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Active Tectonics of Himalaya, Rift Basins in Central India and those Related to Crustal Deformation at Different Time Scales

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The paper provides a review on the scientific research carried by various Indian scientists as well as research groups on the active tectonics of the Himalaya, including the Ganga-Brahmaputra plains, and the crustal deformation of rift basins of central India during the period 2016-2020, as a requirement for the Proceedings of Indian National Science Academy. The research on the Himalayan part includes varied scientific aspects on active fault studies involving trench excavation (paleoseismology), archeoseismological investigations, liquefaction, geodetic strain, tectonic geomorphometry, and neotectonic evolution of landforms, using geochronological techniques.

Active fault studies from remote north-eastern portion and central seismic gap (CSG) of the Himalaya have provided useful insight into the surface rupture scenario of great devastating earthquakes that occurred during the past. Multi-proxy studies provided the first evidence for, 1950 A.D. primary surface faulting along the Himalayan Frontal Thrust (HFT), NE Himalaya at Pasighat suggest that great earthquakes accommodate the convergence between southern Tibet and stable India along the MHT to the HFT. This study corroborates the first instance in using post bomb radiogenic isotopes to help identify an earthquake rupture. In the western part of CSG, the active backthrust in the northern margin of Janauri hill, at Mehandpur (31°18’11.37"N, 76°18’31.47"E) revealed the last event took place after 0.8±0.03 ka ago (i.e. post A.D. 1200). The age of the last earthquake on the back thrust nearly matches with an earthquake event previously documented on the Bhatpur forethrust of the Himalayan frontal thrust system. Field evidence shows fore and back thrusts are active and they form simultaneously, but displacements are episodic suggesting the backthrust develops either due to locking of forethrust or to accommodate a large amount of fault slip due to the magnitude of earthquake event along the forethrust. Further, the backthrust may be used as an indirect method of inferring the age of last event that took place along the forethrust.

The analysis of GPS observations suggests that the present-day plate convergence rate is 18±1 mm/yr towards N213°E and width of the locked frontal portion of Main Himalayan Thrust (MHT) is 100±15 km in Garhwal-Kumaun Himalaya. A strong interseismic plate coupling (>0.6) has been observed in the Outer and Lesser Himalaya, which indicates a large rate of strain accumulation. The slip deficit budget since past major to great earthquakes in the Garhwal-Kumaun Himalaya suggests an overdue of at least 4 m slip on MHT which has the potential to produce a megathrust earthquake (Mw~8) in near future. The plate convergence rate in the Darjiling-Sikkim Himalaya is 18 mm/yr and the depth of locking of the frontal part of MHT is 16 km. The present-day deformation in north-eastern Himalaya provides a slip deficit of 15 meters from the past 800 years and this region has the potential to generate at least one megathrust earthquake in near future.

Though few, but very important researches have been carried out on the central Indian crustal deformation associated with

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rifts. Geomorphological mapping, Structural and Tectonic analysis by means of the study of Shear zones from Central India infers about Neotectonic activities along the Gavilgarh Fault zone events at ca. 65–80 ka, ca. 50 ka, ca. 30–40 ka, and ca. 14 ka.

Keywords: Himalaya; Active Tectonics; Great Earthquake; Central India; Rift

Introduction

The continental collision between India and greater Asia due to under-thrusting of Indian continent underneath Southern Tibet (Valdiya and Sanwal, 2017; Jayangondaperumal *et al*., 2018) along the Indus Tsangpo Suture Zone (ITSZ), that started about 50-55 Myr ago, gave rise to the Himalaya (Jain *et al*., 2016). With the highest uplifted Tibetan plateau having a crustal thickness of ~70-75 km lying to the north, the Himalayan range extends over a length of ~2500 km from west to east between the western syntaxial bend known as the Hazara Syntaxis and the eastern syntaxial bend known as the Namche Barwa. In the western part of Himalayan range, the regional strike of the Himalaya is NW-SE, however, it is E-W and ENE-WSW in the central and eastern parts.

Subsequent to the collision, Indo-Eurasian convergence has decreased from ~15 to ~4 cm/yr (Jade *et al*., 2017), resulting in crustal thickening of the northern margin of the Indian continent and southward activation of several major thrust zones along the ~2500 km long Himalayan arc. The thrusts tectonically dividing five litho-tectonic zones of the Himalaya, i.e., Trans-Himalaya, Tethyan Himalaya, Higher Himalaya, Lesser Himalaya, and the Sub-Himalaya, are the Main Central Thrust (MCT), Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) in Nepal or Himalayan Frontal Thrust (HFT) in India. These tectonic structures merge into a low-angle crustal decollement thrust sheet called the Main Detachment Fault (MDF) (Panda *et al*., 2018c; Sreejith *et al*., 2018), which later modified to Main Himalayan Thrust (MHT) based on observations from the INDEPTH project seismic reflection profiles. The MFT (also known as Himalayan Frontal Thrust or HFT) is a physiographic and tectonic boundary between the Ganga-Brahmaputra alluvial plains and the Tertiary Siwaliks of the Sub-Himalaya (Jayangondaperumal *et al*., 2018). The MBT separates the Tertiary strata of the Sub-Himalaya and the Precambrians and Gondwanas of the Lesser Himalaya. Hornblende ages deduced by $^{40}Ar/^{39}Ar$ dating suggest that the MCT was active around 23-20 Ma. The age of MBT in the central Himalaya is considered to be either older than 11 Ma or less than 5 Ma. The HFT is said to have developed during Quaternary. The MCT, MBT and HFT show southward decrease in age from the zone of collision towards the alluvial foreland basin.

The Indian plate moves northeastward at ~45-50 mm/yr to underthrust beneath Tibet, out of which only ~10 mm/yr is being accommodated by the HFT (Jade *et al*., 2017; Yadav *et al*., 2019). This continued convergence has resulted in the occurrence of large to great earthquakes of magnitudes >7 in the past 100 years. Historical accounts suggest many destructing earthquakes like the A.D. 1255 Kathmandu, 1505 Kashmir, 1713 Bhutan-Arunachal, 1803 Garhwal, 1897 Shillong Plateau, in addition to instrumentally documented earthquakes of 1905 Kangra, 1934 Bihar-Nepal, 1950 Tibet-Assam (Priyanka *et al*., 2017). Officially, the Indian Meteorological Department (IMD) monitors seismicity of the country. However, many other organizations like the Geological Survey of India (GSI), Wadia Institute of Himalayan Geology (WIHG), National Geophysical Research Institute (NGRI), IIT Kanpur, IIT Bombay, etc., have also been carrying out post-earthquake research across India. Other countries like Nepal, France, and US also conduct post-earthquake researches in various segments of the Himalaya. Such collaborative researches have generated ample data thereby enhancing our existing knowledge and understanding of active tectonics in the Himalaya.

Preliminary work on active tectonics was started by Nakata in 1972 and 1989 along the Sub-Himalayan foothills of north Bengal, Pinjor and Dehradun valleys. Later advancements in the field of earthquake geology, geophysics, paleoseismology and allied disciplines helped many Indian as well as foreign research groups to undertake investigations along the HFT (Jayangondaperumal *et al*., 2018). Further, Global Positioning System (GPS) initiated by foreign research groups in Nepal, subsequently in India, and southern Tibet expanded new horizons for such studies in the Indian Himalaya. During 2016-2020, many Indian research groups undertook research work in the Himalaya, as well as in the Central Indian belt, all of which are detailed in this review article.

Active Faults Investigation in Himalaya

The geomorphologic and paleoseismological methods are best to understand the behaviour of strain release at different time windows along tectonically active boundary between the Indian and Eurasian plates i.e. Himalayan Front, by late Quaternary tectonic activity along mega-thrusts due to displacement on a buried decollement fault. Paleoseismological studies along the Himalayan front provide evidence of past historical earthquakes and their sizes in terms of amount of slip along the faults. Discontinuous active fault scarps are observed at several places all along the HFT (Malik *et al*., 2016 and 2017; Jayangondaperumal *et al*., 2017a, b and 2018; Rajendran *et al*.2019). In recent years, field-based active tectonic studies have been focused mainly in the Himalayan frontal zone for active structures and paleoseismology. To understand the occurrence of large magnitude earthquakes in the Himalayan region, investigations of the active tectonic character of the Himalayan Frontal Thrust (HFT) and its palaeoseismology along the entire length of the Himalaya have been carried out at several localities (Fig. 1; Jayangondaperumal *et al*., 2017a; Malik *et al*., 2016, 2017; Rajendran *et al*., 2017, 2018; Mishra *et al*., 2016; Priyanka *et al*., 2017; Priyanka, 2018). Although there are limitations on the constraints of timing of large events and extent of surface rupture, these studies have provided insight into the pattern of strain accommodation and release by paleoearthquakes along the Himalayan front.

Archaeological and Geomorphic Studies

Archaeoseismological investigations by Joshi and Thakur (2016) to study the seismic aspect from the deformation signatures preserved in monuments of Chamba and Bharmour areas of western Himachal Pradesh in NW Himalaya, correlated the deformations with the earthquake in A.D. 1905 Kangra and the historical Kashmir valley earthquake in A.D. 1555. Closer observations showed imprints of earthquake deformation such as fractures, tilting of the structures and pillars in the temples, and cracks in the brick masonry. The Chamba temple, which lies 52 km NW of Kangra, displays shear or rigid body rotation in the N-S direction.

Verma and Bansal (2016) provided a brief overview of the active fault research in India, discussing the achievements and advancements made in this aspect so far, along with the need for preparing Geographical Information System (GIS) based active fault maps for the entire country as part of a central programme started by the Ministry of Earth Sciences, Government of India.

Devender Kumar *et al*. (2016) undertook paleoseismological investigations in the Kopili Fault Zone of the Brahmaputra plains, NE India. Optically stimulated luminescence (OSL) and ^{14}C radiocarbon (AMS) analyses of samples helped constrain the chronology of liquefaction features within three time intervals, i.e., 250 ± 25 yr BP, between 400 to 700 yr BP and 900 ± 50 yr BP, which were correlated with the occurrence of causative seismic events.

Mishra *et al*. (2016b) analyzed river profiles to examine the active tectonics of Dikrong River valley in the northeast Himalaya. They used detachment-limited stream power bedrock incision model as a proxy to identify the areas of variable rock uplift relative to bedrock incision. As per the model, they estimated the Channel Steepness Index (k_{sn}), which is a proxy for the detachment-limited model to estimate the differential rock uplift across the fold-thrust belt. Based on the field observations and analysis of drainage data from 30 m Digital Elevation Model (DEM), Mishra *et al*. (2016b) considered 147 first order channels cutting across the major structural elements in the area, i.e., Bomdila Thrust, Main Boundary Thrust, Tipi Thrust, Himalayan Frontal Thrust and the Simna Parbat Anticline. The k_{sn} value for 147 channels ranges between 22 and 199 with the lithological effect being negligible. Higher values across the nose of the Simna Parvat Anticline suggest the growth and propagation of anticline towards ENE direction. This is also in agreement with the gradual eastward shifting of the Dikrong River with the abandonment of paleochannels.

Baruah *et al*. (2016) used fault plane solutions for stress inversion method to examine the tectonic stress regime in the Shillong Plateau. Their results suggest that the eastern part of the plateau is dominated by NNE-SSW compression, correlated with the influence of oblique convergence of the Indian plate beneath Indo-Burma ranges, and the western part by NNW-SSE compression which were attributed to the tectonic loading induced by the Himalayan orogeny in the north.

In a neotectonic work, Kothyari *et al*. (2017) studied the morphotectonic records of neotectonic activity in the vicinity of North Almora Thrust Zone (comprising major tectonic elements such as the North Almora Thrust, Rasiyari Fault, and Gagas Fault) in central Kumaun Himalaya. They investigated the geomorphic landforms of aggradational type preserved in the upper catchments of Kosi and Gagas River valleys in order to explain the spatiotemporal variability of aggradation and incision as a result of tectonic activity during the late Quaternary and Holocene in central Kumaun Himalaya. Using optically stimulated luminescence chronology dating of the terrace deposits, they suggested that the upper catchment of Kosi and Gagas rivers have witnessed multiple episodes of fluvial aggradation and tectonic uplift that began around 34 ka, and subsequently proceeded during 15.8, 7, and lastly 3 ka. The older uplift event around 34 ka was correlated with the Gagas Fault, the 15.8 ka uplift event was said to have been occurred due to the Rasiyari Fault, the 7 ka event with the hanging wall of North Almora Thrust, and lastly, the youngest uplift event during 3 ka was related to a phase of enhanced uplift and incision of the older valley fill sediments and bedrock, followed by another phase of accelerated incision and erosion due to an increase in uplift rate.

The work of Kothyari *et al*. (2017) attracted acute criticism by Naresh Rana and Shubhra Sharma (2017) which was published as a commentary article. In the commentary article, Rana and Sharma (2017) argued that the paper by Kothyari *et al*. (2017) was based on mere inferences drawn by authors from adequate and vague field observations supported by misquoted references. They argued that the claim of landform evolution in the area due to the tectonic activity of the North Almora Thrust along with other subsidiary faults, as suggested by Kothyari *et al*. (2017) is wrong and biased towards tectonics only, without considering the aspect of the climatic role in the landform development and ignoring the possibility of climate-tectonic interaction. As a reply to Rana and Sharma (2017), Kothyari *et al*. (2017) provided a point-to-point explanation of their queries in a commentary article as Kothyari *et al*. (2018) by rejecting as well as discarding their biasness towards the climate school of thought.

Rajendran *et al*. (2017) presented a review on the seismotectonics of the Himalaya dealing with the current status of seismotectonic understanding of the Himalaya from the analyses of significant earthquakes that have occurred during the past during the period between 1991-2016, such as the 1991 Uttarkashi (Mw 6.8), 1999 Chamoli (Mw 6.6), 2015 Gorkha earthquake of Nepal (Mw 7.8), 2011 Sikkim (Mw 6.9) and the 2016 Imphal (Mw 6.7) earthquake, with a focus on the central Himalayan segment.

Valdiya and Sanwal (2018) have provided a wealth of information of neotectonic movements and subsequent shaping of landscape, drainage alteration, ground vulnerability for the Indian sub-continent including Himalaya, and their work provide direct relevant information for the planners and engineers for hazard mitigation.

Sutar *et al*. (2017) investigated the maximum earthquake potential of Kopili fault zone in northeastern India, using different approaches that are dependent on parameters like fault geometry, slip rate, geodetic moment rate, and convergence rate. Their study suggests that the source zone has accumulated strain energy during the last 72 years since 1943 that is sufficiently capable of producing a strong earthquake of $M_w > 7$. Associating historical earthquakes that occurred in the region, they inferred that the Kopili Fault zone can generate an earthquake of M_w 7.3 in the present day. Towns of Assam like Tezpur, Masamari, Tumuki, Dhekiajuli, Nagaon, Bomdila, Udalguri, Seppa, Hajoi, Behali, Guwahati, and Itanagar that are located ~60-130 km from the source zone have been said to experience very strong to moderate ground shaking, while towns like Jorhat, Ziro, Mokokchung, Dhubri, and Kokrajhar that are located at a distance of 130-300 km from the source will experience low ground shaking.

Pandey *et al*. (2018) investigated the active tectonics in the area lying between the Manas and Dhanshiri Rivers in upper Assam, seismically located within the meizoseismal zones of 1934 and 1950 earthquakes along the eastern Himalayan front, India, previously designated as the 'Assam Seismic Gap'. In order to understand the scenario of paleoearthquake surface rupturing and landform evolution along the Himalayan Frontal Thrust, with a relation to the deformation of these landforms by previous earthquakes, they studied active tectonics of the region using photogrammetric techniques and high resolution satellite imageries together with field survey using RTK-GPS (Real Time Kinematics-Global Positioning System). Their study suggests large scale deformation in the region by thrust sheet translation, which does not give rise to prominent fault-related folds, a case which is not similar to that of the western and central Himalaya where large scale deformation due to plate convergence is manifested by the development of fault-related folds along the frontal Himalaya.

Active Fault Investigations

Northwest and Central Himalaya

In Kashmir Himalaya active tectonics of a deformed Himalayan front constrains the kinematic of the fold-thrust belt and the most-recently accreted foreland basin. The deformed frontal part of the Kashmir Himalaya, the region between the Kangra reentrant in India and the Jhelum River in Pakistan, is blind with no emergent thrust or surface faults cutting the southern limb. The deformation at the front in Kashmir Himalaya is characterized by a series of folds including the Suruin-Mastgarh anticline (SMA). Despite of that numerous trenching studies were undertaken by various workers east of SMA which are as follows:

Trenching investigations were carried out from Hajipur to Ramnagar (Fig. 2) reflects a difference in the timing of surface ruptures (Malik *et al*., 2017; Jayangondaperumal *et al*., 2017a and b; Rajendran *et al*., 2018). Malik *et al*. (2017) documented three event scenarios i.e. during 1344 or 1400 AD, 1505 AD and during 1803 AD earthquakes for the ruptured segment of the HFT in Ramnagar.

Jayangondaperumal *et al*. (2017b) have recalibrated the radiocarbon dates in the seven published trench sites (Hajipur to Ramnagar) of Kumar *et al*. (2006) and Rajendran *et al*. (2015) using OxCal model for large-magnitude ruptures along the Central Seismic Gap (CSG). Their study reveals that

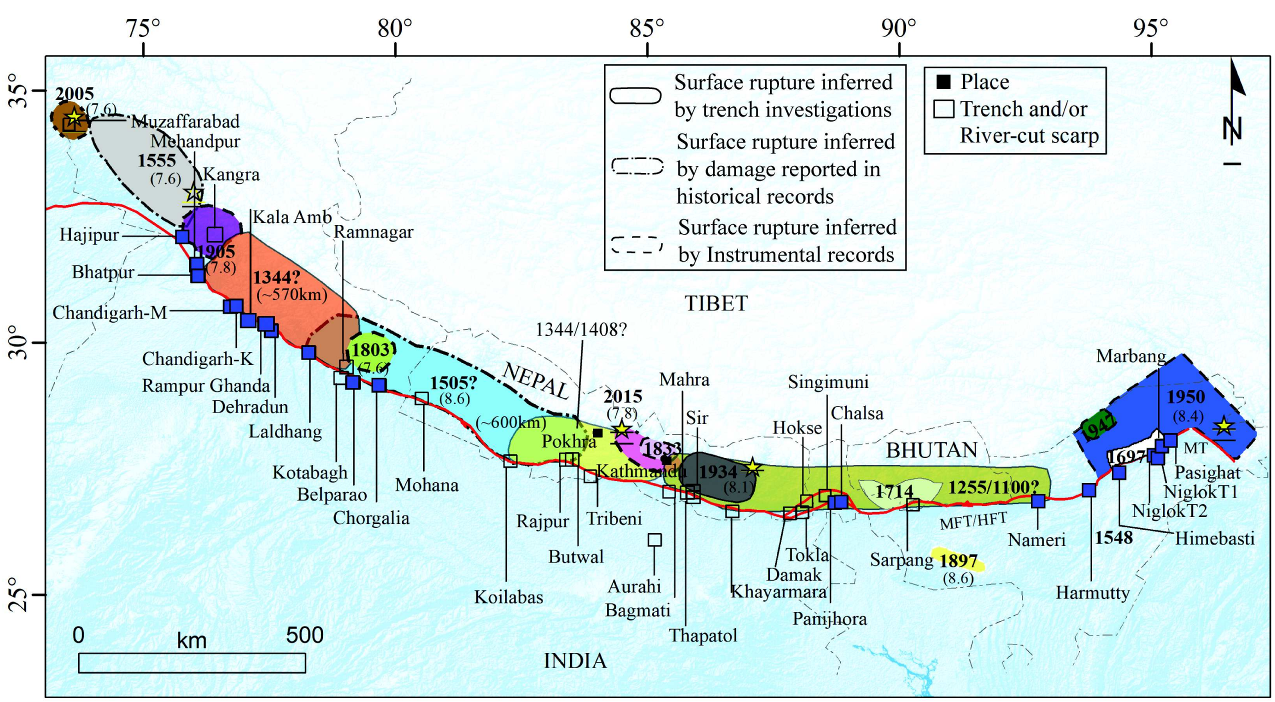

Fig. 1: **Simplified map showing the surface ruptures of great earthquakes along Himalaya arc, and locations of paleoseismological trenches excavated along the Himalayan front so far by WIHG (Solid Blue square). Surface rupture of CE 1344 (Jayangondaperumal *et al*., 2018) and C.E. 1697 (Priyanka, 2018; Pandey *et al* submitted) historical earthquakes were discovered through trench investigation along Himalayan Frontal Thrust by the WIHG. Please see Fig, 1.5 in Jayangondaperumal *et al*. (2018) for localities and references**

the fault rupture exposed at the Hajipur site is likely the 16th century event that occurred in September 1555 A.D. in the area of Kashmir.

At Chandigarh, Kala Amb, Rampur Ghanda, Lal-Dhang and Ramnagar trench site the recalibrated radiocarbon dates gives an age range of 1301-1386 A.D., 1304-1393 A.D., 1265-1417 A.D., 1293 A.D.-1451 A.D., 1281-1405 CE, respectively with 95% (two-sigma) confidence interval for the most recent event, thus corresponds to 1344 A.D. earthquake (Jayangonda Perumal *et al*., 2017b). The OxCal modelled ages of stratigraphically defined radiocarbon ages at sites from Chandigarh to Ramnagar, correspond to a historically documented earthquake in 1344 A.D., with an estimated magnitude of Mw ~8.6. Their results suggest that the most recent large-scale rupture along the western half of the CSG likely occurred during the earthquake in 1344 A.D. (Fig. 2). They also suggest the possibility of the earthquake of 1505 A.D. to rupture this segment of the CSG, but with less confidence due to the small number of charcoal samples collected from these sites including the reworked charcoal samples from colluvium units, which could lead to an over estimation of the event horizon.

In contrast to a previous study by Malik *et al*. (2017), who suggested three earthquakes during A.D. 467-570, 1294-1587 and 1750-1932, the penultimate and most recent event correlated with the historical A.D. 1505 and 1803 Uttarkashi earthquakes, Rajendran *et al*. (2018) negated the previously suggested idea stating multi-episodic displacements leading to the 1803 earthquake. They inferred a single medieval earthquake in the region between A.D. 1266 and 1636, discarding the previous assumption of the 1803 rupture along the HFT.

Jayangondaperumal *et al*. (2017a) mapped a fault scarp related to displacement along a backthrust, west of Mehandpur, along the northern limb of the Janauri anticline (Fig. 1). A 16-m-long, 8-m-deep, and 10-m-wide trench was excavated across the lower fluvial terrace scarp, south of Mehandpur village at the back (northern) limb of the anticline across the NW trending scarp. The OSL modeled age of samples collected from the trench suggest that the last earthquake event occurred after 1200 A.D., close to the last historical earthquake (i.e. 1282-1460 A.D.) reported along the forethrust at Bhatpur trench (Kumahara and Jayangondaperumal, 2013). They postulated that the rupture of last earthquake on the backthrust is in harmony with the documented earthquake on the forethrust (Bhatpur) of the HFT in 1344 A.D. (Jayangonda perumal *et al*., 2017b). Jayangondaperumal *et al*. (2017a) concluded the backthrust may develop either due to locking of the forethrust or to accommodate large fault slip on the forethrust.

Jayangondapeurmal *et al*. (2018) have identified several active faults in Kumaun-Garhwal regions and developed Interactive Web-Based Himalayan Active Fault Database Interface System (http://www.wihg.res.in/whadis-himalaya). Their work provides understanding the level of seismic hazard imposed by great earthquakes in the Uttarakhand State.

Arora *et al*. (2019) explored the spatiotemporal pattern of earthquakes that occurred along the Pinjore Garden and Jhajra Faults, lying towards the hinterland in the northwest Himalaya and suggested two event scenarios along these faults. The most recent event at the Pinjore Garden fault occurred post A.D. 1283-1443 but pre A.D. 1600, thus producing a fault scarp of ~6 m-high and multi-episodic co-seismic slip of 12.7 m while that at Jhajra Fault during A.D. 1223-1442. Comparing the two earthquake events along the hinterland faults with previous trenches in the area, Arora *et al*. (2019) suggested that the hinterland faults might have reactivated by an earthquake that independently occurred between A.D. 1283 and 1600.

Eastern Himalaya

At Panijhora (~88.85°E, 26.88°N), West Bengal, Mishra *et al*. (2016) excavated ~12 m-long and 4 m-deep trench across a ~10 m-high fault scarp. Radiocarbon age constraints from six detrital charcoal samples range between 1688 B.C. and 1152 A.D. and indicate the faulting of surface during the 1255 A.D. earthquake. Mishra *et al*. extended the rupture length of 1255 A.D. event of Sapkota *et al*. at Sir Khola, Central Nepal to Panijhora, Eastern Himalaya and concluded a mega thrust event that ruptured ~800 km of the Himalayan arc between 85.87°E to 93.76°E longitudes.

Priyanka *et al*. (2017) undertook

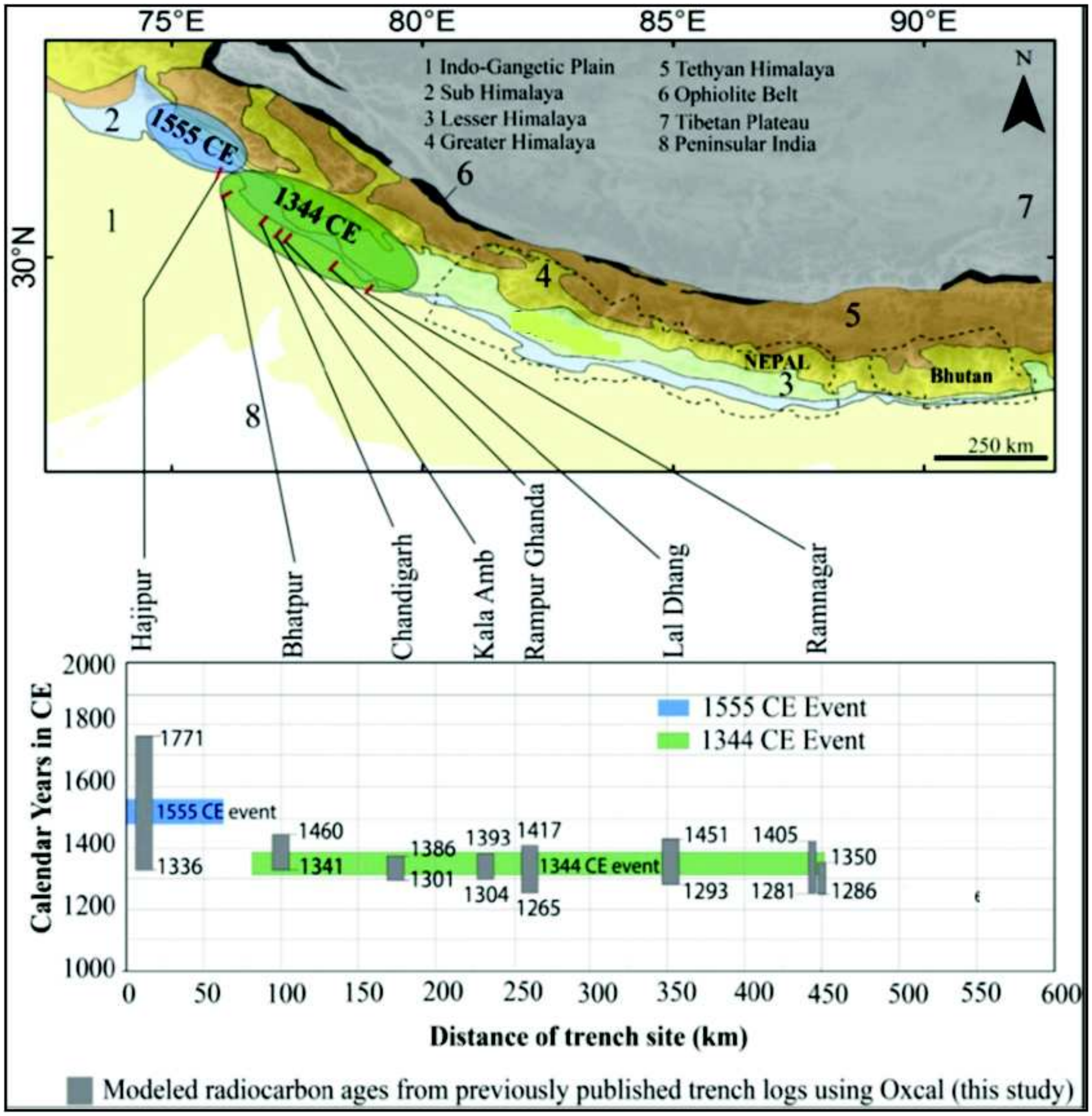

Fig. 2: (Top) Colored ellipses show areas affected by penultimate large-scale (~8 Mw) earthquakes, as inferred from paleoseismological evidence. (Bottom) Grey bars indicate the modeled two-sigma confidence intervals for seismic events at each of the modeled sites. The graph display that the western sector of the Central Seismic Gap is ruptured by the earthquake of 14th century (after Jayangonda perumal *et al*., 2017b)

paleoseismological studies at Pasighat town in frontal part of Arunachal Pradesh, north eastern India. A trench was excavated across a ~3.1 m high fault scarp preserved along the Brahmaputra River. It was for the first time in India, multiple dating techniques were employed in paleoseismology in order to study the paleoearthquake history preserved in the trench. The trench site and the landforms were skilfully mapped using high resolution CARTOSAT-1 and Pleiades satellite imageries and high resolution DEM were also generated from aerial photographs acquired using Unmanned Aerial Vehicle DJI Phantom 1 multi-rotor cod copter camera. The micro-topography was thoroughly surveyed with the help of Real Time Kinematic Differential GPS and robotic Total Station. From the Multi-proxy radiometric dating it was suggested that the A.D. 1950 earthquake (Mw 8.6) which was previously considered to have occurred along a blind fault, ruptured the eastern Himalayan front producing a co-seismic slip of 5.5 ± 0.7 meters. It is for the first time post-bomb radiogenic isotopes were dated to identify an earthquake rupture.

Geological Shortening Rate and GPS Studies in Himalaya

The long-term shortening rate on the main Himalayan Thrust has been estimated at a number of locations along the Himalayan front from geomorphic and geological studies. The fluvial strath terraces preserved along both major perennial and lesser ephemeral streams which originate in the Siwalik range, have been used to estimate the uplift, shortening, and slip rates on the HFT in the Himalaya (Jayangondaperumal *et al*., 2017a and 2018). The Global Positioning System (GPS) has become an important tool to characterize the earthquake processes and anthropogenic activity of a region, thus provides a better constraint for the estimate of seismic hazard of the region. The sub-millimetre level accuracy of plate motion from GPS measurements is useful to deal long-term (tectonic) and short-term (non-tectonic) deformations. The plate convergence rate or fault slip rate provides a direct measure of intensity and recurrence period of future devastating earthquakes. Seismic hazard potential for a tectonically active region depends on slip deficit rate and locking width of the fault. The monitoring of surface deformation in the Himalaya, Gangetic plains and Indian peninsula region is tremendously increased in past five years and thus a better understanding of the plate boundary deformation and plate interior deformation has been derived by the various Indian researchers.

Northwest Himalaya

To understand the neotectonic evolution of landforms along the Kulur River valley, a tributary of the Saryu River in the Berinag Thrust zone of the Kumaun Himalaya from field observations and morphometric indices like Valley floor width-to-height ratio (V_f), Basin shape Index (Bs), Basin Elongation Ratio (R_e), Transverse Topographic Symmetry factor (T), Asymmetry factor (AF), Longitudinal profile with Gradient index (GI), Sinuosity Index (SI), Hydraulic Sinuosity Index (HSI), and Topographic Sinuosity Index (TSI), Joshi and Kotlia (2018) studied the geomorphic landforms like alluvial fans, fluvial terraces, active and stabilized landslides, river paleochannels, waterfalls, deeply dissected hills, lineaments, V-shaped valleys, alignment of springs, triangular fault facets and straight/meandering course of rivers/streams to examine the landform evolution and drainage development. Further, using Stream length-gradient index (SL) and Steepness Index (K_s), the ongoing tectonic uplift along the Berinag Thrust and the associated fault/s were analysed. The Steepness Index (K_s) was calculated according to the formula $S=K_sA^{-\theta}$, where, S is the local channel slope, A is stream drainage area, K_s is Steepness Index and è is the concavity. The K_s and è were calculated using log-log plots between the slope of the river profile (S) and upstream drainage area (A).

Jain *et al*. (2016) summarized various papers on the tectonics and evolution of the Himalaya during the period 2011-2015. Scientific publications on various geological as well as geophysical aspects of the evolution of the Himalaya such as sub-surface configuration, structure and metamorphism of the Lesser Himalayan Metamorphic Belt, geochemistry, magmatism, stratigraphy ad paleontology of the Paleo-Mesozoic Tethyan sedimentary cover, the Himalayan foreland basins, exhumation, paleoseismology and GPS measurements of convergence rates were taken into account.

Reanalysing the subsurface geophysical seismic profiles across the Kangra and Dehradun re-entrants of northwest Himalayan Foreland thrust belt, Joyjit Dey *et al*. (2017) suggested a predictive angular function for establishing quantitative geometric relationships between fault and fold shapes with 'Distance-displacement method' (D-d). It is a simpler and direct procedure to investigate the structural network from a seismic profile. They investigated two seismic profiles of the Kangra re-entrant, Himachal Pradesh, for studying the fault-related folds associated with the Balh and Paror anticlines. To substantiate the interpreted structures, the seismic profiles of the Paror anticline were extended as depth profiles and a cut-off angle $\beta = 35°$ was obtained. The shortening along the Jwalamukhi Thrust and Jhor Fault extending between the HFT and MBT in the Sub-Himalayan fold-thrust belt were obtained to be 6.06 and 0.25 km, respectively. The geometric method of the fold-fault relationship was studied to suggest the existence of a fault-bend fold above the HFT. The procedures were also applied to document the multi-bending configuration of the blind thrust of the Dehradun re-entrant.

Kumar and Srivastava (2017) studied the role of tectonic-climate interaction in the incision and aggradation of the Indus River in the Ladakh Himalaya during the late Quaternary. Examining about ~350 km long stretch of the Indus River and its upper reaches, the geomorphometry was estimated. On the basis of the geomorphometric calculations such as the longitudinal profile of the river, stream length-gradient index, and incised bedrock strath terraces, the 350 km long stretch was divided into four different segments. OSL chronological ages of fluvial/strath terraces indicated that valley aggradation occurred in three episodes, at ~52, ~28, and ~16 ka, yielding incision rates ranging from 1.0 ± 0.3 to 2.2 ± 0.9 mm/yr, which broadly coincide with periods of stronger southwest Indian summer monsoon. The results finally suggested that the increased fluvial incision rates along the studied stretch of the Indus River are suggestive of rapid tectonic uplift on the local faults of the western syntaxis which led to the formation of strath terraces along this section of the Indus River.

A detailed study on present-day crustal deformation in the Uttarakhand region has been done using at least four years (from 2012 to 2016) continuous GPS data from 28 sites situated in the region. The analysis of GPS observations suggests that the present-day plate convergence rate is 18±1 mm/yr towards N213°E and width of the locked frontal portion of Main Himalayan Thrust (MHT) is 100±15 km in the Garhwal-Kumaun Himalaya (Fig. 3) (Yadav *et al*., 2019; Gautam *et al*., 2017). A strong interseismic plate coupling (>0.6) has been observed in the Outer and Lesser Himalaya which indicates a large rate of strain accumulation (Fig. 1). The slip deficit budget since past major to great earthquakes in the Garhwal-Kumaun Himalaya suggests an overdue of at least 4 m slip on MHT which has the potential to produce a megathrust earthquake (Mw~8) in near future.

The dislocation model (inverse modeling of GPS deformation rates) of Jade *et al*. (2017) proposed that the MFT has remained locked over a width of ~110 km from the surface to a depth of 16 km in Garhwal Himalaya with associated dip-slip rate of ~16 mm/year and width of ~110 km from the surface to a depth of ~20 km in Kumaun Himalaya with associated dip-slip rate of ~18 mm/year. A well constrained, GPS-derived surface arc-normal shortening rate of ~10-11 mm/year in Garhwal, ~12 mm/year in the Gori valley and ~14 mm/year in the Kali Valley of Kumaun Himalaya, was estimated by Jade *et al*. (2016). The recent continuous GPS-measurements across the Garhwal and Kumaun Himalaya showed 18 mm/yr of strain accumulation (Gautam *et al*., 2017). That, the GPS shortening rate is higher than the geologically estimated rate may be due to partitioning of strain along other active faults in the hinterland of Sub-Himalaya as reported previously (Jayangondaperumal *et al*., 2018).

Northeast Himalaya

In the past decade, the frequency of strong earthquakes in the Northeast region has increased and thus it becomes important to monitor the ongoing crustal deformation in the region. Mukul *et al*., (2018) have reported the GPS measurements at 17 sites situated in the Darjiling-Sikkim Himalaya from 1998 to 2009. The velocity solution suggests a predominantly reverse slip motion on MHT. The plate convergence rate in Darjiling-Sikkim Himalaya is 18 mm/yr and the depth of locking inthe frontal part of MHT is 16 km. The authors have mentioned that the strike-slip plate convergence is insignificant while, a significant number of past earthquakes show the strike-slip kind focal mechanism in the region. The present-day deformation in the region provides a slip deficit of 15 meters from the past 800 years and the region has the potential to generate at least one megathrust earthquake in near future.

Barman *et al*. (2017) have reported the eleven years (from 2002 to 2013) surface deformation measurements at 34 sites (8-continuous and 26 campaign mode) situated in the central Shillong plateau and Assam valley block to Higher Himalaya and have derived a plate convergence rate of 16 mm/yr and the locking depth of MHT of 17 km in the region. A high rate of surface deformation (~ 9 mm/yr) has been observed in the Lesser Himalaya. The eastern block of Kopili fault show relatively larger southward velocity in the fixed India frame of reference as compared to the western block, which provides a dextral slip of 4.7±1.3 mm/yr with a locking depth of 10.2±1.4 km. The GPS measurements from Indo-Burmese region suggest that the Indo-Burmese fold and the thrust belts accommodate an oblique plate convergence of ~16 mm/yr, including the rate of fault perpendicular component of 6 mm/yr and fault parallel

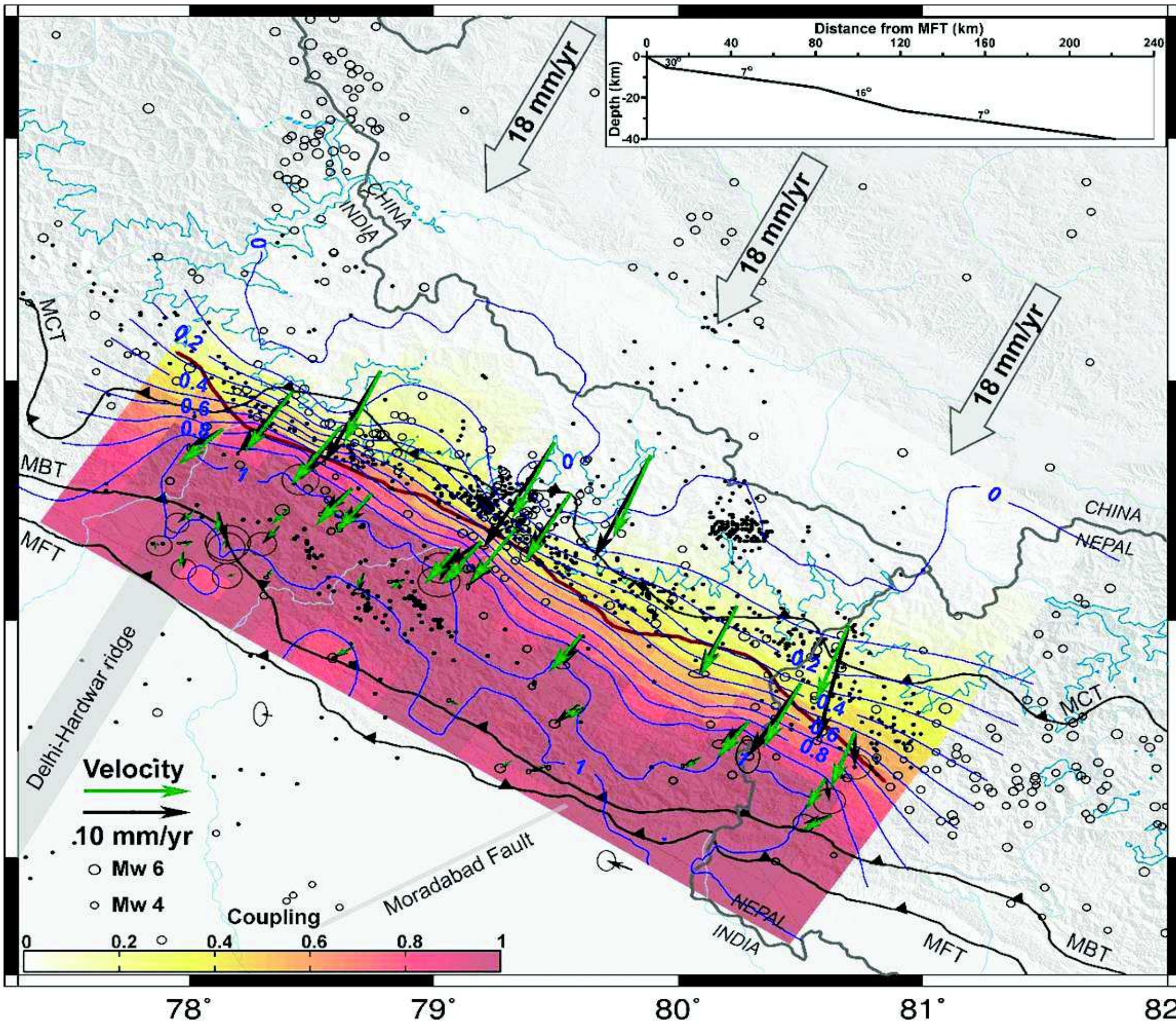

Fig. 3: Interseismic coupling map of Garhwal-Kumaun Himalaya. The black and green colour vector shows the observed and calculated site velocity respectively. Black colour circles show seismicity of the region from 1973 to 2015 (USGS catalogue). Blue colour contour represents the interseismic coupling on decollement with an interval of 0.2. Brown curve show trace of PT2. Top inset shows the geometry of MHT used in the analysis of interseismic coupling. (Yadav *et al.*, 2019)

component of 7-11 mm/yr.

The present-day geodetic measurements suggest that the rate of crustal shortening in the Northwest and Northeast Himalaya is about 20-25% lesser than the overall convergence rate accommodated in the Himalaya. Panda *et al*., (2018a) have proposed that the Assam-Brahmaputra valley in the outer deformation front along Northeast Himalaya act as a sliver to balance the long-term plate convergence rate between the Himalaya and southern Tibet. They mentioned that the Assam-Brahmaputra valley sliver is developed due to the strong eastward extrusion of Tibetan crust and it explains the present-day convergence along Eastern Himalaya syntaxis, low convergence and subdued topography in Bhutan and Arunachal Himalaya, kinematic and space-problem of Indo-Burmese wedge, the contradiction between Tibetan extrusion and oblique convergence model of the Himalayan Tibetan orogeny.

Panda *et al*. (2018b) have mentioned the presence of along-strike segmentation of tSagaing fault based on the geodetic observations and topography governed by lower crustal flow, which indicates that the central segment of Sagaing fault is locked and has a strong rheology while the northern segment is creeping and has a weak rheology.

The recent 25 April 2015 Nepal earthquakes and its aftershock sequence have experienced up to 600 km of the south of source zone due to the effect of basin amplification and directivity. This earthquake has shifted the Patna, Bihar about 7 mm towards the north (Yadav *et al*., 2017). The source and rupture characteristics of the earthquake have been well studied by the help of GPS derived coseismic offsets from the stations situated in Nepal, China and India (Sreejith *et al*., 2016; Yadav *et al*, 2017). The earthquake has occurred on the MHT, which confirms that the MHT plays an important role in the ongoing plate boundary deformation between India and Asia. The earthquake has raised several new facts such as the presence of heterogeneity along the dip and strike direction of the MHT, the existence of potential barrier that retards the westward propagation of seismic waves, and the amplification of seismic wave near Kathmandu. Sreejith *et al*. (2018) have derived the interseismic coupling ratio, and strain rate from past about two decades of continuous GPS data and b-values from the seismicity data. They have reported the two asperity zones possessing high strain accumulation coinciding with low b-values. They have mentioned that one of the asperity zones has released the accumulated energy during the April 2015, Nepal earthquake and the other asperity zone lies west of the epicentre of this earthquake, which has the potential to produce a future large earthquake. The acoustic wave induced by the earthquake has caused a significant perturbation in the ionospheric electron density (Sunil *et al*., 2017).

Peninsular India

The monitoring of crustal motion from continuous GPS measurements has been enhanced since past one decades which provides a better constraint of Euler pole of India and useful to describe the plate interior deformation. Jade *et al*. (2017) have used velocity solution derived from GPS measurements, for the period from 1996 to 2015, at 73 sites situated within India plate zone and have estimated a new angular velocity for the India plate. The newly derived Euler pole of India suggests significant active deformation (10-20 mm/yr) along the northern and eastern India plate boundaries and a low rate (1-2 mm/yr) of intra-plate deformation along the major faults in Peninsular India, Kachchh and Indo-Gangetic plain. The velocity solution from six years (2009-2015) of GPS observations at 15 sites (10 continuous and 5 campaign mode) situated in the Gujarat region suggest that the major fault systems lie in the Kachchh (e.g. KMF, KHF, IBF, SWF, and GF) are active and indicating strike normal compression with maximum rate of deformation of 3±0.5 mm/yr, which are capable to produce an earthquake of Mw~6 (Dumka *et al*., 2019).

Non-tectonic Deformations

The surface deformation due to the non-tectonic processes such as change in continental water mass, land subsidence, slow-moving landslide, and loading (or unloading) of the reservoir can be monitored by the continuous GPS measurements. The continuous GPS measurements from site situated in the Himalaya and plate-interior zone suggest the presence of seasonal variations, caused by the change in hydrological and atmospheric mass loading, in the horizontal and vertical displacement components. The seasonal variation is relatively more in vertical as compared to horizontal displacement components (Gahalaut *et al*., 2017). Panda *et al*. (2018c), have mentioned that the continuous GPS measurements in the Uttarakhand and Nepal Himalaya show relatively higher transient displacement above the base of the seismogenic zone which is the response of modulation in aseismic slip rate on the deep megathrust controlled by the seasonal hydrological load. It is observed that shear-stress perturbations induced by the seasonal hydrological load are about three times larger on the mid-crustal ramp than on the up-dip flat segment of MHT.

The continuous surface deformation monitoring at Gandhinagar from past eight years show a high rate of water depletion (1.3 meters/year) causing the land to subside with subsidence rate ~5 mm/yr (Choudhury *et al*., 2018). The loading (or unloading) of Tehri reservoir produces a significant surface deformation at nearby site Kunair, near Chamba, Garhwal (Gahalaut *et al*., 2017). The monitoring of Koyna-Warna reservoir with five continuous GPS sites from past four years suggest that the eastern block of Koyna-Warna seismic zone moves relatively faster with a rate 0.7±0.2 mm/yr towards northeast as compared to the western block and seasonal deformation due to reservoir filling leads to reduction in the fault strength on the faults of the Koyna-Warna seismic zones (Gahalaut *et al*., 2018). Another study on surface deformation caused by four different hydroelectric reservoirs (Ukai, Tehri, Koyna-Warna and Dharoi) indicates that even small size of the reservoir can produce significant surface deformation in the surroundings and reservoir can produce unusually large deformation caused by the local hydrological conditions (Dumka *et al*., 2018). In conclusion, the reservoir loading (or unloading) plays an important role in the triggering of earthquakes on critically stressed faults and modulation of earthquakes frequency.

Despite the increase in monitoring of crustal movement from continuous GPS measurements from past one decade within India, a major challenge to the researchers and scientists is to detect the potential zones for future megathrust earthquakes in the Himalaya. There is a need for integration of the available information of seismogenic crust from various geological and geophysical investigations and thus an interdisciplinary approach is required to deal with the complex issues. The mitigation and preparedness activity, such as the spread of awareness of earthquakes and safety tools to the local people, is necessary for the seismically risk zones to reduce human and economic loss from all the potential future devastating earthquakes.

Bhattacharjee *et al*. (2016) carried out geomorphological mapping and spatial analyses of rivers to elucidate the imprints of active tectonics on fluvial systems from the region of ENE–WSW trending Gavilgarh Fault Zone (GFZ) within the Central Indian shield. They analyzed the sinuosity index, width–depth ratio of river valleys, longitudinal profile, S–L index and hypsometric index of the rivers flowing from north to south across the GFZ lineament suggest that the northern side of GFZ was tectonically uplifted. Luminescence dating of sediments from river terraces and calculation of knickpoint migration rates in the rivers indicate occurrence of multiple neotectonic events in GFZ at ca. 65-80 ka, ca. 50 ka, ca. 30-40 ka, and ca. 14 ka. Evidence of neotectonic activity, presence of active geothermal springs, and occurrence of recent earthquakes along GFZ suggest that this lineament is tectonically active and there is a need for proper seismic monitoring of this fault zone.

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