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Review Article

Active Tectonics and Geomorphological Studies in India During 2012-2016

MALAY MUKUL[1,*] and VIMAL SINGH[2]
[1]*Continental Deformation Laboratory, Department of Earth Sciences, Indian Institute of Technology, Mumbai 400 076, India*
[2]*Department of Geology, University of Delhi, Delhi 110 007, India*

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This article reviews the literature on tectonic geomorphological studies in India published in peer reviewed journals between 2012-2016. The northward drift of the Indian plate and its collision with the Eurasian plate results in compressive stresses in Indian subcontinent. Based on the broad morphotectonic setup the studies are categorised into the Himalaya and the Indian Peninsula. Studies in the Himalaya mainly demonstrate that most of the deformation during Holocene has occurred in the sub-Himalaya and especially along the Main Frontal Thrust (MFT). Evidences of active tectonics is also reported from several parts of the Himalaya which also includes the Main Boundary Thrust (MBT) zone. The impact of active tectonics on the geomorphology along the active faults is also investigated in several areas of the Himalaya. In the Indian Peninsula Narmada-Son fault, Tapti fault and Katrol hill fault are shown to be active on the basis of sedimentological and geomorphological investigations.

Keywords: Active Tectonics; Himalaya; Main Frontal Thrust; Narmada-Son Fault

Introduction

The Indian subcontinent is under compressive stress as a result of the Indo-Eurasian collision around ~55 Ma (Zoback *et al.*, 1989; Zoback, 1992). The deformation in response to these stresses is manifested over several time scales ranging from millions of years to the present. Deformation over 10^3 to 10^5 years is manifested in uplift, tilting and folding of Quaternary sediments and affect the landscape evolution in this time scale (Keller and Pinter, 1996; 2002). In the Indian context, evidence of deformation in the above time scale is observed along the Himalayan front and in the intra-continental rifts such as Kachchh and Narmada. Active Tectonics and Geomorphological studies in India during 2012-2016 can, therefore, be broadly categorized into studies in the Indian Peninsula and the Himalaya.

Investigations of Active Tectonics in the Indian Himalaya

Studies on Active tectonics in the Himalaya either explore deformation in the frontal part of the Himalayan wedge associated with the Main Frontal Thrust (MFT) (also called as Himalayan Frontal Thrust or Himalayan Frontal Fault) or out-of-sequence deformation in the Himalayan wedge north of the present mountain front.

Himalayan deformation along the Main Frontal Thrust (MFT) and the frontal Himalaya

In the Sub-Himalayan zone, the frontal Siwalik range abuts against the alluvial plain with an abrupt physiographic break along the MFT, defining the present-day tectonic boundary between the Indian plate and the Himalayan orogenic prism (Thakur, 2013). The central idea behind deformation along the MFT in the Himalaya is the understanding that MFT is the surface or the near surface equivalent of the

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*Author for Correspondence: E-mail: malaymukul@iitb.ac.in

basal decollément of the Himalaya or the Main Himalayan Thrust (MHT). The MHT propagates slip from the hinterland towards the foreland. The MFT is activated only when slip can be transferred all the way from the hinterland where it originates, to the MFT in the foreland. This happens only during great earthquakes so active tectonics along the MFT has earthquake hazard implications. Out-of-sequence deformation occurs when the slip does not make it all the way to the foreland but activates a structure within the wedge.

Thakur (2013) summarized structures and geomorphic features associated with the MFT. The frontal Siwalik range is characterized by large active anticline structures, that were developed as fault related folds in the hanging wall of the MFT. Fault scarps showing surface ruptures and offsets observed in excavated trenches indicate that the MFT is active. South of the MFT, the piedmont zone shows incipient growth of structures, drainage modification, and 2-3 geomorphic depositional surfaces. In the hinterland between the MFT and the Main Boundary Thrust (MBT), reactivation and out-of-sequence faulting displace Late Quaternary-Holocene sediments. Geodetic measurements across the Himalaya indicate a ~100-km-wide zone, underlain by the MHT, between the MFT and the main microseismicity belt to north is locked. The bulk of shortening, 15-20 mm/year, is consumed aseismically at mid-crustal depth through ductile creep. Assuming the wedge model, reactivation of the hinterland faults may represent deformation prior to wedge attaining critical taper. The earthquake surface ruptures, $\geq$240 km in length, interpreted on the Himalayan mountain front through paleoseismology, imply reactivation of the MFT and may suggest foreland propagation of the thrust belt.

Jammu-Kashmir Himalaya

In the Jammu-Kashmir Himalaya, Thakur and Jayangondaperumal (2015), invoked activity along the frontal Balakot-Bagh Fault (BBF) with right-step to Reasi Thrust in Jammu region during the 2005 Kashmir Mw 7.6 earthquake that produced 75 km surface rupture and 3-7 m vertical offset. No historical record of a large magnitude Mw > 7 event for the last ~1000 years in the eastern segment of the Kashmir seismic gap, may imply ~12 m slip deficit in the region. Vassallo *et al*. (2015) suggested that three main Cenozoic thrusts at the front of Jammu and Kashmir Himalaya have accommodated most of the India–Eurasia convergence over the last million years and has produced the present-day relief. Their recent tectonic activity is poorly known because of the long period of inaccessibility of the state, and because the latest and only large earthquake recorded in the region occurred in 1555 AD. They also showed where the deformation is localized during the Late-Quaternary and determine shortening rates across the structures by analyzing the geometry and chronology of the geomorphic markers. The MBT in this region ceased moving at least ~30 ka ago. The more external Medlicott–Wadia Thrust and MFT, both merging at depth on the sub-flat detachment of the MHT, exhibited hectometric-scale deformations accumulated during the last thousands of years. The total shortening rate absorbed by these faults over the last 14-24 ka is between 13.2 and 27.2 mm/yr (11.2 ± 3.8 and 9.0 ± 3.2 mm/yr, respectively); the lower bound of their shortening rates is consistent with previously determined geodetic rates. Part of this deformation may be associated with the geometry of the Chenab reentrant, which could generate an extra oblique component. Active deformation on these structures follows an in-sequence/out-of-sequence pattern, with breaking of both ramps being possible for earthquakes triggered on the MHT.

Himachal Himalaya

In the frontal Himachal Himalaya, Philip *et al*. (2014) postulated that at least two major earthquakes occurred along two faults in the Pinjaur Dun between the MFT and the MBT in the Late Pleistocene signifying high seismic potential in this vastly populous mountainous region.

The Kangra recess constitutes a ~ 80-km- wide zone of fold-thrust belt structures in the Cenozoic strata of the foreland basin in Himachal Sub-Himalaya. Earlier workers estimated the total long-term shortening rate of 14 ± 2 mm/year by balanced cross-section between the MBT and the MFT. Geologically estimated rate is nearly consistent with the GPS-derived slip rate of 14 ± 1 mm/year. Thakur *et al*. (2014) mapped active faults developed within 4-8 km depth of the Sub-Himalayan fold- thrust belt of the recess. Dating the strath surfaces of the abandoned fluvial terraces and fans above the thrust faults, the uplift (bedrock incision) rates were computed. The dips of thrust faults were measured in the field and from available seismic (depth) profiles. From the acquired data, late Quaternary shortening rates on the Jawalamukhi Thrust (JT), the Soan Thrust (ST) and the MFT were estimated. The shortening rates on the JT were 3.5-4.2 mm/year over a period 32-30 ka. The ST yielded a shortening rate of 3.0 mm/year for 29 ka. The corresponding shortening and slip rates estimated on the MFT were 6.0 and 6.9 mm/year during a period of 42 ka. On the back thrust of Janauri anticline, the shortening and slip rates were 2.0 and 2.2 mm/year, respectively, for the same period. The shortening was distributed largely across a 50-km-wide zone between the JT and the MFT. The emergence of surface rupture of a great and mega earthquakes recorded on the reactivated MFT implies $\geq$100 km width of the rupture. The ruptures of large earthquakes, like the 1905 Kangra and 2005 Kashmir, remained restricted to the hinterland. The present study indicates that the high magnitude earthquakes can occur between the locking line and the active thrusts.

Garhwal Himalaya

In the Garhwal Himalaya, Philip *et al*. (2012) studied the MFT system along the Himalayan Front near Kala Amb and found evidence of occurrence of multiple large magnitude earthquakes in this region in the period between 29.3 ka and 17 ka in the Late Pleistocene. Another great earthquake with 20-22 m or more surface displacement and magnitude of 7.7 or greater between 5.8 ka and 2 ka in the Holocene was also observed. An uplifted and upwarped strath terrace, 3 to 5 m thick alluvium, resting over the 15 m high Middle Siwaliks, abruptly truncated by the MFT indicates its latest activity. The long term slip rate of the abandoned terraces due to the activity of the MFT is estimated to be 3.4 mm/yr or greater since Late Holocene.

Devrani and Singh (2014) attempted to understand the importance of place and local factors in the process of accumulation of sediments in a valley stretch in an active mountain belt in the Garhwal Himalaya along the Alaknanda River-one of the two uppermost tributaries of the Ganga River. This stretch or the Pipalkoti Valley is located close to the Main Central Thrust (MCT) and falls in the zone of orographic precipitation. Detailed geomorphic mapping revealed four surfaces and two terraces. Three debris flow surfaces suggested their deposition by local mass flows and stream flows with very small contributions from the Alaknanda River. Terrace T2 occurred as a strath in some parts and is made up of fluvial and lacustrine sediments in others. The presence of lacustrine sediments suggested local damming of the river. Thick fluvial sediment were deposited in wide stretches of the rivers when joined by a tributary. Syn-sedimentary deformation has been noted indicating that tectonic activity had affected sedimentation. The results suggested that local processes played a dominant role in the accumulation of sediments in this valley stretch. It was concluded that before correlating valley fill deposits along the lengths of the Himalayan valleys, it is important to evaluate the role of various local processes that have operated in particular stretches.

Kumaon Himalaya

In the Kumaon Himalayan front, evidence of earthquakes between 1200 AD and 1700 AD located across the MFT in the western Indian Himalaya were recognized by Jayangondaperumal *et al*. (2013) at Rampur Ghanda and Ramnagar. The shortening estimates of were ~10-25 %. A parametric study at the trenched fault zone of Rampur Ghanda showed a slip of 16 m beneath the trailing edge of the scarp; this was thought to be sufficient to raise a 8-m- high scarp. A 16-m slip is the most robust estimate of the maximum slip along the MFT in the western Indian Himalaya between 1200 AD and 1700 AD. However, the Ramnagar scarp may also consist of minimum two events (i) pre- 1400 AD and (ii) unknown old events of different lateral extents with overlapping ruptures. If the more optimistic two seismic events scenario is followed, the rupture length would be at least 260 km and would lead to an earthquake greater than Mw 8.5.

Kothyari *et al*. (2012) studied landslides and neotectonic activity in the MBT Zone, Kumaon Himalaya**.** TheMBT zone was recognized as a landslide prone area in southeastern part of Kumaon Sub-Himalaya, as the rocks making up the slopes has been put to a number of brittle deformation phases during the movement along the MBT and are traversed by number of joint sets that form structural wedges and are the most favorable site for initiation of rock falls and other types of landslides. Wedge failure is a common type of landslides in rock slopes characterized by multiple joints and acts as sliding planes for the failed blocks. Field observations and wedge failure analysis indicates that most of the landslides are taking place in the MBT zone of Kumaun Sub-Himalaya and they are primarily joint controlled. Safety Factor analysis suggested that the MBT zone of Kumaun Sub-Himalayan region was prone to landslides and related mass movements. This zone was also neotectonically active as indicated by various geomorphic signatures such as structurally controlled drainage pattern, offsetting of fan by the MBT and formation of number of small lakes.

In the Kumaun Himalaya, Luirei *et al.* (2015) carried out integrated studies of geomorphic indices of drainage networks and landforms developed across the mountain front along the MFT between the Dabka and Baur rivers. In this region, the MFT is a morphogenic structure, creating a 100-m-high E–W trending escarpment that extends over ~ 21 km. Geomorphological evidence indicates ~10.5 km westward migration of the Dabka River and ~ 5.2 km eastward migration of the Baur River. These migrations are a result of uplift of the hanging wall due to slip along the MFT. The MFT is offset by a transverse fault, which suggests that the latter postdates the reactivation of the MFT between 500 and 100 ka. Presence of different levels of strath terraces along the mountain front suggests that the MFT is active. To assess the relative tectonic activity, morphometric indices such as stream-gradient (*SL*) index, mountain front sinuosity (S_{mf}) index, and ratio of valley floor width to valley height (*Vf*) have been analyzed. Results of the former two are consistent with the tectonic landforms developed in thrust zones. Paleochannels of the Dabka and Baur rivers are characterized by high *Vf* values while other valleys show low *Vf* values. Quaternary alluvial sediments have been deformed along the Pawalgarth Thrust, a splay of the HFT. Deformation has resulted in the formation of the Pawalgarh Anticline, a thrust-related asymmetric fold.

Malik *et al.* (2014) studied the Kaladungi Fault (KF) which is a footwall imbricate of the MFT system and described evidence of forward and lateral propagation of the fault as well as fault-related folding both along and across the strike of the fault. The KF displaced the distal Kaladungi fan surface resulting in the formation of a south-facing active fault scarp with variable heights along the front. The height of the uplifted fan surface varies from ~ 80 m in the east, ~ 200 m in the centre to ~ 60 m in the west from the base level. The variation in heights along the fault was attributed to the lateral propagation of the KF and associated fold in both directions (i.e. east and west) from the centre. The northwest and southeast propagation of KF has resulted in diversion of the Dabka and Baur rivers respectively. A marked diversion of the modern Dabka river along its present course from east to west was traced between the Shivlalpur and Karampur towns, covering a distance of about 10-12 km. Similarly, the Baur river was shifted from west to east by about 5-6 km between Kamola and Kaladungi towns. The diversion of Dabka and Baur rivers can also be supported by the existence of paleo-wind gaps through which these rivers flowed earlier. The wind gaps are characterized by about 0.5-1.0 km wide incised valley extending in NE-SW direction between Kaladungi and Karampur in the frontal zone.

Luirei *et al.* (2014) postulate that a section of the MBT in the Kumaun Himalaya experienced recent extensional tectonic activity although no kinematic explanation for this was given. The surface expression of the tectonic activity is faulting of Quaternary fan deposited along the MBT zone. Faulting has caused ground rupturing producing a fault scarp measuring about 37 m in height and 2.5 km in length that is exposed along the MBT. One sample from the fan has been dated using Optically Stimulated Luminescence (OSL) to about 17 ka. Two parallel fault traces are also observed in the western segment of this fault. In the Sukhidang-Shiala area, normal faulting has produced a series of small lakes. Geomorphic evidence suggests the existence of more lakes, which have dried up (as evidenced by palaeolakes) due to headward erosion and landslides. Three pits were excavated in paleolakes to determine if any deformation event was preserved in the lake sediments. In one of the pits (Pit No. 3), soft-sediment deformation structures were observed in strata comprising laminated silty sand and pebbly sand beds at a depth of 1 m. The OSL date of these deformed laminated silty sand and pebbly sand beds and the upper undeformed layer gives ages of 370 ± 28 and

278 ± 28 years, respectively. In the mountain front a fan deposit has been truncated by the MFT exposing a fault scarp of about 5 km in length and 100 m in height. Geomorphic indices have been analyzed along the frontal part of the Kumaun Sub-Himalaya to assess tectonic activities in the area. Values corroborate the field evidence suggesting that this segment of the Himalayan mountain front is tectonically active.

Joshi *et al*. (2016) studied the NNW-SSE trending dextral strike-slip fault Raintoli fault (RF) that runs parallel to the North Almora thrust (NAT) along the Saryu valley from Seraghat-Naichun to Seri in the central sector of the Kumaon Himalaya, India. Reactivation along RF with oblique-slip was observed using various geomorphic indicators.

Darjiling Himalaya

The effects of active tectonics on geomorphic features have been studied in a large alluvial fan in the foothills area of the Darjiling Himalayas (Goswami *et al*., 2013). The interfluve area between the rivers Mal and Murti is an alluvial fan composed of Quaternary sediments characterized by clay, sand, pebble, and boulder beds. Most of the river valleys in this area show well-developed terraces. There are four major terrace surfaces, named as T_1, T_2, T_3 and T_4 according to increasing height from the river bed. Two E-W Matiali and Chalsa scarps cut across the fan represent traces of the MBT and the MFT respectively. There are two other NNW-SSE and NNE-SSW lineaments which have partially guided the courses of the Neora and Murti rivers. These are interpreted as conjugate sets of normal faults transverse to the orogenic trend although no kinematic explanation of these normal faults have been provided. The E-W scarps are interpreted as frontal limbs of the ramp anticlines over two blind thrusts, once again without kinematic explanations that justify this interpretation. They also postulate that fault propagation folding has affected the fan surface, although, how that forms ramp anticlines is not clear. Recurrent movements on the thrusts and consequent down-cutting of the rivers have led to the formation of the raised terraces on the banks of these rivers. The terraces are formed by cut-and-fill process. The impact of neotectonic activity on drainage system in this large alluvial fan has been studied between the Mal River and the Murti River (Goswami *et al*., 2012). It is postulated that rivers have changed their course due to the influence of normal faulting along the Murti and Neora lineaments, and their profiles show knick points where they cross E-W thrusts. The overall drainage pattern is changed from radial pattern north of the Matiali scarp to a sub-parallel one south of it, due to the conjugate normal faults. The interfluve area between these two rivers is uplifted as a result of vertical movements on the above mentioned faults. Four major terraces and some minor terraces are present along the major river valleys and are formed due to episodic uplift of the ground and subsequent down-cutting of the rivers. The uppermost terrace shows a northerly slope north of the Chalsa scarp as a result of folding mentioned above. But rivers on this terrace form incised channels keeping their flow southerly suggesting that they are antecedent to the folding and their down-cutting kept pace with the tectonism. Kar *et al*. (2014) continued work on the Matiali fan and their geomorphologic and sedimentologic study of the fan and associated river terraces revealed two aggradational terraces (T1 and T2; T2>T1) within the river valleys incised on the Matiali fan. Three E-W scarps cross the fan surface, and they represent the steeper limb of the asymmetric fault-propagation folds formed over blind thrusts. These folds have deformed the fan (T3) and T2 terrace sediments, but the youngest T1 terrace deposits have remained undeformed. Sedimentological studies indicate a continuous sedimentation history across the fan, uninterrupted by any evidence of syn-depositional tectonic movement. Poorly consolidated sandy gravels of the terraces indicated deposition through braided fluvial processes during a later period of sediment aggradation that filled up the incised river valleys. Previously published ^{14}C dates indicate that deposition of the Matiali fan started around 34ka coinciding with a period of the intensified Indian summer monsoon of MIS-3. They suggested that the fan was abandoned and river valleys incised during the LGM between 24 and 18ka when the discharge decreased substantially. Increased rainfall and sediment supply, with their inherent fluctuations, during wetter periods of MIS-2 and MIS-1 since 12ka probably resulted in the aggradation of T2 and T1 as shown by OSL dates. OSL dates from the top of deformed T2 and base of undeformed T1 indicate that the Chalsa fold formed between ~11 and ~6ka. Succession of geomorphic and deformational events reconstructed from this study and available age data indicate that the Matiali fan and terrace aggradation coincides with periods of increased monsoonal precipitation, whereas tectonic movements along blind thrusts of Chalsa and Matiali took place later, deforming the fan and older terrace deposits. The evidence unequivocally indicates, contrary to the prevalent notion of tectonic control of geomorphic features in the proximal mountain-front setting, that the deposition of the fan-terrace system was primarily controlled by the fluctuation of the Asian summer monsoon rather than Himalayan tectonics.

Bhutan Himalaya

Dasgupta *et al.* (2013) studied the geomorphic landscape and late Quaternary geological attributes from the Raidak-Manas interfluve in the Bhutan-Himalayan foothills, Kokrajhar District, Assam, and documented the east-west trending, south-dipping, 30km long, active Frontal Back Thrust (FBT), well within the foredeep, south of the MFT. Spectacular north-facing, 6-50m high scarp generated by the north-propagating emerging thrust front along with a complementary subdued south-facing scarp was interpreted as a pop-up structure. Scarp parallel east-west drainage along with linear lakes characterized the emerging thrust front. Field evidence for a major fault-propagation fold structure along with thrust faulting within the late-Quaternary fluvial sediments was ubiquitous. Clay beds deposited in lakes along the footwall of FBT have formed due to blockade of south flowing rivers by episodic uplift of the hanging wall block; three such episodes since 16 k years correspond to three morphogenic earthquakes of magnitude ~6.9 rupturing the FBT during late Pleistocene-Holocene. In light of geomorphological and geological studies, neotectonic activity has been modelled as an active south-dipping backthrust that originated at shallow crustal depth from south vergent basal Himalayan decollément in response to the advancing Himalayan wedge.

Arunachal Himalaya

In the Western Arunachal Himalaya, four levels of unpaired terraces and a paired terrace were observed in the MFT zone along the Kameng river by De *et al.* (2014). They postulated wrench deformation in the MFT zone resulting in a SE propagation of the Balipara anticline, and suggested that the Mikir high basement controlled its orientation; the kinematics of the process, however, was not explained. Ages of fluvial terrace surfaces suggested that since the Late Pleistocene, Kameng River migrated at a rate varying between ~7.5cm/yr in upper reaches and ~13.5cm/yr towards northeast due to MFT related uplift. In the Brahmaputra plains, luminescence ages of abandoned paleochannel deposits suggested eastward shifting of the Kameng river at an average rate of ~1m/yr. Pliocene strath and Quaternary terrace surfaces were displaced by <1ka out-of-sequence thrusts (OOSTs) that do not correspond to the mapped faults in the foreland region. Average slip rate and horizontal shortening rate on OOST during the Holocene, were calculated as ~12 mm/yr and 7mm/yr respectively. A minimum slip rate of Siwalik ~27 mm/yr during the Holocene was estimated suggesting acceleration in shortening rates east of Bhutan.

Farther east, Devi *et al.* (2016) observed tectonic forcing of drainage in the frontal Eastern Arunachal Himalaya. Dikari, a transverse river flowing along the N–S trending western limb of the major Siang Antiform, exhibited structurally controlled nature of its drainage on its downstream flow towards south, through a network of NE-SW and NW-SE trending conjugate faults. The river showed compressed meandering as the regional structural trend of ENE-WSW seemed to be reactivated by the transverse NW-SE trend of neotectonic fault activity. The MFT trace along the Himalaya mountain front has been displaced sinisterly for a distance of ~7 km by a WNW-ESE trending fault running along the Sileng stream. Development of parallel drainages in the southern part of the Sub-Himalaya was interpreted to have formed as a result of uplifting related to the sinistral strike-slip movement. Along the MFT zone, the frontal streams and rivers exhibited deflection of their channels from NE-SW to ENE-WSW directions. Channel of the transverse Siang river has been deflected for a length of 3 km along the NNE-SSW direction across the Himalayan frontal region. In this part of the Himalaya, previous workers did not give much emphasis on the neotectonic role of Siang Antiform. There appeared to be a syntectonic relationship between the active NE-SW-oriented compression direction and the tectonic forcing of the drainages.

Investigations of Active Tectonics in the Indian Peninsula

Narmada Rift

Joshi *et al*. (2013) studied an alluvial bajada along a part of the active Narmada-Son Fault (NSF) and on the basis of sedimentary characteristics, lithofacies analysis and facies associations, between the Karjan and Madhumati rivers, they recognized sediments deposited by debris flows, gravity flows and as extensive bar deposits. Three major aggradational sequences were recognized. Each sequence was composed of coarsening-upward sequence of proximal facies overlain by fining-upward sequence of distal facies. Coarsening-upward sequence recorded periods of tectonic activity related to uplift along the NSF and fan progradation, whereas fining-upward sequence resulted from tectonic quiescence periods. Tectonic activity along the NSF has played a dominant role by controlling the geometry and volume of the bajada sediments. Climate was found to be responsible for compositional and temporal distribution of the bajada sediments. OSL dating suggests that the bajada sediments were deposited during the later part of late Pleistocene. The incision of the sediments is attributed to uplift due to inversion of the lower Narmada basin during the early Holocene.

Copley *et al*. (2014) studied offset alluvial fan surfaces on the Tapti Fault (Maharashtra, western India) that indicated one or more magnitude 7.6-8.4 thrust-faulting earthquakes during the Holocene. The high ratio of fault displacement to length on the alluvial fan offsets implied high stress-drop faulting, as has been observed elsewhere in the peninsula. The along-strike extent of the fan offsets was similar to the thickness of the seismogenic layer, suggesting a roughly equi-dimensional fault rupture. The subsiding footwall of the fault was likely to have been responsible for altering the continental-scale drainage pattern in central India and creating the large west flowing catchment of the Tapti river. A pre-existing sedimentary basin in the uplifting hanging wall implied that the Tapti Fault was active as a normal fault during the Mesozoic and has been reactivated as a thrust, highlighting the role of pre-existing structures in determining the rheology and deformation of the lithosphere. The slip-sense of faults and earthquakes in India suggests that deformation south of the Ganges foreland basin is driven by the compressive force transmitted between India and the Tibetan Plateau. The along-strike continuation of faulting to the east of the Holocene ruptures represents a significant seismic hazard in central India.

Kachchh Rift

Integrated studies of landform development and geomorphic indices of drainage networks across the South Wagad Fault (SWF) zone by Kothyari *et al*. (2016a) indicated that the SWF was a structure that was morphogenic in nature, creating a 40-m-high E-W trending escarpment that extended ~80km at the southern end of the Wagad uplift. The SWF got reactivated during the Bhuj earthquake of 2001 and continued aftershock activity of $M \geq 4$ levels in the epicentral zone, north of the Kachchh Mainland Fault and west of the SWF. Strath terraces along the river valleys and the truncation of alluvial fans along the mountain front, incision, and offset of rivers also suggested an active SWF. The landform development along river valleys in the SWF zone suggested reactivation of the SWF between 12 and 3ka. The southern front of Wagad was found to be uplifting at the rate of 2.8mm/yr during the last 12ka as estimated through OSL dates. The relative index of active tectonics (RIAT) by the study of different geomorphic parameters and field checks indicates that most of the Wagad highland was active.

Kothyari *et al*. (2016b) studied the epicentral region of the 2006 Mw 5.7 earthquake in the Wagad upland along east-west trending Gedi Fault (GF) north of the Kachchh rift basin in western India approximately 60 km northeast of the 2001 Mw 7.7 earthquake epicenter. Development of an active fault scarp, shifting of a river channel, offsetting of streams and uplift of the ground indicate that the terrain is undergoing active deformation. Based on detailed field investigations, three major faults that control uplifts have been identified in the GF zone. These uplifts were developed in a step-over zone of the GF, and formed due to compressive forces generated by left-lateral motion within the segmented blocks. Reconstructions based on geomorphology and terrace stratigraphy supported by OSL suggest that the fluvial aggradation in the Wagad area was initiated during the strengthening (at ~8 ka) and declining (~4 ka) of the Indian Summer Monsoon (ISM). Based on terrace morphology two major phases of enhanced uplift have been estimated. The older uplift event dated to 8 ka was represented by the Tertiary bedrock surfaces which accommodated the onset of valley-fill aggradation. The younger event of enhanced uplift dated to 4 ka was responsible for the incision of the older valley fill sediments and the Tertiary bedrock. These ages suggest that the average rate of uplift ranges from 0.3 to 1.1 mm/yr during the last 9 ka implying active nature of the area.

Bhattacharyya *et al*. (2013) studied a channel fill sequence in the upper catchment of the Khari river south of the Katrol Hill Fault (KHF). Detailed sedimentology and limited luminescence dating suggest that the channel incision occurred during weak summer monsoon (prior to 19.9 ka) and was attributed to activity along the KHF and its subsidiary faults. The results revealed that the post-glacial to early Holocene was a phase of landscape stability (subdued tectonics) until around 7.1 ka. Particularly, between 9.4 ka and 7.1 ka, an enhanced monsoon activity is also inferred. A renewed phase of uplift was suggested after 7.1 ka that probably continues today.

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