Landforms along transverse faults parallel to axial zone of folded mountain front, north-eastern Kumaun Sub-Himalaya, India

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The shape of the frontal part of the Himalaya around the north-eastern corner of the Kumaun Sub-Himalaya, along the Kali River valley, is defined by folded hanging wall rocks of the Himalayan Frontal Thrust (HFT). Two parallel faults (Kalaunia and Tanakpur faults) trace along the axial zone of the folded HFT. Between these faults, the hinge zone of this transverse fold is relatively straight and along these faults, the beds abruptly change their attitudes and their widths are tectonically attenuated across two hinge lines of fold. The area is constituted of various surfaces of coalescing fans and terraces. Fans comprise predominantly of sandstone clasts laid down by the steep-gradient streams originating from the Siwalik range. The alluvial fans are characterised by compound and superimposed fans with high relief, which are generated by the tectonic activities associated with the thrusting along the HFT. The truncated fan along the HFT has formed a 100 m high-escarpment running E–W for ∼5 km. Quaternary terrace deposits suggest two phases of tectonic uplift in the basal part of the hanging wall block of the HFT dipping towards the north. The first phase is represented by tilting of the terrace sediments by ∼30° towards the NW; while the second phase is evident from deformed structures in the terrace deposit comprising mainly of reverse faults, fault propagation folds, convolute laminations, flower structures and back thrust faults. The second phase produced ∼1.0 m offset of stratification of the terrace along a thrust fault. Tectonic escarpments are recognised across the splay thrust near south of the HFT trace. The south facing hill slopes exhibit numerous landslides along active channels incising the hanging wall rocks of the HFT. The study area shows weak seismicity. The major Moradabad Fault crosses near the study area. This transverse fault may have suppressed the seismicity in the Tanakpur area, and the movement along the Moradabad and Kasganj–Tanakpur faults cause the neotectonic activities as observed. The role of transverse fault tectonics in the formation of the curvature cannot be ruled out.

1. Introduction

The present study is aimed at understanding the relationship between the development of the Quaternary landforms and transverse faults formed along the axial zone of the folded mountain frontal part across the Himalayan Frontal Thrust (HFT) in the north-eastern corner of the Kumaun Sub-Himalaya (figure 1). This is an important geomorphological site to observe the ongoing Himalayan tectonics (Valdiya 1992; Valdiya *et al.* 1992; Prakash *et al.* 2015). The HFT is the leading edge of the Himalaya, which is characterised by active faulting and associated uplift (Nakata 1972, 1989; Gansser 1981; Lavé and Avouac 2000; Thakur 2004; Agarwal *et al.* 2009, 2012). The southern limit of the Himalaya is being demarcated by the HFT across which sudden elevational change and
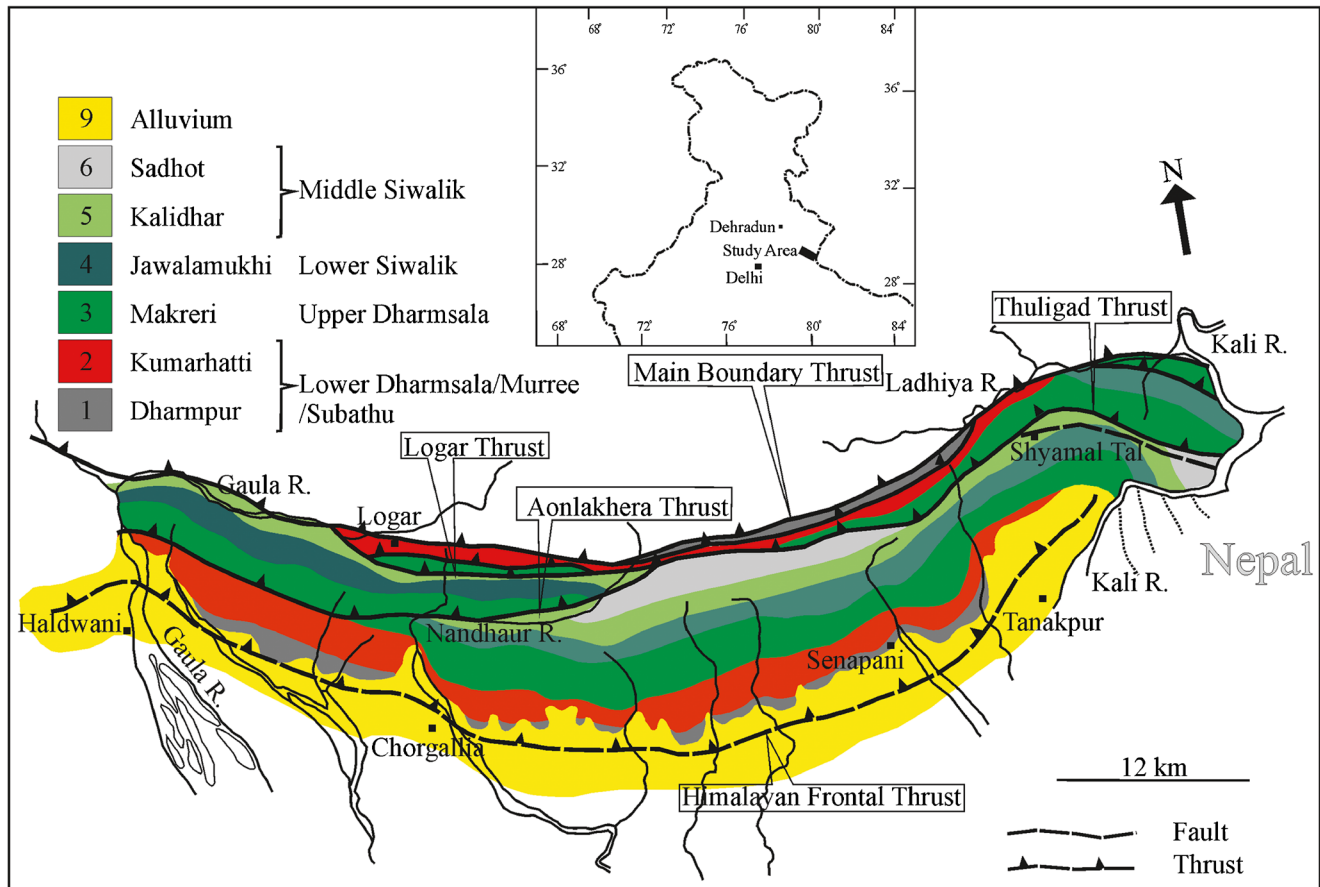
Figure 1. Geological map of the study area (Raiverman 2002).

exposure of the Siwalik rocks (Nakata 1972; Singh 1996). To the south of the HFT is the Piedmont Zone, which is the northernmost geomorphic element in the Ganga Plain (Pathak 1982; Singh 1996). This zone is divided into two geomorphic divisions known as the Bhabar and Terai (Pathak 1982; Singh 1996) that are characterised by subparallel to radiating drainage pattern of low drainage density (Shukla and Bora 2003). In the present study area, the Terai belt is not developed, whereas the Bhabar zone is either terminated as a result of the incision by the Kali River (Sarda River) or superimposed on T_1 surfaces (Singh 1996; Goswami and Yhokha 2010). The Piedmont Zone is formed as a result of the coalescence of several alluvial fans and talus deposits, which are gravelly in the proximal part and silty-fine sandy in the distal part (Singh 1996; Goswami and Yhokha 2010; Goswami 2012). Recent tectonic activity in the frontal part of the Himalaya is expressed by varied geomorphological evidences such as the presence of tectonic escarpment, strath terraces, nick points along valley profile, deflection in drainage pattern and offsetting of the Siwalik rocks (e.g., Nakata 1972; Valdiya 1986, 2003; Valdiya *et al.* 1992; Shukla and Bora 2003; Thakur 2004; Goswami and Pant 2007, 2008; Agarwal *et al.* 2009, 2012).

Morphometric evidences of neotectonic block movement along the transverse fault in the outer Himalaya have also been reported from the Yamuna Tear Zone (Srivastava *et al.* 2013). Deformed Quaternary deposits have been described from various sites in the HFT zone, such as warping, tilting and truncation of fans and terraces and thrusting of the Siwalik rocks over the Quaternary deposits (Valdiya *et al.* 1992; Yeats *et al.* 1992; Malik and Nakata 2003; Goswami *et al.* 2013). Agarwal and Sharma (2011) and Goswami and Deopa (2012) have determined the Quaternary tilting of the tectonic blocks of the eastern Kumaun Himalaya. Occurring between the Himalaya and the Peninsular India, the Gangetic Plain is characterised by a variety of landforms and drainage systems (Singh 1996). On the basis of geomorphic surfaces, the Ganga Plain has been divided into the Upland Terrace Surface (T_2), Marginal Plain Upland Surface (MP), Megafan Surface (F), River Valley Terrace (T_1), Piedmont Fan Surface (PF) and Active Flood Plain Surface (T_0) that resulted from climate change and base-level-adjustment during the last 120 ka (Singh 1996). The Piedmont Fan (PF) surfaces, formed at the base of the Himalayan foothills, are relict features resulted due to coalescence of several fans. They are located in the

Bhabar and Terai belts; the former composed of gravelliferous sediments with steep slopes and ephemeral streams while the latter is made up of silty-fine sand (Pathak 1982; Singh 1996). The surface outcrop shows that near the mountain foot the Piedmont deposits are gravelly (98%) where cross-bedded gravel successions dominate and are both clast-and-matrix supported (Shukla and Bora 2003). Development of alluvial fans is affected by changes in the course of a cycle, varying base level, climatic changes, tectonic movements and slumping of fan deposits (Davis 1938; Blissenbach 1954). Tectonic activities are considered to be of prime importance in controlling alluvial fan sedimentation in active orogenic belts (Steel 1976; Heward 1978; DeCelles *et al.* 1991; Gupta 1997; Kumar *et al.* 2002). The deposition of alluvial fans in mountain front ranges is the obvious setting where a sediment supply controls the development of sedimentary geometries and sequences can be evaluated (Allen and Hovius 1998).

The present paper deals with the folded mountain front traversed by transverse faults, where the morphological features of fans are observed in the mountain front. This study has implication with the recent tectonic activity along the HFT and its splay thrust (Kotlia *et al.* 2008; Goswami and Yhokha 2010) that have deformed the Quaternary deposits, landforms and triggered the landslides in the area (Valdiya 1992; Valdiya *et al.* 1992).

2. Geological setting

Comprising the frontal part of the Himalaya, the Siwalik and pre-Siwalik rocks make up the Sub-Himalaya, while Piedmont surfaces constitute the foothills. The Sub-Himalaya (figure 1) is made up of sequences of the marine Paleocene–Middle Eocene Subathu Formation, non-marine Oligocene–Lower Miocene Dharamsala Formation and fluvial Middle Miocene–Pleistocene Siwalik Group in the NW Himalaya (Karunakaran and Ranga Rao 1979; Powers *et al.* 1998; Raiverman 2002). The Subathu Formation comprises of green shales and grey marls that constitute the southernmost unit and are exposed along the mountain front, and in the north; it forms the footwall block of the Main Boundary Thrust (MBT). This, overlain by the Dharmsala Group (∼Logar Formation), is made up of fine- to medium-grained, grey to greenish grey coloured sandstone and greyish green shales of Oligocene–Early Miocene age (Tiwari *et al.* 1991). The Siwalik Group is represented by the Middle and Lower Siwaliks, the conglomeratic sequence, comprising the Upper Siwalik, is missing (Karunakaran and Ranga Rao 1979; Raiverman 2002). The Lower Siwalik is made up of dark grey to brownish, fine- to medium-grained,

massive sandstone, multi-storeyed salt-and-pepper sandstone and yellowish to reddish-brown mudstone. Cross-stratification, lamination and ripples are important structures in the sandstones. The Middle Siwalik consists dominantly of sandstone interbedded with thin clay, the sandstones are coarse grained, poorly cemented and pebbly (Karunakaran and Ranga Rao 1979). The Sadhot Formation representing the upper part of the Middle Siwalik is marked by massive conglomerates in the Cenozoic sequence, which comprise mainly of alternation of conglomerates, sandstones and clays (Raiverman 2002). Apart from Raiverman (2002), the pre-Siwalik rocks are also reported from south-eastern Kumaun Sub-Himalaya. Ranga Rao and Venkataraman (1959) discovered Nummulitic shale characteristic of the Subathu near Kathgodam, and Kumar (2004) described the Chunadhaki green claystones as possibly being time equivalent to the Murree. The Piedmont surface is made up of gravelliferous and silty-sand belts that are thought to have formed around the latest Pleistocene–Holocene times (Singh 1996; Shukla and Bora 2003). Structurally, it is bounded on the south by the HFT, where in most cases it is a blind thrust (Raiverman 2002).

3. Material and method

Survey of India (SOI) toposheet (1:63,360 scale), Digital Elevation Model (DEM–SRTM) and satellite data (Google Earth) have been used in conjunction with detailed geological field investigations to demarcate and analyse the escarpments and landforms. Apart from the geomorphic evidences of active tectonics, an attempt has also been made to compute the wedge failure analysis (Hoek and Bray 1977) to characterise the vulnerability of the steep slopes to landslides and related phenomena. The International Seismological Centre (ICS) earthquake catalogue was used to review the seismicity pattern around the Kumaun region.

4. Aggradational landforms

The depositional landforms have been grouped into (i) the alluvial fans and (ii) the fluvial deposits. In the study area, the alluvial fans occupy the relatively steeper portions, while the fluvial terraces occupy the flatter surfaces.

4.1 *Alluvial fans*

Along the mountain front of the Tanakpur area, fan surfaces are observed at the base of the steep south-facing hill slopes (figure 2). The fans are
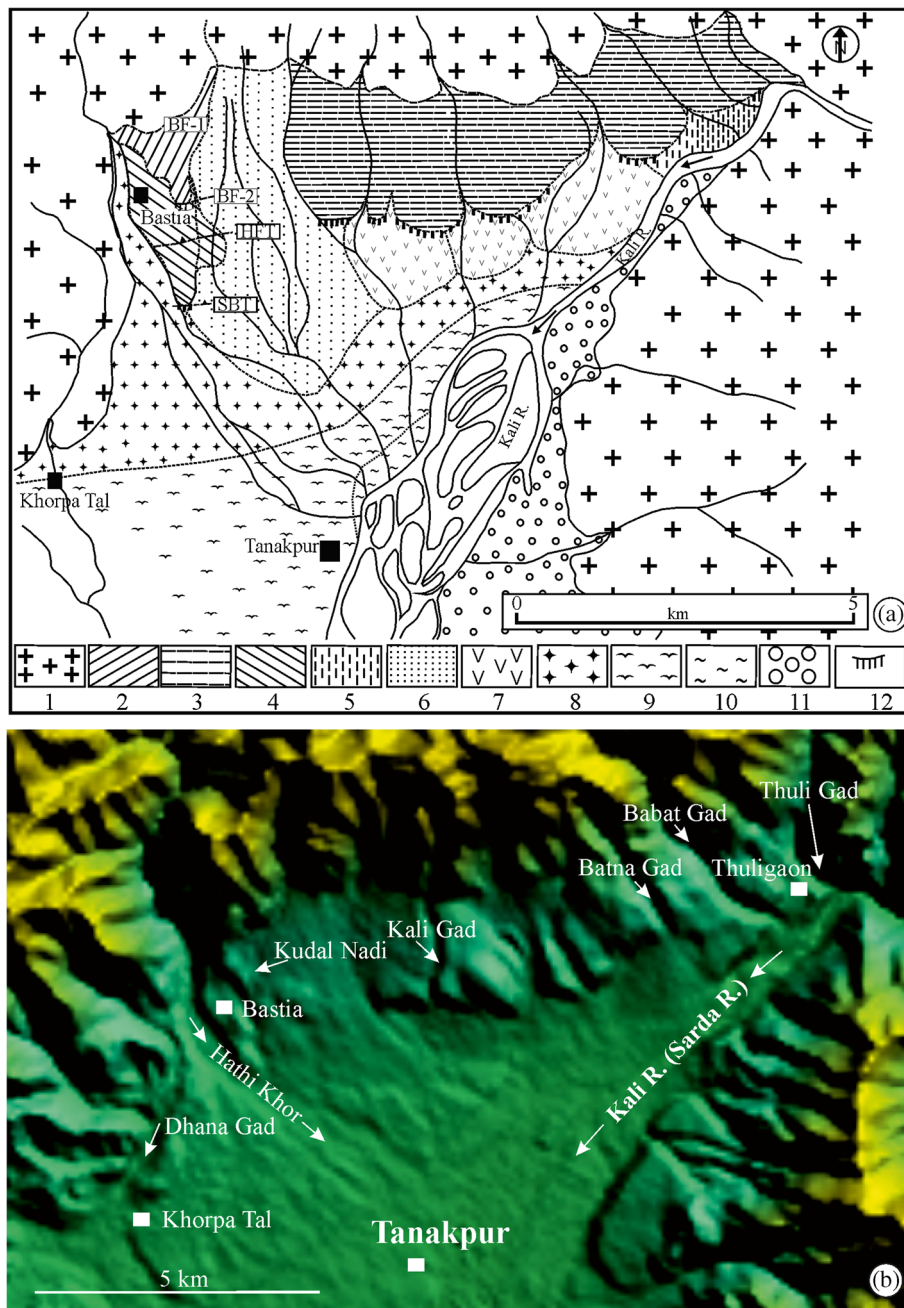
Figure 2. (a) Geomorphological map of Tanakpur area (modified after Valdiya 1992 and Valdiya *et al.* 1992). (b) DEM showing the topography of the terrain around Tanakpur. Incised fan sections are observed along Thuli Gad, Batna Gad, Babat Gad, Kali Gad and Hathi Khor. (1) Siwalik; (2) North Bastia Surface; (3) Batna Gad Fan; (4) Bastai Fan; (5) Babat Gad Fan; (6) Kudal Fan; (7) Recent Fan; (8) Unclassified Fan; (9) Terrace T_2; (10) Terrace T_1; (11) Unclassified Quaternary deposit; (12) Escarpment; BF-1: Basti Fault-1: BF-2: Bastia Fault-2; HFT: Himalayan Frontal Thrust and SBT: South Bastia Fault.

basically debris cones formed by the sediments supplied mainly by landslides taking place in the hinterland and later transported by the streams. The hinterland is made up of rocks belonging to the Siwalik Group. Valdiya (1992) and Valdiya *et al.* (1992) have broadly divided the fans into the Bastia and Uchali Got Fans. In the present study, the fans have been further classified on the basis of variable heights, and the highest fan is designated as the Batna Gad Fan (BGF) formed by

the coalescing of many smaller fans. It is observed in the east of Bastia that extends eastward up to Thuli Gad (figure 2). The fans are deposited by streams originating within the Siwalik terrain. They are entrenched by streams forming steep cliffs of more than 40 m high and the incision is most prominent at the HFT zone. The BGF sections are best exposed along the channels of Thuli, Babat, Batna and Kali Gads. Along Thuli Gad, the incised fan measures more than 40 m in height and is

Figure 3. Field photographs showing exposed sections of fans. (**a**) Batna Gad Fan (BGF) exposed along Thuli Gad. (**b**) Close-up view of Batna Gad Fan. (**c**) Incised sequence of the Batna Gad Fan along Babli Gad. (**d**) BGF exposed along the Kali River, the exposed fan measures ~60 m. (**e** and **f**) Sections of Bastia Fan exposed along the Hathi Khor River. Break in sedimentation is marked by well-defined marker bed indicated by the dashed line.

composed mainly of the clasts of sandstones of the Siwalik (figure 3a, b). The sediments are clasts supported and crudely laminated with a maximum size of the clast ~4 m in diameter; these are intervened by a thin layer of sandy horizon. Large boulders are observed towards the bottom section of the fan, and upward fining sequence is observed. Further downstream of Thuli Gad, near its confluence with the Kali River, the Lower Siwalik sandstones are exposed. Reworking of the fan by the Kali River is evident by the presence of well-rounded clasts in the fan composition, which is not the case a few hundred meters upstream of Thuli Gad. Along Babat Gad the 25 m high fan sediments are

exposed that are composed of crudely laminated angular clasts of sandstone, with thin layers of gravelly sand in between (figure 3c). Erosion of the distal part of the BGF by the Kali River has exposed a ~60 m thick fan deposit (figure 3d). The fan-section comprised mainly of clasts of sandstones of smaller dimension as compared with those observed along Thuli and Babat Gads. The BGF has been deeply incised by the Kali and Batna Gads. The Babat and Kudal Gads fans are covered with thick vegetation and are not incised by the streams; therefore, their sections are obscured. The Babat and Kudal Gads fans are made up of reworked sediments from the BGF with fresh

landslide debris that came from the hinterland. The Bastia Fan is the most accessible of all the fans as the Hathi Khor river traverses throughout its length and the exposed segment measures ∼2.5 km in length, with a maximum height of ∼25 m. In the proximal part of the fan, just north of Bastia, the bottom- and mid-sections of the fan consists of weathered, highly angular to sub-rounded clasts of sandstones with crude laminations, while the matrix consists of rock fragments with very coarse sand. The topmost portion of the fan is characterised by a sandy layer of ∼0.5 m thick, overlain by angular rock fragments. In the distal part, the exposed fan measures ∼22.5 m in height. The fan is made up mainly of the clasts of sandstone of various sizes; the sizes of the clasts are much smaller than those observed at the proximal part, due to the waning of the stream energy transporting the sediments. From the exposed section it appears that there was a time gap in the sedimentation as indicated by sharp contact between the two layers (figure 3e, f). Break in the deposition is marked by a ∼1.5 m thick oxidised sand layers representing a marker layer. In the mid-section of the fan in the HFT zone, the fan sediment thickness is observed to be the least as the exposed section comprised of equal thickness of the Siwalik bed rocks and fan deposits. The youngest fans are characterised by almost barren surfaces. They are made up mainly of debris of landslides with very angular to angular clasts of sandstones of various dimensions. The latest alluvial fan deposit is the one that completely covered a portion of road section between Thuli Gaon and Tanakpur, which was laid down during the monsoon of 2010. Sediments are generated from massive landslides that took place in the steep south facing hill slopes.

4.2 *Terrace*

In the field, there is no clear cut demarcation of disposition between the fans and terraces, as the terraces are overlapped by fan deposits and thick forest cover. Two geomorphic units have been demarcated through the work of Valdiya *et al.* (1992) and Google Earth, toposheet and DEM-SRTM. Two levels of terraces are observed around Tanakpur area (figure 2a). The older Uchali Got Terrace (∼T_2) is at the elevation of ∼272 m asl measured around Uchali Got, the younger Suwa Got Terrace (∼T_1) is situated at ∼268 m asl, and the present river bed of the Kali River is at ∼257 m asl. Terrace T_2 (2–3 m thick) is exposed along a number of streams flowing across the terrace and is best exposed around Uchali Got. This terrace is made up mainly of clasts (cobble size) of the Nagthat quartzite and Siwalik sandstones. The terrace T_1 is similar to terrace T_2 in composition; the main

constituents being quartzite and sandstone. There is a gradual decrease in elevation between T_1 and river bed T_0. Tectonically induced incision by Dhana Gad has exposed a 2-m thick terrace deposit, resting over the inclined pre-Siwalik rocks at Khorpa Tal (figure 4a). There is no distinct boundary separating the two levels of terraces of Khorpa Tal (T_1 of Khorpa Tal) and Uchali Got (T_2 of Uchali Got); only at Khorpa Tal, a 2–3 m break (vertical escarpment) is observed. At Senapani, one level of the terrace is observed in which the terrace sediments are laid down over the inclined pre-Siwalik rocks (∼Dharmsala/Subathu) (figure 4b, c). The terrace is made up clasts of sandstones and quartzite and the maximum size of the clasts are ∼30 cm in diameter. Compositionally this terrace differs from the one observed at Khorpa Tal. Here, a fair amount of representative
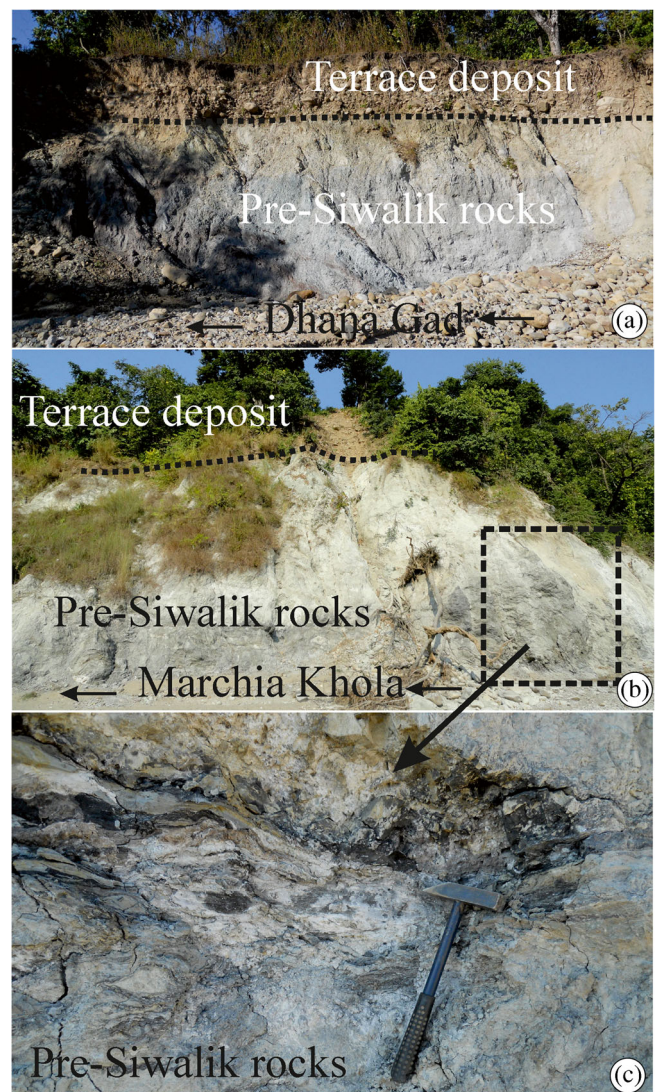

Figure 4. (**a**) Pre-Siwalik rocks exposed along Dhana Gad at Khorpa Tal in the HFT zone with terrace. (**b** and **c**) Highly sheared pre-Siwalik rocks exposed at Senapani overlain by the terrace deposit in the HFT zone.

quartzite pebbles and gravels is observed in the terrace, though this stream originates within the Siwalik terrain. The Upper Siwalik sequence is exposed in the source region of Kalaunia River, as marked in the geological map of Karunakaran and Ranga Rao (1979).

5. Hill slopes, landslides and their relation with fans

Hill slopes and landslides have a direct relationship with fans in the foothills. The south facing hill slope in the Tanakpur area is characterised by a sudden gain in elevation from 540 m asl measured at the proximal part of the fan to ∼1500 m asl at the ridge crest, within a distance of 2 km. To characterise the type of landslides taking place in the area, two wedge failure analyses have been carried out. The first analysis indicates four joints forming wedges in the SE and SW quadrants, while in the second analysis, the bedrock is traversed by three joints forming a wedge in the SE quadrant (figure 5a, b). The rocks in the fault zone are highly sheared (figure 5c, d). The steep hill slope shows
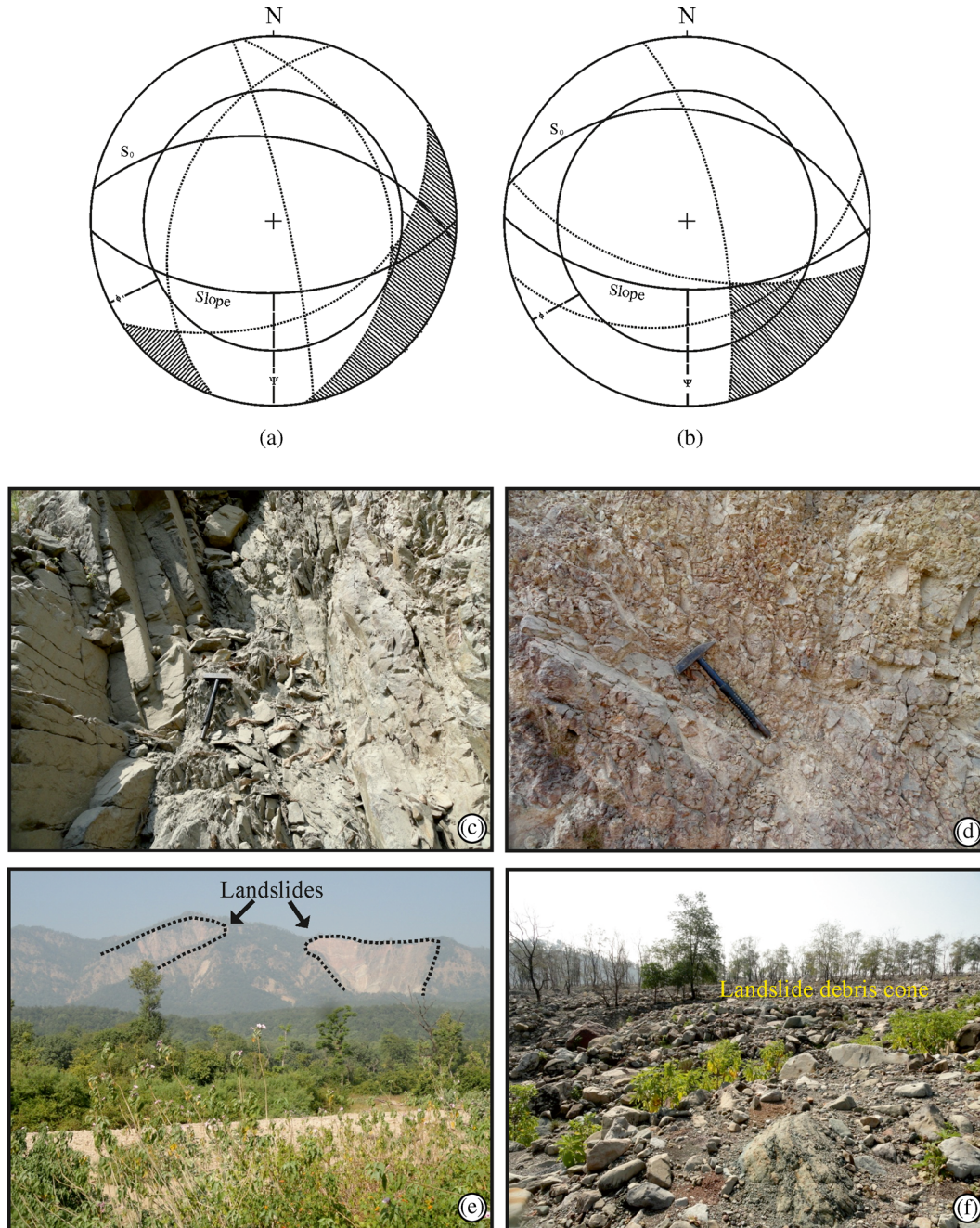

Figure 5. (**a** and **b**) Stereographic projections showing joints forming wedges in the open slope. The friction angle 'Φ' has been assumed to be 30°. Shaded region indicates vulnerability to landslides. (**c** and **d**) Field photographs showing highly sheared rocks in the fault zone. (**e**) South facing slopes are dotted by number of old and active landslides; the photographs show huge crown of active landslides. (**f**) Huge landslide debris fan deposited during the monsoon of 2010.

old and active landslides. Massive landslide is taking place in the catchment area of the Batna Gad; thereby generating huge debris (figure 5e, f). It is evident from the Google Earth image of 2006 that a landslide was active in the past, adjacent to the Batna Gad, but now the slide is inactive as evident by regeneration of vegetation on landslide scar. The adjoining area is dotted by a number of small and large landslides.

6. Tectonic landforms

In the Tanakpur area, major landforms have developed parallel to the faults. It implies that they are controlled by tectonic activities. Kotlia *et al.* (2008) briefly mentioned the existence of the North Bastia Fault and the South Bastia Fault on the basis of the existence of fault gouge along the traces of the faults. The present study on landform suggests the existence of another fault between these faults, which are named as the Bastia Fault-1 (BF-1) and Bastia Fault-2 (BF-2). Towards the extreme south of Bastia, the South Bastia Thrust (SBT) is interpreted as a blind thrust, as no Siwalik bedrocks are exposed, but, nevertheless, an escarpment is observed along this fault. BF-1, BF-2 and SBT are interpreted to be splay of the HFT (figure 6). In the present study, BF-2 and HFT correspond, respectively, to the North Bastia Fault and South Bastia Fault of Kotlia *et al.* (2008). The BF-1 is the northern-most fault across which sudden change in hill slope gradient is observed with the development of brittle shear zones. The change in slope gradient across the BF-1 is regarded as relic mountain front where deformation has shifted southward. In the present study, the active mountain front is observed south of Bastia along the HFT (figure 6a, b). The shear zones related to faulting are best observed along the channel of Hathi Khor and the Tanakpur–Sukhidhang section is also shown by Prakash *et al.* (2015). The hanging wall block of the BF-1 shows recurrent landslides, and the rocks have been weakened by two prominent joint sets, forming a wedge towards the daylight slope. The footwall of the BF-1 is a flat barren rock surface and is designated as the North Bastia Surface (NBS), which resulted from faulting along the BF-2 and is ∼400-m wide, although its length cannot be measured due to a thick vegetation cover and covering by colluvial deposit (figure 6c, d). The NBS is separated from the Bastia Surface by ∼20 m high tectonic escarpment, and the top of the hanging wall is characterised by highly sheared rocks. Faulting along the BF-1 and BF-2 has formed a tectonic wedge, north of Bastia. Along the HFT, a fault gouge has formed that is best exposed along the Hathi Khor where moderately inclined sheared

Siwalik rocks are exposed, covered by ∼5 m fan/ terrace deposit. Across this thrust, a sudden change in slope gradient is observed. Further south of the HFT, no Siwalik rocks are exposed (figure 6e). The Bastia Surface is separated from the unclassified fan by the SBT (figure 6f, g) along which a ∼17-m high escarpment trending E–W is observed. This escarpment runs for ∼5 km, punctuated in between by erosion and deposition of recently deposited alluvial fans. The highest escarpment is observed east of Bastia, extending up to Batna Gad between Kali Gad and Batna Gad, where it measures more than 100 m high. Between Kudal Nadi and Kali Gad, the escarpment has been eroded and depositions of newer fan deposits are observed at the foot of the escarpment. Thrusting along the HFT has lead to the incision of the fans by numerous streams forming V-shaped valleys. West of Tanakpur at Khorpa Tal, a topographic break of ∼2–3 m is observed, where uplift along the HFT has exposed ∼1.5 m high terrace deposit resting over the highly sheared inclined Subathu rocks. Change in the strike of beds from almost NE–SW in Senapani, west of Tanakpur to E–W around Bastia, north of Tanakpur, and to almost N–S near the confluence between Thuli Gad and Kali River, corroborates the existence of structural anomaly due to the presence of faults, and which resulted in the curvature of the mountain range.

7. Folded mountain front

The regional trend of the mountain front in the NW Himalaya is NW–SE, but it locally becomes SW–NE towards the north of Tanakpur and NW–SE and N–S at the exit of the Kali River near Thuligaon. This variation in trend of mountain front is due to the presence of a syntaxial structure. The N–S trending Thuli Gad and other stream, at 1.2 km east of Thuli Gad, flow along the axial zone of this major fold. These tributaries follow the N–S trending brittle axial planar fracture cleavages of fold. The Kalaunia Fault offsetting the trace of the Bastia Fault (Goswami 2012) and the Tanakpur Fault, as shown in figure 8(b), are also parallel to these tectonic fabrics. At Bastia, the Siwalik rocks dip towards north direction, while near the confluence of Thuli Gad and Kali River, the bed rocks dip towards the ENE/E direction. At Senapani, the bedrocks comprise of the pre-Siwalik rocks (∼ Dharmsala/Subathu) where the attitude of the bedrock is moderately (37°–50°) dipping towards N20W–N15W. Here the strike of the mountain front is almost E–W. Further east at Khorpa Tal, north-west of Tanakpur, the attitude of the bedrock is moderately dipping (34°–35°) towards west–N80W, while the trend of the
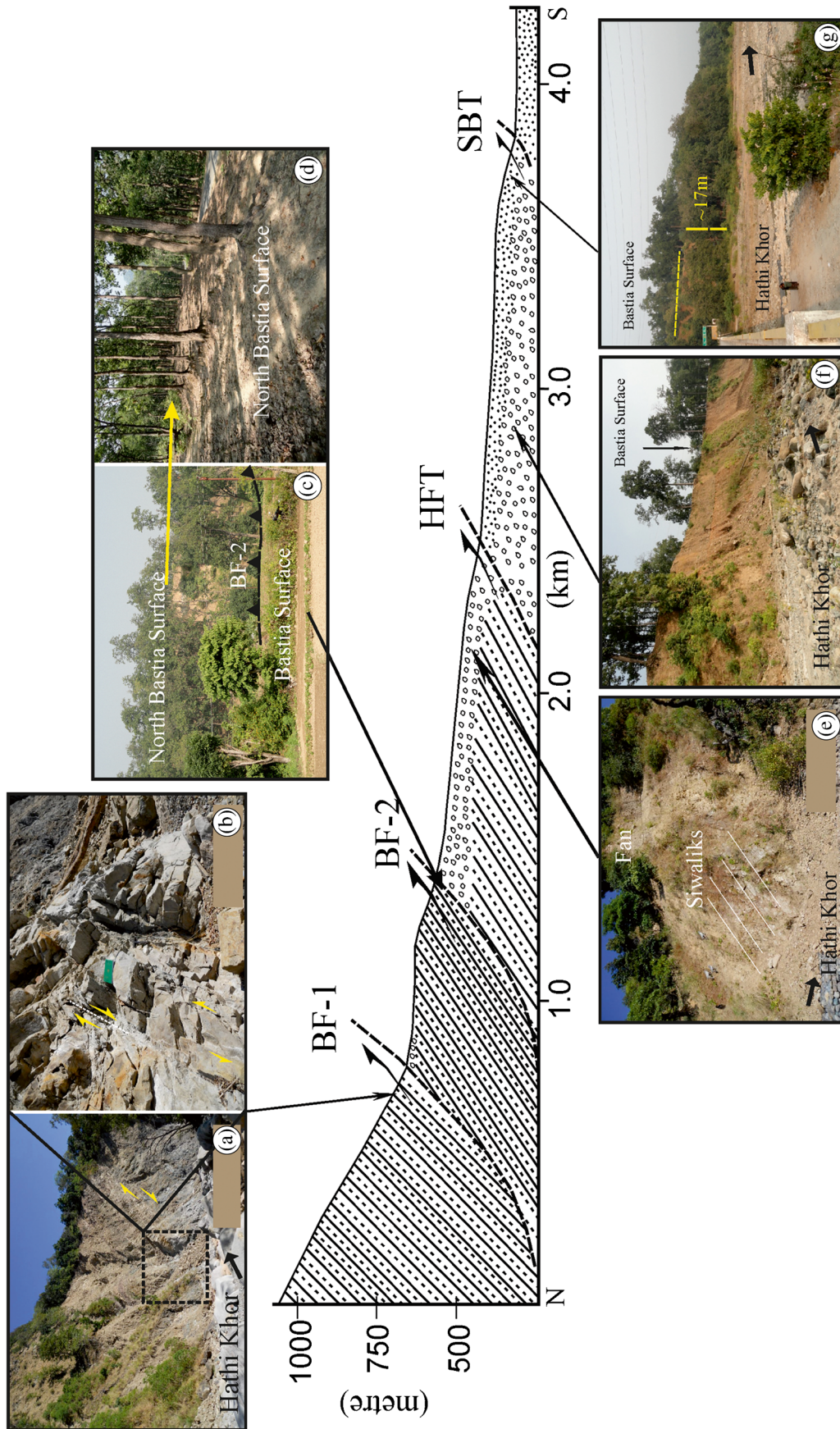
Figure 6. Field photographs and schematic diagram depicting the tectonic geomorphology of the Bastia area. (**a** and **b**) Sudden slope break observed across the Bastia Fault-1 zone characterised by highly sheared rocks with movement taking place along shale beds. (**c** and **d**) Highly sheared rocks at the bottom of the hanging wall of the Bastia Fault-2 and the almost flat surface (North Bastia Surface) formed in the hanging wall block. (**e**) Moderately dipping Siwalik sandstones observed along Hathi Khor in the HFT zone; bedrocks thrust over the fan deposits are not observed due to thick vegetation. (**f** and **g**) Exposed Bastia Fan and escarpment in the frontal part formed by uplift along the splay thrust (South Bastia Thrust) of the HFT.

mountain front becomes NE–SW. At Khorpa Tal, the mountain front shows a 2–3 m high south-dipping gentle fault scarp. The attitude of bedrock along the Hathi Khor River, west of Bastia, just at the point of exit into the Piedmont Zone, the bedrock dips 57°–73° towards N53W–N40W. Along the Tanakpur–Champawat highway, just north of Bastia, the attitude of the bedrock dips moderately (44°–52°) towards N–NNE, and in this section, the trend of the mountain front is almost E–W with a slight curvature. Sudden change in slope gradient is observed along this section and is characterised by sheared bedrocks. This is the relict mountain front, where the present active mountain front lies south of Bastia at ∼3 km

from the former. At Thuligaon, where the Kali River exits into the Piedmont Zone, the attitude of the bedrock becomes steeply dipping (60°–70°) towards N80E–S40E (figure 7). At the Thuligaon section, the mountain front becomes NE–SW trending and the Kali River flows parallel to the strike of the bedrock. Before cutting across the Tanakpur Fault, the Kali River flows across the bedrocks perpendicularly (figure 7a, b), where the strike of bedrock is almost N–S and flow direction of the Kali River is W, thereby resulting in a deep cut V-shaped valley. The bedrock is subjected to brittle deformation as evident from bedding parallel movement having slickensides indicating a sense of movement
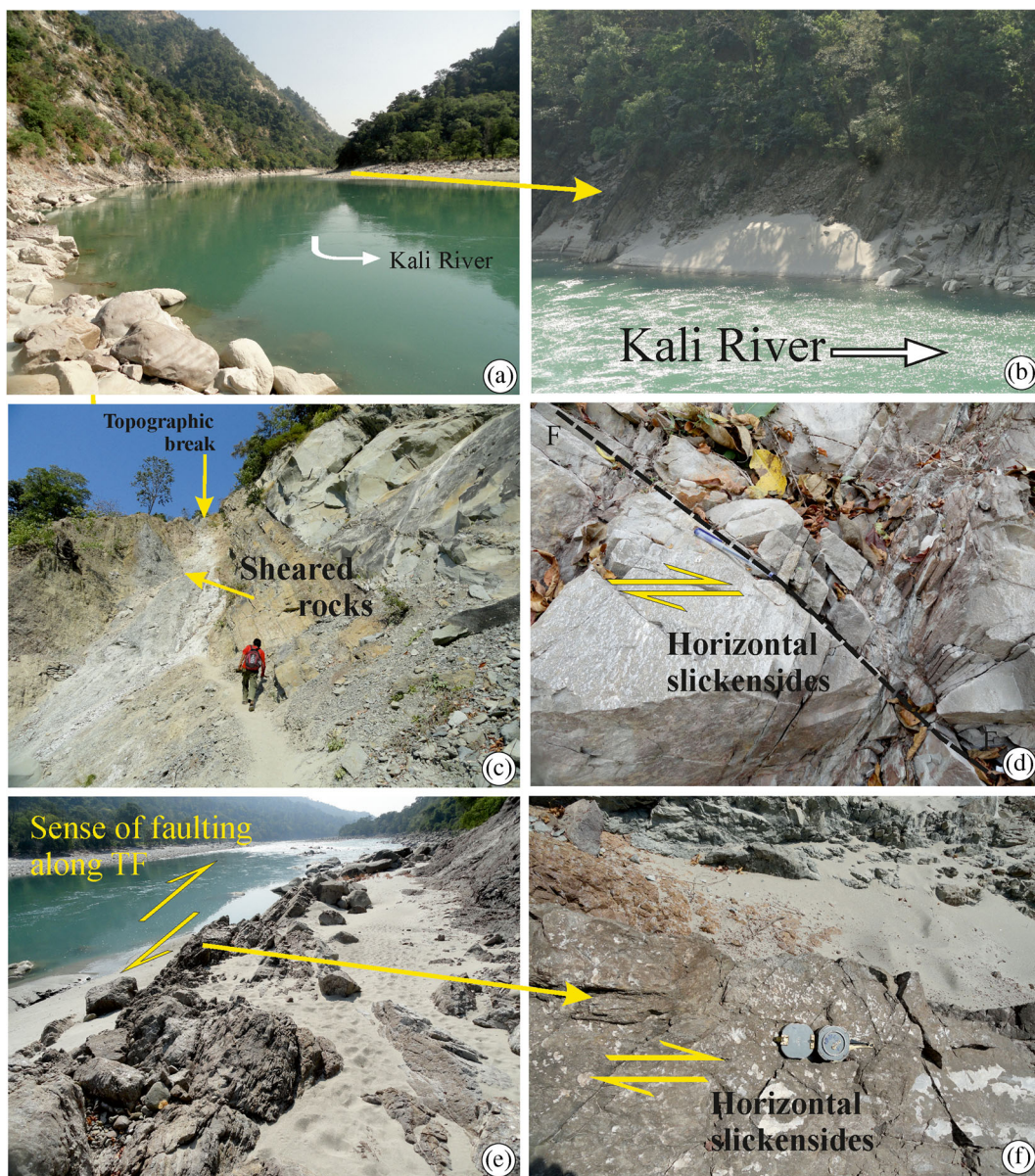

Figure 7. (**a** and **b**) Photographs showing the exit of Kali River into the Gangetic Plain at Thuligaon, the bedrock dip steeply towards NE. (**c** and **d**) Bedrocks characterised by bedding-parallel movement and the original fabric of the rock has been deformed; horizontal slickenside is also observed. (**e** and **f**) SE-dipping bedrocks exposed along the Kali River with horizontal slickenside indicating the sense of movement.
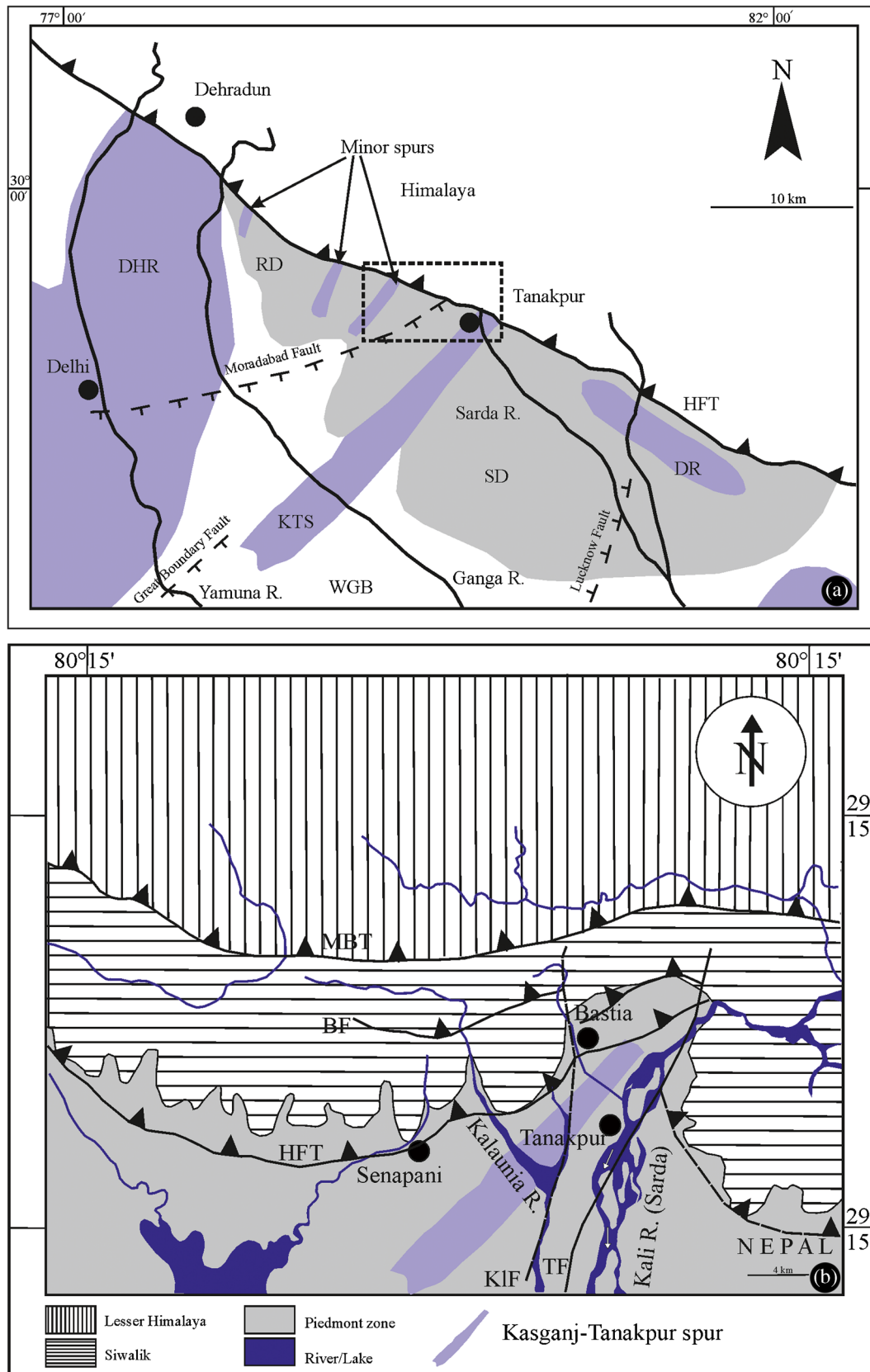
Figure 8. (**a**) Tectonic features of the basement of the Ganga Basin (Goswami 2012). (**b**) Morphotectonic map of Tanakpur area (Goswami 2012). MBT: Main Boundary Thrust, HFT: Himalayan Frontal Thrust, BF: Bastia Fault, KlF: Kalaunia Fault and TF: Tanakpur Fault.

(figure 7c, d, e, f). The sense of movement on the bedrock is similar with the sense of movement indicated in figure 4 of Goswami (2012). Raiverman (2002) has discussed the existence of localised syntaxial bend, north of Tanakpur, due to the indentation of the Delhi–Moradabad ridge into the Sub-Himalaya. Tanakpur area is traversed by right lateral transverse faults, the Tanakpur Fault trending NNE—SSW (Valdiya 1976; Goswami 2012) (figure 8a). The transverse fault produced pronounced displacement that has placed different lithologies in juxtaposition (Valdiya 1976). Goswami (2012) also postulated a N–S trending fault, west of Tanakpur, on the basis of conspicuous dextral movements of the lithounits and also from number of cliff and landslides along this fault, and named it as the Kalaunia Fault (figure 8b).

8. Deformed Quaternary deposits

At Senapani, the tectonic induced erosion has exposed a 30-m high escarpment comprising of 16 m high of the pre-Siwalik rocks (~Dharmsala/Subathu) and 14 m high of terrace deposits. The dip of the pre-Siwalik rocks is 45° towards NW direction (figure 9a). Overlying the pre-Siwalik rocks is the base of the terrace with angular unconformity between them. Stream cutting across the 30-m high escarpment has exposed the terrace that is made up mainly of clasts of the Siwalik sandstones and quartzite, which is ~2.7 m thick. This is overlain by ~2.26 m thick horizons of pebbles and laminated sand. Pebbles and laminated sand horizon are characterised by an upward fining sequence. Pebbles are made of quartzite and sandstones. The top horizon is made up of a thick sequence of cobbles and pebbles of ~9 m, made up of clast of quartzite and sandstones. The terrace sediments are tilted by ~30° towards the NW direction; the tilted sediments are characterised by hosts of deformation structures (figure 9b, c and d). The main deformation structures observed are the closely spaced reverse faults, dipping 38° towards NW direction (figure 10a, b).

Figure 9. (**a**) Highly sheared pre-Siwalik rocks with moderate dip exposed at Senapani. (**b**, **c** and **d**) The pre-Siwalik rocks are overlain by terrace deposits which are tilted and faulted.
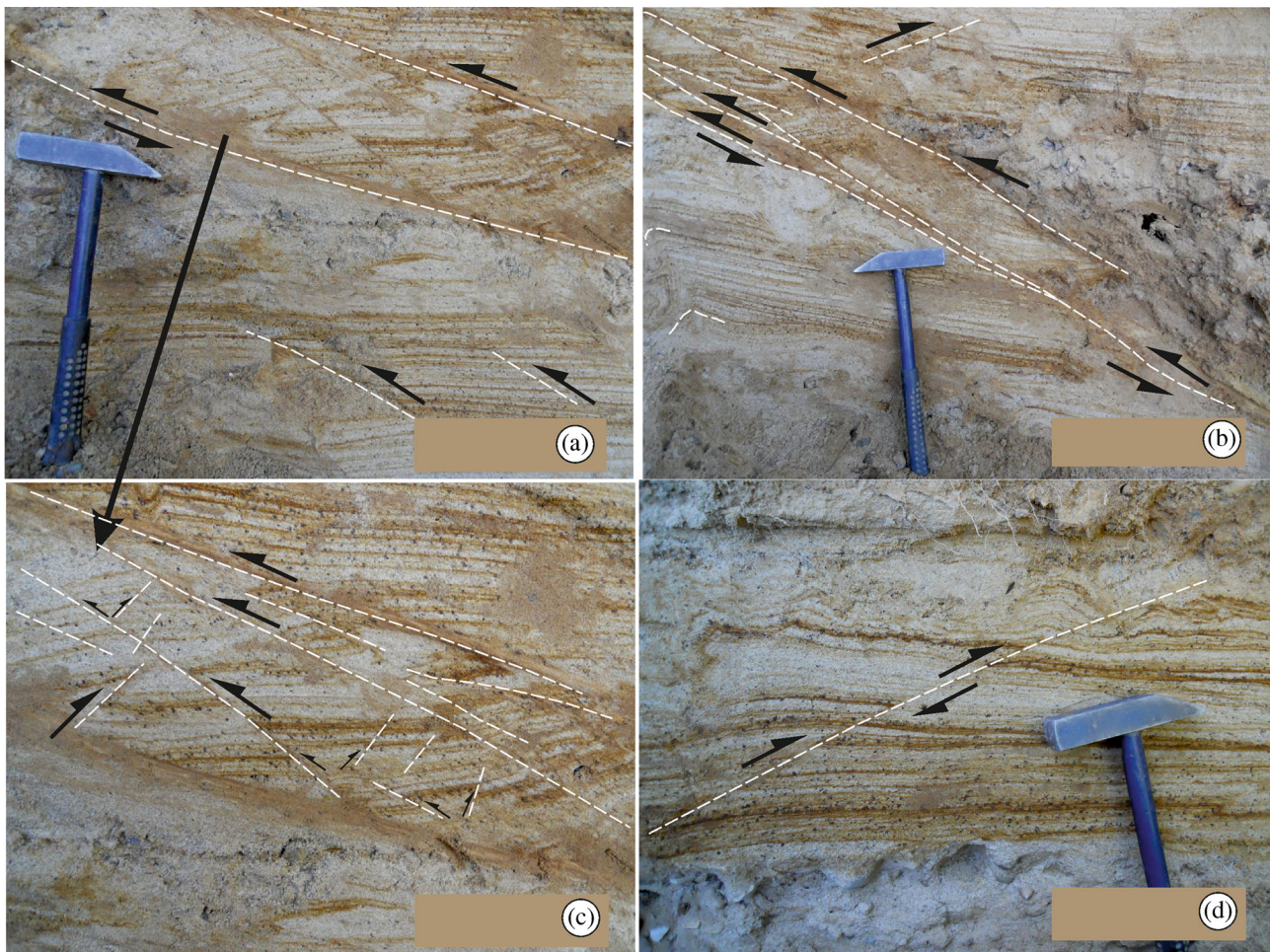
Figure 10. Tilted Quaternary terrace deposit at Senapani in the hanging wall of the HFT. Various deformed structures are embedded within the deposit. Tilting and deformed structures representing different phases of tectonic activity along the HFT. Sense of movement is indicated by arrows.

Maximum displacements have occurred mainly along the basal and the uppermost faults; in between which faults of smaller extent are also observed (figure 10c). The movement along the basal fault has resulted in placing the laminated sand over the upper pebbly horizon. Faulting along the uppermost fault has moved the underlying pebbly horizon forming the base of the laminated sand by ∼65 cm over the laminated sand layer. The maximum displacement along the uppermost fault measures to about a meter. In between the basal fault and the uppermost fault, the NW-dipping laminations have become horizontal to SE-dipping that resulted from the movement along successive minor faults (figure 10c). The reverse faults are associated with other deformed structures, such as crumpled lamination at the top of the thrust plane, kink folds, and wavy undulation of laminations, pop-up structure and folding. Faulting in opposite directions has resulted in small scale flower structures (figure 10c). Fault propagation folds are also observed towards the top of the deformed laminated sand (figures 9d and 10d).

Small-scale parallel reverse faults resembling back thrusting are also observed that dip 7° towards SE direction. The back thrusts are gentler than the main fore fault.

9. Seismicity and lineaments

Bouguer gravity data reveal several continuous Himalayan cross-strike discontinuities, which are interpreted to represent the crustal faults (Godin and Harris 2014), both orogen-parallel and orogen-transverse. The stress change resulting from the active rifts could partly suppress the seismicity in an area (Gahalaut and Arora 2012). The seismicity along the Himalayan arc may also be influenced by the stress changes due to the interaction of faults in the Himalaya and Tibet, and by the occurrence of great and major earthquakes along the arc (Gahalaut *et al.* 2011).

In recent years, field-based active tectonic studies have been focused on understanding the strain rates of the active structures in the

Himalayan frontal zone (Wesnousky *et al.* 1999; Lavé and Avouac 2000). Their study highlights the major seismicity zone occurring near to surface trace of the MCT and above the mid-crustal ramp, which during the interseismic periods may activate only a fraction of the area beneath the Lesser Himalaya. The whole flat, up to the HFT, would only be activated during the M>8 major events. Thus, the influence of seismicity in the Lesser Himalaya would not participate in the active deformation near the HFT.

However, Jackson and McKenzie (1984) explained that the deformation is not distributed uniformly over the whole area of the active zone, but is concentrated in belts. These active belts, spreading hundreds of kilometres in width, may surround the relative aseismic areas. Within such deforming regions, continuum theory is required for a description of the kinematics, even though much of the motion is concentrated on active faults. Their study further state that the evolution of fault systems within the active zones is controlled by geometric constraints. A basic geometrical limit required for simultaneously active faults is that they do not generally intersect (Jackson and McKenzie 1984). The other case when the faults intersects could be described from the study by Robinson *et al.* (2006), which reveals that the earthquake rupture zones are affected and delimited by regional tectonics and subsurface ridges that act as a barrier for the rupture front with no further slip across them, hence produce segmentation in seismic zones most likely due to the structural heterogeneities on the converging plates (Gahalaut and Arora 2012). The structural complexities that appear to control the spatial variation in the Himalayan seismicity include presence of subsurface ridges on the underthrusting Indian plate (Valdiya 1976; Gahalaut and Arora 2012; Godin and Harris 2014), the geometry of the detachment (Ni and Barazangi 1984) and the mid-crustal ramp (Pandey 1995) as well as the active rifts in the overriding Himalayan wedge (Armijo *et al.* 1986). Moradabad Fault is a major lineament zone that traverses near to the west of the study area (Sastri *et al.* 1971; Karunakaran and Ranga Rao 1979; Raiverman 2002; Godin and Harris 2014).

We used International Seismological Centre (ISC) reviewed earthquake catalogue to assess the seismicity pattern around the Kumaun region focusing the seismicity along the Moradabad Fault (figure 11). The earthquake locations give reliable estimates, assured by rigorous checks for inconsistencies and errors (http://www.isc.ac.uk/iscbulletinsearch/catalogue/). Figure 11 shows the epicentres and focal mechanism plots for M≥3.5 (filled black circle) and M>4.5 (star in red) earthquakes,

respectively, from the year 1960 to 2012. The focal mechanism results are used from the global Centroid Moment Tensor solutions, where the method to determine the solutions has been discussed in detail by Dziewoński *et al.* (1981) and Ekström *et al.* (2012). We observe the feeble seismicity patch towards the Himalayan frontal part near the HFT which is nearly absent along the surface trace of the Moradabad Fault. We are limited to comment on the seismicity near the MCT along the surface trace of Moradabad Fault, which could more likely be influenced by the activity along the mid-crustal ramp. The focal mechanism near the study area indicate north-dipping thrust fault and does not indicate any sense of movement which could be related to the NE–SW striking the Moradabad Fault. Therefore, under the studies based on rupture velocity, stress, strain and seismicity analysis, we infer that Moradabad Fault could be an important structural heterogeneity suppressing the seismicity in the Tanakpur area (figure 11). However, the movement along the Moradabad Fault can cause the neotectonic activities in the study area (Valdiya 1976; Goswami and Yhokha 2010; Goswami 2012).

10. Discussion

Raiverman (2002) has discussed the existence of localised syntaxial bend (here referred as the folded mountain front) due to the indentation of the Delhi–Moradabad ridge into the Sub-Himalaya at a high angle (70°–80°) to the Himalayan strike resulting for a syntaxial bend, north of Tanakpur. Similar syntaxial bend is also reported from Kotdwar area (Raiverman 2002). The folded nature of the mountain front is also explained by the existence of two transverse faults, i.e., Tanakpur and Kalaunia faults (Valdiya 1976; Goswami 2012; Srivastava *et al.* 2013). Goswami (2012) is of the view that the active Tanakpur and Kalaunia faults represent the rejuvenated basement faults related to Kasganj–Tanakpur–Spur. However, Srivastava *et al.* (2013) argued that these transverse faults are lateral ramps or connecting splays and are present throughout the mountain front, giving it a very conspicuous sinuosity. The present observation such as swing in the strike of the bedrock attributes to this spur. The NNE trending folded mountain front measures ∼8 km in width. The aggradational landforms especially the alluvial fans have been dealt in relation with the nature of the slopes and landslides. There is a sudden gain in elevations from 540 m asl measured at the proximal part of the fan to ∼1500 m AMSL at the ridge crest within a distance of 2 km. The nature of the slopes has direct bearing with the active HFT, which has
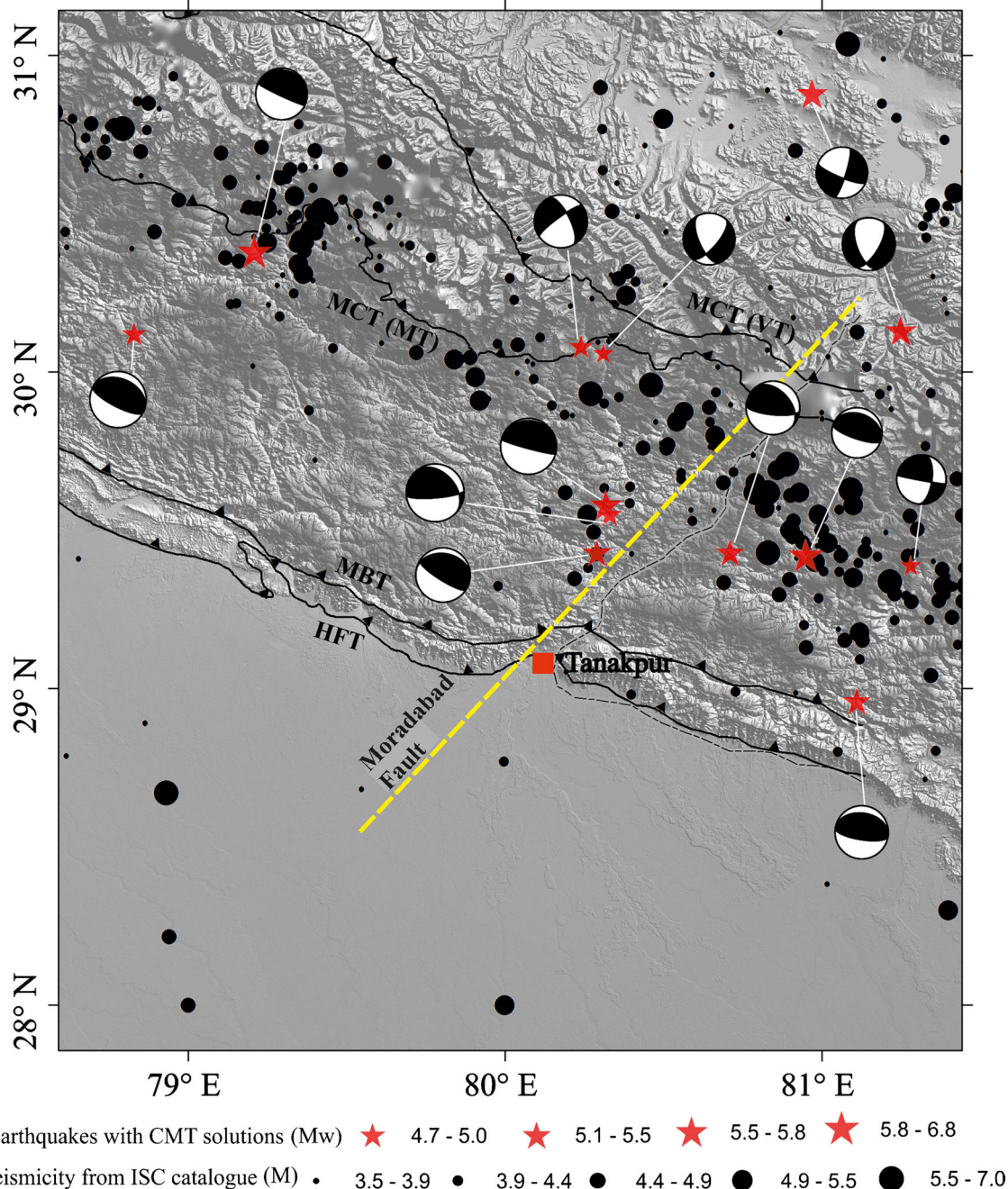
Figure 11. The seismicity map of the Kumaun and western Nepal region. The focal mechanisms are plotted for the earthquakes Mw>4.5. (Trace of Moradabad Fault: Godin and Harris 2014.)

brought up the Siwalik rocks over the Quaternary alluvia (Talukdar and Sudhakar 1972). The mountain front was affected during the tectonic upheaval along the HFT triggering massive landslides and debris flows on the slopes of the destabilised mountain (Valdiya 2003). The steepness of slope in this area can also be explained in terms of shortening rates. The balanced cross-section of the Sub-Himalayan rocks in the Tanakpur area, carried out by Dubey *et al.* (2001), suggests a shortening of 49% or 11.3 km, while balanced cross-section estimates of the Himalaya suggest minimum shortening of ∼400 km between 55 and 40 Ma and a

total Himalayan shortening of ∼1100 km between 55 Ma and present day (Guillot *et al.* 2003). The geometry of the drainage basins is elongated. Most of the small drainage basins in the source region that face south are valleys carved out by landslides (figure 5e). Apart from the steep slopes, the bedrock making up the slope is traversed by a high number of joints. The intersecting joints form wedges towards the open slopes, most of the failures are related to wedge failure. The combination of steep slopes and the intersecting joints have destabilised the slopes that give way to landslides during the rainy season. The available data of

annual rainfall in the region for the last 108 years has been 1900 mm/year with a maximum rainfall during the months of July and August being ∼600 mm on average (Goswami and Yhokha 2010). In many humid uplands and the Himalaya, landscape evolution is dominated by landsliding across a wide range of length scales (Anderson 1994; Gerrard 1994; Greenbaum *et al.* 1995; Schmidt and Montgomery 1995; Burbank *et al.* 1996; Valdiya 1992).

Aggradational landforms in Tanakpur area are dominated by fans that are deposited by streams laden with landslide debris. The landslide debris fans have been incised by a number of streams, thereby exposing more than 50 m of the fan sediments (figures 2b, 3a, c). Compositionally the fans are homogenous, in the sense that they are entirely composed of the Siwalik clasts, though reworking by the Kali River in the distal part of fans. The fans are tectonically driven, as the bedrocks are transported along the HFT and the displaced rocks have not only attained great height but have also endured brittle deformation during the successive phase of uplift along the HFT (Valdiya 2003). These conditions in conjunction with the precipitation favours slope failure of various kinds. In the Tanakpur area, the sediments making up the fans are supplied by landslides, which in turn are related to tectonic activities of the HFT and its splay thrust. Valdiya (1992) has suggested that landslides in Tanakpur area are of huge dimensions and on a very extensive scale is related to tectonic activity. A comparison on landslides that took place in Tanakpur area between 1920–21 and 2004 suggests three-fold increase in landslides (Goswami 2012). The deposition of alluvial fans in the Tanakpur area is a continuum process where active deposition is still taking place. The most recent deposition took placed in 2010, where a section of road between Tanakpur–Thuli Gaon was completely covered by sediments.

The tectonic activity along the HFT has been documented from various segments of the Himalayan front from Indus River, Pakistan, up to the Dibang River (a major tributary of the Brahmaputra River) in north-eastern Assam, India (Nakata 1972, 1975; Armbruster *et al.* 1978; Valdiya *et al.* 1992; Valdiya 1992; Luirei *et al.* 2014; Agarwal *et al.* 2009, 2012; Srivastava *et al.* 2013). Tectonic activity along the HFT has been deduced through tectonic geomorphology, paleoseismology, fluvial incision rate and convergence rates along the HFT (Nakata 1972; Wesnousky *et al.* 1999; Lavé and Avouac 2000; Valdiya 2003; Philip *et al.* 2012). At Senapani, west of Tanakpur, lateral erosion by streams has exposed thick Quaternary deposits in the HFT zone. Uplift along the HFT resulted in increasing the inclination of the tilted bedrock and

tilting the overlying horizontally deposited terrace sediments. The tilted terrace has been imposed by a later phase of uplift along the HFT, as the tilted sediments have been faulted by reverse faults producing many fault-related features in the Quaternary sediments. The faulting event has also made the inclined laminations horizontal to tilt in NW direction. In the west of the present study region, at Kala Amb, Philip *et al.* (2012) reported two large paleoseismic events on the basis of surface displacement and liquefaction, as evident from the presence of sand dykes. The first event took place between 29.3 ka and 17 ka and the second event between 5.8 ka and 2 ka. Paleoseismic records are also reported from different sites of the Frontal Himalaya (Wesnousky *et al.* 1999; Kumar *et al.* 2001; Malik *et al.* 2003, 2010). Paleoseismological studies have also been carried out along the HFT in the southeastern Nepal where 4-m displacement is estimated to have occurred ∼1.2 ka (Upreti *et al.* 2000). Active tectonic studies on the uplift along the HFT has also been documented from various sites of the HFT on the basis of uplift terrace, encased strath terrace, convergent rate, offset terrace and on structural and morphological evidences (Wesnousky *et al.* 1999; Mugnier *et al.* 2004; Parkash *et al.* 2011). Effects of neotectonics activity on geomorphic features are also reported from the foothills of the eastern Himalaya (Luirei and Bhakuni 2008; Devi *et al.* 2011; Bhakuni *et al.* 2017). In the present study, a displacement of ∼1.0 m is observed within the laminated terrace deposit with other host of deformed structures in the terrace deposits. North-west of Tanakpur uplift along the HFT has resulted in the incising of the pre-Siwalik bedrock, as well as the overlying terrace deposit by Dhana Gad (figure 4a).

The lateral variation in structural complexities along the segmented Himalayan arc may be controlled by the presence of subsurface ridges on the underthrusting Indian plate (Valdiya 1976; Arora *et al.* 2012). This implies that the Kasganj–Tanakpur spur including the neotectonic Moradabad Fault may have played the causative role in folding of the mountain front in Tanakpur area as described above.

11. Conclusions

The folding of the mountain front in the Tanakpur area is a result of transverse tectonics related to the neotectonic transverse Kasganj–Tanakpur Spur bounded by active faults, which propagate below the Himalayan mountain front. The area is constituted mainly by various levels of coalescing fans and terraces. Tectonically induced incision of terrace and bedrock, and truncation of fan suggest

neotectonic activity. Fans sediments are supplied from the south-facing hill slopes that are very steep, traversed by a network of joint sets associated with the neotectonic activity of the HFT. The sudden gain in height and the sheared nature of the bedrock in the mountain front resulted from uplift along the HFT and along its splay thrust. Tilting of geographic surfaces and deformation of terraces suggest differential tectonic upheavals along the HFT. The role of transverse fault tectonics in the formation of the curvature cannot be ruled out.

Acknowledgements

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