

# Neotectonic study along mountain front of northeast Himalaya, Arunachal Pradesh, India

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**Abstract** To study neotectonics, the structural and morphotectonic aspects are studied along a part of mountain front region of Northeast Himalaya, Arunachal Pradesh, India. Unpaired river terraces are recognized near north of transverse Burai River exit, which is cut by an oblique fault. Across this fault, fluvial terraces are located at heights of 22.7 and 3 m, respectively, on the left and right banks. A water gap is formed along the river channel where the uplifted Middle Siwalik sandstone beds dipping 43° towards ENE direction, thrust over the Quaternary deposit consisting of boulders, cobbles, pebbles and sandy matrix. This river channel incised the bedrock across the intraformational Ramghat Thrust along which the rocks of the Middle Siwalik Formation thrust over the Upper Siwalik Formation. Recent reactivated fault activity is suggested north of the Himalayan Frontal Thrust that forms the youngest deforming front of the Himalaya. The uplifting along the stream channel is noticed extended for a distance of ~130 m and as a result the alluvial river channel became a bedrock river. The relative displacement of rocks is variable along the length of strike-slip faults developed later within the Ramghat Thrust zone. Longitudinal and Channel gradient profiles of Burai River exhibit knick points and increase in river gradient along the tapering ends of the profiles. The study suggests active out-of-sequence neotectonically active thrusting along the mountain front. Neotectonics combined with climatic factor during the

Holocene times presents a virgin landscape environment for studying tectonic geomorphology.

**Keywords** Geomorphic evidence · Middle Siwalik · Tectonic activity · Quaternary · Water gap · Knick point

## Introduction

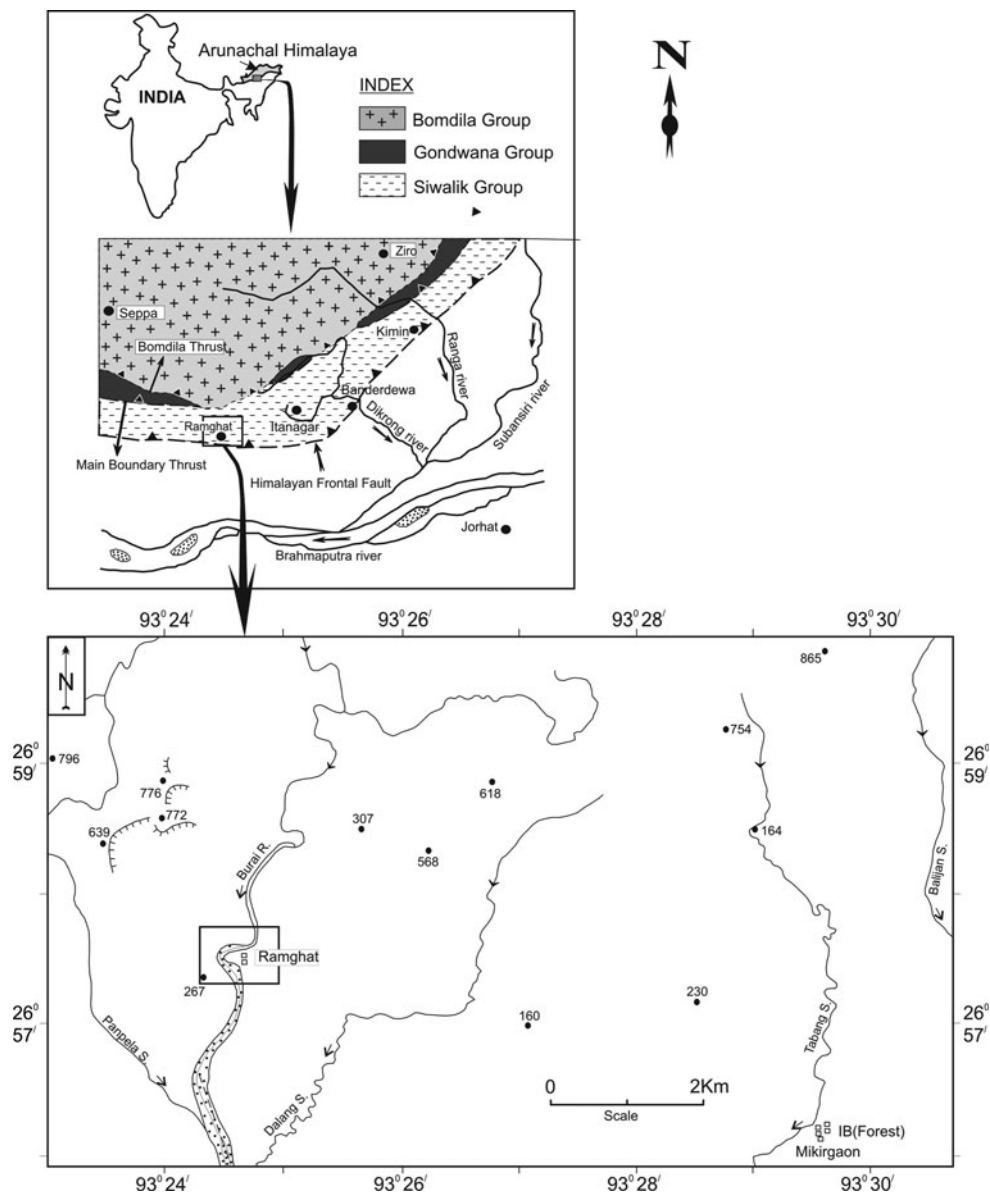
The Global Positioning System (GPS) study indicates that part of convergence rate of the Indian plate towards the Himalaya is being accommodated between the Himalayan Frontal Thrust (HFT) and the Main Central Thrust (MCT), partitioned within the Lesser Himalayan domain. This, ~100-km-wide zone, is interpreted to be locked below the Lesser Himalaya along the decollement (Banerjee and Bürgmann 2002; Thakur 2004). It is reflected in the form of the surface deformation/shortening. The collision speed of India plate relative to Asia plate increases from >40 mm/year in western India including Pakistan to >52 mm/year in eastern India and Burma (Bilham and Gaur 2000). Increasing from west to east ~30% of this convergence velocity is absorbed across the Himalaya (Molnar and Tapponier 1975), which is 10–12 mm/year in Pakistan, 15–18 mm/year in India, ~22 mm/year in Nepal and maximum of ~25 mm/year in the northeastern Himalaya (Yeats et al. 1992). The northeast Himalaya is considered to be the most seismically active region where two great earthquakes occurred recently, e.g., the 1897 Shillong and 1950 Assam earthquakes. The epicenters of moderate-sized earthquakes lie along and south of the surface trace of the Main Boundary Thrust (MBT) that is considered to be not a seismogenic fault and the active seismogenic fault must be located south of it (Holt et al. 1991; Kayal 2003).

The Bomdila Thrust transported the distant Lesser Himalayan Crystallines (LHCs) towards foreland (Fig. 1).

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**Fig. 1** Location map of the study area



This thrust in addition to the MBT, exerted compressional tectonic stress along their foreland propagated younger splays on the Siwalik rocks. During the interseismic period the movement along the decollement is locked and the elastic deformation/strain or energy accumulates to be released by large earthquakes (Lave and Avouac 2000). Most of the N–S shortening rate across the whole Himalaya seems to be absorbed by thrusting along the HFT. The depth of the decollement plane is relatively shallow beneath the Himalayan deforming front as compared to its depth beneath the Lesser Himalayan region. As a consequence, the frontal part of the northeast Himalaya is characterized by occurrence of relatively young tectonic geomorphological and structural features developed over the decollement plane; their study may help in the understanding of neotectonics of the region. Therefore, the

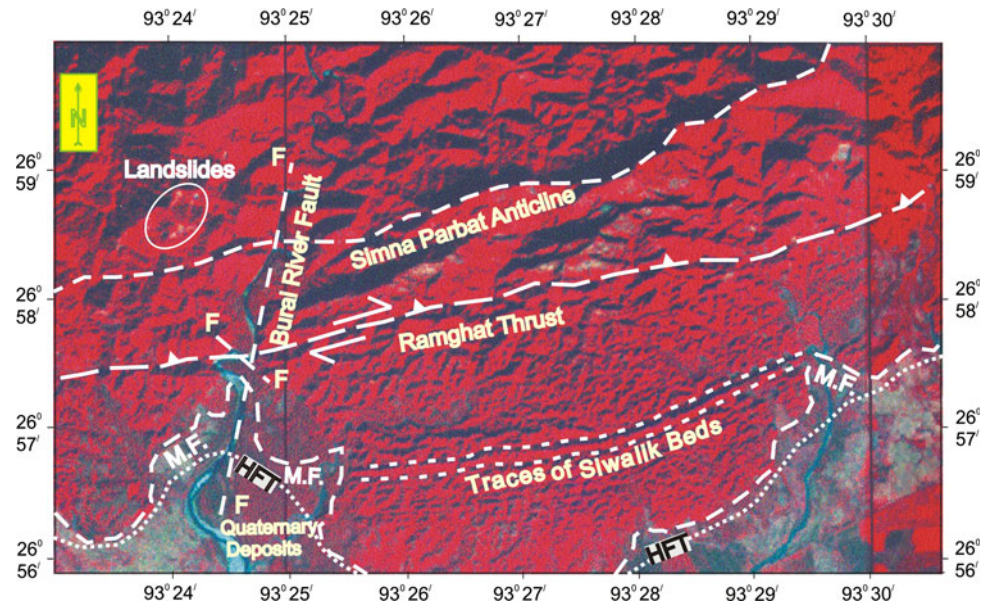
Himalayan frontal part was chosen to study the recent geological activities.

The study area is located along the Burai River valley in district Papumpare, Arunachal Pradesh, India (Figs. 1, 2). Fluvial process studies suggest that the onset of incision may broadly relate to changes in slope, discharge, sediment load and caliber and bedrock erodibility and these may all have been transformed as the direct or indirect result of mid-Pleistocene climatic changes (Gibbard and Lewin 2009).

### The study area

The study area shows broadly the east–west trending Himalayan structure, which defines the Himalayan front

**Fig. 2** Satellite imagery data (IRS, LISS-III) of study area, showing E–W trending Ramghat Thrust and NNE–SSW trending Burai River Fault along Burai River



along which there is a topographic break demarcating the boundary between the low-lying Brahmaputra alluvial plains and Sub-Himalaya. The relief across the Himalayan front is about 800 m. Rapidly flowing river channel suddenly becomes nearly stand still within a short distance at tectonic junction of the Middle and Upper Siwalik rocks and resumed its earlier flow after about 100 m away towards downstream. It takes right angle turns, as shutter ridges block its channel (Fig. 3a). Here one gully channel flows along a wide linear fracture zone trending E–W within sandstone outcrop. This vertical dipping fracture zone is associated with the brittle deformation related to the intraformational thrusting. A 22.7-m-high E–W trending scarp, developed in the Middle Siwalik sandstone is observed on the left bank of river (Fig. 3b). In addition to this height the scarp submerged nearly 4 m below the water level. A terrace section of 3 m high is observed (Fig. 3c) along the right bank. Nearby, in the downstream, deposition of sorted traction-transported gravel material is observed on the left bank above the sandy deposits (Fig. 3d), which might have been deposited during high water flow regime. A NE–SW trending sandstone scarp on right side of river bank shows a height of 3 m above the water level and is submerged ~3 m into the water (Fig. 3e). The average depth of river varies between 1 and 2 m, but along bank with sandstone scarps the water depths are >4 m. These observations suggest the presence of ENE–WSW trending active dextral strike-slip fault along the Ramghat Thrust zone. The reactivation of the Ramghat Thrust and associated strike-slip fault formed a zone of differential uplifts of linear faulted-blocks that checked the river flow and shifted its course.

Neotectonic activities are the episodic crustal movements that have been taking place since the beginning of the Quaternary period (Valdiya 1984). A rapid uplift rate causes the river-incision and prevents its lateral shift, whereas slow uplift rate does the channel adjustment by widening and meandering (Schumm et al. 2000). The creation of transverse drainage within the wedge-top/fore deep zones appears to correspond directly with active tectonic controls on the topography (e.g., Jones 2004). There is a NNE–SSW trending Burai River fault lineament, formed when the movement along the HFT was locked due to steepness of thrust plane. Along this fault the river has eroded the weak Upper Siwalik rocks in a wide area and therefore the mountain front has become sinusoidal. A ~300 m long NW–SE trending fault is mapped that shifted Burai River locally. This fault also caused uplifting along the river channel. Drainage systems adapt to the changes of surface slope and have the potential to record information about the evolution of faults and folds (Ollier 1981; Leeder and Jackson 1993). Deposition of bedload gravel material is also observed upstream of the NW–SE trending fault. Drainages showing rectangular, trellis, radial and sub-dendritic to sub-parallel patterns suggests their structurally controlled nature. Faults and folds are quite prevalent in the northeastern part of map area along the Balijan stream. Here the northern limb of NE–SW trending fault propagation fold and associated syncline are observed (Fig. 4). The strikes of beds indicate that the folds die out or close towards NE direction. NNE/NE SSW/SW trending fault lineaments are also discernible along Dalang and Balijan streams. These lineaments have influenced the drainage patterns of the region.





**Fig. 3** **a** Shutter ridge blocking the Burai River channel and a gully has developed along Burai River (*arrow* indicates river-flow direction). **b** An E–W trending sandstone scarp with a height of 22.7 m above water level developed on the left bank of Burai River (*arrow* indicates the river-flow direction). **c** Intraformational Ramghat Thrust

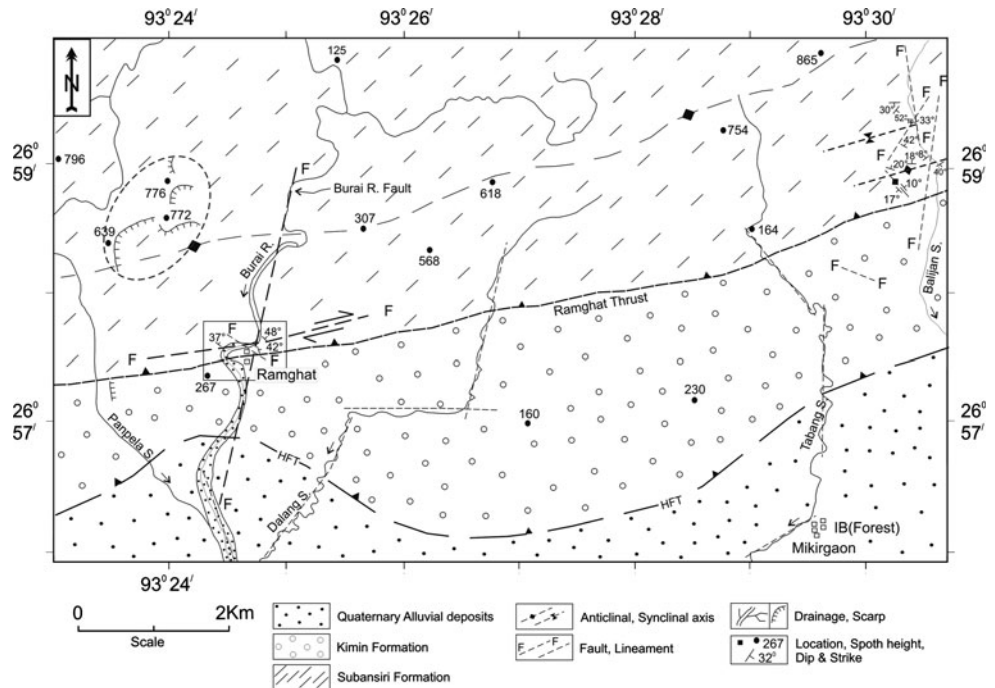
where the Middle Siwaliks thrust over the Quaternary deposit on the right bank, as observed on Burai River. **d** Traction transported, sorted gravel deposit, as observed above the sandy side bar. **e** NE–SW trending sandstone scarp observed on the strath terrace, on the right bank of the Burai River

## Geology

The map area is composed of the Neogene Siwalik rocks and Quaternary sediments (Fig. 4). The Siwalik rocks are made up of the Subansiri (Middle Siwalik) and Kimin (Upper Siwalik) formations, while the Quaternary sediments comprise of poorly sorted alluvial deposits of boulders, cobbles, pebbles, set in a loose and unconsolidated matrix of sand, silt and clay. The Subansiri Formation consists of monotonous soft, massive sandstone while the Kimin Formation comprises alternations of semi-consolidated soft, current bedded sandstone, siltstone, clays

and gravels. On the north, the E–W trending Simna-Parbat anticline is a doubly plunging asymmetric anticline with its relatively steeper southern limb (Kunte et al. 1983). The asymmetric anticline is interpreted to be a fault propagation fold with steepening of its front limb (Suppe 1985) developed on hanging wall (HW) of the Ramghat Thrust due to movement of HW rocks over the fault tip and initiated when thrust was blind. Across the hinge line of anticline the Burai River channel shifted. It implies the growing nature of fold and the shifting of channel reflects the recent activity along incipient axial planar fracture cleavage plane as noticeable in the Sub-Himalayan terrain.

**Fig. 4** Geology of the study area, with Ramghat Thrust and dextral strike-slip faulting which has shifted the course of Burai River at Ramghat. *Ellipse* shows area of landslides



This folding is of active-hinge folding or active-hinge fault related anticlines (Salvini and Storti 2001) and of active axial surfaces (Suppe 1983).

**Geomorphology and drainage**

The region covered by rocks of the Subansiri Formation shows moderate relief of ~900 m. In the central part of the Sub-Himalaya the regional topographical features and drainage pattern are associated with folds and faults and there is development of closely spaced sub-dendritic to sub-parallel drainage pattern. The streams and gullies are long with gentle gradients and have flat steep walled valleys. The Kimin Formation is characterized by rugged topography with low relief ranging between 300 and 700 m. The Quaternary alluvial sediments are observed as fluvial sediments occurring as terrace material and valley-fill deposits.

North of the hinge line of the Simna-Parbat anticline, the drainage pattern is different compared to the south as the northern limb is gently dipping (Figs. 4, 5). But at western and eastern extremities of hinge line, the drainages are transverse. Drainage that is perpendicular/oblique to topographic gradients can incise into emerging thrusts/antiformal folds (blind thrust/growth folds), if incision is greater than the uplift rate, resulting in antecedent or superimposed transverse drainage formation (Burbank et al. 1996c; Alvarez 1999). The transverse drainages observed in the present setting are superimposed drainages

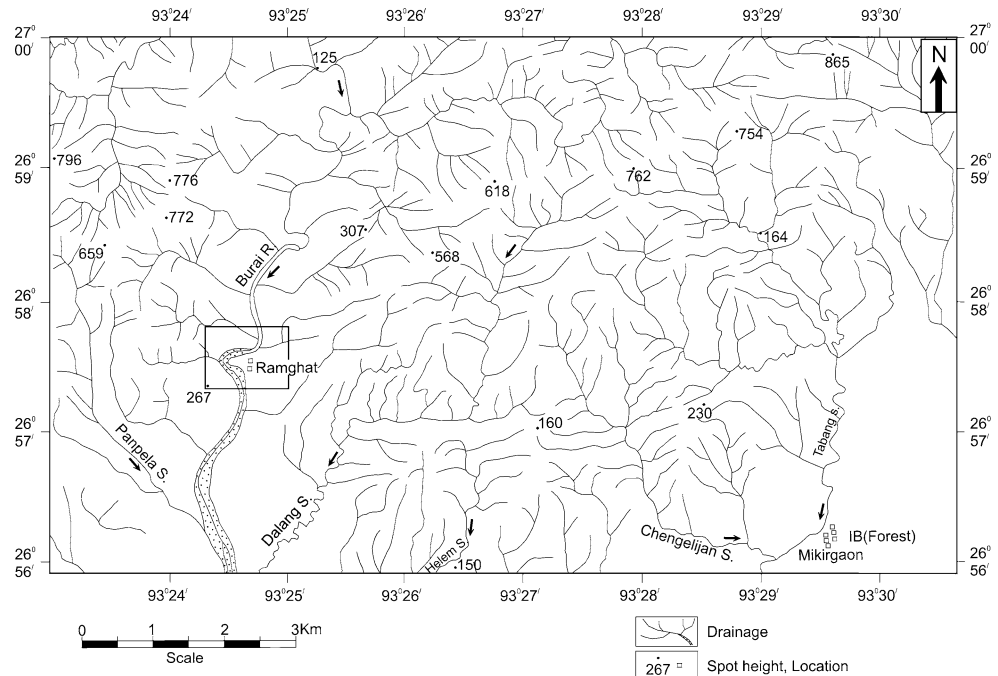
related to the fluvial response to ongoing active tectonics processes on the frontal Himalaya.

The study area exhibits rectangular, trellis, radial, parallel and sub-dendritic to sub-parallel drainage patterns (Fig. 5). The rectangular drainage pattern indicating intersection of joint sets, fault lineaments, are observed on the mainstream channels of the Burai River, Dalang and Tabang streams; whereas trellis patterns indicating folded strata are present on the upper part of the Burai River, Chenglijan and Tabang streams as envisaged by Schumm et al. (2000). Radial drainage pattern is observed on the middle part of the map area indicating presence of domal structure developed due to superposed deformation, whereas parallel drainage pattern is noticeable on the lower middle part indicating slope-controlling nature. Sub-dendritic to sub-parallel drainage patterns indicating structurally controlled nature, are commonly observed in the study area. Devi (2008a) also observed the tectonic forcing of the frontal Sub-Himalayan river and stream channels in her study of Kimin section, Arunachal Himalaya.

**Longitudinal profile and channel gradient**

Longitudinal profile reveals the gradient required by the river to transport its normal bedload and provides surface history as it represents the erosional curve of the river course. Further, the long-profile is the least transient expression of fluvial processes, reflecting geological influences such as the effect on available relief of tectonic

**Fig. 5** Drainage map of study area with lithological control in drainage development, on the southern half of study area



history and base-level change, of climatic change on the processes of erosion and deposition and of the distribution of outcrops of different lithologies (Richards 1982). Knick points marking the breaks in channel gradient, are observed at points A, B, C, D, E and F marking the surface traces of the Bomdila Thrust/MBT, Tipi Thrust, Papum Syncline, Papum and Pam Rivers' confluence, Simna-Parbat Anticline and Ramghat Thrust. The points show their heights at 520, 300, 160, 115, 135 and 115 m with distances of 8.3, 15.8, 25.1, 28.5, 37.25 and 40.15 km, respectively, from the origin (Fig. 6a). Points D and F situated at same heights, and E point lies above in between. This indicates that the area between points D and F has uplifted due to presence of active blind thrust or surface breaking fault where active dextral strike-slip fault has been mapped. Along the Bomdila Thrust, the transported LHCs thrust over the Lower Siwalik rocks so that the Bomdila Thrust coincides with the MBT (Fig. 1). Along the Tipi Thrust, the Lower Siwalik (Dafla) rocks thrust over the Upper (Kimin) and Middle (Subansiri) Siwalik rocks and along the Ramghat Thrust, the Middle Siwalik rocks thrust over the Quaternary deposits. The long-profile of the Papum–Burai River section shows abrupt decreasing of its channel gradient from its origin to the contact regions from the Bomdila Thrust/MBT to Tipi Thrust to Papum Syncline hinge line and up to the confluence of the Pam–Papum Rivers. However, after confluencing with the Pam River, the earlier concavity of the river profile exhibits convex nature later at the hinge zone of the Simna-Parbat anticline and Ramghat Thrust and maintained its decreasing gradient nature after this, suggesting the influence of tectonics along

the mountain frontal part. The convex river gradient profile indicates active relatively rapid uplift of the Simna-Parbat anticline along its hinge zone.

The longitudinal profile of the Burai River defines its channel gradient from its point of origin as  $11^\circ$ ,  $1.7^\circ$ ,  $1^\circ$ ,  $0.1^\circ$ ,  $0.4^\circ$  and  $0.3^\circ$  within 8.3, 7.5, 9.3, 12.15, 2.9 and 3.35 km distances, respectively, as shown in Fig. 6b. Thus, the river gradient abruptly decreases across the Bomdila Thrust/MBT and the Tipi Thrust, from  $11^\circ$  to  $1.7^\circ$ , but later gradually decreases from  $1^\circ$  to  $0.1^\circ$  across the Papum Syncline. However, along the Simna-Parbat anticline and the Ramghat Thrust, the channel gradient shows an increasing trend of  $0.1^\circ$ – $0.4^\circ$  with slight decrease to  $0.3^\circ$ , with decreasing slope angle along the lower reaches. The changes in river gradients may suggest variable uplift rates of rocks across tectonic boundaries. The anomalous increase of channel gradient along the Ramghat Thrust suggests active uplifting along the frontal part of the Sub-Himalaya. Regional geological map of the study area (modified from Kunte et al. 1983), in which the hinge line of fault propagation fold on the hanging wall of the HFT makes an acute angle with the HFT (Fig. 6c) and exhibits the regional correlation of the geological features. Cross section XY (Fig. 6c) has also been drawn from the regional map for a better understanding of the study area.

## Methodology

The Survey of India toposheet numbers 83 F/5, 83 F/9 of 1:50,000 scale of 1973 and 1966 (Publ), respectively, and

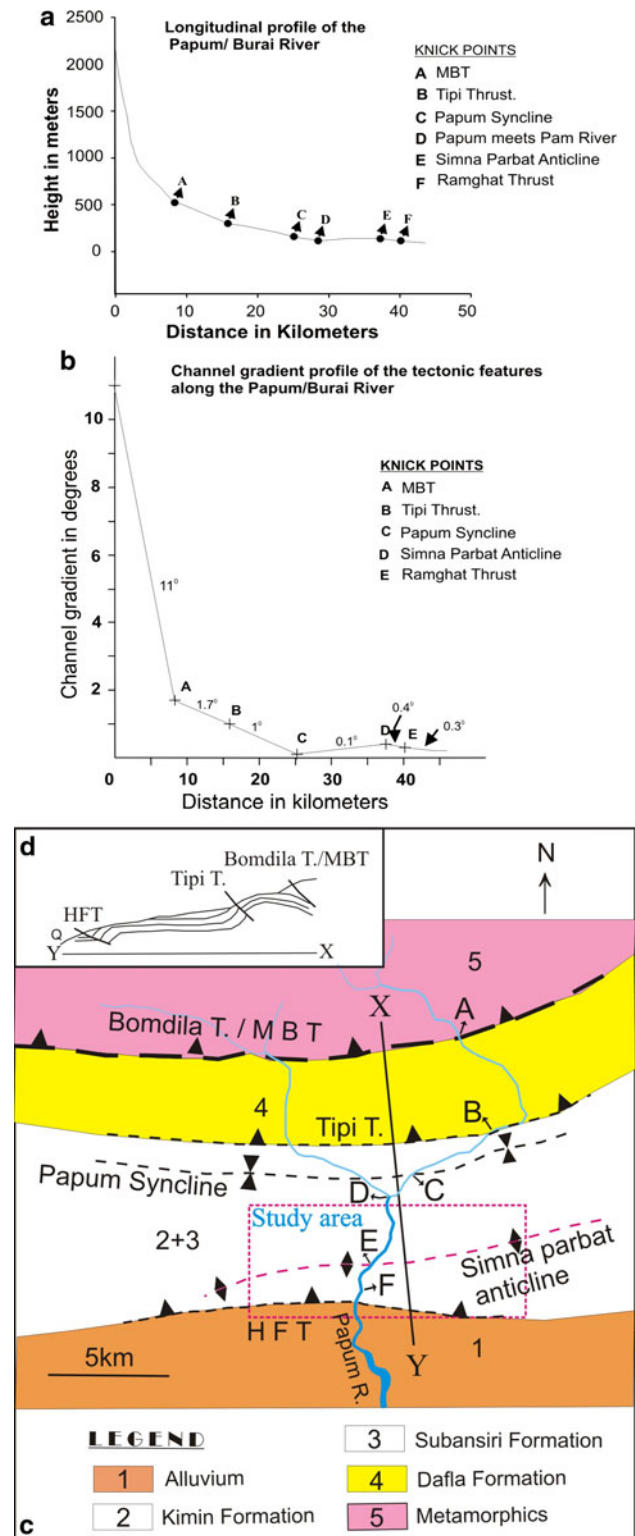


**Fig. 6 a** Longitudinal profile of the Burai/Papum River with knick points A, B, C, D, E and F, where the Papum/Burai River passes through the Bomdila Thrust/MBT, Tipi Thrust, Papum Syncline, Papum and Pam River confluence, Simna-Parbat anticline and Ramghat Thrust, respectively. **b** Channel gradient profile of the tectonic features with slope angles, observed along the Papum/Burai River. **c** Regional geological map of the study area (modified from Kunte et al. 1983), in which the hinge line of fault propagation fold on the hanging wall of the HFT makes acute angle with the HFT. Knick points A, B, C, D, E and F are marked on the Papum R. channel. **d** Cross section XY taken from the map

Satellite imagery data of IRS LISS-III (NRSA 2003) of 1:50,000 were used for data generation related to drainages and lineaments. Ground checking was carried out around potential locations where field observations of geomorphologic and structural data were collected. Lineaments were analyzed by measuring their lengths and orientations. The rose diagram for the lineaments was prepared for analysis of the dominant lineament trends. Field mapping and measurements were done by using Brunton compass and measuring tape. GPS was used for demarcation of locations of measurements made during fieldwork. Longitudinal profile prepared for the Burai River along with channel gradient analysis was done to understand the interplay between erosion and the geological and tectonic features. Water gap representing the continuity of the active channels against obstruction along its path, and presence of an intraformational thrust and transverse fault provide first-hand knowledge about the uplifting nature of the study area along and across the Burai River valley.

**Structural elements and lineaments**

The focus has been made only on those structural elements that help in the understanding of recent geological activities. The interesting structural features are major thrusts and faults along which observations are done to constrain their reactivation and occurrences, whether during the Quaternary period or earlier. The mountain frontal part experienced upliftments that resulted due to thrusting, growing fold and by strike-slip faulting. A distinct, ~6-km-long transverse fault recognized along the Burai River course (Fig. 2) cuts the recent fluvial terrace situated south of Ramghat, and is parallel to the NNE–SSW trending fault along Dalang stream (Fig. 4). A small interpreted NW–SE trending fault developed across the Ramghat Thrust uplifted the river channel (Fig. 3c). The relief difference between the hanging wall and footwall is ~20 m across the Ramghat Thrust. The Burai River reflects the upliftment of the hanging wall of the active Ramghat Thrust, and the river incises the bedrocks deeply. As a consequence, this process resulted in a water gap.



A 22.7-m-high E–W trending fault scarp in the Middle Siwalik rocks is observed on the left bank of the Burai River, while 3–4 m high unconsolidated conglomeratic terrace deposit is observed on the right bank. The amount of displacement of rocks along a fault is variable. A shutter

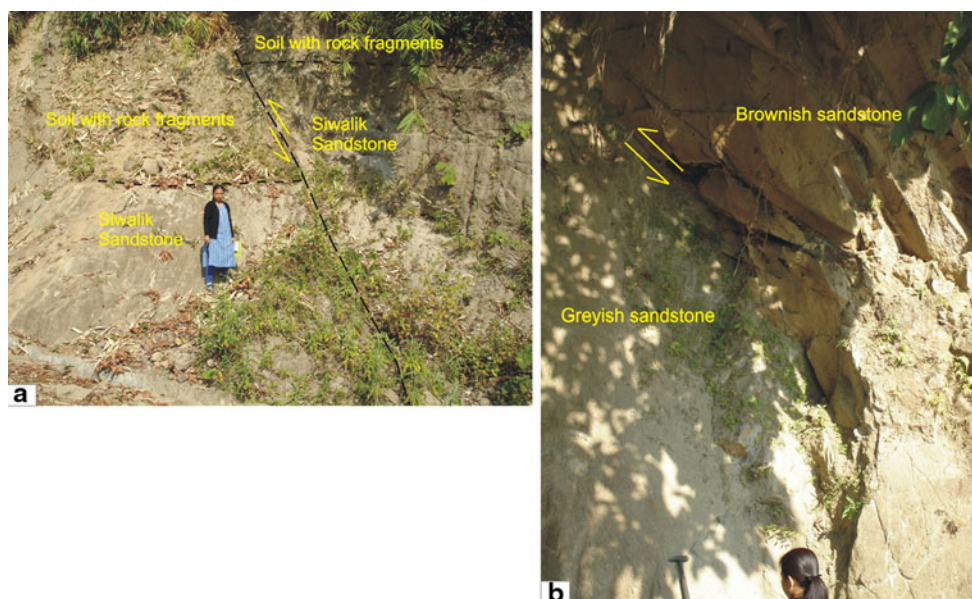
ridge trending NW–SE, deflects the NE to SW flowing channel to a right angle turning. The movement along strike–slip fault has also controlled the local uplift of ENE–WSW



**Fig. 7** Bifurcation of vertical dipping strike slip fault and vertical splays of N–S trending fault, which are cut by later En-echelon fault system

trending linear blocks at Ramghat area. A sandy side bar deposition takes place on the left side of the river as the river flow is checked by the rising Subansiri sandstone. En-echelon pattern of a set of dextral small-scale faults (Fig. 7) is associated with an N–S strike–slip fault. Across these faults, the Burai River at Ramghat has shifted its course (Fig. 4). Schumm et al. (2000) opined that tectonic activity could significantly control river pattern and its behavior, which is especially true for alluvial rivers. Presence of a pair of syncline and anticline is noticeable along the Balijan stream towards NE corner of Fig. 4. Here a superposed anticline with NW–SE trending hinge line is recognized. Its fold axis is perpendicular to the early NE–SW trending major fold axis. Along Balijan road in Balijan stream valley, an N–S trending fault dipping  $61^\circ$  towards east direction extends for  $\sim 5$  km shows a displacement of 2 m on a NW–SE trending scarp (Fig. 8a). Similarly, within a short distance of about 80 m, a NW–SE trending thrust fault dipping  $58^\circ$  towards SW direction was recognized between brownish sandstone bedrock and grayish sandstone bedrock (Fig. 8b). Around this area the N–S and NW–SE trending faults form a set of conjugate faults. The landscape evolved as the tectonically produced slopes are modified by erosion and deposition as well as by the continued growth structures (Schumm et al. 2000).

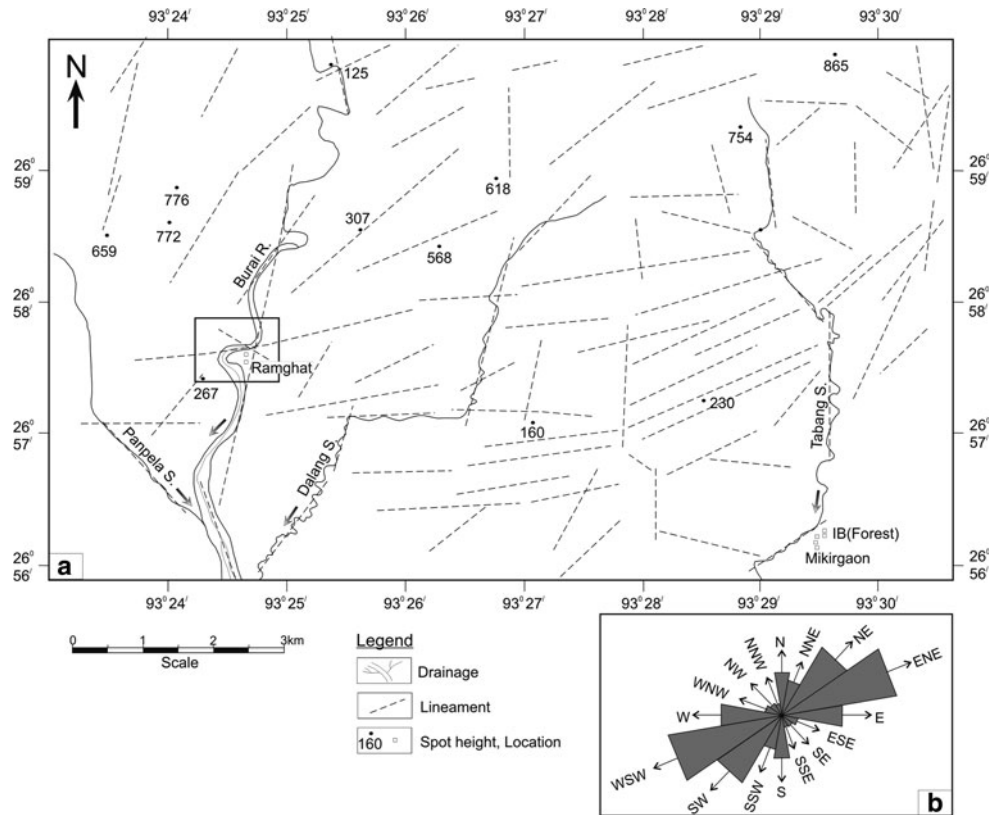
Along the Bomdila Thrust, the Bomdila Crystallines or the LHCs have traveled far distance towards south so that the LHCs directly thrust over the Sub-Himalayan Siwalik rocks along the MBT (Fig. 1). From the geological map and the cross section drawn by Kunte et al. (1983), it is clear that the basal parts of the hanging walls of the HFT and Tipi Thrust represent the fault propagation folds



**Fig. 8** a Displacement of 2 m on a NW–SE trending scarp in sandstone bedrock near Balijan stream. b Fault movement displacing brownish sandstone bedrock from the grayish sandstone bedrock near Balijan stream



**Fig. 9** Lineament analysis and Rose diagram of lineament of study area



(Fig. 6). The hinge line of fault propagation fold related to the HFT makes acute angle with the HFT, and fold dies out near the trace of the HFT. This swing of hinge line implies the later relative movement of rocks sub-parallel to strike of the HFT. Towards east around Banderdewa area, which falls out of study area, the field observations indicate that the FW Quaternary deposits of the HFT are tilted about  $8^{\circ}$ – $10^{\circ}$  both towards north and south directions. This obviously indicates the recent post-Quaternary folding, a signature of neotectonics south of the HFT. This growing fold can be related to the movement of a young in-sequence blind thrust fault/splay-tip of the HFT. As tectonic motion can result in linear deformation of the land surface, the topographically expressed lineaments are often used as fault indicators (Hobbs 1904; Peive1956; Phylosophov 1960; Ollier 1981). From the lineament analysis prepared from the lineament map (Fig. 9), it has been observed that the ENE–WSW, NE–SW, E–W and N–S trending lineaments form 30.94, 21.08, 16.35 and 11.48%, respectively, whereas minor trends are shown by NNE–SSW, ESE–WNW, NW–SE and NNW–SSE trending lineaments that occupy 9.41, 4.31, 3.53 and 2.89%, respectively. The higher order streams mostly follow the ENE–WSW and NE–SW trends of lineaments. The E–W and N–S trends are followed by the structurally deflected streams as well as by the lower order streams suggesting neotectonic surface deformation activities accommodated by reactivation of

faults or possible growing folds. About 60% of the lineaments are identified. Minor lineament trend of NW–SE mostly followed by lower order streams as well as by faults deflecting the streams in the Burai River in Ramghat area, along with the lineament trends of E–W and N–S are suggested to be the neotectonic alignments of the study area compared to the regional structural trend varying from ENE–WSW to NE–SW.

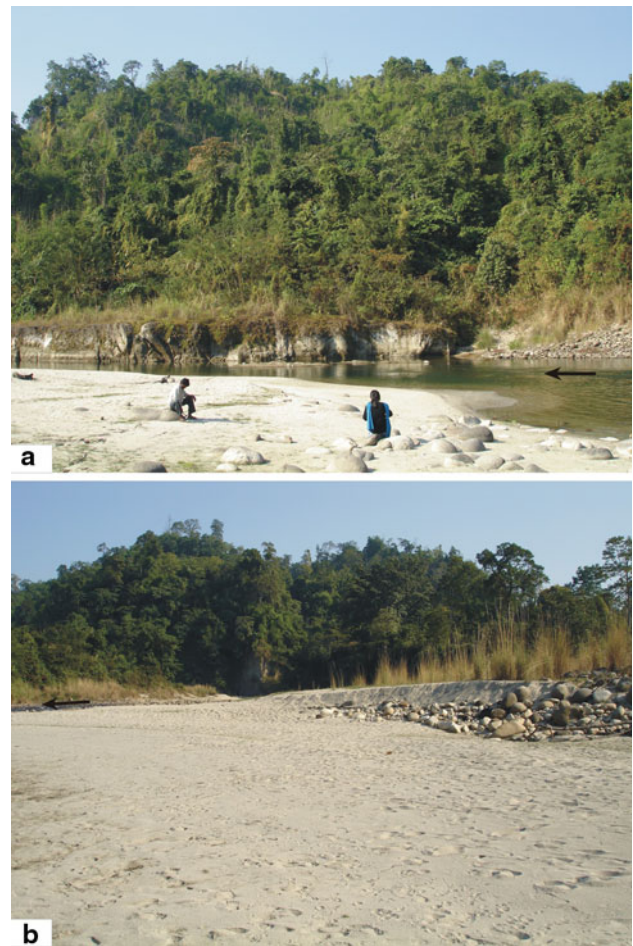
### Discussion

The Middle Siwalik sandstone thrust over the Quaternary terrace deposits along the Ramghat Thrust. Here the river incised the strath terrace resting on the Subansiri (Middle Siwalik) rocks exposed  $\sim 6$  m high, suggesting tectonic uplift of bedrocks. The Quaternary uplift in the Himalaya varies from a few meters to 2,000 meters (Iwata 1987; Selby 1988). However, the perturbations in the climate on multi-millennial scale can have a strong influence on incision history of the fluvial system and therefore the calculated uplift rate may be different from the real uplift rate (Meetei et al. 2006). The terrace deposit of sorted gravel riverbed materials lying 2–3 m above the sandy bar shows the high-energy condition of the river, which defeated the uplifting Subansiri rocks. This high-energy condition of channel may be related to the river gradient

increased due to more rapid upliftment of hanging wall of the HFT and/or Ramghat Thrust than the incision rate by channel. The channel gradient analysis shows steep slope angle of  $11^{\circ}$ – $1.7^{\circ}$  around the BT to  $1^{\circ}$ – $0.1^{\circ}$  around the Simna-Parbat anticlinal region with sudden increase in slope angle of  $0.4^{\circ}$  around Ramghat Thrust, indicating active tectonic uplift along the frontal Sub-Himalayan region. The drainage around the Ramghat area also shows angulate and rectangular drainage pattern, suggesting the influence of out-of-sequence deformation along the Ramghat Thrust north of the HFT. Strike–slip right lateral movement has shifted the Burai River  $\sim 500$  m, and its tributary Dalang  $\sim 1,500$  m in the mountain frontal part. Shifting of stream channels along strike–slip faults is much towards the southern part. Along the Tista River the mountain front in Darjeeling Sub-Himalaya shows signature of out-of-sequence deformation at ca. 20 ka by migrating 150 m eastward and by incising 48 m vertically (Mukul et al. 2007). Similar observations of the latest Pleistocene (15–10 ka) to Holocene deformations associated with the tectonic–climatic interaction are also made by Luirei and Bhakuni (2008) and Srivastava et al. (2009) at the Siang River exit, Arunachal Pradesh. The presence of upliftments was a result of thrusting, growing fold and by strike–slip faulting, indicating the activeness of the mountain front region of the study area.

Wobus et al. (2006) opined that the geometry of a bedrock channel co-evolves with its flow field, which ultimately drives the system to a stable cross-sectional form. There must have been a long period of adjustment as the Burai River channel responded to tectonic influences of active NW–SE trending fault and transverse Burai River Fault and the river is able to pass through its obstacle through a water gap.

If deformation was too rapid, undoubtedly there was a disruption of the existing river system, and if deformation was slow the existing river system could persist in its original location as tectonic movement is the only one way that the gradient of a river and its valley may be modified. Nevertheless, alluvial rivers can provide information concerning syntectonic deformation (Schumm et al. 2000). In Ramghat, incision of the sandstone bedrock is observed in the Burai River, suggesting tectonic incision. On the left bank of the river, a sandy sidebar of 150 m in width suddenly appeared (Fig. 10a, b) as a consequence of the uplift of the sandstone bedrock along the river channel which checked the river flow. A link of climate impacts with tectonic processes is consistent with high sediment fluxes and rapid rates of incision during the Quaternary period (Burbank et al. 1996a; Einsele et al. 1996; Leland et al. 1998). The availability of high water discharge for incision in the uplifted sandstone block is either due to increased rainfall or increased melt water during inter-glacial period.



**Fig. 10** **a** Sandy side bar as observed on the left bank of Burai River (*arrow* indicates the river-flow direction). **b** Continuation of the sandy side bar as observed from another angle (*arrow* indicates the river-flow direction)

Degradation and aggradation can be the evidence of active tectonics, and these processes will be accompanied by changes of channel morphology (depth and width), as the channel incises or as it aggrades (Schumm 1986). In the study area the speed of the Burai River is checked as it incised the sandstone bedrock and deposition of the river-bed materials took place. Climate on the other hand, is the primary factor controlling the nature and intensity of the surface processes resulting in the redistribution of the mass accumulated by tectonics (Kuhni and Pfiffner 2001). Major climatic changes during the Pleistocene–Holocene times seem to have affected the sedimentation pattern of the study area in the frontal Himalayan foreland basin in association with the proximal tectonism associated with active tectonic activities, which placed the Middle Siwalik rocks over the Quaternary deposits. The Quaternary is also the period of increased tectonic activity both in the Alpine orogenic systems as well as in reactivated blocks of older orogenic systems (Starkel 2003). Lineament analysis of the

study area shows major lineament trends, following the structural trend of ENE–WSW to NE–SW, whereas minor lineament trends of NW–SE along with E–W and N–S trend are suggested to be the neotectonics alignments. Because of the much displacement along the Ramghat Thrust, the Middle Siwalik rocks have thrust over the Quaternaries that rest over footwall rocks of the buried Upper Siwaliks, which are not exposed. Around the Balijan stream, on the eastern part of the study area also, right lateral movement is quite evident and N–S and NW–SE trending faults seem to form conjugate fault system. Devi (2008b) also suggested the tectonically active nature of the Sub-Himalayan region of the Arunachal Pradesh in Northeast Himalaya.

About 20% of the Indo-Asian convergence has been accommodated by thin-skinned thrusting within the foreland, often related to detachments localized at the top of the basement or in incompetent foreland strata, and by thrusts with hanging walls more than 4- to 10-km-thick along its proximal margin (Burbank et al. 1996b). In the frontal Darjeeling–Sikkim–Tibet wedge of the eastern Himalaya, Mukul et al. (2007) discussed the role of active deformation and associated seismicity along the basal decollement within the Himalayan wedge and out-of-sequence faults and have given a conceptual model for the active deformation in the Himalaya, based on the critical wedge theory and seismicity pattern. They emphasized the need of out-of-sequence deformation to be included in the existing Himalayan seismic models. Mugnier et al. (2004) in their study in Nepal also emphasized that during the Holocene, the Main Frontal Thrust (MFT) has been active, but portions of the piggyback thrusts of the Outer Belt also show episodes of activity that vary from a few meters to several tens of meters of displacement. In the present study, the Ramghat Thrust is an active fault that suggests out-of-sequence faulting located towards north of the HFT and the transverse drainages are related to the fluvial response to ongoing active tectonics processes on the frontal Himalaya.

## Conclusion

The present study indicates that the Himalayan mountain front has been a region of active tectonic activities since the Late Quaternary times. The drainage patterns suggest tectonic influence due to variable amount of movement along faults. The dextral strike–slip movement along fault trending ENE–WSW to E–W directions, shifts the Burai River and its tributary Dalang stream, indicating neotectonic movements. Amount of offsetting of stream channels is much more towards mountain front. It suggests that towards south near the HFT the offsetting is much than

away from it. The Quaternary deposits including its basement or the buried Upper Siwalik beds, is underthrust below the Middle Siwalik sandstone along the intraformational Ramghat Thrust, which represents active out-of-sequence thrust. Across the Burai River the Middle Siwalik rocks with fluvial terrace material are situated at different heights from river beds, which suggest active tectonic activities due to reactivation of the NNE–SSW trending Burai River transverse fault. This fault propagates towards south towards the HFT and penetrates through the recent sediments. The channel gradient profiles of the Burai River exhibit anomalous increase across the Ramghat Thrust region. Although fluvial channels occupy only a fraction of most landscapes, their behavior is a key control on adjacent hill slopes (Burbank and Anderson 2001). Uplifting as well as right lateral fault movement along with thrusting seems to be related to the proximal tectonism (Burbank et al. 1996b) of the Himalayan foreland basin, and along its front/HFT. Environmental conditions leading to a link of climate impacts with tectonic processes during the Quaternary times with the advent of the Holocene climate has given rise to incision of sandstone bedrock and formation of water gap in the Burai River. Thus out-of-sequence neotectonic activity fits well north of the HFT that represents the mountain front.

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