Intricacies of the Himalayan seismotectonics and seismogenesis: need for integrated research

O. P. Mishra*

SAARC Disaster Management Centre, New Delhi 110 002, India
Geological Survey of India, Central Head Quarter, Kolkata 700 016, India

The 'Science of Himalaya' is a record of the most dramatic and visible creations of modern plate tectonic forces with hidden mystery of mantle dynamics, showing present-day convergence across different segments of the Himalaya. The Himalaya is standing as the water tower of Asia with high rate of uplift, hotspots of moderate to great damaging earthquakes, and the highest concentration of glaciers outside of the polar region, which need to be studied comprehensively using integrated tools of multi-disciplinary science to resolve several intricate issues, including tectonics and seismogenesis beneath the Himalayan region under climate change scenario. The integrated geoscientific research using different tools of geology, geophysics, seismology and geodetic science help to achieve common consensus among geoscientists on debatable issues related with the complex seismotectonic settings and seismogenesis. Here, several debatable issues related to the evolution of the Himalaya, its intricate seismotectonics and seismogenesis are discussed to demonstrate the need of integrated research for generating authenticate inputs for comprehensive developmental planning for the Himalayan region. It is inferred that results derived from integrated research by involving Indian and international institutions can provide a great opportunity to policy makers and planners to evolve a holistic strategy for natural disaster risk mitigation to make the Himalaya, the third pole, safer and prosperous.

Keywords: Geo-scientific tools, integrated research, seismogenesis, seismotectonics.

Introduction

THE science of the Himalaya is more puzzling and intriguing than perhaps any other problem in geosciences today. The Himalaya, the third pole, is one of the best natural laboratories in the world for conducting multidisciplinary research. It has opened up ample avenues for global scientists, who have carried out diverse studies to address a series of intricate problems related to continental tectonics as well as environmental sciences. They include such studies as its origin and biodiversity; geological and seismotectonic set-up; interpretation of geophysical/seismological and geodetic signatures; assessment of natural mineral deposits in the Himalaya and the river systems and erosion features. State-of-the-art techniques of exploration and exploitation have been applied in these studies.

A number of studies have been made by scientists from India and abroad on the issues of the Himalayan evolutionary history/orogeny, geochemistry, seismogenesis and anomalous geophysical and geodetic signatures. However, there is no general consensus among geoscientists of different disciplines. This reflects the dynamism of scientific ideas derived from multidisciplinary research in the realm of advanced geo-scientific tools of exploration, rigorous analytical ability and skillful interpretation of geo-scientific data. With the advent of modern geo-scientific instrumentation and development of powerful algorithms for robust numerical modelling, it has been realized that the need of the hour is to apply multidisciplinary science in an integrated fashion for comprehensive investigation of the Himalaya. This may yield a plausible model of common consensus to understand the intricate tectonic set-up of the Himalaya. Here, some of the intricate issues of Himalayan tectonics have been discussed in the light of deployment of integrated geo-scientific tools to generate common consensus on some of the controversial issues. A study of the 18 September 2011 Sikkim earthquake (Mw 6.9) has been examined to understand the question of what caused the main shock and aftershocks. It is inferred from such a study that an integrated Himalayan geology should consider all the provinces of the Himalaya as a unified dynamic system, not only geophysically, but also socio-environmentally to offer solutions to some of environmental problems[1] related to the establishment of hydroelectric power projects, deforestation and soil erosion in the Himalayan belt of high seismic activity.

Himalayan tectonics and issues of concern

Himalayan geoscience is not a new field of study as it dates back to the first half of the 19th century, when the British began to explore the Indian subcontinent[1]. The origin of the Himalaya, the highest mountain chain in the world, has been the most challenging problem to the geoscientists because of its complex seismotectonic settings

---
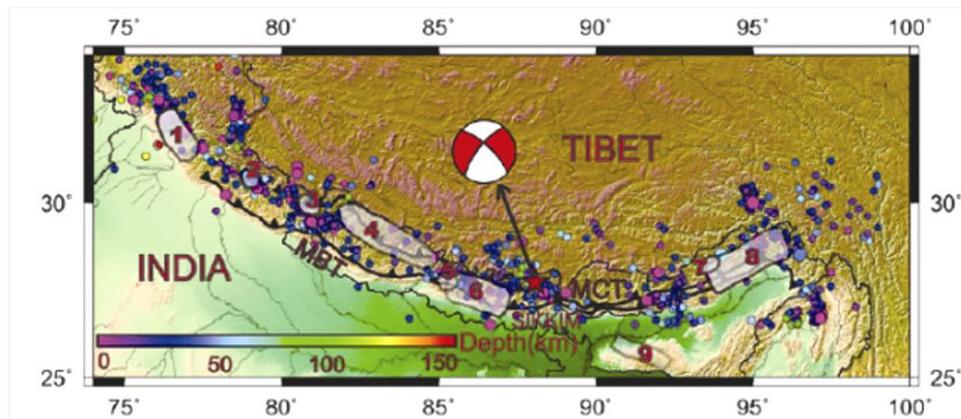
Figure 1. Map of the Himalaya–Tibet region with the major tectonic features and earthquakes of $M > 4.5$ (source: Nath *et al.*[86]). Circles indicating the epicentral locations are colour-coded according to depth (adapted from Kumar *et al.*[76]). Shaded regions (grey colour) indicate rupture areas of major earthquakes in the Himalaya. (1) 1905 (*M* 7.8); (2) 1803 (*M* 7.3); (3) 1916 (*M* 7.5); (4) 1505 (*M* 8.1); (5) 1833 (*M* 7.3); (6) 1934 (*M* 8.3); (7) 1947 (*M* 7.8); (8) 1950 (*M* 8.4) and (9) 1897 (*M* 8.1); MBT, Main Boundary Thrust; MCT, Main Central Thrust. The epicentre of the 2011 *Mw* 6.9 Sikkim earthquake (red star) and its focal mechanism (beach ball) are also shown (adapted from Kumar *et al.*[76]).

and frequent seismogenesis (Figure 1). Several studies have revealed that the Himalaya consists of sedimentary rocks deposited over millions of years in shallow seas; yet it is not clear in what sea these were deposited and how these were sandwiched between the subcontinent of India and the main Asian land mass to the north. The rise of the Himalaya has been explained partly because of deepening of the depositional basins of Indus–Ganga–Brahmaputra due to flexural isostasy[1]. It has been suggested that the Tibetan Plateau is a median mass, forming part of a geo-synclinal block between the continents of Asia and India[2] and it has also been argued that the uniform and very high altitude of Tibet is due to underthrusting of the Indian plate beneath the whole of Tibet, causing almost double thickness of the crust. Such an idea calls for about 1000 km long, shallow fault plane dipping 0–5° separating the underthrusting Indian plate from the overlying Tibetan crust. Neither seismicity nor fault plane solutions provides evidence for such a fault zone at present and nowhere on the Earth has an inclined seismic zone been detected that dips at such a low angle for such a long distance[3]. This observation is also corroborated from the deep seismic sounding results coupled with the seismicity data recorded for the region[3], which may be addressed to a logical end with support of detailed seismic imaging and subsurface modelling using a large set of high-resolution data available from geological, geophysical, seismological, geodetic and geochemical studies.

Gansser[4–6] described the Indus Suture Line at the Indo-Tibetan border as a root-like downbuckling, with orogenic effects on Middle Cretaceous marine sediments of Tethyan facies. Upper Cretaceous flysch contains ophiolites and huge exotic blocks of sediments containing a pelgic facies unknown in the Himalaya. These sediments might have been deposited in deep basins situated between the present Himalaya and the Tibetan Plateau[4]. These original basins have completely disappeared and now are testified only by the presence of Indus Suture Line[4,5]. This is well corroborated by recent detailed seismic tomography carried out in the northeast and Tibetan Himalayan region, which shows that the Indus Suture Line is associated with conspicuously low velocity that may be due to the presence of marine sediments and flysch (O. P. Mishra, unpublished)[7,8]. Some authors proposed that the origin of Himalaya is related to collision of two continents, such as India and Eurasia with Indus Suture Line as the plate boundary. Dewey and Bird[9] have presented the present-day scenario prevailing in the Himalaya, where two continental plates collide with each other and the Indian plate subducts beneath the Eurasian plate. In principle, it seems reasonable to describe the tectonics of Eurasia by the interactions of blocks of lithosphere; it is, however, not yet clear what mechanism of interaction of blocks of lithosphere has been followed as a large numbers of blocks are involved in the process[10]. It is a proven fact that the interaction of blocks of lithosphere becomes much more complex when all the blocks involved are continental than when at least one is an oceanic block. Studies demonstrated that the seismicity pattern in the Tibetan Himalayan region is quite diffused as the pattern is not completely oriented with the known seismogenic structures in the areal extent, which reflects either the presence of more heterogeneous lithosphere due to its continental origin or the reactivated old zones of weaknesses due to interactions among lithospheric blocks of the Indian and Asian plates. It is worth mentioning that because of the low density, it may not be possible to underthrust a block of continental lithosphere into the mantle to depths of several hundred kilometres, which might explain the absence of intermediate and

deep earthquakes in this region. At the same time, the age difference in continental lithospheres invites another explanation of underthrusting of one continental block against another since the older and colder lithosphere block becomes relatively heavier than the younger and warmer block (O. P. Mishra, unpublished).

The concept of the Indus Suture Line as a plate boundary and the height of the Tibetan Plateau is incompatible[11]. Crawford[11] argued that the Indus Suture Line is a relic fracture to the mantle, but for a period only represented by the faunas of the exotic blocks of the Tibetan Himalaya of the Permian–Late Jurassic age. He has indicated that Tibet originally was part of a plate, including India but submerged while India remained continental[3]. Moreover, Molnar and Tapponnier[12] consider most of the large-scale tectonics of Asia to be a result of the India–Eurasia continental collision, which apparently not only created the Himalaya but also rejuvenated an old orogenic belt (Tien Shan) about 1000 km north of the Indus Suture Line. The collision generated prominent strike–slip faulting oblique to the suture zone, and perhaps ripped open two rift systems more than 2000 km away in form of the Baikal rift and the Shansi graben. Based on calculated convergence since collision, shortening and underthrusting of India beneath the Himalaya and Tibet have been estimated to be at least 300 and 700 km. Another 200–300 km shortening is also expected to happen due to thrusting and crustal thickening in the Pamir, Tien Shan, Altai, Nan Shan and other mountain belts[12]. They inferred that probably a total of 500 km and conceivably 1000 km of east–west motion could have occurred and could account for a comparable amount of shortening. The recognition of large strike–slip motion in their opinion[3,12] may obviate the need for postulating the underthrusting of India beneath the whole of Tibet. The issue of extent and amount of shortening and crustal thickening is still debatable for the Himalayan region, which can be addressed with plausible interpretation derived from the integrated geoscientific observational data coupled with the latest geodetic results.

Tectonic models and seismogenesis beneath the Himalayan region

In recent decades, several plate tectonic models have been proposed to discuss the evolution of the Himalaya[13–18]. The Himalaya is generally regarded as a result of continental collision of Indian and Eurasian plates for which several pieces of geological, seismological and geophysical evidences have been put forth to understand the collisional tectonics of the region[13,15–17,19–21]. The initial contact between the two plates occurred along the Indus–Tsangpo Suture Zone in early Eocene. The closure of the Tethys Sea and ancient sea located between the two continents, was completed towards the end of the Eocene[22].

Thereafter the Indus–Tsangpo Suture Zone ceased to be an active plate boundary. This observation is supported by the detailed study[3] based on the scrutiny of the seismotectonics map of the Himalaya and earthquake epicentral location map as characterized over the major portion by a low a-value of 2 (Guttenberg–Richter equation; $\log N = a - bM$), representing the excessive cohesiveness among rock materials. However, this concept of cohesiveness based on a values derived from the Gutenberg–Richter equation does not hold good all along the Indus–Tsangpo Suture Zone, which opens ample avenues to conduct detailed integrated geoscientific study in the zone to understand the plausible cause of low seismicity in the region associated with plate convergence, where active tectonics is supposed to exist under the environment of plate coupling.

At present two tectonic models – a steady state model of Seeber et al.[18], and an evolutionary model of Ni and Barazangi[13] have been proposed to explain the Himalayan seismicity. In the steady state model, the zone of detachment has been identified as a portion of the active thrust fault between the subducting slab and the sedimentary wedge[22], while the portion between the interacting slabs is named as the Basement Thrust (BT). The line of separation between very shallow dipping 'detachment' from the steeper dipping BT is named as the Basement Thrust Front (BTF). The steady state model discusses the tectonics of the central portion of the Himalayan arc. It considers that the great Himalayan earthquakes are associated with the detachment and in the period between great earthquakes, the detachment remains aseismic and moderate magnitude thrust earthquakes occur in a narrow belt down-dip from BTF or in the deeper part of the Main Central Thrust (MCT) that merges into BT[22]. However, the concept of aseismicity during the intermittent period of the great earthquakes needs to be studied using detailed analyses of both seismological and geodetic data in corroboration with geological models in the central Himalayan region.

In the evolutionary model[13], it has been proposed that the zone of plate convergence progressively shifted toward the Indian shield, and MCT and the Main Boundary Thrust (MBT) were formed subsequent to collision between India and Asia during the Eocene. The MCT (Miocene–Pliocene) is older than MBT (Pliocene–Recent)[16]. The seismicity pattern is associated with the geometry of the underthrusting Indian plate, location of thrust, strike–slip and normal faulting events and other tectonic parameters. The zone between MBT and MCT was marked as seismically active[13]. The model suggests that the ruptures of the great Himalayan earthquakes may have started in the interplate thrust zone and propagated south along the detachment to MBT and subsidiary surface and blind thrusts[22]. Ni and Barazangi[13] argued that all the Himalayan thrust earthquakes define a part of the detachment between the underthrusting Indian plate and the upper

block of the Himalaya[22]. Rupture model of the great Himalayan earthquake of 1897 using high-quality data yielded impressive results and was ascertained the role of asperity in triggering the mega earthquake[23]. Similar approach may be adopted for other past damaging earthquakes to understand the rupture dynamics of the Himalayan region.

It has been observed that MCT is active in steady state model and inactive in the evolutionary model[22–25]. However, these two tectonic models are not strictly applicable in every part of the Himalaya as, for example, the Sikkim–Darjeeling Himalaya. Here, Main Himalayan Thrust (MHT) and Lesser Himalayan Duplex (LHD) are found to be active. Critical reviews of these two important tectonic models indicate that the zone of detachment is important. It is observed that basal decollment would be more appropriate than detachment which is usually connected with extensional tectonics. Depth of detachment needs to be properly redefined through remodelling using high-resolution seismic data to estimate the depth constraint of the zone of 'detachment'. Use of earlier seismological dataset of International Seismological Centre (ISC) having poor depth constraints has not illustrated the accurate depth of the detachment layer. Hence, well-relocated data with better depth constraints may provide accurate disposition of the detachment layer beneath the Himalaya. The recently acquired seismological data by various seismological research agencies of India have relatively better depth constraint that can be used to estimate depth of detachment to understand its relationship with Himalayan seismicity. Redefining the zone of detachment is important to assess the impact of earthquakes and earthquake hazard for the Himalayan region. This endeavour may need combined effort of compiling local, regional and national level high-quality seismological data and their relocations using versatile earthquake relocation algorithms. Comprehensive interpretation of the relocated seismological data using the integrated tools of geosciences may yield true picture of the detachment layer beneath the Himalayan region. It is one of the challenging tasks for seismologists and geophysicists.

Earthquake-generating processes have great bearing on the existing seismogenic faults and the plate boundary of the region under collisional–subduction tectonics. The identification of plate boundary and convergence zone has become one of the important topics of research using the integrated science coupled with seismological and geodetic observations. In this context, it is worth mentioning that several studies have been made to understand the stages of tectonic evolution of the mountain by analysing fluvial records and morphotectonic imprints in the light of active deformation scenario in the Himalayan region[26–28]. Based on detailed examination of the landscape to the south of the Himalayan Frontal Thrust (HFT) in the NW Sub-Himalaya, active faulting has been identified and new plate boundary has been established[29]. A similar

study has been carried out in the NE Himalaya[26]. Studies along Tista River in the frontal part of the Eastern Himalaya suggested out-of-sequence surface breaking faults, indicating partial accommodation of active convergence within the Himalayan wedge[30], which can be validated by other supportive methods of geosciences to address the issue of neotectonic rejuvenation of pre-existing faults and deformation of the Himalaya under different tectonic regimes. A detailed study on the evolution of the Himalayan Palaeogene foreland basin in the Eastern Himalaya revealed several fascinating facts about the tectonics of Himalaya[31].

Seismogenesis beneath the Himalayan region is one of the challenging issues. Several past studies have not yet offered plausible and convincing explanation on what causes the great Himalayan earthquakes, their aftershock sequences and the background seismicity of different magnitudes at different depths[32]. The generating mechanism of earthquakes, occurring in different parts of the Himalaya, extending from NW to NE, is not similar because of crustal and sub-crustal/lithospheric heterogeneities with appreciable stress perturbation. Additionally, the existence of seismogenic faults, geometry of subducting Indian plate and its depth of disposition in different parts of the Himalaya may have strong bearing on the earthquake-generating processes beneath the Himalaya[33,34]. Prevalence of the Himalayan transverse tectonics under collisional regime and its parallelism with surface structures have provided plausible cause of seismogenesis[35–37]. However, detailed study is still warranted to understand the constraints of geomorphology and seismo-geotectonic settings in different parts of the Himalaya. Based on studies of recent earthquakes elsewhere in the Himalaya (e.g. Kashmir Himalaya), it has been argued that the Himalayan mid-crustal ramp might be the cause of moderate to strong earthquakes (e.g. the 2005 Muzaffarabad earthquake)[38], while detailed study of aftershock sequences of the 1974 Pattan earthquake and of the 2005 Muzaffarabad earthquake demonstrated that the rupture of the southern part of the unruptured part of the causative fault of the 1974 Pattan earthquake (M 5.9) might have caused the 2005 Muzaffrabad earthquake in the Indo-Kohistan Seismic Zone[39]. Alternate interpretation based on geodynamical model has also been provided to understand the genesis of the earthquake[40]. Recent studies on seismotectonics in the area where the Himalaya terminates in and around the eastern and western syntaxis zones revealed that earthquake-generating processes are related to the crustal asperity of the locked zone in the Himalaya[41]. Such different interpretation of earthquake genesis needs detailed study to evolve a plausible model of understanding the mechanism of seismogenesis beneath the different segments of the Himalayan region. Study on the evolution of the Himalayan fold-and-thrust belt derived from the thrust geometries and deep structure of the outer and lesser Himalaya in the

Garhwal (India) region[42] suggests that the pattern of earthquake follows the tectonic set-up of the region, as the generating mechanism of the earthquake is closely associated with intricate tectonics, which may not be similar in each segment of the Himalaya.

Geotectonic setting of the Sikkim–Darjeeling Himalaya is found to be complicated[43–45] as the region has been associated with several faults and lineaments mapped on the surface, besides other prominent mapped tectonic faults and structures such as MBT, MCT, MFT, MHT, Gish Transverse Fault (GTF) and LHD. Presence of several mapped lineaments in the Sikkim–Darjeeling Himalayan region[43] generated special interest among geoscientists to validate their existence in the field. The Tista lineament, as mapped within the mountain front[43], is shown to cross-cut the western part of LHD as well as the thrust sheet. Recent studies demonstrated that no such fault zone is observed in the field[46,47]. All lineaments are mapped as straight lines that run through all topographic highs and lows[43], suggesting that lineaments are vertical faults. The studies[46,47] claimed that even if the lineaments really exist, their geometry and kinematic significance is not well constrained[48]. Guha *et al.*[44] in Sikkim–Darjeeling Sub-Himalayan region reported several tectonic imprints of Himalayan thrust tectonics on the Quaternary piedmont sediments. In order to resolve the controversy whether lineaments exist in the field and also for better assessment, there is a need to undertake a comprehensive study using fresh dataset from the integrated geoscientific studies coupled with satellite imagery, remote sensing, and extensive 3D subsurface imaging[46,47].

Historical great earthquakes of the Himalayan region generated interest among the scientists and society to know what would be their implication for future earthquakes that may occur along the entire Himalayan arc. Studies using Global Positioning System (GPS) measurements in India demonstrated that collision of India has resulted in flexure of the Indian plate and Tibet along east–west zone of convergence across the Himalaya, which results in the development of potential slip to drive large thrust earthquakes beneath the Himalayan region[49,50]. The studies[49,50] clearly demonstrate that most of NE India is close to failure as the triggering of earthquakes occurs partly from the movement of India through the flexural stress field, and partly from local stress perturbations caused by other tectonic, erosional or dynamic processes. The recurrence interval for great Himalayan earthquakes was observed[50] to remain conjectural since the historic record is incomplete even for the past 500 years. The study inferred that almost two-thirds of the Himalaya is unbroken by recent earthquakes, suggesting several seismic gaps may currently exist and supported by the summation of seismic moment from all known earthquakes since 1505 along the entire arc, yields a slip rate lesser than 30% of that derived from the current geodetic slip rate[50,51]. Smaller seismic gaps are identified in Kashmir, Sikkim and Assam, besides the Central Himalayan seismic gap, which have the potential for earthquake disaster along the Himalayan Plate boundary[50,52]. Existence of several seismic gap zones in the Himalaya requires a comprehensive seismic imaging of asperities of the gap zones to ascertain the nature and extent of structural heterogeneities and their bearing on future failure[33,34]. Recent study[53] on the 1 September 1803 Garhwal earthquake has revealed that the aftershock sequence of this earthquake continued till the year 1817 for fourteen years, followed by a period of seismic lull up to the year 1831. This envisages that such a major earthquake within the central seismic gap in the Himalayas requires reconciliation on available seismic hazard assessment, which can be addressed through the deployment of integrated geoscientific tools of seismology, geophysics, geodetic science, and geology.
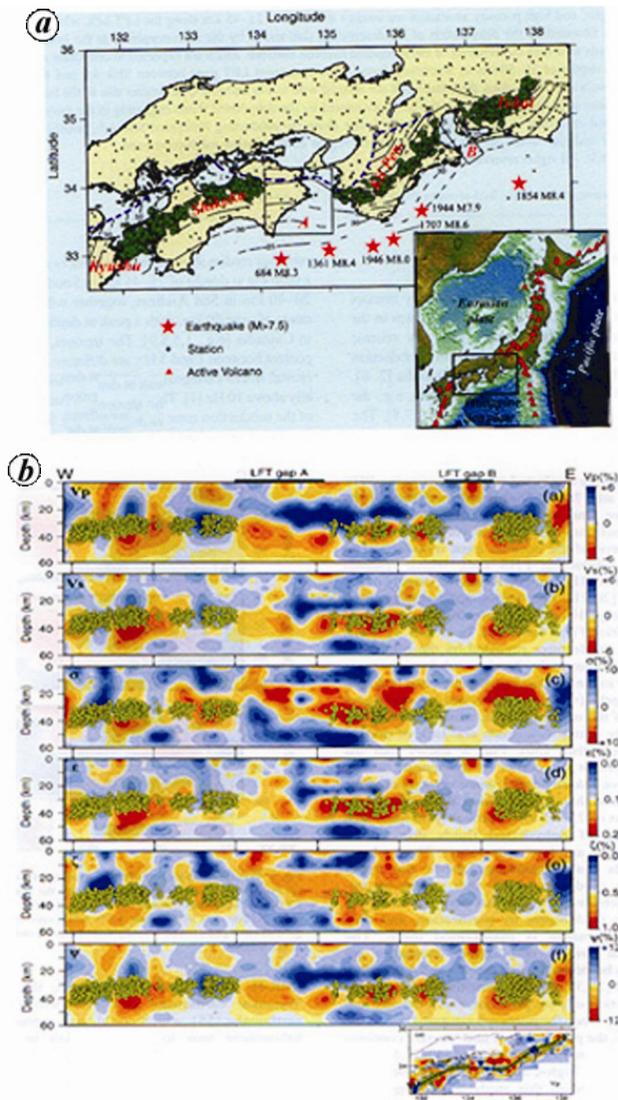
Moreover, the seismic gap theory needs a thorough investigation to ascertain the potential of the seismic gap zone of impending future earthquakes. This is required for better assessment of earthquake hazards as well as to avoid panic among the public in the name of future strong to great earthquake in these demarcated seismic gap zones. It is pertinent to mention that all seismic gaps may not be potential zones for impending future earthquakes, because the genesis of earthquake is dictated by the seismogenic strength of the causative source rocks (O. P. Mishra unpublished)[32–34]. A recent 3D seismic tomographic study[54] made in southwest Japan arc showed that the demarcated seismic gaps are ductile due to super saturation of the cracked volume of subsurface rocks associated with the low frequency seismic tremor gaps, which may not be apt to bring the brittle failure in the demarcated seismic gap zones and hence negating the chance of occurrence of micro- to macro-earthquakes (Figure 2). It is, therefore, imperative to have a detailed 3D seismic imaging in the entire Himalayan arc to understand the nature and extent of crustal/lithospheric heterogeneities of the seismic gap zones that dictate the seismogenesis of the region, besides the prevailing tectonics[32,33,55,56], which may provide a plausible explanation for the potential of seismic gap zones, whether these would impend strong to great earthquakes or not.

Studies[57–60] on spatial variation of seismicity along the Himalayan arc showed that various factors, such as plate motion or convergent rate, lithology, rheology, tectonic complexity, heat productivity, varying asperity or structural heterogeneities and past damaging earthquakes in the different segments of the Himalaya are responsible for causing earthquakes. Segmentation of seismicity along the Himalayan arc due to structural heterogeneities in the underthrusting Indian plate and overriding Himalayan wedge has been studied by Gahlaut and Arora[60]. They surmised that the presence of the ramp which connects the shallow section of seismically active detachment to the aseismically slipping deeper section of the

detachment is the cause of high seismicity in the Himalayan Seismic Belt (HSB). They also showed that the approximately north–south extending active rifts of the Tibetan and Higher Himalaya cause stress shadow near their southern extent in HSB, that inhibits the occurrence of small and moderate magnitude thrust earth-

Figure 2. *a*, Depth distribution of the descending Philippine Sea (PHS) plate (solid and dashed counter lines) beneath southwest Japan. The Pacific slab subducts towards NWW under the PHS plate. Crosses denote the 458 stations located in the land area of Japan. Red stars represent great earthquakes that occurred during the period 684–1998. (Inset) Red triangles in the map indicate active volcanoes. Green dots represent the low-frequency tremors (LFTs) that occurred during the period June 2001–October 2005. Boxes *A* and *B* indicate two gap zones. The blue, thick, dashed line shows the leading edge of the seismic portion of the subducting PHS plate. Square represents the study region. *b*, Vertical cross-sections from top to bottom for *P*-wave and *S*-wave velocity, Poisson ratio crack density, saturation rate and porosity parameter images along the profile shown in (*a*) (inset). The corresponding perturbation scale is shown on the right of each image. Yellow dots denote locations of LFTs. Two bars on the top of cross-sections represent the LFT gaps, which are also shown in (*a*) (inset) (after Wang *et al.*[54]).

quakes[60]. The role of structural heterogeneities in segmenting seismicity pattern along the Himalayan arc needs to be ascertained by deploying integrated tools of receiver function and fine seismic imaging beneath the region. It is found that the nature of seismogenesis along the Himalayan arc varies from transverse tectonics that is more active in the eastern Himalaya to the thrust tectonics, which is dominantly prevalent in the western Himalaya. Moreover, studies using magnetotelluric techniques deciphered the transverse conductive structures beneath the northwest and Sikkim Himalaya[61,62]. Uneven distribution of past damaging moderate to strong earthquakes along the Himalayan arc revealed that the degree of seismic coupling is different in different segments of the Himalayan arc. The western syntaxis is more coupled because of shallower plate angle in comparison to that of eastern syntaxis having relatively deeper plate angle. Distribution of seismicity in clusters, predominantly occurring in the western segment of the Himalaya compared to the eastern segment, also corroborates the concept of varying structural heterogeneities in the Himalayan arc. However, there is a need to demarcate the structural asperity using integrated tools of seismological research, including subsurface imaging of the syntax zones in the Himalayan region.

The northeast region of India has experienced about 18 large earthquakes ($M > 7.0$) during the last 100 years, including the great earthquakes of Shillong (1897, *M* 8.7) and Assam–Tibet border (1950, *M* 8.7). Apart from the major earthquakes, several smaller to moderate-sized earthquakes ($M < 7.0$) have also been reported to indicate that the region is highly vulnerable to earthquake hazards. The complicated tectonics resulting from the collision and continued north–south and east–west convergence of the Indian plate towards Himalaya and Burmese arc apparently accounts for higher level and diffused seismicity in NE India. The Shillong Plateau is tectonically active since the Mesozoic, along with the mountain-building processes in Himalayas. It is believed that the Plateau is a detached portion of the Indian Shield and its seismogenesis has good correspondence with that of peninsular India. Shillong Plateau comprises several seismogenic faults and lineaments such as Dudhnoi Fault, Kulsi Fault, Dauki Fault (DF), Barapani Thrust and Dhansiri–Kopili Fault, and was the seat of a great Shillong earthquake (1897, *M* 8.7). In the south, the Dauki Fault system trending in east–west direction separates the plateau from the thick Tertiary sedimentary rocks of Bengal basin to the south (O. P. Mishra, unpublished)[33]. The earthquakes of micro to moderate type occurred in clusters and swarms. The NW–SE trending Dhansiri–Kopili Fault in the northeastern part of the Plateau shows transverse tectonics yielding normal/strike–slip faults, which separates the Plateau from Mikir massif. The 1897 great Shillong earthquake (*Mw* 8.7) generated the north-south trending Dudhnoi Fault which has sinistral movement along the

sub-vertical oblique strike fault. However, the plausible cause of earthquake swarms and clusters needs to be ascertained in terms of crustal heterogeneities attributed to the generation of differential strain beneath the region. Continuous seismogenesis of micro- to macro-magnitude in the Indo-Burma region demonstrates that the subduction of the Indian plate beneath the Burma micro-plate is still continued[63]. The concept of plateau-pop-up in the 1897 Assam earthquake has been provided to explain the origin of the causative Oldham Fault[64]. The subducting Indian plate beneath the overriding Burma micro-plate has been imaged by 3D seismic tomography that shows strong association of structural heterogeneities with seismicity beneath the Indo-Burma region (O. P. Mishra, unpublished)[33,65]. The deeper earthquakes beneath the Indo–Burma range are found to be related with the dehydration of the subducting Indian plate (O. P. Mishra, unpublished)[33]. These observations envisage that similar approach by imaging the subducting Indian plate may be applied to ascertain the nature of seismicity and subduction dynamics in other segments of the Himalaya.

There is continuing debate on channel flow versus critical wedge tectonics in the Himalaya, which controls the extent of seismogenesis and seismotectonics in the region. A comprehensive report[66] based on deep seismic reflection profiling across southern Tibet from project INDEPTH[67,68] combined with broadband earthquake and magnetotelluric data[69] showed a high-conductivity layer at 15–20 km depth, indicating partial melts and/or aqueous fluids in the middle crust of southern Tibet[68,70]. High geothermal activity and high heat flow at shallow levels in the south Tibetan crust have been attributed to aqueous fluids and steep geo-them beneath south Tibet. Several factors such as radiogenic heating and crustal thickening and shortening could have induced the high temperatures at these mid-crustal levels beneath south Tibet. Analyses of high-quality seismological data showed that higher velocity is associated with upper mantle that extends northwardly from the Himalaya to roughly the centre of the Tibetan Plateau. The detailed seismic structure associated with channel flow beneath the entire Himalayan range may be studied using the 3D passive source of tomography coupled with wide angle reflection (WAR) surveys, shear-wave splitting and receiver function analyses. Detailed results derived from seismological data are required to be corroborated with deep resistivity structure obtained from magnetotelluric observations[71,72] so that common consensus among scientists on the contentious issues of seismogenesis and channel flow can be achieved.

Sikkim–Darjeeling Himalaya and seismogenesis

The Sikkim–Darjeeling Himalaya has generated special interest among geoscientists because of its unique tec-

tonic settings, incomplete earthquake catalogue and the unusual seismicity in the region. Recent occurrence of the 18 September 2011 damaging earthquake (*Mw* 6.9) has provided ample opportunity to conduct detailed study on seismogenesis and seismotectonic setting of the eastern Himalaya. The Sikkim–Darjeeling Sub-Himalaya region has been studied seismologically by setting up temporary seismograph networks in a limited area[73–75] to address different problems based on analyses of seismicity pattern and strong motion data. Seismological evidence has been provided for the existence of transverse tectonics in the Sikkim–Darjeeling Himalaya[36,75,76]. Based on significant change in gravity values (–30–300 mGal) along the Siliguri–Gangtok–Tingda, Melli–Takda and Jorthang–Labha transects, where several past earthquakes ($2.0 \leq M \leq 5.0$) occurred (D. K. Saha *et al.*, unpublished)[77], it has been inferred that a drastic changes have taken place in seismo-mechanical properties of the subsurface rock materials beneath the Sikkim–Darjeeling Himalaya (O. P. Mishra, unpublished)[78]. Detailed studies of the area using integrated geophysical and geological tools can provide convincing explanation for the nature and extent of crustal heterogeneities.

Recently, a comprehensive study of the Sikkim–Darjeeling Himalaya was made by setting up a well-defined seismograph network, which consisted of a total of 18 seismograph stations and collecting data in two consecutive years (2007–2008 and 2008–2009) under the field season programs of Geological Survey of India (O. P. Mishra, unpublished). A total of 756 earthquakes ($M < 6.0$), confined to the lithospheric layers were recorded and relocated. The recorded and relocated event cluster is found to be well concentrated in and around the culminated zone of MCT beneath the Sikkim–Darjeeling Himalaya, covering LHD (Figure 3), suggesting that both MHT and LHD are active[79], which is in good agreement with the observation made using another seismological dataset by Mukul *et al.*[48]. The entire study region[78] has been divided into several blocks to assess the nature and extent of crustal heterogeneities by determining seismological parameters (*a* and *b* values) in each block as shown in Table 1. The type of faulting has also been studied by conducting composite fault-plane solutions (Table 2). Events are found to be located at depths (> 100 km) beneath the Sikkim–Darjeeling Himalayan region, and deeper events are found to be located within LHD (Figure 3 and Table 2). It is found that the area of study has strong variation in crustal/lithospheric heterogeneities for which the *b* value is found to vary from 0.74 to 1.18, indicating the variation of stress that corresponds to genesis of thrust (low *b* value) and strike–slip to normal fault (high *b* value). Most importantly, events located beneath the Sikkim–Darjeeling Himalaya showed mixed type of faulting (thrust, strike–slip, and normal) in different blocks (Table 2), indicating and supporting the intricate seismotectonic set-up and existence of the transverse

tectonics features here. The omega-shaped MCT representing LHD is associated with Daling, Buxa and the Gondwana units, where thrust or thrust with strike–slip faulting prevails with appreciable b value variations within LHD. The fault plane solutions for the blocks inside the culmination zone of MCT show different nature of faulting; these deviations may be caused by several factors, including the local stress perturbation due to local lineaments and faults. However, the role of *in situ* material heterogeneities in the form of fractured/cracked host rocks[54–56,78] cannot be ruled out, and thus the entire culmination zone of eastern Himalaya requires to be studied in detail by applying the multi-fractal approach[80,81]. The epidemic type of earthquakes associated with cracks and faults in the tectonically intricate zone beneath the Sikkim–Darjeeling Himalaya can also be deciphered using the multi-fractal method[82].

Recent studies[83,84] suggested that the occurrence of the 18 September 2011 main shock reflects the ongoing deformation of the subducting Indian plate[84], which may be attributed to the strong anisotropy beneath the lower crust[84] coinciding with an LVL at depth of 20–30 km. It is important to note that the entire area began to witness intense seismicity during 2007–2009, prior to the occurrence of the 18 September 2011 Sikkim earthquake (*Mw* 6.9), whose focus was at a depth of about 19.6 km beneath the Sikkim Himalaya. The cause of genesis of the main shock has been discussed solely in light of geotectonic settings[36,84–86], suggesting tectonic factor as the major facts. In the same context, it is observed that apart from the intricate geotectonic settings, the role of *in situ* material heterogeneities beneath the main shock hypocentre cannot be ruled out as one of the factors of generating the main shock. Detailed 3D seismic

tomography study beneath the 2011 Sikkim earthquake source area may help understand the processes of rupture initiation, propagation and termination of the main shock in Sikkim Himalaya. Such a study would provide a better scope of earthquake hazard assessment for the region.

The main shock of the 18 September 2011 Sikkim earthquake (*Mw* 6.9) is found to be located in Block 14 (Figure 3 *c*), demarcated in the vicinity of the intersection of the Tista and Kanchunjungha lineaments (Figure 3 *a*), which is associated with high a value varying from 4.07

Table 1. A comparative study of a and b values in different blocks estimated by least square method and maximum likelihood method (Mishra *et al.*[78])

| Block | Least square method | | Maximum likelihood method | |
	a	b	a	b
1	3.96	1.06	4.35	1.11
2	3.70	0.81	3.82	0.83
3	3.02	0.64	3.44	0.74
4	4.08	1.08	4.64	1.18
5	5.24	1.24	4.83	1.05
6	4.53	1.01	5.12	1.12
7	3.91	0.95	4.20	0.95
8	4.38	1.08	4.55	1.05
9	4.89	1.10	5.14	1.11
10	4.26	0.91	4.54	0.93
11	3.30	0.74	3.37	0.73
12	2.97	0.54	3.31	0.62
13	3.18	0.57	3.73	0.71
14	4.07	0.90	4.34	0.91
15	3.81	0.84	4.27	0.90
16	2.60	0.55	2.75	0.56

Table 2. Details of fault plane solutions (Mishra *et al.*[78])

Block	Depth (km)	Strike	Dip	Rake	Nature of fault
1	10–130	77.9	82.9	44.6	TSS
2	0–30	286.2	75.8	–44.2	NSS
	30–80	162.2	54.4	80.1	T
	>80	336	88.3	–1.0	SS
3	0–20	258.7	64.3	16.1	TSS
	20–100	67.1	86.8	35.9	TSS
4	20–50	193.8	73.3	25.3	TSS
	50–120	302.7	64.3	16.1	TSS
5	0–12	327	49.1	–39.0	NSS
	12–42	300.5	46.9	69.2	T
	42–100	285.8	72.9	25.0	TSS
6	0–25	303.5	37.5	–43.9	NSS
	25–100	356.4	30.4	80.1	T
7	0–35	265.6	84.0	29.5	TSS
	35–80	98.6	56.4	80.4	T
8	0–20	12.1	61.6	–23.1	NSS
	20–50	204.6	14.1	–44.6	NSS
	50–100	150.4	86.3	11.4	SS
9	0–10	145.7	30.5	78.1	T
	10–50	216.1	64.3	81.1	T
	50–100	46.3	79.6	44.0	TSS
10	0–10	248.5	77.8	–4.5	SS
	10–40	259.9	57.2	32.7	TSS
	40–100	341.0	79.5	–10.7	SS
11	10–50	157.6	84.0	29.5	TSS
	50–100	275.7	71.3	–19.8	NSS
12	20–50	184.8	67.2	–70.4	NSS
	50–100	121.5	71.0	–26.2	NSS
13	0–15	45.6	62.8	–45.0	NSS
	15–45	198.5	58.3	–72.3	N
	45–100	164.9	52.3	20.1	TSS
14	20–40	146.3	74.2	–81.7	N
	40–100	95.6	87.5	–17.8	NSS
15	5–50	356.0	52.8	–64.6	NSS
	50–100	136.2	72.9	–25.0	NSS
16	5–40	182.5	85.4	49.9	TSS
	40–160	278.6	75.5	–26.6	NSS
17	5–20	286.6	34.0	68.1	T
	20–60	327.4	78.5	–73.7	NSS
18	10–80	64.3	18.0	32.9	TSS
19	10–80	55.9	42.1	–31.1	NSS
20	0–25	313.3	47.7	47.5	TSS
	25–50	337.6	39.4	80.5	T
	50–150	189.3	66.1	83.4	T

T, Thrust; TSS, Thrust with strike–slip; N, Normal; NSS, Normal with strike–slip; SS, Strike–slip. Block 14 is marked with **bold** font in which the 18 September 2011 Sikkim earthquake occurred.
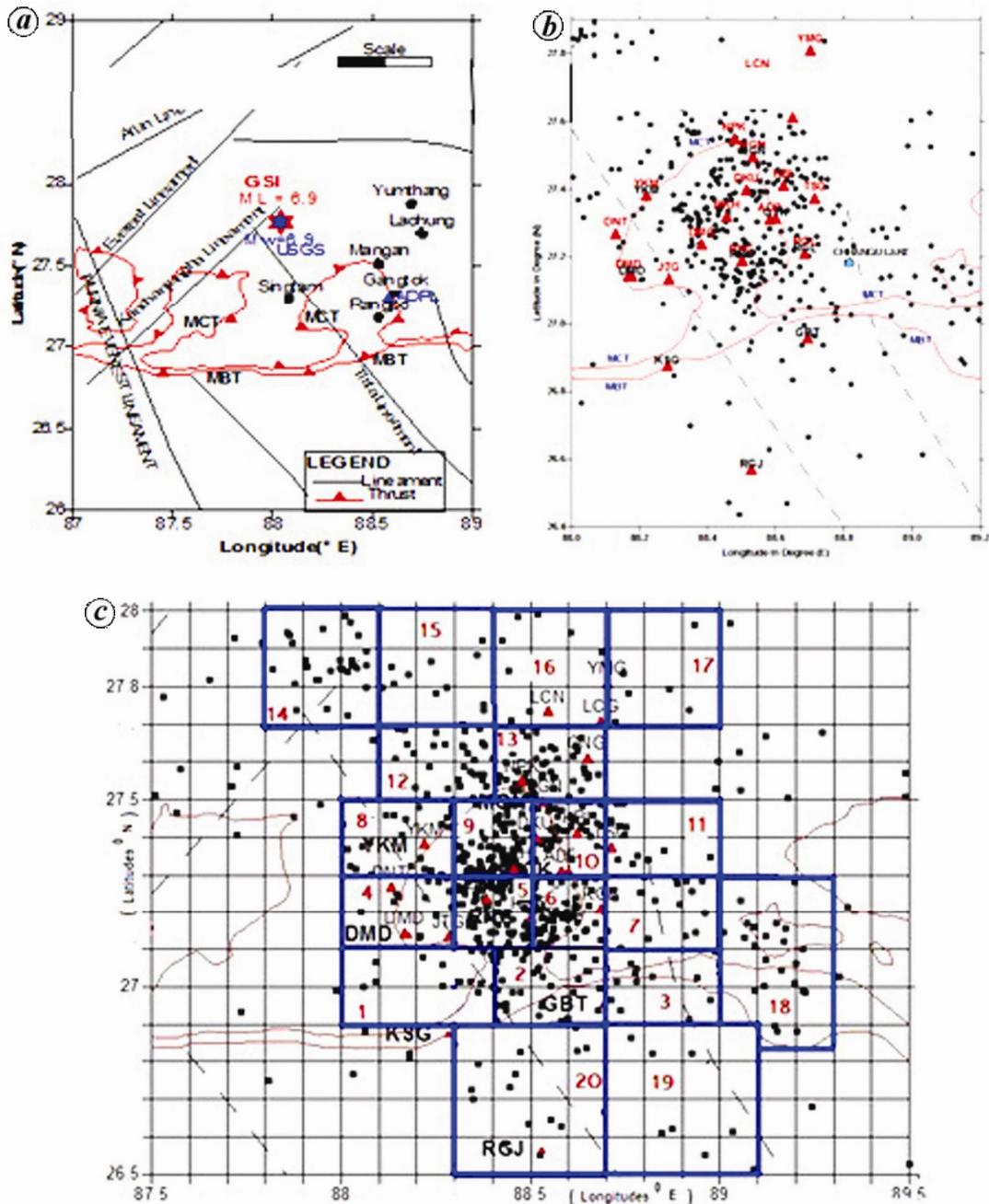
Figure 3. *a*, Tectonic map of the 2011 Sikkim earthquake (*Mw* 6.9) region with the location of the main shock denoted by red–blue star. *b*, Epicentre distribution of earthquakes located during FSP 2007–08 and 2008–09 by the team of Geological Survey of India (Mishra *et al.*[78]). The red triangles denote seismograph station locations. *c*, Epicentre map of earthquakes showing their distribution in different blocks with estimated *b* values and fault plane solutions as shown in Tables 1 and 2 respectively (adapted from Mishra *et al.*[78]).

to 4.34, indicating the seismically active block, and *b* value varies from 0.90 to 0.91 (Table 1), indicating relatively weaker zone that yielded normal or strike–slip fault (Table 2). The main shock of the 18 September 2011 event was also triggered by strike–slip faulting. This observation suggests that continuous detailed seismological and geodetic monitoring may provide precursor information about the enhanced seismic activity of the region and plausible slip in the future.

Climate change vis-a-vis seismogenesis

Our planet underwent an astonishing climatic transformation between about 20,000 and 5,000 years ago. In recent years, climate change is manifested by frequent occurrences of floods, drought, cyclone and storm surge along with other climate change-induced disasters, occurring in the region, such as failure of monsoon or excessive rainfalls during the monsoon, glacial lake outburst floods

and extreme variations in global and regional temperature. Climate change has also led to rain, rather than snow, falling even at higher altitudes. This also accelerates the melting of glaciers. The main concern is to understand the impact of climate change on earthquake genesis and also to understand how genesis of strong to great earthquakes has any impact on climate change. The entire Himalaya is subjected to the great impact of climate change, where melt of glaciers and excessive rains in the region are being reported. As the ice dissipated in soaring temperatures, the crust popped back up like a coiled spring released, at the same time tearing open major faults and triggering great earthquakes in places where they are unheard of today. Recently, it is observed that lateral variations in plate coupling and their temporal changes as an efficient source to induce an uncommon form of plate motion and it has been reported that monsoon speeds up Indian plate motion[87]. It is argued that due to melting of the thicker ice sheets, the reduction in weight on the crust beneath is allowing faults contained therein to slide more easily, which may promote increased earthquake activity in the Himalayan region during recent decades. In order to address the impact of climate-change on earthquake genesis, there is a need of conducting comprehensive seismological research with recently compiled seismological catalogue of strong to great Himalayan earthquakes to explain the extent of seismicity variations in the climate change scenario in the region using the data mining tools based on neural network model[88]. Conversely, the great earthquakes ($M \geq 8.0$) have capability to tilt the axis of rotation of the earth, which in turn influences the secular motion of the earth planet having direct bearing on the climate change-related seasonal changes. It is found that variation of uneven rotation of earth and the planet seismicity is directly related to the triggering events[89], which need to be studied by analysing the seismic moment budget from all strong to great Himalayan earthquake catalogue[90] to better understand the effect of strong to great earthquakes on the tilt of earth rotational axis that may control the extent of climate change in the Himalayan region.

Conclusion

The complexity of Himalaya represents visible creations of modern plate tectonic forces with hidden mystery of mantle dynamics, showing present-day convergence across different segments of the Himalaya[91]. The Himalayan region is the hotspot of moderate to great damaging earthquakes with high rate of uplift having the highest concentration of glaciers outside of the polar region, which rekindled debates on several issues, including the intricate seismotectonics and seismogenesis of the Himalaya. This invites for comprehensive studies by different researchers of Indian institutions/organizations [e.g. Geo-

logical Survey of India (GSI); India Meteorological Department (IMD); National Geophysical Research Institute (NGRI); Ministry of Earth Sciences (MoES); Northeast Institute of Science & Technology (NEIST); Wadia Institute of Himalayan Geology (WIHG); Universities of India involved in geo-scientific research, etc.] to arrive at common consensus on debatable issues of seismotectonics and seismogenesis using integrated tools of multidisciplinary science. The integrated geoscientific research using different tools of geology, geophysics, seismology and geodetic science may be carried out in collaboration with different institutions of India and abroad. Such integrated scientific endeavour would provide a great opportunity to policy formulators and planners to evolve a comprehensive strategy by incorporating findings of integrated geoscientific research to make the Himalaya safer and prosperous by mitigating geological, hydrometeorological and climate-change induced natural hazards.

1. Sorkhabi, R. B., A tale of two eras: notes on Himalayan geology. *Curr. Sci.*, 1996, **70**, 485–488.
2. Holmes, A., The earth inside and out: some major contributions. In *Principle of Physical Geology*, Nelson, London, 1944.
3. Kaila, K. L. and Narain, H., Evolution of Himalaya based on seismotectonic and deep seismic soundings. *Geol. Surv. India, Miss. Publ.*, 1981, No. 41, Part IV, 1–39.
4. Gansser, A., *Geology of the Himalaya*, Wiley, Chichester, 1964, p. 289.
5. Gansser, A., Geology of Himalayas. *Sov. Geol.*, 1965, **10**, 67–79.
6. Gansser, A., The Indian Ocean and the Himalayas: a geological interpretation. *Encl. Geol. Helv.*, 1966, **59**, 831–845.
7. Zhao, W.-L. and Morgan, W. J., Injection of Indian crust into Tibetan lower crust: A two-dimensional finite element model study. *Tectonics*, **6**, 489–504.
8. Gupta, H. K. and Narain, H., Crustal structure in the Himalayan and Tibet Plateau region from surface wave dispersion. *Bull. Seismol. Soc. Am.*, 1967, **57**, 235–248.
9. Dewey, J. F. and Bird, J. M., Mountain belts and the new global tectonic. *J. Geophys. Res.*, 1970, **75**, 2625–2647.
10. Isack, B. and Molnar, P., Mantle earthquake mechanisms and the sinking lithosphere. *Nature*, 1969, **223**, 1121.
11. Crawford, A. R., The Indus Suture Line, the Himalaya, Tibet and Gondwana land. *Geol. Mag.*, 1974, **111**(5), 369–383.
12. Molnar, P. and Tapponnier, P., Cenozoic tectonics of Asia: effects of a continental collision. *Science*, 1975, **189**, 419–426.
13. Ni. J. 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.
14. Bird, P., Lateral extrusion of low crust from under high topography in the isostatic limit. *J. Geophys. Res.*, 1991, **96**, 10275–10286.
15. Chandra, U., Seismicity, earthquake mechanisms and tectonics along the Himalayan range and vicinity. *Phys. Earth Planet. Inter.*, 1978, **16**, 109–131.
16. Le Fort, P., Himalayas: the collided range, present knowledge of the continental arc. *Am. J. Sci.*, 1975, **275**, 1–44.
17. Molnar, P., Fitch, T. and Wu, F., Fault plane solutions of shallow earthquakes and contemporary tectonics in Asia. *Earth Planet. Sci. Lett.*, 1973, **19**, 101–112.
18. Seeber, L., Armbruster, J. G. and Quitmeyer, R. C., Seismicity and continental subduction in the Himalayan Arc. In *Geodynamic*

Evolution (eds Gupta, H. K. and Delany, F. M.), Geodynamics Series, American Geophysical Union, Washington, DC, 1981, vol. 3.

19. Gupta, H. K., Rao, V. D. and Singh, J., Continental collision tectonics: evidence from the Himalaya and the neighboring regions. *Tectonophysics*, 1982, **81**, 213–238.

20. Gupta, H. K., Rastogi, B. K. and Singh, D. D., Seismological investigations in the Himalaya and nearby regions. *Geophys. Res. Bull.*, 1982, **20**, 141–155.

21. Gupta, H. K., Major and great earthquakes in the Himalayan region: An overview. In *Disaster Management*, Universities Press (India) Pvt Ltd, 2003, pp. 100–109.

22. Chandra, U., Seismotectonics of Himalaya. *Curr. Sci.*, 1992, **62**(1–2), 40–71.

23. Gahalaut, V. K. and Chander, R., A rupture model for the great earthquake of 1897, northeast India. *Tectonophysics*, 1992, **204**(1–2), 163–174.

24. Kayal, J. R., Microearthquake activity in some parts of the Himalaya and the tectonic model. *Tectonophysics*, 2001, **339**, 331–351.

25. Kayal, J. R., Himalayan tectonic model and the great earthquakes: An appraisal. *Geomatrics, Nat. Hazards Risk*, 2010, **1**, 51–57.

26. Srivastava, P., *Proc. Indian Natl. Sci. Acad.*, 2012, **78**(3), 295–298.

27. Srivastava, P. and Misra, D. K., Morpho-sedimentary records of active tectonics at the Kameng river exit, NE Himalaya. *Geomorphology*, 2008, **96**, 187–198.

28. Srivastava, P., Bhakuni, S. S., Luirei, K. and Misra, D. K., Morpho-sedimentary records at the Brahmaputra River exit, NE Himalaya: climate–tectonic interplay during the Late Pleistocene–Holocene. *J. Quaternary Sci.*, 2009, **24**(2), 175–188.

29. Yeats, R. S. and Thakur, V. C., Active faulting in South of Himalayan Front: Establishing a new plate boundary. *Tectonophysics*, 2007, **453**, 63–73.

30. Mukul, M., Jaiswal, M. and Singhvi, A. K., Timing of recent out-of-sequence active deformation in the frontal Himalayan wedge: Insights from the Darjiling sub-Himalaya, India. *Geology*, 2007, **35**(11), 999–1003.

31. Acharyya, S. K., Evolution of the Himalayan paleogene foreland basin, influence of its litho-packet on the formation of thrust related domes and windows in the eastern Himalaya – A review. *J. Asian Earth Sci.*, 2007, **31**, 1–17.

32. Mishra, O. P., Seismological research in India (2007–2011). *Proc. Indian Natl. Sci. Acad.*, 2012, **78**(3), 361–371.

33. Mishra, O. P., Three-dimensional tomography of Northeast India and Indo-Burma region and its implications for earthquake risks. In National Workshop on Earthquake Risk Mitigation: Strategy in NE, 2011, pp. 40–54.

34. Mishra, O. P., Singh, O. P., Chakraborty, P. K., Chaudhury, S. N., Bhattacharya, P. M., Ram, S. and Kayal, J. R., 3-D tomography of the western Himalayan region and its implications to the past damaging earthquakes, GSI Special Publication. *KECS*, 2005, **85**, 337.

35. Valdiya, K. S., Himalayan transverse faults and folds and their parallelism with subsurface structures of North Indian Plains. *Tectonophysics*, 1976, **32**, 352–386.

36. Dasgupta, S., Mukhopadhya, B., Mukhopadhya, M. and Nandy, D. R., Role of transverse tectonics in the Himalayan collision: further evidences from two contemporary earthquakes. *J. Geol. Soc. India*, 2013, **81**, 241–247.

37. Dasgupta, S., Mazumdar, K., Moirangcha, L. H., Dutta Gupta, T. and Mukhopadhya, B., Seismic landscape from Sarpang re-entrant, Bhutan Himalaya foredeep, Assam, India: Constraints from geomorphology and geology. *Tectonophysics*, 2013, **592**, 130–140.

38. Gahalaunt, V. K. and Kalpna, Himalayan mid-crustal ramp. *Curr. Sci.*, 2001, **81**(12), 1641–1646.

39. Ghosh, D. and Mishra, O. P., Earthquake-generating process in Pakistan–Kashmir Himalayan Front: A tectonic overview. *Indian Miner. Spec. Issue*, 2008, **61**(3–4); **62**(1–4), 27–40.

40. Khan, P. K., Mohanty, S. and Mohanty, M., Geodynamic implications for the 8 October 2005 North Pakistan earthquake. *Surv. Geophys.*, 2010, doi: 10.1007/s10712-009-9083-1.

41. Mukhopadhay, B., Acharya, A., Bhattacharya, D., Dasgupta, S. and Parde, P., Seismotectonics at the terminal ends of the Himalayan arc. *Geomatics, Nat. Hazard Risk*, 2011, **2**(2), 159–181.

42. Srivastava, P. and Mitra, G., Thrust geometries and deep structure of the outer and lesser Himalaya, Kumaon and Garhwal (India): Implications for evolution of the Himalayan fold-and-thrust belt. *Tectonics*, 1994, **13**, 89–104.

43. Dasgupta, S. *et al.*, In *Seismotectonic Atlas of India and its Environs* (eds Naruala, P. L., Acharyya, S. K. and Banerjee, J.), Geological Survey of India, 2000, p. 87.

44. Guha, D., Bardhan, S., Basir, S. R., De, A. K. and Sarkar, A., Imprints of Himalayan thrust tectonics on the Quaternary piedmont sediments of the Neors–Jaldhaka valley, Darjeeling–Sikkim sub-Himalayas, India. *J. Asian Earth Sci.*, 2007, **30**, 464–473.

45. Mukul, M., First-order kinematics of wedge-scale active Himalayan deformation: Insights from Darjiling–Sikkim–Tibet (DasiT) wedge. *J. Asian Earth Sci.*, 2010, **39**, 645–657.

46. Bhattacharyya, K. and Mitra, G., A new kinematic evolutionary model for the growth of a duplex – an example from the Rangit duplex, Sikkim Himalaya, India. *Gondwana Res.*, 2009, **16**, 697–715.

47. Mitra, G., Bhattacharyya, K. and Mukul, M., The lesser Himalayan duplex in Sikkim: implications for variations in Himalayan shortening. *J. Geol. Soc. India*, 2010, **75**(1), 289–301.

48. Mukul, M., Jade, S., Ansari, K. and Matin, A., Seismotectonic implications of strike–slip earthquakes in the Darjiling–Sikkim Himalaya. *Curr. Sci.*, 2014, **106**, 198–210.

49. Bilham, R., Gaur, V. K. and Molnar, P., Himalayan seismic hazard. *Science*, 2001, **293**, 1442–1444.

50. Bilham, R., Earthquakes in India and the Himalaya: tectonics, geodesy and history. *Ann. Geophys.*, 2004, **47**(2–3), 839–858.

51. Bilham, R. and Ambraseys, N., Apparent Himalayan slip deficit from the summation of seismic moments for Himalayan earthquakes, 1500–2000. *Curr. Sci.*, 2005, **88**(10), 1658–1663.

52. Khattri, K. N., Great earthquakes, seismicity gaps and potential for earthquake disaster along the Himalaya Plate boundary. *Tectonophysics*, 1987, **138**, 79–92.

53. Dasgupta, S. and Mukhopadhyay, B., 1803 earthquake in Garhwal Himalaya: compilation from archives with commentary. *Ind. J. Hist. Sci.*, 2013 (in press).

54. Wang, Z., Zhao, D., Mishra, O. P. and Yamada, A., Structural heterogeneity and its implications for the low frequency tremors in southwest Japan. *Earth Planet. Sci. Lett.*, 2006, **251**, 66–78.

55. Zhao, D., Mishra, O. P. and Sanda, R., Influence of fluids and magma on earthquakes: seismological evidence. *Phys. Earth Inter.*, 2002, **132**, 249–267.

56. Singh, A. P., Mishra, O. P., Rastogi, B. K. and Kumar, D., 3-D seismic structure of the Kachchh, Gujarat, and its implications for the earthquake hazard mitigation. *Nat. Hazards*, 2011, **57**(1), 83–105.

57. Banerjee, P. and Burgman, R., Active tectonics of Himalayan Frontal thrust and seismic hazards to Ganga Plain. *Geophys. Res. Lett.*, 2002, **29**, 301–304.

58. Jade, S. *et al.*, GPS-derived deformation rates in northwestern Himalaya and Ladakh. *Int. J. Earth Sci.*, 2011, **100**, 1293–1301.

59. Yin, A., Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. *Earth Sci. Rev.*, 2006, **76**, 1–131.

60. Gahlaut, V. K. and Arora, B. K., Segmentation of seismicity along the Himalayan arc due to structural heterogeneities in the under-

thrusting Indian plate and overriding Himalayan wedge. *Episodes*, 2012, **35**(4), 493–500.

61. Arora, B. R. and Mahashabde, M. V., A transverse conductive structure in the northwest Himalaya. *Phys. Earth Planet. Inter.*, 1987, **45**, 119–127.

62. Manglik, A., Pavan Kumar, G. and Thiagrajan, S., Transverse tectonics in the Sikkim Himalaya: A magnetotelluric study. *Tectonophysics*, 2013, **589**, 142–150.

63. Satyabala, S. P., Subduction in the Indo-Burma region: is it still active? *Geophys. Res. Lett.*, 1998, **25**, 3189–3192.

64. Bilham, R. and England, P., Plateau 'pop-up' in the great 1897 Assam earthquake. *Nature*, 2001, **410**, 806–809.

65. Bhattacharya, P. M., Mukhopadhyay, S., Majumdar, R. K. and Kayal, J. R., 3-D Seismic structure of the N–E India region and its implications for local and regional tectonics. *J. Asian Earth Sci.*, 2008, **33**(1–2), 25–41.

66. Searle, M. P. and Szulc, A. G., Channel flow and ductile extrusion of the high Himalayan slab-the Kanchenjunga–Darjeeling profile, Sikkim Himalaya. *J. Asian Earth Sci.*, 2005, **25**, 173–185.

67. Zhao, W., Nelson, K. D., Chen, J., Quo, J., Lu, D., Wu, C. and Liu, X., Deep seismic reflection evidence for continental underthrusting beneath southern Tibet. *Nature*, 1993, **366**, 557–559.

68. Nelson, K. *et al.*, Partially molten middle crust beneath southern Tibet: synthesis of project INDEPTH results. *Science*, 1996, **274**, 1684–1688.

69. Wei, W. *et al.*, Detection of widespread fluids in the Tibetan crust in the Tibetan crust by magnetotelluric studies. *Science*, 2001, **716**, 8.

70. Alsdorf, D. and Nelson, K., Tibetan satellite magnetic low: evidence for widespread melt in the Tibetan crust? *Geology*, 1999, **27**, 943–946.

71. Arora, B. R., Unsworth, M. J. and Rawat, G., Deep resistivity structure of the northwest Indian Himalaya and its tectonic implications. *Geophys. Res. Lett.*, 2007, **34**, L04307.

72. Patro, P. K. and Harinarayana, T., Deep geoelectric structure of the Sikkim Himalayas (NE India) using magnetotelluric studies. *Phys. Earth. Planet. Int.*, 2009, **173**, 171–176.

73. De, R. and Kayal, J. R., Seismic activity at the MCT in the Sikkim Himalaya. *Tectonophysics*, 2004, **386**, 243–248.

74. Nath, S. K., Vyas, M., Pal, I. and Sengupta, P., A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization and spectral attenuation laws using strong motion seismometry. *J. Geophys. Res.*, 2005, **110**, B01301.

75. Hazarika, P., Kumar, M. R., Srijayanthi, G., Raju, P. S., Rao, N. P. and Srinagesh, D., Transverse-tectonics in the Sikkim Himalaya: evidence from seismicity and focal-mechanism data. *Bull. Seismol. Soc. Am.*, 2010, **100**, 1816–1822.

76. 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.

77. Chakraborty, P. K. and Lahiri, A. K., Repeat microgravity survey in Sikkim–Darjeeling Himalaya. *Himalayan Geol.*, 2008, **29**(2), 161–169.

78. Mishra, O. P., Chakrabortty, G. K., Singh, O. P., Ghosh, D. C., Mukherjee, K. K. and Das, P. C., Seismogenesis in the Sikkim–Darjeeling Himalaya and assimilation of dynamic snap shots of the regions: Future vulnerability, Unpubl. GSI Report, 2010, p. 55.

79. Ray, S. K., Culmination zones in eastern Himalaya, *GSI Spec. Publ.*, 2000, **55**, 85–94.

80. Dimri, V. P., In *Fractal Behaviour of Earth System*, Springer, New York, 2005, p. 257.

81. Dimiri, V. P. and Bansal, A. R., Indo–Iceland Workshop on Earthquake Prediction, WIHG, 21–22 October 2011.

82. Sunmonu, L. A., Dimri, V. P., Ravi, P. M. and Bansal, A. R., Multifractal approach of the time series of $M > 7.0$ earthquake in Himalayan region and its vicinity during 1985–1995. *J. Geol. Soc. Ind.*, 2001, **58**, 163–169.

83. Rajendran, K., Rajendran, C. P., Thulasiraman, N., Andrews Ronia and Sherpa, N., The 18 September 2011, north Sikkim earthquake. *Curr. Sci.*, 2011, **101**, 1475–1479.

84. Singh, A., Kumar, M. R. and Raju, P. S., Seismic structure of the underthrusting Indian crust in Sikkim Himalaya. *Tectonics*, 2010, **29**(6), TC6021, 1–12.

85. Hazarika, P. and Kumar, M. R., Seismicity and source parameters of moderate earthquakes in Sikkim Himalaya. *Nat. Hazards*, 2012, **62**, 937–952.

86. Nath, S. K., Thingbaijam, K. K. S. and Ghosh, S. K., www.earthqhaz.net/sacat

87. Iaffaldano, G., Husson, L. and Bunge, H.-P., Monsoon speeds up Indian plate motion. *Earth Planet. Sci. Lett.*, 2011, **304**, 503–510.

88. Dutta, P. K., Mishra, O. P. and Naskar, M. K., Evaluation of seismogenesis behaviour in Himalayan belt using data mining tools for forecasting. *Cent. Eur. J. Geosci.*, 2013, **5**(2), 236–253.

89. Outkin, V. I., Yurkov, A. K., Tsurko, I. A., Kozslova, I. A., Mishra, O. P., Dutta, P. K. and Naskar, M. K., Variation of uneven rotation of earth and the planet seismicity due to triggering. *Earth Sci. Res.*, 2014 (under review).

90. Dutta, P. K., Mishra, O. P. and Naskar, M. K., South Asia earthquake catalogue magnitude data regression analysis. *Int. J. Statist. Analys.*, 2011, **1**(2), 161–170.

91. Bilham, R., Larson, K., Freymueller, J. and Members, GPS measurements of present-day convergence across the Nepal Himalaya. *Nature*, 1997, **386**, 61–64.