Proc Indian Natn Sci Acad **82** No. 3 July Spl Issue 2016 pp. 695-704

DOI: 10.16943/ptinsa/2016/48478

Review Article

Paleoseismology: 2010-2016

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(Received on 03 May 2016; Accepted on 01 June 2016)

We present here an overview of progress in paleoseismological/active fault researches in India during 2010-2016. These studies initiated in the country in early nineties have now expanded in scope and gained further momentum. Moving into a greater variety of morphological settings, several groups of researchers are now involved in defining the fault geometry and the nature of near-surface crustal deformation in various tectonic regimes with a view to constrain the frequency and magnitude of fault activations, thereby contributing to earthquake hazard evaluations. Future challenges would include integrating paleoseismological observations with relevant geophysical inputs and developing physical models of the complete earthquake cycle, ultimately leading to an inventory of active faults.

Keywords: Paleoseismology; Active Faults; Earthquakes; Seismites

Introduction

The Indian subcontinent is an amalgamation of diverse tectonic components that range from the Archaean to the Recent. The tectonic boundary in the north is defined by collision between India and Eurasia plates, which resulted in the great Himalayan mountain chain. The eastern part of India's tectonic boundary converges with Burmese plate resulting in the Andaman-Burmese Arc. The active plate interfaces surrounding the Indian subcontinent have led to domains of high stress concentrations and a number of seismogenic faults within as well as along its boundaries. Having generated several major earthquakes during the last 100 years or more and the most recent one on April 15, 2015 in Nepal (Mw 7.8), the Himalaya in the north continues to be a locus of high seismic hazard. The same concern applies to the eastern plate boundary- a source of tsunamigenic earthquakes as exemplified by the 2004 event. The Indian subcontinent has some of the complex active fault settings within its continental interiors, as well. The earthquake activities associated with the Narmada and Kachchh paleo-rifts are classic examples of reactivation of ancient continental rift systems in the present compressive stress regime. The devastating 1993 Killari (within the state of Maharashtra) earthquake, on the other hand, is a typical example of intracratonic earthquake in a slow deforming non-rifted crust. Thus, the Indian subcontinent presents a variety of tectonic settings with varying types of active faults.

A major question is how to characterize these seismogenic structures and understand their behavior in space and time. Further, developing longer-term time series of such events is an important task towards generating recurrence models of active faults. The repeat periods of major earthquakes on most active faults go back beyond the documented history. Reliable historical data on earthquakes are woefully limited to a few hundreds of years and often miss out on the infrequent extreme mega events, which have a repeat period of ~1000s of years.For example, the available historical data is deficient on the previous occurrence of an extreme event like the 2004 tsunami. Subsequent studies on the geological records embedded in the coastal stratigraphy, however, told a different story. It is revealed later in geological studies that such mega tsunami events do occur with an interval of hundreds of thousands of years. Another striking example of underestimating the potential danger is the devastating 1993 (Mw 6.3) Killari (Latur) earthquake that occurred in the Deccan Plateau region in Maharashtra that was

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considered to be least vulnerable to earthquakes. The subsequent geological studies in Latur fault zone suggested past occurrences of similar earthquakes, but with a very long recurrence period (Rajendran *et al*., 1996).

Both the applied and fundamental aspects of Quaternary sciences, geophysics and seismology are used to conduct paleoseismological researches on active faults (McCalpin, 1996). The geological research of active faults is focused on the stratigraphic offsets of marker beds across the faults and their structural interpretations. Aside from these primary fault-specific observations, secondary proxy earthquake indicators like liquefactions and landslides are also being studied. As the ongoing vertical and horizontal movements on active fault systems over hundreds of thousands or millions of years will find expressions on geomorphology, landscape expressions will supplement the primary paleoseismological observations. The essence of active fault studies may be summarized as mapping of active faults and quantifying their nature of activity towards understanding the past and future seismic activity of a region. Active fault researches in India, mainly initiated in early nineties, were focused initially towards identifying various types of seismites preserved in the sedimentary strata and using them in conjunction with age data to constrain recurrence of causative earthquakes. Attempts have also been made to understand the geometry of the causative structures and the nature of near-surface crustal deformation using near-fault geomorphology and trenching investigations.

The Beginnings of a New Research Area

The decade of 1990 was of particular significance for earthquake studies in India, because of the 1993 M 6.3, Killari (Latur) earthquake that occurred in the heartland of India, marked as zone I of the then existing Indian Seismic Zonation map. Interestingly, this earthquake generated a surface rupture, somewhat comparable to the mid-continental earthquakes of Marryat Creek and Tennant Creek in the Australian hinterlands. Recognition that earthquakes can occur in such unsuspecting regions propelled the expansion of seismic network in the peninsular India and research programs in active tectonics and paleoseismology. The nineties also witnessed two moderate, but damaging earthquakes in the Central Himalaya (1991 Uttarkashi and 1999 Chamoli), and in 1997 near Jabalpur in the Narmada rift, central India. In fact, the quick succession of these earthquakes also spurred earthquake monitoring and research activities in the country. The 2001 Bhuj earthquake that killed several thousands of people was also an unusual intraplate earthquake that drew global attention. The 2001 Bhuj earthquake, although not associated with a primary surface rupture, generated a large liquefaction field and several secondary surface features including a secondary fault (Rajendran *et al*., 2008). A newly generated enthusiasm drove several teams of individual Indian and non-Indian researchers to engage in exploration of the Killari and Bhuj seismic zones as well as the other potential hazardous fault zones of the Himalaya. The 2004 Andaman-Sumatra earthquake and the 2005 Kashmir earthquake are the other significant events of the previous decade, which gave further momentum to the active faulting research and paleoseismology. Since 1960s, the Geological Survey of India (GSI) has been attempting to collect evidence of neotectonic activity throughout the country mainly coincided with engineering geology investigations. In 2000, the GSI brought out the “Seismotectonic Atlas of India and its Environs”, which contains the plot of more than 400 regional faults and of which sixty seven faults have been classified as “neotectonic”. Within the last decades, from small beginnings, the Indian research in paleoseismology and active tectonics has expanded to include the tectonically interesting areas of Kachchh, Saurashtra, Cambay basin in the northwest, lower Brahmaputra Valley and parts of Bihar and the different segments of the Himalaya and Andaman-Nicobar Islands. Many institutes and university departments in India are currently involved in paleoseismological and active tectonic researches.

Research Activities During 2010-2016

The Himalayan Zone

During 2010 to 2016 a major thrust area of paleoseismological studies has been the Himalaya and various research groups were involved from Kashmir to Arunachal in deciphering the structures that are capable of generating major earthquakes. For example, Ahmad and Bhat (2012) analyze various geomorphic indices for the Rambiara drainage basin, SW of the Kashmir Valley, and qualify the area as tectonically active. Field and geomorphic data also reveal three NE-dipping active reverse faults, and one of which named as Balapur fault, is traced over at least 40 km along the southwest side of the Kashmir Valley. In a later paper, Ahmad *et al*. (2015) defined the Balapur fault in a more detailed manner, which is a high angle thrust fault (reverse), dipping ~60° NE, with a length of ~40km striking NW–SE of the Kashmir basin. In an overview, Shah (2013) stresses the seismogenic potential of such out of sequence thrusts within the Kashmir Valley. Bhat *et al*. (2016) identified earthquake-triggered and sand blows within the Karewa Formation indicating that the Kashmir Valley had been impacted by damaging earthquakes in the past. Thakur *et al*. (2010), however, underscores the earthquake potential of the structure called "Main Boundary Fault" (designated by Medlicott and Wadia). Located south of Main Boundary Thrust (MBT) in the northwest India, this structure variously called as Riasi thrust (around Jammu), Palampur thrust (around Kangra) and Bilaspur thrust (around Simla) is considered to be an active fault.

In the northwest Himalaya, Malik *et al*. (2015) identified an active right lateral strike-slip fault named Kangra Valley fault and they suggest that the surface rupture of the 1905 was manifest on this structure, which is indicative of oblique convergence and slip partitioning between the Main Boundary thrust in the north, the Jawalamukhi thrust in the south, Paleoseismic investigations revealed four previous events. This study underscores the importance of looking at the potentiality of hinterland structures in hosting major earthquakes.On the south towards the foothills, in an earlier study, Malik *et al*. (2010) reported paleoseismic evidence on the southern flank of the anticlinal ridge called the Janauri anticline that marks an abrupt physiographic break with the Punjab Plains representing the trace of the HFT and consider that this fault on HFT is more active than the hinterland faults. Surface rupture dating back to AD 1400-1460 has been identified on the western margin of Janauri anticline (Kumahara and Jayangondaperumal, 2013). In a more recent study on the northern part of the Jawalamukhi thrust, Jayangondaperumal *et al*. (2016) identifies a backthrust growing in tandem with the forethrust in the region that was activated during AD 1344 earthquake, adding further refinement to the timing of the last earthquake in that region.

Further east in Arunachal, the Himalayan Frontal thrust(HFT) trace occurs at the interface of the Himalayan mountain front and the Brahmaputra alluvial plain. Kumar *et al*. (2010) identify three levels of fluvial terraces along Jia Bharoli River at a location called Harmuty (Kumar *et al*. 2010).This feature is attributed to the displacement along the north dipping HFT. The Harmuty site is located close to the Mw 8.6 1950 Assam earthquake rapture. Further, Jayangondaperumal *et al*. (2011a, b) identify another site on the eastern side of Harmuty toward Passighat where the Himalayan front shows active tectonic activity. They report two levels of terrace surfaces between the Remi and Marbang Korong Creek Rivers that exhibits an 8-m-high scarp and a terrace surface as high as 60 m rising from the streambed within the meizoseismal area of the 1950 Upper Assam earthquake. The terrace surfaces have been attributed to the movement on the HFT. These surface ruptures reported from this locality are interpreted as the expressions of the earthquake ruptures propagating from the hinterland to the Sub-Himalayan front. Devender Kumar *et al*. (2016) report the earthquake-related liquefaction features around the Kopili Fault Zone of the Brahmaputra Plains (NE India). The age constraints suggest three time intervals of paleoliquefactions: 250±25 yr. BP, 400-770 yr. BP and 900±50 yr. BP. According to another work, seismically generated liquefactions identified in the 1950 source region are generally younger than AD 1400, predecessor of the 1897 Shillong earthquake is ~1000 years old (Rajendran and Rajendran, 2011).

It is becoming increasingly clear from GPS-based geodetic measurements that some parts of the Himalayan front are locked and those parts are vulnerable for future major earthquakes. The interseismic strain in the upper crust is released through periodic slips on the Main Himalayan Thrust (MHT) and is released as great earthquakes. From this perspective the central Himalaya appears to be a major seismic gap and questions have been raised on its status as a segment that can generate great earthquakes. Over the last decade several teams have worked on the Indian and Nepal parts of the central Himalaya to gain insights into its earthquake generation capabilities. Historical data from the central Himalaya suggest damaging earthquakes in AD 1255, 1344, 1408, 1505, 1803, and 1833, although their sources and magnitudes remain debated (Rajendran *et al*., 2015) present new evidence for a great earthquake from a trench across the base of a 13-m high scarp near Ramnagar at the Himalayan Frontal Thrust. Age data suggest that the last great earthquake in the central Himalaya most likely occurred between AD 1259 and 1433. Stratigraphic clues also imply an earlier event, which can most tentatively be placed between AD 1050 and 1250. In an independent study comprising geometric and kinematic analyses of the Ramnagar scarp also suggests that the it is a product of more than one earthquake (Jayangondaperumal *et al*., 2013). If the two-earthquake scenario is realistic, then the successive ruptures may have occurred in close intervals and were sourced on adjacent segments that overlapped at the trench site. Rupture(s) identified in the trench closely correlate with two damaging earthquakes of 1255 and 1344 or 1408 reported from Nepal. The present study suggests that the frontal thrust in central Himalaya may have remained seismically inactive during the last ~700 years. Observations presented in an earlier paper by Rajendran and Rajendran (2011) suggest that the last major earthquake in the Central Himalaya occurred during AD 1119-1292.

Because the central part of the Himalaya (Kumaun and Garhwal Provinces of India) is noted for its prolonged seismic quiescence, and therefore, developing a longer-term time series of past earthquakes to understand their recurrence pattern in this segment assumes importance. In addition to direct observations of offsets in stratigraphic exposures or other proxies like paleoliquefaction, deformation preserved within stalagmites (speleothems) in karst system can be analyzed to obtain continuous millennial scale time series of earthquakes. The Central Indian Himalaya features natural caves between major active thrusts forming potential storehouses for paleoseismological records. Rajendran et al. (2016a) focuses on the stalagmites from the caveslocated in the eastern Kumaun Himalaya. The growth anomalies instalagmites include abrupt tilting or rotation of growth axes, growth termination, and breakage followed by regrowth. The U-Th age data from three specimens bracket the intervals of growth anomalies at 4273±410 years BP (2673- 1853 BC), 2782±79 years BP (851-693 BC), 2498±117 years BP (605-371 BC), 1503±245 years BP (262- 752 AD), 1346±101 years BP (563-765 AD), and 687±147 years BP (1176-1470 AD). The dates may correspond to the timings of major/great earthquakes in the region and the youngest event (1176-1470 AD) shows chronological correspondence with either one of the great medieval earthquakes (1050-1250 and 1259-1433 AD) evident from trench excavations across the Himalayan Frontal Thrust. The great 1934 Himalayan earthquake of moment magnitude (Mw) 8.1 generated a large zone of ground failure and liquefaction in north Bihar, India, in addition to the earthquakes of 1833 (Mw ~7.7) and 1988 (Mw 6.7) that have also impacted this region. The paleoliquefaction features from the plains of north Bihar and eastern Uttar Pradesh were dated at AD 829-971, 886-1090, 907-1181, 1130-1376, 1112-1572, 1492-1672, 1733-1839 and 1814-1854 (Rajendran *et al*., 2016b). One of the liquefaction events dated at AD 829-971, 886-1090 and 907-1181 may correlate with the great earthquake of AD ~1100, recognized in an earlier study from the sections across the frontal thrust in central eastern Nepal. The available data suggest temporally close spaced earthquakes of both strong and large types have affected the Bihar Plains during the last 1500 years with a combined recurrence interval of 124 ± 63 years.

Andaman Subduction Zone and Eastern/Western Seaboards

Geological evidence along the northern part of the 2004 Aceh-Andaman rupture indicates. five tsunamis in the region in the last 2000 years (Rajendran *et al*., 2013). The evidence comes from geologic records of land-level changes and the tsunami deposits from the Andaman and Nicobar (A&N) Islands. These proxy tectonic indicators include subsided mangrove swamps, uplifted coral terraces, liquefaction, and organic soils coated by sand and coral rubble. The earliest tsunamis occurred between the second and sixth centuries AD, evidenced by coral debris from the southern Car Nicobar Island. A subsequent tsunami, probably in the range AD 770-1040, is inferred from deposits both in A&N and on the Indian subcontinent. It is the strongest candidate for a 2004-caliber earthquake in the past 2000 years. The tsunami deposits from AD 1250 to 1450 probably match the dates previously reported from Sumatra and Thailand. Unlike the transoceanic tsunamis generated by full or partial rupture of the subduction interface, the

Andaman-Nicobar geology further provides indications for the smaller-sized historical tsunamis of 1762 and 1881.

The studies conducted in south Andaman by Malik *et al*. (2015) suggest three historical earthquakes and associated transoceanic tsunamis during past 1000 years, in addition to the Mw 9.3 tsunamigenic earthquake of 26 December 2004. Event I predated AD 800 and Event II dated around AD 660-800; this event attributed to a near source rupture along Andaman-Arakan segment, The Event III, occurred around AD 1120-1300, and is marked by a 50-cm-thick sand deposit. The 2004 tsunami resulted in the deposition of a 15-cm thick medium to coarse sand at the same location. Four events reported from here along with the record of a subsidence event of AD 1679 from the east coast of Andaman, near Port Blair (Malik *et al*., 2011), suggest that mega-subduction zone earthquakes and associated tsunamis recur at an interval of 300-500 years at variable locations along the Sumatra-Andaman subduction zone. Coastal stratigraphy near Port Blair, Andaman Islands, where the AD 2004 Sumatra-Andaman earthquake was accompanied by ~1 m of subsidence, provided evidence for two previous earthquakes, perhaps both from the past 400 yr and the earlier one is ascribed to AD 1762 Arakan earthquake (Malik *et al*., 2011).

To validate the paleotsunami time series from the Andaman-Nicobar Island or from the Myanmar Coast, it is important to analyze the geological record of tsunamis on the east coast of India as the impact of such tsunamis is expected to be high here. Literature of the ancient Chola Dynasty (AD 9th-11th centuries) of South India as well as the archaeological excavations allude to a sea flood that crippled the ancient port at Kaveripattinam, a trading hub for Southeast Asia, and probably affected the entire South Indian coast, analogous to the 2004 Indian Ocean tsunami. Rajendran *et al*. (2011) presented sedimentary evidence from Kaveripatinam, a seaport on the southeastern coast of India during the Chola period validating the textual references to this early medieval tsunami event.

A major tsunami threat for the west coast of India occurs on the Makran Coast of north Arabian Sea. Therefore it is crucial to evaluate the hazard potential of the Makran subduction zone. This problem can be addressed by searching for earthquake and tectonic proxies along the Makran Coast and linking those observations with the available constraints on historical seismicity and the tell-tale characteristics of sea floor morphology. The earthquake of Mw 8.1 of 1945 and the consequent tsunami that originated on the eastern part of the Makran are the only historically known hazardous events in this region. Rajendran *et al*. (2011) investigated the near-shore shallow stratigraphy of the central part of Makran near Chabahar on the Iranian Coast that showed evidence of seismically induced liquefaction, attributed to the distant effects of the 1945 earthquake. The coastal sites further westward around Jask are remarkable for the absence of liquefaction features, at least at the shallow level. This possibly implies that western segment of the Makran Coast region may not have been impacted by near-field large earthquakes in the recent past—a fact also supported by the analysis of historical data. On the other hand, the elevated marine terraces on the western Makran and their uplift rates are indicative of comparable degree of long-term tectonic activity. The various lines of evidence thus suggest that although the western segment is potentially seismogenic, large earthquakes have not occurred there in the recent past, at least during the last 600 years. The recurrence period of earthquakes may range up to 1,000 years or more, an assessment based on the age of the youngest dated coastal ridge. The long elapsed time points to the fact that the western segment may have accumulated sufficient slip to produce a major earthquake.

The global examples suggest that imbricate boulders seen on the coast can also be used as proxies of paleotsunamis. In a study by Prizomwala *et al*. (2015), the dimensions, morphology and other characteristics of the boulders on the coastal segment of Diu Island on west coast of India were used to understand the wave types that could have carried them to their present position. Although cyclonic storms could have been the carrying agents, the authors conclude that a 3.5-high tsunami wave is responsible for mobilizing these boulders to their final position. The triggering mechanism for the tsunami, according to them, must have been a mega-submarine landslide along the Southern Owen Ridge.

Mid-Continental Areas

The paleoseismological studies initiated after the 2001 Bhuj earthquake (Gujarat, northwest India) the research have continued into 2011 and succeeding years. Thakkar *et al.* (2012) studied the liquefaction attributes and crater geometry related to the 2001 Bhuj earthquake. The study characterizes the liquefied sediments during the 2001 earthquake in a large reactivated crater and distinguishes them from a non-reactivated crater located nearby. Thakkar *et al.* (2012) investigated the morphology and drainage around the Allah Bund, a scarp believed to have formed during the 1819 earthquake in western Great Rann of Kachchh. They also identified a submerged/ subsided tax collection port around 60 km southwest of Sindri Fort whose subsidence may have been coeval with the subsidence of the Sindri fort in the 1819 earthquake. This would imply that during 1819 there were two subsiding areas separated by a marginally high land mass (Sunda high). The study suggests flexure folding of the footwall during the 1819 earthquake. Ngangom *et al.* (2012) look at the relative contributions of climate and tectonics in shaping the course of Nara River, which was impounded during the 1819 earthquake due to faulting related land-level changes in the Allah Bund region. Bhattacharya *et al.* (2014) focused on the coupling of climate and tectonics in relation to the evolution of Katrol hill range (in the Kachchh region) during the last 20,000 years. Kothyari *et al.* (2016a, b) focuses on the meiszoseismal area of the 2001 Bhuj earthquake. They describe the landform evolution around Gedi fault and South Wagad fault (causative fault of the 2001 earthquake) and relate them to ongoing tectonics of the region. They identify two major uplift events dated at 8 ka and 4 ka, with an average uplift rate of 0.3 to 1.1mm/yr during the last 9 ka for the Gedi fault and 2.8 mm/y during the last 12 ka for the South Wagad fault. Pande (2013) revisits the epicentral area of the 2001 Bhuj earthquake and reports on the significance of seismites.

The Narmada-Son Lineament (NSL) is a subcrustal Precambrain zone of weakness and both the northern and southern parts of NSL experienced vertical block movements in the early period. It is established that NSL facilitated the deposition Vindhyan sediments and their deformation in the Meso-Neoproterozoic and Permo-Carboniferous-lower Cretaceous times. Some parts of the Narmada-Son region are active today as evidenced by high heat flow, thermal activity, thermal springs and seismicity. Like the Kutch region of Gujarat, the Narmada-Son fault (NSF) also continued to receive attention from researchers as in the previous reporting period. Joshi *et al.* (2013) conducted morphometric analysis of various segments of NSF to detect active faults. They inferred differential uplifts in recent geological past and the high angle reverse faulting with oblique-slip movements in various segments. Singh (2014) analyzed the drainage geomorphology of the area between Kanahar and Rihand Rivers (tributaries of the tectonically controlled Son River) around Renukoot area to evaluate active tectonics of the region, integrating detailed analysis of landforms and drainages. Various geomorphic features present in the study area such as incision of valley, aligned drainage, aligned valleys, linear valleys, offset channels, offset ridges and fault scarps demonstrate that the area is undergoing active deformation.

During the reporting period research initiatives have been made also on the Archaean terrain of south India, For example, Praseeda *et al.* (2015) investigated the paleoseismic activities along the Achankovil shear zone, a major NW-SE trending crustal scale shear zone with a strike length of 120 km. A number of parallel lineaments demarcate this 15-20 km wide shear zone. They have identified a couple of active faults in the southern end of this shear system. The traces of these faults are observed as multiple slip planes with varying deformation pattern. A group of N-S trending lineaments are also observed. Similarly, the traces of NW-SE trending brittle faults observed in these areas crosscut all the joints including the N-S trending vertical ones suggesting their response to the currently ongoing compressive stress regime. These observations suggest that the geomorphic signature associated with Thenmala lineaments may be representing the youngest active brittle deformation of the region. In another study from a nearby area, Singh *et al.* (2016) reported a number of brittle faults at the western terminus of Palghat Gap in north-central Kerala. These NW-SE trending faults show indications of geologically recent movements. The current seismic activities also coincide with the zone of these lineaments that is also overlapped by the northern part of Periyar lineament-a major coast-parallel structure in Kerala. These observations suggest that the NW-SE trending Periyar lineaments/faults may be responding to the present N-S trending compressional stress regime that are also reflected as the subtle readjustments on the drainage configuration in the area.Babar *et al.* (2012) revisits the epicentral zone of 1993 Killari (Latur) earthquake and analyse the morphology, lithostratigraphy and sedimentary structures of Terna River basin in the Deccan basaltic Province of West Central India. Radiocarbon dating of some charcoal fragments collected from folded beddings indicates that paleoseismic activity might have taken place along the basin between AD 120 and AD 1671.

Seismites of the Quaternary Period and Beyond

Earthquake-induced soft-sediment deformation structures including convolute laminations, flame structures, and deformed cross-stratifications (broadly grouped as "seismites") preserved in geological formations belonging to Quaternary Period and further back in geological time have also found significant reporting internationally and a few such studies have been published by Indian researchers as well. Kundu *et al*. (2011a) discuss such deformation structures within the Middle Siwalik sequence (~10 Ma) in the Darjeeling Himalaya. Similar structures are also reported from the early Proterozoic Damtha Group in the Garhwal Lesser Himalaya, of an inter-tidal to supra-tidal depositional environment (Ghosh *et al*., 2012). Another area that provides ample evidence of seismites of deep time is the Lower Triassic sedimentary formations (~250 Ma) of the Damodar Valley, although ascribed by the authors to minor to moderate magnitude earthquakes (Kundu *et al*. (2011b). Two different classes of soft-sediment deformation structures (SSDs) have been reported from the Proterozoic Bhander Limestone from the banks of Tamas River near Maihar in Central India- one set of these SSDs are reported to be nonseismic and the other set owes its origin to fluidization and liquefaction triggered by seismicity (Sarkar *et al*., 2014). Structures like slump folds, clastic dyke, syn-sedimentary faults and convolute bedding are reported from the Upper Jurassic (~200 Ma) Formations along the Khari River in Kachchh (Kale *et al*., 2016). These soft sediment deformation structures are spatially restricted to lower and middle parts of the section and in the close proximity of Kchchh Mainland Fault.

Future

Paleoseismological and active tectonics studies in India during 2010-2016 cover a greater variety of morphological settings, compared to previous reporting periods. New groups of researchers have also entered the scene with freshness of approach, and studies on the plate boundary systems have gathered greater momentum. On the flip side, the paleoseismological researches in many cases, although made great efforts in extracting time series of ancient earthquakes, have not been very successful in placing the findings in a regional tectonic and geodynamic framework. One important aspect that will also become important in the years to come is how the varied and site-specific paleoseismological results can be integrated to develop an inventory of active faults for the whole country. From research point of view greater attention may be given to the observational and theoretical elements of tectonic geomorphology and develop it as tool to constrain tectonic activity. The use of aerial photography and remote sensing (e.g. LIDAR and InSAR techniques) at many scales and in many radiation bands will have to become a part of this endeavor. This will also help in augmenting the measurement precision of various parameters related to morphology and landscape evolution dynamics. Equally important is to initiate geophysical surveys (e.g. seismic, thermal, electrical, magnetic and gravitational) to complement the paleoseismological studies. Shallow and deep reflection techniques should be employed in critical areas to understand the nature and style of faulting. This becomes critical in areas where primary seismogenic structures do not extend to the surface or where surface faulting is poorly expressed. Efforts should also be made to develop longer-term time-series of paleo-earthquakes using different proxies, which may give a better handle to characterize the nature and persistence of segment boundaries in time and space and directivity of individual ruptures. Another important aspect is to refine the existing or develop new methods for dating the Quaternary deposits and surfaces that can be used to quantify the rates of deformation. From a theoretical perspective, it will be important to develop physical models of the complete earthquake cycle and test against relevant observations and to determine new ways of using such inputs in developing earthquake forecast hazard models and to prepare the society to face the extreme natural events.

Acknowledgments

I thank Ashok Kumar Singhvi for the invitation to contribute to this volume and the reviewer (anonymous) for the helpful suggestions. Jaishri Sanwal and Anandasabari have rendered help while preparing this overview.

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