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Geomorphic assessment of the factors contributing to the evolution of landforms in Ukhaldhunga area, Kosi River valley, Kumaun Himalaya, Uttarakhand

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ABSTRACT: This paper documents the various factors contributing to the evolution of landforms in the Kosi River valley, Ukhaldhunga area of the Kumaun Himalaya, Uttarakhand. The area falls in the major tectonic boundary between the Lesser Himalaya and the sub-Himalaya. Passing through the Parewa-Ukhaldhunga-Dabara area, this tectonic contact is known as the Main Boundary Thrust (MBT), which is characterized by presence of varied landforms. Study of the development of geomorphology, particularly those evolved in the MBT zone, suggests that the morphological features are intimately associated with the tectonic activities related to the movement of rocks along the MBT and the surface processes such as fluvial and mass movement. The various landforms observed in the MBT zone include strath terraces, fill terraces, paleochannels and V-shaped valley that pertain to fluvial genesis; gravity induced landforms such as landslide debris and colluvial fans; and tectonic landforms such as linear fault traces, swerving/swing of river course and linear depressions. Signature of recent tectonic activity along the MBT is observed between Dabara and Khakrakot. The activity is evident in the form of 8-km-long active fault trace trending NW-SE. Normal fault related landforms are observed in the hanging wall block of the MBT. Neotectonic strath terraces and fill terraces are well developed in the MBT zone. Multiple events of recurrence of landslides are evident from exposed section of landslide debris fans. The bedrocks are highly sheared, suggesting successive tectonic movements along the MBT. As a consequence, tectonic wedges have developed in the bedrocks. These wedges have facilitated for the recurrence of a number of landslides. The anthropogenic activities have also aggravated the slope stability. Truncation of older debris fan surfaces by an erosional/fault scarp is observed and the scarp separates the older fans from the youngest debris fan deposit. The scarp runs parallel to the MBT and Kosi River. Swerving of the Kosi River is as a result of the tectonic forcing along active lineaments/faults. The trend of lineaments of the maximum and high density is NE-SW, which is transverse to the trend of the NW-SE trending Himalayan fold-thrust belt.

Keys words: Kumaun Himalaya, Main Boundary Thrust, Kosi River, strath terraces, normal fault

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1. INTRODUCTION

The present study is aimed at understanding of the roles of tectonics and surface processes in shaping the Quaternary landforms in the Main Boundary Thrust (MBT) zone along Parewa-Ukhaldhunga-Dabara section in the outer Kumaun Himalaya (Fig. 1). The MBT is a chain of distinct steeply inclined imbricate thrusts and faults constituting the boundary between the Lesser Himalayan rocks and Cenozoic sedimentary units (Medlicott, 1864; Valdiya, 1992). Neotectonic activities along the MBT have been reported in various parts of the Himalaya from the NW to NE Himalaya based on the morphotectonic features (Valdiya, 1992; Valdiya et al., 1992; Luirei and Bhakuni, 2008). The extensional tectonics related to normal faulting has been reported from the MBT zone and its thrust splays (Valdiya et al., 1992; Mugnier et al., 1994). Structural control of the rivers in the MBT

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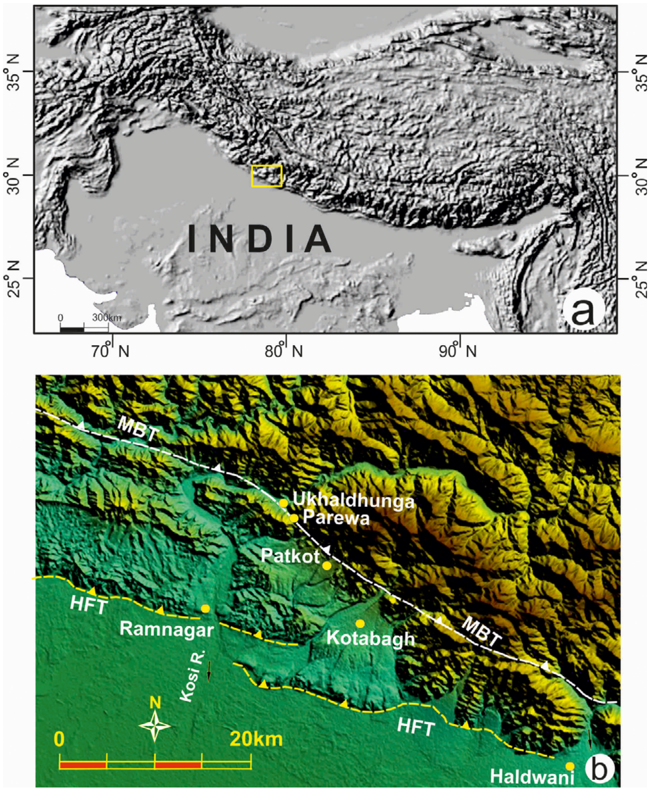

Fig. 1. (a) DEM showing the Himalayan arc, study area marked by inset box. (b) DEM of the present study area in the Kumaun sub-Himalaya.

zone is described, which reveals the strike-slip movement along the MBT as the bedrocks have high angle (> 70°) of dip (Valdiya, 1980). Mass movements also play an important role in shaping the landscape as they are occurring frequently in the MBT zone (Valdiya, 1987; Luirei, 2007). Slope failures of various kinds are common natural phenomena in the southern margin of the Kumaun sub-Himalaya (Bartarya and Valdiya, 1989). The frequency of landslide in the Siwalik Range is very high and varies from place to place as a result of the underlying structural set up and the neotectonic activity taking place along the MBT zone (Valdiya, 2001, 2003; Pant and Luirei, 2005; Luirei, 2007). Recent tectonic activity along the MBT encompassed a variety of landforms from the uplifted terrace to faulted Quaternary fan deposits. In the Gaula river valley, active fault trace of the MBT is observed at Logar where not only the surfaces of the Quaternary fans deposits are faulted but also responsible for the formation of two lakelets (Valdiya, 1992; Kothyari et al., 2010; Luirei et al., 2014).

Fluvial geomorphology provides an insight on the tectonic processes that the area has been experiencing, as the fluvial system is very sensitive to tectonic activity (Keller and Pinter, 1996). Thus it provides host of evidences to understand the relative tectonic activity that is undergoing in the area. Fluvial landforms, such a strath terraces, linear valleys, swerving of rivers, offset streams and abandoned channels provide a hint about the readjustment of the streams due to tectonic activity. Therefore, in the present paper the roles of tectonic activity and surface processes in shaping the morphology of landforms are described.

2. METHODOLOGY

Reconnaissance field survey and detail field studies were conducted along and across the MBT. Emphasis was given to understand their lithological variation along with its structural setup. As river channel courses and their valleys are sensitive to tectonic uplift, the landforms associated around this region are extensively studied to correlate their formation with the tectonic movements of different thrusts and associated transverse faults.

At different landslide locations, joints data were collected and analysed to understand the tectonic stresses manifestation on the rock surface. For any landslide consisting of rockmass, the kinematic analysis is based on the angular relationship of rock mass discontinuities and slope surface orientations to determine the potential and likely modes of slope failure, i.e., plane, wedge, and toppling failure (Mueller, 1968; Ashby, 1971; Markland, 1972; Goodman and Bray, 1976; Goodman, 1980; Hoek and Bray, 1981; Hudson and Harrison, 1997) The analysis is known as 'kinematics' because it is concerned with the motion of rockmass without reference to the forces that cause the motion (Beggs, 1983). Kinematic-based slope stability analysis has been traditionally carried out on stereo-nets considering lower hemisphere stereographical projection (equal angle) method (Goodman and Bray, 1976; Hoek and Bray, 1981; Pant and Luirei, 2005; Kothyari et al., 2012; Gupta et al., 2017; Kumar et al., 2018). In the present study, Dips software was used to perform the kinematic analysis. The following conditions must be satisfied for planar, wedge and toppling failure to occur.

For areas inaccessible to physical touch or investigation, development in remote sensing and geographical information system (GIS) technology has assisted geoscientists tremendously to explore areas beyond the line of sight as it gives a bird's eye view of the terrain in local or regional scale (Clarke, 1986; Miliene et al., 2011). In the study area lineaments were extracted visually using high resolution satellite imagery (IRS P6-LISS III, Cartosat 1 and Google Earth Image) as this manual procedure of data acquirement is much more reliable than those generated automatically using algorithm (Chang et al., 1998; Costa and Starkey, 2001; Raj et al., 2017). Before commencing with the extraction of lineament data, satellite imagery was georeferenced, and necessary image processing techniques such as contrast stretching, band ratioing and colour composite analysis was carried out using ERDAS IMAGINE software. The criteria for delineation of lineaments were done maintaining a consistency scale of 1:25,000 and were based on the geological structures such as fractures, faults, bedding trend, geomorphological features such as parallel and linear ridges and valleys, linear drainage segments, linear scarp faces and breaks in valley and hillslopes, abrupt changes of river courses, etc. This operation was done using ArcGIS software and validations of some of the lineaments mapped were done during fieldwork. From these lineaments, the rose diagrams were prepared for directional analysis. An interpolation surface map of lineament density was also prepared as lineaments per unit area of 500 m^2.

3. GEOLOGICAL AND GEOMORPHOLOGICAL SETUP

The area forms a part of the MBT zone across which rocks belong to the Tertiary and pre-Tertiary in age (Fig. 2). The immediate hanging wall block of the MBT is made up of rocks belonging to the Mussoorie and Jaunsar groups while the footwall block is made up of the Lower Siwaliks. Along the MBT, the Lesser Himalayan rocks are placed over the deformed foreland basin sediments of the Siwaliks of the Late Miocene–Early Pliocene (Medlicott, 1864; Valdiya, 1992). A thin stretch of phyllites and slates of the Blaini Formation of the Mussoorie Group is exposed in Parewa-Ukhaldhunga-Dabara section while in the upstream of Ukhaldhunga it is made up of quartzites of the Jaunsar Group (Valdiya, 1980). The Jaunsar Group is represented by an assemblage of purple, fawn, white and green quartzite of the Nagthat Formation. The Lower Siwalik, in greater part, is made up of highly indurated, medium-grained sandstones interbedded with reddish-brown and greyish-green clay-shale bands and mudstones near Ukhaldhunga (Tandon, 1976; Karunakaran and Ranga Rao, 1979). Between Parewa and Patkot, the Middle Siwaliks are exposed and are composed of variably indurated sandstones interbedded with alternating pepper and salt appearance sandstone with dark grey to black mudstone, and are not observed east of the Kosi River (Tandon, 1976).

The NW-SE trending MBT is a major structural unit of the study area. Geomorphologically the study area is divided into three distinct geomorphic units (Fig. 1). It comprises of the Gangetic Plain in the south, the moderate hills of the Lesser Himalaya in the north and the low-lying hills of the Siwalik range in between. The low-lying hills of the Siwalaik range are highly dissected by high density of drainage of dendritic pattern; and are separated from the Gangetic Plain by the Himalayan Frontal Thrust (HFT). Structural control on drainages is shown by the Kosi River at two sections, one at Ukhaldhunga and the other at Chaunphula Chaur.

4. EVOLUTION OF LANDFORMS

Evolution and morphology of landforms are studied with reference to tectonically induced landforms; landforms of fluvial

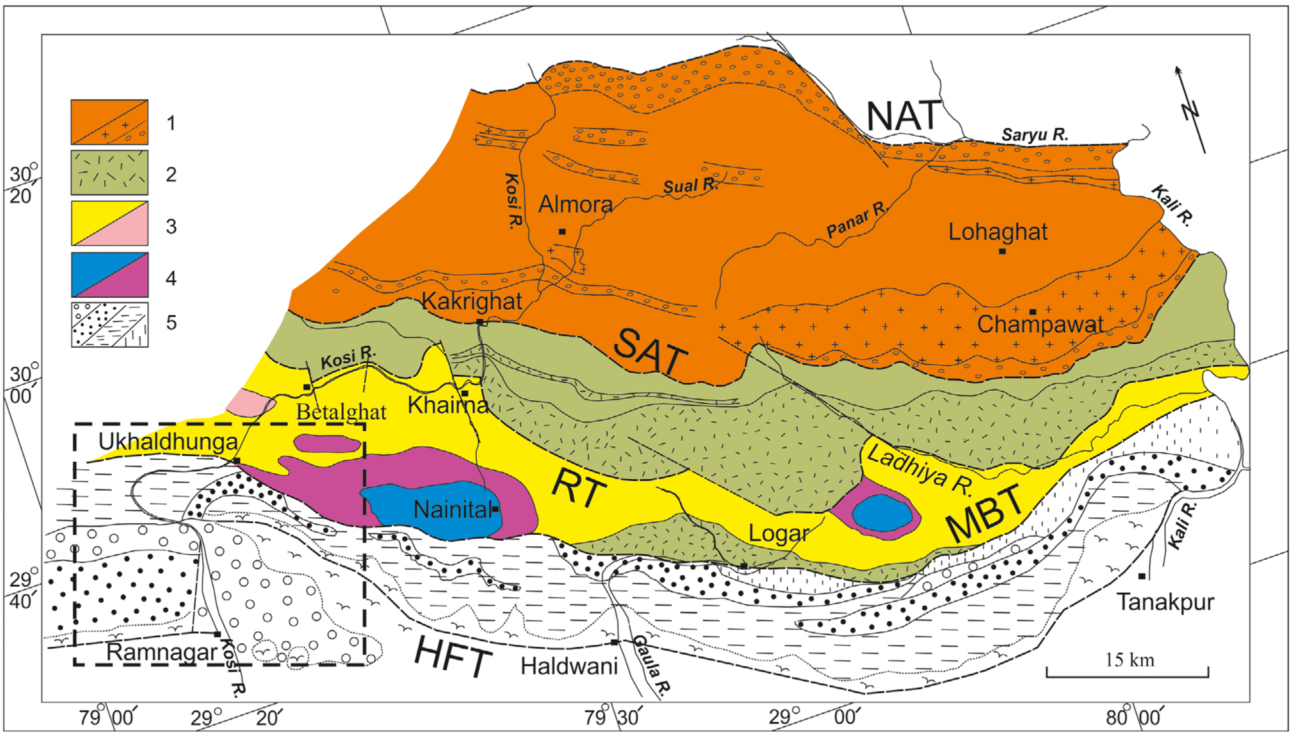

Fig. 2. Geological map of the Lesser Himalaya (Valdiya, 1980) and sub-Himalaya (Karunakaran and Ranga Rao, 1979). Inset box is present study area. (1. Almora Group, 2. Ramgarh Group, 3. Jaunsar Group, 4. Mussoorie Group, and 5. Siwalik Group). NAT – North Almora Thrust; SAT – South Almora Thrust; RT – Ramgarh Thrust; MBT – Main Boundary Thrust; HFT – Himalayan Frontal Thrust.

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genesis and landforms formed by mass movement/landslide. Lineaments analysis has also been carried out which may be a result of large tectonic fabrics, lithological control such as bedding or erosional features. The evolved morphology of landforms is discussed in detail based on the field evidences and analysis of Google Earth Images. Landform evolution has been grouped into endogenic and exogenic processes; exogenic includes surface processes such landslides and fluvial while endogenic pertains to tectonically induced landforms.

4.1. Landslides

Landslide is one of the major modifying agents of landforms in the present area. They are both old and active landslides, which are taking place in the basal part of the hanging wall block of the MBT (Fig. 3). A total of 11 landslides, both active and dormant landslides, have been considered. Settlements in Bakule, Dabara, Bawas and Dauna villages are nestled in old landslide debris. The bedrocks are highly sheared with multiple joint sets that form wedges and are favourable to mass movement (Fig. 3). In Parewa-Dauna area, the erosion by Kamchiya Sot has exposed more than 60 m thick section of landslide debris. From the exposed landslide debris, a minimum of two phases of major landslides activities are observed. The older landslides occurred in the older country rocks of quartzite of the Lesser Himalaya and the younger rocks of the Siwalik terrain. At site No. 1 the rocks are traversed by four prominent joints (J1, J2, J3 and J4) that form wedges towards the open/daylight hill slope (Fig. 4a). The type of landslide observed is rockfalls and the detached masses have travelled a distance of about 2 km from the crown of the landslide (Figs. 3c–e). The later phase of landslide occurred in the Siwalik bedrocks as the landslide debris composed of black shales and sandstones of the Siwalik Group; this debris has travelled lesser distance than the earlier landslide and overlies the earlier landslide generated debris with contrasting difference in debris composition. The second landslide (Site No. 2) is approximately 1.5 km from the MBT zone where small scale rock fall activity is observed intermittently (Figs. 3f and 4b). Here the bedrock comprising of quartzite of the Nagthat Formation is traversed by four prominent joint sets, the bedding plane is also an important fracture plane or a prominent discontinuity. The joint sets and the bedding planes form wedges on the daylight hill slope. The highly jointed sets of the fracture plane with steep slopes are the main causes of rock falls. The third investigated site (Site No. 3) is 0.5 km upstream from site No. 2, here also the type of landslide is rockfalls (Fig. 8c). A total length about of 0.5 km of the road section is affected by the rockfalls, which are taking place intermittently. In this section, the valley slopes of the Kosi River are steep, the wedges formed by intersecting joints have facilitated the detached boulders and rock fragments to fall under gravity. The bedrock is cut across by two fracture planes forming a wedge on the day light slope; one of the fracture plane is the bedding-parallel foliation S_1. At Site No. 4, the intermittent rockfalls are taking place along a triangular facet where the slopes are very steep. Here the intersecting fracture planes fall in SW quadrant, and form prominent wedges (Fig. 4d). The bedding related fabrics is not important as they form wedges towards the shadow zone. At Site No. 5, two data have been collected from either side of the affected area (Fig. 4e). On the southern end in the daylight zone, the intersecting joint sets have formed prominent wedges in the NW and SW quadrants while on the northern end two prominent joint sets have formed wedges on the daylight side in the western side. Site Nos. 6 and 7 represent opposite valleys where the valley slopes is mainly towards east. The landslides are taking place along the same stretched of motorable road section where a small stretched in between is not affected by landslides. Site No. 6 has affected road section of about 300 m; the multiple join sets have formed wedges on the daylight slope (Fig. 4f). The country rock, making the slope, is phyllitic quartzite of the Chandpur Formation. Site No. 7 represents the severest landslides that have affected the road section between Betalghat and Dabara; the type of landslides taking place is rockfalls (Figs. 4a, b, and g). The intersecting joint sets have formed wedges on the daylight slope and the joints are closely spaced rendering the slope very weak. Landslide in Site No. 8 is taking place in country rocks composed of alternation of phyllite, quartzite and slate sequence (Fig. 4h). This landslide is recent and active (Figs. 3g and h), which is generating volumes of debris and forms fresh debris fan near Dabara village where fresh material is being deposited every monsoon by the Gaunchil gadhera. Multiple wedges are formed by intersecting joint set on the daylight slope rendering the slope very susceptible to landslide, which is of complex type. The joints are grouped into two with J1 and J2 forming the first group while J3, J4 and J5 forming the second group; both the groups intersect with each other forming a wedge in the SE quadrant.

Dabara and Bakule villages are situated on old landslide debris, where the paleolandslide generated a large volume of material thereby forming a huge fan deposit. The debris fan has been incised by the Gaunchil gadhera and Kosi River where about 15 m high escarpment is observed. The landslide debris is made up mainly of clasts of phyllitic rocks. The landslide was a result of a continuous process as evident from the presence of layered sediments. The layered sediments, as evident from eroded section of fan, are tilted toward the hill slope. Bawa village is also settled on the cone of paleolandslides. The detached rock masses were laid down by Gharani gad that is a small seasonal tributary of the Kosi River. The thickness of the landslide debris suggests the

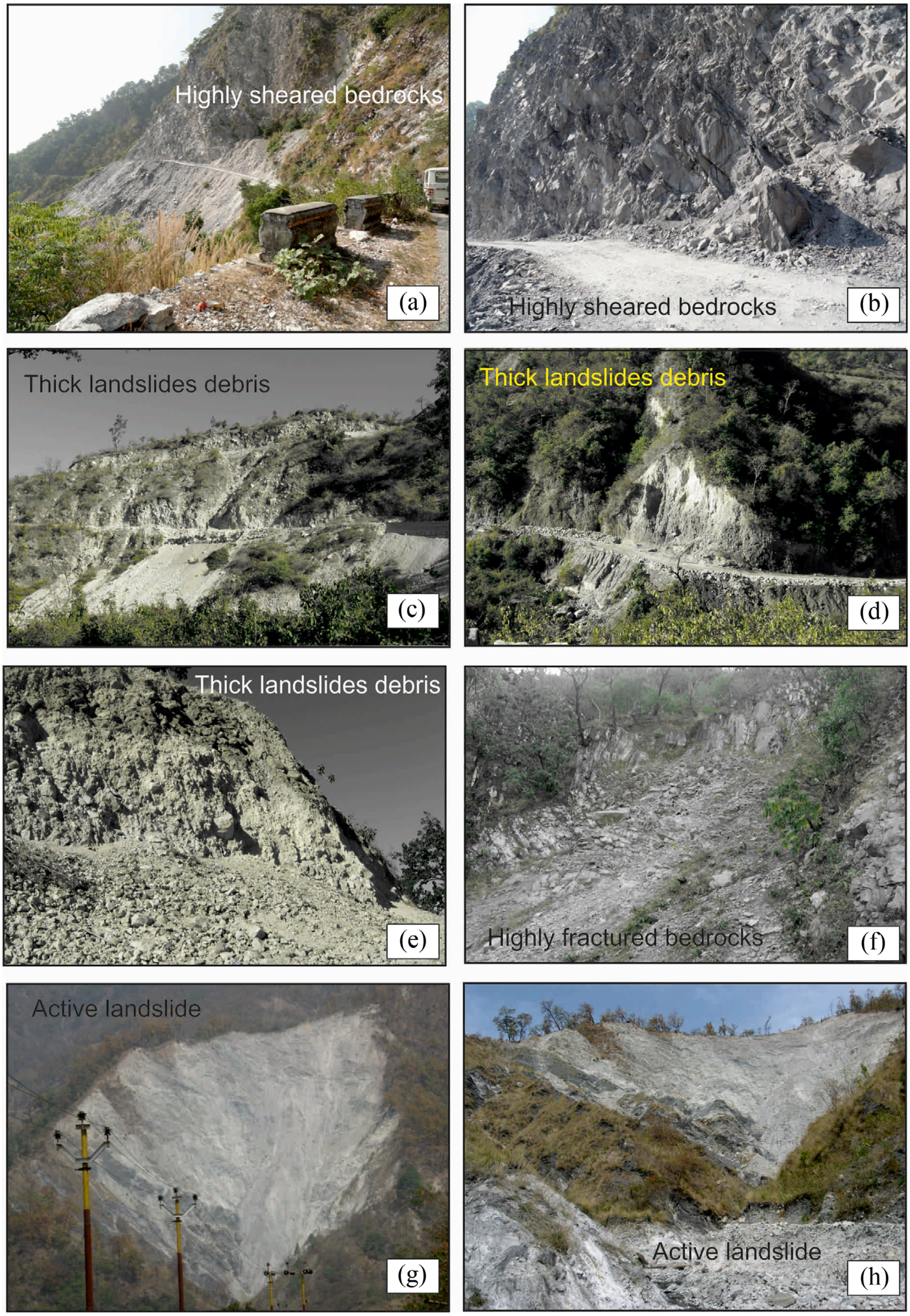

Fig. 3. Landslides and related landforms in Ukhadhunga area of the Kosi River valley. (a) and (b) Road constructed along highly shear bedrocks and active landslide. (c–e) Thick landslide debris observed along the narrow valley of Kamchiya Sot. (f) Highly fractured quartzite of the Jaunsar Group. (g and h) Photographs of active landslide in the immediate hanging wall block of the MBT at Dabara.

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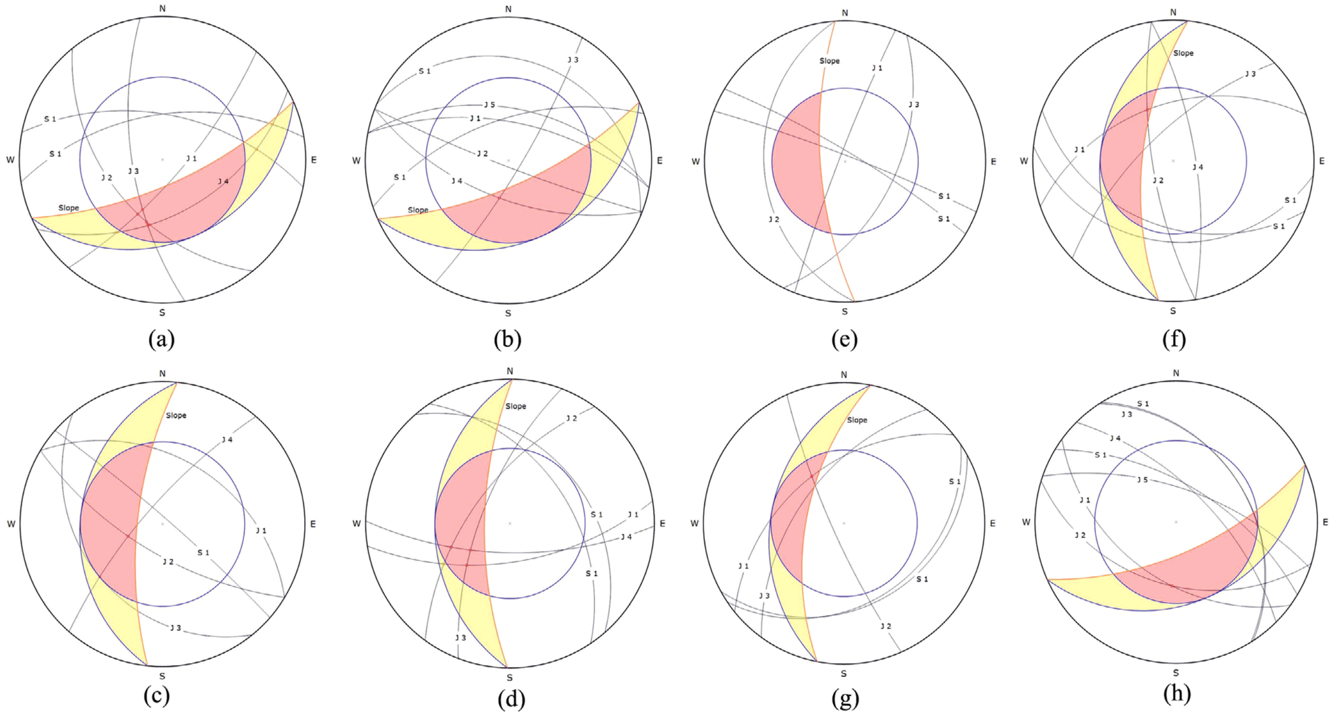

Fig. 4. Kinematic analysis of the several landslides that are occurring in the hanging wall block of the MBT in the Kosi River valley of Ukhaldhunga area.

presence of temporally damming of the Kosi River during the recent past. The clasts making up the debris fan is mainly of quartzite and the thickness of the fan measures about 100 m. Parewa-Dauna section in the MBT zone is one of the most affected sections by occurrence of landslides though at present the hill slopes are relatively inactive. Both the slopes in the hanging wall and foot wall blocks have been affected by landslides, as thick columns of debris fans are observed. Exposed sections and levels of debris fans suggest multiple phases of landslide events.

4.2. Fluvial Landforms

4.2.1. Fill terraces

Fluvial geomorphology is the study of the form and function of streams and the interaction between streams and the landscape around them (Adams, 1980; Schumm, 1986; Saucier, 1987; Bull, 1991; Deffontaines and Chorowicz, 1991). River is one of the best recorders of active tectonic movements (Keller and Pinter, 1996). A stretch of about 15 km in length has been considered for analysing the valley floor geomorphology for the present study. Seti Talla is the upstream extremity of the Kosi River where four levels of unpaired filled terraces are observed, which are T_4 at 697 m asl; T_3 at 682 m asl; T_2 at 667 m asl and T_1 at 658 m asl (Fig. 5a). Exposed section of T_3 is characterized by presence of upward fining sequence, where the base is made up of rounded to angular clast of the Lesser Himalayan rocks, followed upward by coarse sand and silt. The terraces are of small in extent as compared with other sites. Seven levels of unpaired terraces are observed at Ukhaldhunga, some are well developed while some occur in patches as a result of erosional activities (Figs. 5b, c, and 6). The highest level of terrace (T_7) is developed at 640 m asl and the most widely developed in terms of area. This is a paired terrace that is observed at three sites situated along both sides of the Kosi River at Ukhaldhunga. Type of this terrace is compound terrace because it is formed by fluvial deposit as well as landslide deposit. T_6 is developed at 620 m asl, T_5 at 618 m asl, T_4 at 604 m asl, T_3 at 600 m asl, T_2 at 590 m asl, T_1 at 588 m asl and T_0 at 586 m asl. Older terraces T_7–T_3 are composed of very angular to well-rounded pebbles and boulders. In the northern part of Ukhaldhunga village, T_2 is a strath terrace where the bed rock of phyllite is overlain by 2 to 3 m thick stratified fluvial deposit. T_1 is composed mainly of clasts of quartzite, phyllite and shale. It is exposed mainly along the southern extremity of the village along a small stream. The youngest terrace is made up mainly of coarse- to medium-grained sand. At Dabara village, one level of terrace is observed, which is made up of both reworked fan and river deposit. Its best section is observed along gully erosion where the sediments are laminated and composed of angular to sub rounded class in a matrix of coarse sand. In the immediate downstream of the MBT at Kunkhet, only one level of terrace is developed at 540 m asl while the present active river bed is at 536 m asl.

Fig. 5. Field photographs of aggradational and erosional landforms in Seti Talla-Ukhadhunga area where high number of terraces is observed. Paleochannels and strath terraces are evidences of fluvial channels adjusting to tectonic activity in the MBT zone.

4.2.2. Strath terraces and paleochannels

Strath terraces are observed at different areas and at different heights. In some cases these terraces represent the paleochannels. At Basela, strath terrace is observed at 641 m asl, the river borne sediments of more than 25 m thick are deposited on highly fractured quartzite bedrocks of the Nagthat Formation (Fig. 5d). Paleochannel of the Kosi River is observed in this terrace. In the northeastern part of Ukhaldhunga, a single paleochannel of the Kosi River is observed, which in the field is represented by a hanging valley. The width of the paleochannel is about 180 m and there is no alluvium cover on the bedrock. Towards the southwestern end of Ukhaldhunga village, different stages of migration of the Kosi River are evident from presence of different levels of the paleochannels at T_7 (Figs. 5e and 6). A 35 m wide paleochannel has incised the T_2 and a strath terrace. In the field, this 3 m thick strath terrace is made up of phylitic rocks, and is overlain by thin veneer of fluvial sediments. Towards the western site of Ukhaldhunga in the immediate footwall block of the

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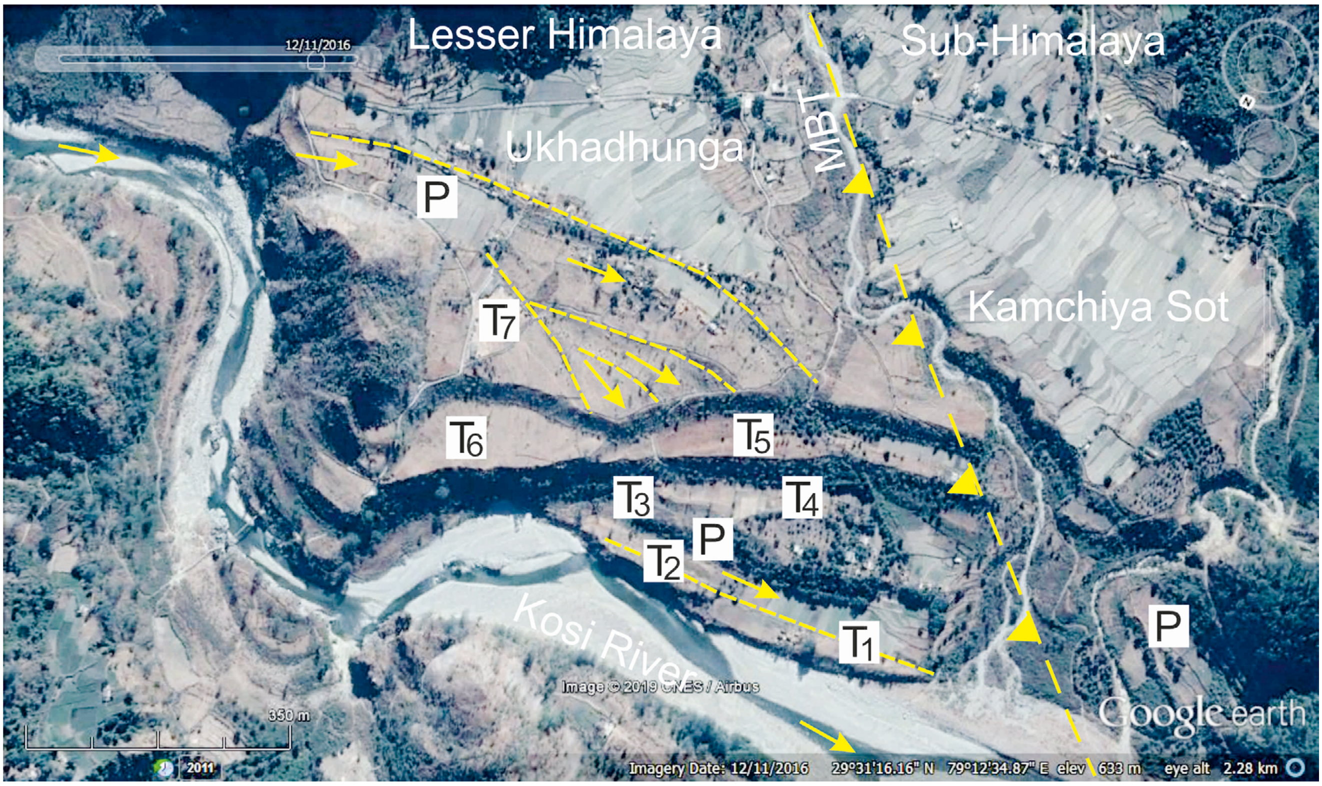

Fig. 6. Google Earth Image showing various levels of terraces, strath terraces and paleochannels in Ukhaldhunga area of the Kosi River valley (In the figure, P stands for paleochannels).

MBT, a 2–3-m high strath terrace made up of highly indurated sandstones of the Siwalik (Fig. 5f). Here the NW-SE striking bedrock of the Siwalik is almost vertical.

4.3. Tectonic Landforms

Active fault trace of the MBT is observed in the Google Earth Image between Dhauli gadhera and Bhakrakot gad. The NW-SE trending active normal fault trace measures about 8 km in length (Fig. 7). In this segment the hanging wall block has moved downward with respect to the footwall block of the MBT. The faulting activity postdates the deposition of landslide debris fan at Bhakrakot; as Bhakrakot is nestled on old landslide debris. Landforms related to the normal faulting along the MBT, form a characteristic nature of valley developed in the Baurar gadhera, a tributary of the Kosi River. In the hanging wall block of the Baurar gadhera the valley is wide about 450 m while in the immediate footwall block the valley is a few metres wide only. The Kosi River also shows similar feature in the MBT zone, in the basal part of the hanging wall block of the MBT, the Kosi River valley is very about 800 m wide while in the immediate footwall block it is about 80 m wide (Figs. 8a and b). In Parewa-Patkot stretch of the MBT, it is represented by a depression where pre-Siwaliks have a prominent tectonic contact with the landslide debris (Fig. 8c). The bedrocks in the MBT zone are very steep to vertical dipping and are highly sheared (Figs. 8d and e). At the southern end of Ukhaldhunga uplift, some paleochannels are observed in the form of valley fill deposits. While in the adjacent area, Luirei et al. (2020) have observed the Lesser Himalayan rocks thrust over the landslide debris along the MBT along Patkot-Amgari section indicating recent tectonic activity associated with the MBT. Multiple phases of debris fan deposits in the hanging wall block of the MBT are also observed, where three phases are clearly discernible in the field between Dabara and Ukhaldhunga (Fig. 8f). A sharp scarp separates the older fan surfaces and the youngest surface, and the scarp trends almost E-W parallel to the trend of the MBT and Kosi River.

4.4. Lineaments

In the study area a total of 4563 lineaments were delineated (Fig. 9a). The population of lineaments deduced from the rose diagram is seen to occupy four dominant sets of trends, viz. NNW/SSE, NW/SE, NNE/SSW and NE/SW directions that correspond to the tectonic activities associated with the NW-SE trending MBT and its conjugate transverse fault settings (Fig. 9b). In addition to this, the other major trends of lineaments can be

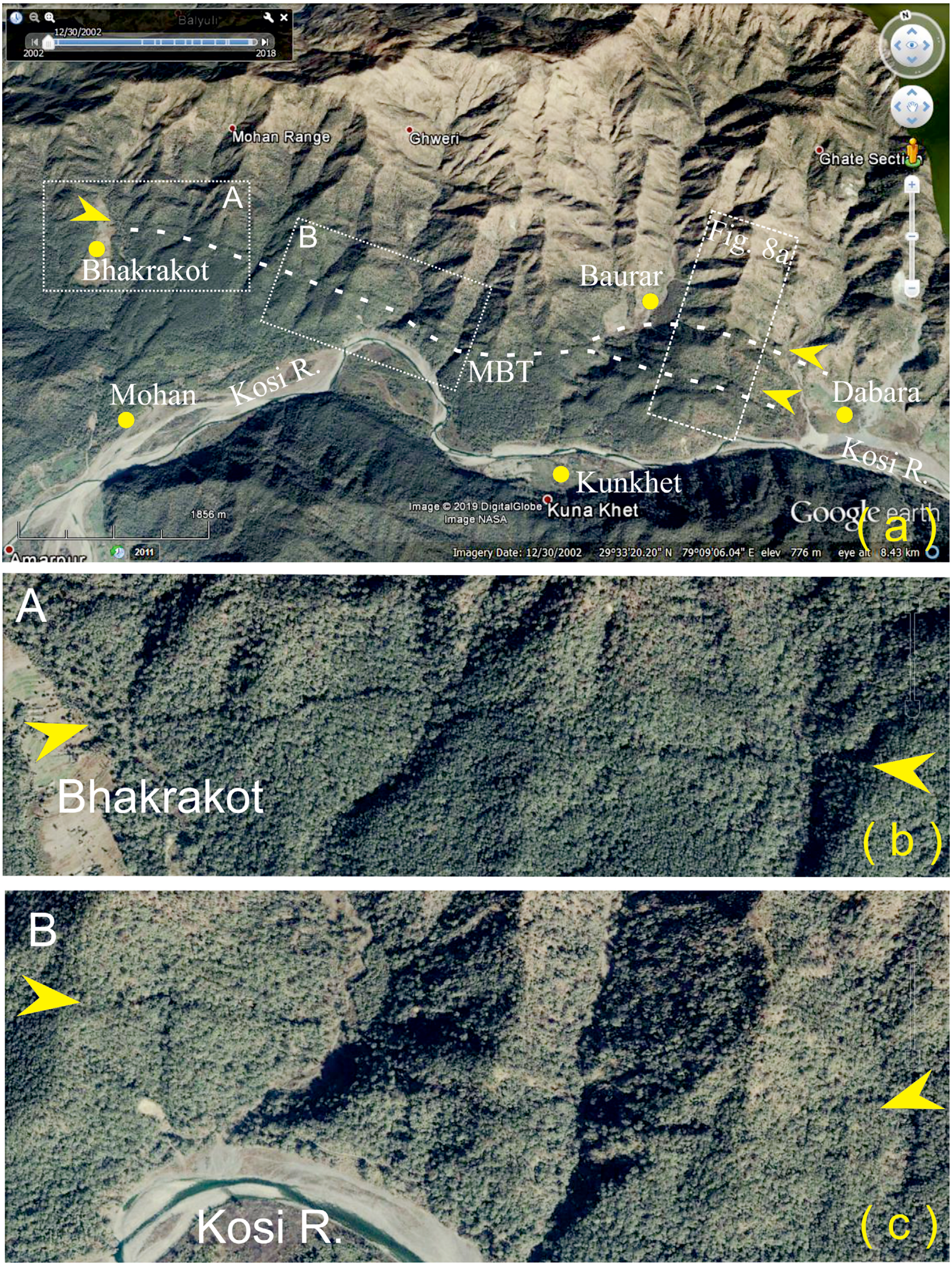

Fig. 7. Google Earth Image showing active fault trace along the MBT between Dabara and Bhakrakot. (a) and (b) are the enlarge portions of the active fault trace. Location of Figure 8a is marked by dash box.

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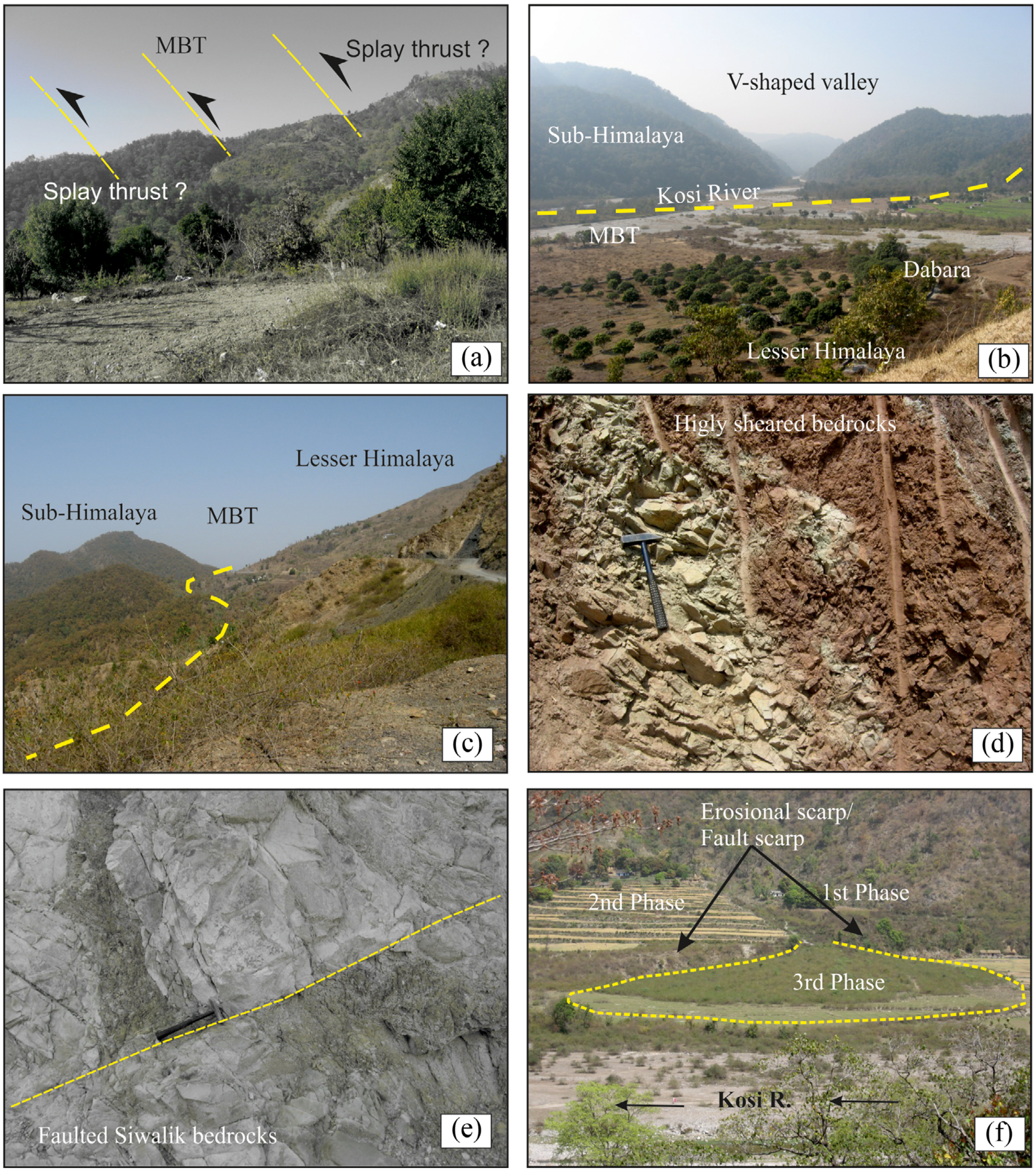

Fig. 8. (a–c) Various landforms associated with tectonic activity of the MBT. (d and e) Highly sheared and faulted bedrocks are observed in the MBT zone. (f) Multiple phases of debris fan deposited in the MBT zone, with sharp erosional/fault scarp separating the youngest from the older fan deposits.

interpreted as NNE-SSW trending normal faults, NW-SE trending wrench faults and strike-slip faults (synthetic shears) and NE/SW as strike-slip faults (antithetic shear). This inference drawn is based on comparison with the geometric and kinematic data acquired from clay-model studies by Wilcox et al. (1973) and Sylvester et al. (1976). From the lineament map, most of the lineaments are transverse to the regional trend of major structure of the Himalayan fold-thrust belt. Of the total lineaments delineated 16% (733) are transverse, 61.61% (2812) are oblique, while 22.3 (1018) are parallel to the general trend of the Himalayan orogen. The highest concentration of lineaments is observed in the northern part of the map; while obviously a relatively less density is observed in Gangetic plain as well as in thick alluvium which overlain the bedrocks and are observed as Patkot fan and Chopra fan areas. In the Ross diagram 57.17% falls in NE-SW trend while the remaining in NW-SE trend.

5. DISCUSSION

The Himalayan mountain resulted from the collision between the Indian and the Asian continental plates, and as a result of progressive and continuous process of the convergence of the Indian plate towards the Himalaya led to the development of a variety of landforms depending on the time and spatial scales considered (Gansser, 1964; Valdiya, 1998; Fort, 2011). In the long term the tectonic process is the main mechanism in uplifting the rocks and exerts the main control on gross landform geometry, after which weathering processes take place and towards the end of cycle the medium and short terms climate parameters and fluvial incision control both the slope evolution and sedimentary fluxes out of the mountains (Fort, 2011). In this work, the role of tectonics and surfacial agents such as fluvial and landslides have been discussed. The geodynamic conditions and the steep slopes of the tectonically active Himalaya have made the slopes vulnerable to landslides. Numerous small and large scales landslides are common surfacial phenomena in the Lesser and Higher Himalaya (Valdiya, 1987; Hagesawa et al., 2009). There are two extremely vulnerable landslide prone zones in the Himalaya, viz. the Main Central Thrust and the MBT zones. Valdiya (1985) suggested that these zones are made up of weak rocks and are defined by 5 to 20 km wide belt in the Kumaun Himalaya that is marked by presence of aprons of gigantic fans and landslide debris; whereas the situation in the MBT is more severe. The present study area is from the MBT zone where numerous old and active landslides are observed. Very thick landslides debris are observed in the hanging wall block of the MBT and the thickest debris are along the Kamchiya Sot. The thickness measures > 60 m, and along the road cut section two phases of landslides are clearly discernable on the basis of the different morphology of stratification of clasts of the landslide debris, otherwise different phases of landslides are difficult to differentiate. Maximum number of landslides are observed to be taking place in the hanging wall block of the MBT; while in the footwall block a fewer landslides are observed. This observation is similar to what Valdiya (1985) reported that the hanging wall block of the MBT is the zone of severe mass movement and erosion while the footwall block as zone of moderate erosion and landsliding. In the present observation the hanging wall bedrocks are highly fractured with multiple joint sets in quartzite and phyllite; while the footwall block is made up of highly indurated sandstone of the Lower Siwalik that is less deformed. Most of the landslide activities are the result of closely spaced joints that are formed during the successive movement along the faults. The intersection joints and joint sets form wedges which further weakened the slope making materials. Out of the eight landslides that have been kinematically analysed, seven landslides are of wedge failure in nature while one of them occurred due to toppling failure (Fig. 4).

We have examined landforms through detail field investigations and by analysing satellite images. It is found that some anomalies suggest tectonic activity in the recent past. An active fault trace along the MBT of about 8-km-long is observed. This fault trace is an indication of recent activity as the surface processes has not obliterated the surface trace of the fault. Similar observations are also reported from other segments of the MBT (Valdiya, 1992; Luirei et al., 2012; Bhakuni and Luirei, 2016). In the Kosi River valley, Bhakuni and Luirei (2016) are of the view that the deformation related to N-S extensional tectonics has taken place at the uppermost crustal level as a result of gravity, where influence of the Himalayan subsurface compressional tectonics is no more significant. Detail kinematics cannot be ascertained due to presence of huge vegetation and lack of fresh exposures. The authors are of the view that the fault traces are formed due to extensional tectonics, which resulted in moving downward of the hanging wall block of the MBT. In the present study one fault trace is like a linear depression which points towards normal faulting. Apart from the fault trace, other surface geomorphology associated with the active fault is the nature of the valley in the hanging wall and footwall blocks of the faults recognized. In the hanging wall block the valley of the Baurar gadhera is wider than in the footwall block, which suggests that the hanging wall block has moved downward with respect to the footwall block as a result of extension tectonics. Similar wide and narrow valleys are also observed in the adjacent Kosi valley where there is vast difference in width of the valley in the hanging wall and footwall blocks of the MBT. The drainage pattern across the MBT trace also suggests the recent tectonic activities associated with the movement of rocks along the MBT. Strath terraces and paleochannels give evidences of fluvial geomorphology of the recent past that has been reshaped to the present landscape as a result of influence of active tectonics; or climate induced fluvial characteristics (Kothyari and Juyal, 2013; Luirei et al., 2015; Gao et al., 2016). Strath terraces and paleochannels also give the different tectonic phases that have taken place in the area. The high number of fluvial terraces at Ukhaldhunga village area is an example of complex system as both fill terraces and strath terraces are observed that resulted from tectonic and climatic influences, similar to those reported by Burbank and Anderson (2001). A part from surface evidences of the neotectonics, tilted surfaces of the Quaternary deposits such fans and terraces also lend a support on the recent tectonic activity in the area.

From lineament density map (Fig. 9), it is observed that the highest density of lineament attains a value of 31. These higher values of lineament density are located on the hanging wall and footwall blocks of the MBT. The high values trend to the MBT

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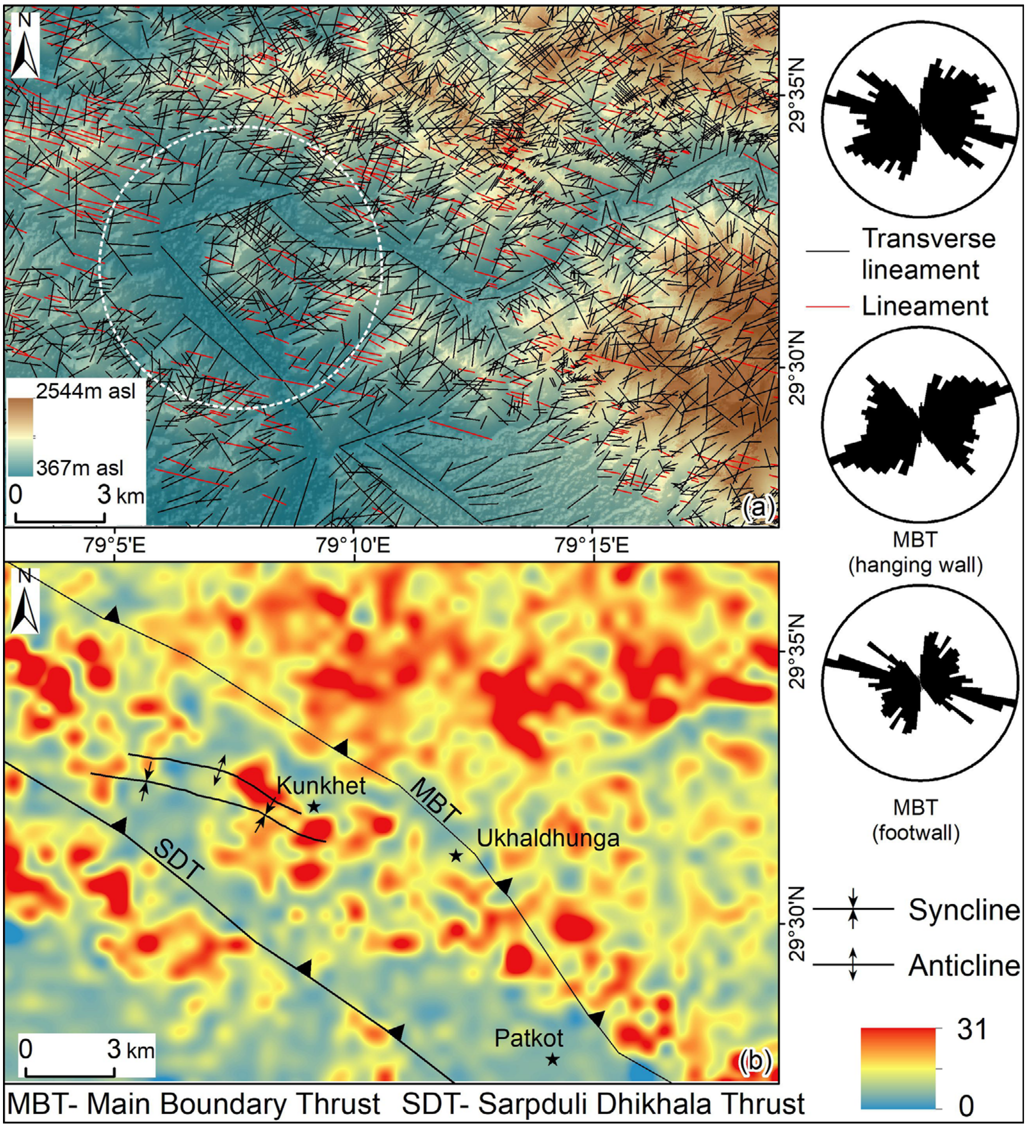

Fig. 9. (a) Lineament map of the sub-Himalaya and Lesser Himalaya of Ukhaldhunga area in the Kosi River valley. (b) Interpolation surface map of lineament density with three colour ramp corresponding to higher density values in order of blue, pale-yellow, and brown.

trend and their NNW-SSE trend suggest a swing as indicated by the rose diagram. On the hanging wall block, the dominant trend of lineament population is along NE-SW and NW-SE, indicating that their tectonic regime is controlled by the strike-slip faults (antithetic shear), wrench faults and strike-slip faults (synthetic shear) as described above. The lower values are located on the valley portion of the Kosi River and the southern sector of the study area where the underlying bedrocks are covered with the thick Quaternary alluvial sediments. These low values may be just a fraction of the total subsurface deformations that become undetectable due to the alluvial and recent sediment cover. However, their influence can be noted on the changing morphology of the Kosi River and its tributaries. On the western sector of the study area the Kosi River flows in NNW direction but it takes an abrupt U-turn towards SSE marked by circle (Fig. 9a). This changing morphology of the river may be attributed to the interactions between the NNW-SSE trending MBT and Sarpduli Dhikala Thrust and their associated transverse faults. The positioning of the anticline and syncline at the periphery of this location may also have facilitated the change in course of the river.

6. CONCLUSIONS

Based on geomorphic and morphometric investigations, the following conclusions can be drawn from the present study:

1. Landslide is also one of the main surface agents for the evolution of landforms in Ukhaldhunga area. Kinematic analyses

of a number of old and active landslides in the hanging wall block of the MBT suggest wedge failure as the main cause of landslides in quartzitic terrain. Field evidences suggest multiple phases of landslides; in some instance blocking of the Kosi River is also evident. Road constructions and toe erosion by the Kosi River are also contributing factors.

2. Active fault trace of about 8-km-long evident from Google Earth Image, suggests a relatively local extension tectonics taking place along the MBT. Morphology of fluvial valleys also supports this observation.

3. Different levels of strath terraces and paleochannels are indicative of neotectonics activities in the area. This also suggests importance of study of active tectonics as a factor influencing river morphology in areas undergoing active tectonics.

4. Maximum lineaments are oriented transverse to or at high angle to the regional trend of the Himalayan orogen; the transverse lineaments are the later developed faults/fractures that resulted from N-S compression related to the ongoing Himalayan tectonics. Structural influence on the Kosi River morphology is observed in the MBT and Sarpduli Dhikala Thrust.

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