INDO–US WORKSHOP ON
“INTRAPLATE SEISMICITY”

Under Indo-US Science and Technology Forum (IUSSTF), New Delhi
and Department of Science and Technology, Government of Gujarat

(15-18 January 2012)
at
Institute of Seismological Research
Raisan, Gandhinagar-382009, Gujarat, India

ABSTRACT VOLUME

IUSSTF
Indo-US Science and Technology Forum

INDO-U.S. SCIENCE AND TECHNOLOGY FORUM

Fulbright House, 12 Hailey Road, New Delhi 110 001, India

Website: www.indousstf.org

The Indo-U.S. Science and Technology Forum (IUSSTF) was established in 2000 under an agreement between the Governments of India and United States of America with a mandate to promote, catalyze and seed bilateral collaboration in science, technology, engineering and biomedical research through substantive interaction amongst government, academia and industry.

As its mandate, IUSSTF provides an enabling platform to the scientific enterprises of the two nations by supporting an S&T program portfolio that is expected to foster sustainable interactions with a potential to forge long term collaborations. IUSSTF program manifests are largely catalytic in nature that helps to create awareness through exchange and dissemination of information and opportunities in promoting bilateral scientific and technological cooperation.

IUSSTF has an evolving program portfolio that is largely conceived and driven by scientific communities of both the countries through extending support for symposia, workshops, conferences on topical and thematic areas of interest; visiting professorships and exchange programs; travel grants; fellowships; advanced training schools; public-private networked centres and knowledge R & D networked centers. IUSSTF also works towards nurturing contacts between young and mid career scientists by convening stimulating flagship events like the Frontiers of Science and Frontiers of Engineering symposium through the U.S. National Academies model. At the same time it reaches out to industries by partnering with business associations to generate high quality events on technology opportunities for business development to foster elements of innovation and enterprise through networking between academia and industry.

IUSSTF maintains a close working relationship with the federal agencies, laboratories, government institutions, and the academia in U.S. and India, cutting across all disciplines. IUSSTF has been entrusted to administer the bi-national US-India S&T Endowment Fund (for joint research and development, innovation, entrepreneurial and commercialization activities in S&T) and the Indo-US Joint Clean Energy Research and Development Center (to support multi-institutional network projects in clean energy using public-private partnership model of funding).

As an autonomous, not-for-profit society, IUSSTF has the ability, agility and flexibility to engage and involve industry, private R&D labs; and non governmental entities in its evolving activity manifold. This operational uniqueness allows the IUSSTF to receive grants and contributions from independent sources both in India and USA, besides the assured core funding from the two governments.

IUSSTF solicits proposals for its activities thrice a year (January, May and September) and awards are made on the basis of peer reviews both in India and USA.

IUSSTF values your interactions and looks forward to work with the S&T community of both countries to implement new ideas that endeavor to promote cutting edge Indo-U.S. Science and Technology collaborations.

ABOUT THE WORKSHOP

INTRODUCTION

The scientific issues associated with the earthquakes that strike away from active plate boundaries are of paramount importance for understanding earthquake hazard in both India and the United States. The potentially devastating consequences of such earthquakes were illustrated by the severe damage and loss of life caused by the 2001 Bhuj earthquake in Gujarat. The issue is of significant concern in the US as well, in part due to the critical need to understand hazard associated with the New Madrid, central U.S., seismic zone, which produced a series of large earthquakes in 1811-1812. Topics covered will include lectures on intraplateseismicity, seismic hazard, and tectonic models, with emphasis on key recent theoretical and observational advances, as well as identification of key data sets that could be collected and/or made available to address outstanding issues. The workshop will focus on scientific issues that are relevant for hazard assessment. The goal of workshop is to improve our understanding of earthquake science as well as our understanding of earthquake hazard in India and the United States.

BACKGROUND, CONCEPT AND PURPOSE

In recent years scientists have recognized that stable continental regions (SCR) are more vulnerable to earthquakes than was once thought. The Himalayan front is an active plate boundary, with high rates of earthquakes generated by the ongoing collision of the Indian subcontinent into Eurasia. Peninsular India is characterized by a much lower strain rate; large earthquakes are therefore expected to be less frequent. Similarly low strain rates are observed throughout central/eastern North America. However, large earthquakes have struck SCRs at a number of locations, including the New Madrid Zone, United States; Tennant Creek, Australia; Ungava, Canada; and Kachchh, Koyna, Latur, and Jabalpur, India. In several developing countries, such as India, the hazard associated with SCR earthquakes has become very serious because of high population density and the proliferation of structures not built to withstand earthquake damage. Devastating SCR earthquakes have also struck the US in historical times: in 1811-1812, three earthquakes with estimated magnitudes of at least 7.0 occurred within just 53 days in the New Madrid, Central U.S., Seismic Zone. The need to understand hazard associated with the New Madrid Seismic Zone has provided the impetus for focused research that has led to improved understanding of hazard and intraplate earthquake processes.

Devastating earthquakesin the SCR regions of India include the 1993 Killari earthquake (mb 6.3, intensity VIII), 1997 Jabalpur earthquakes (mb 6.0, intensity VIII) in the central part of peninsular India shield area, and the 2001 Bhuj earthquake (Mw 7.7, intensity X) in the western part of shield area which caused severe damages and large casualties. The 2001 Bhuj earthquake is the deadliest SCR event in the world.

The Kutch region in Gujarat and adjoining region in the western India had been affected in the past by large damaging earthquakes. In 1668, an intensity X (M7) earthquake razedSamaji town (25.0N, 68.0E), 200 km west of Kutch on the Indus delta in Pakistan. In 1819, an earthquake of Mw 7.8, intensity XI, 100 km NW of Bhuj, formed a 90-km long and 6-m high scarp along the Allah Bund Fault. In 1845, an earthquake of MMI VIII hit Lakhpat in the western part of Kutch. In 1956, Mw 6 (intensity VIII) Anjar earthquake caused 115 deaths. Nine damaging earthquakes of M 5–6 have occurred during the past 155 years. Ground deformation and acceleration due to the Bhuj earthquake of 26January 2001 (23.408N, 70.288E, focal depth 25km, magnitude Mw 7.7) caused large-scale destruction including 13,819 deaths, collapse or severe damage to over a million houses and economic loss of US$10 billion. This earthquake was a rare great intraplate earthquake, as the western plate boundary of the Indian Plate is about 400 km away and the Himalayan plate boundary in the north is more than 1000 km away.

The Latur earthquake generated a surface rupture that was traceable for about 2 km. The maximum height of the scarp observed near Killari was about one meter (Photo: CESS)

The Latur earthquake was another major recent event. The epicenter of Latur (Killari), Maharashtra, earthquake (mag 6.3) of September 30, 1993 is located in aregion that had been considered to be largely aseismic. This earthquake occurred in the typical rural setting of India. Over 10,000 lives were lost in this earthquake and several villages were destroyed.

Reservoir–induced seismicity has also been observed in Koyna region of India. Seismicity associated with the ShivajiSagarlake formed by the Koyna dam is considered to be a classic example of earthquake activity triggered by reservoirs. An earthquake of magnitude 6.3 (1967) and many of magnitude >5.0, have occurred at Koyna.

The Jabalpur earthquake 1997 in the Jabalpur area, Madhya Pradesh in India caused widespread devastation in and around Jabalpur left 48 people dead and many injured and homeless.

In U.S., three major earthquakes occurred in New Madrid region during 1811-1812, with magnitudes of at least 7.0. These powerful earthquakes were felt widely over the entire eastern United States. In the epicentral area the ground surface was described as in great convulsion with sand and water ejected tens of feet into the air (liquefaction). This sequence of three very large earthquakes is usually referred to as the 1811-1812 New Madrid earthquake sequence. On the basis of the large area of damage (600,000 square kilometers) and the complex physiographic changes that occurred, the effects of the New Madrid earthquakes of 1811-1812 were among the most widespread in the United States since its settlement by Europeans. They were the largest earthquakes in historical times east of the Rocky Mountains in the U.S. and Canada.

The 1886 Charleston earthquake is the most damaging earthquake to occur in the Southeast United States and one of the largest historic shocks in eastern North America. It damaged or destroyed many buildings in the old city of Charleston. Hardly a structure there was undamaged, and only a few escaped serious damage. The earthquake and resulting fires caused an estimated 3,000 deaths and $524 million in property loss.

Large SCR earthquakes remain poorly understood. The Kutch region has produced two very large (magnitude > 7.5) earthquakes in the past 2000 years. It is enigmatic that such large strain can accumulate in a region away from active plate boundaries. Therefore, the study of SCR earthquakes is important to answer basic questions regarding the source processes responsible for generating such intraplate earthquakes. Such events can also potentially provide clues to help understand the geodynamical processes and earthquake hazard of the region. The purpose of the proposed workshop is to strengthen the earthquake research, to learn from the recent experiences in both India and US, and to promote interaction and collaboration among researchers and students from these two countries. A discourse about recent developments in our understanding of SCR earthquakes will benefit both countries. During the workshop we will identify promising collaborative projects to address important scientific questions. The workshop will thus lay the groundwork for fruitful long-term collaborations between the two countries.

The Workshopwill providetheopportunity for exchange of state-of-the art information for understanding earthquake processes and hazard in stable continental regions in India and the U.S.A. We have identified exciting conceptual models and previous experience to design the workshop around the elements that will complete and reinforce the knowledge of the participants and facilitate cooperation and dissemination of information.

The USGS and several agencies of India have developed different tectonic models and discussions and exchange of ideas will further provide foundation for accurate statements of the future seismic hazard evaluation of the stable continental regions around the world. By including students in the workshop, we will lay the groundwork for future cooperative research projects to address issues discussed during the workshop.

Indo-US 2012 PROGRAM

15 January, 2012		
18:00-19:00	**Inaugural function**	
19:00-20:00	Dinner and interaction with scientists	
16 January, 2012		
08:00-10:00	**Registration**	
09:00-10:00	**Poster session I**	
Time	***Session***	***Subject***
10:00-13:15	**S1 (7 Papers)**	Faulting and Seismicity in Continental Intraplate Regions
14:00 -15:15	**S2 (5 papers)**	Recent Intraplate Earthquakes: Source Parameters and Effects
15:15-16:00	**Poster session II**	
16:00-17:30	**DISCUSSIONS ON SESSIONS 1&2** **(Coordinators: Roger Bilham & Susan Hough)**	
20:00-21:00	DINNER	
17 January, 2012		
09:00 – 10:30	**S3 (4 Papers)**	Long Term Behavior of Faults and Earthquake Hazards in Intraplate Continental Regions
10:30-12:15	**S4 (5 Papers)**	Paleoseismology and Archaeoseismology
12:15-13:15	**S5 (4 Papers)**	Crustal Structure and Processes
14:00-16:45	**S5 (10 Papers)**	Crustal Structure and Processes-Contd
17:00-18:00	**DISCUSSIONS ON SESSIONS 3,4&5** **(Coordinators: M Ravikumar and Roger Bilham)**	
20:00-21:00	DINNER	
18 January 2012		
09:00-11:00	**S6 (7 Papers)**	The New Madrid and Kachchh Seismic Zones
11:00-12:30	**S7 (7 Papers)**	Strain Accumulation inside Continents
12:30-13:15	**DISCUSSIONS ON SESSIONS 6&7** **(Coordinators: P Mandal and Susan Hough)**	
14:00-16:30	**CONCLUDING SESSION**	

Lunch will be served during 13:15 to 14:00.

Tea Break (15 mts) time to be decided by Session Chairman

LIST OF PAPERS

	16 Jan POSTER SESSION- I, 09:00 – 10:00, Display Area	
	S1: Faulting and Seismicity in Continental Intraplate Regions	
	Session Chairman: Harsh Gupta Co-Chairman: VP Dimri	
	Session date: 16 Jan Session time: 10:00-13:15	
S1.1	Historical Earthquake Hazards and Future Seismic Risks in India Roger Bilham, University of Colorado, Boulder CO 80309-0399 USA	30 mts
Spl.	Medieval Multihazards and Future Earthquakes in Kashmir Roger Bilham, University of Colorado, Boulder CO 80309-0399 USA	15 mts
S1.2	A Unified Model for Intraplate Earthquakes Pradeep Talwani, Dept. of Earth and Ocean Sciences, University of South Carolina, Columbia, USA.	30 mts
S1.3	Intra-Plate Dynamics and Active Tectonic Zones of the Indian Plate SK Biswas, Ex-Director, KDM Institute of Petroleum Exploration, ONGC.	30 mts
S1.4	Mechanism of Intraplate Earthquakes BK Rastogi, Inst. Seism. Res., Raisan, Gandhinagar 382009, India, Prantik Mandal, NGRI, Hyderabad	30 mts
S1.5	Reservoir Triggered Seismicity at Koyna, India Harsh Gupta, National Geophysical Research Institute, Hyderabad 500007, India.	30 mts
S1.6	Heat flux and crustal temperatures in the Indian shield: implications for depth of intraplate earthquakes Sukanta Roy, CSIR-National Geophysical Research Institute, Hyderabad 500606	30 mts
S1-P1*	Seismicity Studies along Kopili Lineament D. Srinagesh,National Geophysical Research Institute, Hyderabad, 500 007, India	
S1-P2*	Seismicity of Gujarat state, Western India. Santosh Kumar*, Sandeep Kumar Aggrawal and BK Rastogi, Institute of Seismological Research, Gandhinagar- 382 009, India	
	S2: Recent Intraplate Earthquakes: Source Parameters and Effects	
	Session Chairman: Rufus D Catchings Co-Chairman: Pradeep Talwani	
	Session date: 16 Jan Session time: 14:00-15:15	
S2.1	Recent Intra-plate Earthquakes in India: Crustal Structures and Seismic Source Processes JR Kayal, CSIR Emeritus Scientist, Jadavpur University, Thakurpur, Kolkata 700032, India.	15 mts
S2.2	A Comparison of Intraplate and Interplate Seismic Wave Propagation (Peak Ground Velocity) RD Catchings, US Geological Survey, 345 Middlefield Rd., MS 977, Menlo Park, CA 94025	15 mts
S2.3	Tectonic Setting and Indian Shield Seismicity – Sources and Mechanisms RK Chadha and D Srinagesh, National Geophysical Research Institute, Hyderabad-500 007, India	15 mts
S2.4	3D Static Numerical Modeling of Strike-Slip Fault for Studying Ground Surface Deformation Ramancharla Pradeep Kumar, Earthquake Engineering Research Centre, IIIT Hyderabad, India.	15 mts
S2.5	Role of Fluids in Delayed Triggering of Aftershocks-an Example of the 2001 Bhuj Earthquake Kalpna Gahalaut, National Geophysical Research Institute (CSIR), Hyderabad, India.	15 mts
S2-P1*	Study of Source Parameters and Focal mechanism solutions of earthquakes occurring in the Gujarat region, India. B Sairam1 BK Rastogi1 and Prantik Mandal2 1. Institute of Seismological Research, Gandhinagar-382009, Gujarat, India 2. National Geophysical Research Institute, Hyderabad-500 007, India	
S2-P2*	Stress Inversion using Focal Mechanisms of Local Earthquakes in the Koyna-Warna Region, Western India D. Shashidhar*, N Purnachandra Rao and Harsh Gupta National Geophysical Research Institute (CSIR), Hyderabad	
S2-P3*	Seismic Site Condition Assessment Using Seismic Surveying Techniques N Thulasiraman and K Rajendran, Centre for Earth Sciences, In Institute of Science, Bangalore, India	

S2-P4*	Source Parameters and effects of Talala, Saurashtra M5 earthquake of Oct 20, 2011 and aftershock study BK Rastogi, Santosh Kumar, Sandeep Aggrawal, Kapil Mohan, NagabhushanRAo (ISR), Sumer Chopra (MoES, New Delhi)	
S2-P5*	Source Parameters and Scaling relation for the Earthquakes in Jamnagar region of Gujarat Santosh Kumar, Dinesh Kumar and B.K.Rastogi, ISR	
	POSTER SESSION-II, 15;15-16:00, Display Area	
	DISCUSSIONS ON SESSIONS 1&2, 16:00 – 17:30 **Coordinators: Roger Bilham & Susan Hough**	
	S3: Long Term Behavior of Faults and Earthquake Hazards in Intraplate Continental Regions	
	Session Chairman: Mian Liu Co-Chairman: John Ebel	
	Session date: 17 Jan Session time: 09:00-10:30	
S3.1	Migrating Earthquakes and Faults switching On and Off: A Complex System view of Intracontinental Earthquake Seth Stein, Mian Liu and Eric Calais Department of Earth and Planetary Sciences, Northwestern University, Evanston, USA	30 mts
S3.2	How do Intraplate Earthquakes differ from Interplate Earthquakes? Mian Liu, Dept. of Geological Sciences, University of Missouri, Columbia, MO 65211-1380, USA.	15 mts
S3.3	Intraplate Earthquakes as Aftershocks John E Ebel, Weston Observatory, Dept. Earth and Environmental Sciences, Boston College, USA	30 mts
S3.4	On Epidemic Type Aftershock Sequence (ETAS) Modeling for Finding Anomalous behavior of Seismicity AR Bansal and VP Dimri, National Geophysical Research Institute (CSIR), Hyderabad – 500 007	15 mts
	S4: Paleoseismology and Archaeoseismology	
	Session Chairman: Javed Malik Co-Chairman:Kusala Rajendran	
	Session date: 17 Jan Session time: 10:30-12:15	
S4.1	Diversity of earthquake sources in Kachchh and Saurashtra, NW India CP Rajendran and Kusala Rajendran, Indian Institute of Science, Bangalore	30 mts
S4.2	Active fault and paleoseismic evidence: Implication towards seismic hazard in Kachchh region, western Gujarat Javed N. Malik[1] , Michio Morino[2], Mahendra S. Gadhavi[3,4], Khalid Ansari[1], Chiranjeeb Banerjee[1], BK Rastogi[3], Fumio Kaneko[2], F Bhattacharjee[3], AK Singhvi[5] [1]Department of Civil Engineering, IIT Kanpur. Kanpur 208016. UP. India, [2]OYO International Corporation ,Japan. [3]Institute of Seismological Research, Gandhinagar 382018, Gujarat, India, [4]Now at L. D. College of Engineering, Ahmedabad, [5]Physical Research Laboratory, Ahmedabad	30 mts
S4.3	Role of climate and seismicity in mid-Holocene sedimentation and landform development in the western Great Rann Navin Juyal, Physical Research Laboratory, Navrangpura, Ahmedabad-380 009	15 mts
S4.4	Optical chronology of sediments deposited by Extreme Wave Events along the Gujarat Coast, Western India Nilesh Bhatt[1], MK Murari[2], Vishal Ukey[1] and AK Singhvi[2] [1]Department of Geology, MS University, Vadodara-390002 (India) [2]Physical Research Laboratory, Navrangpura, Ahmedabad-380009 (India)	15 mts
S4.5	Suspected Archeological Evidence of an Earthquake near Vishakhapatnam Biju John, D.T. Rao, Yogendra Singh, G.H. Kotnise and Kannababu National Institute of Rock Mechanics, Bangalore, India.	15 mts
S4-P1*	Paleoseismic and Active Fault Studies in Kachchh Rastogi BK[1] , M. S. Gadhvi[2], J. N. Malik[3] , AK Singhvi[4] and M. Morino[5] [1]Institute of Seismological Research, Raisan, Gandhinagar, [2]LD Engineering college, Gandhinagar, [3]Indian Institute of Technology, Kanpur, [4]Physical Research Laboratory, Ahmedabad, 5Oyo Intl. Corpn., Japan	
S4-P2*	Ascertaining the sesimicity using morphometric indices in the vicinity of Wagad and Gedi Faults, eastern Kachchh, Gujarat, India Falguni Bhattacharya, BK Rastogi, GC Kothyari	

	Institute of Seismological Research, Gandhinagar	
S4-P3*	Surface deformation zone of the North Wagad Fault and neotectonic evidences in the Gedi Fault area of Kachchh Kothyari, GC, BK Rastogi and Rakesh Dumka, ISR	
	S5: Crustal Structure and Processes	
	Session Chairman: M Ravi Kumar Co-Chairman: Charles Langston	
	Session date: 17 Jan Session time: 12:15-13:15	
S5.1	Thermo-mechanical models of the continental crust of central India: Constraints from lower crustal intraplate seismicity Ajay Manglik, National Geophysical Research Institute, Hyderabad 500606, INDIA	15 mts
S5.2	Gravity Anomalies, Effective Elastic Strength and Crustal Structure over the Intraplate Earthquake (M>6) Regions in India VM Tiwari, PA Dileep and B Singh National Geophysical Research Institute (CSIR), Hyderabad 500 007, India	15 mts
S5.3	Earthquake Locations and Three-Dimensional Elastic Structure in the Koyna-Warna Region, Western India from Local Earthquake Tomography Madan M Dixit and Sanjay Kumar, National Geophysical Research Institute, Hyderabad India	15 mts
S5.4	Identification of Active or Passive Faults – Evidence from Magnetotelluric Studies in Earthquake Region of India. T Harinarayana Director, GERMI Research Innovation and Incubation Center (GRIIC), Gandhinagar, Gujarat, India	15 mts
	S5: Crustal Structure and Processes-Contd.	
	Session Chairman: SS Rai Co-Chairman: VC Thakur	
	Session date: 17 Jan Session time: 14:00-16:45	
S5.5	Seismic Crust near the 2001 Bhuj ($M_w = 7.7$) Epicentral Region in Western India Kalachand Sain, PR Reddy, L. Behera, D Sarkar National Geophysical Research Institute, Hyderabad-500007 R.D. Catchings and W.D. Mooney, US Geol. Surv., Menlo Park, California, USA	15 mts
S5.6	Varied Crustal Structure in and around Kutch mainland and it`s significance in understanding segment wise lithospheric Dynamics P Ramachandra Reddy, Ex-Scientist, NGRI	15 mts
S5.7	Seismic Structure of the Active Rift Zones in the Indian Shield M Ravi Kumar, Narendra Kumar, Arun Singh, D Saikia and D Sarkar National Geophysical Research Institute, CSIR, Hyderabad 500007, India.	15 mts
S5.8	Earthquake pattern and Crustal images in the Kumaon-Garhwal Himalaya and Ganga basin inferred from broadband seismological observation SS Rai, Seismic Tomography Program, National Geophysical Research Institute, Hyderabad-500007	15 mts
S5.9	Joint Inversion of Rayleigh Wave Group Velocities from Ambient Seismic Noise Correlation and Earthquake data in the Indo-Gangetic Plains near Central Himalaya N Purnachandra Rao, Peter Gerstoft, Azizul Haque and D Srinagesh 1. National Geophysical Research Institute, Uppal Road, Hyderabad 500 007	15 mts
S5.10	Terrestrial Heat Flow in India: Variation and Implications Mohan L Gupta Formerly Head Geothermics, NGRI, Hyderabad – 500017, India.	15 mts
S5.11	Analysis of gravity fields of Kuchchh, Saurashtra and adjoining Central India-inference on regional structures based on isostatic consideration Bijendra Singh*, Sanjay K. Prajapati1 and Ch. Swarna Priya* *National Geophysical Research Institute (CSIR), Hyderabad 500 007, India. 1 Ministry of Earth Science, New Delhi	15 mts
S5.12	Structure and Tectonics of the Eastern Continental Margin of India KSR Murthy, National Institute of Oceanography. Regional Centre,Visakhapatnam, 530017, India.	30 mts
S5.13	Satellite Geoid/Gravity for Offshore Subsurface Features Extraction TJ Majumdar, CSIR Emeritus Scientist, Space Applications Centre (ISRO), Ahmedabad - 380 015, India	15 mts
S5.14	A complex tectonic model of Shillong-Mikir Platea, Northeast India: Inferred through waveform inversion, multiple inverse method, stress tensor inversion with subsequent seismic anisotropy and receiver function analysis	15 mts

	Saurabh Baruah*, Santanu Baruah, Aditya Kalita and Dipok Bora, CSIR North East Institute of Science and Technology, Jorhat-785006, Assam, India	
S5.P1*	Crustal Structure beneath Gujarat region Sumer Chopra*, Tao-Ming Chang#, B.K.Rastogi^ and RBS Yadav~ * Seism. Dn., Ministry Earth Sc, New Delhi# National Centre for Research on Earthquake Engineering, Taipei, Taiwan ^ Institute of Seismological Research, Gandhinagar, Gujarat, India ~ Indian National Centre for Ocean Information Services, Hyderabad, India	
S5-P2*	Shear Wave Velocity Tomography of Crust beneath the Dharwar Craton, India Using Ambient Noise Kajaljyoti Borah, K. Surya Prakasam S. S. Rai and Sudesh Kumar, NGRI, Hyd.	
S5-P3*	Electrical Resistivity Imaging of the Kutch Rift Basin: Seismogenic Implication P B V Subba Rao, A K Singh and B R Arora, Ind. Inst. Geomagnetism, Mumbai	
S5-P4*	Seismic constraints on anisotropy and structure beneath Northwestern Deccan Volcanic Province of India K.Madhusudhana Rao (ISR), M. Ravi Kumar (NGRI) and B.K.Rastogi, ISR	
S5-P5*	3-D Rayleigh Wave Group Velocity Tomography of Gujarat, India AP Singh, OP Mishra (Disaster Cell, SARC, New Delhi), Navaneeth Annam, Libu Jose, and Santosh Kumar, ISR, Raisan, Gandhinagar	
S5-P6*	Crustal structure structure across Saurastra Horst, Gujarat as revealed through magnetotelluric studies C.K. Rao, A.K. Singh, P.B.V. Subba Rao and Atul Tyagi[1] Indian Institute of Geomagnetism, Kalamboli Highway, Navi Mumbai, India.[1]Now at Reliance Industries Ltd, Navi Mumbai, India	
S5-P7*	Attenuation of Seismic Waves in Kachchh and Saurashtra Regions, Gujarat, India Babita Sharma[1] and B.K.Rastogi[2] [1]Ministry of Earth Sciences, New Delhi, [2]Institute of Seismological Research, Gandhinagar, Gujarat	
S5-P8*	2D-Geoelectric Subsurface structure in the surroundings of the Epicenter Zone of 2001, Bhuj Earthquake Using Magnetotelluric Studies Kapil Mohan, Sunita Devi, Inst Seismol. Res., Raisan, Gandhinagar-382009, Gujarat, India K. Veeraswamy and T. Harinarayana, Nat. Geophys. Res.Inst, Hyderabad 500007, India	
S5-P9*	Lithospheric Structure of the Lower Indus Basin as well as Onshore and Offshore Western India Evaluated from Surface-Wave Data Srichand Prajapati1 and S. N. Bhattacharya2 1Institute of Seismological Research, Raisan, Gandhinagar-382 009, Gujarat, India 2Department of Earth Sciences, IISER-K, Mohanpur, West Bengal-741 252, India	
	Discussions on Sessions 3,4 and 5 Time: 17:00-18:00 **Coordinators: M Ravikumar and Roger Bilham**	
	S6: The New Madrid and Kachchh Seismic Zones	
	Session Chairman: Susan Hough Co-Chairman: Prantik Mandal	
	Session date: 18 Jan Session time: 09:00-11:00	
S6.1	Triggered Seismicity due to the 2001 M_w7.6 Bhuj Earthquake, Western India BK Rastogi, Sandeep K Aggrawal, Nagabhushan Rao and Pallabee Choudhury Institute of Seismological Research, Gandhinagar- 382 009, India	15 mts
S6.2	Wave Propagation, Crust, and Mantle Structure within Intraplate Rift Basins Charles A Langston, Center Earthq. Res. and Information, Univ. Memphis, Memphis, USA.	30 mts
S6.3	Searching for Long duration Aftershocks in Continental Interiors Miguel Merino and Seth Stein Department of Earth and Planetary Sciences, Northwestern University, Evanston, USA.	15 mts
S6.4	Earthquake Forecasting in Bhuj, Western India Alok Kumar Mohapatra, William K Mohanty, Kaushik Kislay and Kristy F Tiampo Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur, India	15 mts
S6.5	Seismic characteristics of the New Madrid (USA) and Kachchh (India) seismic zones: Implications toward seismogenesis of earthquakes occurring in the continental rift zones Prantik Mandal, Principal Scientist, CSIR-NGRI, Hyderabad -500007, India	15 mts

S6.6	Tectonic History and Related Seismicity along Rift and Grabens of Peninsular India, with Special Reference to Kutch and Contiguous areas of Gujarat KS Misra, University of Petroleum and Energy Studies, Dehradun – 248007	15 mts
S6.7	An Analysis of Seismic Intensity Patterns of Destructive Earthquakes of Kachchh Rift Basin, Gujarat, India **Prabhas Pande,** Former Additional Director General, GSI	15 mts
S6-P1*	Preparation of 1 m.gal Interval Bouguer Anomaly Contour map of Kachchh and identification of Faults RK Singh, BK Rastogi, Gopal Rao, Om Behari, Sidharth Dimri Inst. Seism. Res., Gandhinagar 382 009, India	
S6-P2*	Overview of Current Research Being Conducted at the Center for Earthquake Research and information, Memphis,TN with particular Emphasis on the NVT Project Blaine Bockholt and Charles Langston Department of Earth-Science, University of Memphis, Memphis, USA.	
S6-P3*	New Model for Crack density, Saturation rate and Porosity at the 2001 Bhuj earthquake Hypocenter: Vindicating fluid driven earthquake? AP Singh, OP Mishra and BK Rastogi, ISR	
S6-P4*	Coulomb stress changes and Seismogensis beneath Kachchh region due to 2001 Bhuj earthquake AP Singh, RBS Yadav, Santosh Kumar and BK Rastogi, ISR	
	S7: Strain Accumulation inside Continents	
	Session Chairman: N Purnachandra Rao Co-Chairman: Vineet K Gahalaut	
	Session date: 18 Jan Session time: 11:00-12:30	
S7.1	Stable Continental North America: Concentrated or Distributed Strain? Susan E Hough, United States Geological Survey (USGS), Pasadena, California, USA	20 mts
S7.2	Indian Plate Motion: Constraints from the GPS measurements VK Gahalaut, National Geophysical Research Institute (CSIR), Uppal Road, Hyderabad 500007, India	15 mts
S7.3	Crustal deformation in 13ntraplate regions of Indian sub-continent C.D. Reddy, Mahesh N Srivastava (Indian Institute of Geomagnetism, Navi Mumbai-410218) and Sanjay K Prajapati (Ministry of Earth Sciences, New Delhi)	15 mts
S7.4	Crustal deformation studies by DGPS in Kachchh Pallabee Choudhury, Rakesh Dumka, BK Rastogi , Inst. Seismological Res., Gandhinagar	5 mts
S7.5	InSAR and GPS evidences for crustal deformation in Kachchh, India K. M. Sreejith, T. J. Majumdar, A. S. Rajawat and Ajai (Geosciences Division, Marine, Geo and Planetary Sciences Group, EPSA, Space Applications Centre (ISRO), Ahmedabad -380015, India) B.K. Rastogi, Pallabee Choudhury, and Rakesh Dumka (Institute of Seismological Research, Gandhinagar – 382009, India]	10 mts
S7.6	Crustal Deformation Studies Based on InSAR Technique: Case Study of Kutch Region, Gujarat Kanika Sharma, Arun K. Saraf and J. D. Das Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee – 247667	5 mts
S7.7	**Mineral, Virginia, earthquake illustrates seismicity of a passive-aggressive margin** Seth Stein[1], Frank Pazzaglia[2]**, Emily Wolin[1]**, Alan Kafka[3] [1]Department of Earth and Planetary Sciences, Northwestern University Evanston, IL 60208 [2]Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, PA 18015 [3]Weston Observatory, Department of Earth and Environmental Sciences, Boston College	15 mts
	Discussions on Sessions 6 and 7, Time: 12:30-13:15 **Coordinators: M Ravikumar and Roger Bilham**	
	CONCLUDING SESSION 14:00 – 16:30	

* Poster sessions have been scheduled at 09:00 hrs and 15:15 hrs on 16 January.

S1: Faulting and Seismicity in Continental Intraplate Regions

There has been tremendous progress in seismological research but the seismogenesis in the intraplate regions of the world is still a great puzzle for geoscientists. Plausible mechanisms for intraplate seismicity have been proposed, but many key questions remain unanswered. The location and charactertistics of most seismic sources remain unknown. To address the physics of intraplate seismicity, understanding of the evolution structure and processes of the shield area is necessary. The session discusses case-studies on different aspects of significant intraplate earthquakes.

Session Chairman: Harsh K Gupta **Co-Chairman: V P Dimri**

S1.1

Historical Earthquake Hazards and Future Seismic Risks in India

Roger Bilham, University of Colorado, Boulder CO 80309-0399 USA

Fully 80% of the million or so fatalities in the past thousand years have occurred in 12% of the world's land area, a region roughly coinciding with the southern and western margins of the Eurasian plate. This belt of disaster starts in the western Mediterranean, the passes through the Middle East, Turkey, Iran, Afghanistan, India, Indonesia, China and Japan. In some of these nations strain rates are high and earthquakes are frequent reminders of the need to improve earthquake resistant construction, but in many cases strain rates are low and earthquakes occur so infrequently that for many unfortunate people their first earthquake may be devastating. The most fatal earthquakes are typically in the range $7<Mw<7.9$ partly because these occur more frequently than $Mw\geq8$ earthquakes but also because the midcontinent settings of these events are populated by faults with dimensions that limit the maximum sized earthquakes that can occur.

The Indian plate is endowed with both classes of earthquake hazard. Great earthquakes and numerous smaller ones occur along its northern and western boundaries with the Eurasian plate, and infrequent minor and occasionally severe earthquakes occur within the continental area where most of its peoples live. Geodetic measurements across the Himalaya suggest that the present convergence rate of 16-18 mm/yr is approximately consistent with the observed seismic-moment release of elastic energy in all earthquakes since 1500, and hence a future large earthquake would not be unexpected. Since there has not been a significant earthquake in the central Himalaya for almost 80 years the probability of a M>7 earthquake must be considered high, and numerous segments of the Himalaya are potentially ready for a M≥8 earthquake with a potential slip of at least 8 m.

Just as elsewhere in the world, the recurrence of small and moderate earthquakes in the Himalaya, and a strain geodetic rate approaching 1 µstrain/year, act as a reminder to local authorities of the importance of enforcing building codes. The same cannot be said of the sub-continent. Here strain rates are closer to 1 nanostrain/yr and earthquakes are somewhat uncommon, but when they occur they can result in considerable damage because the need for code enforcement may have been neglected. The estimation of earthquake risks from scant data in central India is perilous if it is based on the short seismic record of the past few decades, and is not much improved if a 200 year record of historical earthquakes is included. It can easily be shown that a 10,000 year record of historical earthquakes must be considered insufficient if we are to pretend that earthquake risk analysis has any predictive value. Further aggravating the utility of historic earthquake recurrence rates in mid-continent it appears quite probable that recent hydraulic load changes in India have changed the "a-value" in the Gutenberg/Richter "b-value" relation that characterizes frequency/magnitude relations. Finally, many earthquakes in the mid-continent occur on blind faults that are not amenable to geological investigation. A physics-based approach may be essential to guide future planning for earthquake resistance in India. In the absence of reliable physics it may be necessary to embark on the ubiquitous application of sound building practices throughout the subcontinent.

Spl.

Medieval Multihazards and Future Earthquakes in Kashmir

Roger Bilham, University of Colorado, Boulder CO 80309-0399 USA

The legendary Medieval hydraulic engineer Suyya is known to all schoolchildren of Kashmir. An earthquake c. 883 AD caused a landslide to block the Jhelum, which thereby flooded much of the arable land in the Kashmir Valley leading to widespread famines and poverty to its displaced populations. The historian Kalhana relates that Suyya was overheard to say he could unblock the landslide had he the resources to do it, which so intrigued the King that he offered to provide the pots filled with coins that Suyya consider necessary. To everyone's surprise Suyya in full view of puzzled villagers tossed the coins into the flood waters, proclaiming that the money could be recovered by anyone, but they must first help him clear the landslide. In short order the villagers did so and the flood waters subsided.

Aurel Stein's reconstructions of the geography of Medieval Kashmir permit us to examine the physics underlying the legend. The location of the landslide is very likely to be one of several slides that border the northern bank of the Jhelum in a stretch 3-8 km west of Baramula. The remnants of one particular landslide upstream from the town of Khadniyar has an appropriate breadth and elevation to have flooded the valley to a depth of 15 m, a level that would be sufficient to drown most of the valley including the capital, Srinagar.

Yet, there are problems with the chronology of Suyya's exploits. Avantavarman, who is credited with funding Suyya died in 883 and was succeeded by Sankaravarma, who is famous for both cannibalizing the Buddhist temples of Parihasapora to construct Hindu temples in his newly founded capital of Pattan, and in the early part of his reign for forming a marauding army that looted the neighboring kingdoms in Chamba, Kangra and the Punjab. If Avantavarman funded Suyya, then the earthquake that dammed the Jhelum would have to have predated the flooding by many months or years based on present-day discharge rates. Although the mean level of Wular lake would initially rise 50cm/day its rise would rapidly decay to less than 6 cm/day as its area increased. The flooding of the entire valley to near Anantnag 15 m higher would take several years due to this greatly expanded area of the flooding. The timing of earthquake, landslide and flood is suggested by the archaeological stratigraphy of collapsed blocks of the Sugandhesa temple whose construction is alleged to have been initiated after 883AD. The dates of collapse of this temple apparently followed a flood, but its construction may have followed an earlier earthquake that had already raised the flood level to roughly 1600 m. That is, the puzzling location of Pattan as Sankaravarma's new capital may have been because Avantavarman's capital was already underwater. The hunger of his people and the collapsed economy may have caused Sankaravarma to form the marauding armies that characterized the early part of his reign. In this scenario the draining of the floodwaters would thus have occurred long after Avantavarman's rule.

Notwithstanding the apparent discrepancies in the recorded dates, the prodigious extent of the 883 flood is important since it is probable that this is not the first time that an earthquake-triggered landslide has blocked the exit of the Jhelum. An earthquake-triggered landslide without a significant flood may have occurred in 1555, but a valley wide flood may be the origin of the c. 3000 BC legend of the Kashmir lake that forms the early part of the Rajatarangini. Of concern to those involved in assessing future hazards in Kashmir must therefore be the possibility that a similar earthquake-induced flood may potentially threaten Srinagar in the future.

S1.2

A Unified Model for Intraplate Earthquakes

Pradeep Talwani (E-mail: pradeep@sc.edu, talwani@geol.sc.edu)

Dept. of Earth and Ocean Sciences, University of South Carolina, Columbia, SC, 29208, USA.

In the past 3.5 decades, various observations and models have been proposed to explain the occurrence of intraplate earthquakes (IPE). Schulte and Mooney (2005) showed that more than 98% of the total global seismic moment release associated with IPE occurs in former rifts and taphrogens. Mooney and Ritsema (2010) have shown that these rifted basins are associated with a weaker lower crust, mappable by seismic tomography. Modeling results by Hansen and Nielsen (2003) have shown that when rifted sedimentary basins which had been formed under extension, with á priori weaknesses, are inverted under compression, the results are weak conjugate and boundary faults with up-welled lower crust. These resulting features of stress inversion are associated with local (~10s km x10s km surface area) elevated strain rates. These features have also been identified as local stress concentrators (LSC) where IPE nucleate in response to the ambient compressional stress field (Gangopadhyay and Talwani, 2003). At many locations of IPE this compressional stress field is modified by regional stress perturbations (e.g. due to glacial rebound, sediment deposition etc., Talwani and Rajendran, 1990), or subjected to the weakening effect of fluids. This modified stress field is further perturbed on a **local** scale (~ 100s sq. km) by the stress field due to the LSC leading to detectable, localized increases in strain rates.

We use these observations and modeling results to suggest the following testable, unified model for IPE, UMFIE. Major IPE occurs in reactivated rifted basins, with conjugate and boundary faults and an up-welled lower crust. (The precise geometry and seismic potential of each site depends on its tectonic history and geometry after stress inversion). These features are sites of **local** stress concentrations and elevated strain rates, and potential IPE. To test this model and to predict potential locations of IPE, seismic tomography can be used to define the weaker lower crust associated with rifted basins, and dense, continuous GPS observations can be used to identify **local** pockets of elevated strain rates; and seismicity and geophysical observations can be used to identify stress concentrators and locations of IPE.

S1.3

Intra-Plate Dynamics and Active Tectonic Zones of the Indian Plate

S. K. BISWAS

Ex-Director, KDM Institute of Petroleum Exploration, ONGC.

Tectonic framework of Indian Plate started to evolve since the breakup of Gondwanaland in Late Triassic. It evolved mainly during the time between its separation from the latter in Early Cretaceous and its collision with the Eurasian plate in the north in Late Middle Eocene and with the Indosinian plate in the northeast in Late Oligocene. Present active tectonic zones, responsible for earthquake generation, were created by the collision pattern and subsequent plate motion. Continued subduction and plate motion due to ridge push and slab pull are responsible for activation of primordial faults in the inherent structural fabric of the craton depending on the related stress field. Major tectonic zones of this continental plate are related to the collision fronts and the reactivated intracratonic faults along the resurgent paleo-sutures between the proto-cratons. Major Tectonic zones (TZ) are: Himalayan TZ, Assam-Arakan TZ, Baluchistan-Karakoram TZ, Andaman-Nicobar TZ and Stable Continental Region (SCR) earthquake zone. The structure of the continental margins developed during break up of Gondwana continental fragments. Western margin evolved during the sequential separation of Africa, Madagascar and Seychelles since Late Triassic to Late Cretaceous time. The Eastern margin structure evolved during separation of Antarctica in Mid Cretaceous. The Orogenic belt circumscribing the northern margin of the Indian plate is highly tectonized zone as subduction of the plate continues due to push from the Carlsberg Ridge in the SW and slab pull towards northeast and east as the subduction of the plate along the orogenic and island arc fronts continues. This stress pattern induced an

anticlockwise rotatory plate motion. The back thrust from the collision front in the direction opposite to the ridge push put the plate under an overall compressive stress. This stress pattern and the plate motion are responsible for the reactivation of the major intra-cratonic faults. While the tectonized orogenic belts are the zones for earthquake nucleation, the reactivated faults are also the strained mega shear zones across the plate for earthquake generation in SCR. These faults trending WNE-ENE are apparently the transform faults which extends across the continent from Carlsberg ridge in the west to the collision zones in the northeast. As such, they are described here as the 'trans-continental transform faults'. Three such major fault zones from north to south are, (i) North Kathiawar fault - Great Boundary fault (along the Aravalli belt) zone, (ii) South Saurashtra fault (extension of Narmada fault) – Sonata-Dauki fault zone, and (iii) Tellichery-Cauvery-Eastern Ghat-T3-Hail Hakalula-Naga thrust zone. All these trans-continental faults are traceable from western offshore to the northeastern orogenic belts along mega tectonic lineaments across the continent. The neotectonic movements along these faults, their relative motion and displacement are the architect of the present geomorphic pattern and shape of the Indian craton. The overall compressive stress is responsible for strain build up within these fault zones and consequent earthquake nucleation. The mid-continental Sonata-Dauki shear zone follows the Central Indian Suture Zone that joins the northern Bundelkhand and southern Deccan proto-cratons. With the reactivation of the shear zone the two proto-cratonic blocks are subjected to relative movement as the plate rotates anticlockwise. The kinematics of these movements and their implications are discussed here.

S1.4

Mechanism of Intraplate Earthquakes

BK Rastogi, Inst. Seism. Res., Raisan, Gandhinagar 382009, India & **Prantik Mandal**, NGRI, Hyderabad

The occurrence of large earthquakes within continents, far from plate boundaries, has been attributed to the steady large strain/stress accumulation associated with faults in the plate interiors, which is periodically released in the form of large infrequent events. These earthquakes are classified as stable continental region (SCR) earthquakes, which have struck stable continental regions in plate interiors at several locations worldwide viz. the New Madrid zone, United States; Tennant Creek, Australia; Ungava, Canada; and Kachchh and Latur, India. However, in most cases no surface ruptures were evidenced, including the latest 2001 Mw 7.7 Bhuj earthquake. These earthquakes generally have very large return periods on the order of thousands of years. The occurrences of these earthquakes can account for only 0.5% of the average annual global energy release by earthquakes. However, these earthquakes are in general complex and rare in nature, but can be devastating. These earthquakes caused widespread damage not only because they were large, but also because the rigid continental crust of plate interiors transmits seismic energy more efficiently than the heavily fractured crust near plate boundaries. The New Madrid earthquakes damaged buildings as far as 1500 km away on the East Coast (Johnston and Kanter 1990) and Bhuj earthquake collapsed multi-storey buildings to 250 km distance. Thus, it is very important to identify the locales of future SCR earthquakes. To understand where intraplate earthquakes might occur, it is necessary to have an idea about the mechanism that causes them.

The main source of stress in the Indian plate interior is the plate boundary forces, which include the ridge-push (at Carlsberg and southeast Indian ridges), trench pull (at Java-Sumatra and Tonga trenches), Himalayan collision forces, viscous drag at the base of Indian lithosphere, and recoil/back push from the Himalayan front. From base of the lithosphere, it is transmitted upwards in causing uplift and deviatoric stresses that may cause faulting. In the proximity of the Himalayan front, the shield elements of Archaean and Proterozoic age in Meghalaya, Mikir and Kopili in the east and Mesozoic rift of Kachchh in the west are locales of large earthquakes. The NE transverse Proterozoic trends abutting against Himalaya like Aravalli trend, Moradabad fault, Faizabad Ridge and Mongyer-Saharsa Ridge also produce small to moderate earthquakes. Further south Narmada zone is active. And the entire region south of it displays neotectonics as well as small to moderate earthquakes. Neotectonics has been mapped in the form of gullies, terraces etc. in Kerala, Karnataka and Tamilnadu (Valdiya, 2010). Kachchh and Maharashtra regions of Western India show relatively high stress/strain and high seismicity being nearer to the source of ridge push. Moreover the Archean and Proterozoic rocks in the south being old and broken have lesser dimensions and hence, can produce smaller earthquakes in comparison to the regions of younger Mesozoic rifts. Due to this reason the southern part of the Indian Peninsula is rising with western part raising more than the eastern part. Elevation of 1 to 1.5 km in the Sahyadri range in the western part gradually tapers eastward.

After docking of the India plate with Eurasia during Eocene 40 Ma, tectonic inversion took place. In response to the NE directed plate tectonic stress the older NW and younger NE faults are failing in strike-slip sense of motion. The normal faults of the Narmada and Kachchh rifts had tectonic inversion in the form of transpessional / reverse faults extending to Moho depth. At places like Latur in Maharashtra, the shallow faults also showed reverse faulting.

The favoured locales of stress concentration could be presence of mafic crustal intrusive or fault-intersection/bend in the plate interior. In the zones of weakness and high heat flow, the faults would require lesser stress/strain to rupture and hence can produce relatively more number of earthquakes than the surrounding regions. The crustal zones of weakness are associated with rifts where weak-zone in lower crust can amplify the stresses in the upper crust, thereby, causing earthquakes. The high heat flow due to thin lithosphere/crust in the failed rift like New Madrid, USA and Kachchh, India, where the warm mantle can play a key role in weakening the crust, thereby, causing earthquakes along pre-existing zones of weakness. In Australia attempts have been made to correlate high heat flow zones with seismicity (Holford et al. 2011 EPSL).

In general Generation of SCR earthquakes in the upper crust have been attributed to the sudden movement along the pre-existing weak zones due to local stress perturbation of the regional plate tectonic stress due to surface as well as subsurface loading, reservoir loading, presence of fluids and intersection of crustal weak zones (Richardson et al. 1979, Gupta and Rastogi 1976, Talwani, 1988; Mareschal and Kuang, 1985; Andrews, 1989; Talwani and Acree, 1984; Ma et al. 1997).

Among the SCR regions worldwide, only the New Madrid and Kachchh regions have the distinction of having earthquakes of magnitude approaching 8. The New Madrid seismic zone (NMSZ) in the central United States was struck by three Mw≥7 earthquakes in 1811–1812, where smaller earthquakes are occurring even today. While the Kachchh region, Gujarat, India is located 1000 km away from the Himalayan plate boundary in the north and 400 km away from the Herat-Chaman plate boundary in the west, has already experienced two large earthquakes within a time span of 182 years viz., the 1819 Mw7.8 Allah Bund earthquake and the 2001 Mw7.7 Bhuj earthquake. And, the aftershock activity of the 2001 main-shock is continuing until today. In addition to the plate tectonics stress, various local stress sources have been explored to explain the seismicity associated with the NMSZ or KSZ. For instance, NMSZ seismicity has been attributed to stress changes induced by melting of the Laurentide ice sheet or stresses generated by sinking of an ancient high-density mafic body or from a sudden weakening of the lower crust (Mooney et al. 1983; Calais et al. 2010; Pollitz et al. 2001). Similarly, the seismicity in KSZ has been attributed to the stresses caused by mafic crustal intrusive bodies and in-plane plate compression, which has further been facilitated by the presence of aqueous fluids or volatile CO_2 released from the metamorphism of olivine-rich lower crustal rocks (Mishra and Zhao 2003; Mandal and Pujol 2006; Mandal and Chadha 2008) as revealed by seismic tomographic studies. Seismic, gravity and magnetotelluric surveys have revealed sedimentary thickness, basement configuration, crustal structure and disposition of faults. Further, marked upwarping of Moho and astheonsthere underlying KSZ has been modeled through receiver functions, which also revealed the presence of patches of partial melts in the asthenosphere that can lead to emanation of volatile CO_2 into the lower crust, thereby, causing continued occurrence of aftershocks (Mandal, 2011). Further, GPS studies during 2001-2006 suggest a high strain rate (0.3 x 10^{-6} /year) in the Kachchh seismic zone relative to the smaller regional strain rate (~ 10^{-9} /year) of the Indian peninsula (Reddy et al. 2008, Paul et al. 2001). The GPS and InSAR studies by ISR and SAC-ISRO (Rastogi et al. 2011) indicate large vertical uplift of 13-40 mm/yr at several locations. Palaeoseismological investigations indicate active faulting along several faults in Kachchh and Narmada zone. Drilling indicates weak Mesozoic rocks along faults. Thus, it is apparent that the KSZ is deforming very fast in comparison to the surrounding regions, which indicates a local causative associated with the KR. Otherwise, why are the earthquakes concentrated on the Kachchh rift when the continent contains many fossil structures that would seem equally likely candidates for concentrated seismicity? A key to answering this question is the understanding of the thermo-mechanical structure of the KSZ. Now, we know that the KSZ is characterized by a high heat flow of 60-70 mW/m^2, thereby, a thin lithosphere of 70 km thickness. Thus, the KSZ seems to be hotter and weaker than surrounding regions. Therefore, it is likely to be a long-lived weak zone on which intraplate strain release would concentrate.

The intermediate to deep crustal earthquakes of moderate-to-large magnitudes have occurred in several continental rift zones like Amazonian (Brazil), East African (Africa), Baikal (Russia), Rio-grande (North America), Narmada (India) and Reelfoot (New-Madrid, USA), which have been explained in terms of failure of old rift due to local stress perturbations associated with substantial crustal as well as astheonspheric thinning, intruded magmatic material from the underlying mantle and deepening of the brittle-ductile transition depth (Mukherjee 1942, Mooney et al. 1983, Prodehl et al. 1994, Johnson 1996, Liu and Zoback 1997, Singh et al. 1999, Kruger et al. 2002, Wilson et al. 2003, Gao et al. 2004, Mooney et al. 1983, Kumar et al. 2000, Deverchere et al. 2001, Nyblade and Langston 1995, Manglik and Singh 2002). Until today, several models have been proposed to explain the occurrence of Indian SCR earthquakes viz. the 1819 Allah bund earthquake, the 1956 Anjar earthquake, the 1993 Mw6.2 Latur, the 1997 Mw5.8 Jabalpur and the 2001 Mw7.7 Bhuj earthquakes. Existing focal depths of Indian SCR events suggest that these earthquakes are mainly of upper crustal in nature except the lower crustal earthquakes associated with the Kachchh and Narmada-son rift zones. These rift-associated lower crustal earthquakes are found to be associated with reverse/strike-slip mechanisms. But, the occurrence of the 1993 Latur earthquake at 7 km depth has been attributed to the sudden movement along a south-dipping reverse fault due to the prevailing N-S compression resulted from the northward movement of Indian plate and local tectonic forces associated with topography and subsurface heterogeneities (Mandal et al., 1996). Whilst the occurrence of the 1997 Jabalpur at 35 km depth (in the lower crust with a reverse mechanism) has been explained in terms of large stresses associated with rift pillow or intrusives (Richardson et al., 1987; Rajendran and Rajendran, 2002). However, the mechanisms underlying the seismogenesis of lower-crustal earthquakes occurring in the continental rift zones like the Kachchh and Narmada son rift zones is not well understood.

Thus, none of existing intraplate models appears to provide a successful explanation of the seismogenesis of earthquakes associated with the rift zones, which demands a concerted multi-disciplinary study through active international collaborations between scientists from India and US.

Outstanding problems:

1. Modelling of the ideas about prevailing stresses with the boundary conditions of known parameters of heat flow, ages of rocks, rift valleys, presence of mafic intrusive etc.
2. Modelling of generation process for long aftershock sequence of the 2001 Bhuj event.
3. Modelling of non-volcanic tremors (if any)
4. Development of a time-dependent model for the generation of repeated intraplate earthquakes in Kachchh
5. Geodynamical modeling using available geological and seismological constraints
6. Ground motion modeling using available broadband and strong-motion data
7. Design of source scaling for intraplate earthquakes
8. Development of model for seismogenesis of crustal earthquakes associated with continental rift zones
9. Modeling of earthquake occurrence processes in Bhuj and NMSZ regions

S1.5

Reservoir Triggered Seismicity at Koyna, India

Harsh Gupta (Email: harshg123@gmail.com)

National Geophysical Research Institute, Hyderabad 500007, India.

Artificial water reservoirs have triggered the occurrence of earthquakes at over 100 sites on Earth. Triggered earthquakes exceeding M 6 have occurred in China, Zambia, Greece and India. Changes in the sub-surface pore fluid pressure regime and mechanical properties of the near-field zone are proposed to be the causative factors.

A classical Reservoir Triggered Seismicity (RTS) site is Koyna, West Coast of India. Triggered earthquakes have been occurring in Koyna since the impoundment in 1962, including the largest RTS event of M 6.3 on December 10, 1967; 22 M > 5 earthquakes, and several thousand smaller ones (Figure 1). RTS increases following the monsoon rains and almost every year we have one or more M ~ 4 earthquakes. RTS was intense in 2009 and the latest M 5.1 earthquake occurred on December 12, 2009. The shallow (mostly < 6 km) RTS is confined to a small area of 20 x 30 sq. km with no other seismic activity within 50 km of the Koyna Dam. The Koyna region was stressed close to critical before the impoundment of the Koyna Dam and the maximum credible earthquake for the region is M 6.8. It is estimated that more than one half of this energy has been released since impoundment and RTS will continue for many more years. The occurrence of M > 5 is governed by factors like rate of loading, highest water level reached, duration of retention of high water levels, and whether the previous water level maxima has been exceeded or not (Kaiser Effect). Nucleation precedes M ~ 4 earthquakes, and its real time monitoring has led to short term forecasts.

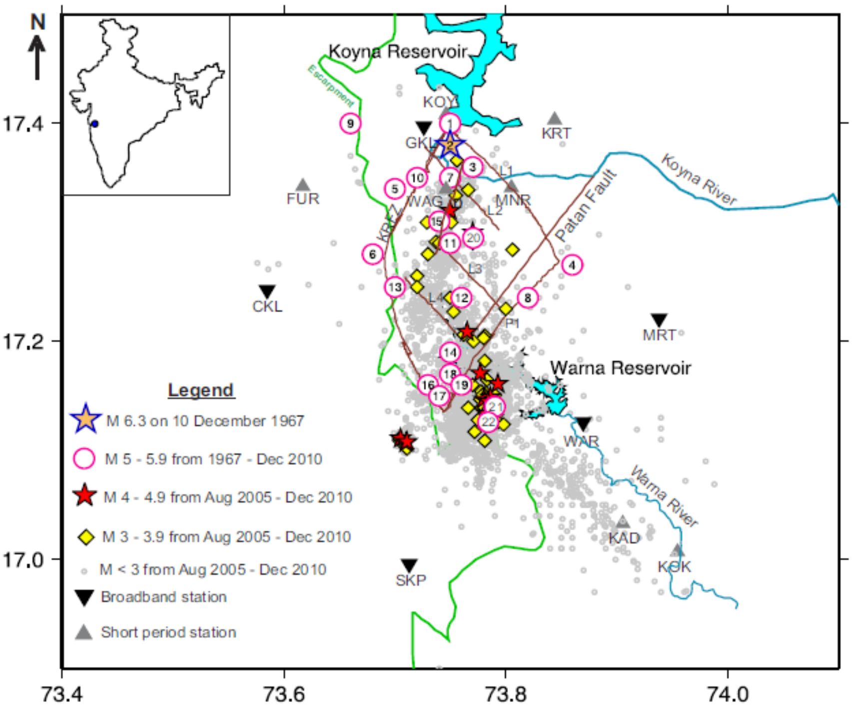

Fig. 1: A map of Koyna-Warna region in Western India indicating the current and past seismicity along with the existing seismograph network and fault zones. Inset: Map of India indicating the study region.

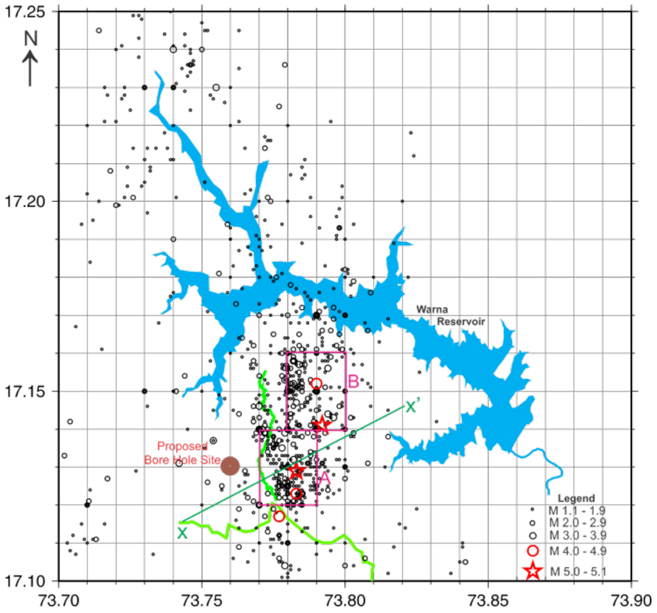

Fig. 2: Seismic activity near the Warna reservoir during 2009 and 2010. A and B are the two areas, where intense clustering is visible. XX' is the P-wave velocity section shown in Figure 3.

Currently, a drilling project in the area is in a first conceptual planning phase. Tentatively, it is planned to be placed close to the Warna reservoir where the seismic activity has been most intense during the past two years (Figure 2). A 3D velocity model has been developed based on the operation of 97 seismic stations in the vicinity of the Koyna and the Warna reservoirs. This site of the proposed bore hole is located close to the location of the recent intense seismic activity (Figure 3). Depth sections for blocks A and B are shown in Figure 4. A deep borehole would provide direct observational data on the composition, physical state and mechanical behavior of a major active fault zone at focal depths of RTS. It would also be possible to test and constrain RTS hypotheses, faulting and earthquake generation in an intra-plate seismic zone, and contribute to earthquake hazard reduction. Down-hole measurements complemented by observations on cores and cuttings, analyses of fluid and gas samples, geophysical and geological site characterization studies including fault zone monitoring would help answer questions related to the genesis of RTS.

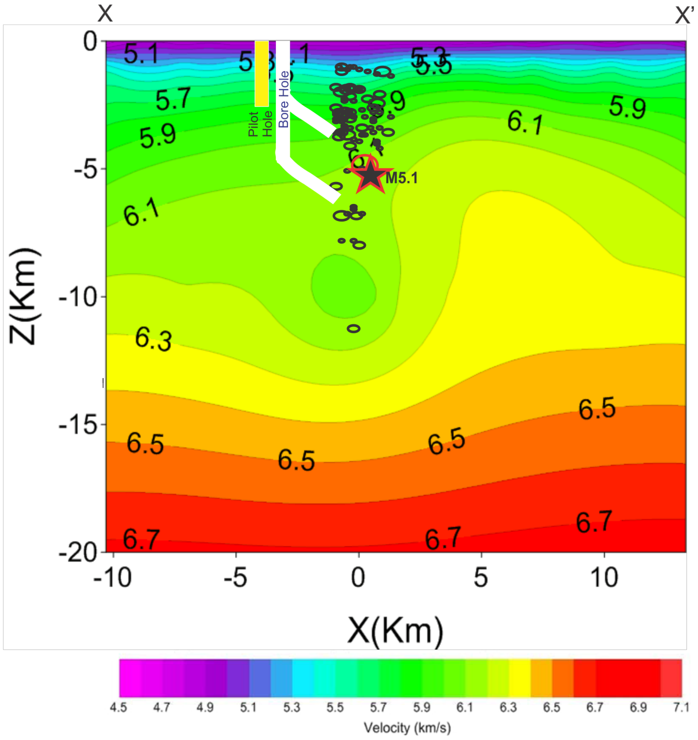

Fig. 3: XX’ is the vertical section from the 3D P-wave velocity model from DD tomography. Earthquakes that occurred during 2009 and 2010 near the proposed borehole site are also plotted.

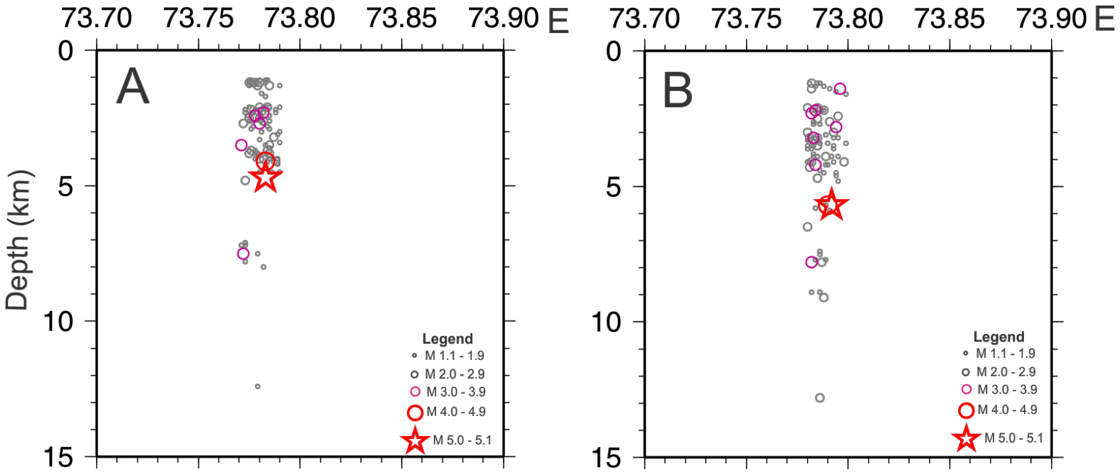

Fig. 4: Depth sections across the fault in Blocks A and B shown in **Figure 2**. Number of earthquakes during 2009 and 2010 in Block-A: M 1.1–1.9 of 81 events; M 2-2.9 of 26 events; M 3-3.9 of 5 events and one earthquake each of M 4.3 and M 5.0. Block-B: M 1.1–1.9 of 54 events; M 2-2.9 of 24 events; M 3-3.9 of 7 events and one earthquake each of M 4.2 and M 5.1.

Heat flux and crustal temperatures in the Indian shield: implications for depth of intraplate earthquakes

Sukanta Roy*, CSIR-National Geophysical Research Institute, Hyderabad 500606, INDIA
Email: sukantaroy@yahoo.com

A number of notable earthquake occurrences in stable continental regions worldwide during the past decades are not consistent with the general inverse correlation of surface heat flux with a depth of seismic-aseismic transition reported previously in literature (e.g., Sibson, 1982; Chen and Molnar, 1983; Chen, 1988; Ito, 1990). Those exceptions point to the inadequacy of (1) heat flux, *per se*, as indicative of thermal conditions at depth, and (2) treating the brittle-ductile transition as the seismic-aseismic transition (Rao et al., 2003). However, temperature, rather than heat flux, is the key parameter in examining rheology and thereby earthquake phenomena. There is a growing recognition that tectonic earthquakes occur by sudden slippage along a pre-existing fault or plate interface and are therefore frictional, rather than fracture phenomena, with brittle fracture playing only a secondary role (see for example, Scholz, 1998). The seismogenic behaviour of a fault is therefore determined by its frictional stability, not its strength. Therefore, central to the problem of seismogenesis is to figure out the expected variation of a *frictional stability parameter* with depth. The region of instability, characterized by a negative value for this parameter, delineates the seismogenic layer in the crust. A transition to a region of stability takes place at its base corresponding to the onset of plasticity of the major mineral of the prevalent rock type, which is 300^{o}C for quartz and 450^{o}C for felspar. The temperature-depth profile in the crust that is considered for determination of onset of plasticity is derived from steady-state heat flux considerations. Such assumptions are applicable for tectonically stable regions only and not for currently active regions where transient components in present-day heat flux would dominate.

The stable continental region (SCR) of the Indian landmass is characterized by a wide spectrum of heat flux values ranging from 25 to 105 mW m^{-2} (Roy and Rao, 2000; Ray et al., 2003; Roy, 2008; Gupta, 1995). The Precambrian terrain of south India, comprising the Dharwar craton and the gneiss-granulite province, is characterized by low heat flux values generally ranging between 25 to 50 mW m^{-2}. The low heat flow of the Dharwar craton extends northward into the Deccan Traps Province south of the Son-Narmada-Tapti lineament zone and near the southwestern fringes of the Cuddapah basin, both of which overlie Dharwar basement rocks. The low heat flow in the Deccan Traps province confirms that the thermal perturbations associated with the ~65 Ma - old Deccan volcanic episode were localized and the transients have decayed. In contrast, the Archaean to Proterozoic segments in the northern and eastern parts of the shield show heat flux consistently higher than 50 mW m^{-2}: 59–63 mW m^{-2} along the Singbhum Thrust Zone (in Singbhum craton), 51–62 mW m^{-2} in the Bastar craton, and 56–96 mW m^{-2} in the Aravalli Province. The Gondwana basins have a generally high but variable heat flow in the range 46–107 mW m^{-2}. While the Damodar Valley basins reveal a narrow range (69–79 mW m^{-2}) in heat flow, the other basins show large variability. The Tertiary Cambay basin shows higher heat flow, 75–96 mW m^{-2} in the northern than in the southern parts, 55–67 mW m^{-2}. On the basis of heat flux distribution, available datasets for thermal conductivity and radiogenic heat production of crustal rocks, constraints from upper mantle seismic shear wave velocities and xenolith geothermobarometry (Roy and Mareschal, 2011), temperature computations indicate that the entire upper- to- middle crust in the Indian SCR could be a region of instability. However, the great majority of M>5 earthquakes have occurred in the shallow (<10 km) and relatively cold crust, pointing to the influence of other factors in additional to temperature in causing failure.

References

Chen, W.-P. (1988) A brief update on the focal depths of intracontinental earthquakes and their correlations with heat flow and tectonic age. Seis. Res. Lett., v.59, pp.263-272.

Chen, W.-P. and Molnar, P. (1983) Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere. J. Geophys. Res., v.88, pp.4183-4214.

Gupta, M.L. (1995) Thermal regime of the Indian shield. *In*: M.L. Gupta and M. Yamano (Eds.), Terrestrial heat flow and geothermal energy in Asia, Oxford & IBH, pp.63-81.

Ito, K. (1990) Regional variations of the cut-off depth of seismicity in the crust and their relation to heat flow and large inland earthquakes. J. Phys. Earth, v.38, pp.223-250.

Rao, R.U.M., Roy, S. and Srinivasan, R. (2003) Heat Flow Researches in India: Results and Perspectives. Memoir, Geol. Soc. India, v. 53, pp. 347-391.

Ray, L., Kumar, P.S., Reddy, G.K., Roy, S., Rao, G.V., Srinivasan, R., and Rao, R.U.M. (2003) High mantle heat flow in a Precambrian granulite province: Evidence from Southern India. Journal of Geophysical Research, v.108, 2084, doi:10.1029/2001 JB000688.

Roy, S. (2008) Heat flow in India during the past five decades. Memoir, Geol. Soc. India, v. 68, 89-122.

Roy, S. and Mareschal, J.-C. (2011) Constraints on the deep thermal structure of the Dharwar craton, India, from heat flow, shear wave velocities, and mantle xenoliths. J. Geophys. Res., 116, B02409, doi:10.1029/2010JB007796.

Roy, S. and Rao, R.U.M. (2000) Heat flow in the Indian shield. J. Geophys. Res., v.105, pp.25,587-25,604.

Scholz, C.H. (1998) Earthquakes and friction laws. Nature, v.391, pp.37-42.

Sibson, R.H. (1982) Fault zone models, heat flow, and the depth distribution of earthquakes in the continental crust of the United States. Bull. Seis. Soc. Am., v.72, pp.151-163.

S1-P1

Seismicity Studies along Kopili Lineament

D. Srinagesh

National Geophysical Research Institute, Hyderabad, 500 007, India
srinagesh@ngri.res.in

Seismicity monitoring around Kopili lineament in Assam valley since 2007 is in progress with the installation of a nine station broadband seismological station network by National Geophysical Research Institute, Hyderabad. This study reveals the seismicity distribution, orientation of the Kopili fault, average P-wave velocity of this region and b value. The 1-D P wave velocity structure has been determined using VELEST inversion and the velocity model is conspicuous with a P- wave low velocity layer at 26-30 km depth and the Moho is at 41 km depth. In this study a total of 300 local earthquakes were recorded in the vicinity of Kopili lineament during the three and a half years period 2007-2011of the network operation and were located by analyzing arrival times of P and S wave phases. Further these locations were improved by HYPODD relocation program. Intense micro tremor activity (M≤3.5) is confined and clustered around Kopili lineament. More than 97% of the seismicity is observed in the form of micro tremor activity. Very few M 4.0-5.0 earthquakes observed during this period. Two clear segments of Kopili lineament is seen, through clear concentration of seismicity along these segments. Depth distribution of the seismicity distribution suggests that the lineament is dipping towards east-southeast with the deepest seismicity in the Kopili lineament extends up to a depth of 50 km indicating the seismicity extends into the mantle. Frequency magnitude analysis reveals 'b' value of 0.71 for this region. A high value of P-wave average velocity of 6.71 km/s and low b value of 0.71 probably indicates the region is under high stress.

S1-P2

Seismicity of Gujarat state, Western India.

Santosh Kumar*, Sandeep Kumar Aggrawal and B.K. Rastogi,
Institute of Seismological Research, Gandhinagar- 382 009, India
*Corresponding author email: sundriyal007@gmail.com

Physiographically Gujarat state can be divided into three parts– Kachchh, Saurashtra and Mainland. Since 1970, seismicity in Gujarat was monitored with several analogue seismographs in the mainland and at Bhuj and this network has not missed any earthquake of M>3 in Gujarat in last four decades. In 1980s only one or two digital seismic station were operating in Gujarat. From mid 2006 a dense network has been installed by ISR which currently has 50 broadband seismographs and 48 accelerographs in Gujarat state. 36 stations are connected via VSAT to ISR data center which works round the clock. The detectibility is M2.0 in Kachchh active area and M2.5 in other areas.

The Kachchh region is considered seismically one of the most active intraplate regions of the World. It was known to have high hazard but low seismicity in view of the occurrence of several large earthquakes but fewer moderate or smaller shocks. After 2001 Bhuj earthquake of 7.7, seismicity defused for some time, but there was a spurt of increased activity for the two years in 2005 and 2006. During this period the activity spread around the aftershock zone and to nearby faults such as to the Wagad area towards East and Gedi fault to the NE. Subsequently it further spread to Allah Bund and Island Belt in the North. Seismicity has increased several fold in Kachchh after the Bhuj (23.44^0N 70.31^0E) earthquake of $M_w7.6$

The main shock and most of the aftershocks occurred along a south dipping (~45^{o}) hidden fault from 10 to 40 km depth.

In Saurashtra many districts showed the seismic activity prominently Jamnagar, Junagarh, Rajkot, Surendernagar, Bhavnagar and Porbandhar. Near Lalpur about 200 shocks were felt with blast like sound in 2006 and 2007. The maximum magnitude was 4.0 on September 30, 2006. Talala region in Junagarh district was rocked with 2 earthquakes of M 4.8 and M5.0 on 6th Nov. 2007 and in 2011 earthquake of M5.0 occurred in Talala, on 20th Oct. 2011. The main shock and most of the aftershocks occurred up to 10-15 km depth. In mainland Gujarat shock of M.4.4 occurred on 2nd September 2010 near Patan on Cambay rift and lies in east of Kachchh rift. There is no historical earthquake reported nearby the epicenter of current earthquake and this may be a sign of further spreading of Kachchh seismicity. A shock of M3.2 occurred near Mehsana on 30th March 2010 and other shock of M3.5 occurred on May 20th, 2008 in Surat. Some microshocks occurred west of Godhra and 50 km east of Gandhinagar also in period 2001-2010.

We have prepared a catalogue of Gujarat seismicity since 1668 to 2011 and the adjoining region bound by 20^{0}–25.5^{0} N and 68^{0}–75^{0} E with the help of all available earthquake catalogues (historical and recent) pertaining to the region. Historical earthquakes of this region before 1900 were taken from the catalogue prepared by Oldham (1883). The catalogues prepared by Tandon and Srivastava (1974), Chandra (1977) Srivastava and Ramachandran (1985), Ramachandran and Srivastava (1991), Srivastava and Rao (1997), and Malik et al. (1999) for this region has been also used. The sources of modern seismicity database are India Meteorological Department (IMD); Geological Survey of India (GSI); NEIC-USGS; International Seismological Centre (ISC); Gujarat Engineering Research Institute (GERI), National Geophysical Research Institute (NGRI) and Institute of Seismological Research (ISR). Aftershocks have been removed from the whole catalogue. Stochastic analysis of earthquakes of Gujarat region using Weibull, Gamma and Lognormal models indicated recurrence intervals of earthquake of $M \geq 5.0$ in Saurashtra, Mainland Gujarat and Kachchh as 40, 20 and 13 years, respectively (Yadav et al. 2008).

S2: Recent Intraplate Earthquakes: Source Parameters and Effects

The essence of seismology lies in the observation and interpretation of earthquakes in terms of seismicity, seismological characteristics, source parameters and the source processes. There is a continuing need to improve knowledge on the intra-plate as well as on the inter-plate seismicity. The information that are extracted from seismograms need to be reviewed and expanded so as to provide the best possible analysis and interpretation. Thus methods for seismological interpretation need to make an account of the Earth complexities, development of seismic modeling and intensive computation that has benefited greatly from advances in computer technology. Most earthquakes in continental areas require an understanding of the distribution of seismicity and faults beyond; how the structural and tectonic setting condition earthquakes of various kinds of geological, geophysical and seismological phenomena. This session discusses all aspects of the collection, analysis and interpretation of seismological data in intra-plate and inter-plate seismic environments.

Session Chairman: Rufus D. Catchings **Co-Chairman: Pradeep Talwani**

S2.1

Recent Intra-plate Earthquakes in India: Crustal Structures and Seismic Source Processes

J. R. Kayal (Email: jr.kayal@gmail.com)
CSIR Emeritus Scientist, Jadavpur University, 73/B, Thakurpur, Kolkata 700032, India

A review of crustal structures and tectonic processes of the recent intra-plate earthquakes that caused severe damages and large casualties during the last decades in peninsular India is presented here. Chronologically these events are the 1993 Killari earthquake (m_b 6.3, intensity VIII+) and the 1997 Jabalpur earthquake (m_b 6.0, intensity VIII) in the central part and the 2001 Bhuj earthquake (M_w 7.7, intensity X) in the western part of the peninsular shield area. Detailed *macroseismic* data as well as aftershock data recorded by temporary *microearthquake networks* were well studied, and these data are further analysed and re-examined in this study. The 1993 Killari event, a typical shallow (depth <10 km) shield earthquake, occurred by thrust faulting at intersecting faults. The 1997 Jabalpur and the 2001 Bhuj events, on the other hand, are identified as the deeper (25-35 km) *paleo-rift* events, and are caused by reverse faulting in the present inverse tectonic environments. The intensity characteristics, aftershock attenuation (p-value), fault plane solutions, 3-D crustal velocity structures by seismic tomography, b-value and fractal dimension characteristics of each earthquake source zone shed new light on our understanding of the tectonic processes of these strong/large intra-plate earthquakes. Seismic intensity of these Indian shield earthquakes attenuates in a similar manner to those in the Eastern United States. The

aftershock decay rates, on the other hand, are found to be slower compared to the inter-plate earthquakes in the Himalaya. The b-value and fractal dimension characteristics differ from shallow shield seismicity to deeper paleo-rift seismicity within the shield area. The seismic tomography well imaged 3-D crustal velocity structures, low velocity intersecting active fault zones and high velocity main shock source zones at the ‘fault ends’ at depths.

S2.2

A Comparison of Intraplate and Interplate Seismic Wave Propagation (Peak Ground Velocity)

R.D. Catchings (Email: catching@usgs.gov)

US Geological Survey, 345 Middlefield Rd., MS 977, Menlo Park, CA 94025.

The recent 23 August 2011 M 5.8 Virginia earthquake in the eastern United States (US) was reportedly felt from Florida (~900 km) to Canada (~1200 km) and as far west as Chicago (~900 km). This earthquake demonstrated that relatively moderate magnitude intraplate earthquakes in the eastern United States are generally felt over much greater distances than similar-magnitude interplate earthquakes in the western United States. For example, a typical M 5.8 to 6.0 earthquakes in California is seldom felt more than 400 km from its epicenter, whereas typical Central and Eastern US earthquakes are often felt to epicentral distances of 1000 to 1200 km (http://earthquake.usgs.gov/earthquakes/dyfi/archives). Because reported (Modified Mercalli Intensity - MMI) and instrumentally recorded shaking (Peak Ground Velocity - PGV) is strongly correlated (Atkinson and Kaka, 2007), such reports of distant shaking are a good indicator of regional variations in PGV.

Earlier studies suggested that PGV is higher for intraplate (Eastern US) earthquakes than for interplate (Western US) earthquakes, owing to greater stress drops, hypocentral depths, and Q in the intraplate settings. However, more recent studies indicate that there are not significant differences in stress drop and hypocentral depths, with stress drops about the same and hypocentral depths shallower in the Eastern US (Hanks and Johnson, 1992). Studies also show that it is difficult to differentiate between the effects of stress drop and attenuation on PGV using most strong ground motion data (Boore et al., 2010).

Most studies utilize a wide range of seismic data that are acquired with multiple types of seismographs and sensors and highly variable sources (earthquakes), all of which can significantly affect the measured PGV. In this study, we investigate differences in seismic P-wave propagation (peak ground velocity - PGV) in intraplate (central US) versus and interplate (California) settings by comparing data in each setting using a matched set of seismographs and matched (active) sources. For seismic sources, we utilized 3000-lb explosions in boreholes of essentially the same depth and diameter, and to record the data, we utilized a set of seismographs with 2-Hz vertical velocity sensors at a constant spacing of 1 and 2 km over distances of 150 to 200 km.

Our data show that PGV for the Central US and for California are similar within the first 100 km, but the peak velocities differ significantly beyond that range. In the first 150 km, differences in the PGV are largely related to crustal and Moho reflections, which persist to distances of ~150 km in the central US but only to about 100 km in California. Beyond 100 km, PGV is about 5 to 10 times greater in the central US than in the western US, with little decrease in PGV for distances up to 200 km.

Our present observations are limited to only one profile in each type of setting, however, these observations suggest that differences in attenuation and crustal structure are the primary factors accounting for the differences in PGV in intraplate (central US) and interplate (western US) settings. In general, intraplate settings have colder, less-fractured crust, which contributes to the lower attenuation (1/Q). Furthermore, the crust is generally thicker in intraplate settings (Mooney et al., 1998), resulting in crustal and Moho reflections that cause higher values of PGV at greater epicentral distances. These results are consistent with studies indicating that stress drop is not a major factor in the difference between PGV in intraplate and interplate settings.

S2.3

Tectonic Setting and Indian Shield Seismicity – Sources and Mechanisms

R K Chadha (Email:chadha@ngri.resin) and **D Srinagesh** (Email:srinagesh@ngri.res.in)

National Geophysical Research Institute, Hyderabad-500 007, India.

The first decade of the 21st century has witnessed an increase in the number of large earthquakes exceeding M 7.0, globally. In 2011 eighteen earthquakes have already occurred above this magnitude with twenty two occurring in the previous year. Whether, these earthquakes are related is a question which is being debated in the scientific community. The Mw 7.7 Bhuj earthquake in 2001 occurred in a Stable Continental Region (SCR) environment of the Indian Peninsular shield which experienced several moderate to small size earthquakes recorded by improved digital broadband seismological networks in the country. The epicentral map shows that earthquakes in the Indian shield occur in the interior rift systems (Narmada-Son and Godavari), rifted continental margins (Bhuj and the passive margins) and blind faults in the non-rifted parts (Latur, Coimbatore, Bellary). In addition, earthquakes also occur near water reservoirs and as swarms. Recent data suggest several new regions, which are becoming seismically active with smaller earthquakes. The earthquakes which occur in the rift systems generally have greater depths and show thrust mechanism while in non-rifted parts, the earthquakes are shallow with either thrust or strike slip mechanism. There are few exceptions to these observations and thus, in the light of new data sets and the *apriori* knowledge of tectonic systems in which earthquakes occur in the Indian shield, there is an urgent to understand the seismotectonics of the Indian shield through modeling approach. It is also essential to re-evaluate state of stresses in the region and provide upper bounds, if possible to make a realistic seismic hazard assessment.

S2.4

3D Static Numerical Modeling of Strike-Slip Fault for Studying Ground Surface Deformation

Ramancharla Pradeep Kumar (Email:ramancharla@iiit.ac.in)
Associate Professor & Head, Earthquake Engineering Research Centre, IIIT Hyderabad,
Gachibowli, Hyderabad-500 032, India.

This paper contributes to understanding the response of soil deposits due to underlying bedrock fault displacement in three dimensions. When an active bedrock fault ruptures, the movement along the fault propagates through the overlying soil and produces zones of intense shear. Hence, it is important to study the surface behavior based on the fault characteristics. For this reason, we attempted to develop a new application to Applied Element Method (AEM) by modeling the fault rupture zone. In this paper, we model the fault rupture problem in three dimensions. First, a simple model is used to illustrate the absorption of the bedrock deformation by the overlying soil in elastic case. The results are compared with the analytical and numerical models, wherever applicable. In the later part, the non-linear analysis is carried out to study the complex failure propagation in three dimensions. Influence of mechanical properties of the material is also discussed.

S2.5

Role of fluids in delayed triggering of aftershocks-an example of the 2001 Bhuj earthquake

Kalpna Gahalaut
National Geophysical Research Institute (CSIR), Hyderabad, India

Post seismic Coulomb failure stress modification because of poroelastic relaxation may qualitatively explain the spatiotemporal variation in the aftershocks of an earthquake. In fact, all aftershocks do not occur instantaneously following the main event and there is a time delay which depends upon the modification of Coulomb failure stress, magnitude and slip distribution on the rupture, nature of poorly understood diffusion process and also spatial distribution of the critically stressed fault zones in the surrounding region. Pore pressure gradients produced by the coseismic stress in the surrounding rock mass eventually dissipate as crustal fluids mobilize in the days, weeks and months after the main event. The decay of induced pore pressure is time dependent and obeys poroelastic diffusion laws.

The January 26, 2001 Bhuj earthquake (M_w=7.6) occurred in the Kachchh failed rift region, India. This earthquake was the largest intra-continental earthquake instrumented by modern seismic observation. We compute postseismic stress changes due to the poroelastic stress relaxation in the surrounding volume containing the main fault zone of the 2001 Bhuj earthquake. The temporal variation of the pore pressure, and hence the postseismic Coulomb stress, is exponential which is consistent with the exponential decay in the aftershock frequency. Also, rising fluid pressure due to pore-fluid and the resulting Coulomb stress change are found to be strongly correlated with the time and location of aftershocks. Thus we suggest that the delayed triggering of aftershocks was governed by the fluid diffusion in the region, at least in the first few months.

S2-P1

Study of Source Parameters and Focal mechanism solutions of earthquakes occurring in the Gujarat region, India

B.Sairam[1*], B. K. Rastogi[1] and P. Mandal[2]

1. Institute of Seismological Research, Raisan, Gandhinagar-382009, Gujarat, India
2. National Geophysical Research Institute, Uppal road, Habsiguda, Hyderabad-7, (A.P.), India,*Email: sairambharat@rediffmail.com

Seismicity in Kachchh seismic zone is continuing since the occurrence of the 2001 Bhuj mainshock (Mw 7.7). However, seismicity of the Gujarat state is not only confined to the Kachchh seismic zone (KSZ), but it has also spread over other parts of Gujarat. Interestingly, a series of earthquakes with magnitude up to 5.3 took place in the Saurashtra region during 2006-2011, which motivated us to carry out the present study on the estimation of source parameters and focal mechanisms of earthquakes occurring in different parts of Gujarat that would provide a much better understanding of seismic hazard associated with the Gujarat state. Besides, the intense aftershock activity in Kachchh for last eleven years enabled us to work on a reliable digital waveform data set to estimate the earthquake source parameters like seismic moment, source radius and stress drops. For estimating these source parameters, we use the spectral analysis of SH-wave from the transverse component of the 3-D broadband recordings of the earthquakes. The SH spectra were corrected for the near-surface attenuation parameter k and the path attenuation. The corrected spectra are used to compute the seismic moment (Mo), stress drop ($\Delta\sigma$), source radius (r) and corner frequency assuming a ω-square Brune's circular source model. The estimated seismic moment (Mo), stress drops ($\Delta\sigma$), source radii (r) and corner frequencies (fc) for 450 earthquakes (Mw1.3-4.8) in the Kachchh seismic zone range from 1.25×10^{11} to 1.99×10^{16} N-m, 0.06 to 16.61 MPa, 96.8 to 800 m, 1.6 to 13.0 Hz, respectively, while the Mo, $\Delta\sigma$, r, and fc estimates for 250 earthquakes (Mw1.8-5.0) in the Saurashtra region vary from 7.9×10^{11} to 4×10^{16} N-m, 4.8 to 10.1 MPa, 90 to 1400 m and 0.9 to 6.8 Hz, respectively. The near-surface attenuation factor (k) has also been estimated, which is varying from 0.025 to 0.03 for the stations in Kachchh while it is about 0.02 for stations in Saurashtra. Finally, the estimated source parameters are used to characterize the seismic sources and to design probable earthquake scaling for earthquakes occurring in the Kachchh and Saurashtra

regions. Next, the estimated source parameters are compared with those of other stable continental region earthquakes, which have occurred in India and other parts of the world. This comparison study reveals that stress drop and seismic moment estimates of the 2001 Bhuj mainshock are found to be higher in comparison to all other stable continental earthquakes in the world. Based on the high stress drop, an intensity XI close to the epicenter and severe damage up to 350 km away from epicenter, we infer that near source ground accelerations associated with the 2001 mainshock may have been strong. We also use the deviatoric moment tensor inversion modeling of broadband waveforms for estimating the focal mechanism solutions for 13 earthquakes, which have occurred in different seismically active zones of Gujarat viz, KSZ, Cambay faults, Narmada-Son lineament and Saurashtra. These focal mechanisms show two consistent features. One feature suggests that one of the nodal planes for most of events strikes in an east-west to northwest-southeast direction showing a reverse mechanism with a minor right-lateral strike-slip component. Another feature is that the orientation of P axes is on a nearly NNE–SSW direction with some scatter. We propose that the estimated compressive stress direction being in the direction of plate motion may cause a state of high compressive stress in the region.

S2-P2

Stress Inversion using Focal Mechanisms of Local Earthquakes in the Koyna-Warna Region, Western India

D. Shashidhar, **N. Purnachandra Rao** and **Harsh Gupta**
National Geophysical Research Institute (CSIR), Hyderabad <shashi.geo@gmail.com>

The Koyna-Warna region is a well known seismic zone in western India associated with the largest reservoir triggered earthquake of M 6.3 in 1967. Using comprehensive data set of focal mechanism solutions the stress field of the region is inferred using the inversion method of Michael (1984, 1987). The data set comprises focal mechanism solutions of 48 earthquakes of magnitude of the order of 4 and above that occurred during 1967 to December 2010, which includes 31 solutions from previous studies and 17 solutions derived from waveform inversion approach in the present study. In the recent times most of the seismic activity is confined to the Warna reservoir situated about 25 km SSE of the Koyna

Dam which has been monitored since 2005, using a network of 11 digital seismic stations. In general fault plane solutions indicate mostly normal type faulting while a few solutions indicate strike-slip faulting. It can be seen that the Warna region is subjected to an east-west extension with sub horizontal tensile stress axis (σ_3) and sub vertical compressive axis (σ_1) whose azimuth is in agreement with the tectonic scenario of the Indian plate collision with the Eurasian plate in the NNE direction. Further, a seismo tectonic model had been proposed based on the comprehensive focal mechanism data set that reveals alternate cycles of strike-slip and normal faulting followed by a period of seismic quiescence in the study region.

S2-P3

Seismic Site Condition Assessment Using Seismic Surveying Techniques

N. Thulasiraman* (Email:geothulasi@gmail.com) and **K.Rajendran**[1]
(Email:kusala@ceas.iisc.ernet.in)

[1]Centre for Earth Sciences, Indian Institute of Science, Bangalore, India.

The Rann of Kachchh, part of the Indian stable continental region (SCR), is a unique region in the world where two large earthquakes (1819 & 2001) have occurred within a short span of 200 years. Both of the events caused wide spread liquefaction and damages due to site amplification. The rupture of 1819 M7.5 event reached the ground and created a distinct scarp of ~ 90 km length and 3-5 m high, popularly known as the “Allah Bund”. The 2001 Mw 7.7 Bhuj event occurred on a blind fault and did not create any primary surface rupture. However, the secondary effects such as liquefaction and ground deformation were wide spread around the epicentral region and they are well documented. A noteworthy feature of both these earthquakes is the large distances up to which the liquefaction effects were observed. For example, the 1819 earthquake is reported to have produced liquefaction at Porbandar located about 250 km from its source. Similarly, the 2001 earthquake produced severe damage in the city of Ahmedabad, located about 200 km away from the source of the earthquake. Apart from other lessons learned from these earthquakes, the observation that multifold amplification of seismic energy even at far locations, based on the local site conditions has become an important consideration in seismic hazard assessment.

In India, regional level maps on site conditions are very scarcely available and they are seldom validated with actual field observations. Also, preparing such maps require huge investment, time and efforts in geological and geophysical data acquisition, processing and interpretation. In our study, we have used various field methods for assessing the local site conditions. We have selected sites within the mesoseismal area of the 2001 earthquake to map the shear wave velocity structure of the sites that were intensely liquefied. We also chose sites that were not affected, within the mesoseismal areas. By using Multichannel Analysis of Surface Waves (MASW), passive seismic surveying (Ambient seismic noise recording) and weak and strong motion earthquake data recorded by the permanent seismic stations, we attempt to compute the range of characteristic frequencies and their spatial variations.

Here, we present the preliminary results obtained from the MASW and ambient noise surveys carried out during March 2011. We had analyzed MASW data recorded at three distinct site conditions, one at an area of massive liquefaction, second near a hard rock exposure and third in a built-up area near Bhuj. Their shear wave velocity profiles correlates well with the variations in the expected lithology. Similarly, the processed H/V ratio curves at the liquefaction site (0.9 Hz) and the built-up area (7.04 Hz) show distinct peaks. We have also attempted to derive H/V spectral ratio curve from the Rayleigh wave part of strong motion data recorded at seismic stations on hard rock and alluvium in the Bhuj region. Though the curves did not show very significant difference in the peak frequency, multiple peaks were observed for the alluvium station’s H/V curve.Our preliminary interpretation shows a good correlation between MASW and H/V method in assessing the site condition. This needs to be experimented in all types of site conditions and validated with borehole data.

S2-P4

Investigations of M_w 5.1 Talala earthquake of October 20, 2011 and aftershocks in Junagadh District in south Saurashtra

B.K. Rastogi, Santosh Kumar, Kapil Mohan, Sandeep Aggrawal, Kishan Zala, Vandana Patel &
Nagabhushan Rao, Institute of Seismological Research, Gandhinagar 382009
Sumer Chopra, Ministry of Earth Sc, New Delhi

Sasangir area of Talala taluka of Junagadh district of Gujarat is experiencing tremors since 2001. The swarm type of earthquake activity in 2001, 2004 and every year from 2007 onwards has occurred after monsoons and lasted 2-3 months each time. In 2007 some 200 shocks and in 2011 over 300 shocks down to M1 are well recorded with 1-2 km location error. The focall depths are about 2-10 km and shocks are accompanied by blast-like subterranean sounds. An earthquake of magnitude M_w 5.1 (USGS m_b 5.0 and IMD M_L 5.0) occurred on 20 Oct 2011. The epicenter (21.09N 70.45E, focal depth 5km) has occurred about 12 km WNW of Talala or 8 km SSW of the 2007 M_w 5.0 mainshock epicenter. The epicentral trends deciphered with local networks indicate two // ENE trends (Narmada trend) for about 50km length and a conjugate 15km long NNW trend (Aravali trend). The focal mechanisms by moment-tensor analysis of full wave forms of two 2007 Mw4.8 and 5.0 and the 2011 M_w 5.1 tremors indicate rupture along either of the two trends. The ENE trends follow a gravity low between the gravity highs of Girnar mounts. Most of Saurashtra region, as also the Talala area is covered by Deccan Trap Basalt forming plateaus and conical ridges.

For the 20/10/2011 Talala earthquake, the MM intensity is estimated to be 6.5. Intensity areas of 6, 5 and 4 and felt distance give M_w 5.1 based on Johnston's empirical regressions. The source parameters from 14 stations are, Seismic Moment: 16.6 Newton-m, Stress Drop: 16 bars, Corner Frequency: 0.62 Hz, Source Radius: 2.3 km. The b and p values are obtained to be low, being 0.67 and 0.71, respectively. Decay rate has been estimated from strong motion recorded at 5 stations from 32 to 200 distance. PGA of 80cm/sec^2 is noted.

S2-P5

Source parameters and Scaling relations for the earthquakes in Jamnagar region of Gujarat.

Santosh Kumar#, Dinesh Kumar* and B.K. Rastogi#

Institute of Seismological Research, Gandhinagar, Gujarat,*Department of Geophysics, Kurukshetra University, Kurukshetra,Corresponding author: <sundriyal007@gmail.com>

The possible scaling and self-similarity of small and moderate earthquakes for the Jamnagar, Saurashtra region of Gujarat have been investigated in this study. For this purpose, the source parameters (magnitude, moment, fault dimension, stress drop, corner

frequency) of the twenty earthquakes recorded at 3-8 BBS stations with the magnitudes in the range 3.0 to 4.0 have been estimated using Brune's ω^{-2} model. Both p and s wave spectra has been used in this study. All the earthquakes had occurred in Jamnagar region. A two step search procedure for determining the optimum values of the parameters has been used. The corner frequency has been obtained using Andrews approach. The seismic moment estimated is between 1.56E+13 N-m to 1.04 E+15 N-m. The analysis of the source spectra obtained from the observed near field displacement spectra of these events suggests that there is self-similar scaling for small and moderate seismic sources of Saurashtra. A linear regression analysis between the estimated seismic moment (M_0) and corner frequency (fc) gives the scaling relation $M_0 fc^{3} = 2.09 \times 10^{36}$ N-m/sec^3. The proposed scaling law of seismic spectrum is found to be consistent with similar scaling relations obtained in other seismically active regions. The analysis gives a static Brune stress drop of about 10 bars for Saurashtra earthquakes. The corresponding dynamic stress drop can be 2-3 times the static stress drop. Therefore dynamic stress drop of ~ 30 bars can be expected in the region. The corner frequencies calculated are 2.5-8.0Hz. The source radius varies from 700m to 2900m. The relation developed in this study can be utilized in estimating source dimension given the moment of the earthquake. Such an investigation should prove useful in seismic hazard and risk related studies of the region.

S3: Long Term Behavior of Faults and Earthquake Hazards in Intraplate Continental Regions

Understanding the long-term behavior of faults is a very important aspect for constructing models of seismogenesis and assessing earthquake hazards in continental interiors. This session emphasizes recent advances in terms of deciphering and modeling of geological and geophysical records of fault behavior including their implication on seismogenesis and earthquake hazard assessment.

Session Chairman: Mian Liu **Co-Chairman: John Ebel**

S3.1

Migrating Earthquakes and Faults switching On and Off: A Complex System view of Intracontinental Earthquakes

Seth Stein[1] (Email:seth@earth.northwestern.edu), **Mian Liu**[2] (Email:lium@missouri.edu),
Eric Calais[3] (Email:ecalais@purdue.edu)

[1].Department of Earth and Planetary Sciences, 1850 Campus Drive, Northwestern University, Evanston, IL 60208, USA, [2].101 Geology Building, Dept. of Geological Sciences, University of Missouri, Columbia, MO 65211-1380, USA, [3].Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47906, USA.

Intracontinental seismic zones have traditionally been treated like slowly deforming (< 2 mm/yr) plate boundaries. In that model, one expects steady deformation focused in narrow zones, such that the past rates and locations shown by geology and the earthquake record would be consistent with present and future deformation and seismicity. However, data from China, North America, NW Europe, and Australia reveal a different picture: earthquakes migrate between faults, which remain inactive for long periods and then have pulses of activity. A 2000-year record from North China shows that large (M>7) earthquakes migrated, with none repeating on the same fault segment. In addition, GPS studies in the New Madrid and other intracontinental seismic zones still fail to detect significant strain accumulation, also in contrast with a slow plate boundary-type model.

This time- and space-variable behavior arises because in mid-continents tectonic loading is slow and stress in the crust is strongly influenced by mechanical interaction among a network of widespread faults. Slow loading also causes aftershock sequences to continue for hundreds of years, much longer than at plate boundaries. As a result, the past earthquake history can be a poor predictor of the future. Conventional seismic hazard assessment, which assumes steady behavior over 500-2500 years, can overestimate risks in regions of recent large earthquakes and underestimate them elsewhere. For example, the May 2008 Sichuan earthquake occurred on a fault system that was considered to be at low level of hazard, due to the lack of recent seismicity and low slip rates.

In contrast to a plate boundary fault that gives quasi-periodic earthquakes, the interacting fault networks in midcontinents predict complex variability of earthquakes. Approaching intracontinental seismic zones as a complex system is necessary to improve our understanding of midcontinental tectonics, the resulting earthquakes, and the hazards they pose.

S3.2

How do Intraplate Earthquakes differ from Interplate Earthquakes?

Mian Liu (Email:lium@missouri.edu)

Dept. of Geological Sciences, University of Missouri, Columbia, MO 65211-1380, USA.

The spatiotemporal patterns of intraplate earthquakes are more irregular than those of interplate earthquakes. The latter are concentrated along plate boundary faults, which are loaded by the steady relative motion of tectonic plates and rapture quasi-periodically. In contrast, the loading mechanisms for intraplate faults are complex and the loading rates may be unsteady, leading to complex spatiotemporal patterns of intraplate earthquakes. In diffuse plate boundary zones, such as the western United States and the Tibetan Plateau, the relative plate motion is partitioned among faults in the plate boundary zone, and the seismicity on one fault may affect the loading rates and hence seismicity on the other faults. In the plate interior, such as central-eastern US and North China, tectonic loading is accommodated collectively by complex systems of interacting faults that are distributed over large regions, each of the fault can be active for a short period after long dormancy. Because the tectonic loading is slow in stable plate interior, secondary and transient loading mechanisms, including loading related to glacial isostatic adjustment and erosion-depositional processes may play an important role in triggering large earthquakes. The slow loading rates in plate interior also lead to abnormally long durations for aftershock sequences. For the same reason, stress transferred from a large intraplate earthquake to the surrounding regions can become the dominate cause of seismicity in those regions for centuries. We have been exploring the mechanics of loading and fault interaction in diffuse plate boundary zones and plate interiors. I will use examples from China, US, and western India to illustrate how various fault interactions may have contributed to the observed spatiotemporal patterns of large earthquakes in these regions.

S3.3

Intraplate Earthquakes as Aftershocks

John E. Ebel (Email:ebel@bc.edu)

Weston Observatory, Department of Earth and Environmental Sciences, Boston College, Devlin Hall 213,140 commonwealth Avenue, Chestnut Hill, Massachusetts 02467,USA.

It has been suggested that in intraplate regions aftershocks of strong earthquakes can be observed for many hundreds of years or even longer. This may be because regional stresses build up very slowly within the tectonic plates, and thus relatively little of the intraplate seismicity reflects regional stress accumulation. Thus, for intraplate regions spatial clusters of locally enhanced small earthquake activity may indicate locations where past strong earthquakes have taken place. In eastern North America (ENA), there are many localized clusters of small earthquakes that may indicate where strong earthquakes have occurred, most notably in the New Madrid and Charlevoix seismic zones. A number of M≥4 earthquakes have taken place near the edges of many of ENA clusters, and these moderate earthquakes may reflect the ends of faults that ruptured in the strong earthquakes that give rise to the aftershock clusters. Thus, localized clusters of locally enhanced earthquake activity in intraplate regions may give clues about where to look for seismically active structures. In ENA there are a number of such localized clusters that may reflect the locations of strong earthquakes (M 7 or greater) that have taken place during the past 1000-2000 years. An example of such a localized cluster is in central New Hampshire, where an earthquake of about M 6.5 is suspected to have taken place in 1638. A few scattered historical reports from Massachusetts and Quebec document this earthquake, but its location and size are impossible to determine from the historical accounts alone.

S3.4

On Epidemic Type Aftershock Sequence (ETAS) Modeling for Finding Anomalous Behaviour of Seismicity

A. R. Bansal and V. P. Dimri (Email:dimrivp@yahoo.com)

National Geophysical Research Institute (CSIR), Uppal Road, Hyderabad – 500 007, India

The epidemic type aftershock sequence Model (ETAS) model is based on point process representation of the seismicity. In the ETAS model background rate and aftershocks are assumed to follow stationary and non-stationary Poisson process, respectively. The aftershocks are governed by modified Omori laws and each aftershock can trigger their own aftershocks. The model is found suitable to define anomalous behaviour of the seismicity in many parts of the world before the large earthquakes in term of activation and quiescence. We apply this model to the seismicity of North – Eastern Himalaya and Sumatran seismicity. A stationary ETAS model is found suitable for the North-Eastern Himalayan seismicity whereas Sumatran seismicity before the mega event of 2004 follows a non-stationary ETAS model. The activation in Sumatran seismicity started around 4.3 years before the mega event of 2004. During this period seismicity changes from sub-critical to the critical stage.

S4: Paleoseismology and Archaeoseismology

The use of paleoseismic studies for the seismic hazard in regions of low-to-moderate seismicity has increasingly become formalized. The focus of this session is on the new developments and applications of Paleoseismology and Paleoliquefaction studies for assessing seismic hazard. This session also discusses Archaeoseismology.

Session Chairman: Javed Malik **Co-Chairman: Kusala Rajendran**

S4.1

Diversity of earthquake sources in Kachchh and Saurashtra, NW India

C.P.Rajendran and Kusala Rajendran, Indian Institute of Science, Bangalore
cprajendran@gmail.com

The fascination about the Kachchh province in the northwest India is just not about its unique landscape, its dynamic environment and its rich archive of geology. It also represents a unique tectonic domain variously interpreted as a diffuse plate boundary and also as a part of a stable continental region. Proximity to the active Himalaya plate boundary and the faults associated with Mesozoic rift, make this region seismically more productive, compared to other mid-continental rift systems. The Mw ≤7.5, 1819 earthquake in the northern boundary of the Kachchh rift is perhaps the best-known example of large earthquakes on the boundary fault of any continental rift systems. The lower crustal source of the 2001 Bhuj earthquake and its aftershocks on the other hand, reflect the role of mafic bodies in localizing the stress and leading to occasional large earthquakes within the rift.

The variations in the structural settings have perhaps given rise to disparate seismic sources, in terms of their temporal and spatial characteristics as well as the style of deformation. For example, the 1819 earthquake generated a 60-90 km-long scarp called the Allah Bund, considered a classic example of surface expression of a mid-continental earthquake. The 1819 source has generated a previous earthquake, which corroborates with a historically documented earthquake in AD 893. This event is reported to have affected a major port at Debal at the mouth of Indus River. The 2001 Bhuj earthquake on the other hand occurred on a blind fault within the rift and the surface deformation features were mostly from secondary effects. Both these earthquakes produced intense liquefaction, which have served as pointers to past earthquakes. The paleoseismic information on the 2001 Bhuj earthquake is mostly derived from previous offsets recorded on a secondary faulting. The paleoseismic data suggests repeated activity at this source and the last event may have occurred 4000 years ago. The repeat period in the Bhuj source is apparently longer compared to the 1819 source (about 1000 years).

In addition, we have extended our studies to Saurashtra and the Cambay regions. It is likely that there are other earthquake sources in these areas, but the spatial association of earthquake induced liquefaction with the respective causative source remains to be constrained. For example, the sandblow excavated at Bet Dwarka Island is 2000 years old and may be associated with an independent source in the vicinity. Existence of multiple sources with varying inter-event intervals and distinctive deformational styles may be attributed to the diversity of seismogenic structures in this region.

S4.2

Active fault and paleoseismic evidence: Implication towards seismic hazard in Kachchh region, western Gujarat

Javed N. Malik[1] , Michio Morino[2], Mahendra S. Gadhavi[3,4], Khalid Ansari[1], Chiranjeeb Banerjee[1], B. K. Rastogi[3], Fumio Kaneko[2], F. Bhattacharjee[3], A. K. Singhvi[5]

[1]Department of Civil Engineering, IIT Kanpur. Kanpur 208016. UP. India. Email: javed@iitk.ac.in, [2]OYO International Corporation Yushima 1-Chome Bldg. 4F, 1-6-3 Yushima, Bunkyo-ku, Tokyo 113-0034, Japan. [3]Institute of Seismological Research, Gandhinagar 382018, Gujarat, India, [4]Now at L. D. College of Engineering, Ahmedabad, [5]Physical Research Laboratory, Ahmedabad

The state of Gujarat has two fold hazard posed by earthquakes, one on-land along the active faults in Kachchh region and its neighbourhood, and another offshore along the Makran Subduction Zone (MSZ) located in the west (Figure 1). The entire coastline is highly vulnerable from the tsunami triggered by an earthquake occurring along the MSZ. Two such tsunami events have been recorded during historic and recent times by earthquakes along MSZ, i.e., during 325 BC and 1945 AD. Apart from this the Kachchh region which falls under seismic zone V outside the Himalaya has been struck by several large to moderate magnitude earthquakes during last 300 years, viz. 893 AD, 1668 Indus Delta (M7); 1819 Allah Bund (M7.8), 1956 Anjar earthquake (Ms6.1), and the recent 2001 Bhuj earthquake (Mw7.6) (Malik et al., 1999a; Bilham, 1999). From these events, only 1819 Allah Bund earthquake has been reported to have accompanied with 80-90 km long surface rupture and uplift resulting into formation of about 4-6 m high scarp (Quittmeyer and Jacob, 1979; Johnstan and

Kanter, 1990). The recent 2001 Bhuj earthqukae with magnitude Mw7.6, the rupture remained concealed below the ground at a depth of 7-10 km, suggestive of occurrence on blind fault (Mandal and Horton, 2007). It is a matter of concern that if movements on a blind fault are capable of producing large magnitude earthquakes, than having earthquakes of similar magnitude or larger on active faults with surface rupture cannot be ruled out (Malik et al., 2008; Morino et al., 2008). Active faults are considered to be the source for large magnitude earthquakes in seismically active regions. Their proper identification and distribution significantly help in knowing the seismic potential and associated hazard in the region. The landscape of Kachchh is marked by several E-W striking longitudinal faults viz. the Allah Bund Fault (ABF), Island Belt Fault (IBF), South Wagdh Fault (SWF), Kachchh Mainland Fault (KMF), and Katrol Hill Fault (KHF). Under the project sponsored by Gujarat State Disaster Management Authority (GSDMA) on Seismic Microzonation of Gandhidham, Kachchh, we carried out active fault mapping and paleoseismic investigations along ABF, KMF and KHF. In this paper we highlight in brief our findings based on detailed satellite data interpretation for identification of active faults and related geomorphic features as well as paleo-earthquake signatures preserved in sediment succession (Figures 1 & 2).

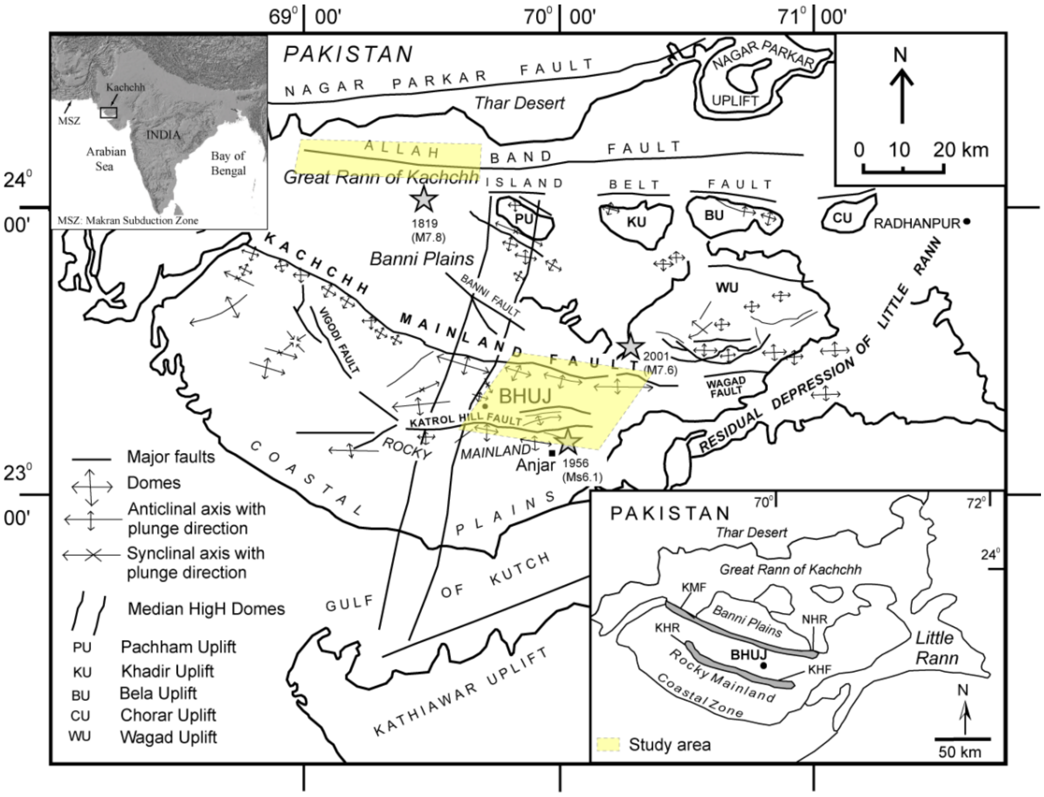

Figure 1. Generalized structural map of Kachchh region (after Biswas and Deshpande, 1970). Inset at the left top show DEM of India highlight the location of Kachchh peninsula and Makran Subduction Zone (MSZ). Inset at the lower right shows major geomorphic zones of Kachchh. Yellow box marks the study area along Kachchh Mainland Fault and Katrol Hill Fault, and along Allah Bund Fault. NHR- Northern Hill Range, KHR- Katrol Hill Range, KMF- Kachchh Mainland Fault and KHF- Katrol Hill Fault.

Active fault and paleoseismic investigations:

Katrol Hill Fault:

Several new active fault traces were identified along Katrol Hill Fault (KHF) (Figure 2). A new fault (named as Bhuj Fault, BF) that extends into the Bhuj Plain was also identified. These fault traces were identified based on satellite photo interpretation and field survey. Trenches were excavated to identify the paleoseismic events, pattern of faulting and the nature of deformation. New active fault traces were recognized about 1km north of the topographic boundary between the Katrol Hill and the plain area. The fault exposure along the left bank of Khari River with 10m wide shear zone in the Mesozoic rocks and showing displacement of the overlying Quaternary deposits is indicative of continued tectonic activity along the ancient fault. The E-W trending active fault traces along the KHF in the western part changes to NE-SW or ENE-WSW near Wandhay village. Trenching survey across a low scarp near Wandhay village reveals three major fault strands F1, F2, and F3 (Figures 3a & b). These fault strands displaced the older terrace deposits comprising Sand, Silt and Gravel units along with overlying younger deposits from units 1 to 5 made of gravel, sand and silt. Stratigraphic relationship indicates at least three large magnitude earthquakes along KHF during Late Holocene or recent historic past.