Herrera, Jose´ Frez and Ewa Glowacka.** ***Pure appl. geophys., 162 (2005), 1347–1366, 0033 – 4553/05/071347 – 20, Doi: 10.1007/s00024-005-2673-z.***

Abstract:

Seismogenic regions within some geographic area are interrelated through tectonics and seismic history, although this relation is usually complex, so that seismicity in a given region cannot be predicted in a straightforward manner from the activity in other region(s). We present a new statistical method for seismic hazard evaluation based on modeling the transition probabilities of seismicity patterns in the regions of a geographic area during a time interval, as aMarkov chain. Application of the method to the Japan area renders good results, considering the occurrence of a high probability transition as a successful forecast. For magnitudes M 5:5 and time intervals Dt ¼ 0:10 year, the method yields a 78% aftcast (forecast of data already used to evaluate the hazard) success rate for the entire catalog, and an indicative 80% forecast success rate for the last 10 transitions in the catalog. A byproduct of the method, regional occurrence probabilities determined from the transition probabilities, also provides good results; aftcasts of regional activity have a 98% success rate, and those of activity in the highest probability region about 80.5% success rate. All results are superior to those from the null hypotheses (a memory-less Poissonian, fixed-rate, or uniform system) and have vanishingly small probabilities of resulting from purely random guessing.

Key words: Seismic hazard, Markov chains, Japan.

- **Logic-tree Approach for Probabilistic Tsunami Hazard Analysis and its Applications to the Japanese Coasts. Tadashi Annaka, Kenji Satake, Tsutomu Sakakiyama, Ken Yanagisawa and Nobou Shuto.** ***Pure appl. geophys., 164 (2007), 577–592, 0033–4553/07/030577–16, Doi: 10.1007/s00024-006-0174-3.***

Abstract:

For Probabilistic Tsunami Hazard Analysis (PTHA), we propose a logic-tree approach to construct tsunami hazard curves (relationship between tsunami height and probability of exceedance) and present some examples for Japan for the purpose of quantitative assessments of tsunami risk for important coastal facilities. A hazard curve is obtained by integration over the aleatory uncertainties, and numerous hazard curves are obtained for different branches of logic-tree representing epistemic uncertainty. A PTHA consists of a tsunami source model and coastal tsunami height estimation. We developed the logic-tree models for local tsunami sources around Japan and for distant tsunami sources along the South American subduction zones. Logic-trees were made for tsunami source zones, size and frequency of tsunamigenic earthquakes, fault models, and standard error of estimated tsunami heights. Numerical simulation rather than empirical relation was used for estimating the median tsunami heights. Weights of discrete branches that represent alternative hypotheses and interpretations were determined by the questionnaire survey for tsunami and earthquake experts, whereas those representing the error of estimated value were determined on the basis of historical data. Examples of tsunami hazard curves were illustrated for the coastal sites, and uncertainty in the tsunami hazard was displayed by 5-, 16-, 50-, 84- and 95-percentile and mean hazard curves.

Key words: Logic-tree approach, probabilistic tsunami hazard analysis, tsunami hazard curve, epistemic uncertainty, aleatory uncertainty.

- **From Earthquake Prediction Research to Time-Variable Seismic Hazard Assessment Applications. Peter Bormann. *Pure Appl. Geophys. 168 (2011), 329–366, 2010.***

Abstract:

The first part of the paper defines the terms and classifications common in earthquake prediction research and applications. This is followed by short reviews of major earthquake prediction programs initiated since World War II in several countries, for example the former USSR, China, Japan, the United States, and several European countries. It outlines the underlying expectations, concepts, and hypotheses, introduces the technologies and methodologies applied and some of the results obtained, which include both partial successes and failures. Emphasis is laid on discussing the scientific reasons why earthquake prediction research is so difficult and demanding and why the prospects are still so vague, at least as far as short-term and imminent predictions are concerned. However, classical probabilistic seismic hazard assessments, widely applied during the last few decades, have also clearly revealed their limitations. In their simple form, they are time-independent earthquake rupture forecasts based on the assumption of stable long-term recurrence of earthquakes in the seismotectonic areas under consideration. Therefore, during the last decade, earthquake prediction research and pilot applications have focused mainly on the development and rigorous testing of long and medium-term rupture forecast models in which event probabilities are conditioned by the occurrence of previous earthquakes, and on their integration into neo-deterministic approaches for improved time-variable seismic hazard assessment. The latter uses stress-renewal models that are calibrated for variations in the earthquake cycle as assessed on the basis of historical, paleoseismic, and other data, often complemented by multi-scale seismicity models, the use of pattern-recognition algorithms, and site-dependent strong-motion scenario modeling. International partnerships and a global infrastructure for comparative testing have recently been developed, for example the Collaboratory for the Study of Earthquake Predictability (CSEP) with test regions in California, Italy, Japan, New Zealand, and the Western Pacific. Algorithms and data bases are operated in a permanently learning and upgrading mode. Future perspectives and research requirements and the feasibility and possible problems encountered with the implementation of earthquake predictions in practice are briefly summarized.

Key words: Earthquake prediction, forecast, precursory phenomena, seismic hazard, time-variable seismic hazard assessment, self-organized criticality, non-linear systems, implementation of predictions; social impact of predictions.

- **Advanced Seismic Hazard Assessment. G.F. Panza, K. Irikura, M. Kouteva, A. Peresan, Z. Wang and R. Saragoni.** ***Pure Appl. Geophys., 168 (2011), 1–9 2010, Doi: 10.1007/s00024-010-0179-9.***

Introduction:

Issues pertaining to urban risks are a pressing concern for people involved in disaster mitigation. With the progressing urban sprawl and the emergence of mega-cities around the world, disasters of all kinds become an inevitable consequence of uncontrolled urbanization. Growing environmental and social (purely scientific and practical disaster mitigation and preparedness) concerns, both on the part of decisionmakers and public opinion, have brought a new perspective to the perception of hazard assessment as a vali alternative in the long-term (e.g. retrofitting), and an effective complement in short and medium terms, to traditional design procedure for a resistant and safe environment. Recent earthquakes, Haiti earthquake of 12 January 2010 and Chile earthquake of 27 February 2010, in particular, exemplify the urgent need for society to develop the effective strategies and policies to reduce seismic risk and to mitigate earthquake disasters. Chile and Haiti are both set on active plate boundaries and have a long history of earthquakes. However, the impacts on the two countries were dramatically different. The magnitude M7.1 earthquake in Haiti resulted in a disaster killing more than 200,000 people, while the magnitude M8.8 earthquake in Chile did not result in a comparable disaster, killing fewer than 1,000 people, even though the seismic energy released is several hundred times larger. Chile was prepared for earthquakes and had modern seismic design codes for buildings, bridges, and other structures, while Haiti was not prepared and had no seismic consideration for buildings. The aim of this volume is to supply multifaceted information on the modern tools for seismic hazard assessment (SHA), and to make clear the significant difference between hazard and risk, and hazard mitigation and risk reduction. In general, there are many regions where, due to lack of specific instrumentation/ equipment and monitoring, very few data is available. Thus, it has become necessary to develop tools for SHA, primarily techniques suitable for implementation in both developed and developing countries, and the optimal use of already available and published data and information is a must. The purposes of this volume are to: (1) identify the issues in the current SHAs, (2) facilitate the development of a scientifically consistent approach for SHA and (3) disseminate, both in scientific and in engineering practice societies, advanced reliable tools for independent hazard estimates, which exploit, as much as possible, the available seismological, geological and geophysical information. We believe that this topical issue will reach different end-users—decision makers and stake-holders—and thus it will contribute to the link between the modern interdisciplinary research and the public administration to cope with the problems of the earthquake risk management and natural disasters preparedness.

- **Sequential processes in a landslide hazard at a slate quarry in Okayama, Japan. Hiroshi Suwa, T. Mizuno, S. Suzuki, Y. Yamamoto, K. Ito.** ***Nat Hazards (2008), 45, 321–331 Doi: 10.1007/s11069-007-9163-9.***

Abstract:

The 12 March 2001 landslide at a slate quarry in Okayama, Japan killed three workers. Composite studies based on field surveys of the landslide slope, interviews with local residents and quarry workers, and inspections of hydrological and seismological data have been used to clarify the causes of this slide and its movements. The results indicate that the landslide was enabled firstly by the steepness of the slope, which had been undercut by river; secondly, the structure was that of a dip-slope that was prone to deepseated slides along bedding planes; thirdly, numerous joints and faults were present. Surprisingly, rainfall, earthquakes, and explosions do not appear to have played any role in the triggering of this slide. The interviews demonstrated that the frequency of precursory failures increased over a period of several hours before the 12 March 2001 landslide. Inspection of the seismograph records and the eyewitness evidence both indicate that the main part of the landslide consisted of two phases of slope failure within 23 s. After the slide, the frequency of the failures gradually decreased with time over a period of several days. Three new terms are proposed for landslides: foreslide, mainslide, and afterslide, following the terms foreshock, main shock, and aftershock used in seismology.
Keywords: Quarry, Landslide, Dip-slope, Undercut slope, Precursor, Progressive, failure

- **Soil Condition and Seismic Characteristics in Shiga Prefecture, Japan. Teizo Fujiwara, Kazumasa Fukumoto, Koji Matsunami and Takeshimorii. *Natural Hazards, 29, 523–542, 2003.***

Abstract:

The seismic observation network in Shiga prefecture is composed of four systems. All the observation data obtained were used to estimate the dynamic characteristics of the surface soils around the lake and the seismic hazard for Hikone City. Since 1995, 21 records have been obtained at the USP site of which those for the 1999 Shigaken-Hokubu Earthquake and 1999 Wakayarnaken- Hokubu Earthquake were used in this study. Transfer functions of the surface soil in each ward of Shiga Prefecture based on the Mt. Kojin site (KJY), which has relatively hard soil, were calculated from the records of the two earthquakes. Assuming a scenario earthquake at the Hyakusaiji fault close to Hikone City, maximum ground motions were obtained for 15 city blocks in order to establish a damage estimation for that city. The number of collapsed wooden houses and the damage ratio were calculated based on the distribution of construction of wooden houses by year. Blocks with a larger ratio of old, wooden houses in Hikone showed a close correlation with blocks with a large ratio of aged persons in them, indicative that weak persons, such as the elderly, may find themselves in a severe situation during a natural disaster.

Key words: damage estimation, observation network, soil profile, Hikone, Shiga.

- **Global Seismic Hazard Assessment Program Maps are Erroneous. V. G. Kossobokova and A. K. Nekrasova. *ISSN 07479239, Seismic Instruments, 2012, Vol. 48, No. 2, pp. 162–170, Doi: 10.3103/S0747923912020065.***

Abstract:

The March 11, 2011 megathrust on the Pacific coast of the Tohoku Region, Japan, and its consequences once again confirmed the presence of evident problems in the conventional

methodology of risk and earthquake loss evaluation. A systematic analysis shows that the results of the Global Seismic Hazard Assessment Program (GSHAP, 1992–1999) contradict the actual occurrence of strong earthquakes. In particular, since the publication of the GSHAP final results in 1999, all 60 earthquakes with magnitudes of 7.5 or higher were "surprises" for the GSHAP maps. Moreover, in half of the cases they were "big surprises," when instead of the expected "light" or "moderate," "significant" or even "total" destruction took place. All twelve of the deadliest earthquakes happened in 2000–2011 (total number of deaths exceeded 700000 people) prove that the GSHAP results, as well as underlying methodologies, are deeply flawed and, evidently, unacceptable for any critical risk assessments entitled to prevent disasters caused by earthquakes.

Keywords: earthquake, megaearthquake, earthquake magnitude, earthquake intensity, peak ground acceleration.

- **Coulomb stresses imparted by the 25 March 2007 Mw=6.6 Noto-Hanto, Japan, earthquake explain its 'butterfly' distribution of aftershocks and suggest a heightened seismic hazard. Shinji Toda. *Earth Planets Space, 60, 1041–1046, 2008.***

The well-recorded aftershocks and well-determined source model of the Noto Hanto earthquake provide an excellent opportunity to examine earthquake triggering associated with a blind thrust event. The aftershock zone rapidly expanded into a 'butterfly pattern' predicted by static Coulomb stress transfer associated with thrust faulting. We found that abundant aftershocks occurred where the static Coulomb stress increased by more than 0.5 bars, while few shocks occurred in the stress shadow calculated to extend northwest and southeast of the Noto Hanto rupture. To explore the three-dimensional distribution of the observed aftershocks and the calculated stress imparted by the mainshock, we further resolved Coulomb stress changes on the nodal planes of all aftershocks for which focal mechanisms are available. About 75% of the possible faults associated with the moderate-sized aftershocks were calculated to have been brought closer to failure by the mainshock, with the correlation best for low apparent fault friction. Our interpretation is that most of the aftershocks struck on the steeply dipping source fault and on a conjugate northwest-dipping reverse fault contiguous with the source fault. Since we found that the Coulomb hypothesis works well for the Noto Hanto sequence, we subsequently computed stress changes on the nearby active faults. Although the calculated stress changes were found to be negligible on the major faults south of the Noto Peninsula, several short active faults near the epicentral area were calculated to have been brought several bars closer to failure. Thus, the probability of strong shaking in and around the epicentral area may still be high due to the transfer of stress to the adjacent faults by a short blind thrust fault.

Key words: 2007 Noto Hanto earthquake, Coulomb stress change, aftershocks, off-fault aftershocks, blind thrust.

- **Crustal block kinematics and seismic potential of the northernmost Philippine Sea plate and Izu microplate, central Japan, inferred from GPS and leveling data. Takuya Nishimura, Takeshi Sagiya and Ross S. Stein. *J. Geophys. Res., 112, B05414, Doi:10.1029/2005JB004102.***

Abstract:

We clarify the contemporary deformation observed by GPS and leveling for the greater Tokyo (Kanto, eastern Tokai, and the Izu islands) region, where the Izu-Ogasawara (Bonin) arc is subducting and colliding with the central part of the Japan arc. From these data, we develop a kinematic model of fault sources with variable components of seismic and aseismic slip. Under the assumption that the contemporary deformation during 1995-2000 is representative of the longterm interseismic strain field, the geodetic data are inverted to estimate the rotation poles of the crustal blocks, the degree of elastic strain accumulation on faults, and the volumetric inflation sources beneath volcanoes. The present crustal movements are explained by four crustal blocks: the Izu micro-plate, the Central Japan block, the Pacific plate, and the Philippine Sea plate. Along the Suruga and Sagami margins of the Philippine Sea plate lie strongly coupled faults, which include sites of the 1854 M=8.4 Tokai, 1923 M=7.9 Kanto, and 1703 M~8.2 Genroku Kanto earthquakes. In contrast, the Philippine Sea plate boundary immediately north of the Izu peninsula, site of M ≤ 7.5 collisional earthquakes, is only weakly coupled. The boundary between the Izu micro-plate and the Philippine Sea plate experiences left-lateral motion with the rate of ~30 mm/yr. Most of this boundary is locked and thus has a large potential of future earthquakes. The Izu micro-plate is found to rotate rapidly clockwise at 10º/Myr, with a rotation pole relative to the Central Japan block located just north of its northern boundary. The pole and angular velocity of the Izu micro-plate depends, however, on the assumed location of the boundary. With the exception of the site of the 1938 M ≥ 7 earthquake swarm, which we infer has the current potential to produce a M~8.1 earthquake, the Pacific megathrust has a very low seismic potential, although the geodetic data have little resolving power for much of the Pacific plate interface east of Tokyo.

- **Estimation of the spatial distribution of ground motion parameters for two recent earthquakes in Japan. Khosrow T. Shabestaria, Fumio Yamazakib, Jun Saitaa and Masashi Matsuokaa. *Tectonophysics, 390 (2004), 193– 204.***

Abstract:

A recent development in strong motion instrumentation in Japan provides an opportunity to collect valuable data sets, especially after moderate and large magnitude events. Gathering and modeling these data is a necessity for better understanding of regional ground motion characteristics. Estimations of the spatial distribution of earthquake ground motion plays an important role in early-stage damage assessments for both rescue operations by disaster management agencies as well as damage studies of urban structures. Subsurface geology layers and local soil conditions lead to soil amplification that contributes to the estimated ground motion parameters of the surface. We present a case study of the applicability of the nationally proposed GIS-based soil amplification ratios [J. Soil Dyn. Earthqu. Eng. 19 (2000) 41–53] to the October 6, 2000 Tottori-ken Seibu (western Tottori Prefecture) and the March 24, 2001 Geiyo earthquakes in Japan. First, ground motion values were converted to those at a hypothetical ground base-rock level (outcrop) using an amplification ratio for each 11 km area, based on geomorphological and subsurface geology information. Then a Kriging method, assuming an attenuation relationship at the base-rock as a trend component, is applied. Finally, the spatial distribution of ground motion at ground surface is obtained by applying GIS-based amplification factors for the entire region. The correlation between the observed and estimated ground motion values is reasonable for both earthquakes. Thus, the proposed method is applicable in near real-time early-damage assessments and seismic hazard studies in Japan.

Keywords: The 2000 Tottori-ken Seibu earthquake; The 2001 Geiyo earthquake; Strong ground motion parameters; Attenuation relationship; Site amplification ratio; Digital national land information; Geomorphologic land classification; Kriging technique.

- **Magnitude-Period Scaling Relations for Japan and the Pacific Northwest: Implications for Earthquake Early Warning. Andrew B. Lockman and Richard M. Allen.** ***Bulletin of the Seismological Society of America, Vol. 97, No. 1B, pp. 140–150, February 2007, Doi: 10.1785/0120040091.***

Abstract:

Scaling relations between the predominant period of P-wave arrivals and earthquake magnitude are explored using datasets from the Pacific Northwest and Japan, and compared with previous observations in southern California (Allen and Kanamori, 2003). We find the same scaling for events in all three geologically diverse regions. The sensitivity of the predominant period observation to magnitude can be optimized using various frequency bands for different magnitude ranges and in different regions. The ability to estimate the magnitude using the first few seconds of the P wave offers a methodology for earthquake early warning. The accuracy of magnitude estimates increases with the number of stations reporting predominant period observations. The most significant improvements in the magnitude estimate occur when the number of reporting stations increased from one to four. As in southern California, we find that the average absolute magnitude error is 0.5 magnitude units when the closest four stations to the epicenter are used.

- **A new probabilistic seismic hazard assessment for greater Tokyo. Ross S. Stein, Shinji Toda, Tom Parsons and Elliot Grunewald.** ***Phil. Trans. R. Soc. A doi:10.1098/rsta.2006.1808.***

Abstract:

Tokyo and its outlying cities are home to one-quarter of Japan's 127 million people. Highly destructive earthquakes struck the capital in 1703, 1855 and 1923, the last of which took 105,000 lives. Fuelled by greater Tokyo's rich seismological record, but challenged by its magnificent complexity, our joint Japanese–US group carried out a new study of the capital's earthquake hazards. We used the prehistoric record of great earthquakes preserved by uplifted marine terraces and tsunami deposits (17 Mw approximately 8 shocks in the past 7000 years), a newly digitized dataset of historical shaking (10000 observations in the past 400 years), the dense modern seismic network (300,000 earthquakes in the past 30 years), and Japan's GeoNet array (150 GPS vectors in the past 10 years) to reinterpret the tectonic structure, identify active faults and their slip rates and estimate their earthquake frequency.We propose that a dislodged fragment of the Pacific plate is jammed between the Pacific, Philippine Sea and Eurasian plates beneath the Kanto plain on which Tokyo sits. We suggest that the Kanto fragment controls much of To-

kyo's seismic behaviour for large earthquakes, including the damaging 1855 approximately Mw 7.3 Ansei-Edo shock. On the basis of the frequency of earthquakes beneath greater Tokyo, events with magnitude and location similar to theMw7.3 Ansei-Edo event have a ca 20% likelihood in an average 30 year period. In contrast, our renewal (time-dependent) probability for the great M > or 7.9 plate boundary shocks such as struck in 1923 and 1703 is 0.5% for the next 30 year, with a time-averaged 30 year probability of ca 10%. The resulting net likelihood for severe shaking (ca 0.9 g peak ground acceleration (PGA)) in Tokyo, Kawasaki and Yokohama for the next 30 years is ca 30%. The long historical record in Kanto also affords a rare opportunity to calculate the probability of shaking in an alternative manner exclusively from intensity observations. This approach permits robust estimates for the spatial distribution of expected shaking, even for sites with few observations. The resulting probability of severe shaking is ca 35% in Tokyo,Kawasaki and Yokohama and ca 10% in Chiba for an average 30 year period, in good agreement with our independent estimate, and thus bolstering our view that Tokyo's hazard looms large. Given 1 trillion estimates for the cost of an M approximately 7.3 shock beneath Tokyo, our probability implies a 13 billion annual probable loss.

- **Applications of GIS in Probabilistic Seismic Hazard Analysis of Urban Areas. *L.* Sunuwar, M.B. Karkee, J.C. Tokeshi and C. Cuadra.** ***Fourth International Conference of Earthquake Engineering and Seismology, 12-14, May 2003, Tehran, Islamic Republic of Iran.***

  Abstract:

  GIS is used in carrying out seismic hazard analysis of urban areas as a first step of risk analysis of building damages by earthquakes. It has been demonstrated that GIS environment has many useful features that can be used to carry out statistical and spatial analysis efficiently for seismic hazard analysis. The most recent historical earthquake data of Japan is used for the probabilistic seismic hazard analysis of urban areas located in the North-eastern part of Japan. The recent attenuation laws are employed for the estimation of ground motion parameter that consider crustal and subduction zone earthquakes separately. This paper demonstrates a new methodology of seismic hazard analysis for the risk analysis of urban areas.

CHAPTER 6: REVIEW AND COMPARISON OF THE STUDIES CARRIED OUT IN NE INDIA AND OTHER COUNTRIES

6.1 REVIEW OF MOST VALUABLE LITERATURES ON EARTHQUAKE HAZARD ASSESSMENT IN NE INDIA

Review of the various research publications on seismological and seismic hazard studies in and around Northeastern India having impact factor above 2.0 are carried out. The prime findings in each of the studies are considered as the inputs to the seismic hazard assesement in the region. These parameters are indicated below.

Anomalous behaviour of precursor resistivity in Shillong area, NE India. J. R. Kayal and B. Banerjee. ***Geophys J. Int. (1988) 94, 97-103.***

The study looks after the resistivity variation as precursor. Prior to earthquakes, resistivity may increase or decrease or may not even show any change depending on the orientation of measuring electrodes, the elastic nature of the geological formation.

Aseismic plate boundary in the Indo-Burmese wedge, northwest Sunda Arc. Vineet K. Gahalaut, Bhaskar Kundu, Sunil Singh Laishram, Joshi Catherine, Arun Kumar, M. Devchandra Singh, R.P. Tiwari, R.K. Chadha, S.K. Samanta, A. Ambikapathy, P. Mahesh, Amit Bansal & M. Narsaiah. Geology, Vol. 41, No. 2, pp. 235-238.

Recent GPS measurements of crustal deformation and available long-term rates of motion across the Sagaing fault suggest that ∼20 ± 3 mm/yr of the relative plate motion of ∼36 mm/yr between the India and Sunda plates is accommodated at the Sagaing fault through dextral strike-slip motion. Our analysis of these measurements and the seismicity of the IBW suggest that the steeply dipping Churachandpur-Mao fault in the IBW accommodates the remaining motion of ∼18 ± 2 mm/yr between the India and Sunda plates through dextral strike-slip motion.

A deterministic seismic hazard map of India and adjacent areas. Imtiyaz A. Parvez, Franco Vaccari and Giuliano F. Panza. *Geophys. J. Int. (2003) 155, 489–508.*

This is the first study aimed at producing a deterministic seismic hazard map for the Indian region using realistic strong ground motion modeling. The epicentral areas of the great Assam earthquakes of 1897 and 1950 in northeast India represent the maximum hazard with DGA values reaching 1.2–1.3 g. The peak velocity and displacement in the same region is estimated as 120–177 cm s−1 and 60–90 cm, respectively.

A homogeneous and complete earthquake catalog for Northeast India and the adjoining region. R.B.S. Yadav, P. Bormann, B.K. Rastogi, M.C. Das and S. Chopra. Seismological Research Letters, 80, 609-627.

Long-term seismic hazard assessment, however, necessitates catalogs that are complete both with respect to the relative frequency of occurrence of events in a wide range of magnitudes and over as long as possible a time span; in addition, magnitudes, which characterize the differences in earthquake “size” or “strength,” should be well defined and consistently determined, i.e., unique and homogeneous.

A seismotectonic study of the Burma and Andaman arc regions using centroid moment tensor data. M. Ravi Kumar, N. Purnachandra Rao and S.V. Chalam. *Tectonophysics, 253 (1996), 155-165.*

This study enables a classification of focal mechanisms. Distinct trends on the surface and in depth sections emerge on examination of these categories. In the Burmese arc there is a clear segregation along the slab between strike-slip type mechanisms down to a depth of about 90 km and thrust events which occur exclusively below this depth.

Constraints on the seismic wave velocity structure beneath the Tibetan Plateau and their tectonic implications. W. P. Chen and P. Molnar. *J. Geophys. Res. (1981), 86(B7), 5937–5962, Doi:10.1029/JB086iB07p05937.*

Group and phase velocity dispersion of Rayleigh waves are observed. Tibetan crustal thickness can be from 55 to 85 km. Simple one-dimensional heat conduction calculations suggest that the volcanic activity could be explained by the recovery of the geotherm maintained by a mantle heat flux of about 0.9 HFU at the base of the crust.

Crustal structure variations in northeast India from converted phases. M. R. Kumar, P.S. Raju, E.U. Devi, J. Saul and D. S. Ramesh. ***Geophys. Res. Lett. (2004), 31, L17605, Doi:10.1029/2004GL020576***.

Teleseismic receiver functions are studied region. The Shillong plateau and Mikir hills, away from the convergent margins, reveal remarkably simple crust with thickness (~35 km) and Poisson's ratio (~0.25), akin to the Indian shield values. eastern Himalaya further north, with values in excess of 50 km.

Crustal properties in the epicentral tract of the Great 1897 Assam Earthquake, Northeastern India. S. Mukhopadhyay, R. Chander and K. N. Khattri. ***Tectonophysics (1997), 283, 311-330.***

The velocity structure for the upper and middle crust in the epicentral tract of the Great 1897 Assam Earthquake (western half of the Shillong massif) was estimated using locally recorded microearthquake data. The relatively homogeneous upper crustal layer has P and S wave velocities of 5.9 4- 0.2 and 3.4 4- 0.1 km/s, respectively, with a thickness of 11 to 12 km. The average P and S wave velocities in the middle part of the crust down to a depth of about 26 km were estimated to be 6.3 4- 0.6 and 3.5 4- 0.2 km/s, respectively.

Deep geoelectric structure over the Lower Brahmaputra valley and Shillong Plateau, NE India using magnetotellurics. S. G. Gokarn, G. Gupta, D. Walia, S.S. Sanabam and Nitu Hazarika. ***Geophys. J. Int. (2008) 173, 92–104 doi: 10.1111/j.1365-246X.2007.03711.x.***

Dauki fault as a NE–SW striking thrust zone with a dip angle of about 30º, along which the low resistivity layer of Bengal sediments and the underlying oceanic crust subduct to the northwest. We thus propose that the NE Indian crust responds to the compressive forces differently at different depths. At deeper levels the crustal readjustments take place through the subduction along the Dauki and Brahmaputra thrusts where as, at the shallow levels the relative deformability of the supracrustal blocks have a strong influence on the tectonics, leading to the strike slip mechanism along the surface expression of the Dauki fault.

Deep structure and tectonics of the Burmese Arc: Constraints from earthquake and gravity data. M. Mukhopadhyay and S. DasGupta. ***Tectonophysics (1988), 149, 299-322.***

Burmese Benioff zone is characterized by shallow angle thrusting at its upper edge whereas down-tip tensional events dominate its lower edge. The gravity anomalies along a profile in central Burma and in adjacent areas of the Bengal basin are interpreted in terms of plate subduction as well as near-surface mass anomalies.

Earthquakes beneath the Himalayas and Tibet: Evidence for Strong Lithospheric Mantle. Wang Ping Chen and Zhaohu Yang. Science, Vol.304, 25 June (2004). (IF-31.027)

High-resolution seismic waveforms show that some focal depths exceeded 100 kilometers, indicating that these earthquakes occurred in the mantle portion of the lithosphere, even though the crust has been thickened there.

Earthquake focal mechanism studies—A review. Kailash Khattri. *Earth-Science Reviews, Volume 9, Issue 1, March 1973, Pages 19–63.*

This article depicts the recent advances in the application of surface waves, free oscillations and static dislocations for the determination of focal mechanisms is given.

Earthquake mechanisms in the Himalayan, Burmese, and Andaman Regions and continental tectonics in Central Asia. T. J. Fitch. *J. Geophys. Res. (1970), 75(14), 2699–2709, Doi:10.1029/JB075i014p02699*.

This study indicates that the axis of minimum compression (the T axis) at intermediate depths beneath the Burmese mountains is oriented approximately down the dip of the seismic zone, as are T axes at intermediate depths in several other seismic zones.

Earthquake occurrence processes in the Indo-Burmese wedge and Sagaing fault region. Kundu, Bhaskar and Gahaulat, V.K. *Tectonophysics, 524-525 (2012), 135-146.*

The dip of the slab steepens in the east direction and earthquakes occur down to a depth of 150 km and our analysis of their focal mechanisms suggest that these earthquakes are of intra-slab type which occur on steep plane within the Indian plate and the sense of motion implies a northward relative motion with respect to the Sunda plate.

Earthquake processes of the Himalayan collision zone in eastern Nepal and the southern Tibetan Plateau. T.L. de la Torre, G. Monsalve, A.F. Sheehan, S. Sapkota and F. Wu. *Geophys. J. Int. (2007) 171, 718–738 doi: 10.1111/j.1365-246X.2007.03537.x.*

Focal mechanisms of the Himalayan Nepal Tibet Seismic Experiment (HIMNT) mostly strike-slip faulting near or below the crust–mantle boundary (Moho).

Earthquake Recurrence and Rupture Dynamics of Himalayan Frontal Thrust, India. Senthil Kumar, Steven G. Wesnousky, Thomas K. Rockwell, Daniel Ragona, Vikram C. Thakur and Gordon G. Seitz. *Science, 14 December, 2001, Vol. 294.*

Abandoned terraces of the adjacent Markanda River record uplift due to slip on the underlying HFT of 4.8 ± 0.9 millimeters per year or greater since the mid-Holocene. The uplift rate is equivalent to rates of fault slip and crustal shortening of 9.6−3.5 +7.0 millimeters per year and 8.4−3.6 +7.3 millimeters per year, respectively, when it is assumed that the HFT dips 30° ± 10°.

Estimates of interseismic deformation in Northeast India from GPS measurements. Sridevi Jade, Malay Mukul, Anjan Kumar Bhattacharyya, M.S.M. Vijayan, Saigeetha Jaganathan, Ashok Kumar, R.P. Tiwari, Arun Kumar, S. Kalita, S.C. Sahu, A.P.

Krishna, S.S. Gupta, M.V.R.L. Murthy and V.K. Gaur. ***Earth and Planetary Science Letters 263 (2007) 221–234.***

The results show that there is a statistically insignificant present-day active deformation within the Shillong Plateau and in the foreland spur north of the plateau in the Brahmaputra valley. Convergence rate of the northeastern GPS sites with respect to the IGS station Lhasa along baselines that are normal to the Himalayan arc in this region is 16 ± 0.5 mm/yr.

Estimation of crustal discontinuities from reflected seismic waves recorded at Shillong and Mikir Hills Plateau, Northeast India. Saurabh Baruah, Dipok K. Bora and Rajib Biswas. ***Int. J. Earth Sci. (Geol Rundsch) (2011) 100:1283–1292, Doi:10.1007/s00531-010-0541-2.***

In this study, an attempt is made to determine seismic velocity structure of the crust and upper mantle beneath the Shillong-Mikir Hills Plateau Conrad discontinuity is at 18–20 (±0.5) km beneath the Shillong-Mikir Hills Plateau and the Moho discontinuity is at 30 ± 1.0 km beneath the Shillong Plateau and at 35 ± 1.0 km beneath the Mikir Hills.

Evidences for cessation of Indian Plate Subduction in the Burmese Arc Region. N. Purnachandra Rao and M. Ravi Kumar. ***Geophys. Res. Lett., Volume 26, Issue 20, (/doi/10.1002/grl.v26.20/issuetoc), pages 3149–3152, 15 October 1999.***

Here the issue of whether subduction is still active in the India-Burma plate boundary. We propose a major right-lateral shearing of the Indian plate along with its subducted slab past the Burmese plate in the NNE direction.

Fault interactions and seismic hazard. C.H Scholz and Anupma Gupta. ***Journal of Geodynamics, Volume 29, Issues 3–5, April 2000, Pages 459–467.***

We propose that the probability of an earthquake jumping from one fault to another will increase with the degree of stress interaction between the faults, and introduce a simple criterion to estimate the degree of interaction based on separation and overlap of echelon normal fault pairs. We point out that with rapid data acquisition and proper preparation, it is feasible to issue a short-term hazard assessment regarding triggered earthquakes shortly after the occurrence of a potentially triggering event.

FAULT PLANE SOLUTIONS OF SHALLOW EARTHQUAKES AND CONTEMPORARY TECTONICS IN ASIA

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The tectonics of Asia are interpreted as a result of convergence of the Indian and Eurasian plates. The Indian shield bends down and underthrusts the Himalayas to the northeast along a shallow dipping fault plane while the Eurasian plate underthrusts the Pamir mountains, and therefore presumably the Indian Plate, to the south. The convergence of the Indian and Eurasian plates appears to cause relatively high stress to be transmitted across a broad area, north and east of the Himalayas, and this stress in turn causes earthquakes and renewed tectonic activity in some of the ancient Paleozoic and Mesozoic fold belts that separate more stable, aseismic blocks in Asia.

Focal depths and fault plane solutions of earthquakes and active tectonics of the Himalaya. J. Baranowski, J. Armbruster, L. Seeber and P. Molner. J. Geophys. Res. (1984), 89(B8), 6918-6928.

Assuming India to be a rigid plate, the radially oriented slip vectors imply that southern Tibet extends at about half the rate of underthrusting in the Himalaya and therefore probably at about 5–10 mm/yr. The steeper dips of fault planes in the western part of the arc might reflect deformation of the overriding thrust plate or simply a steepening of the main underthrusting zone beneath the Greater Himalaya.

Great earthquakes, seismicity gaps and potential for earthquake disaster along the Himalayan plate boundary. K.N. Khattri. Tectonophysics (1987), 138, 79-92.

Analysis of the space-time patterns of seismicity in the Himalaya plate boundary has established the existence of three seismic gaps:
1) The “Kashmir gap” lying west of the 1905 Kangra earthquake;
2) The “Central gap”, situated between the 1905 Kangra and the 1934 Bihar earthquakes;
3) The “Assam gap” between the 1897 and 1950 Assam earthquakes.
This study has shown that the above great earthquakes were preceded as well as followed by long periods (⩾ 19 years) of decreased levels of seismic activity in the epicentral regions.

Imaging lithospheric structure of the eastern Himalayan syntaxis : New insights from receiver function analysis. Qiang Xu, Junmeng Zhao, Shunping Pei and Hongbing Liu J. ***Geophys. Res. Solid Earth, 2013, 118, 2323–2332, Doi:10.1002/jgrb.50162.***

Our migrated images reveal that (1) the LAB of the Tibetan plate exists at relatively shallow depths (~110 km) and exhibits a gap beneath the Namche Barwa syntaxis, which may have formed by the delamination of mantle lithosphere due to local mantle upwelling, and (2) the LAB of the Asian plate is observed at a depth of ~180 km, which implies that the Asian plate has advanced southward to about 30N under the Lhasa terrane.

Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, Northeast India earthquake: Implications for regional tectonism. C.P. Rajendran, K. Rajendran, B.P. Duarah, S. Baruah and A. Earnest. ***Tectonics (2004), 23, TC4009, doi:10.1029/2003TC001605.***

The geophysical and geological data examined in this paper conform to a south dipping structure, but its location is inferred to be in the Brahmaputra basin, further north. Paleoseismic data suggest a 1200-year interval between the 1897 event and its predecessor.

Large and great earthquakes in the Shillong Plateau-Assam valley area of Northeast India region: Pop-up and transverse tectonics. J.R. Kayal, S.S. Arefiev, S. Baruah, D. Hazarika, N. Gogoi, J.L. Gautam, Santanu Baruah, C Dorbath and R. Tatevossian. ***Tectonophysics (2012), 532-535, 186-192, Doi.10.1016/j.tecto.2012.02.007.***

The dominating thrust/reverse faulting earthquakes in the western plateau may be explained by the proposed pop-up tectonics between two active boundary faults, the Oldham–Brahmaputra fault to the north and the Dapsi–Dauki thrust to the south, though the northern boundary fault is debated.

Low b-value prior to the Indo-Myanmar subduction zone earthquakes and precursory swarm before the May 1995 M 6.3 earthquake. Sangeeta Sharma, Saurabh Baruah, Om Prakash Sahu, Pabon K. Bora and Ranju Duarah. ***Journal of Asian Earth Sciences (2013), 73, 176-183.***

A sudden drop in the b-value, from 1.4 to 0.9, prior to the occurrence of larger earthquake(s) at the deeper depth is observed. A precursory swarm during January 1989 to July 1992 and quiescence during August 1992 to April 1995 are identified before this large earthquake.

Magnitude calibration of north Indian earthquakes. N.N. Ambraseys and J. Douglas. ***Geophys. J. Int. (2004) 159, 165–206 doi: 10.1111/j.1365-246X.2004.02323.x***

This article is concerned primarily with the evaluation of the size and location of northern Indian and southern Tibetan earthquakes during the last 200 yr. The study derives the formulae for the conversion of Ms to Mw. The study finds that the Mw–Ms scaling for India yields smaller Ms than the global relation and that the methodology used can help to evaluate more realistic slip rates as well as to address other issues related to earthquake hazard in northern India.

Occurrence of anomalous seismic activity preceding large to great earthquake in Northeast India region with special reference to 6th August, 1988. H.N. Singh, D. Shanker and V.P. Singh. ***Physics of the Earth & Planetary Interiors (2005), 148, 261-284.***

The large earthquakes of 1897, 1946, 1947, 1950 and 1951/1952 were preceded by well-developed epoch of swarm/anomalous seismic activity in space and time well before their occurrence. A prediction was made using the 1964 swarm based on the Mp and Tp values that a large earthquake with M 8 ± 0.5 with focal depth 100 ± 40 km could occur any time from 1986 to 1990 in an area bound by 21°-25.5°N latitudes and 93°-96°E longitude in Arakan Yoma fold belt.

Paleoliquefaction evidence and periodicity of large prehistoric earthquakes in Shillong Plateau India. B.S Sukhija, M.N Rao, D.V Reddy, P. Nagabhushanam, S Hussain, R.K Chadha and H.K Gupta. ***Earth Planet. Sci. Lett., 167, 269-282.***

Our paleoseismic investigations in the meizoseismal area of the 1897 earthquake revealed well-preserved liquefaction and deformed syndepositional features at 10 selected sites. The analysis of the 14C data suggests a return period of about 400–600 yr for the large earthquakes in the Shillong Plateau. This finding is the first of its kind from the Himalaya and adjoining region.

Paleoseismological evidence of surface faulting along the northeastern Himalayan front, India: Timing, size, and spatial extent of great earthquakes. Senthil Kumar, Steven G. Wesnousky, R. Jayangondaperumal, T. Nakata, Y. Kumahara and Vimal Singh. ***J. Geophys. Res., Vol. 115, B12422, Doi:10.1029/2009JB006789.***

The correlation between the two sites is supported by the observation that the large displacements as recorded at Chalsa and Nameri would most likely be associated with rupture lengths of hundreds of kilometers or more The easternmost site is located within Harmutty Tea Estate (site C) at the edges of the 1950 Assam earthquake meizoseismal area.

Plate motion of India and interseismic strain in the Nepal Himalaya from GPS and DORIS measurements. Pierre Bettinelli, Mireille Flouzat, Laurent Bollinger, Jean-Philippe Avouac, Francois Jouanne, Pascal Willis, Gyani Raja Chitrakar. ***J. Geod.(2006), Doi:10.1007/s00190-006-0030-3.***

We analyse geodetically estimated deformation across the Nepal Himalaya in order to determine the geodetic rate of shortening between Southern Tibet and India, previously proposed to range from 12 to 21 $mmyr^{-1}$. Based on an elastic dislocation model of interseismic strain and taking into account the uncertainty on India plate motion, the mean convergence rate across Central and Eastern Nepal is estimated to 19 ± 2.5$mmyr^{-1}$, (at the 67% confidence level). The main Himalayan thrust (MHT) fault was found to be locked from the surface to a depth of about 20km over a width of about 115 km. Further west, a convergence rate of 13.4 ± 5$mmyr^{-1}$, as well as a fault zone, locked over 150 km, are proposed.

Plateau Pop-up during the 1897 Assam earthquake. R. Bilham and P. England. ***Nature(Lond), 410, 806-809, 2001.***

The great Assam earthquake of 12 June 1897 reduced to rubble all masonry buildings within a region of NE India. The northern edge of the Shillong Plateau rose violently more than 11 m during rupture of a buried, 110-km-long, reverse fault, dipping steeply away from the Himalaya. The stress drop implied by the rupture geometry and the prodigious fault slip of 18±7 m, explains observed epicentral accelerations exceeding 1 g vertically, and surface velocities exceeding 3 m/s1 where Indian plate to contract locally by 4±2 mm/year, reducing seismic risk in Bhutan, but increasing it to the large populations of northern Bangladesh.

Pop-up tectonics of the Shillong Plateau in the great 1897 earthquake (Ms 8.7): Insights from the gravity in conjunction with the recent seismological results. G.K. Nayak, V.K. Rao, H.V. Rambabu and J.R. Kayal. Tectonics (2008), 27, TC1018, Doi:10.1029/2006TC002027.

To examine the possible 'pop-up' of the plateau during the great 1897 earthquake, we have estimated the energy released by this earthquake and compared it with the energy required for the 'pop-up' of the plateau, using a simplistic rigid model. It is found that the Shillong Plateau between the Oldham Fault and Dauki-Dapsi Thrust would require an energy of 4.5 _ 1019 J, which does match well with the energy released by the great earthquake of Ms = 8.7.

Precursory variation of seismicity rate in the Assam area, India. K. Khattri and M. Wyss. ***Geology, Vol. 6, No. 11, pp. 685-688, Doi: 10.1130/0091-7613 (1978) 6<685:PVOSRI> 2.0.CO,2.***

The seismicity data from 1825 to the present for the Assam (northeastern India) region show that seismicity rates there deviate from normal before and after major earthquakes.
The Assam gap, defined by the 1897 and 1950 great earthquakes, it is likely that a future major or great earthquake in this gap will be preceded by seismic quiescence.

P-wave anisotropic tomography in Southeast Tibet: New insight into the lower crustal flow and seismotectonics. Wei Wei, Dapeng Zhao and Jiandong Xu. ***Physics of the Earth and Planetary Interiors, 222 (2013), 47–57.***

A remarkable low-velocity layer with a thickness of about 20 km is revealed in the lower crust, which may reflect a mechanically weak zone capable of flow on a geological timescale. Our seismic anisotropy results suggest that the flow direction changes when it encounters the mechanically strong Sichuan basin. Most of the large earthquakes including the 2008 Wenchuan earthquake (M 8.0) and the 2013 Lushan earthquake (M 7.0) occurred at the margin of the ductile flow in the lower crust, suggesting that the seismogenesis is controlled by the deep dynamic processes.

Revisiting the earthquake sources in the Himalaya: Perspectives on past seismicity. Kusala Rajendran and C.P. Rajendran. ***Tectonophysics, Volume 504, Issues 1–4, 9 May 2011, Pages 75–88.***

This paper addresses two issues concerning earthquakes along the Himalaya plate boundary. One, the absence of surface rupture associated with the great earthquakes, vis-à-vis the purported large slip observed from paleoseismological investigations and two, the current understanding of the status of the seismic gaps in the Central Himalaya and Assam, in view of the paleoseismological and historical data being gathered.

Seismic Images of Crust and Upper Mantle Beneath Tibet: Evidence for Eurasian Plate Subduction. R. Kind, X. Yuan, J. Saul, D. Nelson, S. V. Sobolev, J. Mechie, W. Zhao, G. Kosarev, J. Ni, U. Achauer and M. Jiang. ***Science, 8 November 2002, Vol. 298, no. 5596, pp.1219-1221, Doi: 10.1126/science.1078115.***

The 410- and 660-kilometer mantle discontinuities are sharply defined, implying a lack of a subducting slab beneath the plateau. The discontinuities appear slightly deeper beneath northern Tibet, implying that the average temperature of the mantle above the transition zone is about 300°C hotter in the north than in the south.

Seismic signatures of detached lithospheric fragments in the mantle beneath eastern Himalaya and southern Tibet. Arun Singh and M. Ravi Kumar. ***Earth and Planetary Science Letters, Volume 288, Issues 1–2, 30 October 2009, Pages 279–290.***

Although presence of water in the MTZ can result in such a thickening, issues like 1) low amplitudes of the P410s and P660s conversions, 2) small dependence of their amplitudes with frequency, 3) absence of a detectable low velocity layer atop 410 and 4) lack of evidence for a 520 km discontinuity, preclude such an interpretation.

Seismicity and one-dimensional velocity structure of the Himalayan collision zone: Earthquakes in the crust and upper mantle. G. Monsalve, A. Sheehan, V. Schulte-Pelkum, S. Rajaure, M.R. Pandey and F. Wu. ***J. Geophys. Res. (2006), 111, B10301, doi:10.1029/2005JB004062***.

Earthquakes beneath the Himalayan collision zone occur at depths between near surface and around 100 km below sea level along the front of the Himalayan arc. Seismicity at depths between 50 and 100 km, confirming the presence of earthquakes in the upper mantle in the region of continental collision. The occurrence of earthquakes at sub-Moho depths favors the idea that the continental upper mantle deforms by brittle processes.

Seismicity patterns in the Himalayan plate boundary and identification of the areas of high seismic potential. K.N. Khattri and A.K. Tyagi. ***Tectonophysics (1993), 96, 281-297.***

Three possible trends of migration of epicentres of great earthquakes have been recognised:
1) The first trend starts from the 1905 Kangra earthquake, the epicentres of subsequent earthquakes migrating eastwards along the plate boundary.
2) The second trend of migration starts from the great Nepal earthquake of 1833 associated with eastward migration.
3) The third trend commences from the great Assam earthquake of 1897 and shows a westward migration of earthquake epicentres.

Seismotectonics and rates of active crustal deformation in the Burmese arc and adjacent regions. M. Radha Krishna and T.D. Sanu. ***Journal of Geodynamics, Volume 30, Issue 4, 1 November 2000, Pages 401–421.***

The study identified 12 broad seismogenic zones of relatively homogeneous deformation. The results indicate that along the Kopili–Bomdila fault zone in eastern Himalaya, the deformation is taken up as a compression of 0.12±0.01 mm/yr along N16° and an extension of 0.05±0.004 mm/yr along N104° direction. The average shear motion of about 13.7 mm/yr is observed along the Sagaing fault.

Seismotectonics of transverse lineaments in the eastern Himalaya and its foredeep. Manoj Mukhopadhyay. ***Tectonophysics, Volume 109, Issues 3–4, 10 November 1984, Pages 227–240***.

A model of basement reactivation below the Valley is proposed in order to explain the style of tectonic deformation and current seismicity in the Himalayan and Burmese orogens adjoining the Valley.

Seismotectonics of the Himalaya and its vicinity from centroid-moment tensor (CMT) solution of earthquakes. D.D. Singh. ***Journal of Geodynamics (2000), 30, 507-537.***

The study indicates that the Indian plate is subducting eastward beneath the northeast India and Burmese arc regions. The overriding Burmese arc has overthrust horizontally with the underthrusting Indian plate at a depth of 20±80 km and below 80 km depth. The Indian plate is underthrusting in the western side beneath the Pamir±Hindu Kush region.

Seismotectonics in Northeast India: A stress analysis of focal mechanism solutions of earthquakes and its kinematic implications. Jacques Angelier and Saurabh Baruah. ***Geophys. J. Int. (2009) doi: 10.1111/j.1365-246X.2009.04107.x***

The study determines the regional seismotectonic stress from the stress inversion of 285 double couple focal mechanism solutions of earthquakes with an average magnitude of 5. They then compare the reconstructed stress regimes with the available information about geodetically determined relative displacements. North–south compression, in a direction consistent with India–Eurasia convergence, prevails in the whole area from the Eastern Himalayas to the Bengal Basin, through the Shillong–Mikir Massif and the Upper Assam Valley.

Shear wave anisotropy beneath the Tibetan Plateau. Daniel E. Mc Namara and Thomas J. Owens. ***Journal of Geophysical Research, Vol. 99, No. B7, Pages 13, 655-13, 665, July 10, 1994***.

Eleven broadband digital seismic stations were deployed across the Central Tibetan Plateau in the first extensive passive-source experiment attempted within the Tibetan Plateau. One year of recording resulted in 186 event-station pairs which we analyze to determine the characteristics of shear wave splitting in the uppermantle beneath the array. The large delay times suggest that a relatively high number of anisotropic crystals are preferentially aligned within the mantle-lid beneath the north central portion of the Tibetan Plateau. In most cases fast polarization directions appear to be parallel to the surface geologic features suggesting as much as 200 km of the upper mantle has been involved in the collisional deformation that has produced the Tibetan Plateau.

Some observations on the mechanism of earthquakes in the Himalaya and the Burmese arc. Satyajit Biswas and Amit Das Gupta. ***Tectonophysics, Volume 122, Issues 3–4, 15 February 1986, Pages 325–343.***

The fault mechanisms, by and large, consistent with the northward thrusting of the Indian plate. However, orientations of pressure axes, as obtained from present and earlier mechanism solutions, suggest that the dominant northward driving force of the Indian plate is resolved into differential forces in various directions along the Indian-Burmese plate boundary.

Source parameters of the Burma-India border earthquake of July 29, 1970, from body waves. B.K. Rastogi and D.D. Singh. ***Tectonophysics, Volume 51, Issues 3–4, 20 December 1978, Pages T77–T84.***

The source parameters are determined for the Burma-India border earthquake of July 29, 1970, from body-wave spectra. We obtain seismic moment [$\overline{M}_o(P) = 4.83$, $\overline{M}_o(S) = 3.40$] · 10^{26} dyne cm, source dimension [$\bar{r}(P) = 22.5, -r \quad (S) = 27.7$] km, radiated energy [$\overline{E}_R \quad (P) = 7.19$, −ER (S) = 1.35]· 10^{20} ergs and the stress drop = 11 bars.

Spectral analysis of body waves for earthquakes and their source parameters in the Himalaya and nearby regions. D. D. Singh, B. K. Rastogi and Harsh K. Gupta. ***Physics of the Earth and Planetary Interiors, Volume 18, Issue 2, February 1979, Pages 143–152.***

The source characteristics of 33 earthquakes with magnitude m_b between 4.4 and 6.0, which occurred in the Himalayan and nearby regions, are investigated using the records of the Hyderabad seismograph station. The P- and S-wave spectra of these events are interpreted in terms of Brune's seismic source model for estimating the source parameters, i.e., seismic moment, source dimension, stress drop, average dislocation, apparent stress and the radiated energy. In general, the stress drop and apparent stress are found to be high, indicating high stresses in these regions.

Stress buildup in the Himalaya. L. Bollinger, J.P. Avouac, R. Cattin and M.R. Pandey. ***J. Geophys. Res.(2004), 109, B11405, doi:10.1029/2003JB002911.***

The pattern of current deformation along the Himalayan arc, show significant lateral variations, providing a possible explanation for the uneven microseismic activity along the Himalayan arc. The uneven seismicity pattern is shown to reflect the impact of the topography on the stress field, indicating low deviatoric stresses (<35 MPa) and a low friction (<0.3) on the Main Himalayan Thrust. Arc-normal thrusting along the Himalayan front and east-west extension in southern Tibet are quantitatively reconciled by the model.

Teleseismic P-wave residual Investigations at Shillong, India. H.K. Gupta and V.P. Singh. ***Tectonophysics (1980), Vol. 66, pp. 19-27.***

The northeast India region is seismically very active and it has experienced two large earthquakes of magnitude 8.7 during the last eight decades (1897 and 1950). We have analysed teleseismic P-wave residuals at Shillong, the only reliable seismic station operating in the region, to investigate a possible association of travel-time residual anomaly with earthquake occurrence. The period covered is from October 1964 through March 1976. The total number of events is 9479, including 1767 events with depth >/ 100 km. Six-monthly average residuals have been calculated. The standard deviations are less than 0.10 sec for these data sets. During the period of investigations, no major earthquake took place close to Shillong. The earthquake of June 1, 1969 with a magnitude (Mb) of 5.0, at an epicentral distance of 20 km from Shillong is the only significant event. This earthquake is found to be associated with a travel-time increase with a maximum amplitude of 0.4 sec. It appears that, in general, the P-wave velocity has decreased in the neighbourhood of Shillong since 1969. A quadrant-wise analysis of residuals indicates that the residual anomaly is most prominent in the SE quadrant from Shillong.

Thickening of a basalt layer as a possible cause for the uplift of the Himalayas — A suggestion based on gravity data. M.N. Qureshy. *Tectonophysics, Volume 7, Issue 2, February 1969, Pages 137–157*.

The study indicates a crustal thickness of 42.5 km beneath the northern peninsular shield, 31.5 km beneath the Indo-Gangetic Basin and of 81 km beneath the middle Himalayas is obtained. It is inferred that the Himalayan block is an activated portion of the peninsular shield, where the crustal thickening has been achieved by thickening of the basaltic layer by an amount of 50 km, which in turn might be causally related to the uplifting of the Himalayas. Movement of nappes and formation of recumbent folds might be due to gravity gliding as a consequence of the vertical movements.

The Active Tectonics of the Eastern Himalayan Syntaxis and Surrounding Regions. Williame Holt, James F. Ni, Terry C. Wallace and A.J. Haines. *Journal of Geophysical Research, Vol. 96, No. B9, Pages 14,595-14,632, August 10, 1991.*

Earthquakes near the Sagaing fault show strike-slip mechanisms with right dateral slip. Earthquakes on its northern splays, however, indicate predominant thrusting evidence that the dextral motion on the Sagaing fault, which accommodateas portion of the lateral motion between India and Southeast Asia, terminates in a zone of thrust faulting at the Eastern Himalayan Syntaxis. Relative to a point within Western Sichuan (32ºN, 100ºE), the velocity field shows that the Yunnan crust is moving S-SE at rates of 8-10 mm/yr. Relative to South China, there is no eastward expulsion of crustal material beyond the eastern margin of the Tibetan plateau.

The Great 1950 Assam Earthquake revisited- Field evidence of liquefaction and search for paleoseismic events. D.V. Reddy, P. Nagabhusanam, Devender Kumar, B.S. Sukhik, P.J. Thomas, Anand K. Pandey, R.N. Sahoo, C.V. Ravi Prasad and K. Datta. *Tectonophysics (2009), 474, 463-472.*

14C dating of the organic material associated with some of the features indicates a paleoseismic record of about 500 yrs archived by the sediments in this region. Out of the two historically reported seismic events (1548 AD and 1697 AD) from this region, 14C dating could constrain the 1548 AD event though not distinctly.

The motion and active deformation of India. J. Paul, R. Burgmann, V.K. Gaur, R. Bilham, K.M. Larson, M.B. Ananda, S. Jade, M. Mukal, T.S. Anupama, G. Satyal and D. Kumar. ***Geophysical Research Letters, Vol. 0, No. 0, Pages 0-0, M 0, 2000.***

The GPS velocities of plate-interior sites constrain the pole of the angular velocity vector of India with respect to Eurasia to lie at 25.6±1.0ºN 11.1±9.0ºE, approximately 6º west of the NUVEL-1A pole of < 3 Ma plate motion.

The seismic b-value and its correlation with Bouguer gravity anomaly over the Shillong Plateau area: Tectonic implications. P.K. Khan and Partha Pratim ChakrabortyD:\Project-0273\Project_Bibliography\GPP-0273\ScienceDirect.com - Journal of Asian Earth Sciences - The seismic b-value and its correlation with Bouguer gravity anomaly over the Shillong Plateau area Tectonic implications.htm - aff2**.** ***Journal of Asian Earth Sciences, Volume 29, Issue 1, 15 January 2007, Pages 136–147.***

The study indicates correlation between the seismic b-value and the Bouguer gravity anomaly for the plateau. Positive Bouguer anomaly values as high as +40 mgal, a steep gradient in the Bouguer anomaly map and low b-values in the southwestern part of the plateau are interpreted as indicating a thinner crustal root, uplifted Moho and higher concentration of stress.

The source of the Great Assam Earthquake—An interplate wedge motion. Ari Ben-Menahem, Ezra Aboodi and Rivka Schild. ***Physics of the Earth and Planetary Interiors, 9 (1974), 265—289.***

The source of the Assam earthquake of Aug. 15, 1950 is revealed from amplitude observations of surface and body waves at Pasadena, Tokyo and Bergen. It is believed that the earthquake was caused by a motion of the Asian plate relative to the eastern flank of the Indian plate where the NE Assam block is imparted a tendency of rotation with fracture lines being developed along its periphery.

The status of central seismic gap: A perspective based on the spatial and temporal aspects of the large Himalayan earthquakes. C.P. Rajendran and Kusala Rajendran. ***Tectonophysics, Volume 395, Issues 1–2, 6 January 2005, Pages 19–39.***

We suggest that the long-term quiescence and the spatial and temporal clustering that characterize the distribution of large earthquakes in the Himalaya, is a manifestation of the tectonic deformation associated with a highly evolved fold and thrust belt. Our analyses also indicate that the large/moderate earthquakes are mostly concentrated on higher-level thrusts.

The tectonic stress field and deformation pattern of northeast India, the Bengal basin and the Indo-Burma Ranges: A numerical approach. Md. Shofiqul Islam, Ryuichi Shinjo and J.R. Kayal. ***Journal of Asian Earth Sciences, Volume 40, Issue 1, 4 January 2011, Pages 121–131.***

The modeling indicates that the Brahmaputra valley to the north of the Shillong plateau and to the south of the Himalayan frontal thrust exhibits thrust/reverse faulting with a strike-slip component, and in the Indo-Burma Ranges, strike-slip faulting is predominant with a reverse fault component.

3-D seismic structure of the northeast India region and its implications for local and regional tectonics. Pankaj Mala Bhattacharya, S. Mukhopadhyay, R.K. Majumdar and J.R. Kayal. ***Journal of Asian Earth Sciences (2008), 33, 25–41.***

3-D P-wave velocity structure of northeast India has been ascertained. High Vp is mapped beneath the Shillong Plateau–Mikir hills and in the vicinity of Indo-Burma ranges at shallower crust (<10 km) suggesting dense crystalline rocks under compressional stress. A prominent NW–SE trending low Vp structure is imaged between the Shillong Plateau and Mikir hills at 20 km depth, which corresponds to the Kopili fault. The Kopili fault system extends down to 30 km depth as evidenced by the low Vp. A high Vp is imaged below the Mikir hills at 40 km depth, which is possibly the stress concentrator for high seismic activity along the Kopili fault, particularly at the fault end. The Bengal basin, south of the Shillong Plateau, is identified as a low Vp zone extending down to a depth of about 20 km, that indicates the thick alluvium sediments.

6.1.1 Critical parameters evaluated for NE India

There is imminent need in finding out how to establish a precursory phenomena.
It is essential to pursue various aspects of computational seismology.
Strengthening pre-disaster earthquake preparedness and mitigation plan in NE India.
Seismic microzonation studies of populous cities.
Vulnerability assessment.

6.2 REVIEW OF MOST VALUABLE LITERATURES ON EARTHQUAKE HAZARD ASSESSMENT IN USA, TAIWAN, IRAN AND JAPAN

USA

Ebel and Kafka (1999) Monte Carlo methodology is developed for seismic hazard estimation by resampling earthquake catalogues supplemented by parametric models to produce synthetic catalogues and calculation of earthquake ground motions and hence hazard values. Estimates are randomly selected from observed ground motions or a parametric ground motion attenuation relationship is used. The method yields good results at standard seismic hazard values. The hazard values depend to some extent on the duration of the synthetic catalog and the specific ground motion attenuation used, and the uncertainty in the ground motions increases with decreasing hazard probability.

Field et al (1999) Previously developed probabilistic-hazard source model shows a deviation from the observed data rate due to the upper magnitude level built into the model. A new and more promising model is proposed that agrees well with the historical record and does not invoke any unsubstantiated phenomena where several factors are found to be influential as the *b*-value and minimum magnitude applied to Gutenberg-Richter seismicity; the percentage of moment released in characteristic earthquakes; a round-off error in the moment-magnitude definition; bias due to historical catalog incompleteness; careful adherence to the conservation of seismic moment rate; uncertainty in magnitude estimates obtained from empirical regressions; allowing multisegment ruptures (cascades); and the time dependence of recurrence rates.

Cramer et al (2000) A model of PSHA incorporating available consensus information of the seismotectonics, for California is developed for the purpose of sensitivity testing. Intrinsic (aleatory) sigma, multisegment (cascade) vs. independent segment (no cascade) ruptures, and time-dependence vs. time-independence are estimated in the sensitivity testing.
Stirling and Petersen (2006) Comparison is performed between the historical record of earthquake hazard experienced at 78 sites distributed across New Zealand and the continental United States with the hazard estimated from the national probabilistic seismic-hazard (PSH) models. The hazard rate is seen to be higher than the experienced for the interplate region and lower for the intraplate region.

Harmsen et al (1999) The separation of the exceedance contributions into bins whose base dimensions are magnitude and distance is carried out in the hazard analyses for the new USGS national probabilistic ground-motion hazard maps. For grids in United States (CEUS), maps of the geographical variation of mean and modal magnitudes ($\bar{M}$, $\check{M}$) and distances ($\bar{D}$, $\check{D}$) for ground motions having a 2% chance of exceedance in 50 years are prepared. These maps are displayed for peak horizontal acceleration and for spectral response accelerations.
Mcguire (1977) The effect of decisional and statistical uncertainties on the calculated seismic hazard for the east coast US is assessed by deriving probability distributions on the important parameters. It was not justifiable to predict the highest magnitude of possible earthquake, which may or may not exceed the past highest magnitude. The intensity associated with a probability of exceedance in the magnitude range VII to IX are studied carefully. Several disadvantages of using a strictly deterministic procedure to determine design intensities are disclosed by this study.

Harmsen and Frankel (2001) The seismic hazard calculations for the 1996 national seismic hazard maps have been geographically deaggregated to assist in the understanding of the relative contributions of sources. Ground-motion exceedance hazard by each geographical unit are studied. Geographic deaggregation for 0.2-sec and 1.0-sec pseudo spectral acceleration (SA) is performed for 10% probability of exceedance (PE) in 50 yr (475-yr mean return period) and 2% PE in 50 yr (2475-yr mean return period) for four western U.S. cities. This allows the investigator to to determine the distance and azimuth to predominant sources, and their magnitudes.

Cao et al (2005) Monte Carlo simulation is implemented to explore the source and ground-motion model uncertainty and parametric sensitivity for the existed PSH maps, which allows for independent sampling from fault to fault in each simulation. The uncertainties from one-fault and two-fault systems are studied in detail. The variation of Co-efficient of variation from 0.1 to 0.6 (ratio of the standard deviation to the mean) is observed among different faults.

Petersen et al (1996) The seismic ground motion hazard is assessed for a 10% probability of exceedance in 50 years for the three counties (Los Angeles, Ventura, and Orange) impacted by the 1994 Northridge earthquake (*Mw* 6.7). Peak horizontal ground acceleration (pga) and 5% damped spectral acceleration (SA) (0.3 and 1 sec) were calculated with three equally weighted attenuation relationships of Boore *et al.* (1993), Campbell and Bozorgnia

(1994), and Sadigh (written comm., 1994). A Monte Carlo uncertainty analysis for two sites yields 95% confidence limits for peak ground acceleration at the two sites that range between ±0.1 and ±0.2 *g*.

Haase et al (2011) The PSHA is conducted for the Evansville region incorporating new information from recent surficial geologic mapping efforts, as well as information on the depth and properties of near-surface soils and their associated uncertainties with modifications modifications to incorporate estimates of local site conditions and their uncertainties, in a completely probabilistic manner. The resulting analysis shows strong local variations of acceleration with 2% probability of exceedance in 50 yr, which are clearly correlated with variations in the thickness of unconsolidated soils above bedrock.

Cao et al (1987) Seismic hazard Assessment is carried out for Southern California from background seismicity of magnitude 6.5 or smaller. Declustered California seismicity catalog is used to compute the rate of earthquakes on a grid and then smoothed to account for the spatial distribution of future earthquakes. It is found to follow 1/r power-law relationship with distance. PGA is calculated for 10% probability of exceedance in 50 yr and found to be ranged between 0.25 and 0.35 *g*.

Ihnen and Hadley (1987) A PGA distribution map constructed for hazard estimation in Washington incorporating the effects of local seismicity patterns, type of soil, and subsurface geology, shows the average PGA for the region where a 5 per cent chance of exceedence in 50 yr is approximately 0.3*g*. PGAs on the map vary from 02g to 0.6g.

Agnew et al (1995) Geodetic, geologic and seismic information are integrated to estimate frequencies of damaging earthquakes in three types of seismotectonic zones in Southern California. Each zone is assumed to have randomly distributed earthquakes plus characteristic earthquakes on specific faults within which, distributed earthquakes are assumed uniform in time and space, with a truncated Gutenberg-Richter magnitude distribution. Thus, seismic hazard is defined by the characteristic earthquake rate, the rate of all distributed events, and the limiting (characteristic) magnitude. A preferred hazard model is presented with lognormal recurrence and an alternate Poissonian model.

Hashash et al (2008) Probabilistic seismic hazard analysis (PSHA) with nonlinear site effects (NL) with extensions to (1) incorporation of a finite-fault model capable of generating near-source motions instead of using point source models only, (2) better approximation of the range of available attenuation relations for the Central and Eastern United States (CEUS), (3) examination of the hazard at very high levels of shaking, and (4) propagation of generated rock motions through randomized soil profile properties to achieve a more consistent probabilistic procedure, procedure is used to develop updated depth-dependent site coefficients for the Upper Mississippi Embayment.

Mcguire and Shedlock (1981) Efficient and accurate methods of estimating the sensitivity of seismic hazard calculations to statistical uncertainties in models and parameters which incorporates the knowledge of the earthquake magnitude and distance that contribute most to the probability of exceedence of a chosen acceleration level are demonstrated. The methods estimate sensitivities using point-source seismic-hazard approximations for which closed-form solutions are available. Use of Bayesian estimates for seismicity and ground motion parameters in the hazard analysis produces unbiased Bayesian estimates of the seismic ground motion hazard, due to the almost linear relationship between ground motion amplitudes at a given probability level, and parameter uncertainties.

Cao et al (1999) The formulas for the estimation of expected loss from probabilistic seismic hazard are presented systematically by using the basics of calculating expected values and the concept of distributing the total loss between the insurer and the insured. The conversion from acceleration to intensity and then to loss factor (the ratio of damage value to the property value) is applied in the calculation. The calculated loss values show a strong dependence on the hazard and the soil conditions. The deaggregation of total loss with respect to intensity, acceleration, and loss factor shows that a greater portion of the total loss in the high-hazard region is from large intensities and accelerations compared with the low-hazard region.

Mueller (2010) Sensitivity of seismic-hazard estimates in the central and eastern United States (CEUS) to maximum magnitude (*m*max) is analyzed by USGS probabilistic hazard model. For 2% probability of exceedance in 50 years (about 0.0004 annual probability), the strong *m*max truncation produces hazard ratios equal to 0.35–0.60 for 0.2- sec spectral acceleration, and 0.15–0.35 for 1.0-sec spectral acceleration. Hazard ratios increase 0–15% for 0.002 annual exceedance probability and decrease 5–25% for 0.00001 annual exceedance probability.

Hamdache (1998) The seismic hazard in northern Algeria is estimated using both physical strain energy release and Gumbel's extreme values approaches. Gumbel's extreme values approach has been used to estimate seismic hazard in terms of magnitude and P.G.A at each point of an equispaced grid all over the north of Algeria. The results are presented mainly in the form of graphs and contour maps of magnitudes (respectively PGA) with a 60% probability of not being exceeded in the next 100 and 200 years.

Adams and Halchuk () Estimation of median ground motion on firm soil sites for a probability of exceedence of 2% in 50 years in done by summarizing the methods being used for new seismic hazard maps of Canada. Spectral acceleration at 0.2, 0.5, 1.0 and 2.0 second periods and peak acceleration forms the basis of the seismic provisions of the 2005 National Building Code of Canada.

Adams and Atkinson (2001) A new seismic hazard model for Canada incorporatig new knowledge from recent earthquakes (both Canadian and foreign), new strong ground motion relations to describe how shaking varies with magnitude and distance, the newly recognized hazard from Cascadia subduction earthquakes, and a more systematic approach to reference site conditions is developed with new innovations as hazard computation at the 2% in 50 year probability level, the use of the median ground motions, the presentation of results as uniform hazard spectra, and the explicit incorporation of uncertainty via a logic-tree approach.

Chang and Smith (2002) Combined effects of different sources that influence earthquake hazard of the populated Wasatch Front, Utah are examined. Estimates of the static-stress change for two largest historic earthquakes): the 1959 Hebgen Lake (*M*s 7.5) and the 1983 Borah Peak (*M*s 7.3) revealed an increase in Coulomb failure stress in areas of extended aftershocks. The modeling technique to the Wasatch Fault applied and examined the relation between the pattern of stress change and the space– time distribution of paleoearthquakes. Here multisegment rupture model is preferred. After analysis it is found that the occurrence rate of *M*w ! 6.6 Wasatch paleoearthquakes is three times higher than that inferred by the historical seismicity. The recurrence rate of large earthquakes estimated by the geodetic-measured strain, on the other hand, is three to four times higher than that estimated by the long-term fault-slip rate. Authors also examined a major consideration for along-strike segmentation, namely, how stress "contagion" could affect the probability of failure of adjacent faults. Including paleoearthquake-derived fault-slip rates, global positioning system derived geodetic moment rates, and the effect of stress contagion in the earthquake-hazard estimation for a specific location in the Salt Lake Valley revealed an increase in the annual frequency of peak ground acceleration! 0.25g by a factor of 1.4, 4.0, and 5.4, respectively, compared with that derived from historical seismicity only.

Bryant G. Nielson, M.EERI and Reginald Des Roches. This study develops seismic fragility curves for nine classes of bridges (common three-span, zero-skew bridges with non-integral abutments) common to the central and southeastern United States using 3-D analytical models and nonlinear time-history analyses which shows that multispan steel girder bridges are the most vulnerable of the considered bridge classes while single-span bridges tend to be the least vulnerable.

Susan E. Hough (2001). The results of this study suggest that potentially damaging triggered earthquakes may be common following large mainshocks in stable continental regions. Thus, in areas of low seismic activity such as central/ eastern North America, the hazard associated with localized source zones might be more far reaching than previously recognized. The results also provide additional evidence that intraplate crust is critically stressed, such that small stress changes are especially effective at triggering earthquakes.

Robert L. Wesson, Arthur D. Frankel, Charles S. Mueller, and Stephen C. Harmsen Probabilistic seismic hazard maps have been prepared for Alaska portraying ground motion values (peak ground acceleration and spectral amplitude at periods of 0.2, 0.3 and 1.0 seconds) at probabilities of exceedance of 2% and 10% in 50 years. Preparation of these maps followed the same general strategy as that followed for the U.S.G.S. seismic hazard maps of the contiguous United States, combining hazard derived from spatially-smoothed historic seismicity with hazard from fault-specific sources. Preparation of the Alaska maps presented particular challenges in characterizing the hazard from the Alaska- Aleutian megathrust.

S.T. Algermissen, D.M. Perkins, P.C. Thenhaus, S.L. Hanson and B.L. Bender (1982). Maximum horizontal accelerations and velocities caused by earthquakes are mapped for exposure times of 10, 50 and 250 years at the 90-percent probability level of nonexceedance for the contiguous United States. In many areas these new maps differ significantly from the 1976 probabilistic acceleration map by Algermissen and Perkins because of the increase in detail, resulting from greater emphasis on the geologic basis for seismic source zones. This new emphasis is possible because of extensive data recently acquired on Holocene and Quaternary faulting in the western United States and new interpretations of geologic structures controlling the seismicity pattern in the central and eastern United States.

Zhenming Wang (2007). In this paper, seismic hazard is defined as the natural phenomenon generated by earthquakes, such as ground motion and is quantified by two parameters: a level of hazard and its occurrence frequency or mean recurrence interval; seismic risk is defined as the probability of occurrence of a specific level of seismic hazard over a certain time and is quantified by three parameters: probability, a level of hazard and exposure time.

Zhenming Wang (2006). Seismic hazard and risk are fundamentally different concepts. Seismic hazard describes phenomena generated by earthquakes that have potential to cause harm, but seismic risk is the likelihood (chance) of experiencing a specified level of seismic hazard in a given time exposure. Seismic hazard occurs naturally and can be evaluated from instrumental, historical, and geological observations. Seismic risk depends not only on the hazard and exposure, but also on models (i.e., time-independent [Poisson] and time-dependent ones) used to describe the occurrence of earthquakes. High seismic hazard does not necessarily mean high seismic risk, and vice versa.

IRAN

ROWSHANDEL et al (1981) Point, line, and area seismic sources with a modification of line source model to take into account the uncertainty associated with the exact location of the line (i.e., fault). cumulative functions of PGA for major sites in the northwest Iran are presented. Iso-acceleration maps for two different return periods are also developed for each seismic source model and a comparison is made among the results of the models.

QUITTMEYER and JACOB (1979) Both historical (noninstrumental) and modern (instrumental) data are compiled and critically reviewed to document the seismicity of Pakistan, Afghanistan, northwestern India, southeastern Iran, and neighboring areas. For some of the larger earthquakes, in both historical and modern times, the orientation and length of the rupture zone, and an approximate value of the seismic moment, are estimated.

PAPASTAMATIOU (1980) The incorporation of the crustal deformation to the inputs of the PSHA is discussed on the basis of a relationship between the rate of crustal deformation and the seismicity parameters. The formulation is in terms of the seismic moment, a function of the crustal deformation at the earthquake source, and a 3D representation of seismogenic sources. The relationship between tectonic and seismicity parameters is presented in a graphical form, and its implications are discussed on the hazard of a seismic dislocation at a site on an earthquake fault.

HEDAYATI (1976) Microearthquake survey of part of north central Iran is carried out. The cumulative number versus magnitude relation was obtained from the study. Composite fault-plane solutions were made for each of the three principal groups. The seismic intensity risk curve calculated for the area.

Amiri et al (2003) Amiri et al (2008) A collected catalogue, (4th century BC to 1999) is used. Seismic sources are modelled and recurrence relationship is established using method of Kijko [2000] considering uncertainty in magnitude and incomplete earthquake catalogue. The calculations were performed using the logic tree method and three weighted attenuation relationships; Ramazi [1999], 0.4, Ambraseys and Bommer [1991], 0.35, and

Sarma and Srbulov [1996], 0.25. SHA is carried out using SEISRISK III. Two seismic hazard maps of the studied area based on (PGA) over bedrock for 10% probability of exceedance in two life cycles of 50 and 100 years are presented.

Hamzehloo (2007) A hybrid method for the calculation of realistic synthetic seismograms in laterally heterogeneous, anelastic media has been used to model the ground motion in Tehran city. The amplification pattern of seismic waves in Tehran were found by studying the ratio between the response spectrum for the signals calculated along a laterally varying structure, Sa(2D), and that for the signals at the bedrock regional reference structure, Sa(1D). Zamani et al (2012) The classification and regression tree method is used to extract rules that predict regions with high hazard of earthquakes. The multivariate rule-based seismicity map (MRBSM) allows identification of the most important parameters associated with earthquakes. For Iran it is found that the isostatic anomaly has the strongest correlation with earthquakes while magnetic intensity, regional Bouger anomaly, Bouger anomaly, and gravity anomaly also correlate well.

Ghasemi (2009) A new ground-motion prediction equation applicable at wider ranges of magnitude and distance for 5%-damped horizontal spectral acceleration applicable to Iran is presented and applicability of the proposed model, as well as those of several other models developed for shallow crustal environments, is also investigated by means of statistical tools.

Jafari (2007) A time-independent Bayesian approach, which yields the probability that a certain cut-off magnitude will be exceeded at certain time intervals is examined for the region of Alborz, Iran. In this study an updated earthquake catalog is compiled for the Alborz Then, by assuming a Poisson distribution for the number of earthquakes which occur at a certain time interval, the probabilistic earthquake occurrence is computed by the Bayesian approach.

Vaziri et al (2010) A new optimization model is presented to help cities in seismically active developing countries decide (1) How much to spend on pre-earthquake mitigation versus waiting until after an event and paying for reconstruction or simply not rebuilding damaged buildings? (2) Which buildings to mitigate and how? and (3) Which buildings to reconstruct and how?

Omidvar et al (2012) The aim of this research is to prepare vulnerability curves for the residential buildings of Iran to provide a proper base for estimating probable damage features by future earthquakes. Through the use of the European Macroseismic method, a model for evaluating the vulnerability of the Iranian buildings is proposed. This method allows the vulnerability assessment for numerous sets of buildings by defining the vulnerability curves for each building type based on the damage observations of previous earthquakes.

Ali Shafiee et al (2011) The International Institute of Earthquake Engineering and Seismology (IIEES) performs both probabilistic and deterministic seismic hazard analysis. IIEES uses his own fault map for seismotectonic studies and develops modulus and damping curves for the soils in the study area. IIEES made improvement by including developing 2D and 3D modelling of basin and topographical effects, using microtremor measurements to find shear-wave velocity profiles in high-density urban areas and providing maps for spectral acceleration in the study area.

Ali M Rajabi et al (2011) Estimation of earthquake-induced landslide hazard. Evaluation of the expected permanent displacement (named ''Newmark displacement'') induced by seismic shaking of defined energy on potential sliding surface characterized by a given critical acceleration. The method proposed by Jibson (Eng Geol 91:209–218, 2007) consists of evaluating the shear resistance required to slopes to limit the occurrence of seismically induced failures, on the basis of the Newmark's model.

Hosseini and Ghayamghamian (2012) In this paper Strategies toward risk mitigation in the country are addressed, and a number of indices for the assessment of the geo-hazard risk reduction plans and activities are introduced. Finally, a conceptual model for the evaluation of the preparedness level against geo-hazards is proposed and discussed.

Ghobadi and fereidooni (2012) (DSHA and PSHA) is done for Hamedan city by using historic and instrumented earthquakes, geologic and seismotectonic parameters of the region and studying faults and fault zones in the study area. MCE and PGA is calculated for each fault zone and probabilityof recurring of certain earthquake at certain period is determined and also the 'a' and 'b' parameters were estimated.

Yaghmaei and Motallebzade (2012). Application of site modifications to the ground motion prediction equation based on generic site classes and use of constant coefficients and use of a close-form solution that modifies the hazard results at the rock level is done in order of PSHA of Tehran. Also, efficiency of the Monte Carlo method in modeling of amplification function for the six selected sites in the study area was examined.

Tavakoli (2002) The sensitivity and overall uncertainty in peak ground acceleration (PGA) estimates have been calculated for the city of Tabriz, northwestern Iran by using a specific randomized blocks design. Eight seismic hazard models and parameters with randomly selected uncertainties at two levels have been considered and then a linear model between predicted PGA at a given probability level and the uncertainties has been performed.

Abdalla and Homoud (2004) PSHA is done for UAE. Geology and tectonics of the area is reviewed. An updated earthquake catalogue is used. Seismic source regions are modeled and relationships between earthquake magnitude and earthquake frequency is established. Seismic hazard maps based on probable PGA for 10% probability of exceedance for time-spans of 50 and 100 years is shown.

Boore et al Ground motion prediction equations are derived for average horizontal components ground motion as PGA, PGV, 5% damped pseudo absolute acceleration spectra (PSA) at periods between 0.01s and 10s derived by empirical regression of an extensive strong-motion database

Arkady S. Karakhaniana et al. (2004). Active fault zones of Armenia, SE Turkey and NW Iran present a diverse set of interrelated natural hazards. Three regional case studies in this cross-border zone are examined to show how earthquakes interact with other hazards to increase the risk of natural disaster. The case study demonstrates that natural hazards that are secondary with respect to earthquakes may considerably increase the damage and the casualties and increase the risk associated with the seismic impact.

Hojjat Ollah Safari et al. (2010). In this paper, we have used remote sensing techniques and image interpretation for the identification of the Niayesh, Lahbari, Andika and MIS fault zones in the studied area. Further, the study exploited seismic potential mapping using the remote sensing techniques.

MAX WYSS and AZM S. AL-HOMOUD (2004). We estimate the losses due to 10 scenario earthquakes in 150 settlements of the United Arab Emirates (UAE). For southern Iran, we use four source zones and the maximum magnitudes in them as determined by GSHAP ($7.2 \leq M \leq 8.1$).

JAPAN

Wu et al (1995) A renewal hybrid mode incorporating a renewal-time, characteristic-magnitude model for larger earthquakes with the conventional exponential-time, exponential-magnitude model for smaller earthquakes is proposed for seismic hazard analysis. The exact and the approximate ("first-event") hazards estimated by this model are discussed and found convincing. The new hybrid model is expected to produce hazard estimates close to those of more complicated non-Poissonian models.

Kanno et al (2006) A suitable attenuation model for strong ground motion having only three variables: earthquake magnitude, shortest distance to the seismic fault plane, and focal depth is developed. To improve predictions given by the model, site correction terms are adopted and additional terms for correcting regional anomalous seismic intensity with respect to the base model are determined.

Uetake and Kudo (2005) Site amplifications at rock sites and sediment sites of Ashigara Valley, Japan, using ground-motion data from five remote large events are compared. Coherency at low frequency and long wavelength is found for both sites. The amplification factors of sediment sites deviated 2–10 times with respect to the rock site in the frequency range higher than 0.1 Hz, in which significant peaks at about 1–2 Hz were found at most sites.

Wesnousky et al (1984) Integration of geological and seismological data for the analysis of seismic hazard is demonstrated. Several observations indicate that the geologic record of Quaternary fault offsets contains sufficient information to predict both the spatial and size distribution of intraplate earthquakes in Japan. A contour map of the average recurrence time of ground shaking of JMA intensity ≧V is thus computed using an empirical relation and assuming that the repeat time T of earthquakes on each Quaternary fault equals M0/M0 . The map demonstrates how Quaternary fault data may be used to assess long-term seismic hazard in areas of active faulting where historical records of seismicity are relativel short or absent. A simple procedure is used to demonstrate how the time-dependent nature of the earthquake cycle affects the evaluation of seismic hazard.

Wesnousky (2010) Possibility of Biases in the Estimation of Earthquake Recurrence and Seismic Hazard from Geologic Data is studied. It is suggested that large earthquakes rupture to increasingly greater depths below the seismogenic layer and that the portion of slip on faults accommodated by aseismic processes may be inversely related to the length of rupture expected to occur on them. Hence expected seismic moment per unit area of earthquakes on mapped faults may be systematically overestimated as a function of rupture length/

Goda and Atkinson (2009) Characterization of Spatially Correlated Response Spectra for Earthquakes in Japan is done by Probabilistic method. Seismic hazard and risk assessments of spatially distributed infrastructural systems require seismic demand models that capture random but correlated simultaneous seismic effects at multiple sites. This study characterizes spatially correlated ground-motion parameters probabilistically using comprehensive databases of the K-NET and KiK-net strong-motion networks in Japan by developing a ground-motion prediction equation and then investigating the correlation structure of regression residuals from the prediction equation.

Goda and Atkinson (2009) A Probabilistic model of the peak ductility demand of inelastic SDOF systems with various hysteretic characteristics is developed using comprehensive sets of strong ground-motion records observed in Japan. Nonlinear dynamic analysis of inelastic SDOF systems is carried out for statistical analysis and probabilistic modeling of the peak inelastic seismic demand. Analysis results indicate that the inelastic seismic demand depends on earthquake type, selection criteria, and seismological parameters to some degree.

NAVA and ESPÍNDOLA (1993) A method for the evaluation of seismic hazard for a seismogenic region from catalog seismicity data is presented. This method includes consideration of causal processes involved in elastic energy accumulation that result in the concept of seismic gaps and deals in a stochastic way with random effects that cannot be treated deterministically. Information contained in catalogues corresponding a seismic gap is used for to calibrate a model describing the distribution of magnitudes as a function of the elastic energy stored in it. Afterwards distributions of recurrence times are obtained from results of long simulations using the calibrated model.

Miyazawa and Mori (2009) Maximum seismic intensity maps for Japan are constructed using the recorded intensity data from 1498 to 2007 and are used to test the probabilistic seismic hazard map. The historical intensity maps are compared with the hazard maps of probable maximum sei smic intensity for a 475-yr return period, assuming a Poisson distribution (10% in 50 yrs). All types of earthquakes including subduction zone and crustal earthquakes are considered for the study. Statistically for the events over magnitude 4, good correlation is found between the observed and predicted intensity for all events except onshore crustal earthquakes.

Koravos et al (2006) A probabilistic seismic hazard assessment was performed for the Japanese islands and surrounding areas. Seismic hazard parameters characteristic of the seismic history of the regions were obtained. The probability of occurrence of a large M ‡ 7 earthquake within a 10- and 50-year period was also calculated.

Nava et al (2005) A new statistical method is presented for seismic hazard evaluation based on modeling the transition probabilities of seismicity patterns in the regions of a geographic area during a time interval, as a Markov chain. A byproduct of the method, regional occurrence probabilities determined from the transition probabilities, also provides good results.

Bormann (2011) (Review paper) Earthquake prediction research and applications are discussed in brief. It outlines the underlying expectations, concepts, and hypotheses, introduces the technologies and methodologies applied and some of the results obtained, which include both partial successes and failures. Dependence on classical probabilistic seismic hazard assessment, developments over last 50 years. arrival of new methodologies are discussed in brief.

Panza et al (2011) Advanced seismic hazard assessment is carried out to supply multifaceted information on the modern tools for seismic hazard assessment (SHA), and to make clear the significant difference between hazard and risk, and hazard mitigation and risk reduction. The steps of the study are identification of the issues in the current SHAs, facilitation of the development of a scientifically consistent approach for SHA and to disseminate, both in scientific and in engineering practice societies, advanced reliable tools for independent hazard estimates, which exploit, as much as possible, the available seismological, geological and geophysical information.

Fujiwara et al (2003) Seismic observation data obtained were used to estimate the dynamic characteristics of the surface soils around the lake and the seismic hazard for Hikone City. Transfer functions of the surface soil in each ward were calculated from the earthquake records. Assuming a scenario earthquake at the Hyakusaiji fault close to Hikone City, maximum ground motions were obtained for 15 city blocks in order to establish a damage estimation for that city. . The number of collapsed wooden houses and the damage ratio were calculated based on the distribution of construction of wooden houses by year.

Kossobokova and Nekrasova (2012) Reliability of Global Seismic Hazard Assessment Program is analyzed in detail by studying the trend of large earthquakes occurred in period 2000-2011. The GSHAP map were found flawed and contradictory with the observed program.

Toda (2008) Well recorded aftershocks and well-determined source models of Noto Hanto earthquake are studied to see the stress pattern associated with the faulting mechanism. Focal mechanism solutions were carried out for almost 755 of the moderate sized aftershocks and were brought closer to the main shock , with the correlation best for low apparent fault friction. Coulomb Hypothesis seemed to be worked well for the sequence and due to less stress change observed, probability of strong shaking in and around the epicentral area were predicted still to be high.

Shabestaria et al (2004) Observed peak ground motion distribution due to two past earthquakes were compared with the estimated spatial distribution of ground motion using subsurface geology layers and local soil condition information. Ground motion values were converted to those at a hypothetical ground base-rock level (outcrop) using an amplification ratio based on geomorphological and subsurface geology information. An assumed attenuation relationship is applied. Finally, the spatial distribution of ground motion at ground surface is obtained by applying GIS-based amplification factors for the entire region and found in good correlation with the observed data.

Lockman and Allen (2007) Scaling relations between the predominant period of P-wave arrivals and earthquake magnitude are studied and interpreted to estimate/determine the magnitude of the earthquake. The accuracy of magnitude estimates increases with the number of stations reporting predominant period observations.

Stein et al (2006) Reinterpretation of Tokyo's tectonic structure, identification of active faults and their slip rates and estimation of their earthquake frequency have been done in order to assess probabilistically the earthquake hazard. Recurrence period for large earthquakes has been calculated with a certain level of probability. This approach permits robust estimates for the spatial distribution of expected shaking, even for sites with few observations. Shaking probability at difference places has also been calculated.

Sunuwar et al (2003) GIS is applied for PSHA in urban areas. The most recent historical earthquake data of Japan is used for the probabilistic seismic hazard analysis of urban areas located in the North-eastern part of Japan. The recent attenuation laws are employed for the estimation of ground motion parameter that consider crustal and subduction zone earthquakes separately.

TAIWAN

Lin and Lee (2008) Subduction zone earthquakes in Taiwan are taken into account for the prediction of peak ground motion variation. Strong motion data obtained for both intraslab and interface type earthquakes are used to establish attenuation relationship for PGA and SA for two site classes and two source types. Predicted values were found higher than older predicted values for crustal earthquakes but found lower than the worldwide subduction zone earthquakes.

Chuang and Miller (2012) An interseismic block model for two strands namely eastern Peinan strand and a western Luyeh strand which comprises southernmost Longitudinal Valley fault of eastern Taiwan using data from a small-aperture Global Positioning System (GPS) campaign and leveling. The potential earthquake magnitude for the two strands may be as high as Mw 6.5.

Huang et al (2010) The shallow crust in the metropolitan region is investigated using surface wave array tomography with time domain empirical Green's function (TDEGF) inferred from correlation of ambient seismic noise. Feasibility of ambient seismic noise tomography at very low periods of 0.5-3s make it useful for high resolution studies of near-surface heterogeneity. Different phase velocities were observed for different crustal structures which could be used in seismic hazard assessment.

Chen et al (2012) Extreme value theory based on Gumbel equation derivations are used to estimate the a & b value distribution for Tawan. These a & b Values are used grid wise to determine the probability of occurrence of large earthquakes. The result shows two high probability paths for large earthquakes characterized by low b-value. Also PG A and PGV distributions are also estimated.

Peng et al (2009) A procedure considering amplification of ground motion amplitudes at the mountains tops is developed for seismic landslide hazard assessment. The theoretical topographic amplification factors are derived from a derived 3D dynamic numerical model with irregular topography. By taking ground motion record as reference the amplified acceleration time history and amplified seismic intensity parameters are obtained. By combining regression equation and the seismic parameter of PGA and Arias intensity the seismic landslide hazard is calculated using Newmark's Displacement Model.

Sokolov and Wenzel (2011) Comparison of the effects of variations in earthquake correlation and site-to-site correlation on probabilistic estimations of seismic damage and loss for the extended objects (hypothetical portfolio) and critical elements (e.g. bridges) of a network is done. The hazard and loss estimations were performed using Monte Carlo approach on the basis of stochastic catalogues and random ground-motion fields. Parameters of seismic hazard, characterization, damage probability are found to be dependent.

Trandafir and Sassa (2006) A methodology for evaluating the likelihood of landslide occurrence on gentle slopes in liquefiable soils during earthquake based on a modified Newmark sliding block model is developed. By using shear resistance-displacement relationship the simulation model incorporates the sensitivity of computed displacements to variations in yield acceleration involves an examination of undrained seismic slope performance under various horizontal seismic waveforms scaled to different specific values of the PGA.

Liao et al (2006) A study describing the procedures of damage assessments for building structures for Taiwan is carried out having primary objectives as to classify the buildings, describe the failure mechanism and to provide fragility functions using available data. Parameters for describing the fragility functions for each class are also generated and shown in the paper.

Wang et al (2011) The recurrence probability of earthquakes of certain magnitude is calculated using the earthquake catalogues from 1900 to 2009 with different level of uncertainty. The mean value of annual maximum earthquake magnitude is found to be 6.43 with coefficient of variation around 10%. More tests of goodness are carried out and site specific probability of recurrence is computed.

Lin et al (2012) A model of bridge structure and a set of alarm and action values to formulate guidelines for bridge maintenance and seismic hazard prevention are developed. Onsite ambient vibration measurement are incorporated and modal analyses is also performed. The maximum displacements for different sections of the bridge are compared, and statistical regression analyses are used to explore their correlation. Information for bridge safety assessment is proposed, which can mitigate loss of property and lives due to bridge failure.

Wang et al (2012) By using earthquake catalog with the use of ground motion models PGA distribution is estimated for three different cities of Taiwan. Statistical goodness of fit tests are also carried out. Using a verified probability distribution, probabilistic seismic hazard by means of annual exceedance probability is also carried out.

ZHU Shou-biao and SHI Yao-lin (2002) In this paper, the stress release model is improved and discussed whether the stress release model is still applicable or not in the case of smaller spatio-temporal scale and weaker earthquakes. The earthquake conditional probability intensity in Taiwan area is calculated with the improved stress release model and seen that accuracy of earthquake occurrence time predicted by the improved stress release model is higher than that by Poisson model in the test of retrospect earthquake prediction.

Key word: improved stress release model; conditional probability intensity; Poisson model; Taiwan area

XÜ Guang-yin and GAO Meng-tan (2007) A potential rupture surface model is proposed in this paper. Adopting this model, the seismic hazard near the Chelungpu fault that generated the Chi-Chi (Jiji) earthquake with magnitude 7.6 was analysed and the following conclusions are reached. 1. This model is reasonable on the base of focal mechanism, especially for sites near potential earthquakes with large magnitude; 2. The attitudes of potential rupture surfaces have great influence on the results of probabilistic seismic hazard analysis and seismic zoning.

Key words: potential seismic source; fault rupture attitude; potential rupture surface; probabilistic seismic hazard Analysis; seismic zoning.

Donat Fäh, Fortunat Kind & Domenico Giardini (2003) H/V spectral ratios from microtremors are used to retrieve the S-velocity structure from a single ambient vibration record, by using its relation to the ellipticity of the fundamental mode Rayleigh wave and the amplitude of observed H/V ratio. The accuracy with which S-wave velocity structures can be retrieved from observed H/V ratios is therefore sufficient for an application of the method in seismic hazard analysis for a specific site.

Key words: site effects, microtremors, S-wave velocity, seismic ambient vibrations, seismic hazard assessment, inversion for structure.

Yih-Min Wu, Nai-Chi Hsiao and Ta-Liang (2004) Teng In this paper, the relationships between earthquake loss, intensity and strong motion peak values was investigated, mainly based on the Chi-Chi earthquake. Both the strong-motion peak values and the earthquake loss are related. From the results, it was found that peak ground acceleration (PGA) and peak acceleration response spectra at 1 s period (1 s Sa) values are two parameters that give slightly higher correlation coefficients than other parameters for earthquake loss analysis.

Key words: seismic hazard mitigation, seismic damage assessment, peak ground motion, earthquake rapid reporting system.

Vlacimir Sokolov, Arkady Ovcharenko, Chin-Hsiung Loh and Kuo-Liang Wen (2004) The paper describes an integrated approach to seismic hazard assessment, which was applied to the Taiwan region. The approach allows introduction of a new parameter that describes the dependency of seismic hazard on time, the so-called "period of maximum hazard". The parameter shows the period, during which every considered site will be subjected by the maximum value of ground motion characteristic (PGA or RS).

Key words: future earthquake zonation, ground-motion models, integrated approach, time dependent seismic hazard.

Yih-Min Wu, Nai-Chi Hsiao, Ta-Liang Teng and Tzay-Chyn Shin (2002) An empirical method of assessing the near real-time damage using the rapid reporting system in Taiwan was established. Relationships between peak ground velocity and damage rates (fatality rate, total and partial household collapsing rates) during the 1999 Chi-Chi earthquake were determined in this study.

Key words: Seismic damage rate, Seismic rapid reporting system, Peak ground acceleration, Peak ground velocity.

Chin-Hsiung Loh, R. Scott Lawson and Weimin Dong This paper summarizes the development of an earthquake risk assessment methodology for Taiwan. The frame work of this model includes five basic components: ground shaking/failure, building damage, lifeline damage, economic losses, and social losses.

John G. Anderson, James N. Brune, Rasool Anooshehpoor and Shean-Der Ni (2000) This review article discusses several important issues that have the potential to cause major impact on seismic hazard analysis. They are: (i) partitioning of uncertainties into epistemic contributions, (ii) quantification of precarious rock observations and use of the data to constrain and improve ground motion models, (iii) continuing to deploy strong motion instruments near major faults since only more strong motion data will definitively resolve the issues of what is normal behaviour, and (iv) understanding through modelling and observations, the physical phenomena that affect strong motion, including the effect of total fault offset, surface rupture and type of faulting.

Jacques Angeliera, Hao-Tsu Chub, Jian-Cheng Leec, Jyr-Ching Huc (2000) Active faulting of the Chihshang Fault and of the entire Longitudinal Valley Fault Zone accounts for 24% and 37% (respectively) of the total shortening across the Taiwan collision in the N548W direction of relative motion between the Philippine Sea Plate and the South China shelf. This distribution of relative displacements illustrates the major role played by this boundary, as a zone of mechanical weakness where tectonic partitioning occurs. Permanent surveying of the displacement on the Chihshang Fault has the potential to detect significant decrease in slip rates, and hence to predict forthcoming locking stages, which would increase earthquake hazard.

Claudio Vita-Finzi and Jiun-Chuan Lin (2005) Neotectonic data may indicate whether stored elastic energy will be dissipated or released destructively. Radiocarbon dating of fossil shorelines on the peninsula shows that it has been uplifted at an average rate of 3.8 mm/yr during the Holocene. About 1/3 of the uplift is due to deformation along the Hengchun reverse fault but, in contrast with the Chelungpu and other low angle reverse faults west of the Central Range, it accommodates strain principally by aseismic creep.

Keywords: Taiwan; Seismicity; Neotectonics; 14C Dating; Geodesy

Chin-Tung Cheng, Shian-Jin Chiou, Chyi-Tyi Lee and Yi-Ben Tsai (2007) This study conducted a review of readily available information on tectonic setting, geology, and seismicity, and the attenuation of peak ground acceleration (PGA) of Taiwan for completing the revised probabilistic seismic hazard maps by the state-of-the-art probabilistic seismic hazard analysis (PSHA) method. The revised PSHA in this study takes into consideration the fact that subduction plate sources induce higher ground-motion levels than crustal sources, and active faults induce the hanging-wall effect in attenuation relationships.

Key words: probabilistic seismic hazard, fault, ground motion.

6.3 Comparison of studies among NE INDIA and USA, TAIWAN, IRAN AND JAPAN

There are several common approaches to the studies made among these developed countries and Northeastrn India. Among commonality, two important studies are mostly common a.) the understanding of earth's crust through basic research and b.) the seismic hazard assesment and risk mitigation. The comparison indicates only one aspect. A thorough study on both the topics have been carried out in developed countries while not much comprehensive efforts have been made in Northeastern India.

In these developed countries, much efforts have been given on generation of primary quality database for the extensive research. In northeastern India, scenario related generation of database still needs to be improved with good detection capability with lower threshold magnitude earthquake. A good database will facilitate good research output only.

Delineation of seismic source is the prime important parameter which is the thrust area of research among these developed countries. After identification of seismic source, next emphasis is given to characterization of source zone to define the rupture mechanism. The rupture mechanism will asses the probable maximum credible earthquake from source. Finally ground motion prediction equation pertinent to respective vulnerable site are estimated which is the most important parameter towards the seismic hazard assesement. These algorithms are followed strictly in developed countries. However in Northeastern India, these algorithms are not followed comprehensively.

CHAPTER 7: ESTIMATION OF PARAMETERS THAT NEEDED FURTHER RESEARCH

7.1 PART 1:

List of parameters /questions that needs further research

Based on information from original scientific research by the Indian and Foreign research communities, **eleven** important parameters/topics have been proposed that need further extensive research, and are as follows :

a. **SEVEN**(T1, T2, T3, T4, T5, T6, T8) pertaining to **Hazard** assessment
b. **THREE** (T7, T10, T11) related to **Risk** and
c. **ONE**(T9) related to earthquake **precursory** phenomena.

T1 : Earthquake catalogue since historical till present
T2 : Earthquake database comprising phase data and waveforms
T3 : Active fault mapping and source characterization

T4 : Modelling of Geodetic strain rate
T5 : Application of remote sensing and GIS towards mitigating hazard
T6 : Prediction of ground motion parameters
T7 : Seismic microzonation and site characteristics
T8 : Re-evaluation of Intensity Scale of great earthquakes of 1897(M~8.7) & 1950(M~8.5) and recurrence period.
T9 : Multiparametric geophysical studies towards earthquake precursory research
T10 : Seismic vulnerability studies
T 11: Impact of earthquake shaking on lifeline structures including industrial complexes

7.2 LIST OF PARAMETERS/QUESTIONS THAT NEED FURTHER RESEARCH IN NORTHEATSERN INDIA & THE DETAILS WHY WE NEED IT

7.2.1 Multidisciplinary approach towards hazard seismic assesssment

Hazard Assessment Findings present probabilistic seismic hazard approaches (PSHA) widely used in the earthquake engineering community, still have large epistemic and aleatory uncertainties. A robust and shared validation of the available numerical procedures for assessing seismic hazard,computing earthquake probabilities and calculating ground shaking scenarios is still lacking. The next generation of seismic hazard assessment is emerging and will represent a paradigm shift from purely statistical and time-independent towards more realistic, time-dependent and physicsbased approaches. The probability of loss of life in seismic events is highest for developing countries. Despite this, the present transfer of disaster prevention knowledge (including hazard assessment methodology) to the developing world is far from sufficient. Recommendations Seismological communities should be encouraged to improve probabilistic seismic hazard assessments by combining statistical with deterministic approaches and moving towards timedependent hazard assessments from a local to a global scale. The creation of international validation centres for seismic hazard assessment and for the forecasting of seismicity evaluation should be promoted. Closer communication between the seismological and engineering communities should be encouraged for the proper translation of seismic hazard information into engineering and emergency decision-making.To foster outreach and preparedness activities, hazard assessment methods and their evaluations should be diffused with the help of special training and education programmes, particularly in the developing world.

7.2.2 Densification of Broadband Seismic station, Strong Motion accelerograph, GPS station and Multiparamertic Geophysical observatory in Northeast India.

[Dense seismic arrays that record continuously have the potential to dramatically increase the resolution of subsurface imaging, and they can also be used to monitor micro-seismicity. However, the sensors that are used in these arrays usually lack the low-frequency response of conventional earthquake monitoring networks, and are often deployed at the surface in noisy environments. This presents challenges for extracting the signal from the noise. Densification of Broadband Seismic station, Strong Motion accelerograph, GPS station and Multiparamertic Geophysical observatory will farther resolute the principal techniques to be used in earthquake seismology in more effectively]

7.2.2.1 Earthquake source inversion

[Earthquake source inversion and high-frequency rupture imaging provide time-dependent information on earthquake rupture processes, but a synoptic view of the origin and impact of the resulting uncertainties on the estimated source parameters has not been fully developed. Furthermore, the optimal integration of various datasets, and the combination of source inversion and source imaging, to derive a complete understanding of the kinematic rupture evolution in space and time, still pose many open questions. In this context, reliable near-real-time finite-fault parameter estimation are needed, as well as high-

fidelity rupture-history inversions. Comparative studies in finite-fault earthquake source inversion, including the development of innovative inversion and imaging methods and the rigorous estimation of model uncertainties are the prime requirements.This farther enables new developments in source characterization, to define new metrics for source inversion validation, and to help build more realistic dynamic models of the earthquake rupture process]

7.2.3 Proper identification of seismogenic zones.

7.2.3.1 Identification of source zone charcteristics.

[Identifcation and characterization of seismic sources are essential input for seismic hazard analysis. A complete and consistent catalog of earthquakes in a region can offer good data for studying the distribution of earthquakes with respect to space,time, and magnitude. This is the first step towards further solution and understanding.]

7.2.3.2 Estimation of potential surface rupture mechanism

[Advances in numerical modeling methodology in seismology are not only driven by emerging requirements in observational seismology (e.g., the advent of very dense seismic arrays; demand for near-real-time simulations; the multi-scale, multi-physics modeling of seismic phenomena ; etc.),but also by developments in the mathematical sciences, and through the adaptation of methods originating in other scientific fields. Moreover, future methods for very large scale simulations will be increasingly influenced by (and may in turn influence) the evolution of computer architectures and programming models.
Here it is focused on development, verification and validation of numerical-modeling methods, and methodologically important applications especially to earthquake ground motion and rupture dynamics to estimate the rupture mechanism]

7.2.3.3 Fractal dimension analysis of seismicity

[Seismicity has fractal structures with respect to time, space and magnitude. The Gutenberg-Richter relation means that there is no characteristics fracture size and that size-distribution has a self similar property. In one dimension, earthquakes are represented by self-similar mathmatical construct - the fractal while the scaling parameter is fractal dimention. The spatial distribution of an earthquake epicenter has a fractal structure. It is a powerful tool to characterize the geometery that has a self-similar structure. Various tectonic process such as folding and faulting are extremely complex, but they satisy fractal statistics. The fractal dimension characterizes the degree to which the fractal fills up the surrounding space. It is scale invariant and has introduced an efficient statistical parameter to quantify the dimensional distribution of seismicity and with that the proportion of randomness and clusterization. Fractal dimension also gives vital informationabout the seismo-tectonic statibility of the region]

7.2.3.4 Delineation of 3D velocity structure, seismic imaging from digital waveforms

[This will highlight leading-edge theoretical and practical developments in seismic imaging and monitoring applied on different scales (e.g., the meter-scale in near-surface seismology up to the kilometer-scale in crustal seismology) using both active and passive seismic data. This includes various techniques inferring the structure of the Earth as well as velocity and attenuation models derived at local, regional, and global scales, for example, ambient noise tomography and coda-wave interferometry. Here, innovations and advances in 3D traveltime tomography, waveform tomography, surface wave inversion, joint inversion of multiple geophysical observations as well as multi-repeated observations of geophysical data to detect

temporal variations of large-scale environments as well as smaller structures such as volcanoes, fault zones and landslides]

7.2.3.5 Calibration of duration magnitude from digital seismogram

The earthquake magnitude estimate is a routine task in all seismological observatories. Several magnitude scales are available, based on amplitude measurement of different seismic phases, and/or on total signal duration. Among them, the duration magnitude (MD) is adopted in many regional networks because it provides a rapid and reliable estimate of the earthquake size through a fairly simple procedure based on the measure of the duration of recorded seismograms. The duration magnitude is defined as MD determined through a regression analysis. Calibration of duration magnitude scale for the area monitored by the different Seismic Network in Northeastern is of very much importance as it does not persist based on digital waveform. Further, the duration magnitude is very much conformable with local Richter magnitude.

7.2.3.6 Online realtime microseismicity analysis from digital network for precursory study

[Microearthquake networks are especially well suited for intensively studying seismically active areas and are a powerful tool for investigating the earthquake process in great detail in relatively short time intervals. Their applications are numerous, such as monitoring seismicity for earthquake prediction purposes, mapping active faults for hazard evaluation, and investigating the Earth's crust and mantle structure. Utilizing the micriseismicity analysis some of the features related to prediction of an impending earthquake, usually on the basis of the observation of a precursory signal may be made. The prediction would still be probabilistic, in the sense that the precise magnitude, time and location might not be given precisely or reliably, but that there is some physical connection above the level of chance between the observation of a precursor and the subsequent event. Forecasting would also have to include a precise statement of the probabilities and errors involved, and would have to demonstrate more predictability than the clustering referred to in time-dependent hazard. The practical utility of this would be to enable the relevant authorities to prepare for an impending event on a time-scale of months to weeks. Practical difficulties include identifying reliable, unambiguous precursor and the acceptance of an inherent proportion of missed events or false alarms, involving evacuation for up to several months at a time, resulting in a loss of public confidence. Lots of effort is needed towards this aspect to be more effective for precursory study]

7.2.3.6.1 Earthquake Early Warning

[*Earthquake early warning (EEW) systems have been built in selected parts of the world, and are currently being developed in several more regions including in Northwestern India. While all of these systems aim to use data obtained near to the earthquake source to warn population centers of imminent shaking, there is great diversity in the methodologies and data types used. Performance of early warning systems; incorporation of new datasets such as geodetic data, gravity observations, and data from low-cost instruments; proposed new methodologies; and related real-time earthquake response issues such as tsunami early warning, damage assessment, and public communication should be attained under this domain]*

7.2.3.7 Preparation of homogenous earthquake catalougue and recurrence model.

The prime requirement for studying earthquake seismology is the development of accurate seismicity catalogue. As the catalogue, however, the expected worldwide threshold magnitude levels are relatively high : MS ≥ 5.5, MS ≥ 6.25 and MS ≥ 7.5 for the 1960 – 2009, 1918 – 1959 and 1900 – 1917 periods respectively. However threshold magnitude levels locally should be lower as much as possible. In the practice of seismic hazard model develop-

ment, catalogue thresholds on the order of MW 4.5 to MW 4.0 or even lower are routinely used for estimation of recurrence parameters. Whilst it should be emphasised that the local regional instrumental Catalogue provides the most accurate homogenous representation of seismicity across the globe, a need has emerged in NE India to supplement the catalogue with other, possibly more local, catalogues at lower magnitudes. It is expected, therefore, that local catalogues also should include the events reported by other institutes/agencies (including those from the contributing other institutes). The process of catalogue preparation and homogenisation of multiple catalogues from a nonwaveform approach can essentially be broken down into four steps:i) Identification of the event solutions (time and location) common to the catalogues (duplicate finding) ii) For a set of solutions (time and location) representing an event, selection of the preferred solution for the event iii) Given a catalogue containing the full set of solutions and magnitudes for an event, development of empirical or physical relations between the magnitudes in the originally recorded scales ("native" magnitudes) by the original agencies ("native" agencies), and those in the magnitude scale to which the catalogue should be homogenised ("target" magnitude and agency) iv) Given a set of empirical models relating the native magnitudes to the corresponding target magnitude, the hierarchy in which conversion models should be applied for the purposes of homogenisation.

7.1.4 Dynamics of slow earthquake

[Earthquake faults show a variety of motion – from slow slip and associated tremor to supershear rupture. Slow earthquakes emerge as a major player in releasing and redistributing stress over much of the seismic cycles. They are observed globally over multiple spatial and temporal scales. A unifying theory connecting this diversity and its implications on the fault dynamics, however, remains elusive. Moreover, the factors (fault properties, rheology, frictional and material heterogeneity etc.) controlling varied fault slip behaviors and their interplay are poorly understood. Different aspects of this broad spectrum of fault slip including, but not limited to, slow earthquakes and associated phenomena in all forms and sizes – from episodic tremor and slip in the subduction zones to seismic swarms operating in smaller scales are the given thrust. Studies encompassing multiple styles of fault slip (slow and fast) and their interactions in space and time are required]

7.1.5 Development of strain map from GPS directivity

[GPS to measure plate boundary deformation based on "campaign style" measurements, where only a few days of data were collected each year. By providing high-precision GPS orbits in a well-defined terrestrial reference frame, the IGS has nurtured the development of new GPS applications : GPS seismology. The potential for GPS seismology was first focused on very short baselines, they were the first to show that GPS should be able to measure large displacements over short time intervals. In this mapping GPS receivers could be used to estimate the strain rate in the crustal domain underneath]

7.1.7 Mapping and identification of major faults

[The East Himalayan syntaxis has been the site of the largest recorded continental earthquakes (Assam, 15th August 1950, Mw=8.7) while the largest ever Intraplate earthquake in Northeastern India occurred on 12th June, 1897 (Shlliong, M≈8.5). Within the India/Asia collision zone, it is arguably the region where present-day deformation is fastest and most complex and seismic hazard greatest. Active faults are still insufficiently mapped, and slip-rates poorly documented due to regional partitioning. How the Frontal Himalayan Thrust (MFT) connects with still controversial thrusts under the Shillong Plateau or the orthogonal, Sagaing strike slip Fault in Myanmar remains unclear. In a recent exploratory trip, we made progress in identifying the surface expression of active thrusts in NE India. It is planned to unravel the seismic behavior of these thrusts, in an improved crustal structure framework, by using High resolution seismic studies and tomography, quantitative geomorphology, and paleo-seismological trenching. The study should pertain to highly seismically active regions].

7.1.8 Site characteristics, reponse spectra and ground motion prediction equation

[Site effects on strong ground motions include the effects of surface and sub-surface topography, stratigraphic discontinuities, and soil layering. These three-dimensional (3D) effects are known to affect the amplitude, frequency and duration of ground motion through mechanisms of ground response (including impedance and resonance effects), basin effects (e.g., preferential focusing, and/or trapping of seismic energy), and topographic effects (resonance of a topographic feature, energy reverberations in confined space). Site effects have been documented extensively in the literature and have been studied through experiments, analytical, numerical and empirical methods. In practice, site effects are accounted through semi-empirical GMPEs, which capture the average net site effect (primarily from soil amplification) conditional on the site parameter that is used (typically Vs30 and basin depth), ignoring higher-dimensional (3D) site effects such as topographic amplification. The purpose of this session is to facilitate the dissemination of recent advances in understanding, monitoring, simulation and parameterization of 3D site effects in ground motion. Specific topics include recent advances in the mapping and inference of site parameters (Vs30, basin depth and beyond), semi-empirical models for 3D site effects, simulation-based models and experimental studies on 3D site-specific response effects, and procedures to account for 3D site effects in seismic code provisions]

7.1.8.1 Site specific MASW and GPR survey

[MASW and GPR methods were used as exploration techniques to locate potential mineral deposits within a geologic setting of highly deformed metamorphic rocks overlain by lateritic soil horizons. Multi channel sesimograph system is used to profile overlying lateritic horizons and bedrock up to depths of 100 feet. MASW survey geometry is optimized for depths up to certain feet and high horizontal resolution. The primary goal of the investigation is to test the effectiveness of geophysics to provide depth information for overburden calculations. Secondary considerations are to obtain information on the shear wave velocity profile , ore potential of the overburden and bedrock. The two exploration methods provide independently derived constraints to the bedrock depth and structural model. The GPR method is effective in identifying shallow targets in the laterite, determining depth to competent bedrock, and identifying targets within the shallow bedrock zone. The MASW 2-D shear wave velocity (Vs) profiles were useful for delineating the laterite/rock interface and identifying anomalies near the top of and within the competent bedrock zones. The data from both these observations should be integrated to develop a bedrock structure map and spatially delineate exploration targets. These studies are yet to be initiated in northeastern India]

7.1.8.2 Studies on sustainble design and constuction strategies

[The objective of this topic is to develop sustainable strategies specific to research buildings. Research buildings as defined are those buildings created by public or private organizations that involve research personnel working directly with hazardous materials in a laboratory setting. The focus of this research will be related to the design of the laboratory component of research buildings. The concept of design efficiency will be the basis of this research, and will be used as a means to achieve sustainable performance. The means of attaining research building sustainability can be traced through the stages of the design process. The first strategies for sustainability is in the pre-design phase of the design. In this phase, large-scale conceptual questions are explored that relate to regulatory bodies, environmental issues, and financial constraints. All of these considerations must be at the scale of the laboratory, the research building, and needs farther necessary application strategy].

7.1.8.3 Seismic vulnerability studies

[The Northeastern India is one of the most seismically active zones in the world; the region is jawed between the two arcs, the Himalayan arc to the north and the Indo-Burmese arc to the east. The region bounded by latitude 22-29^{0}N and longitude 90-98^{0}E, produced two great earthquakes (M> 8.0) and about 20 large earthquakes (8.0>M$\geq$7.0) since 1897. The Shillong Plateau was the source area for the 1897 great earthquake M 8.7, and the Assam syntaxis zone for the 1950 great earthquake M 8.6. Several large earthquakes occurred along the Indo-Burma ranges. Earthquake is the only natural disaster, which cannot be precisely predicted till now and may occur at any time and hence pre-planned strategies for rescue of life and property are not possible making the devastations maximum than other natural disaster. So, earthquake disaster mitigation and responses takes an important role to reduce the destruction of life and property. A mitigation strategy is one of the prime concepts in order to reduce the hazard. This includes landuse regulations, seismic construction and retrofit codes, and improved engineering practices. Effective mitigation will result in the avoidance of many losses that could result from future earthquakes. Additionally, although mitigation measures do provide considerable protection, one of the key features of earthquake disasters is that they produce unanticipated impacts that overwhelm the coping capacities of affected social units. For the estimation of hazard parameters, the seismicity of region is one of the prime inputs. Beside seismicity pattern of the region, the present increase in population as well the urbanization are the other two parameter that constrain the hazard assessment to a realistic one. Determinations of probable isoseismal map through deterministic approach are the major concern of the study. During the process the study is supplemented by estimation of peak ground acceleration of North-Eastern India due to a probable maximum credible earthquake from different seismogenic zones identified. There has been a phenomenal increase in the population density and development programmes in the Northeast India. Besides, the region has witnessed a mushroom growth of unplanned urban centres in the previous three decades. This has resulted into increasing vulnerability of human population and physical structures to the earthquakes. Keeping the above in view, the status of seismicity in Northeast India is critically assessed along with the seismotectonics. To manage and minimize risk in future earthquakes, by design, planning and retrofitting, we need to understand and evaluate the earthquake vulnerability of the built and natural environments. This is best done by developing models by studying damage in the past earthquakes and quantifying the data on damage to a much greater degree. Seismic risk of any region can be determined from its hazard and vulnerability. Northeastern India is characterized by high seismic hazard and high vulnerability of settlements due to various seismotectonic and socio-economic factors. Most of the cities in NER are prone to earthquake effects like landslides, ground fissures, liquefaction, damage to human settlements, causalities and injuries. It is extremely unavoidable that the entire Northeastern India will be affected by future great earthquakes, similar to the one in the past. Preparations should be made to protect the population as far as possible. In order to estimate the order of fatalities and the patients to be expected in a range of scenario, including worst cases, two different source types would be considered: the repeat of 1897 and 1950 earthquakes. Simultaneously an average attenuation for collision zones would be assumed to match the intensities of the 1897 earthquake. In addition building stock of the major city of NER would be compiled. All calculations would be performed assuming the time of the earthquake, when people are mostly indoors. In earlier time, building materials used in the region were locally available; long thick wooden logs, stones, slates and clay. A judicious use of all these made the constructions earthquake resistant. These days all over the region the traditional practice of house construction is being replaced by modern construction practices and technology. This is important because of increasing restriction imposed due to environment protection. A traditional right to felling trees has been curbed, which has led to its scarcity, growing demand and increase in price and transportation costs. Quarrying of stone has also met the same fate. Earlier, construction in the area was restricted to single storey buildings, but with the growing populations two to three story buildings now are in vogue. In several instances, old building has been raised to higher stories without altering the foundation and design of the single store building. Moreover, 80% of the buildings are built without consideration of the site specific parameters obtained through microzonation studies. Effects of soil condition, differ-

ences of building stock, and its condition and propagation directions are the important measures towards assessment of vulnerability]

7.1.9 Extensive use of remote sensing satellite imageries

CONCLUSION

The database of literature on seismic hazard assesment will be an extremely useful tool for upcoming research towards its formulation and execution. Almost all the subjects of Earthsciences are consulted and compiled for ready reference. In the process, thousands of literatures are compiled and reviewed. As a result, the key parameters pertinent to NE India which remains still unsovled could be ascertained. These are depicted in Chapter 7 in detail in terms of the list of parameters/questions that need further research. We have also compiled a repository of soft copies of more than thousands of reprint in .pdf file for ready reference.

Northeast India in particular has a shortage of specialists in the areas of natural hazards and disaster management. In fact, institutions dealing with these specializations are also limited. The multidisciplinary character of these specializations is not yet fully understood. Hence, issues connected with the developement of experts and expertise will have to be accorded a high priority.

This is an attempt made for the budding researchers. It was wished to continue with network and statistical analysis through IBM-COGNOS statistical software, however it could not be accomplished . This becomes the scope of further study.

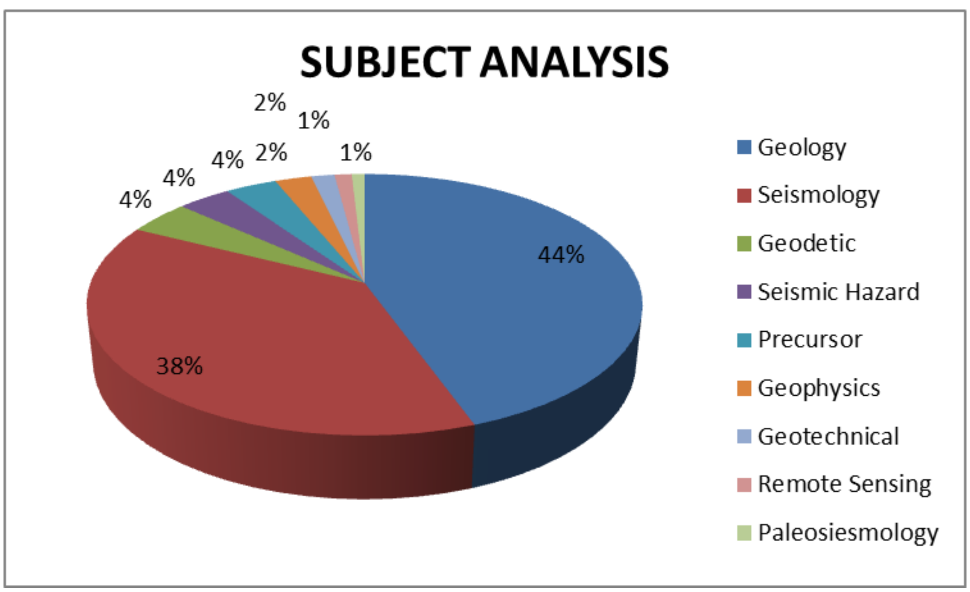

Figure depicting percentage of subjectwise publication in NE India

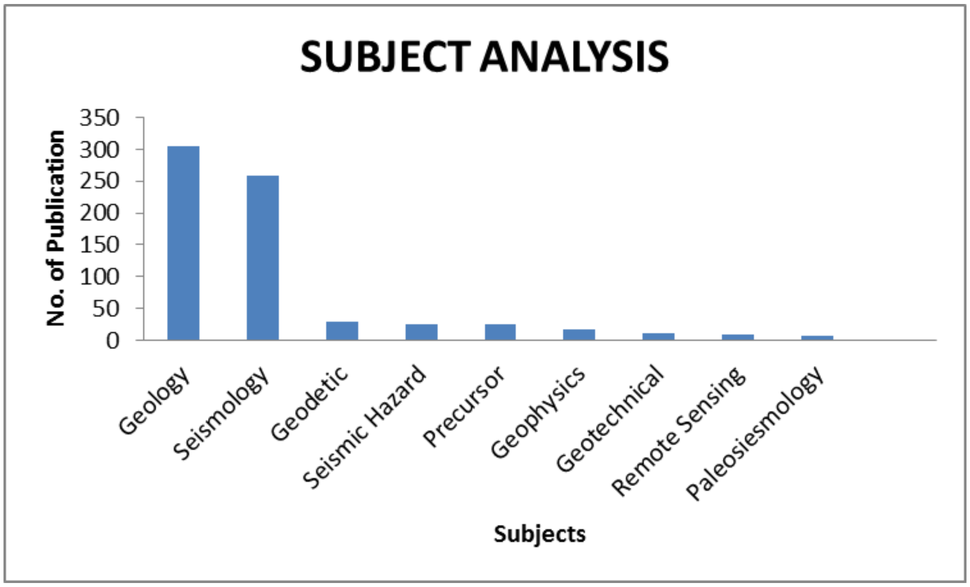

Figure depicting percentage of subjectwise publication in NE India

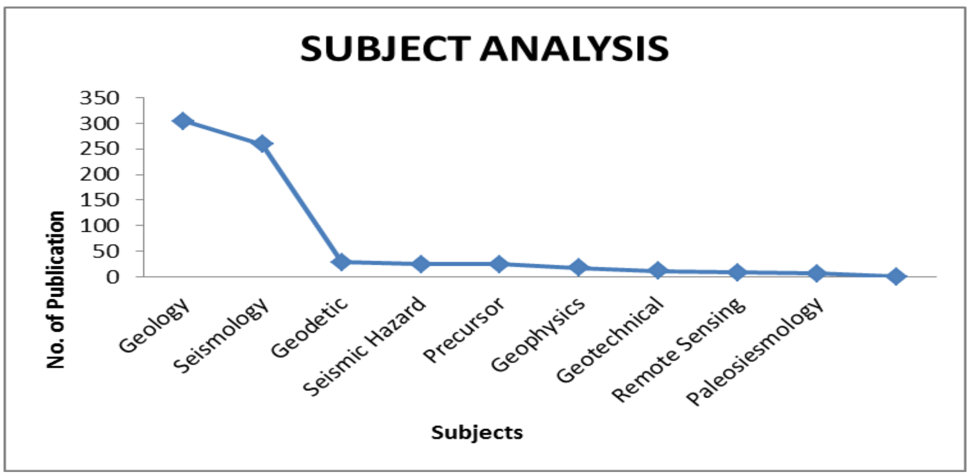

Figure depicting percentage of subjectwise publication in NE India

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Annexure I MoU

Terms and Conditions for 'Literature Survey for Earthquake Hazard Assessment Studies related to NE Region' between Assam State Disaster Management Authority (ASDMA) & CSIR - North East Institute of Science & Technology (NEIST), Jorhat

1. NEIST will undertake the project titled "**Literature Survey for Earthquake Hazard Assessment Studies related to NE Region**" with a total cost of **Rs 17.80 Lakhs (Rupees Seventeen Lakhs and Eighty Thousands only) within a time frame of 12 (Twelve) months**
2. The said Literature Survey Project will have to meet the entire requirement as per the scope of the work **(Copy Enclosed at Annexure-I)**
3. In addition to said Scope of Work and as per the suggestions of the Technical Committee, NEIST will undertake some additional activities (without any extra cost) as agreed upon:
   i. NEIST would be uploading the survey details on its Web-Portal after completion of six months of the project and hyperlink to the ASDMA web site in future
   ii. NEIST would include literatures having authorized documentation, articles from Journals with high impact factor, etc.
4. NEIST, Jorhat will complete the Literature Survey for Earthquake Hazard Assessment Studies related to NE Region within 12 (Twelve) months from the date of receipt of this document
5. NEIST, Jorhat will submit a **phase-wise Action Plan (mentioning time line against each activity)** along with fund requirement for the project. The Action Plan will be submitted by NEIST along with the signed copy of this document
6. NEIST, Jorhat will keep all the data and facts of ASDMA confidential & secret and will not disclose any confidential information furnished by ASDMA to outsiders/ Third Party
7. After the final draft report is ready, it would be examined by the concerned Technical Committee and may require to incorporate the suggestions if any by the said committee
8. NEIST, Jorhat will submit quarterly reports to ASDMA and may be asked for presenting the same before the Technical Committee
9. **Payment Terms:**
   Payment will be released by the ASDMA in Indian Rupees as per phase wise action plan and related requirement of fund
10. **Force Majeure:** Neither Party will be liable in respect of failure to fulfill its obligations, if the said failure is entirely due to acts of God, Governmental restrictions or Instructions, Natural calamities or Catastrophe, Epidemics or disturbances in the State. The Party affected by an event of Force Majeure will immediately notify the other party of such an event.

Authorized Signatory (Signature & Seal)

....

(CSIR – North East Institute of Science and Technology)

JORHAT .... 11.9.2012 ....

Place Date

निदेशक
DIRECTOR
उत्तर-पूर्व विज्ञान तथा प्रौद्योगिकी केन्द्र
NORTH-EAST INSTITUTE OF SCIENCES & TECHNOLOGY
जोरहाट JORHAT-785 006, असम ASSAM

Annexure II Bibliography Part 1 (irrespective of Impact factor)

List of bibliographic references (alphabetic) published in various national and international journals related to various subjects of earthscience which are the prime inputs to the Seismic Hazard Assesment studies in northeastern India and its vicinity. A graphical presentation is made alongwith (based on database so far made).

Acharyya, S.K., Ghosh, S.C. and Ghosh, R.N. (1983). Geological framework of the Eastern Himalaya in parts of Kameng, Subansiri, Siang districts, Arunachal Pradesh. Geol. Surv. India, Misc Pub. No. 43, pp. 145-152. (Geology)

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Annexure III Bibliography Part II (irrespective of Impact factor)

List of bibliographic references (alphabetic) published in various national and international journals related to various subjects of earthscience which are the prime inputs to the Seismic Hazard Assesment studies in northeastern India and its vicinity. A graphical presentation is made alongwith (based on database so far made). (Irrespective of IF)

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Annexure IV Earthquake Catalogue (enclosed separately)

Annexure V PhD and M. Tech thesis on earthquake seismology / Geology

THE LIST OF THESIS WORK RELATED TO THE AWARD OF PhD/ MPHIL/ M.TECH DEGREE ON THE SUBJECT PERTAINING TO SEISMIC HAZARD ASSESSMENT/ GEOLOGY/ SEISMOTECTONICS IN NORTH- EASTERN INDIA :						
Sl. No.	Title of the Thesis	Author	Year	Name of the Supervisor/ Co-Supervisor	Name of the University	Remarks
TITLES OF PhD THESIS:						
1.	Geology of the Precambrian rocks of the Barapani area, Khasi and Jaintia Hills, Assam.	M. Ahmed	1971		Gauhati University	Geology
1.	A Study on the Cretaceous formation in and around Dawki, Meghalaya.	Chaturbhuj Pathak	1973	Dr. D.N.D. Goswami	Gauhati University	Geology
2.	A study on Seismic Risk in the Northeast Indian Region.	Hem Chandra Goswami	1984	Dr. S.K. Sarmah	Gauhati University	Seismic Hazard
3.	Geochemistry of the Barail group of rocks in Upper Assam valley and Naga hills with special reference to its oil, gas and coal bearibility.	Kabita Goswami	1984	Dr. Madan Mohan Saikia	Dibrugarh University	Geology
4.	A study of the geology of the area around Elephant, Kameng District and Arunachal Pradesh with special reference to coal.	Daijee Gogoi	1985	Dr. S.K. Dutta	Dibrugarh University	Geology
5.	Sedimentological studies around Siju, Meghalaya with special emphasis on limestone.	Prabhat Kataky	1986	Dr. Madan Mohan Saikia	Dibrugarh University	Geology
6.	A study of Seismic Hazard for Northeast India & Neighbourhood.	Hidangmayum Kulachandra Sarma	1989	Dr. S.K. Sarmah	Gauhati University	Seismic Hazard

7.	Travel times of longitudinal waves for the earthquake in and around Northeast India.	George John	1989	Dr. M.V.D. Sitaram	Dibrugarh University	Seismotectonics
	The active tectonics and structure of the Eastern Himalayan Syntaxis and surrounding regions.	W.E. Holt	1989	A.Z. Tueson	Arizona University	Seismology
8.	An study of Seismic Activity in the North-East India and determination of its Seismic potential.	Dilip Kumar Deka	1990	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
9.	Geomorphological studies along Iril River Basin.	Ibeyaima Devi H.	1992	Dr. R.A.S. Kushwaha	Manipur University	Geology
10.	Petrology and geochemistry of the carbonate rocks in and around Ukrul, Manipur State, India.	Ibotombi S.N.	1992	Dr. Rajesh Anand	Manipur University	Geology
11.	Hydrogeological studies in Imphal district.	Rajen Singh K.	1993	Prof. Arun Kumar	Manipur University	Geology
12.	Landuse and Geo-environmental assessment of Khuga River catchment.	Dinachandra S. L.	1994	Prof. Arun Kumar	Manipur University	Geology
13.	Geomorphology of Leimatak river basin.	Girija Devi E.	1994	Dr. R.A.S. Kushwaha	Manipur University	Geology
14.	Geological implications of Thermoluminescence (TL) of some sedimentary materials of Ukhul District of Manipur (India).	Ingotombi Singh S.	1994	Prof. R.K. Gartia	Manipur University	Geology
15.	A Geomorphological study of the Dikhow river basin, India.	Nurul Amin	1995	Dr. J.N. Sarma	Dibrugarh University	Geology

16.	Seismicity Patterns, Earthquake Source Mechanism & Seismic Hazard in Northeast India.	Tilaka Das	1995	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
17.	Petrochemistry of Disangs between Imphal and Mao, Manipur.	Debojit Singh Ch.	1995	Dr. R.A.S. Kushwaha	Manipur University	Geology
18.	Body wave investigations of Northeastern India.	Mrinmayee Barua	1996	Dr. M.V.D. Sitaram	Dibrugarh University	Seismotectonics
19.	Hydrogeological studies of Imphal valley.	Minaketan Singh L.	1996	Prof. Arun Kumar	Manipur University	Geology
20.	Geochemical and Radiogenic Isotope study of groundwater of Imphal area.	Anita C. Ak.	1997	Dr. Rajesh Anand	Manipur University	Geology
21.	Study of heavy metal distribution in the river basin-A case study, Jhanji river, Assam.	N.K. Baruah	1997	Dr. Prabhat Kataky	Gauhati University	Geology
22.	Geochemical Studies of Loktak Lake with special reference to Geo-environment.	Geeta Devi O.	1998	Dr. Rajesh Anand	Manipur University	Geology
23.	*S*edimentological Investigation of Arenaceous Rocks in and around Ukhrul, Ukhrul District.	Devala Devi Th.	1998	Dr. R.A.S. Kushwaha	Manipur University	Geology
24.	Structural and tectonic analysis of Manipur with special reference to evolution of imphal valley.	Soibam I.	1998	Dr. Soibam Isotombi	Imperial College, UK	Geology
25.	The Jhanji river basin, Assam / Nagaland- A Fluviogeomorphological and Geochemical Appraisal.	Jyotish Baruah	1998	Dr. Prabhat Kataky and Dr. J.N. Sarma	Dibrugarh University	Geology

26.	Petrochemical study of the Lakadong limestone of Cherrapunjee and Mawamluh areas,Khasi Hills, Meghalaya.	Baby Baruah	1998	Dr. Prabhat Kataky	Dibrugarh University	Geology
27.	A Study of seismic Risk in the Western Part of Northeast India & Adjoining Regions.	Anjoli Pujari Khound	2001	Dr. S.K. Sarmah and Dr. P.K. Das	Gauhati University	Seismotectonics
28.	Study of some Geophysical Properties of the Basement and its overlying sediments of greater Guwahati area, District: Kamrup, Assam.	Babul Pathak	2001	Dr. Surya Kumar Sarmah	Gauhati University	Geology
29.	Petrology and geochemistry of the ultramafics in ophiolites of the Sangshak- Singcha area, Ukhrul district, Manipur.	Ranjit Th.	2002	Dr. Soibam Ibotombi	Manipur University	Geology
30.	Morpho-tectonic evolution of Thoubal river basin.	Pushparani Devi H.	2002	Dr. R.A.S. Kushwaha	Manipur University	Geology
31.	Seismotectonic studies in Manipur.	Manichandra S.	2002	Prof. Arun Kumar	Manipur University	Seismotectonics
32.	Seismotectonics of Arunachal Himalaya.	Dilip Kumar Yadav	2002	Dr. M.V.D. Sitaram	Dibrugarh University	Seismotectonics
33.	Environmental geochemistry around Jorhat-A case study.	R.K.Bordoloi	2003	Dr. Prabhat Kataky	Dibrugarh University	Geology
34.	A study on local richter magnitudes and signal durations of earthquakes in and around Northeast India.	Pabon Kr Bora	2004	Dr. M.V.D. Sitaram and Prof. Sushil Goswami	Dibrugarh University	Seismology

35.	Tectonic significance of minor structutes of the rocks of Imphal valley.	Hemanta Singh R.K.	2004	Dr. R.A.S. Kushwaha	Manipur University	Geology
36.	Sedimentological Investigation along NH-53 between Imphal and Nungba, Manipur.	Chandra Singh M.	2005	Dr. R.A.S. Kushwaha	Manipur University	Geology
37.	Crustal Structure of Northeast India & its Neighbourhood from Dispersion of Seismic Surface Waves.	Sarat Chandra Sahu	2005	Dr. S.K. Sarmah and Dr. P.K. Das	Gauhati University	Seismotectonics
38.	Hydrogeomorphological appraisal of the Brahmaputra River channel from Majuli to Kaziranga, Assam.	Debajit Bezbaruah	2005	Dr. Prabhat Kataky	Dibrugarh University	Geology
39.	The study of the pattern of erosion and bankline migration of the river Brahmaputra in Assam using Remote Sensing Data and GIS.	Manoj Kumar Phukan	2006	Dr. J.N. Sarma	Dibrugarh University	Geology
40.	The Bhogdoi river basin-A fluviogeomorphological and geochemical assessment.	K.K. Borthakur	2006	Dr. Prabhat Kataky	Dibrugarh University	Geology
41.	Attenuation of coda wave and wave form analysis for North-eastern region of India with special emphasis on seismotectonics of Chedrang valley, the rupture area of 1897 (M=8.7) Great Assam earthquake.	Devajit Hazarika	2006	Dr. Saurabh Baruah	Dibrugarh University	Coda Wave
42.	Geological and geomorphological studies along NH-53 from Imphal to Nungba with special em-	Okendro M.	2006	Dr. R.A.S. Kushwaha	Manipur University	Geology

	phasis on landslide.					
43.	Facies variation and Depositional environment of Tertiary sedimentary rocks along Imphal-Moreh Road section, Manipur.	Gobin Singh Ch.	2006	Dr. R.A.S. Kushwaha	Manipur University	Geology
44.	Petrography and Geochemistry of ultramafic rocks of ophiolitic complex from Siroi to Nunghar of Ukhrul District, Manipur state with reference to mineralization.	Debala Devi L.	2006	Dr. Soibam Ibotombi	Manipur University	Geology
45.	Palaentological and stratigraphical studies of Disang group in parts of Manipur, Unpublished thesis, Nagaland University.	Jayajit L.	2006	Prof. Rajendra Prasad Kachhara	Nagaland University	Geology
46.	Application of GIS and Remote Sensing in Landslide Hazard Studies along parts of National Highways in Manipur.	Dolendro Singh Th.	2007	Prof. Arun Kumar	Manipur University	Geology
47.	Dhasiri river channel, Assam-A geomorphologic attribute.	Mrinal Kumar Dutta	2007	Dr. Prabhat Kataky	Dibrugarh University	Geology
48.	Seismicity & Seismotectonics of Indo-Burma Orogenic belt & Earthquake Hazard Implications in Northeast India.	Narayan Chandra Barman	2007	Dr. M.M. Saikia and Dr. S. Kalita	Gauhati University	Seismotectonics
49.	Source zone characteristics and site amplification behaviours in seismic microzonation of greater Guwahati, Assam.	Ranju Duarah	2009	Prof. Sushil Goswami	Dibrugarh University	Seismic Hazard

50.	Environmental studies around Makum coalfields, Margherita.	Baby Baruah	2009	Dr. Prabhat Kataky	Dibrugarh University	Geology
51.	Petrological and geo-chemical studies of the ophiolite belt in parts of Chandel and Ukhrul districts, Manipur and their tectonic significance.	Khuman M. Ch.	2009	Dr. Soibam Isotombi	Manipur University	Geology
52.	Study of Geo-environmental aspects of Landslides in Guwahati Metropolitan area for their Sustainable Management using Geoinformatics.	Kuntala Bhusan	2010	Dr. D.C. Goswami	Gauhati University	Geology
53.	Estimation of Crustal Discontinuities using Digital Seismic Waves in Shillong-Mikir hills plateau of Northeastern Region.	Dipok Kumar Bora	2010	Dr. Saurabh Baruah	Dibrugarh University	Seismology
54.	Seismic study of the Mat and Sylhet faults in the Surma Valley North East India.	Saitluanga Saia	2010	Dr. Saurabh Baruah and Prof. R.P. Tiwari	Mizoram University	Seismotectonics
55.	Geological studies on Chandel District with reference to its structural and tectonic framework.	Ranjitkumar Singh E.	2010	Dr. Soibam Isotombi	Manipur University	Geology
56.	Geotechnical studies on landslide mitigation along NH-39, between Imphal and Mao, Manipur.	Pradip Singh M.	2011	Dr. Soibam Isotombi	Manipur University	Geology
57.	Seismic Ambient Noise Analysis: Its application to evaluate the site characteristics of Shillong City. (submitted)	Rajib Biswas	2011	Dr. Saurabh Baruah	Dibrugarh University	Seismology

58.	Waveform modeling and stress tensor inversion for simultaneous determination of source mechanism and current stress regime in Northeastern India.	Santanu Baruah	2012	Dr. Saurabh Baruah	Dibrugarh University	Seismology
59.	Fuzzy neural network modeling for hydrological studies.	Paresh Chandra Deka		Dr. V. Chandramouli & Dr. A. Dutta	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./01	Civil Engineering
60.	Geotechnical and Environmental performance of Residual Lateritic Soil Stabilised with Flyash and Lime.	Rajib Kumar Goswami		Dr. C. Mahanta	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./02	Civil Engineering
61.	Development of optimal operating policy for Pagladia multipurpose reservoir.	Juran Ali Ahmed		Dr. A. K. Sarma	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./03	Civil Engineering
62.	Dynamic Response of ageing Concrete Gravity Dams with Unbounded Reservoir.	Indrani Gogoi		Dr. D. Maity	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./04	Civil Engineering
63.	Simulation of dam break hydraulics in natural flood plain topography.	Mimi Das Saikia		Dr. A. K. Sarma	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./05	Civil Engineering

64.	Updating of Finite Element Model of Cablestayed Bridges for Improved Dynamic Characteristization and Active Seismic Response Control Implementation.	Atanu Kumar Dutta		Dr. A. Dutta & Dr. S. K. Deb	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./06	Civil Engineering
65.	Water quality modeling in an untreated effluent dominated urban river.	Girija T. R.		Dr. C. Mahanta	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./07	Civil Engineering
66.	Study of Rheological Behavior of High-Performance Concrete.	Aminul Islam Laskar		Dr. S. Talukdar	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./08	Civil Engineering
67.	Application and evaluation of amine based polymers for heavy metals adsorption and recovery from wastewater.	P. Albino		Dr. S. Chakraborty	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./09	Civil Engineering
68.	Response of Horizontally Curved Thin-Walled Box-Girder Bridge to Vehicular Loads.	K. Nallasivam		Dr. S. Talukdar & Dr. A. Dutta	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./10	Civil Engineering

69.	Geocell-sand Mattress Overlying Soft Clay Sub-grade: Behaviour under Circular Loading.	Minaxi Rai		Dr. T. L. Ryntathiang & Dr. S. K. Dash	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./11	Civil Engineering
70.	A Study on Performance Improvement of Expansive Soil Using Residual Soil and Lime.	Monowar Hussain		Dr. S. K. Dash	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./12	Civil Engineering
71.	Batch and Column Adsorption Studies for Simultaneous Removal of Iron, Arsenic and Fluoride by Wooden Charcoal and River Sand used as Filter Media in Indigenous Household Iron Filter Units of Rural and Semi-Urban Assam (India).	Kamal Uddin Ahamad		Dr. M. Jawed	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./13	Civil Engineering
72.	Performance improvement of weak clay foundation using stone column and geocell-sand mattress.	Mukul Chandra Bora		Dr. S. K. Dash	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./14	Civil Engineering
73.	Study on size effect of RC beam-column joints with and without retrofitting under cyclic loading.	Abdul Munim Choudhury		Prof. A. Dutta & Prof. S. K. Deb	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./15	Civil Engineering
74.	Reservoir operation considering downstream impact of a hydroelectric project.	Maya Rajnarayan Ray		Prof. A. K. Sarma	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./16	Civil Engineering

75.	Stochastic erosion in the composite banks of alluvial river bends.	Tapas Karmakar		Dr. S. Dutta	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./17	Civil Engineering
76.	Seismic microzonation of Imphal city and probalisitc seismic hazard assessment of Manipur state.	Kumar Pallav		Dr. K. D. Singh	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./18	Civil Engineering
77.	Performance Enhancement of expansive soil by Application of Fly Ash and Lime.	Sailen Deka		Dr. Sreedeep S. & Dr. S. K. Dash	IIT-G, Dept.Lib.Ref.No.-CE/Ph. D./19	Civil Engineering
78.	Hydrological Response of a Preferential Infiltration Dominated Natural Hillslope in Brahmaputra River Basin.	Rupak Sarkar		Dr. S. Dutta	IIT-G, Dept.Lib.Ref.No.-CE/Ph. D./20	Civil Engineering
79.	A Study on Plastic Cell Filled Concrete Block Pavement for Low Volume Rural Roads.	Y. Arunkumar Singh		Dr. K. D. Singh & Dr. T. L. Ryantathiang	IIT-G, Dept.Lib.Ref.No.-CE/Ph. D./21	Civil Engineering
80.	Identification of system parameters of multi-storey building with limited sensors.	Arun Chandra Borsaikia		Prof. S. K. Deb & Prof. A. Dutta	IIT-G, Dept.Lib.Ref.No.-CE/Ph. D./22	Civil Engineering
81.	A study on measuring methodologies and critical parameters influencing soil suction-water content relationship.	Malaya Chetia		Dr. S. Sreedeep	IIT-G, Dept.Lib.Ref.No.-CE/Ph. D./23	Civil Engineering
82.	Transient Analysis of Aged Concrete Gravity Dam-Foundation Coupled System.	Avijit Burman		Dr. S. Sreedeep	IIT-G, Dept.Lib.Ref.No.-CE/Ph. D./24	Civil Engineering

83.	A study on geotechnical performance of residual latertic soil and Brahmaputra sand blended with fly ash and cement.	Ajanta Kalita		Dr. B. Singh	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./25	Civil Engineering
84.	Experimental study on rehabilitated RC beam-column connections under cyclic loading.	Comingstarful Marthong		Prof. S. K. Deb & Prof. A. Dutta	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./26	Civil Engineering
85.	Design and development of an arsenic removal filter using Indigenous materials.	Sandip Mondal		Prof. C. Mahanta	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./27	Civil Engineering
86.	"Analytical Predictions of Flow into Auger Holes and Ditch Drains in Homogeneous Anisotropic Soil.	Wazir Alam		Dr. G. Barua	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./28	Civil Engineering
87.	Evaluation of factors controlling release and mobilization of Arsenic in parts of Brahmaputra floodplains.	Lalsangzela Sailo		Prof. C. Mahanta	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./29	Civil Engineering
88.	Strength and deformation characteristics of geocell-fiber reinforced granular soil.	Akash Priyadarshee		Dr. S. K. Dash	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./30	Civil Engineering
89.	Evaluation of suspended sediment flux along a cross-section of the Brahmaputra river	Bhupendra Barman		Prof. C. Mahanta	IIT-G, Dept.Lib.Ref.No.-CE/Ph.D./31	Civil Engineering
TITLES OF M PHIL DISSERTATION:						
90.		A.C. Sarma	1987	Dr. S.K. Sarmah	Gauhati University	Seismotectonics

91.	A Study of Seismicity in the Western part of Northeast Indian Region.	S.B. Hazarika	1987	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
92.	A study of Seismicity in Northeast Region & Seismic Potential of the Assam Gab.	C.N. Bepari	1988	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
93.	A study of seismicity of Indo-Burma Border region.	R. Gogoi	1989	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
94.	A study of P& S wave velocities and Crustal Structure of Assam region.	Dhurba Jyoti Bhuyan	1989	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
95.	A Study of Geology and Seismicity of Shillong plateau & its adjoining region.	Partha Sarathi Dey	1990	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
96.	Geology, Tectonics & Seismicity on Indo-Burma border region and upto 5ºN latitudes.	P.P. Deka	1990	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
97.	Study of Seismicity of the part of Southern Tibet adjoining Northeast India.	Mallika Baruah	1990	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
98.	Earthquake Prediction Oriented Studies in the region bounded by 88.0ºE-93.0ºE, 24.30′N-29.0ºN in eastern region.	Ranjana Borah	1990	Dr. S.K. Sarmah	Gauhati University	Precursor
99.	A Study of Seismotectonics of the Region bounded by Longitude 85.0ºE-93.0ºE & Latitude 24.5ºN-29.5ºN.	Anusuya Barua	1992	Dr. S.K. Sarmah	Gauhati University	Seismotectonics

100.	Study of Seismicity of Shillong Plateau & its adjoining region.	Ashok Kumar Das	1993	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
101.	Study of Spatial and Temporal Variation of a few Earthquake Prediction Parameters in Western part of North-east India.	A.P. Khound	1993	Dr. S.K. Sarmah	Gauhati University	Precursor
102.	A Study of Seismicity of parts of Arunachal Pradesh, North of Brahmaputra Valley.	N.C. Barman	1994	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
103.	A study of Seismicity of Assam Gap.	L. Nath	1995	Dr. S.K. Sarmah	Gauhati University	Seismotectonics
104.	Study on some Seismic Parameters in the region bounded by Latitude 25.0ºN to 27.0ºN & Longitude 89.5ºE to 93.0ºE.	Bhaskar Saikia	1998	Dr. S. Kalita	Gauhati University	Seismotectonics
TITLES OF M TECH DISSERTATION:						
105.	Log based sequence stratigraphyof Upper Paleocene to Lower Eocene sediments for the Upper Assam Basin.	Ankujyoti Chutia	2005	Dr. Siddhartha Kumar Lahiri and Dr. K.C. Kalita	Dibrugarh University	Startigraphy
106.	Fractal Dimension and b-value mapping of the Northeastern India.	Partha Pratim Kalita	2009	Dr. Saurabh Baruah	Tezpur University	Geodynamic Studies
107.	State of Stress Regime in the Northwest Himalaya and Nepal Himalaya.	Puspa Saikia	2010	Dr. Saurabh Baruah	Tezpur University	Geodynamic Studies

108.	Seismic Site Response characteristics of Greater Tezpur, Assam.	Barsha Das	2010	Dr. Ranju Duarah	Tezpur University	Microzonation

Annexure VI Reports / proceedings volumes / etc.

- Acharyya, S.K. (1997). Geological Setting and Natural Resources potential of the Northeastern Region, India. Keynote address, Seminar on the Great Shillong Earthquake -1897: A Centennial Retrospective, Shillong, Nov. 18-21, 1997.

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- Bayan, Gokul K. (2013). Riverbank scouring, its orientation of studies and prevention process-a permanent practical aspect. Proceedings of the International Conference on Ground Improvement and Ground Control, ISBN 978-981-07-3560-9, Doi:10.3850/978-981-07-3560-9 09-0903.

- Bayan, Gokul K. (2012). Road foundation– A new avenue for its stable and everlasting aspects. Proceedings of the International Conference on Ground Improvement and Ground Control, ISBN, 978-981-07-3560-9, Doi:10.3850/978-981-07-3560-9 10-1001 1639.

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Annexure VII

DAMAGING EARTHQUAKES OF THE REGION

1. Cachar Earthquake of 10th January 1869 (M=7.5)

Introduction

The outer limit of the felt area of the earthquake started from western coast of Bay of Bengal in Medinipur, running northwestward to Hazaribag, Patna and then through Darjeeling over the Himalaya to Lakhimpur and Dibrugarh in Assam where the shock was felt severely. The felt area measured 6,65,600 sq km. The area where the earthquake shock was very much intense with a lot of damage and destruction included within the line joining Guwahati, Nowgang, Nagaland, Manipur, Cachar (NE India) and Sylhet in Bangladesh. Many *pucca* buildings at Silchar, Nowgang and Imphal were seriously damaged; some of which were completely laid to the ground. There were many land fissures along the Barak and Surma river valleys, mostly running parallel to the river course with many liquefaction phenomena and sand venting in the Barak valley. 4 persons died and many got injured when the two storied building of the Maharaja's palace at Imphal collapsed (Oldham etal., 1882). Land fissures were also observed in the Manipur valley.

From consideration of direction of earthquake wave movements felt by different persons over the vast region and from orientation of ground fissures etc., Oldham et al., (1882) deduced the epicenter in the intersection of latitude 26^0 N and longitude 92^0 40'E lying over the northern border of Jaintia Hills, Meghalaya. It is interesting to note here that the suggested e4picentral tract was located in the Kopili gap area and might have been related to the movements along the Kopili fault. The depth of focus was estimated at 50 km. Though no idea about the magnitude was given in the GSI, Memoir., Vol. 19 (1882), from the description of damage pattern incorporated it may be inferred that the magnitude of the earthquake might have been greater than 7.

(Geodynamics of Northeastern India – D.R.Nandy 2001)

Abstracts (Cachar Earthquake of 10th January 1869)

- 'The Cachar Earthquake of 10th January 1869' *Tomas Oldham (Edited by R.D. Oldham);* ***Memoirs of the Geological Survey of India****, Volume XIX Part 1, pp. 1-29,* ***1882*** *[Selected Transcription]*

On the afternoon of Sunday, the 10th day of January 1869, all Calcutta was startled by one of the sharpest shocks of earthquake ever felt there. On that evening I was myself sitting reading in a house at Barrackpore about 15 miles from the city when, without any warning, the chair was violently rocked under me, everything in the room was shaken, doors and windows rattled and the chandeliers hanging from the
ceiling were set swinging with considerable force. At once noting the time of the shock by my own watch, and just then feeling a second but less violent shock pass under me, I got up to see more particularly what had occurred. The loud cries of alarm raised by all the native servants in the compound, and from the bazaar at no great distance, first struck the ear. All stood in the open air, with mouths gaping or violently gasping out their short exclamations of entreaty or worship calling on their deities to protect them, and in the greater crowd of the bazaar surged back and forwards for a few minutes, when finding that no further shocks occurred, their amazement died away, and they quieted down to their wonted occupation as if

nothing had happened. During the succeeding hours a few trifling undulations were felt, but no distinct wave or shock. Carefully noting, from such indications as were available, the direction in which the great wave had passed under Barrackpore, we felt satisfied that, as soon as time admitted of the news reaching the capital, we should hear of some very violent and possibly very destructive shock in the country beyond the limits of the great alluvial plain far away in East Bengal, and, as we determined from such evidence as was then before us, in the direction of Sylhet and Cachar.

Nor were our anticipations in this respect without sound basis; for next morning the telegraph wires brought the intelligence that Silchar town had been shaken to its very center, that serious destruction had caused, and, allowing for sensational terms in which some of the messages were conveyed, the result obviously of the first alarm before the facts had been realized, it was still clear that a very unusually severe shock had occupied, that much injury to property and possibly destruction of life had resulted and further that, as the news could be gathered up, it would be found that other places also as well as Silchar had suffered severely……..

- 'The Cachar Earthquake of 1869'; *W.M.Davis; **Science**; Vol. 1, No. 3, pp. 67-67, **Feb. 23, 1883***

The Geological Survey of India publishes in vol. xix., part 1., of its memoirs (1882), an account and discussion of the Cachar earthquake of north-eastern India, Jan. 10, 1869. The observations were made and the study begun by the late Dr. Thomas Oldham, then superintendent of the Survey: the work is lately completed by his son, R.D.Oldham, now a member of the geological corps. The memoir gives a general account of the shock and its destructive effects; notices of previous descriptions by Oldham, Godwin-Austen, H.F.Blanford, and Archdeacon Pratt, which in the present view seem largely erroneous in their theoretical parts; and a discussion of the position, depth, and shape of the seismic area, and the velocity of the earth-wave's motion and translation. It is well illustrated by photographs, lithographs, diagrams, and maps.
Cachar (or Silchar), where the shock produced great destruction, and after which it was named, is a town on the Barak river, at the southern base of the rainy Jaintia hills, about 300 miles north-east of Calcutta. The seismic vertical was some 80 miles farther north, as determined by thirty-six intersectionsfalling within an area forty miles by four or five; or excluding the less satisfactory lines, on an area twenty miles by three or four. The depth of the focus is estimated from several tolerably accurate observations at two stations, at thirty miles – or somewhere between twenty-five and thirty-five miles below the surface. The area over which the shock was felt was an oval measuring 650 miles north-eastand south-west, and 400 miles across, covering 250,000square miles, and including Patna and Hazaribagh on the west; the Ganges delta and Chittagong on the south; the head waters of the National (branch of Irrawaddy)on the east; and the southern slope of the Himalayaon the north. In the latter direction, the extension of the shock was not determined. Within this, a smaller oval or isoseismal line is drawnto show the region of great destruction; this is symmetrically placed around the seismic centre. The velocity of wave-translations, estimated over a difference of seismic radii of 180 miles, was 1.2 miles a second, which is regarded as very high and improbable, although the observations on which it is based – chronometer time noted by Major Godwin-Austen in the hills forty miles north-east of Cachar, and the clocks stopped by the shock in the surveyor general's office in Calcutta seem trustworthy. The wave-motion, even at a dis-

tance of eighty five miles from the seismic vertical, was thirty feet a second; decidedly greater than the found of Mallet for the Neapolitan earthquake of 1857. The large value of the angle of emergence at Cachar is ingeniously accounted for as a result of upward refraction of the wave in passing through the loose alluvial sands. In spite of the violence of the shock, few lives were lost, and few buildings overthrown: the reason being that most of the houses are of wood and bamboo, elastic enough to escape great injury; or, if of masonry or brickwork, the walls are heavy and low, supporting each other against overthrow. A church tower, a saw mill, and a two storied palace were thrown down. A secondary action of the shock produced greater destruction at certain points. The alluvial deposits along the river bottoms sometimes contain strata of soft, water logged quicksand; and where heavy clays overlying these are cut through by the streams, they are often cracked parallel to the steep bank by the earth wave, and then settle down, and slide on the soft sands beneath. If this happen in a village, the buildings are torn to pieces by the differential motion of their foundations, even if able to escape the effect of the shock. Connected with this effect is the formation of 'sand craters', which are shown to result from the wet quicksand being forced up through a vent or crevice opened in the overlying clays; the open cup like form being produced by the back flow of the water after the shock passes on. These are finely illustrated, and at once recall the figures given in Lyell's Principles' of the 'circular hollows' formed on the Calabrian plains by the earthquake of 1783.

The memoir closes with an appendix giving simple instructions for earthquake observations, and we cordially join the author in the hope that such observations may soon be undertaken at the meterological stations throughout the earthquake districts of India.

W.M.Davis

- 'Deterministic seismic scenarios for North East India'; *S.T.G.Raghu Kanth, Sujit Kumar Dash;* ***J Seismol****; Vol. 14, No. 2, pp. 143-167,* ***2010****; DOI:10.1007/s10950-009-9158-y*

Abstract

In this paper, ground motion during six past devastating earthquakes and one possible future event in the northeastern part of India is estimated by seismological approaches. Considering uncertainty in the input source parameters, a series of ground motions have been simulated. The peak ground acceleration (PGA) and response spectra at important cities and towns in the epicentral regions of these events are obtained. The PGA distribution over the entire northeastern region of India, encompassing the epicenter, is presented in the form of contours. The obtained results can be used for the seismic analysis and design of structures in this region.

Keywords; Strong ground motion, PGA, Stochastic finite fault model, Northeast India, Response spectra

- 'Surface level ground motion estimation for 1869 Cachar Earthquake (M_W 7.5) at Imphal City'; *Kumar Pallav, S.T.G.Raghukanth, K.D.Singh;* ***Journal of Geophysics and Engineering****;* ***07/2010****; 7:321-331. DOI:10.1088/1742-2132/7/3/010*

Abstract

In this paper, the seismic susceptibility of Imphal city with respect to ten synthetically generated samples of the historic 1869 Cachar (Mw 7.5) earthquake that occurred in the Kopili

fault is presented based on the finite-fault seismological model in conjunction with nonlinear site response analyses. For all the synthetic sample earthquake events, the mean and standard deviation of surface level spectral ground acceleration at peak ground acceleration (PGA) and natural periods of 0.3 and 1 s have been reported in the form of contour maps. These contour maps can serve as guidelines for engineers and planners to identify vulnerable areas for possible seismic disaster mitigation of Imphal city.

- 'Deterministic Seismic Scenarios for Imphal City'; *S.T.G.Raghu Kanth, Konjenbam Darunkumar Singh, Kumar Pallav;* ***Pure and Applied Geophysics****;* ***04/2012****; 166(4): 641-672; DOI:10.1007/s00024-009-0460-y*

Abstract

In this article, the spatial variation of ground motion in Imphal City has been estimated by the finite-fault seismological model coupled with site response analysis. The important seismic sources around Imphal City have been identified from the fault map and past seismicity data. The rock level acceleration time histories at Imphal City for the **1869 Cachar (M_W 7.5) earthquake** and a hypothetical M_W 8.1 event in the Indo-Burma subduction zone have been estimated by a stochastic finite-fault model. Soil investigation data of 122 boreholes have been collected from several construction projects in Imphal City. Site response analysis has been carried out and the surface level ground motion has been determined for Imphal City for these two earthquake events. The results are presented in the form of peak ground acceleration (PGA) contour map. From the present study it has been ascertained that the maximum amplification for PGA over Imphal City is as high as 2.5. The obtained contour maps can serve as guidelines for identifying vulnerable areas and disaster mitigation in Imphal City.

- 'Liquefaction Hazard Scenario of Imphal City for 1869 Cachar and a Hypothetical Earthquake'; *Kumar Pallav, S. T. G. Raghukanth and Konjengbam Darunkumar Singh;* ***International Journal of Geotechnical earthquake engineering****, Volume 3, Issue 1, pp. 34-56,* ***January-June 2012***

Abstract

In the present article liquefaction potential of Imphal city is reported in the form of two indices, i.e., LPI (Liquefaction Potential Index) and LSI (Liquefaction Severity Index), for 1869 Cachar earthquake (Mw 7.5) along the Kopili fault and probable future great earthquake (Mw 8.1) in the Indo-Burma subduction zone. The Factor of Safety (FS) against liquefaction has been computed by using modified procedure given by Idriss and Boulanger (2006) for all depths of 122 boreholes. The computed FS have been used as input parameters for evaluating LPI and LSI indices for Imphal City. Based on these LPI and LSI indices, liquefaction potential hazard contour maps of Imphal city is prepared. It is observed that over a large area of Imphal city is highly vulnerable to liquefaction failure in the events of the selected earthquake. The liquefaction hazard obtained at each site exhibits a good agreement with the damages documented for 1869 Cachar earthquake. This contour map can be served as a guideline for engineer and planner in site selection for upcoming projects and helps city administration in mitigating the city from future hazards.

Keywords: Cachar Earthquake, Imphal City, Liquefaction, Liquefaction Potential Index (LPI), Liquefaction

Severity Index (LSI)

2. Great Assam Earthquake of 12th June 1897 (M=8.7)

Introduction

"At about quarter past five in the afternoon of 12th June, 1897, there burst on the western portion of Assam an earthquake which, for violence and extent, had not been surpassed by any of which we have historic record. Lasting for about two and a half minutes, it had not ceased at Shillong before an area of 150,000 square miles had been laid in ruins, all means of communication interrupted, the hills rent and east down in landslips and the plains fissured and riddled with vents, from which sand and water poured out in most astounding quantities; and ten minutes had not elapsed from the time when Shillong was laid to ruins before about one and three quarter millions of square miles had felt shock which was everywhere recognised as one quite out of common". – ***R.D.Oldham, 1899***.

This was the short description of violence of the Great earthquake of 1897, scientific study of which was taken up by Dr. R.D.Oldham and many other officers of Geological Survey of India. Oldham (1899) had drawn the isoseists up to 6 intensity levels, No. 1 being the most intense. He had equated his no. 1 isoseist with degree X of Rossi-Forel intensity scale and no. 6 with those of the degree II and III of the same scale. The first isoseist within which all brick and stone masonary buildings were universally destroyed included the places like Shillong, Goalpara, Rangpur and Cooch Bihar. No. 2 isoseist included Murshidabad, Malda, Darjeeling where damage to brick masonary buildings was universal, often serious. No. 3 isoseist covered Bhagalpur, Krishnangar and Calcutta where all or nearly all brick buildings were damaged.

Reports of personal experience at Shillong stated that the surface of the ground vibrated visibly in every direction as if it was made of soft jelly. A stone in the parade ground at Tura, about 50 cm in diameter and 25 cm in thickness, partly embeded in ground was thrown to a distance of about 1 m and turned upside down (Oldham 1899). Land fissures and sand veins were universal throughout Goalpara, Kamrup, western part of Darrang, Nowgang and northern part of Cachar districts of Assam. Just after the earthquake the water level of Brahmaputra river was raised by 2.30 m at Guwahati by 6 P.M on the fateful day. Landslides developed more conspicuously along the southern edge of Garo and Khasi Hills, Meghalaya. The eastern limit of landslides was extended up to the North Cachar Hills.

The earthquake occurred at 17h 15m local time (11h 09m GMT) and was recorded by 12 primitive seismographs in Europe at distances between 64° and 72° (Germany, Italy, France and UK). Instrumental readings, however, are not good enough to be used to establish its position, even approximately, and the macroseismic location of the event has been estimated by various authors at 26°N, 91°E with magnitude M 8.7. The mean geodetic location is 25.7°N. 91.1°E.

Abstracts (Great Assam Earthquake of 12th June 1897)

- '**Report on the Great Earthquake of 12th June 1897'**; *R.D.Oldham;* ***Memoirs of the Geological Survey of India, Vol. XXIX, 1899;*** *(379 pages)*

Foreword (Reprinted 1981)

"*The Geological Survey of India's pioneering contributions to the Science of Seismology are well known. Of these, R. D. Oldham's Memoir on the Great Assam Earthquake of 12th June, 1897, which laid the foundations of modern seismological studies, will remain forever a classic contribution. The subsequent Memoirs, on the Kangra Earthquake of the 4th April, 1905, by Middlemiss and on the Bihar-Nepal Earthquake of 1934, by officers of the G.S.I, and others, continued the fine tradition set by R.D.Oldham. These excellent accounts of three of the large magnitude Indian earthquakes, published by the G.S.I. respectively in 1899, 1910 and 1939, had gone out of print several years ago.*

Although the Science of Seismology has made rapid strides in recent years, the scientific workers throughout the world, who have been engaged in the study of the causes and the prediction of earthquakes, needed for their constant reference, the comprehensive accounts of past major Indian earthquakes. In early 1980, the demand for the above-cited Memoirs on Indian earthquakes was voiced by Dr. Jai Krishna, President of the International Association for Earthquake Engineering, when he had requested that the G.S.I. may arrange to reprint and issue these three classical Memoirs for the use of the scientific community all over the world. The G.S.I. compiled very willingly with this request.

I am very happy that all the three Memoirs, as reprinted now, will once again be available to all those who are interested in the study of earthquakes. The first Memoir to be reissued is the Volume 29 by R.D.Oldham, dealing with the Great Assam Earthquake of 1897, and this will be followed by the Volume 38 on the Kangra Earthquake of 1905 and the Volume 73 on the Bihar-Nepal Earthquake of 1934. If these three reprinted volumes of the classical Memoirs og G.S.I. further stimulate research on earthquakes and promote advances in the Science of Seismology, I shall consider the effort made by the G.S.I. to reprint these well-known Memoirs to be amply rewarded.

Dated, *Calcutta*
V.S.Krishnaswamy
The 30th June, 1981 *Director General*
Geological Survey of India

- 'A rupture model for the great earthquake of 1897, northeast India'; *V.K.Gahalaut and R.Chander;* ***Techtonophysics**, 204, 163-174,* ***1992***

Abstract
We assume that the unusually deep, extensive and long-lasting floods of 1897 along the section of the Brahmaputra River north of the western Shillong plateau were due to local ground subsidence associated with the great earthquake which occurred on June, 12 of that year in the western part of northeast India. Numerical simulations of ground-level changes due to slip on a buried low-angle thrist fault, dipping due north, then show that the northern limit of the rupture zone of this earthquake should have been along the E-W-flowing Brahmaputra River, about 40 km north of the northern edge of the Shillong plateau and about

70 km south of the Himalayan mountain front. A similar interpretation of a ground tilt observation suggests that the western limit of the 1897 rupture zone was along the western margin of the Shillong plateau. The E-W and N-S dimensions of the rupture zone are estimated to be 170 km and 100 km respectively, so that it enclosed the western half of the Shillong plateau and areas north of it up to the Brahmaputra River. The rupture depth could not be estimated from the available data on ground-level changes, and was constrained at 15 km beneath the southern margin of the Shillong plateau, on other evidence. The above thrust fault should be of the nature of a detachment at midcrustal depth, which arose because the continental crust associated with the Indian Shield terrains of the Shillong plateau and Mikir Hills immediately to the east could not subduct under the continental crust of the Eurasian plate to the north and east. It is tentatively suggested that, although this detachment may extend under the Himalaya, it may not be the detachment on which the great earthquakes of 1905, 1934 and 1950 have occurred in the northwestern, central and eastern Himalaya, respectively. It is also suggested that a distinction should be made between the seismicity of the Himalaya and the seismicity of the Himalayan convergent plate margin (HCPM). An earthquake of the Himalayan seismic belt is also an earthquake of the HCPM, but the converse need not hold true. Since the inferred northern limit of the 1897 rupture zone is about 70 km south of the Himalayan mountain front, it is suggested that this earthquake belongs to the HCPM but not to the Himalayan seismic belt, Thus, conservatively, a seismic gap of about 700 km may exist along the Himalayan seismic belt between the eastern and western limits of the rupture zones of the great 1934 and 1950 earthquakes respectively.

- 'Crustal properties in the epicentral tract of the Great 1897 Assam Earthquake, north-eastern India'; *S.Mukhopadhyay, R.Chander, K.N.Khatti;* ***Tectonophysics*** *283, pp. 311-330,* ***1997***

Abstract
The velocity structure for the upper and middle crust in the epicentral tract of the Great 1897 Earthquake (western half of the Shillong massif) was estimated using locally recorded microearthquake data. The relatively homogeneous upper crustal layer has P and S wave velocities of 5.9 ± 0.2 and 3.4 ± 0.1 km/s, respectively, with a thickness of 11 to 12 km. The average P and S wave velocities in the middle part of the crust down to a depth of about 26 km were estimated to be 6.3 ± 0.6 and 3.5 ± 0.2 km/s, respectively. The larger scatter in P velocity estimate of the mid-crustal layer was investigated using synthetic examples. Our preference is for the model in which this crustal region is assumed to comprise of a number of thin layers with alternate low and high seismic velocities. From theoretical considerations we confirm that it is possible to estimate the velocity structure for a horizontally layered model using the velocity estimation procedure (a combination of the Wadati, Riznichenko and Bune method) we have used. We also carried out detailed model analysis to check how effective this velocity estimation procedure is for the type of array data we have. Combining the estimated velocity structure with our earlier work on seismicity of this area we propose that the upper homogeneous crustal layer in the Shillong massif may be moving relatively southward across an intracrustal thrust zone. We suggest that the Great 1897 Assam Earthquake may represent the most recent episode of this relative southward movement of the massif.

Keywords : Shillong massif; velocity; Great 1897 Assam Earthquake; Riznichenko method

- ‘MSK Isoseismal intensities evaluated for the 1897 Great Assam Earthquake’; *Ambraseys, N., and R. Bilham;* ***Bull. Seism Soc. Am****. 93 (2) 655-673,* ***2003***

Abstract

The great 1897 Assam earthquake of 1897 is the largest known Indian intraplate earthquake (8<M<8.1). The earthquake raised the northern edge of the Shillong Plateau by more than 10 m, resulting in the destruction of structures over much of the Plateau and surrounding areas, and causing widespread liquefaction and flooding in the Brahmaputra and Sylhet floodplains. Shaking intensity data for the earthquake are crucial for estimating future earthquake hazards in NE India and Bangladesh since similar earthquakes will no-doubt recur. Yet despite the availability of numerous felt reports, no evaluation of isoseismal contours has been attempted since Oldham's (1898) approximation. We have re-evaluated 365 accounts of the earthquake and quantified 287 on a simplified version of the "MSK 1981" Intensity scale. The reappraised isoseismals are consistent with the geodetic mechanism for the earthquake and are smaller, less regular, and less elliptical than those inferred by Oldham. They suggest that Oldham's intensities were inflated by 1-1.5 intensity units. The revised intensity data provide new quantitative constraints on the attenuation of perceived intensity as a function of distance in northeastern India.

- ‘Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake: Implications for regional tectonism’; *C. P. Rajendran, Kusala Rajendran, B. P. Duarah, S. Baruah, and Anil Earnest;* ***TECTONICS****, VOL. 23, TC4009, doi:10.1029/2003TC001605,* ***2004***

Abstract

[1] The 1897 Shillong (Assam), northeast India, earthquake is considered to be one of the largest in the modern history. Although Oldham’s [1899] classic memoir on this event opened new vistas in observational seismology, many questions on its style of faulting remain unresolved. Most previous studies considered this as a detachment earthquake that occurred on a gently north dipping fault, extending from the Himalayan front. A recent model proposed an alternate geometry governed by high-angle faults to the north and south of the plateau, and it suggested that the 1897 earthquake occurred on a south dipping reverse fault, coinciding with the northern plateau margin. In this paper, we explore the available database, together with the coseismic observations from the region, to further understand the nature of faulting. The geophysical and geological data examined in this paper conform to a south dipping structure, but its location is inferred to be in the Brahmaputra basin, further north of the present plateau front. Our analyses of paleoseismic data suggest a 1200-year interval between the 1897 event and its predecessor, and we identify the northern boundary fault as a major seismic source. The Shillong Plateau bounded by major faults behaves as an independent tectonic entity, with its own style of faulting, seismic productivity, and hazard potential, distinct from the Himalayan thrust front, a point that provides fresh insight into the regional geodynamics.

KEYWORDS: earthquake, tectonics, paleoseismology, faulting, seismicity, northeast India.

- ‘Tom La Touche and the Great Assam Earthquake of 12 June 1897: Letters from the Epicenter’; *Roger Bilham;* ***Seismological Research Letters****,* ***May/June 2008****, v. 79, p. 426-437*

Abstract
Richard Dixon Oldham's classic memoir on the great M_w = 8.1 Assam earthquake of 1897 is seminal for its seismological observations, insights, and conclusions (Oldham 1899). Teleseismic arrivals of waves from Shillong led Oldham (1858–1936) to distinguish the three types of seismic waves and eventually to recognize from them the distinctive presence of the Earth's core. Oldham, however, did not feel the earthquake. He had left the Calcutta office of the Geological Survey of India (GSI) in the care of his colleague Thomas Henry Digges La Touche (1856–1938) two weeks previously (see figure 1). Now recently discovered letters written by La Touche from Calcutta and the epicentral region to his wife, Nancy, provide a firsthand, day-by-day account of the post-earthquake investigation and include a seismogram from an instrument that he constructed in the field at a cost of “less than sixpence” from pieces of tin, a suspended boulder, a glass bead, and a bamboo needle that scratched a glass plate (LaTouche papers, 1880–1913). In his memoir Oldham notes that he focused his team of geologists on the physics of the earthquake. Their reports were submitted “under specific instructions to report only on the facts observed, and to refrain from any expressions of opinion as to the conclusions to be drawn, as this could only be profitably done after a review of the whole of the facts, of which only part could become known to each individually.” (Oldham 1899, p.257). He deduced from their observations that local accelerations in the earthquake had exceeded 1 g, that velocities had exceeded 3 m/s, that electrical currents in the ground had accompanied aftershocks, that postseismic crustal deformation continued to deform the plateau in the year following the earthquake, and that many of the largest aftershocks lay 15 km beneath the plateau. …

- ‘Ground motion estimation at Guwahati city for an M_W 8.1 earthquake in the Shillong plateau’; *S.T.G.Raghu Kanth, S.Sreelatha, Sujit Kumar Dash;* ***Tectonophysics,*** *448 , 98-114,* ***2008***

Abstract
In this paper, the ground motion at Guwahati city for an 8.1 magnitude earthquake on Oldham fault in the Shillong plateau has been estimated by stochastic finite-fault simulation method. The corresponding acceleration time histories on rock level at several sites in the epicentral region have been computed. These results are validated by comparing them with the estimates obtained from Medvedev–Sponheuer–Karnik (MSK) intensity observations of 1897 Shillong earthquake. Using the local soil parameters, the simulated rock level acceleration time history at Guwahati city is further amplified up to the ground surface by nonlinear site response analysis. The results obtained are presented in the form of peak ground acceleration (PGA) contour map. The maximum amplification for PGA over Guwahati city is as high as 2.5. Based on the simulated PGA, the liquefaction susceptibility at several locations in the city has been estimated. The results are presented in the form of contours of factor of safety against liquefaction at different depths below the ground surface. It is observed that over a large part of the Guwahati city, the factor of safety against liquefaction is less than one, indicating that the city is highly vulnerable to liquefaction in the event of this earthquake. The contour maps obtained can be used in identifying vulnerable areas and disaster mitigation.

- ‘A Probable Isoseismal Map due Maximum Credible Earthquake (M=8.7) in NER, India; an Approach towards Risk Mitigation’; *Saurabh Baruah,* ***12th International***

Conference of ***'International Association for Computer Methods and Advances in Geomechanics (IACMAG)****,* ***1-6 october, 2008****, Goa, India*

Abstract
The study estimates the extent of seismic hazard in North East India in correlation to the past great earthquakes. Probable isoseismal maps through deterministic approach are prepared based on the basic information from two major earthquakes of 12th June 1897 (M=8.7) and 6th August 1988 (M=7.3). The study utilizes the database in the form of percentage increase in population and urbanization to the respective seismogenic zones available during the past earthquake besides the estimated peak ground acceleration for NER, India from GSHAP. The study shows that if an earthquake of M=8.7 were to recur today the devastation would be manifold because of abrupt increase in population and urbanization. The new isoseismal map depicts that much larger area covers maximum intensity at present in comparison to the isoseismal map during 1897 earthquake.

Keywords: Great Assam earthquake, isoseismal map

- 'Evaluation of seismic soil-liquefaction at Guwahati city'; *S.T.G.Raghu Kanth, Sujit Kumar Dash;* ***Environ Earth Sci.*** *(****2010****) 61; 355-368; DOI: 10.1007/s12665-009-0347-3*

Abstract
Great earthquakes in the past (e.g. 1869 Cachar earthquake, 1897 great Assam earthquake) have caused large scale damage and ground liquefaction in the Guwahati city. Moreover, seismologists are of opinion that a great earthquake might occur in the unruptured segment of the North-East Himalaya that is near to Guwahati city. In this paper, the liquefaction hazard due to these events have been simulated. The obtained results are in general agreement with the reported damages due to the past earthquakes. The central part of the city (i.e. Dispur, GS road), that has large thickness of soft soil deposit and shallow ground water table, is highly vulnerable to liquefaction.

Keywords: Earthquake , Ground liquefaction , Guwahati city

- 'Intrinsic and scattering attenuation in Chedrang Fault and its vicinity – the rupture area of Great Assam earthquake of 12 June 1897 (M = 8.7)'; *Saurabh Baruah1, Devajit Hazarika, Aditya Kalita and Sumana Goswami;* ***Current Science****, VOL. 99, NO. 6,* ***25 SEPTEMBER 2010***

Abstract
The attenuation of seismic waves is one of the basic physical parameters used in seismological studies, which is closely related to the seismicity and tectonic activity of a particular area. In the present study, attenuation properties of the crust beneath the Chedrang Fault and its vicinity, the rupture area of the great Assam earthquake of 12 June 1897 (M = 8.7) are studied using waveforms recorded by a local seismic network composed of five stations. In total 20 local earthquakes have been analysed to estimate (i) coda wave attenuation quality factor (Q_c) applying single scattering model, (ii) total attenuation quality factor (Q_d) from direct S-wave applying spectral ratio method and (iii) intrinsic and scattering attenuation quality factors (Qi and Qs) following the Wennerberg's approach. Coda Q (Qc) values are obtained us-

ing different coda window lengths (20, 30 and 40 s) for frequency bands centred at 1, 1.5, 2, 3, 4, 6, 8, 12, 16 and 18 Hz. This study indicates that *Q*c increases with increasing lapse time and that *Q*c is frequency dependent following the attenuation–frequency relation *Q*c(20) = 36.29 □1.18*f* 1.45 □□0.09, *Q*c(30) = 69.92 □□1.11*f* 1.23 □□0.06 and *Q*c(40) =117.08 □□1.08*f* 1.07 □□0.05 for 20, 30 and 40 s respectively. This behaviour is usually correlated to the presence of heterogeneity in the crust and to the degree of tectonic complexity underneath the study area. The Qc^{-1} values for this area follow a substantially similar trend of Qc^{-1} decay with frequency as the other tectonically active regions of the world. Finally, from the separation of *Q*s and *Q*i values, it is observed that the study area can be characterized by a low scattering attenuation (small scattering *Q* inverse, Qs^{-1}) and by a relatively high intrinsic attenuation (high intrinsic *Q* inverse, Qi^{-1}).

Keywords: Chedrang Fault, coda waves, frequency dependence, intrinsic attenuation seismic waves, quality factor.

- ‘Seismic event of the Dauki Fault in 16th century confirmed by trench investigation at Gabrakhari Village, Haluaghat, Mymensingh, Bangladesh’; *Michio Morino, A.S.M.Maksud Kamal, Dicky Muslim, Reshad Md. Ekram Ali, Mohammad Ashraful Kamal, Md. Zillur Rahman, Fumio Kaneko;* ***Journal of Asian Earth Sciences****; Volume 42, Issue 3, pp. 492-498,* ***10 August 2011****,*

Abstract

The Dauki Fault, which is inferred to go through the southern margin of the Shillong Plateau, is an E–W trending reverse one inclined towards the north. The Dauki Fault was believed to be active during the Late Quaternary time by the geomorphic features of the Shillong Plateau, the gravity anomaly data, and uplifted Tertiary and Quaternary deposits on the southern foothills of the Shillong Plateau. However, previous studies did not show any specific evidence that the Dauki Fault is active, since active fault survey such as satellite photo interpretation and trench investigation was not performed hitherto. We carried out CORONA satellite photo interpretation and trench investigation across the Dauki Fault at Gabrakhari Village for the first time. Consequently small fault strands and clear unconformity accompanied with faulting were confirmed in the trench. However, these small fault strands may be secondary ones branched from a main fault which may be concealed under the trench. The time of seismic event, which is inferred from unconformity, is dated back to A.D. 1500–1630. The seismic event during A.D. 1500–1630 may correspond with the 1548 earthquake which is currently a first recorded large earthquake in Bangladesh. Furthermore, sand dikes due to paleo-liquefaction, which reach near the ground surface, were confirmed at the trench. According to radiocarbon age, the sand dikes were formed during the 1897 Ms. 8.0 Great Assam earthquake.

Keywords: Dauki Fault; 1548 Earthquake; Shillong Plateau; Active fault; Trench investigation

- ‘Seismotectonics of the great and large earthquakes in Himalaya’; *J.R.Kayal;* ***Special Section: Science of the Himalaya; Current Science****, Vol. 10 188 6, No. 2,* ***25 January 2014***

Abstract

The best known seismotectonic model of the Himalayan Seismic Belt (HSB) suggests that the great and large earthquakes in the Himalaya occur at a shallow depth (10–20 km) by thrust faulting on the Main Himalayan Thrust, i.e. on the plane of detachment. The plane of detachment is the interface between the Indian shield and the Himalayan sedimentary wedge. The recent earthquake data of the permanent and temporary local networks in the Himalaya, however, indicate bimodal seismicity at shallow (0–20 km) as well as greater depths (30–50 km). The source processes of the great and large earthquakes are reexamined in this article (the observations do not support a uniform seismotectonic model for the entire HSB). The four known great earthquakes (*Ms* ~8.0–8.7) in the Himalayan region, from west to east are the 1905 Kangra, 1934 Bihar, 1897 Shillong and the 1950 Assam earthquakes that occurred by different tectonic processes; each occurred in its own unique complex tectonic environment. Most recently, the 1988 strong earthquake (*Ms* 6.6) in the Bihar/Nepal foothill Himalaya and the 2011 strong earthquake (*Mw* 6.9) in the Sikkim Himalaya show that these are not the plane of detachment events; these occurred by strike–slip faulting at mantle depth (~ 50 km). A review of all these significant earthquakes in HSB is presented in this article.

Keywords: Fault plane solutions, plane of detachment, seismotectonics, thrusts, lineaments

3. Dhuburi Earthquake of 2nd July 1930 (M_b=7.1)

Introduction

Centering round the northeastern corner of Garo Hills, Meghalaya and the adjoining valley of Brahmaputra river, this earthquake was attended with disastrous results in northern Bengal, northwest Bangladesh and western Assam. The earthquake was felt over an area of 924,320 sq km extending from Dibrugarh (27^0 28': 94^0 57') and Manipur valley in the east to Chittagong (22^0 21': 91^0 53') and Calcutta (22^0 34': 88^0 24') in the south to Patna (25^0 37': 85^0 13') in the west, and beyond the frontier of Bhutan, Sikkim and Nepal in the north.

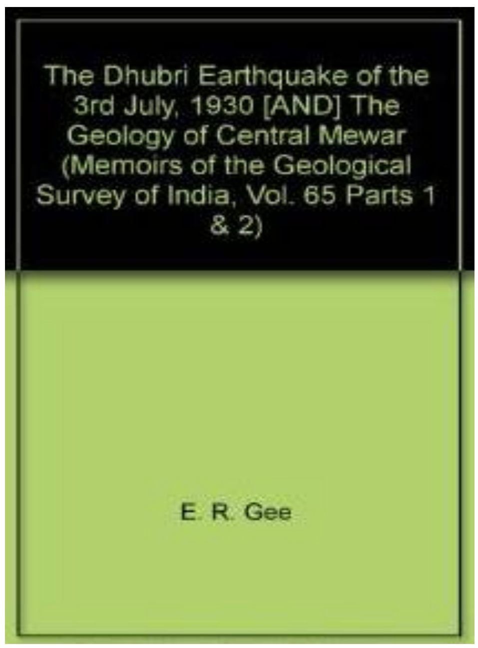
The epicenter of this earthquake was determined at a place few kilometer south of Dhubri at the intersection of latitude 25^0 57' N and longitude 90^0 00' E, deduced from the physical evidence as well as from the seismograph records. The time of origin was estimated at about 2 hr. 33 min. 54 sec. (IST) or 21 hr. 3 min. 49. Sec. (GMT) on 2nd July, 1930 with magnitude M_b=7.1. The maximum intensity reached was of isoseist 2 (equivalent to intensity IX of the Rossi-Forel scale). At Dhubri a few of the brick masonary buildings escaped severe damage. Majority of them were badly cracked and partially collapsed, while in at last one instance total collapse of structure took place after the main shock. Most of the semi-pucca structure suffered considerable damage. The Railway station at Gauripur lying within the epicentral tract was very badly damaged with ground upheaving near the booking office. However, no loss of life was reported in the epicentral tract mainly due to the fact that most of the houses were flexibly structured.

The isoseist 3 (= intensity VIII of Rossi-Forel scale) included the town of Rangpur, Cooch Bihar, Alipur; east of Brahmaputra river and the town of Tura. The intensity of the main shock within this isoseist was almost of same degree as it was within the isoseist 2. Within this zone most of the damages occurred due to ground fissures and soil liquefaction, especially within the alluvial tract of North Bengal and NW-Bangladesh, and west and north of the Brahmaputra river. Masonary buildings through which these fissures traversed were badly damaged. The light structures made of wood and *ikra* prevalent at Tura were also severely affected. Number of bridges and culverts were cracked and railway lines were distorted due to subsidence. At Cooch Bihar town, as it was reported, the ground was thrown into a succession of waves which appeared to vibrate along a general NNW-SSE direction. Old buildings were badly shattered here and in some cases they partially collapsed. Many buildings in Tura were severely affected. From the damage scenario, from the knowledge of local geology and from the tectonic setting of the area of the meizoseismal zone, the source of this earthquake event may be assigned to the N-S Dhubri or Jamuna Fault.

(Geodynamics of Northeastern India – D.R.Nandy 2001)

Abstracts (Dhubri Earthquake of the 2nd July 1930)

- 'The Dhubri Earthquake of the 2nd July 1930'; ***E.R.Gee****; Memoirs of the Geological Survey of India, Volume LXV, Part 1, Page 1-106,* ***1934***



A large portion of northeastern India was, during the early hours of the morning of 3rd July, 1930, affected by seismic activity. Centering near the northwestern end of the Garo hills and adjoining valley of the Brahmaputra river, this earthquake was attended with disastrous results in northern Bengal and in western Assam, and was felt very distinctly over a wide area, extending from Dibrugarh and Manipur in the east, to Chittagong and Calcutta in the south, to Patna in the west, and beyond the frontiers of Nepal, Sikkim and Bhutan in the north. The sensible zone of the earthquake includes widely contrasting types of topography and geology. The epicentral tract, in the vicinity of the town of Dhubri adjoining the Brahmaputra river, and the areas badly affected to the northwest, west and south, comprise a portion of the alluvial plain country which is traversed by the lower courses of the Brahmaputra and Ganges rivers and by their numerous tributaries. To the north, in the outer part of the sensitive zone, rise the outer ranges of Nepal, Darjeeling, Sikkim and Bhutan Himalayas. To the NE and ENE of Dhubri, the higher reaches of the Brahmaputra river traverse a wide alluvial valley, narrowing eastward and dotted by a number of prominent hills, whilst the more distant southeastern areas include the alluvial plains of Mymensingh and Sylhet. Between these two latter tracts, east of the Brahmaputra, are the jungle-clad ridges of the Garo hills rising to well over 4,000 feet; these continue eastwards to link up with the Khasi and Jaintia hills of the Shillong plateau…….

4. Great Assam Earthquake of 15 August 1950

Introduction

It is one of the few earthquakes to which the instrumentally determined magnitude, 8.7 is assigned. The epicenter was near Rima village situated on the border of India and China. This shock was more damaging in Assam, in terms of property loss, than the earthquake of 1897. To the effects of shaking were added those of flood; the rivers rose high after the earthquake, bringing down sand, mud, trees and all kinds of debris. Pilots flying over the meizoseismal area reported great changes in topography; this was largely due to enormous slides, some of which were photographed. The only available on the spot account is that of F.Kingdon-Ward, a botanical explorer who was at Rima. However, he had little opportunity for observation; he confirms violent shaking at Rima, extensive slides, and the rise of the streams, but his attention was perforce directed to the difficulties of getting out and back to India. Aftershocks were numerous; many of them were of magnitude 6 and over and well enough recorded at distant stations for reasonably good epicenter location. From such data, Dr Tandon, of the Indian Seismological Service, established an enormous geographical spread of this activity, from about 90^0 to 97^0 east longitude, with the epicenter of the great earthquake near the eastern margin. One of the more westerly aftershocks, a few days later, was felt more extensively in Assam than the main shock; this led certain journalists to the absurd conclusion that the later shock was 'bigger' and must be the greatest earthquake of all time. This is a typical example of confusion between the essential concepts of magnitude and intensity.

'Elementary Seismology' by Charles F.Richter

" Though this earthquake is known as the Assam earthquake its epicenter was located in the territory near the tri-junction of India, Myanmar (Burma) and China adjacent to the Mishmi Hills of Arunachal Pradesh of India, in higher reaches of the Lohit river. One of the biggest earthquake of the twentieth century was recorded at about 7.40 p.m (IST) on the 15^th^ August, 1950. It caused wide spread devastation throughout Upper Assam, Abor and Mishmi Hills of Arunachal Pradesh. The meizoseismal area covered 99,840 sq km and the felt area measured 2,892,000 sq km with 1526 death (500 due to subsequent flood); 40% to 50% wild lives perished in the hilly tract of the meizoseismal area; widespread collapse of buildings took place in Upper Assam. Estimated loss of the Assam Oil Company at Digboi was Rs. 11,000.00 (1950 price index), and damage to road, railways and bridges was more than Rs. 50,00,000.00 (1950 price index), 126 acres of tea garden in Upper Assam area were covered with thick silts and sands. In badly affected areas, the ground cracked and fissured; water and sand spouted throughout the fissure; road and railway tracks were broken up and twisted. Many bridges were destroyed and river bed silted up (Poddar 1950). The town of Sadiya, lying in between the confluences of Dibang and Lohit rivers with the Brahmaputra, was totally destroyed. Damage and casualties subsequently increased considerably, owing to sudden floods in the Subansiri valley shortly after the earthquake, caused by bursting of a temporary dam formed by landslide materials. As the meizoseismal zone was sparsely populated

and the earthquake occurred when most people were awake loss of life was little in comparison to the magnitude of the shock.

The isoseists drawn (Poddar, 1950) for this earthquake, from intensity X to VI in MM scale, covered an area elongated in NE-SW direction within the Indian territory, mostly along the Brahmaputra valley. Isoseists X covered the lower reaches of the Subansiri, Siang, Dibang and Lohit rivers. Digboi and Dibrugarh towns in Assam fell in between the isoseists IX and VIII where there was devastating damage to property. The isoseist VI extended southwestward upto Nowgang and Lumding. It is interesting to note that at some places of low intensity greater damage took place such as in Balibat area near Jorhat, lying just within isoseist VIII; a narrow belt of about 150m width running NNW-SSE direction was severely affected. This phenomenon was also observed during 1897 Great Assam earthquake in this narrow belt (Poddar, 1950). Immediately after the shock several major tributaries of the Brahmaputra river, particularly the Subansiri, Dihang (Siang), Dibang and Lohit were blocked by landslides caused by violent earthquake. The Subansiri river dried up after the shock due to damming. The dam had burst on the night of 19th August, 1950 causing havoc and inundating about 500 sq km area and killing about 500 people.

From the geological and tectonic setting of the epicentral tract and from focal mechanism solution of the earthquake event it has been suggested that the event occurred due to right lateral shear movement along the Po Chu fault (Ni and York, 1978; Ben-Menahem, et al., 1974).

(***Geodynamics of Northeastern India – D.R.Nandy 2001)***

Abstracts (Great Assam Earthquake of 15 August 1950)

- **'The Great Assam Earthquake of 15th August 1950'; *Current Science; Vol. XIX; No. 9, pp. 265-267, September 1950***

Introduction

On the evening of the 15th August 1950, about forty minutes past seven, an earthquake of catastrophic violence occurred off the north-east border of Assam. The earthquake was recorded by the seismological observatories all over the world as a very great earthquake and various adjectives such as tremendous, very violent, unprecedented, biggest ever recorded, have been used to describe the magnitude of the earthquake. It is one of the biggest ever recorded. Seismologists of the United States of America consider it as one of the five biggest in human history. The magnitude of the shock, as calculated by them, was between 8.25 and 8.5, the highest ever calculated so far being 8.5…………

- **'The Assam Earthquake of 15th August, 1950'; *M.C.Poddar; Indian Minerals; Vol. IV, No. 4, pp. 167-176, October, 1950***

Introduction

One of the biggest earthquakes of the twentieth century was recorded at about 7-40 p.m. (Indian Standard time) on the 15th August, 1950. It caused widespread devastation throughout the Upper Assam, particularly in the frontier tribal districts of the Mishmi and Abor hills and parts of the Lakhimpur and Sibsagar districts. The earthquake shock lasted for a period ranging from 4 minutes to 8 minutes within the severely affected area. It is not known how far this was felt on the Tibetan side, but news from this side of the McMahon Line shows that extensive damage has occurred in the hills, and heavy casualties took place among the hill tribes bordering the North-East Frontier. The shock was felt throughout Eastern India. In badly affected areas, the ground cracked and fissured, water and sands spouted through the fissures, road and railway tracks were broken up and twisted. Many bridges were destroyed and river beds silted up. Damage and casualties subsequently increased considerably, owing to the sudden floods in the Subansiri valley shortly after the quake, due to the bursting of a temporary dam formed by landslips.

It is, however, fortunate that the affected area is generally sparsely populated, and the earthquake occurred just after nightfall when most of the people were awake. Hence the loss of life has been small in comparison with the magnitude of the shock……..

- **'The Great Assam Earthquake of August 15, 1950'; *Ernest Tillotson; Nature, Vol. 167, pp. 128-130, 27 January, 1951***

An earthquake, which appears to have benn the greatest since the time when seismological observations were first established. Occurred at 14h. 09m. 30s. G.M.T. on August 15, 1950. The epicentre was near lat. 28.6^0 N., long. 96.5^0 E., which is just in Assam near the borders of India and Tibet. There is no reason for supposing, with the data at present to hand, that the depth of focus was other than normal, that is, some 14 km. below the earth's surface. The magnitude of the earthquake on the Richter instrumental scale, calculated independently using seismogram measurements at Pasadena (California) and at Strasbourg was 8.6. There has only been another earthquake with this magnitude since instrumental recording became general, namely, that of january 31, 1906, in Colombia. Its depth of focus was normal. Other shocks of normal depth with only slightly smaller magnitude occurred on August 17, 1906 in Chile (8.4); January 3, 1911, Tien Shan (8.4); December 16, 1920, Kansu (8.5); and March 2, 1933, Japan (8.4). The greatest shock of intermediate depth occurred on June 15, 1911, in the Ryukyu Islands (8.4), with a depth of focus of 160 km. The greatest deep-focus earthquake happened on January 21, 1906, in Japan (8.0) with a depth of focus of 340 km……….

- **'Aftermath of the Great Assam Earthquake of 1950'; *F.Kingdon-Ward; The Geographical Journal, Vol. 121, No. 3 (Sep., 1955), pp. 290-303***

On the evening of 15 August 1950 one of the biggest earthquakes ever recorded took place in south-eastern Tibet, close to the Assam frontier (Geogr.F.120 (1953) 169-82). Its epicentre was about twenty miles north-west of Rima, in the valley of the Lohit river, or rather, in the valley of its north-western branch, called the Rong Tho Chu. Incalculable damage was done in the mountains, but there was little direct loss of life, either here or on the plains. Since that date the Brahmaputra has overflowed its bank every year; both Sadiya and Dibrugarh have been partly destroyed – the latter especially in 1954 – and worse may happen.

Before one can indicate possible means of flood control, it is necessary to examine closely why the floods occur; and that implies not only a knowledge of the climate of this region, but also of its geography. Under the latter heading I include some knowledge of the sources and courses of the main rivers, and their chief tributaries ; the topography of the country through which they flow; the types of vegetation found at all levels within the several basins; and the nature of the rocks…….

- **'The source of the great Assam earthquake — an interplate wedge motion'; *Ari Ben-Menahem, Ezra Aboodi, Rivka Schild; Physics of the Earth and Planetary Interiors, 01/1974; DOI:10.1016/0031-9201(74)90056-9***

Abstract
The source of the Assam earthquake of Aug. 15, 1950 is revealed from amplitude observations of surface and body waves at Pasadena, Tokyo and Bergen. Seiches' amplitudes in Norway, initial P motions throughout the world, aftershocks and landslides distribution, PP/P ratio at Tokyo, R/L ratio and directivity at Pasadena, are also used. The ensuing fault geometry and kinematics is consistent with the phenomenology of the event and the known geology of the source area. It is found that a progressive strike-slip rupture with velocity 3 km/sec took place on a fault of length 250 km and width 80 km striking 330–337° east of north and dipping 55–60° to ENE. The use of exact surface-wave theory and asymptotic body-wave theory which takes into account finiteness and absorption, rendered an average shear dislocation of 35 m. A three-dimensional theory for the excitation of seiches in lakes by the horizontal acceleration of surface waves was developed. It is confirmed that Love waves near Bergen generated seiches with peak amplitude up to 70 cm depending strongly on the width of the channel. It is believed that the earthquake was caused by a motion of the Asian plate relative to the eastern flank of the Indian plate where the NE Assam block is imparted a tendency of rotation with fracture lines being developed along its periphery. Comparison with other well-studied earthquakes shows that although the magnitude of the Assam event superseded that of all earthquakes since 1950, its potency U0dS (700,000 m × km2) was inferior to that of Alaska 1964 (1,560,000 m × km2) and Chile 1960 (1,020,000 m × km2).

- **'Investigations on the aftershock sequence of the great Assam earthquake of August 15, 1950'; *R. K. S. CHOUHAN , V. K. GAUR and J. SINGH; Received on April 10th, 1974; pp. 245-266***

Summary
The strain release curve of the aftershock sequence of the great Assam earthquake of August 15, 1950 exhibits three linear segments. A secondary aftershock sequence has also been reported; the strain release curve in this case is also linear. The *b* value, using the maximum likelihood method of Utsu, for the sequence is 0.52 ± 0.095. The fault plane solution shows that the fault strikes almost cast-west and dips northward at an angle of 80°; the motion is predominantly strike slip (right lateral type). The spatial distribution of aftershocks shows two main centers of activity at the two ends of the probable fault.

- **'Simulation of Strong Ground Motion During the 1950 Great Assam Earthquake'; *S.T.G.Raghukanth; Pure and Applied Geophysics, 165 (2008) 1761-1787; DOI 10.1007/s00024-008-0403-z***

Abstract
In this paper, ground motion during the Independence Day earthquake of August 15, 1950 (M_w 8.6, BEN-MENAHEM *et al.*, 1974) in the northeastern part of India is estimated by seismological approaches. A hybrid simulation technique which combines the low frequency ground motion simulated from an from an analytical source mechanism model with the stochastically simulated high-frequency components is used for obtaining the acceleration time

histories. A series of ground motion simulations are carried out to estimate the peak ground acceleration (PGA) and spectral acceleration at important cities and towns in the epicentral region. One sample PGA distribution in the epicentral region encompassing the epicenter is also obtained. It is found that PGA in the epicentral region has exceeded 1 g during this earthquake. The estimated PGA's are valued to the extent possible using the MMI values. The simulated acceleration time histories can be used for the assessment of important engineering structures in northeastern India.

Keywords: Strong ground motion, PGA, stochastic finite fault model, hybrid technique, response spectra

- **The great 1950 Assam Earthquake revisited: Field evidences of liquefaction and search for paleoseismic events'; *D.V.Reddy, P.Nagabhusshanam, Devendra Kumar, B.S.Sukhija, P.J.Thomas, Anand K.Pandey, R.N.Sahoo, G.V.Ravi Prasad, K.Datta; Tectonophysics; 474, 463-472, 2009***

Abstract
Extensive field investigations were carried out for the first time in the meizoseismal area of the great 1950 Assam Earthquake aimed at exploring the paleoseismic history of the NE Indian region through documentation of liquefaction features and radiocarbon (^{14}C) dating. Trenching at more than a dozen locations along the Burhi Dihing River valley and within the alluvial fans adjoining the Brahmaputra and Dibang Rivers resulted in the identification of more than a dozen very prominent liquefaction features (sand dykes, sills, sand blows etc.) as evidences of large to great earthquakes. ^{14}C dating of the organic material associated with some of the features indicates a paleoseismic record of about 500 yrs archived by the sediments in the region. Compelling geological evidence(s) of the great 1950 earthquake are well constrained by ^{14}C dating. Out of the two historically reported seismic events (1548 AD and 1697 AD) from this region. ^{14}C dating could constrain the 1548 AD event through not distinctly. Further studies using combined ^{14}C and OSL dating may better constrain the seismochronology of the study region.

- **Revisiting the earthquake sources in the Himalaya: Perspectives on past seismicity'; *Kusala Rajendran and C. P. Rajendran; Tectonophysics, 2011, DOI:10.1016/j-tecto.2011.03.001***

Abstract
The ~2500 km-long Himalaya plate boundary experienced three great earthquakes during the past century, but none of them generated any surface rupture. The segments between the 1905-1934 and the 1897-1950 sources, known as the central and Assam seismic gaps respectively, have long been considered holding potential for future great earthquakes. This paper addresses two issues concerning earthquakes along the Himalaya plate boundary. One, the absence of surface rupture associated with the great earthquakes, vis-à-vis the purported large slip observed from paleoseismological investigations and two, the current understanding of the status of the seismic gaps in the Central Himalaya and Assam, in view of the paleoseismological and historical data being gathered. We suggest that the ruptures of earthquakes nucleating on the basal detachment are likely to be restricted by the crustal ramps and thus generate no surface ruptures, where as those originating on the faults within the wedges promote upward propagation of rupture and displacement, as observed during the 2005

Kashmir earthquake, that showed a peak offset of 7 m. The occasional reactivation of these thrust systems within the duplex zone may also be responsible for the observed temporal and spatial clustering of earthquakes in the Himalaya. Observations presented in this paper suggest that the last major earthquake in the Central Himalaya occurred during AD 1119-1292, rather than in 1505, as suggested in some previous studies and thus the gap in the plate boundary events is real. As for the Northwestern Himalaya, seismically generated sedimentary features identified in the 1950 source region are generally younger than AD 1400 and evidence for older events is sketchy. The 1897 Shillong earthquake is not a décollement event and its predecessor is probably ~1000 years old. Compared to the Central Himalaya, the Assam Gap is a corridor of low seismicity between two tectonically independent seismogenic source zones that cannot be considered as a seismic gap in the conventional sense.

Key words*: Central Himalaya, earthquakes, paleoseismology, seismic gaps,Northeast India*

- **'Largest earthquake in Himalaya: An appraisal';** ***H.N.Srivastava, B.K.Bansal, Mithila Verma; Journal Geological Society of India, Volume 82, Issue 1, pp 15-22, July 2013***

Abstract

The largest earthquake (Mw 8.4 to 8.6) in Himalaya reported so far occurred in Assam syntaxial bend in 1950. However, some recent studies have suggested for earthquake of magnitude M_w 9 or more in the Himalayan region. In this paper, we present a detailed analysis of seismological data extending back to 1200 AD, and show that earthquake in Himalayan region may not be expected to be as large as those of subduction zones. Also, there appears to be a lateral variation in the earthquake magnitude, being lesser in the western syntaxial bend when compared close to the eastern syntaxial bend. This is attributed to the difference in the plate boundary scenario; dominance of strike-slip and thrusting along the western syntaxis as against thrusting and remnant subduction along the eastern syntaxis.

5. Cachar earthquake 1984

Though this earthquake event does not belong to the category of large and great earthquake it inflicted considerable damage in a small area along the lower reaches of Sonai river near its confluence with the Barak river, about 15 km upstream of Silchar, Cachar district, Assam. The mud houses in the meizoseismal zone were worst affected. 13 people died in the area mainly due to collapse of such houses where long walls of houses were mostly collapsed. Thatched roof houses with strong timber and bamboo frames were not damaged. Assam type houses made of ikra wall with wooden framed roof also escaped damage except for those with brick masonry wall up to lintel level which suffered cracks. Number of light houses constructed by timber and wood got tilted. Several mosque of brick masonry in the meizoseismal area had suffered damage. At Lakhipur, 15 km northeast of the epicenter, bank of Barak river had developed extensive longitudinal fissures. Extensive liquefaction had occurred in the cultivated fields on the banks of Sonai river at Barabak, Narsinghpur and Hatikhal. The R.C.C bridge at Sonaimukh had also developed severe cracks.

(***Geodynamics of Northeastern India – D.R.Nandy 2001)***

The Cachar earthquake, ML 5.8, mb 5.6, origin time December 30, 1984, 23h 33m, 39.1s; 24.598N, longitude 92.939E, depth 33km (USGS), although not a large event magnitude-wise, but it rocked the entire area in the early hours of December 31, and was responsible for a loss of about 20 human lives and considerable damage to properties (GSI, 2000). The maximum intensity of the earthquake reached VIII on the Modified Mercalli (MM) scale. The VIII intensity was assigned in view of the formation of fissures in flat ground through which sand and water were ejected. In the meizoseismal area of about 250 sq km, a considerable damage was caused to a well designed concrete structure (bridge) and total collapse of the weak structures. Based on the rapid attenuation of the isoseismals, it was suggested that the earthquake was probably focussed at a shallow depth ($\leq$ 10km) (GSI report 2000). The earthquake was followed by seven felt aftershocks in the subsequent 11 days (Dube et al., 1986). Focal mechanism of the main shock indicated a thrust-fault mechanism with a compressional stress in the NW-SE direction (Dube et al., 1986).

(Microearthquake Seismology and Seismotectonics of South Asia, JR Kayal)

6. Indo-Burma border earthquake of 06 August 1988

The Indo-Burma earthquake of August 6, 1988, M_L 7.5, M_S 7.5, m_b 6.8, origin time : 00h 36m 29.6s (GMT), latitude 25^0.116N, longitude 95^0.171E, depth 115 km (USGS report), rocked the whole northeastern region of the country in the early morning of August 6 at 6.10 AM (local time). The tremor was felt all over northeast India, Bangladesh and parts of Burma. It lasted for about two minutes, and caused a loss of four human lives, considerable damage to buildings, railway tracts, roads etc. Field survey showed that the maximum intensity reached VIII on the MM scale (GSI, unpublished report). The survey revealed three areas (viz. Jorhat, Silchar and Diphu) where maximum damages were recorded. Landslides, formation of fissures, ejection of sand, mud and water were observed at several places. The focal mechanism study based on P-wave first-motions indicated thrust-faulting solution with a compressional stress parallel to the trend of tectonic trend of the Indo-Burma ranges. The result of inversion, however, shows a mixture of strike-slip and reverse-fault mechanism (Chen and Molnar, 1990). Considering the depth and the fault-plane solution, there is little doubt that this large earthquake occurred within the subducted Indian plate.

(Microearthquake Seismology and Seismotectonics of South Asia, JR Kayal)

Abstracts (Indo-Burma border earthquake of 06 August 1988)

- **'Medium Term Earthquake Prediction and Earthquake Swarms Precursory to Moderate Magnitude to Great Earthquakes' ; *H. K. Gupta and H. N. Singh; Special Publications, Evaluation of Proposed Earthquake Precursors, Vol. 32. Eos, Dec. 1988 and J. Geol. Soc. India, 28, 367-406, 1986***

Abstract
Since 1897, ten earthquakes of M>77 / 2 have occurred in the northeast India region and its vicinity including the great earthquakes of June 12, 1897 and August 15, 1950 both of M 8.7. The last earthquake belonging to this category occurred on August 17, 1952. With the exception of three earthquakes, others are found to be associated with the epochs of background/normal seismicity, precursory swarm, quiescence and mainshock (and the associated

foreshocks and aftershocks). In our investigations, the earthquake data have been critically examined, taking due care of prevalent location capabilities and other parameters. The mainshock magnitude (Mm) is related to the magnitude of the largest events in the swarm *(Mp*) and the time interval *Tp* (in days) between the beginning of the swarm and the main shock. The regression equations are:

Mm = 1.37 *Mp* - 1 . 41

And

Mm = 3 log1 0 7 , - 3 . 27

Installation of the World Wide Standard Seismograph Network during 1962-63 improved the earthquake detection and location capabilities considerably in the northeast India region and all earthquakes of *mb* > 4.5 are being located. Consequently, for the period 1963 throughout 1985, we have investigated all events *mb* > 6.1 for occurrence of precursory swarms. Ten such events have occurred, four of which in quick succession in the Arakan Yoma fold belt within a time span of only six months, and constitute a well defined swarm. Two other earth-quakes are possibly gap events of Arakan Yoma swarm. Out of the remaining four, three are found to be associated with epochs of normal/background seismicity, precursory swarm, qui-escence and mainshock (and the associated foreshocks and aftershocks). The latest killer earthquake in northeast India of Dec. 30, 1984 of *mb* 5.6, which occurred in the vicinity of the Arakan Yoma fold belt and Shillong Plateau, was preceded by a well-defined precursory swarm and seismic quiescence. The most important thing is to recognize the precursory swarms and quiescence in real time, before the occurrence of the main shock. We believe we have recognized one such sequence in the vicinity of Arakan Yoma fold belt. On the basis of *Mp* and *Tp* values, lateral extent of the swarm activity and the fact that no event of *mb* ≥ 6.1 has occurred since 1975 in the preparation zone defined by the 1963-65 swarm, we estimate that an earthquake of M 8 ± ½ could occur any time from now in an area bound by 21°N and 25½°N latitude and 93°E and 96°E longitude, with a focal depth of 100 ± 40 km. We have also recognized a region in Eastern Syntaxis where repeated swarms have occurred during 1968, 1977 and 1980. The largest events in these swarms, however, were only of *mb* 5 and the swarms were very localized. These may have been caused by magmatic emplacement at shallow crustal depths.

- **'Earthquake swarms precursory to moderate to great earthquakes in the northeast India region'; *H.K. Gupta, H.N.Singh; Tectonophysics, Vol. 167, Issues 2-4, pages 285-298, 10 October 1989***

Abstract
The Northeast India region has seen ten $\boldsymbol{M \geq 7^{1}/_{2}}$ earthquakes since 1897, including two great earthquakes of *M* = 8.7 in 1897 and 1950. The last $\boldsymbol{M \geq 7^{1}/_{2}}$ **earthquake occurred on August 17, 1952.** With the exception of three earthquakes others are found to be associated with periods of background/normal seismicity, precursory swarms, quiscence and mainshocks (and the associated foreshocks and aftershocks). The dataset has been critically examined for completeness considering the current capabilities for defining locations and also considering other parameters. Regression equations relating the mainshock magnitude

(M_m) , the average magnitude of the largest two events in the swarm (M_p) and the time interval (T_p) between the beginning of the swarm and the mainshock have been developed.
These are: $\boldsymbol{M_m = 1.37\, M_p - 1.41}$ ***and*** $\boldsymbol{M_m = 3\log_{10} T_p - 3.27}$
It is important to recognize precursory swarms and quiscence in real time, indeed, we belief we have recognizes one such sequence in the vicinity of the Arakan Yoma Fold Belt. On the basis of M_p- and T_p- values, the lateral extent of swarm activity and the fact that no event of $M > 6$ has occurred since 1975 in the preparation zone defined by the 1963-1965 swarm, we estimate that an M ~8 earthquake could occur at any time in the area bounded by 21^0 and $25^1/_2{}^0$ N and 93^0 and 96^0 E. The focal depth of this impending earthquake is estimated to be 100 + 40km in view of the focal depths of the other.

- **'Liquefaction During 1988 Earthquakes and a Case Study.; *M. K. Gupta; Proceedings: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, 1993, Paper No. 14.19***

Abstract

Several parts of north eastern India, Bangladesh and Burma were rocked by an earthquake on August 6, 1988. The author carried out earthquake damage survey due to liquefaction *in* Assam region. Wide spread liquefaction *in* the area was observed. Guide bunds and approach roads of a road bridge near tezpur performed excellently against liquefaction during the earthquake for which they were designed. Another earthquake of magnitude 6.6 visited Nepal Bihar border region which shook northern Bihar and Nepal region and was felt as far as Jaipur in the west and Shillong in the east. Large scale liquefaction has also been reported due to this earthquake.

- **The *b*-value before the 6^{th} August, 1988 India-Myanmar Border Region Earthquake-a case study'; *O.P.Sahu, M.M.Saikia; Tectonophysics; Vol. 234, Issue 4, pages 349-354, 15 July 1994***

Abstract
Smith (1981, 1986) and Wyss et al.(1990) have observed that intermediate-term quiscence is often associated with an increasing b value. This study pertains to the temporal behaviour of the b value before the earthquake of 6^{th} August, 1988, which occurred in the India-Myanmar border region. The b value in the preparation zone of the earthquake (21^0-25.5^0N, 93^0-96^0E), as identified by Gupta and Singh (1986, 1989), is gound to have increased gradually from 1976 to a maximum value of 1.33 during July, 1987, followed by a short-term drop before the occurrence of the earthquake. The quiscence period observed by Gupta and Singh (1986, 1989) for this earthquake is better reflected by the intermediate-term increase in the b-value. A drop in the mean magnitude since 1978 is supported by a CUSUM plot.

- **'Medium-term forecast of the 1988 north-east India earthquake';*Harsha K. Gupta, Tectonophysics, 338, pp. 281-286, 2001***

Abstract
Northeast india is seismically one of the most active intra-continental regions in the world. It has been a site of 10 earthquakes of magnitude (M) $\geq$7.5 during the last 100 years. Gupta and Singh [J.Geol.Soc.India. 28 (1986) 367-406] systematically analysed the series of

earthquakes associated with several main shocks in and area bound by 20^0N and 32^0N latitude and 87^0E and 100^0E longitude and concluded: (1) Moderate magnitude to great earthquakes in the north-east India region are found to be preceded, generally, by well defined earthquakes swarms and quiescene periods, (2) On the basis of an earthquake swarms and quiescene period, an area bounded by 21^0N and 25.5^0N latitude and 93^0E and 96^0E longitude is identified to be the site of a possible future earthquake of M = 8 $\pm$ 0.5 with a focal depth of 100 $\pm$ 40 km. This earthquake should occur any time from now onwards. Should it not occur till the end of 1990, this forecast could be considered as as a false alarm. This medium-term earthquake forecast came true with the occurrence of M = 7.3 earthquake on August 6, 1988, within the specified spatial and temporal parameters. The forecast of the earthquake was based on the concept of precursory swarms and quiescene preceeding main-shock. It is worthwhile noting that the entire region under study, the August 6, 1988 earthquake was the largest since the August 17, 1952 earthquake of M = 7.5. This lends support to the worldwide effort to study and identift spatial and temporal variation of seismicity and recognise patterns that precede major earthquakes.

- **'Occurrence of anomalous seismic activity preceding large to great earthquakes in northeast India region with special reference to 6 August 1988'; *H.N.Singh, D.Shankar, V.P.Singh; Physics of the Earth and Planetary Interiors; 148, 261-284, 2005***

Abstract
Seismicity database from 1860 to 1985 of northeast India region bounded by the area 20◦–32◦N and 82◦–100◦E have been analyzed for the identification of precursory swarm/anomalous seismic activity preceding large to great earthquakes with $M \geq 7.5$. It is observed that with the exception of three earthquakes (1908, 1912 and 1918), the large earthquakes of 1897, 1946, 1947, 1950 and 1951/1952 were preceded by well-developed epoch of swarm/anomalous seismic activity in space and time well before their occurrence. The seismicity is observed to fluctuate in the order of low-high-low ranging from 0–0.5, 01–33 to 0–0.7 events/year prior to these main shocks during the epochs of normal/background, swarm/anomalous and gap/quiescence, respectively. The duration of precursory gap is observed to vary from 11 to 17 years for main shocks of M 7.5–8.0, and from 23 to 27 years for M 8.7 and this period is dependent on the magnitude of the main shocks. Using the values of magnitude of main shock (Mm), average magnitude of swarm (M_p) and the precursory time gap (T_p), the following predictive equations are established for the region:
$M_m = 1.37M_p - 1.40$
$M_m = 3 \log T_p - 3.27$
All the major earthquakes with $m_b \geq 6.1$ occurred during 1963–1988 have been investigated for their association with anomalous seismicity/precursory swarms using the events with cut-off magnitude $m_b \geq 4.5$. Eleven such events have occurred in the region during the period except one earthquake of 29 May 1976. All the remaining 10 earthquakes were associated in some forms of anomalous seismicity epochs. Well-defined patterns of anomalous seismicity are observed prior to 1964–1965, 12 August 1976 and 30 December 1984 (m_b 5.6). All these mains hocks are preceded by seismicity patterns in the order of low-high-low similar to that observed prior to the main shocks from 1897 to 1962. The anomalous seismicity epoch is delineated with extremely high annual earthquake frequency, which was preceded and followed by extremely low seismicity epochs of background and gap/quiescence phases. Consequently, seismicity rates during anomalous seismicity epoch have always been above normal

(1event/year) whereas it is always below normal during the preceding and the following epochs. A prediction was made using the 1964 swarm based on the M_p and T_p values that a large earthquake with M 8±0.5 with focal depth 100±40 km could occur any time from 1986 to 1990 in an area bound by 21◦–25 5◦N latitudes and 93◦–96◦E longitude in Arakan Yoma fold belt. It is interesting to note that the 6 August 1988 earthquake with magnitude 7.5 and focal depth 115 km had occurred within the delineated zone. In addition, three consecutive swarm activities are identified in a limited area within the Eastern Syntaxis and these were not followed by any main shock till date and could be potential zone for future earthquake.

Keywords: Anomalous seismic activity; Quiescence; Precursory swarm; Precursory time gap; Seismicity rates

- **'Low *b*-value prior to the Indo-Myanmar subduction zone earthquakes and precursory swarm before the May 1995 M 6.3 earthquake'; *Sangeeta Sharma, Saurabh Baruah, Om Prakash Sahu, Pabon K.Bora, Ranju Duarah; Journal of Asian Earth Sciences, 73 ,pp. 176-183, 2013***

Abstract

Some 455 events (mb $\geq$ 4.5) in the Indo-Myanmar subduction zone are compiled using the ISC/EHB/NEIC catalogues (1964–2011) for a systematic study of seismic precursors, b-value and swarm activity. Temporal variation of b-value is studied using the maximum likelihood method beside CUSUM algorithm. The b-values vary from 0.95 to 1.4 for the deeper (depth $\geq$ 60 km) earthquakes, and from 0.85 to 1.3 for the shallower (depth <60 km) earthquakes. A sudden drop in the b-value, from 1.4 to 0.9, prior to the occurrence of larger earthquake(s) at the deeper depth is observed. It is also noted that the CUSUM gradient reversed before the occurrence of larger earthquakes. We further examined the seismicity pattern for the period 1988–1995 within a radius of 150 km around the epicentre (latitude: 24.96^0N; longitude: 95.30^0E) of a deeper event M 6.3 of May 6, 1995 in this subduction zone. A precursory swarm during January 1989 to July 1992 and quiescence during August 1992 to April 1995 are identified before this large earthquake. These observations are encouraging to monitor seismic precursors for the deeper events in this subduction zone.

- **'Earthquake forerunner as probable precursor – an example from north burma subduction zone'; *Sujit Dasgupta, Basab Mukhopadhay, Manoj Mukhopadhyay; Journal of the Geological Society of India; August 2013, 80(3); DOI:10.1007/s 12594-012-0157-1***

ABSTRACT

The Burmese Arc seismic activity is not uniform for its ∼ 1100 km length; only the Northern Burmese Arc (NBA) is intensely active. Six large earthquakes in the magnitude range 6.1–7.4 have originated from the NBA Benioff zone between 1954–2011, within an area of 200 × 300 km2 where the Indian plate subducts eastward to depths beyond 200 km below the Burma plate. An analysis on seismogenesis of this interplate region suggests that while the subducting lithosphere is characterized by profuse seismicity, seismicity in the overriding plate is rather few. Large earthquakes occurring in the overriding plate are associated with the backarc Shan-Sagaing Fault (SSF) further east. The forecasting performance of the Benioff zone earthquakes in NBA as forerunner is analysed here by: (i) spatial earthquake clustering, (ii) seismic cycles and their temporal quiescence and (iii) the characteristic temporal b-value

changes. Three such clusters (C1–C3) are identified from NBA Benioff Zones I & II that are capable of generating earthquakes in the magnitude ranges of 7.38 to 7.93. Seismic cycles evidenced for the Zone I displayed distinct quiescence (Q1, Q2 and Q3) prior to the 6th August 1988 (M 6.6) earthquake. Similar cycles were used to forecast an earthquake (Dasgupta et al. 2010) to come from the Zone I (cluster C1); which, actually struck on 4 February 2011 (M 6.3). The preparatory activity for an event has already been set in the Zone II and we speculate its occurrence as a large event (M > 6.0) possibly within the year 2012, somewhere close to cluster C3. Temporal analysis of b-value indicates a rise before an ensuing large earthquake.

7. Sikkim earthquake of 14 February 2006

Introduction

The moderate earthquake (reported as Mw 5.3 by USGS and as ML 5.7 by IMD) occurred in the state of Sikkim (India) on February 14 2006 at 06:25:23 a.m. local time. The earthquake's epicenter and focal depth were reported from two different sources as, (a) at 27.35°N 88.35°E, near Ralang (South Sikkim), with a focal depth of 30 km (www.usgs.gov), and (b) at 27.7°N 88.8°E, near Lachung (North Sikkim), with a focal depth of 33 km (www.imd.ernet.in). The shaking was also felt in the North-Eastern states of India and in the neighbouring countries. However, shaking-related damage was reported only from the East and South districts of Sikkim. Two Indian Army soldiers died in landslides after the ground shaking at Sherathang near Nathula in Sikkim; there were no reports of any other fatalities. Several aftershocks with smaller magnitudes were recorded at the IMD observatory at Gangtok. Most of the structural damage was observed in and around the state capital Gangtok with the maximum intensity of shaking as VII on MSK scale. Damages observed in buildings in and around Singtam (East Sikkim) towards the south-west of Gangtok, suggested an intensity level of VI. It is interesting to note in Figure 1 that the epicentral location as per USGS and IMD lies well outside the area of maximum damage (25 km west of Gangtok as per USGS and 44 km North of Gangtok as per IMD). This may be due to inaccurate estimation of the epicenter.

(14 February 2006 Sikkim Earthquake Reconnaissance Report)

Abstracts Sikkim earthquake of 14 February 2006

- **'Performance of structures during the Sikkim earthquake of 14 February 2006'; *Hemant B.Kaushik, Kaustubh Dasgupta, Dipti R.Sahoo and Gayatri Kharel; Current Science, Vol. 91, No. 4, 25 August 2006***

Performance of structures in different areas of Sikkim, during the earthquake of 14 February 2006, is reviewed. The earthquake caused damage to heritage structures as well as modern buildings. Both masonry and reinforced concrete buildings showed poor performance. On the other hand, traditionally constructed wooden houses performed extremely well. The damage seen in and around Gangtok was clearly disproportionate to the size of the earthquake, which was a moderate 5.7 on the Richter scale. This very clearly establishes the high level of seismic vulnerability of the region. The damage is primarily attributed to poor design and construction practices, and lack of quality control. Urgent need for trained human resources and for creation of a system of checks and balances, to ensure safe constructions in Sikkim is highlighted.

Keywords: Masonry structures, reinforced concrete structures, Sikkim earthquake, structural performance, traditional wooden construction.

8. Sikkim earthquake of 18 September 2011

The Indian subcontinent is among the world's most disaster prone areas. Almost 85 percent of the India's area is vulnerable to one or multiple hazard. Of the 28 states and 7 union territories, 22 are disaster-prone. An earthquake of magnitude 6.8 occurred on 18th of September, 2011 at 18:11 hrs IST in Sikkim - Nepal Border region. This region has experienced relatively moderate seismicity in the past, with 18 earthquakes of magnitude 5 or greater being experienced over the previous 35 years within 100 km of the epicenter of the September 18th event. The largest of these was magnitude 6.1 earthquake of 19th November, 1980 that had its epicenter around 75 km to the southeast of the 18th September event. The preliminary hypo-central parameters of the 18th September, 2011 earthquake, as estimated by the Seismic Monitoring Network of India Meteorological Department (IMD) are as given below:

Date and time of occurrence	:	18/09/2011 at 18:11 hrs
Magnitude	:	6.8
Focal depth	:	10 Km
Epicenter latitude and longitude	:	27o 42'N & 88o12'E
Region	:	Sikkim-Nepal Border region

The event that falls under the category of Severe Earthquake was also reported to be widely felt in Sikkim, Assam, Meghalaya, and northern parts of West Bengal, Bihar, parts of other eastern and northern regions of India. The epicenter lies in a seismically known and active belt called Alpine-Himalayan Seismic Belt. The entire area of Sikkim lies in Zone IV of the Seismic Zonation Map of India (IS1893: 2002). The seismic Zone IV is broadly associated with seismic intensity VIII on the Modified Mercalli Intensity (MMI) Scale. The Sikkim and adjoining region is known to be part of the seismically active region of the Alpine-Himalayan seismic belt, with four great earthquakes of the world of magnitude 8.0 and above occurring in this region. Earthquakes in this region are broadly associated with strain accumulation associated with the northward tectonic movement of the Indian Plate and its subsequent abrupt release. The strain is generally released by activity along Himalayan faults and thrusts of regional dimensions of which Main Boundary Thrust (MBT) and Main Central Thrust (MCT) are particularly important.

Abstracts Sikkim earthquake of 18 September 2011

- **'The 18 September 2011, North Sikkim Earthquake'; Kusala Rajendran, *C. P. Rajendran, N. Thulasiraman, Ronia Andrews and Nima Sherpa; Current Science, Vol. 101, No. 11, 10 December, 2011***

Abstract
The 18 September 2011, magnitude *Mw* 6.9 earthquake close to the Nepal–Sikkim border caused significant damage due to ground shaking and caused several landslides. Observations from the post-earthquake surveys in the affected areas within Sikkim suggest that the poorly engineered, multistoried structures were relatively more impacted. Those located on alluvial terraces were also affected. The morphology of the region is prone to landslides and the possibility for their increased intensity during the forthcoming monsoon need to be considered seriously. From the seismotectonic perspective, the mid-crustal focal depth of the North Sikkim earthquake reflects the ongoing deformation of the subducting Indian plate.

Keywords: Epicentre, focal depth, post-earthquake survey, seismotectonic setting.

- **'Tectonic implications of the September 2011 Sikkim earthquake and its aftershocks'; *M. Ravi Kumar, Pinki Hazarika, G. Srihari Prasad, Arun Singh and Satish Saha. Current Science, Vol. 102, No. 5, 10 March 2012***

Abstract
This study presents results of the spatial patterns of 292 aftershocks of the *Mw* 6.9 Sikkim earthquake of September 2011, accurately located through analysis of three component waveforms registered by a five station broadband network operated immediately after its occurrence. Refined hypocentral parameters achieved through application of the hypo DD relocation scheme reveal tight clustering of events along a NW–SE trend with focal depths reaching ~60 km.These trends viewed in conjunction with the strike–slip mechanisms of past earthquakes in Sikkim, including the main shock, affirm the predominance of transverse tectonics in this segment of the Himalaya where the Indian plate convergence seems to be accommodated by dextral motion along steeply dipping fault systems.

Keywords: Aftershocks, earthquakes, hypocentral parameters,spatial patterns, transverse tectonics.

- **'The M 6.9 Sikkim (India-Nepal Border) earthquake of 18 September 2011; Durgesh C.Rai, Vaibhav Singhal, Goutam Mondal, Neha Parool, Tripti Pradhan and Keya Mitra; Current Science, Vol. 102, No. 10, 25 May 2012**

Abstract
The *M* 6.9 Sikkim earthquake of 18 September 2011 was a remarkable event in the long history of the Himalayan earthquakes which presented a unique opportunity to reflect on the unacceptable rising trend of the seismic risk in the hilly regions. Many dramatic collapses and damages were disproportionate to the observed intensity of shaking and can be attributed to poor construction material, deficient workmanship and lack of compliance with seismic codes and earthquake-resistant construction practices. Many private and governmental buildings were constructed neglecting the seismic design and detailing requirements necessary in the Zone IV of the Indian seismic code IS 1893. The traditional construction practices prevalent in the area performed rather satisfactorily due to their inherent earthquake-resistant features. Old monastery temple structures of distinctive construction in stone masonry and timber suffered varying degree of damage to masonry walls ranging from minor damages to partial collapse. This event should be regarded as a preview of what is likely to happen in the

event of a greater shaking expected for the region and should hasten the community to take necessary steps in identifying seismic vulnerabilities and improving construction practices through an effective intervention.

Keywords: Earthquake effects, Himalayan earthquake, seismic risk.

- **'2011 Sikkim Earthquake: Effects on Building Stocks and Perspective on Growing Seismic Risk'; *D.C. Rai, G. Mondal, V. Singhal, N. Parool & T. Pradhan. 15 WCEE, Lisboa 2012.***

Abstract
The M6.9 Sikkim Earthquake of Sept. 18, 2011 caused widespread damage in the state and adjoining areas and it exposed the seismic vulnerability of the recently built multi-storied construction. Many building collapses and structural damages were disproportionate to the observed intensity of shaking, primarily due to poor compliance with seismic codes, inferior quality of raw materials and shoddy workmanship. In addition, many unique and inherently poor construction features specific to the affected region significantly added to their structural deficiencies. The event provided ample evidence of growing seismic risk in the region with ever increasing inventory of vulnerable construction. On the other hand, some traditional buildings, like Shing-Khim and Ikra performed well but the preference for such construction is on steady decline. It is, therefore, important that earthquake-resistant construction practices should be promoted and implemented to mitigate the risk and hence, minimize the damage to property and loss of life.

Keywords: Seismic risk, Seismic vulnerability, Himalayan earthquakes.

- **Intensity map of M*w* 6.9 2011 Sikkim-Nepal border earthquake and its relationships with PGA: distance and magnitude'; *Sanjay K.Prajapati, Ashok Kumar, Sumer Chopra, B.K.Bansal; Nat Hazards (2013) 69: 1781-1801; DOI; 10.1007/s11069-013-0776-x***

Abstract
We compiled available information of damages and other effects caused by the September 18, 2011, Sikkim-Nepal border earthquake from the print and electronic media, and interpreted them to obtain Modified Mercalli Intensity (MMI) at over 142 locations. These values are used to prepare the intensity map of the Sikkim earthquake. The map reveals several interesting features. Within the meizoseismal area, the most heavily damaged villages are concentrated towards the eastern edge of the inferred fault, consistent with eastern directivity. The intensities are amplified significantly in areas located along rivers, within deltas or on coastal alluvium such as mud flats and salt pans. We have also derived empirical relation between MMI and ground motion parameters using least square regression technique and compare it with the available relationships available for other regions of the world. Further, seismic intensity information available for historical earthquakes which have occurred in NE Himalaya along with present intensity has been utilized for developing attenuation relationship for NE India using two-step regression analyses. The derived attenuation relation is useful for assessing damage of a potential future earthquake (earthquake scenario-based planning purposes) for the northeast Himalaya region.

Keywords: Earthquake, Sikkim, Intensity, Attenuation

- **'Attenuation character of seismic waves in Sikkim Himalaya'; *Pinki Hazarika, M.Ravi Kumar and Dinesh Kumar; Geophysical Journal International; (2013); DOI: 10.1093/gji/ggt241 (First published online: July 18, 2013)***

Abstract

In this study, we investigate the seismic wave attenuation beneath Sikkim Himalaya using *P*, *S* and coda waves from 68 local earthquakes registered by eight broad-band stations of the SIKKIM network. The attenuation quality factor (*Q*) depends on frequency as well as lapse time and depth. The value of *Q* varies from (i) 141 to 639 for *P* waves, (ii) 143 to 1108 for *S* waves and (iii) 274 to 1678 for coda waves, at central frequencies of 1.5 Hz and 9 Hz, respectively. The relations that govern the attenuation versus frequency dependence are $Q_\alpha = (96 \pm 0.9) f^{(0.94 \pm 0.01)}$, $Q_\beta = (100 \pm 1.4) f^{(1.16 \pm 0.01)}$ and $Q_c = (189 \pm 1.5) f^{(1.2 \pm 0.01)}$ for *P*, *S* and coda waves, respectively. The ratio between Q_β and Q_α is larger than unity, implying larger attenuation of *P* compared to *S* waves. Also, the values of Q_c are higher than Q_β. Estimation of the relative contribution of intrinsic (Q_i) and scattering (Q_s) attenuation reveals that the former mechanism is dominant in Sikkim Himalaya. We note that the estimates of Q_c lie in between Q_i and Q_s and are very close to Q_i at lower frequencies. This is in agreement with the theoretical and laboratory experiments. The strong frequency and depth dependence of the attenuation quality factor suggests a highly heterogeneous crust in the Sikkim Himalaya. Also, the high *Q* values estimated for this region compared to the other segments of Himalaya can be reconciled in terms of moderate seismic activity, unlike rest of the Himalaya, which is seismically more active.

Keywords Body waves, Coda waves, Seismic attenuation, Continental margins: Convergent

- **'The September 2011 Sikkim Himalaya earthquake Mw 6.9: Is it a plane of detachment earthquake?'; *Santanu Baruah, Sowrav Saikia, Saurabh Baruah, Pabon K. Bora, Ruben Tatevossian and J.R.Kayal; Geomatics, Natural Hazards and Risk, 2014; doi:10.1080/19475705.2014.895963***

Abstract

The 18 September 2011 Sikkim Himalaya earthquake of Mw 6.9 (focal depth 50 km, NEIC report) with maximum intensity of VII on MM scale (www.usgs.gov) occurred in the Himalayan seismic belt (HSB), to the north of the main central thrust. Neither this thrust nor the *plane of detachment* envisaged in the HSB model, however, caused this strong devastating earthquake. The Engdahl-Hilst-Buland (EHB) relocated past earthquakes recorded during 1965-2007 and the available global centroid moment tensor solutions are critically examined to identify the source zone and stress regime of the September 2011 earthquake. The depth section plot of these earthquakes shows that a deeper (10-50 km) vertical fault zone caused the main shock in the Sikkim Himalaya. The NW (North-West) and NE (North-East) trending transverse fault zones cutting across the eastern Himalaya are the source zones of the earthquakes. Stress inversion shows that the region is dominated by horizontal NNW-SSE (North of North-West-South of South-East) compressional stress and low angle or near horizontal ENE-WSW (East of North-East-West of South-West) tensional stress; this stress regime is conducive for strike-slip faulting earthquakes in Sikkim Himalaya and its vicinity. The Coulomb stress transfer analysis indicates positive values of Coulomb stress changes ΔS_f

for failure in the intersecting deeper fault zone that produced the four immediate felt aftershocks ($M \geq 4.0$).

- **Causative source of Mw 6.9 Sikkim–Nepal border earthquake of September 2011: GPS baseline observations and strain analysis.** ***Rashmi Pradhan, Sanjay K. Prajapati, Sumer Chopra, Ashok Kumar, B.K. Bansal and C.D. Reddy. Journal of Asian Earth Sciences, Volumes 70–71, July 2013, Pages 179–192.***

Abstract:
The recent earthquake of Mw 6.9 which occurred on September 18, 2011 in Sikkim–Nepal border region (epicenter 27.72°N, 88.06°E, depth 20.7 km, ∼68 km NW of the Capital city Gangtok) is the strongest earthquake in the instrumentally recorded history of the region. The fault plane solution of this earthquake indicates a strike-slip motion. However, the seismological and geological studies carried out so far after the earthquake could not confirm the causative fault plane. In the present study, GPS observations are used to ascertain causative source in the generation of earthquake and its correlation with the observed seismic data of the region. The co-seismic displacements recorded by GPS show maximum displacement of ∼11 mm at Phodong and ∼9 mm at Taplejung station, near the epicenter. A simple rigid cross fault model using GPS baseline observations was employed to figure out the causative fault plane and seismological characteristic of the region. It is inferred that the movement represents the kinematic adjustment of the subsidiary faults as a result of the displacement along the NW–SE principal plane. Strain analysis using GPS baseline inferred that the region southeast of epicenter has undergone large deformation. In addition, a significant part of the measured deformation across the surface fault zone for this earthquake can be attributed to post-seismic creep.

Keywords: GPS baseline; Fault movement; Riedel shear; Strain.