Seismotectonics of the great and large earthquakes in Himalaya

J. R. Kayal*

Institute of Seismological Research, Gandhinagar 382 009, India

The best known seismotectonic model of the Himalayan Seismic Belt (HSB) suggests that the great and large earthquakes in the Himalaya occur at a shallow depth (10–20 km) by thrust faulting on the Main Himalayan Thrust, i.e. on the plane of detachment. The plane of detachment is the interface between the Indian shield and the Himalayan sedimentary wedge. The recent earthquake data of the permanent and temporary local networks in the Himalaya, however, indicate bimodal seismicity at shallow (0–20 km) as well as greater depths (30–50 km). The source processes of the great and large earthquakes are re-examined in this article (the observations do not support a uniform seismotectonic model for the entire HSB). The four known great earthquakes (*Ms* ~8.0–8.7) in the Himalayan region, from west to east are the 1905 Kangra, 1934 Bihar, 1897 Shillong and the 1950 Assam earthquakes that occurred by different tectonic processes; each occurred in its own unique complex tectonic environment. Most recently, the 1988 strong earthquake (*Ms* 6.6) in the Bihar/Nepal foothill Himalaya and the 2011 strong earthquake (*Mw* 6.9) in the Sikkim Himalaya show that these are not the plane of detachment events; these occurred by strike–slip faulting at mantle depth (~50 km). A review of all these significant earthquakes in HSB is presented in this article.

Keywords: Fault plane solutions, plane of detachment, seismotectonics, thrusts, lineaments.

Introduction

THE entire ~2500 km long Himalayan arc, 75–98°E, extending from Kashmir in the northwest to Arunachal Pradesh in the northeast, evolved as a consequence of collision of the Asian and Indian continents some 50–60 m.y. ago[1–3]. As the Indian land mass moved northwards, the sedimentary pile with its crystalline basement was complexly folded and repeatedly split by faulting and thrusting. These faults, from north to south, are: the Trans Himadri Fault (THF), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT; Figure 1)[2–4]. The Indus Suture Thrust (IST) farther north represents the junction of the two colliding continents. Recent studies suggest that HFT to the south is now the primary surface expression of shortening between the Himalaya and the Indian plate[2–4]. It is also suggested that some of the Indian shield structures extend into the Himalaya as sub-surface ridges[2,5,6]. Further, there are various surface transverse features like lineaments, faults, rifts, nappe, etc. across the Himalaya that may affect source zones and mechanisms of the earthquakes[7–10].

The overall definition of the Himalayan Seismic Belt (HSB) that lies between MBT and MCT is based on the observation of intermediate magnitude ($M \geq 4.5$) earthquakes at regional and teleseismic stations outside the Himalaya. Based on the global seismic stations, the hypocentre location errors are large, and most of the earthquakes, as recorded in the catalogues of the US Geological Survey (USGS) and in the International Seismological Centre (ISC) bulletins, are assigned to a fixed depth (33 km). Using these constrained teleseismic data which are less precise in estimating the depth and using the surface geological evidences, a conceptual tectonic model was envisaged to explain the Himalayan earthquakes[11,12]. In the absence of local seismological network data in the Himalaya, it was not possible to correlate the observed seismicity and tectonic features of the Himalaya with a realistic model; particularly the past great earthquakes in the Himalaya which occurred much before the worldwide seismograph station network was established are yet to be well understood.

Over the past three decades large amount of earthquake data are recorded by the local temporary and permanent networks in different parts of the Himalaya[7,13–15]. These data shed new light on our understanding of the tectonic model of the Himalaya that differs from west to east. In this study, the source areas of the great earthquakes are re-examined in the light of the well-located earthquakes recorded by the local seismic networks in the Himalaya. The spatial and depth characteristics of seismicity along with the structural complexities inherent to the Himalaya are critically examined. These observations are reviewed in fitness with the widely accepted conceptual tectonic model of HSB.

Tectonic model

Based on the teleseismic hypocentral data, a conceptual tectonic model of the Himalaya was first suggested by

*e-mail: jr.kayal@gmail.com

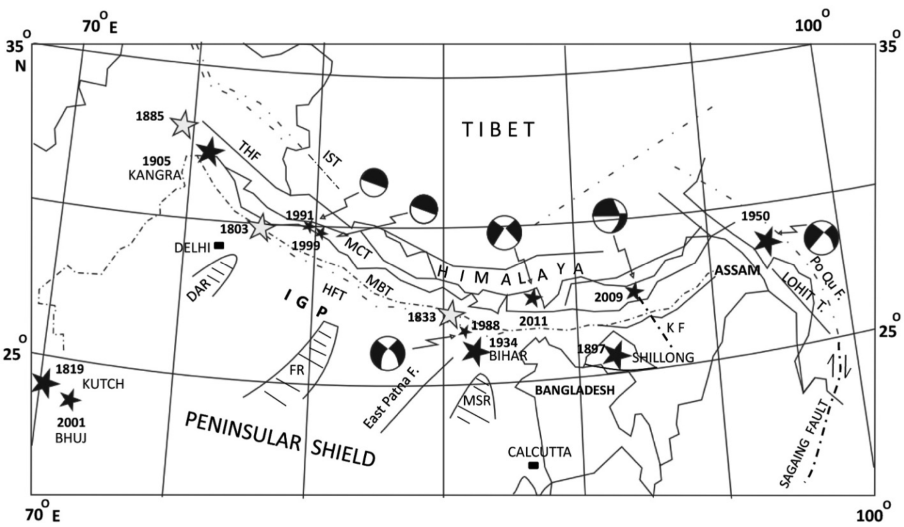

Figure 1. Map showing major tectonic features in the Himalaya and the great/large earthquakes in India since 1897 (bigger black stars). Five recent significant strong earthquakes (1988, 1991, 1999, 2009 and 2011) are shown by smaller black stars. Open stars indicate the historical (prior to 1897) great events (intensity IX–X) in the Himalaya. Subsurface Ridges, DAR, Delhi–Aravalli Ridge; FR, Faizabad Ridge; MSR, Mungher Saharsa Ridge (modified from Kayal[24]).

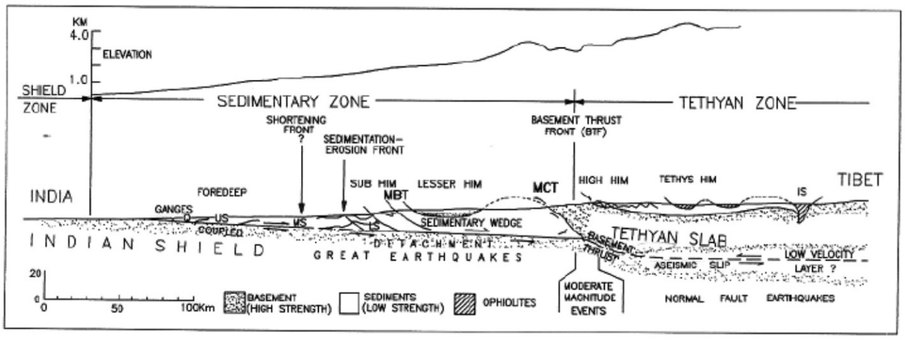

Figure 2. Conceptual tectonic model of the Himalaya[11]. Q, Quaternary; US, MS, LS, Upper, Middle and Lower Siwalik; IS, Indus Suture (compiled by Kayal[24]).

Seeber *et al.*[11]. The model consists of the gently dipping Indian shield, the overriding Tethyan slab and the Himalayan sedimentary wedge which is decoupled from the two converging slabs (Figure 2). In this model, MBT and MCT are two active thrusts, and are contemporaneous features. Ni and Barazangi[12], however, argued that MCT is dormant now, and MBT is active. In the proposed model, the interface between the subducting slab and the Himalayan sedimentary wedge is named plane of detachment. Nelson and Zhao[16] later named it the Main Himalayan Thrust (MHT). Further north, the interface between the Tethyan slab and the dipping Indian slab is named Basement Thrust (BT). The transition zone from the plane of detachment to the basement thrust is named Basement Thrust Front (BTF; Figure 2). Spatially, the BTF coincides with the high topographic gradient between the lesser Himalaya and the high Himalaya[2,17]. Lyon-Caen and Molnar[17] proposed that the change in elevation as well as the steep dip of MCT caused ramping of the Himalayan crust over the northern edge of the Indian plate. The 'ramp' represents BTF, which is the zone of moderate magnitude earthquakes. The model further postulates that MBT and MCT converge to the plane of detachment at a depth 10–20 km. Beneath the foothills and foredeep Ganga basin, to the south of MBT, the Indian shield basement or the plane of detachment is shallow (3–5 km; Figure 2). The HFT is the southernmost youngest active thrust; this thrust is marked by the topographic break between the Himalaya and the alluvial-filled Indo-Gangetic Plains (IGP). Under the thick cover of sediments in IGP, the flexed Indian plate is corrugated by some basement ridges; these are the northeast extension of the Indian shield structures, like Delhi–Aravalli Ridge, Faizabad Ridge and Munger Saharsa Ridge (Figure 1). Several authors argue that junction zones of these subsurface ridges at the Himalayan arc are the source zones of concentrated seismicity as well as large earthquakes[2,6,15].

Little is known about the Himalyan seismicity prior to AD 1800. Despite the diverse quality of data, it is, however, believed that there have been seven great earthquakes in the Himalaya region since 1800. Four great earthquakes are instrumentally recorded since 1897, but there are three more known great earthquakes prior to 1897; these are the 1803 event near Delhi, the 1833 event in Nepal, and the 1885 event in Kashmir Himalaya (Figure 1). These three events have no instrumental data and the locations are mostly based on the macroseismic data[18], which reported maximum intensity of the order of IX–X.

Since 1897 the instrumentally recorded great earthquakes are, from west to east, the 1905 Kangra, the 1934 Bihar, the 1897 Shillong and the 1950 Assam events. Seeber *et al.*[11] interpreted that all these four great earthquakes were the HSB earthquakes having uniform rupture geometries. Further, based on teleseismic data, it was suggested that these four great earthquakes occurred on the plane of detachment and the rupture propagated to the south.

In a recent study, Kayal[7] based on aftershock investigations using temporary microearthquake networks, reported that the two strong earthquakes – the 1991 Uttarkashi (*Mw* 6.3) as well as the 1999 Chamoli (*Mw* 6.5), that occurred to the north of MBT in the western Himalaya, fit fairly well with the proposed tectonic model (Figure 2), and supported the argument of Ni and Barazangi[12] that the MCT is dormant. The aftershock data show that these two (1991 and 1999) shallow earthquakes (depth $\leq$20 km) occurred on the plane of detachment and triggered the local active faults to the north of MBT, but much south of MCT. The 'fault ends' on the plane of detachment were the sesimogenic source zones for the main shocks, and the aftershocks were generated by triggering at these active faults[7]. The 1999 Chamoli earthquake sequence is shown in Figure 3; it shows that the main shock occurred on the plane of detachment at the Alokananda Fault end to the south of MCT, and the aftershocks occurred along this fault.

The great/large earthquakes

Seismogenic source zones of the past four great ($M \geq 8.0$) earthquakes, that occurred since 1897 are being re-examined and reviewed here with data available from the recent local seismic network. Source zones of these great earthquakes are debated due to lack of much instrumental data as these events occurred before the World Wide Seismograph Network came into existence in 1964. The well-recorded and well-studied source zones and tectonic processes of the recent strong/damaging earthquakes ($M > 6.0$) in the Himalaya, like the 1988 Bihar/Nepal, 1991 Uttarkashi, 1999 Chamoli, 2009 Bhutan and the 2011 Sikkim earthquakes, have also been reviewed here. They shed further light on the understanding of the non-uniqueness of the Himalayan seismotectonic model for the great and large earthquakes.

The 1905 Kangra earthquake

The 4 April 1905 Kangra earthquake, $M \sim 8.6$ assigned by Richter[19], revised to *Ms* 7.8 ± 0.05 by Ambraseys and Douglas[20], that occurred at the HFT zone in the western Himalaya, produced intense destruction in the Kangra valley with a maximum intensity X (MM scale) and with an isolated intensity VIII (MM scale) about 250 km southeast, near Dehradun[21] (Figure 4). Further, Middlemiss[21] estimated the depth of focus at 21–40 km. Hough *et al.*[22] re-evaluated the intensity distribution with geodetic observations, and reexamining the few original seismograms they interpreted that the damage pattern reflects two large earthquakes *Ms* 7.8 and *Ms* 7.0; the second (triggered) earthquake *Ms* 7.0 occurred near Dehradun at a depth 30–35 km within a few minutes after the *Ms* 7.8 main shock in Kangra.

The local earthquake data that have been recorded in the western Himalaya during the last three decades by semi-permanent and permanent networks of India

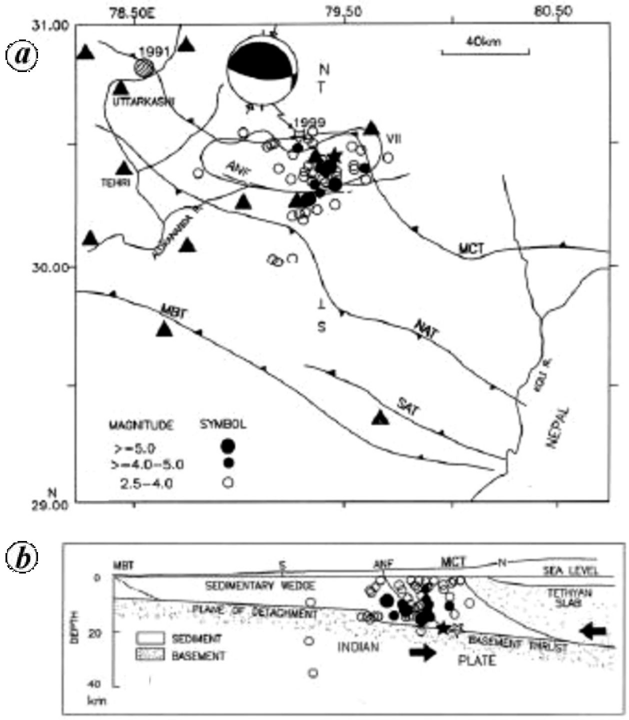

Figure 3. The Himalayan tectonic model and the 1999 Chamoli earthquake sequence[7]; the main shock occurred on the plane of detachment at the Alokananda Fault (AF) end. Black star indicates location of the main shock by the local network and open star by the USGS. The aftershocks are located by the local network (after Kayal[7]).

Meteorological Department (IMD) were re-analysed by Bhattacharya and Kayal[23] (Figure 5). They reported that the 1905 Kangra earthquake source zone was beneath HFT, south of MBT, and the seismogenic source zone could be much deeper, at the lower crust at a depth 30–40 km as interpreted by Middlemiss[21] (Figure 5). As mentioned above, the triggered Dehradun event *Ms* 7.0 is also estimated at a depth 30–35 km to the south of MBT[22]. These observations of the deeper source zones do not conform to the conceptual tectonic model that the great or large 1905 Kangra and Dehradun earthquakes occurred on the plane of detachment. The plane of detachment is shallow (< 5 km) at HFT, to the south of MBT (Figure 2). The large set of local network data, on the other hand, shows a much deeper seismogenic source zone (30–40 km) at the fault end of HFT in the Kangra region (Figure 5). This source zone to the south of MBT is much below the so-called plane of detachment envisaged in the HSB tectonic model[11]. It is argued by Kayal[24] that HFT is the possible seismogenic fault, and at the 'fault end' the tectonic stress is accumulated in the lower crust of the under thrusting Indian plate at a depth 30–40 km, much below the plane of detachment, that generated this great/large Kangra earthquake.

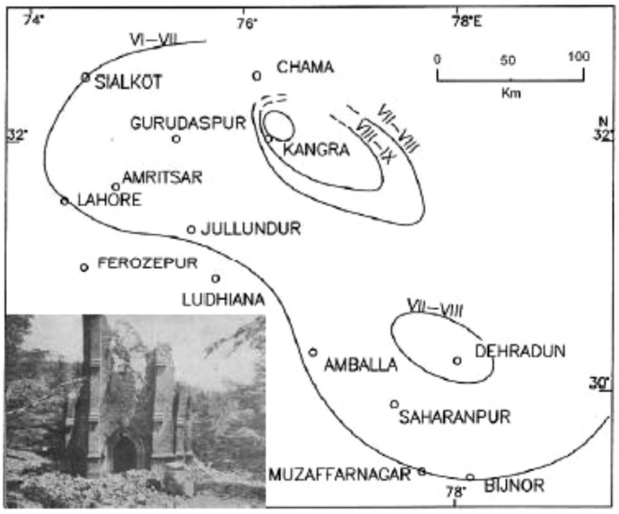

Figure 4. Isoseismal map of the 1905 Kangra earthquake. (Inset) Damage to a Church near Kangra in the maximum intensity zone[21].

The 1934 Bihar earthquake

The 15 January 1934 great Bihar earthquake is well documented by Dunn *et al.*[25]; the epicentre is given at 26.50°N and 86.50°E, about 50 km south of the MBT, magnitude *Ms* 8.4 and depth at ~ 30 km (Figure 1)[19,26]. Molnar and Deng[27], on the other hand, gave its epicentre at 27.55°N

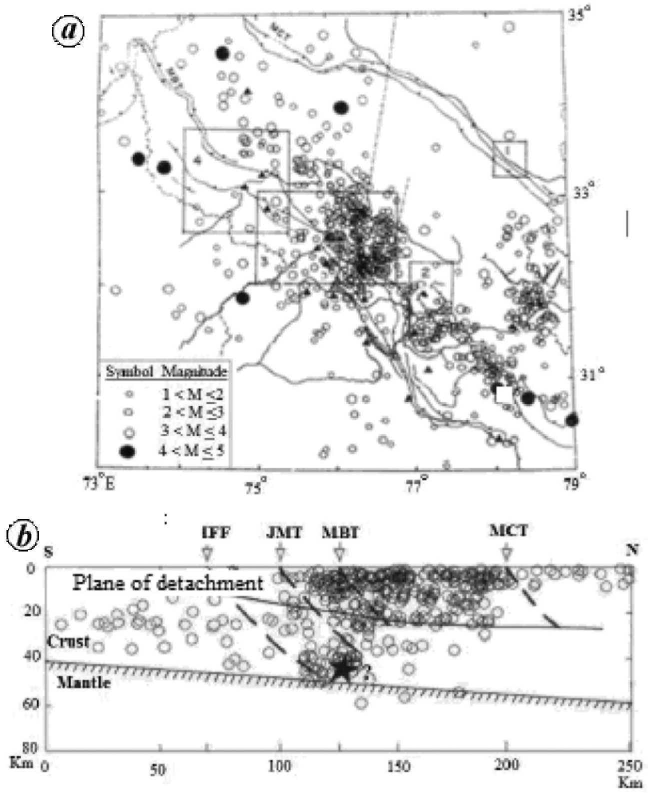

Figure 5. ***a***, Seismicity map in the Kangra region recorded by the local networks. ***b***, Tectonic model for the 1905 Kangra earthquake source area[23]; the star indicates the 1905 Kangra earthquake; JMT, Jalamukhi Thrust. See text for other tectonic features.

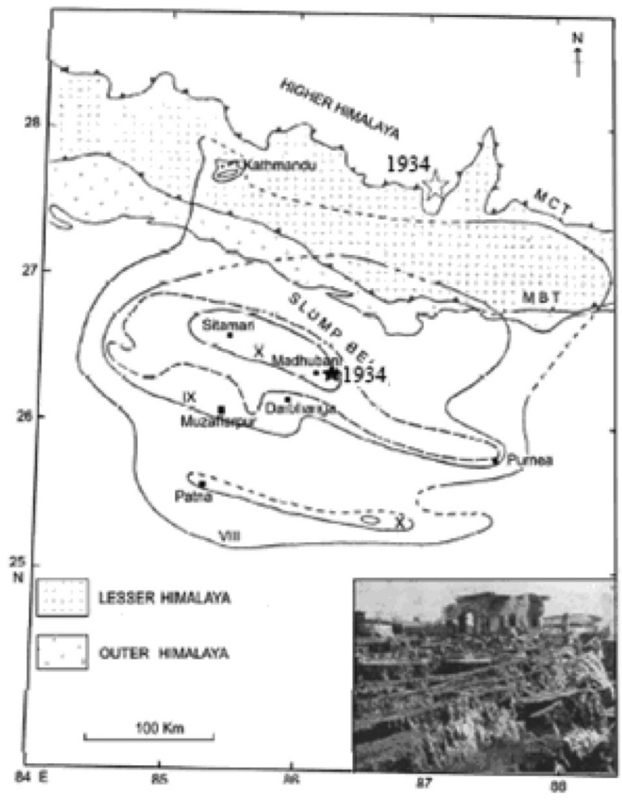

Figure 6. Isoseismal map of the 1934 Bihar/Nepal earthquake. (Inset) Damage to a house and lurching ground in the maximum intensity zone[29]. Solid star indicates the epicentre given by Abe[26] and open star by Molnar and Deng[27].

and 87.09°E, about 60 km north of MBT (Figure 6). The macroseismic study reported a maximum intensity X (MM scale); this is well mapped with a larger area, 120 km long and 35 km wide in Munger, Bihar, much south of MBT and with a smaller (spot) area in Kathmandu, Nepal, to the north of MBT (Figure 6). No surface rupture was reported by the macroseismic study[25]. Based on geodetic data, Bilham *et al.*[28] suggested that the hidden rupture terminated to the north of Nepal/India border.

The 20 August 1988 earthquake is instrumentally well recorded by the national and the global network. Its well-located epicentre at 26.72°N and 86.63°E, *Ms* 6.6 and depth 65 km (ISC catalogue) shows that it occurred near the epicentre of the 1934 great Bihar earthquake (Figure 1). Based on a detailed investigation of the 1988 earthquake, the Geological Survey of India (GSI)[29] re-interpreted the seismogenic source zone of the 1934 event. Both the epicentres, the 1934 epicentre given by Abe[26] and the well-located 1988 epicentre lie to the south of HFT (Figure 1). Using surface wave inversion, Singh and Gupta[30] determined thrust faulting with strike–slip component for the 1934 event. The CMT (centroid moment tensor) solution depicts strike–slip solution for the 1988 event. GSI[29] interpreted that both these events are deeper and are caused by the East Patna fault, a long transverse fault which runs across the Indo-Gangetic Plains and transverse to the Himalayan trend (Figure 1). However, Sapkota *et al.*[31], based on the geological evidences by trenching, argued that the 1934 great earthquake occurred on the plane of detachment to the north of MBT, and the rupture propagated to the south along HFT; they assigned its magnitude *Mw* 8.2 and supported the epicentre location given by Molnar and Deng[27] at 27.55°N and 87.09° (Figure 6).

Similar to that of 1988 earthquake in the foothills region, the most recent 2011 Sikkim (*Mw* 6.9) earthquake also illustrates a deeper source zone and strike–slip mechanism (Figure 7)[32]. The 2011 Sikkim earthquake (epicentre at 27.718°N, 88.136°E, *Mw* 6.9, depth 50 km; USGS report) occurred in the lesser Himalaya to the north of MBT. The CMT solutions of both the events, 1988 and 2011, show that these events occurred by strike–slip mechanism at deeper source (Figure 1). It has been reported that the near-vertical Tista Fault is a mantle-reaching deeper structure, transverse to the Himalayan trend, and it caused the 2011 Sikkim earthquake (Figure 7)[32]. Aftershock study of this event by a local seismic network also revealed the mantle reaching deeper vertical structure[33]. In an earlier study, based on temporary microearthquake network data, De and Kayal[10] reported deeper transverse tectonics in the Sikkim Himalaya. It is thus evident that the long NE and NW trending transverse structures/faults from foredeep to the high Himalaya, even beyond, which may be existing since a time predating the birth of the Himalaya, produce intersecting patterns, and accommodate the plate convergence by conjugate shear failure on some of these faults[9]. These observations suggest that source zones of all the great/strong earthquakes cannot be related only to the shallow plane of detachment in HSB. Deeper seismogenic source zones exist, which are mostly related to the transverse faults/structures in the Himalaya. It may be mentioned that a moment tensor solution of the 2009 Bhutan Himalaya earthquake (*Mw* 6.3) also shows a strike–slip solution (Figure 1), and the Kopili Fault, a long transverse structure to Himalayan trend, is interpreted to be the causative fault[34].

Monsalve *et al.*[13], based on high-precision digital network data of the Nepal Himalaya, reported bimodal seismicity, one above the plane of detachment and the other at the crust–mantle boundary at a greater depth (40–50 km) to the south as well as north of MBT (Figure 8). The well-located 1988 event occurred at the deeper source zone to the south of MBT. Kayal[24] supported the GSI[29] interpretation for a deeper source of the 1934 event to the south of MBT with a mark of interrogation (Figure 8).

The 1897 Shillong earthquake

The 7 June 1897 great Shillong earthquake *Ms* 8.7, is the first event in India that was instrumentally recorded by a few stations outside the country; a detailed macroseismic study was done by Oldham[35]. The hat shaped maximum isoseismal is truncated by the Dapsi thrust to the south (Figure 9)[35]; the Dapsi thrust is conjugate or a secondary fault to the Dauki Fault[7]. The isoseismal map of this great earthquake is shown in Figure 10, which indicates that the earthquake was widely felt. Oldham's maximum isoseismal was rated X–XII in MM scale by Richter[19], and VIII in MSK scale by Ambraseys and Bilham[36]. Based on field observations, boulder thrown into the air (Figure 10), Oldham[35] assigned the peak ground acceleration (PGA) to 1 *g*. This estimate of PGA without any strong motion instrumental record is now highly appreciated by the modern strong-motion seismologists of the world. The magnitude of this great earthquake is, however, revised to *Mw* 8.1 by Bilham and England[37]. The earthquake occurred beneath the Shillong plateau, a fragment of the Indian shield that was dragged to the east by the E–W Dauki Fault (Figure 9)[38]. The plateau is now bound by the Dauki Fault to the south and Brahmaputra river to the north. The epicentre of the 1897 great earthquake lies to the south of the Brahmaputra river fault, which is about 150 km south of MBT (Figure 9).

Oldham[35], without much instrumental data or any fault plane solution, conjectured that the 1897 great earthquake occurred by thrust faulting on a north-dipping thrust fault. A few microearthquake field surveys revealed that the north dipping Dapsi thrust at the southern boundary of

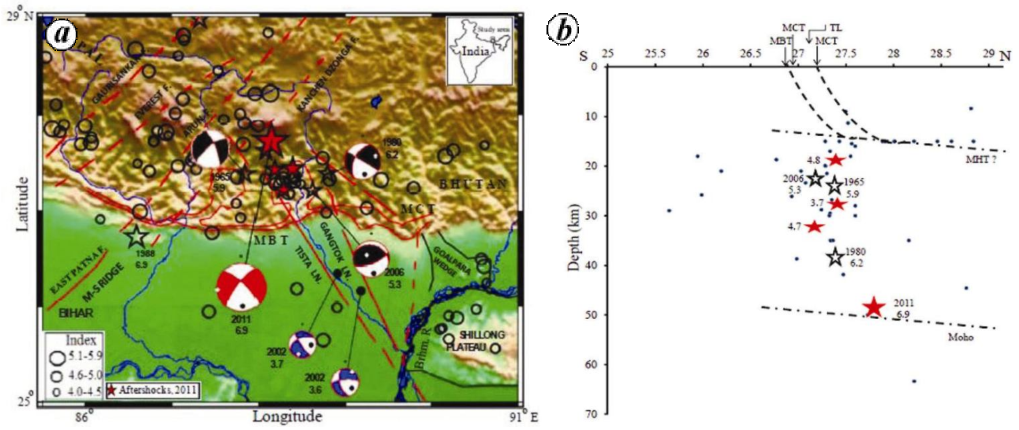

Figure 7. ***a***, Tectonic map of Sikkim Himalaya showing epicentres of the (ISC/EHB) relocated earthquakes (1965–2007). The 18 September 2011 main shock and felt aftershocks ($M \geq 3.7$) are shown by red stars. Black stars show the two past damaging strong earthquakes ($M \geq 5.9$) with CMT solutions in the study area[32]. Two open stars indicate the two recent significant earthquakes, the 1988 (M_s 6.6) and the 2006 (M_w 5.3) events. Moment tensor solutions of two smaller events of 2002 recorded by local broadband network are also shown. MCT, Main Central Thrust; MBT, Main Boundary Thrust; MS-Ridge, Munger-Saharsa Ridge. (Inset) Key map showing the study area. ***b***, A north–south cross-section of the earthquakes across the 2011 main shock epicentre zone showing the past significant earthquakes (solid dots) including the three (1965, 1980 and 2006) strong earthquakes (black stars) and the 2011 main shock (bigger red star) and its three felt aftershocks (smaller red stars) which occurred on a vertical fault zone at depth 10–50 km below the Tista lineament, named Tista fault[32].

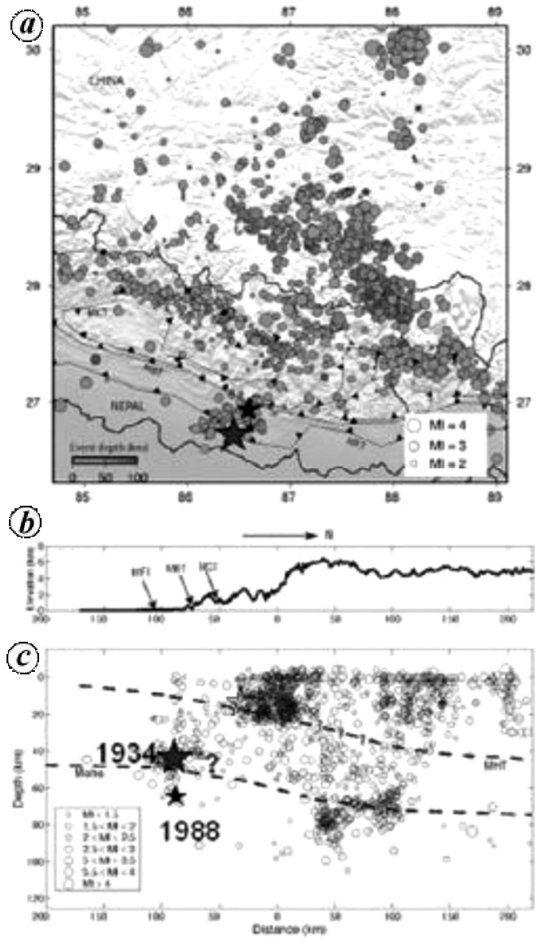

Figure 8. ***a***, Seismicity map of the central Himalaya recorded by digital telemetric network, Nepal. ***b***, ***c***, Elevation (***b***) and N–S cross-section of the events showing bimodal seismicity (***c***)[13]. The source zones of the 1934 (?) and the 1988 earthquakes are indicated[24]. The open star indicates the source zone given by Molnar and Deng[27], and Sapkota *et al.*[31].

the Shillong plateau is the seismogenic fault that generates earthquakes in the Shillong plateau[7,39]. Recently, Bilham and England[37], based on the earlier geodetic and recent GPS data, however, argued that the 1897 great earthquake was caused by a south-dipping hidden fault, named Oldham fault, at the northern boundary of the Shillong plateau (Figure 9). They further suggested that the plateau earthquakes are generated by ‘pop-up’ tectonics between the two boundary faults, the Dauki fault and the Oldham Fault. Rao and Kumar[40] first proposed the pop-up tectonics for the Shillong plateau, and suggested that the pop-up mechanism is facilitated by the Dauki fault to the south, Brahmaputra fault to the north, Dhubri fault to the west and Disang thrust to the east (Figure 9). Bilham and England[37], however, illustrated a quantitative model of the Shillong plateau pop-up tectonics for the 1897 great earthquake (Figure 11). In this model they argued for the pop-up tectonics between the proposed south-dipping hidden Oldham fault and north-dipping Dauki fault.

Geological evidences, however, do not support these two boundary faults for the proposed model (T. Paul, 2011; pers. commun.). Nandy[41] argued that the Dauki fault is a south-dipping or a near-vertical normal/strike–slip fault, not a north-dipping thrust fault. He further emphasized that the large (~ 20 km) difference in basement depth between the Shillong plateau and the Bengal basin cannot be in any way explained by a thrust movement. Rajendran *et al.*[42] argued that the gravity map or the surface geological evidences do not support the south-dipping Oldham fault. The gravity model of Nayak *et al.*[43], on the other hand, supported the pop-up tectonic model. Kayal *et al.*[44], based on recent broadband digital seismic data, suggested that the pop-up tectonics of the plateau may happen between the Brahmaputra fault and the Dapsi thrust (Figure 11). Kayal and De[39], based on local microearthquake network data, reported that the seismic activity in the Shillong plateau is caused by the north-dipping Dapsi thrust, and the Dauki fault is not much active. The activity is confined to the north of the Dapsi thrust, which also truncated the isoseismals X–XII of the 1897 great earthquake along this thrust (Figure 10). The NW–SE trending Dapsi thrust separates the Archaean gneiss to the north and the Tertiary metasediments to the south within the plateau, and it is interpreted to be conjugate to the E–W Dauki fault that separates the Shillong plateau and the Bengal basin (Figure 10).

Seismic cross-section of the well-located events recorded by the recent permanent broadband seismic stations in the Shillong plateau clearly show that the Dauki fault is not much active (Figure 11). The activity beneath the plateau is confined between two boundary faults, the Dapsi thrust to the south and the Brahmaputra fault to the north. Fault plane solutions of the events ($Mw \geq 3.5$) were examined, and the inferred fault planes corroborated well with the north-dipping Dapsi thrust and the south-dipping Brahmaputra fault (Figure 11). At the epicentre zone of the 1897 earthquake, the Oldham fault and the Brahmaputra fault are, however, very close, within 20 km. Kayal *et al.*[44] supported the pop-up tectonics of the plateau between the Dapsi thrust and the Brahmaputra fault. The pop-up tectonic model is, however, much debated and needs more geophysical studies. The microearthquake seismological data to the north of Brahmaputra river fault are not complete (Figure 11 *b* and *c*). This is due to the absence of a seismic station in the alluvium country to the north of Brahmaputra river fault and in the Bhutan Himalaya to record microearthquakes in the Assam valley foredeep region to develop a realistic seismological model.

It may, however, be argued that the 1897 earthquake is a shield earthquake like that of the 1819 great Kutch earthquake ($M \sim 8.0$; revised[20] to Mw 7.8) or the 2001 Bhuj earthquake (Mw 7.7) in western India (Figure 1). The 1819 Kutch and the 2001 Bhuj events are the rift basin earthquakes in the western part of the Indian shield and these are caused by inversion tectonics[45]. The 1897 event is also a shield earthquake, the present broadband seismic data and the GPS data do not support it to be a Himalayan earthquake as was proposed earlier[11].

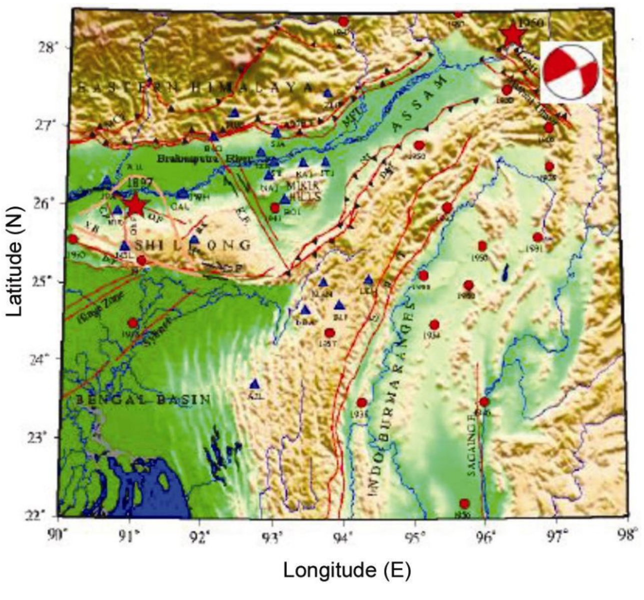

Figure 9. Tectonic setting in the Northeast India; the two (1897 and 1950) great earthquakes ($M > 8.0$) are shown by stars, the large events ($M > 7.0$) by circles. Triangles indicate broadband seismic stations. OF, Oldham Fault; DF, Dauki Fault; DT, Dapsi Thrust; BF, Brahmaputra Fault; KF, Kopili Fault; NT, Naga Thrust (after Kayal *et al.*[44]).

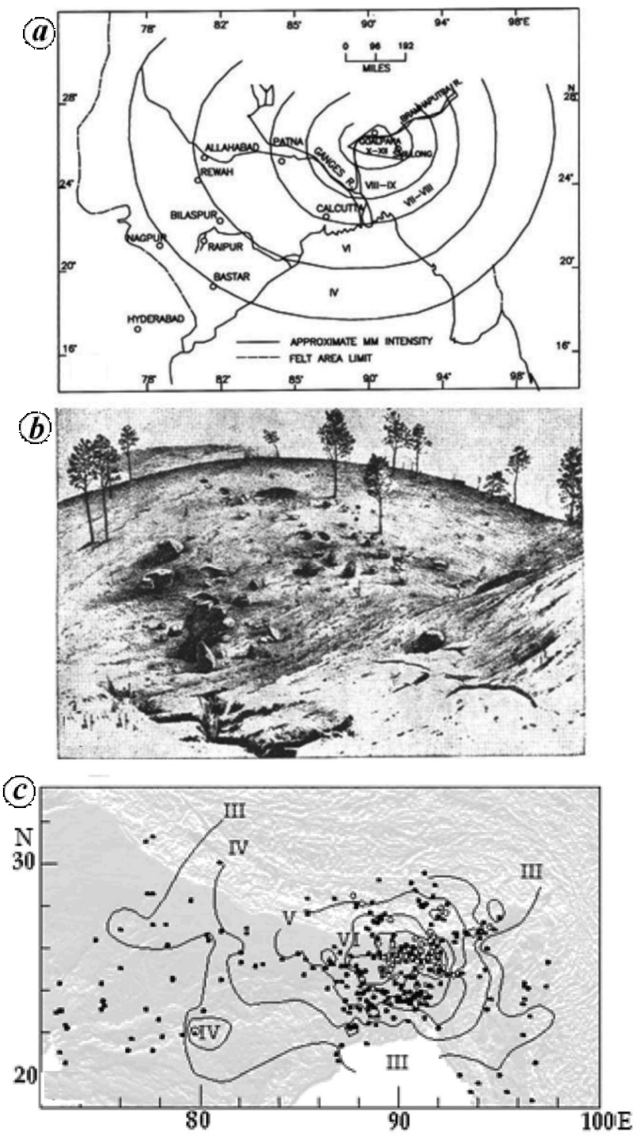

Figure 10. ***a***, Isoseismal map of the 1897 Shillong earthquake. ***b***, Dislodged boulders in the maximum intensity zone[35]. ***c***, MSK intensities evaluated by Ambraseys and Bilham[36].

The 1950 Assam earthquake

Sixteen years after the 1934 great Bihar earthquake, the great Assam earthquake occurred on 15 August 1950. It is instrumentally a well-recorded event, the assigned *Ms* 8.7, maximum intensity XII (MM scale, Figure 12) and focal depth ~20 km are fairly well determined[46]. This earthquake occurred in the eastern syntaxis zone where the E–W Himalayan arc meets the N–S Burmese arc (Figure 12). The damage in the Assam area in terms of property loss was more than that of the 1897 Shillong earthquake. Aftershocks were numerous, and many of them were of magnitude 6.0 and above. From amplitude inversion, Ben-Menahem[47] *et al.* interpreted a strike–slip solution for this great earthquake with a northeast-dipping NNW–SSE fault plane (Figures 9 and 12). Chen and Molnar[48], however, based on first motion data, determined a thrust faulting solution. Armijo *et al.*[49] preferred the strike–slip solution of the 1950 earthquake interpreting the right-lateral strike–slip on the Po Qu fault zone in southeast Tibet, which wraps around the eastern syntaxis and connects with the rightlateral strike–slip Sagaing fault zone (Figure 12). They further argued that a discontinuation of ophiolite in the syntaxis zone is the geological evidence of strike–slip movement on the faults that wrap around the syntaxis, and the plate movement is accommodated by the strike–slip faults.

Holt *et al.*[50] reported 15 reliable fault plane solutions in the region; 6 to the north of the MBT zone in the northeast Himalaya, 6 in the eastern syntaxis zone, and 3 on the Sagaing fault (Figure 12). All the solutions (events 1–5) to the north of MBT show northeast-dipping low-angle thrust fault that accommodates under thrusting of the Indian plate below Himalaya. One well-constrained solution (event 6) that occurred at a greater depth (35–40 km) shows south-dipping low-angle nodal plane. The crustal thickness estimated in this region ranges from 50 to 65 km (ref. 51); this indicates that event 6 occurred in the mid-lower crust within the under thrusting Indian plate, much below the envisaged plane of detachment. This implies deeper source of earthquakes even to the north of MBT in this complex zone. Based on local microearthquake network data, much deeper source (50–70 km) to the south of MBT in the northeast Himalaya was reported by Kayal *et al.*[52]. Six fault plane solutions (events 7–12) are reported in the southeast corner of the syntaxis zone on the southeast extension of the Mishmi thrust. Valdiya[2] reported that the Mishmi metamorphics over thrust the Tertiary sediments eroded from the northern Indo-Burma ranges. All the solutions show dominantly thrust faulting with a northeast-

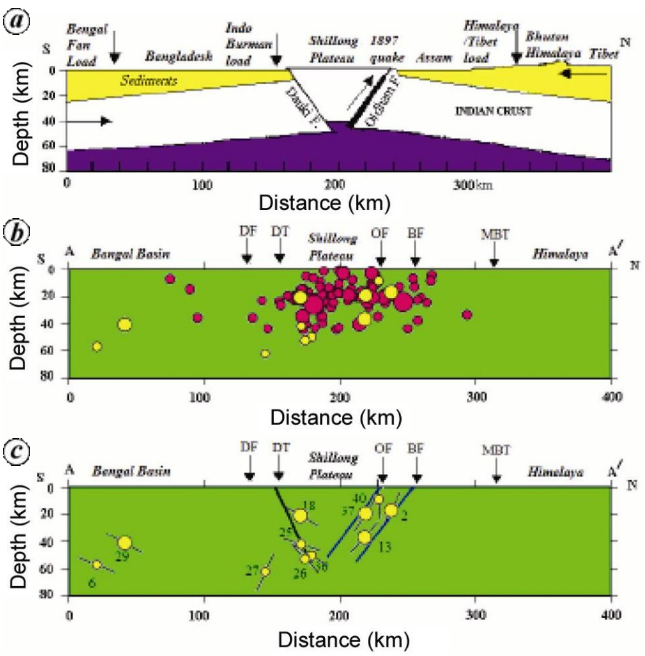

Figure 11. ***a***, Pop-up tectonic model of the Shillong plateau[37]. ***b***, Earthquakes beneath the Shillong plateau. ***c***, Fault planes of the annotated earthquakes indicate that DT and BF are the boundary faults[44].

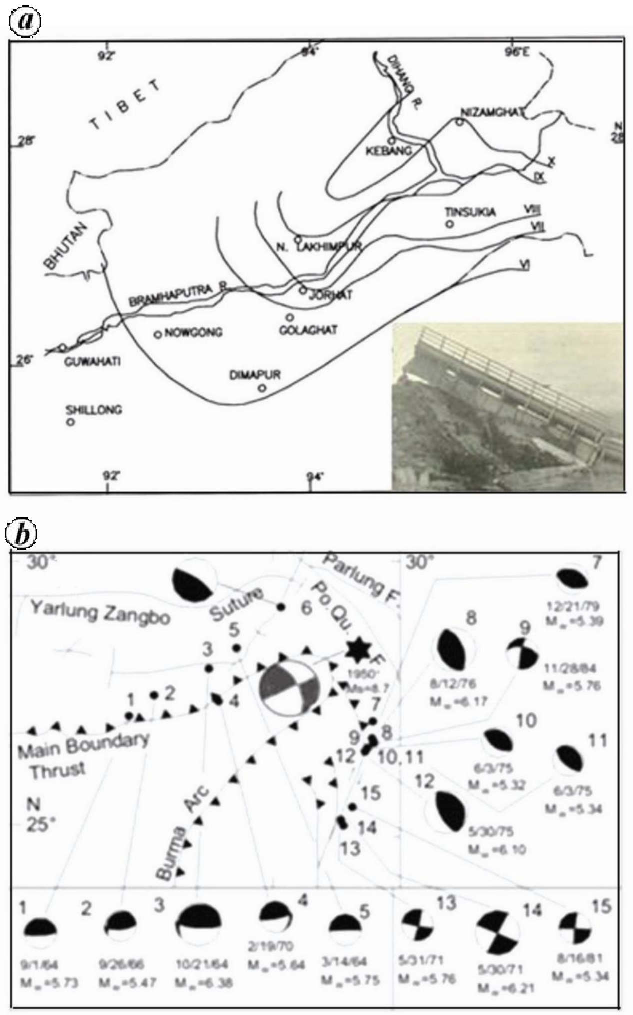

Figure 12. ***a***, Isoseismal map of the 1950 Assam earthquake. (Inset) Damaged bridge in the maximum intensity zone. ***b***, Fault plane solutions of the earthquakes in the eastern syntaxis zone (compiled by Kayal[24]).

dipping nodal plane; the earthquake source depth is at 8–10 km, except the shallower (3 km) event 9 which shows a strike–slip component. Three solutions of the events 12–15, that occurred on the northern end of the Sagaing fault, show strike–slip motion on this fault. Thus the syntaxis zone seems to be more complex where link between the right-lateral slip on the Po Qu fault requires an extensional right step near the northern end of the Sagaing fault[49]. Armijo *et al.*[49] suggested that the reliable fault plane solution of the great 1950 earthquake by amplitude inversion and the geological evidences confirm the right lateral movement on the Po Qu fault and its possible connection with the Sagaing right-lateral fault. These evidences indicate that this great earthquake may have occurred by strike–slip mechanism and cannot be categorized as a plane of detachment shallow thrust event.

Conclusions

Although the western Himalayan earthquakes, for example, the two recent strong earthquakes ($M \geq 6.0$), the 1991 Uttarkashi and the 1999 Chamoli events, that occurred to the north of MBT in HSB, fit fairly well with the envisaged tectonic model of the Himalaya, the large/great earthquakes that occurred to the south of MBT/HFT do not fit with the HSB model. In this study, it is argued that the 1905 Kangra earthquake occurred at the fault end of HFT; the source zone might be in the lower crust (30–40 km) within the under thrusting Indian plate beneath the foothills. The 1934 Bihar earthquake was earlier argued to have occurred at the East Patna transverse fault at a deeper source zone to the south of MBT, but geological evidences are now put forward with an argument that this great event occurred on the plane of detachment to the north of MBT. The deeper source zone or bimodal seismicity is, however, well established with recent local seismic network data[13], and the 1988 Bihar/Nepal (*Ms* 6.6) and the 2011 (*Mw* 6.9) Sikkim earthquakes are the examples of such deeper source zones. All the recent strong earthquakes in the eastern Himalaya, the 1988 (Bihar/Nepal), 2009 (Bhutan) and the 2011 (Sikkim), have occurred by strike–slip mechanism. We believe that the transverse structures, long lineaments and ridges in the foothills region that cut across the Himalayan trend, are the source zones for large/great earthquakes at greater crustal depth. The 1897 great Shillong plateau earthquake is not a Himalayan earthquake; it occurred about 200 km south of MBT in the Shillong plateau shield, and now it is explained by pop-up tectonics. The pop-up tectonic model is, however, much debated, and needs a detailed geophysical investigation. The 1950 great Assam earthquake occurred at the strike–slip fault system in the eastern syntaxis zone; it is not a typical plane of detachment thrust event. We believe that the Indian shield structures, long lineaments and ridges in the foothills region that transversely hit HFT, are the source areas for large/great earthquakes at greater crustal depth.

In assessing the seismic risk, Bilham *et al.*[53], based on geodetic data, argued that any segment of the Himalaya is presently ready for generating a great earthquake. The population of India in the foothills region has increased more than ten times since the 1905 great Kangra earthquake, when it killed about 19,500 people. Today, 50 million people will be at risk from if an earthquake were to occur in the Himalayan region. Now, several dense local digital seismic networks are available and some are upgraded to permanent telemetric systems in different parts of the Himalaya by different agencies. The data will certainly enhance our knowledge and understanding of earthquakes, but, the enforcement of building codes would be the only precaution we can take to save lives and properties in the towns and villages in the Himalayan foothills/foredeep region.

1. Gansser, A., *Geology of the Himalaya*, Interscience, New York, 1964, p. 289.
2. Valdiya, K. S., Himalayan transverse faults and their parallelism with subsurface structures of north Indian plains. *Tectonophysics,* 1976, **32**, 352–386.
3. Powers, P. M., Lillie, R. J. and Yeats, R. S., Structure and shortening of the Kangra and Dehradun reentrants. *Geol. Soc. Am. Bull.*, 1998, **110**, 1010–1027.
4. Nakata, T., *Geomorphic History and Crustal Movements of Foothills of the Himalaya*, Sendai Institute of Geography, Tohuku University, Japan, 1972, p. 77.
5. Ni, J. F., Active tectonics of the Himalaya. *Proc. Indian Acad. Sci.* (*Earth Planet. Sci.*), 1989, **98**, 71–89.
6. Raval, U., Laterally heterogeneous seismic vulnerability of the Himalayan arc: a consequence of cratonic and mobil nature of underthrusting Indian crust. *Curr. Sci*., 2000, **78**, 546–549.
7. Kayal, J. R., Microearthquake activity in some parts of the Himalaya and the tectonic model. *Tectonophysics*, 2001, **339**, 331–351.
8. Mukhopadhyay, M., Seismotectonics of transverse lineaments in the eastern Himalaya and its foredeep. *Tectonophysics*, 1984, **109**, 227–240.
9. Dasgupta, S., Mukhopadhyay, M. and Nandy, D. R., Active transverse features in the central portion of the Himalaya. *Tectonophysics*, 1987, **136**, 255–264.
10. De, R. and Kayal, J. R., Seismotectonic model of the Sikkim Himalaya: constraint from microearthquake surveys. *Bull. Seismol. Soc. Am.*, 2003, **93**, 1395–1400.
11. Seeber, L., Armbruster, J. G. and Quittmeyer, R., Seismicity and continental subduction in the Himalayan Arc. In *Zagros, Hindu Kush, Himalaya Geodynamic Evolution* (eds Gupta, H. K. and Delany, F. M.), Geodyn. Series, 1981, vol. 4, pp. 215–242.
12. Ni, J. F. and Barazangi, M., Seismotectonics of the Himalayan collision zone: geometry of the underthrusting Indian plate beneath the Himalaya. *J. Geophys. Res*., 1984, **89**, 1147–1163.
13. Monsalve, G., Sheehan, A. F., Schulte-Pelkum, V., Rajaure, S., Pandey, M. R and Wu, F., Seismicity and 1-D velocity structure of the Himalayan collision zone: results from the Himalayan Nepal Tibet Seismic Experiment (HIMNT). *J. Geophys. Res*., 2006, **111**, B10301, doi: 10.1029/2005 JB004062
14. Mahesh, P., Rai, S. S., Sivaram, K., Paul, A., Gupta, S., Sarma, R. and Gaur, V. K., One dimensional reference velocity model and precise locations of earthquake hypocenters in the Kumaon–Garhwal Himalaya. *Bull. Seismol. Soc. Am.*, 2013, **103**(1), doi: 10.1785/0120110328

15. Arora, B. R., Gahalaut, V. K. and Kumar, N., Structural control on alongstrike variation in the seismicity of the northwest Himalaya. *J. Asian Earth Sci.*, 2012, **57**, 15–24.
16. Nelson, K. D. and Zhao, W., Partially molten middle crust beneath southern Tibet: synthesis of project INDEPTH Results. *Science*, 1996, **274**, 1684–1688.
17. Lyon-Caen, H. and Molnar, P., Gravity anomalies and the structure of western Tibet and southern Tarim basin. *Geophys. Res. Lett.*, 1984, **11**, 1251–1254.
18. Chandra, U., Seismotectonics of Himalaya. *Curr. Sci.*, 1992, **62**, 40–71.
19. Richter, C. F., *Elementary Seismology*, W.H. Freeman and Co, San Fancisco, 1958, p. 768.
20. Ambraseys, N. N. and Douglas, J., Magnitude calibration of north Indian earthquakes. *Geophys. J. Int.*, 2004, **159**, 165–206.
21. Middlemiss, C. S., The Kangra earthquake of 4 April 1905. *Geol. Surv. India Mem.*, 1910, vol. 38, p. 409.
22. Hough, S. E., Bilham, R., Ambraseys, N. and Feldi, N., The 1905 Kangra and Dehradun earthquakes. *Geol. Surv. India*, *Spec. Publ.*, 2005, **85**, 15–22.
23. Bhattacharya, S. N. and Kayal, J. R., Seismicity of the Himachal Himalaya: constraint from local seismic network. *Geol. Surv. India*, *Spec. Publ.*, 2005, **85**, 71–79.
24. Kayal, J. R., Himalayan tectonic model and the great earthquakes: an appraisal. *Geomatics, Nat. Hazards. Risk*, 2010, **1**, 51–67.
25. Dunn, J. A., Auden, J. B., Ghosh, A. M. and Wadia, D. N., The Bihar–Nepal Earthquake of 1934. *Geol. Surv. India Mem.*, 1939, **73**, 205.
26. Abe, K., Magnitudes of large shallow earthquakes from 1904 to 1980. *Phys. Earth Planet. Inter.*, 1981, **27**, 72–92.
27. Molnar, P. and Deng, Q., Faulting associated with large earthquakes and the average rate of deformation in central and eastern India. *J. Geophys. Res.*, 1984, **89**, 6203–6227.
28. Bilham, R., Blume, F., Bendick, R. and Gaur, V. K., Geodetic constraints on the translation and deformation of India: implications for future great Himalayan earthquakes. *Curr. Sci.*, 1998, **74**, 213–229.
29. GSI, *Bihar–Nepal Earthquake, 20 August 1988*. Geol. Surv. India Sp. Pub. (eds Nandy, D. R. *et al.*), 1993, vol. 31, p. 104.
30. Singh, D. D. and Gupta, H. K., Source dynamics of two great earthquakes of Indian subcontinent: The Bihar–Nepal earthquake of 15 January 1934 and the Queta earthquake of 30 May 1935. *Bull. Seismol. Soc. Am.*, 1980, **70**, 757–773.
31. Sapkota, S. N., Bollinger, L., Klinger, Y., Tapponnier, P., Gaudemer, Y. and Tiwari, D., Primary surface ruptures of the great Himalayan earthquakes in 1934 and 1255. *Nature Geosci.*, 2013, **6**, 71–76; doi: 10.1038/ngeo1669
32. Kayal, J. R., Baruah, Santanu, Baruah, Saurabh, Gautam, J. L., Arefiev, S. S. and Tatevossian, R., The September 2011 Sikkim deeper centroid *Mw* 6.9 earthquake: role of transverse faults in eastern Himalaya. *Deep Continental Studies India*, 2011, **21**(2), 13–16.
33. Kumar, M. R., Hazarika, P., Prasad, G. S., Singh, A. and Saha, S., Tectonic implications of the September 2011 Sikkim earthquake. *Curr. Sci.*, 2012, **102**(5), 788–792.
34. Kayal, J. R. *et al.*, The 2009 Bhutan and Assam felt earthquakes (*Mw* 6.3 and 5.1) at the Kopili fault in the northeast Himalaya region. *Geomatics, Nat, Hazards Risk*, 2010, **1**(3), 273–281; doi: 10.1080/19475705.2010.486561
35. Oldham, R. D., Report on the great earthquake of 12 June 1897. *Geol. Surv. India, Mem.*, 1899, **29**, 379.
36. Ambraseys, N. and Bilham, R., MSK isoseismal intensities evaluated for the 1897 Great Assam Earthquake. *Bull. Seismol. Soc. Am.*, 2003, **93**(2), 655–673.
37. Bilham, R. and England, P., Plateau 'pop up' in the great 1897 Assam earthquake. *Nature*, 2001, **410**, 806–809.
38. Evans, P., The tectonic framework of Assam. *J. Geol. Soc. India*, 1964, **5**, 80–96.
39. Kayal, J. R. and De, R., Microseismicity and tectonics in northeast India. *Bull. Seismol. Soc. Am.*, 1991, **81**, 131–138.
40. Rao, N. P. and Kumar, M. R., Uplift and tectonics of the Shillong plateau, northeast India. *J. Phys. Earth*, 1997, **45**, 167–176.
41. Nandy, D. R., *Geodynamics of Northeastern India and the Adjoining Region* (acb Publ., India), 2001, p. 209.
42. Rajendran, C. P., Rajendran, K., Duarah, B. P., Baruah, S. and Earnest, A., Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India earthquake: implications for regional tectonism. *Tectonics*, 2004, **23**, TC4009; doi: 1029/2003 TC001605
43. Nayak, G. K., Rao, V. K., Rambabu, H. V. and Kayal, J. R., Pop-up tectonics of the Shillong plateau in great 1897 Assam earthquake: Inference from gravity and seismological data. *Tectonics*, 2008, **27**, TC1018; doi: 1029/2006TC002027
44. Kayal, J. R. *et al.*, Large and great earthquakes in the Shillong plateau–Assam valley area of northeast India region: pop-up and transverse tectonics. *Tectonophysics*, 2012, **532**(53), 186–192; doi: 10.1016/j.tecto.2012.02.007
45. Kayal, J. R., Large and great earthquakes in stable continental region of India: a review. *J. Geol. Soc. India, Mem.*, 2008, **68**, 31–46.
46. Tandon, A. N., A study of Assam earthquake of August 1950 and its aftershocks. *Indian J. Meteorol. Geophys.*, 1954, **5**, 95–137.
47. Ben-Menahem, A., Aboodi, E. and Schild, R., The source of the great Assam earthquake – an interplate wedge motion. *Phys. Earth Planet. Inter.*, 1974, **9**, 265–289.
48. Chen, W. P. and Molnar, P., Seismic moments of major earthquakes and the average rate of slip in central Asia. *J. Geophys. Res.*, 1977, **82**, 2945–2969.
49. Armijo, R., Tapponnier, P., Mercirr, J. L. and Han, T., Quaternary extension in southern Tibet: field observations and tectonic implications. *J. Geophys. Res.*, 1986, **91**, 13803–13872.
50. Holt, W. E., Ni, J. F., Wallace, T. C. and Haines, A. J., The active tectonics of the eastern Himalayan syntaxis and surrounding regions. *J. Geophys. Res.*, 1991, **96**(B9), 14,595–14,632.
51. Holt, W. E. and Wallace, T. C., Crustal thickness and upper mantle velocities in the Tibetan plateau region from the inversion of regional Pnl waveforms: evidence for a thick upper mantle lid beneath southern Tibet. *J. Geophys. Res.*, 1990, **95**, 12,499–12,525.
52. Kayal, J. R., De, R. and Chakraborty, P., Microearthquakes at the main boundary thrust in eastern Himalaya and the present day tectonic model. *Tectonophysics*, 1993, **218**, 375–381.
53. Bilham, R., Gaur, V. K. and Molnar, P., Himalayan seismic hazard. *Science*, 2001, **293**, 1442–1444.

ACKNOWLEDGEMENTS. I thank the editor, *Current Science* for inviting me to contribute to this special section, and the Director General, Institute of Seismological Research, Gandhinagar for his support. I also thank the anonymous reviewers for their useful comments.