

Quaternary extensional and compressional tectonics revealed from Quaternary landforms along Kosi River valley, outer Kumaun Lesser Himalaya, Uttarakhand

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Abstract A portion of the Kosi River in the outer Kumaun Lesser Himalaya is characterized by wide river course situated south of the Ramgarh Thrust, where huge thickness (~200 m) of the landslide deposits and two to three levels of unpaired fan terraces are present. Brittle normal faults, suggesting extensional tectonics, are recognized in the Quaternary deposits and bedrocks as further supported by surface morphology. Trending E–W, these faults measure from 3 to 5 km in length and are traced as discontinuous linear mini-horst and fault scarps (sackungen) exposed due to cutting across by streams. Active normal faults have displaced the coarsely laminated debris fan deposits at two sites located 550 m apart. At one of the sites, the faults look like book-shelf faulting with the maximum displacement of ~2 m and rotation of the Quaternary boulders along the fault plane is observed. At another site, the maximum displacement measures about 0.60 cm. Thick mud units deposited due to blocking of the streams by landslides are observed within and above the fan deposit. Landslide debris fans and terrace landforms are widely developed; the highest level of fan is observed ~1240 m above mean sea level. At some places, the reworking of the debris fans by streams is characterized by thick laminated sand body. Along the South Almora Thrust and Ramgarh Thrust zones, the valleys are narrow and V-shaped where Quaternary deposits are sparse due to relatively rapid uplift across these thrusts. Along the South Almora Thrust zone, three to four levels of fluvial terraces

are observed and have been incised by river exposing the bedrocks due to recent movement along the RT and SAT. Abandoned channel, tilted mud deposits, incised meandering, deep-cut V-shaped valleys and strath terraces indicate rapid uplift of the area. Thick mud sequences in the Quaternary columns indicate damming of streams. A ~10-km-long north–south trending transverse Garampani Fault has offset the Ramgarh Thrust producing tectonic landforms.

Keywords Fan deposits · Ramgarh Thrust · South Almora Thrust · Sackungen · Outer Kumaun Lesser Himalaya

Introduction

The Himalayan mountain arc is a result of intercontinental collision between Indian and Eurasian plates during 65–40 Ma ago (Molnar and Lyon-Caen 1988). The structures of the Himalayan range show a number of large south-verging thrusts emplaced successively from north to south (Le Fort 1975), indicating predominant compressional tectonics in the Himalaya. However, post-orogenic structures, e.g. normal faults, are well distributed in the Himalaya (Joshi and Hayashi 2010). Secondly, out-of-sequence thrusting (Mukherjee et al. 2012; Mukherjee 2015) and back thrusts (Mukherjee 2013) are also present in the Himalayan orogen. It is believed that two categories of normal faults are developed in the Himalaya, viz. (a) E–W trending normal fault north of the Main Central Thrust (MCT) developed during Miocene, and (b) relatively active and young normal faults present south of the MCT (Nakata 1989; Mugnier et al. 1994). The younger normal sense of faulting in the Himalayan region could be due to either localized extension of footwall blocks of pre-existing

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thrusts (Searle et al. 1988, 2008) or local adjustment of tectonics regime due to the taper angle readjustment of the Himalayan décollement (Joshi and Hayashi 2010). Normal faults are reported from various mountainous regions of the world, from the high plateaus of the Andes, Basin and Range provinces, western Apennines, Pamir, Central Himalaya and Tibet (England and Molnar 1993, and references therein). In the Himalaya, normal faults are reported from major thrust zones, from the MCT zone (Herren 1987), Panjal Thrust zone (Thakur et al. 1995) and Main Boundary Thrust (MBT) zone. The Kumaun Lesser Himalaya is the most strained part of the entire Himalayan range since the collision ~50–60 Ma ago of Indian and Eurasian plates (Molnar and Tapponnier 1975; Valdiya 1998, 2001a, b). It shows intercontinental faults and rejuvenated topography (Valdiya 1993, 2005). A number of NNW–SSE trending right lateral tear faults have been recognized (Middlemiss 1890a, b; Gansser 1964; Valdiya 1976, 1988b) in the Kumaun Himalaya. The Himalaya is cut across by an extensively active fault system that extends from the Karakoram Fault to the Bengal Plain producing landforms pertaining to active faults (Nakata et al. 1984; Nakata and Kumahara 2002). The neotectonic movements concentrated

mostly not just along the MBT and the Himalayan Frontal Thrust (HFT), but also in the hinterland region of the Himalaya, e.g. along the South Almora Thrust (SAT), North Almora Thrust (NAT) and transverse fault zones (Nakata 1982; Valdiya 1993, 2003; Valdiya and Kotlia 2001; Thakur 2004; Pant et al. 2007; Mehta and Sanwal 2011; Paul et al. 2010; Kothiyari 2014). In the Lesser Himalayan domain of Uttarakhand, the tear faults and fracture zones are oriented predominantly NW/NNW–SE/SSE (Valdiya 1976). Along these faults, the streams and rivers have carved wide and straight valleys (Valdiya and Kotlia 2001). In the adjoining Ramganga Basin, Goswami and Pant (2008) described the neotectonic activity along the SAT and Bhikiyasain Fault and their direct influence on the morphology of landscape. The development of river valleys is intrinsically related to the response to the nature and response to the fault movement, arrangement of the fault and fracture and the relative resistance of different rock types and to climatically influenced hydrologic parameters (Burbank and Anderson 2001; Kothiyari and Juyal 2013). In the present study area of the outer Kumaun Lesser Himalaya, the geomorphic expressions of neotectonics are observed along the SAT, Garampani Fault (GF) and E–W trending system of

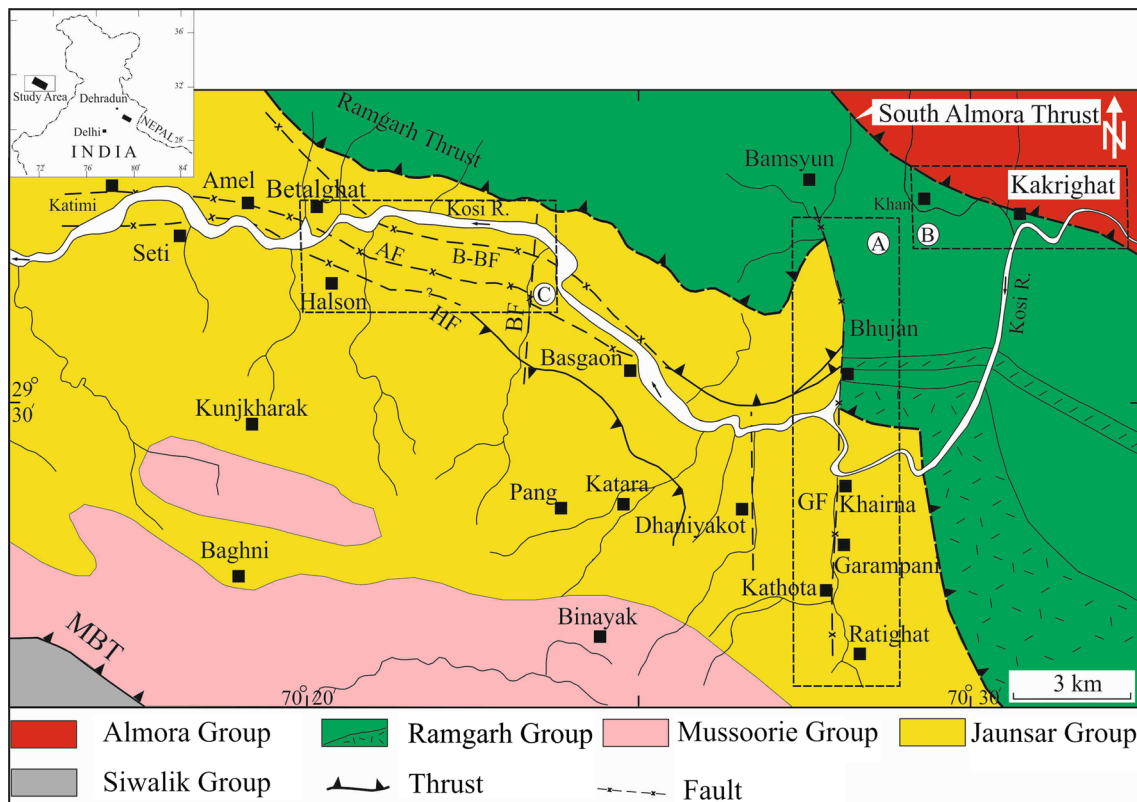


Fig. 1 Geological map of the study area (Valdiya 1980, 1988b). Insets A and B represent the sites of Figs. 7, 11, and inset C represents the sites of Figs. 6, 10. (B-BF Betalghat–Basgaon Fault; AF

Amel Fault; HF Halson Fault; BF Basgaon Fault; GF Garampani Fault.) Location of the study area marked by thick black rectangle in the inset map of India

normal faults, e.g. the Amel and Betalghat–Basgaon Faults (Fig. 1). The GF is an important transverse fault traceable through Ratighat and Garampani up to Bamsyu. Several unpaired fluvial terraces, displaced and dismembered colluvium deposits, series of landslide cones and fans reflect active tectonics and multiple phases of tectonic rejuvenation in the SAT and RT zones in Kosi River valley in the outer Kumaun Lesser Himalaya. Mehta and Sanwal (2011) have shown evidence of active tectonics along the Kosi River valley based on normal faulted Quaternary deposits. Valdiya (1988b) described mini-horst and mini-graben formed due to vertical movement along parallel to sub-parallel deep faults. The present study has been carried out along the SAT, RT, GF and the normal faults with an aim to present landforms associated with extensional and compressional tectonics along the same river valley (Valdiya 1988b). Surface expressions of extensional and compressional tectonics have been dealt in the Kosi River valley with Quaternary landforms and tectonic geomorphology as the main tools to assess the tectonic activity. Gad is a local term for stream.

Geology

The Lesser Himalayan region is divided into twofold divisions, (1) younger and older regions (Valdiya 1980; Srivastava and Gairola 1990; Srivastava and Mitra 1994; Ahmad et al. 2000; DeCelles et al. 2001; Richards et al. 2005; C  l  rier et al. 2009) and (2) inner and outer Lesser Himalayan sequences (Valdiya 1980; Ahmad et al. 2000). The investigated area of Betalghat–Kakrighat in the Kosi River valley forms a part of the outer Lesser Himalayan Sequence (Fig. 1). The Precambrian metamorphics and metasedimentaries of the Jaunsar, Ramgarh and Almora Groups constitute the bulk of the lithologies of the study area (Valdiya 1980) (Table 1). The Nagthat Formation of the Jaunsar Group is made up of a thick succession of early Proterozoic quartzarenite with subordinate greenish and purple slates and interbedded metabasic volcanics (Valdiya 1976) exposed between Khairna and Betalghat. The Ramgarh Group comprises of quartz-porphry and porphyritic granite suite occurring in a succession of phyllites, fine-grained quartz-wackes and metasilstone and carbonaceous pyritous slates alternating with banded white-blue marble (Valdiya 1980). The hanging wall of the Ramgarh Thrust is characterized fine-grained, chlorite- and biotite-rich schistose gneiss above which occurs alternating sequence of shale and turbidite (Ahmad et al. 2000; C  l  rier et al. 2009). The Saryu Formation of the Almora Group comprises of chlorite phyllonite, chlorite-sericite schist, which is locally garnetiferous and subordinate mylonitized micaceous quartzite interbeds. Table 1 presents the litho-tectonic succession of the region. Only Nagthat,

Table 1 Tectonic succession of the outer Kumaun Lesser Himalaya (Valdiya 1980)

		Gumalikhet Formation
Almora Nappe	Almora Group	Champawat Granitoid
		Saryu Formation
South Almora Thrust		
		Debguru Porphyroid
Ramgarh Nappe	Ramgarh Group	
		Nathuakhan Formation
Ramgarh Thrust		
		Tal Formation
	Mussoorie Group	Krol Formation
		Blaini Formation
Krol Nappe		
		Nagthat Formation
	Jaunsar Group	Chandpur Formation
		Mandhali Formation
Krol Thrust (Main Boundary Thrust)		

Blaini, Nathuakhan, Debguru Porphyroids and Saryu Formations are exposed in the present study area.

The SAT and RT run through the study area. The SAT separates the Almora Group of rocks from the Ramgarh Group striking E–W. The RT delimits the Ramgarh Group and metasedimentaries of the outer Lesser Himalaya. All these lithounits have been multiply deformed and characterized by three to four phases of deformation (Valdiya 1988a). The Almora Group of rocks in general dip 26°–46° towards NW to NE. The Ramgarh Group of rocks also dips in the same direction, while their dip amount varies between 22° and 56°. The base of the Ramgarh Thrust hanging wall is made up of mylonitized gneisses that contain recrystallized quartz grains indicative of Regime-3 quartz dislocation creep (C  l  rier et al. 2009). The SAT defines the plane of abrupt change in grade of metamorphism between the Ramgarh and Almora Groups of rocks: the Ramgarh Group is exhibited by greenschist facies, while the Almora Group is exhibited by almandine amphibolite facies (Valdiya 1980). Particularly along and near to the major thrust, the earlier tectonic fabrics have been obliterated and superimposed by later main prominent schistosity. The garnets of the Ramgarh Group are undeformed, while those of the Almora Group formed syntectonically exhibiting helicoidal pattern of inclusion indicative of rotation during growth of the crystals (Valdiya 1980). The rocks of the Nathuakhan Formation exhibit close to tight overturned folds. The area is traversed by one major strike-slip fault known as the GF. The strike-slip faults trend NNW–SSE with dextral sense of movements (Valdiya 1988b). The area is also traversed by a localized system of faults running parallel to the Ramgarh Thrust (Valdiya 1988b).

Quaternary landforms and deposits

Landslide debris fan

The wide valley of the Kosi River between Bhujan and Katimi is characterized by enormous thickness of landslide debris fan deposits. The dimension of these debris fan deposit varies place to place at Bhujan ~105 m high, 520 m wide and 1.20 km long; at Katimi 200 m high, 600 m wide and 2.2 km long; and at Rauligaon ~145 m high, 700 m wide and 1.8 km long. The sediments constituting the fans are mainly derived from north- and south-facing hill slopes. The thickness of the fans indicates that the sediments are generated by massive landslides. The fans are of multiple events as indicated by the distinct levels of debris fans. There are many fan surfaces, only the prominent fan surfaces have been dealt in the present study. The highest fan in the Ochakot area is observed at Rikhohli village and is termed as the Rikhohli Fan Terrace (RFT₁) (Fig. 2a). The highest debris fan surface is about 390 m high above the present active channel of the Kosi River. Present active channel is at 790 m a.s.l., while the RFT₄ is at 1200 m a.s.l. The RFT₃ is at an elevation of 1140 m a.s.l., and RFT₂ is at 1010 and RFT₁ at 880 m a.s.l. The fans are characterized by crudely bedded to well sorted sediments. The clasts constituting the fans are mainly angular to sub-rounded clasts of the Nagthat quartzite and subordinate clasts of slates and siltstone of the Infra-Krol in clast-supported matrix. Maximum thickness of the fan in the Ochakot area is exposed along Khairna–Betalgat road section where the thickness exceeds 120 m. In the mid-section at Simalkha area, two fan surfaces are observed, SFT₂ at 975 m and SFT₁ at 850 m elevation a.s.l. (Fig. 2b). The distal part of the fan has been eroded by the Kosi River and is exposed as an erosional scarp as illustrated in Fig. 2b (inset cross section). While at Dhaniyakot area, the highest fan (DFT₃) is observed at Pang–Katara, it is at an elevation of about 1240 m a.s.l., and the subsequent lower fans DFT₂ and DFT₁ are observed at 1145 and 995 m a.s.l., respectively (Fig. 2c). Debris fan sections exposed along Simrar Gadhera and Ghat Gad consist of clasts of quartzite and mafic rocks of the Bhimtal volcanics. At Halson, south of Betalgat, the debris fan is >200 m thick and the fan is best exposed along Ghiroli Nala. All the debris fans are incised by streams and have carved out wide stream valleys. Ghat Gad in particular has incised the fan in the form of deep V-shaped valley and runs almost straight ~3 km following an N–S trending lineament. The compositions of the fans are best exposed along road-cut sections (Fig. 3). Exposed sections of debris fans with intervening mud horizons suggest that the fan sediments were laid down by multiple landslides. The clasts making up the debris fans are of smaller dimension (<5 cm),

suggesting that the exposed section is of distal part to mid-fan. The south-facing slopes forming the northern valley of the Kosi River in comparison with the north-facing slopes have lesser amount of fan sediments. Halson village in particular is where huge thickness of debris fan in the south-facing slope is observed. The Betalgat and Dabarbari fans are formed by reworking of older landslide debris fans. Towards the upstream of the Kosi River valley from Bhujan, the river incised into the bedrock and ‘V’ shape narrow valley was developed. The valley between Khairna and Kakrighat is V shaped. The dimension and thickness of the fan deposits are of smaller dimension and constitute the top of aggradational landforms as observed at Naugaon and Khan. At Manarsa, the debris fan deposits are overlain by thick fluvio-lacustrine deposits. Landslide debris fans are also observed along Kuch Gad, which is overlain by thick mud sequence. Kuch Gad valley also exhibits several landslide debris cones. Section between Kakrighat and Khairna is characterized by lack of Quaternary deposits. Only at Chara and Lohali, much localized deposits of fans and terraces are observed.

Terraces

The terraces occupy the lower elevations of the valleys. Between Simalkha and Betalgat in the Kosi valley, three levels of fluvial terraces are observed. At Raula, the terraces developed are unpaired with three levels in the southern bank while one terrace in the northern bank. T₃ is at 795 m a.s.l., T₂ at 788 m a.s.l. and T₁ at 786 m a.s.l. Terrace T₃ is observed only in small patches, while T₂ and T₁ terraces occupy wide areas (Fig. 2a). At Simalkha, one level of terrace (T₁) is observed at an elevation of 840 m a.s.l. (Fig. 2b). At Naugaon, the fluvial deposits have developed five levels of unpaired river terraces and in a much localized area where the width of each terrace is very narrow (Fig. 4a, b). The width of each terrace from T₅ to T₁ is 205, 67, 128, 108 and 28 m, respectively. Terrace T₅ consists of pebbles and granules interbedded with silty matrix representing normal fluvial sedimentation, and the sediments are characterized by fan and terrace, suggesting reworking of the fan sediment by the Kosi River. Terraces T₄ and T₃ were deposited under tectonic quiescence as evident from granules interbedded with sandy and silty matrix showing graded bedding and fine laminations. The later terraces T₂ and T₁ are characterized by huge boulders and small to large rock fragments within sandy matrix. Down cutting by the Kosi River has exposed the bedrock (Fig. 4b). At Khan along Sarod Gad, four levels of fluvial terraces are observed, which is overlain by fan deposits (Fig. 4c). T₄ is at an elevation of 1064 m a.s.l. and is comprised of boulders and coarse- to fine-grained sands with upward fining sequence. The clasts are mainly

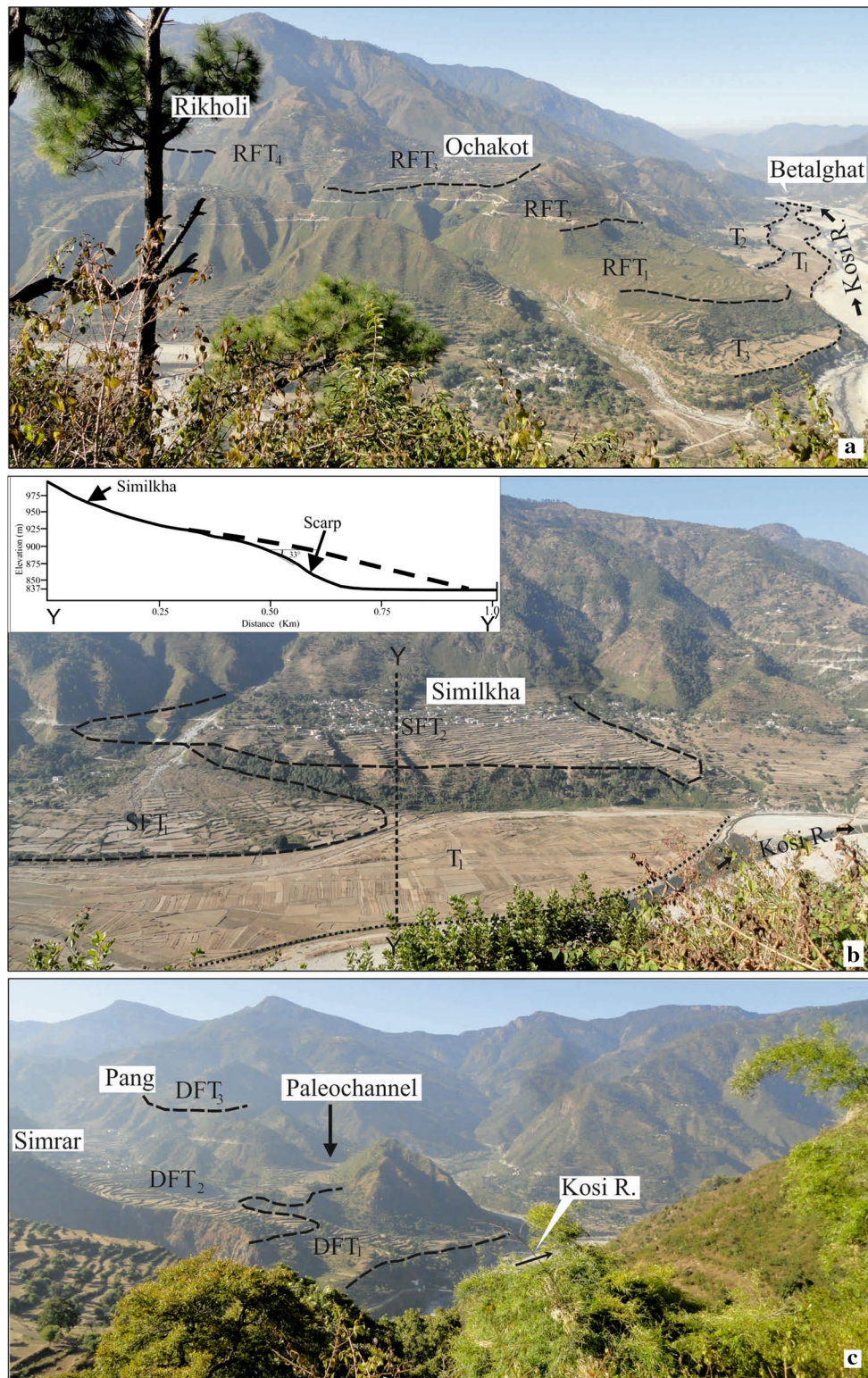


Fig. 2 a Very wide Kosi River valley between Betalghat and Ochakot characterized by huge thickness of Quaternary deposits (fans and terraces). b At Similkha, two levels of fans and one level of terrace are

observed (*inset* cross section y–y'—showing the erosional scarp). c At Pang–Simrar area, three well-developed fans are observed



Fig. 3 Sections of fan deposits exposed along roadside. **a–e** in Kosi River valley and **f** in Kuch Gad

of the Almora Group of rocks. Terraces T_3 , T_2 and T_1 are at elevations of 1055, 1047 and 1042 m a.s.l., respectively. The tread of the terrace has been obscured due to vegetation, and its composition remains indeterminate. The terraces at Majhera area near Bhajun, 98-m-thick fluvial sequence developed with five levels (Fig. 4d, e). The terrace T_5 is made up of clast-supported massive gravels, deposited due to pseudo-plastic debris flow of turbulent river flow. The terraces T_4 and T_2 are mostly made up of clast-supported gravels, suggesting plastic debris flow with high river velocity (River Kosi). Terraces T_3 and T_1 are mainly made up of matrix-supported gravels with pseudo-plastic debris flow of low-strength viscous material carried by the Kosi River. At Khairna, just at the confluence of the Kosi River and Khairna Gad, two levels of

terraces are observed on the left bank and another on the right bank. T_2 is a fan deposit reworked by streams as evident from the exposed section along the road. T_2 is at a height of about 20 m from the river bed and are composed mainly of sub-rounded, angular to very angular clasts of quartzites and volcanics.

Mud deposit

Temporary damming of streams or river is evident from huge thickness of mud sequences in between and topping the landslide debris fans in the valleys carved out by the tributaries of the Kosi River. At Manarsa near Kakrighat in Kosi River valley, about 12-m-thick mud deposit is observed overlying 4-m-thick fan deposit (Fig. 5a, b).

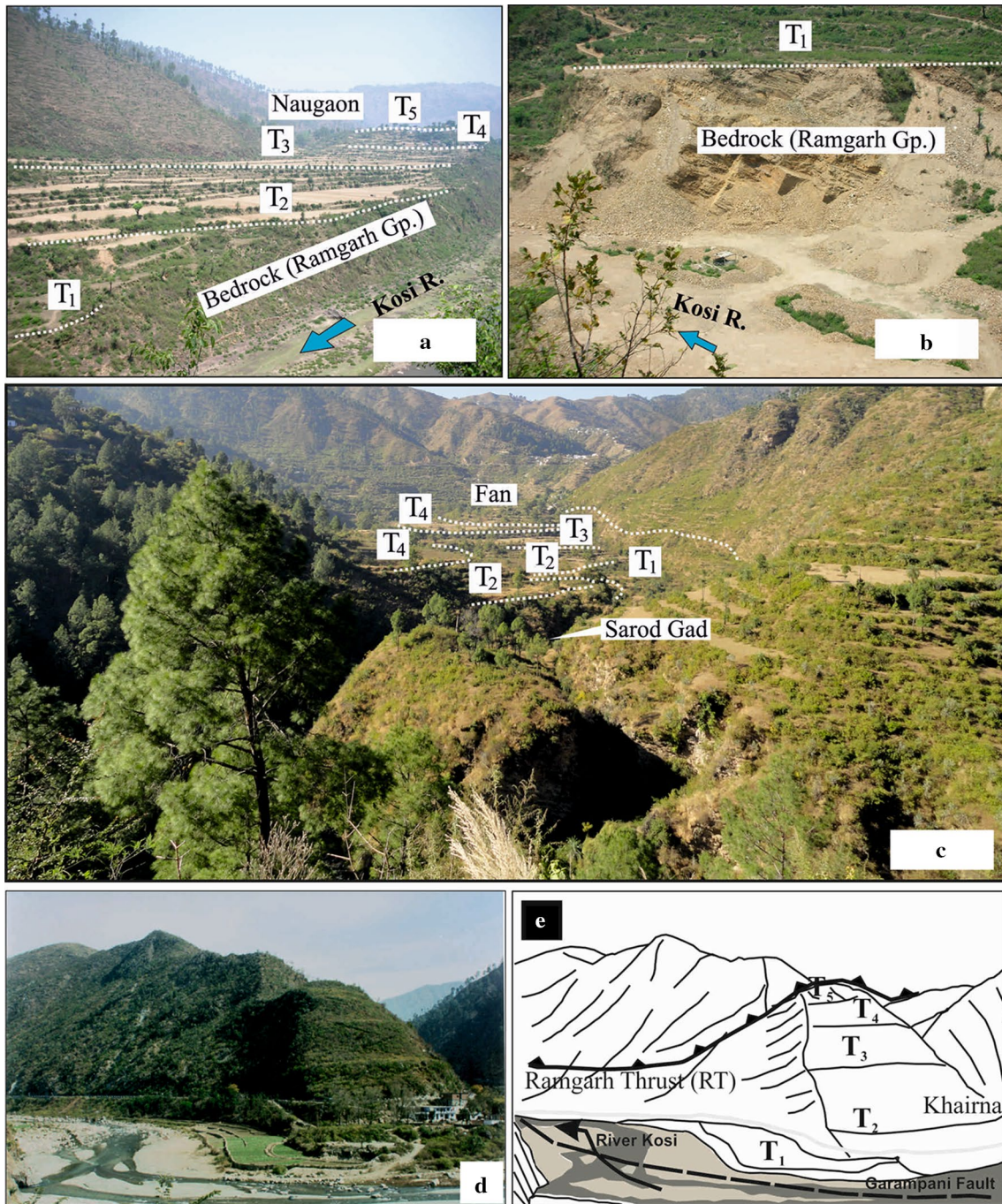


Fig. 4 **a, b** At Naugaon in the South Almora Thrust zone, five levels of fluvial terraces are observed deposited over the inclined Ramgarh Group of rocks. **c** At Khan along Sarod Gad (a tributary of Kosi River), four levels of terraces are observed, the highest level of ter-

race overlain by the debris fan. **d, e** Near the confluence of the Kosi River and Khairna Gad at Khairna, five levels of terraces are observed in the Ramgarh Thrust zone

The fan deposits making up the base for mud deposit are tilted by 30° towards N40E; the basal part of the mud deposit is also tilted by 10° towards N50E (Fig. 5c, d). The upper mud deposit looks undeformed as indicated by normal horizontal bedding of the mud sequence, which is

intervened by layers of rock fragments. Along Kuch Gad, about 12-m-thick alternating landslide and mud deposit are observed, and the bottom is characterized by landslide debris intervened by thick mud sequence and overlain in top by landslide deposits (Fig. 5e). At Ochakot, thick



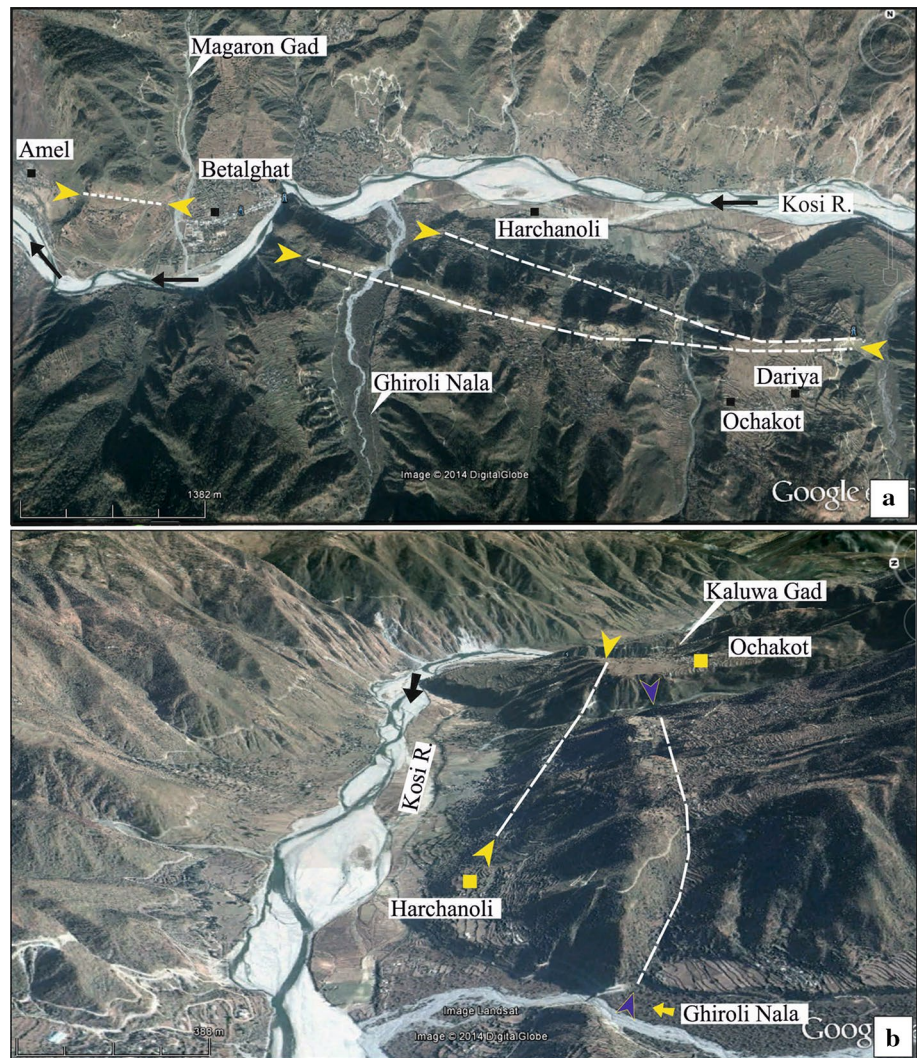
Fig. 5 **a, b** Mud deposits of about 12 m thick are observed in the South Almora Thrust zone at Manarsa in the Kosi valley near Kakrighat with intervening thin gravelly horizons. **c, d** The mud deposits are underlain by incline fan deposit dipping about 30°

towards NE which is overlain by tilted (10° towards NE) mud deposit. **e** Intervening mud layers in landslide debris fan along Kuch Gad. **f, g** Inclined mud deposits at Dariya and near Dhaniyakot

alternating sequence of mud and rock fragments comprised the top of fan deposits and the mud sequence measures about 5 m (Fig. 5f). The thickness of sediments is more than 100 m and is best exposed along Khairna–Betalgat road. The base of fan deposits is characterized by angular

to very angular clasts followed upwards by mud sequence, which is overlain by thick fan sequence and is again overlain by thick mud deposits. Near Katara, alternating silt and rock fragments are observed towards the top of the fan deposits (Fig. 5g).

Fig. 6 a, b Google images showing active fault traces of Betalghat–Basgaon Fault and Amel Fault



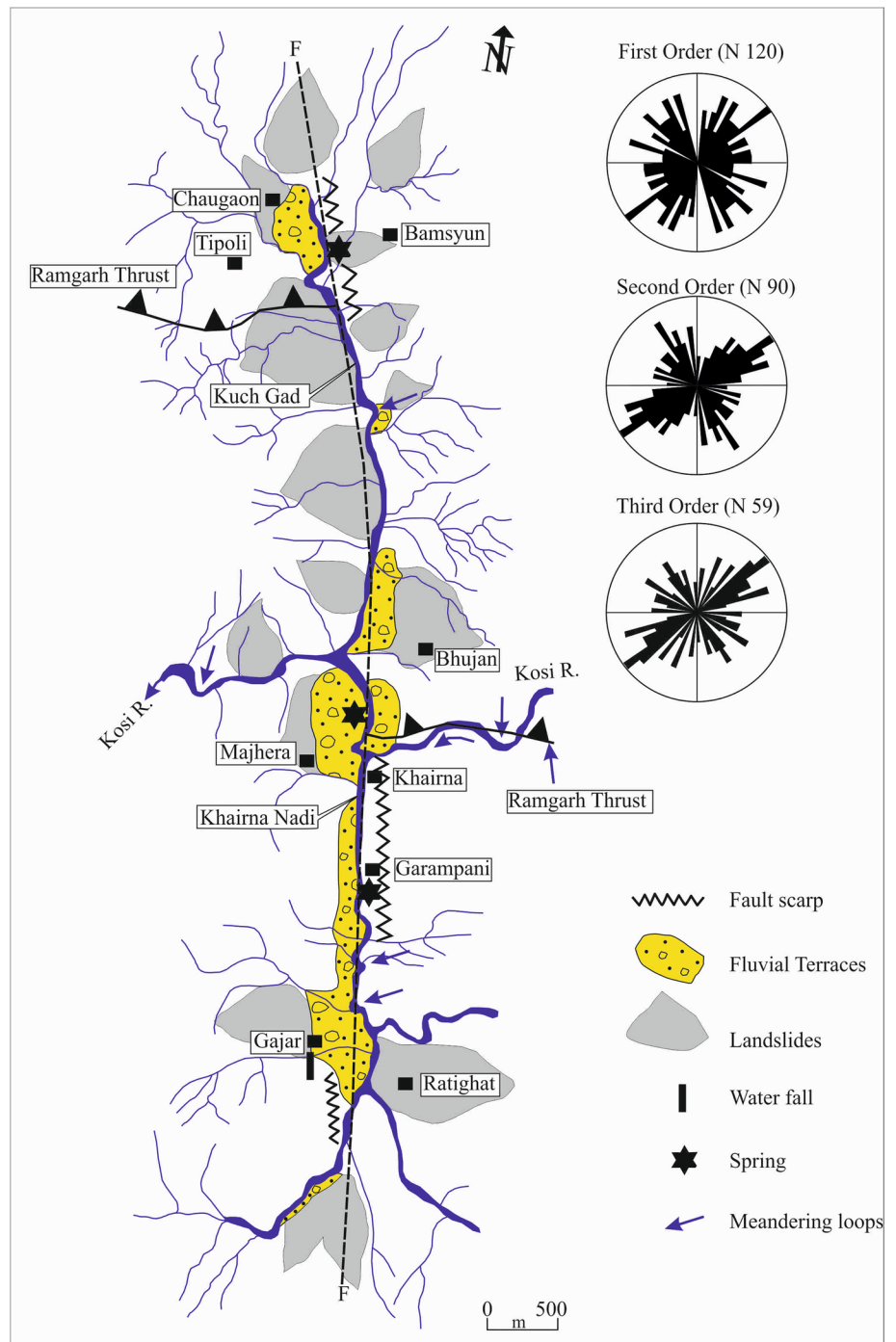
Faults

Betalghat–Basgaon Fault (B–BF) and Amel Fault (AF of Valdiya 1988a) are two normal faults observed in the Betalghat area. These two faults have surface traces of about 3 and 5 km, respectively, and trend E (Fig. 6). The bedrocks are traversed by a conjugate set of normal faults. One normal fault plane dips 43° towards NNW, while the other dips 42° towards SSW. Eastwards of Basgaon, these faults merged together as a single thrust and the rocks are highly sheared. The fault zone is ~ 10 m wide. Along the Amel Fault at Amel village, fault scarp measuring about 450 m in length is observed (Fig. 6). The GF is traceable through the Ratighat–Garampani–Khairna–Bamsyu area in the outer Lesser Himalayan domain of Uttarakhand and trend \sim NNW (Figs. 1, 7). The fault zone is marked by gravel-filled wide and straight course of Khairna Gad and Kuch Gad. This fault is a right lateral strike-slip that has displaced the Ramgarh Thrust and appears to be a

most crucial fault line (Valdiya 1988a, b). In this fault zone, brittle deformation has been observed. Fault breccia at Ratighat and offsetting of lithounits about 700 m are also observed between Khairna and Bhujan along the Kosi River valley. Strike-slip component is overprinted by dip-slip, which may suggest a rotational or strike-slip to dip-slip nature of the GF. Down-dip movement of 5–2 m has also been observed within the Garampani Fault zone. The east valley slope exhibits fault escarpment running parallel to the GF for about 3.5 km between Kathota and Khairna (Figs. 1, 7).

Drainage pattern developed along the GF has been studied to deduce the structural and lithologic control. The main streams of the present study area are Khairna, Kuch and Kosi Rivers, which show dendritic pattern. The drainage map shows that most of the streams, like first, second and third orders of the study by Strahler (1952), align in a prominent NNW–SSE direction having a close association with the GF (Fig. 7). The major river Kosi flows along

Fig. 7 Drainage and landforms observed along the NNW–SSE trending Garampani Fault



the SAT and RT, but has attained sudden shift in the fault zones. The river valleys, along the fault zones, are linear gravel-filled valleys; however, those that follow the thrust zones characterize deep-cut V-shaped valleys. Various abundant channels, entrenched meandering loops, waterfalls, etc., are other important geomorphic features (Fig. 7). Thus, the drainage map of the study area suggests that the drainage is tectonically controlled by a NW–SE trending lineament of the GF.

Evidence of Quaternary reactivation of faults

We inferred reactivation of faults from the faulted and tilted Quaternary deposits through detailed field observations. For the present study, reactivation of faults has been inferred from the faulted and tilted Quaternary deposits. Landslide debris fans and fault scarps are the most remarkable tectonic landforms as observed at Betalghat–Ochakot section. These deposits mainly comprise of debris of several

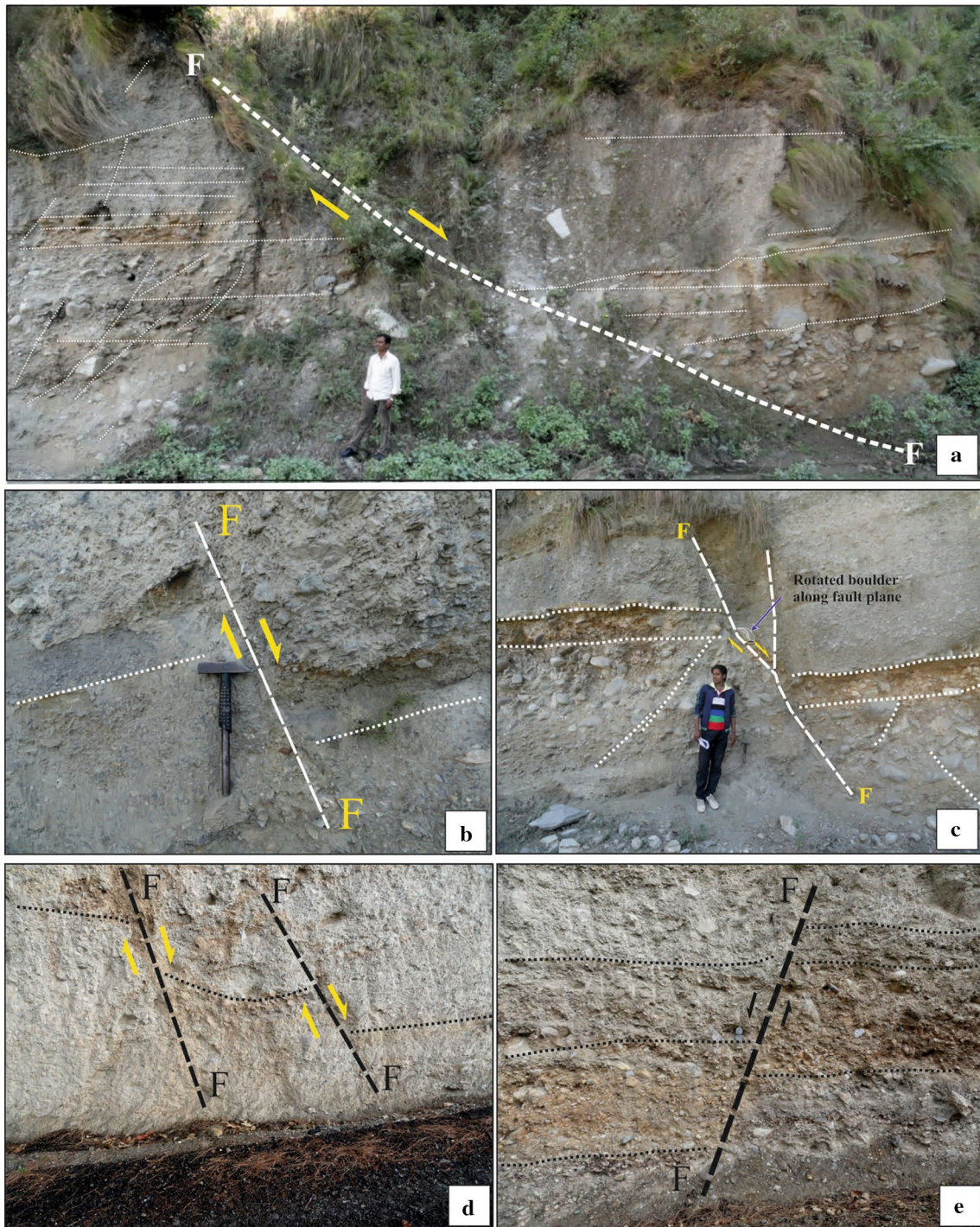


Fig. 8 a–c At Site No. 1, Quaternary fan deposit affected by normal faults in the form of bookshelf faulting; displaced beds are clearly discernible along the fault plane; rotation of boulder along the fault

plane is also observed. **d, e** At Site No. 2, displacement of the Quaternary deposits by normal faults

landslides. After deposition of the debris fans, later phase of tectonic activities along the faults is evident from faulting of the deposits. In the observed sections, the debris fan comprised of alternation of layers of conglomerate and rocks fragments representing mid- or distal part. Normal faults in

the Quaternary deposits are observed along road-cut section at two sites 550 m apart near Harchanoli. At Site No. 1, the sediments have been affected by bookshelf faulting producing displacements ranging from a few centimetres to about 2 m (Fig. 8a–c). The fault plane dips 50° – 57° towards south.

This normal faulting in the Quaternary deposit is observed within a zone of 100 m exposed along road-cut section. This bookshelf faulting is a part within a broader normal fault zone of about 700 m wide. Movement along the fault plane is evident from the rotation of boulder. At Site No. 2, the Quaternary deposits have been faulted by normal faults steeply dipping towards SE. Normal faulting is evident from the displacement of the coarsely laminated horizon by about 0.60 cm; in the fault plane, the almost horizontally laminated sequence becomes steeply dipping (Fig. 8d, e). West of Ochakot, the contact between the Quaternary deposits and the steeply dipping bedrock is defined by an oblique contact. At Manarsa at the SAT zone, fluvio-lacustrine deposits overlying fan deposits are tilted by 10° towards NE, and the underlying fan is tilted by 50° towards NE (Fig. 5a, b). Abandoned channel and incision of the bedrock are observed in the SAT zone near Kakrighat. At Khan, the once broadly meandering Sarod Gad has not only incised the sediment laid by it but also incised the bedrock forming deep gorges though still maintaining its meandering pattern.

Morphotectonic features

Fresh fault scarp is not observed, but faulting-related landforms are observed in Amel–Basgaon area. Near Amel, normal faulting has produced fault scarp measuring about 450-m-long south-facing fault scarp (Fig. 9a). In the outcrop, the N dipping thinly bedded limestone bedrock is traversed by numerous south dipping fractures. Displacement cannot be ascertained due to the absence of marker beds and nature of the bedrock. The brittle planes are considered as fault planes due to the presence of fault gouges, which are cemented by carbonates in the fault zone (Fig. 9b, c). The fault planes and the fault scarp have the same attitude dipping and facing towards south. Movement along this fault has not only formed fault scarps, but also formed a fault terrace (Fig. 9a). Fault terrace (FT₁) is at a height of about 120 m from the present river bed while T₁ at about 100 m. Small discontinuous linear horst is observed eastwards of Betalghat (Fig. 9d, e), which also forms discontinuous linear fault scarps (sackungen) facing the slopes (McCalpin 1995). The mini-horsts are composed of bedrocks, while the depressions are filled by sediments. Parallel to the fault traces, mini-horst is also aligned in E–W trend furrowed by numerous streams. Maximum thickness of the depression-filled sediments is observed at Ochakot to be 150 m (Fig. 9f, g).

Discussion

In the Himalayan region, the major thrusts, like the MCT, MBT and HFT, and major folds are formed in

compressional tectonic regime (Gansser 1964; Valdiya 1998). During orogenesis, normal faulting is also recognized as one of the deformations though the main style of deformation is thrust faulting (England and Molnar 1993; Nakata et al. 1990). During the underthrusting of Indian plate beneath the Himalayan wedge during the Miocene time, the rocks of the Higher Himalaya were exhumed by northerly dipping normal faults defining the northern boundary of the Higher Himalaya (Burg et al. 1984; Burchfiel and Royden 1985; Herren 1987; Valdiya 1989; Burchfiel et al. 1992; Hodges et al. 1992; Searle et al. 1988). England and Molnar (1993) suggested that the most probable cause of Miocene normal faulting was either uplift of the Himalaya or cessation of slip on the MCT at the base of orogenic wedge and creation of new, deeper thrust faults and a new base to the deforming Himalaya. In the Himalaya, the localized normal faulting is reported from various terrains of the Himalaya from the Higher Himalaya up to the HFT zone, where HFT is the youngest crustal boundary where at present is the zone of maximum convergence (Thakur 2004; Thakur et al. 2009). In the MBT zone, recent movement along this intra-crustal boundary is characterized by thrusting of the older bedrocks over the younger sediments (Thakur et al. 2009; Kothiyari et al. 2010). In the frontal part, the compressional characteristic of the HFT is defined by thrusting of the Siwalik rocks over the Gangetic alluvia, uplift terrace, tilted terrace and fault scarps. In Zanskar area of the north-west Himalaya, Herren (1987) has described the normal faulting between the Higher Himalayan Crystallines of the Higher Himalaya and Tethyan Sedimentary Sequence of the Tethys Himalaya. In the Panjal Thrust zone, the mesoscopic scale of normal faults suggests NE-directed subhorizontal extension (Thakur et al. 1995). Ductile normal shearing are reported from MCT (=Munsiri Thrust) and from the upper strand of the MCT (=Vai-krita Thrust) along Sutlej River section, near Karcham (Mukherjee and Koyi 2010), and from Sainj area where the lower strand of MCT passes in the Bhagirathi River section (Mukherjee 2013). In the Nepal Himalaya, Mugnier et al. (1994) reported normal displacement along most of the length of the MBT; suggesting that the orientation of the major principal stress within the Himalayan Thrust wedge deviates significantly from the horizontal and when this deviation exceeds the dip of the vectors normal to back-tilted thrusts, the normal component of displacement may act along these faults. In the north-east Himalaya, south of the Siang Window normal faulting has truncated the Quaternary fan deposit (Luirei et al. 2012).

In the present study area, normal faults are observed near the Ramgarh Thrust in the outer Kumaun Lesser Himalaya. The wide valley of the Kosi River between Seti and Bhujan is explained by extensional tectonic regime. Valdiya (1988b) suggested the exceedingly wide valley of

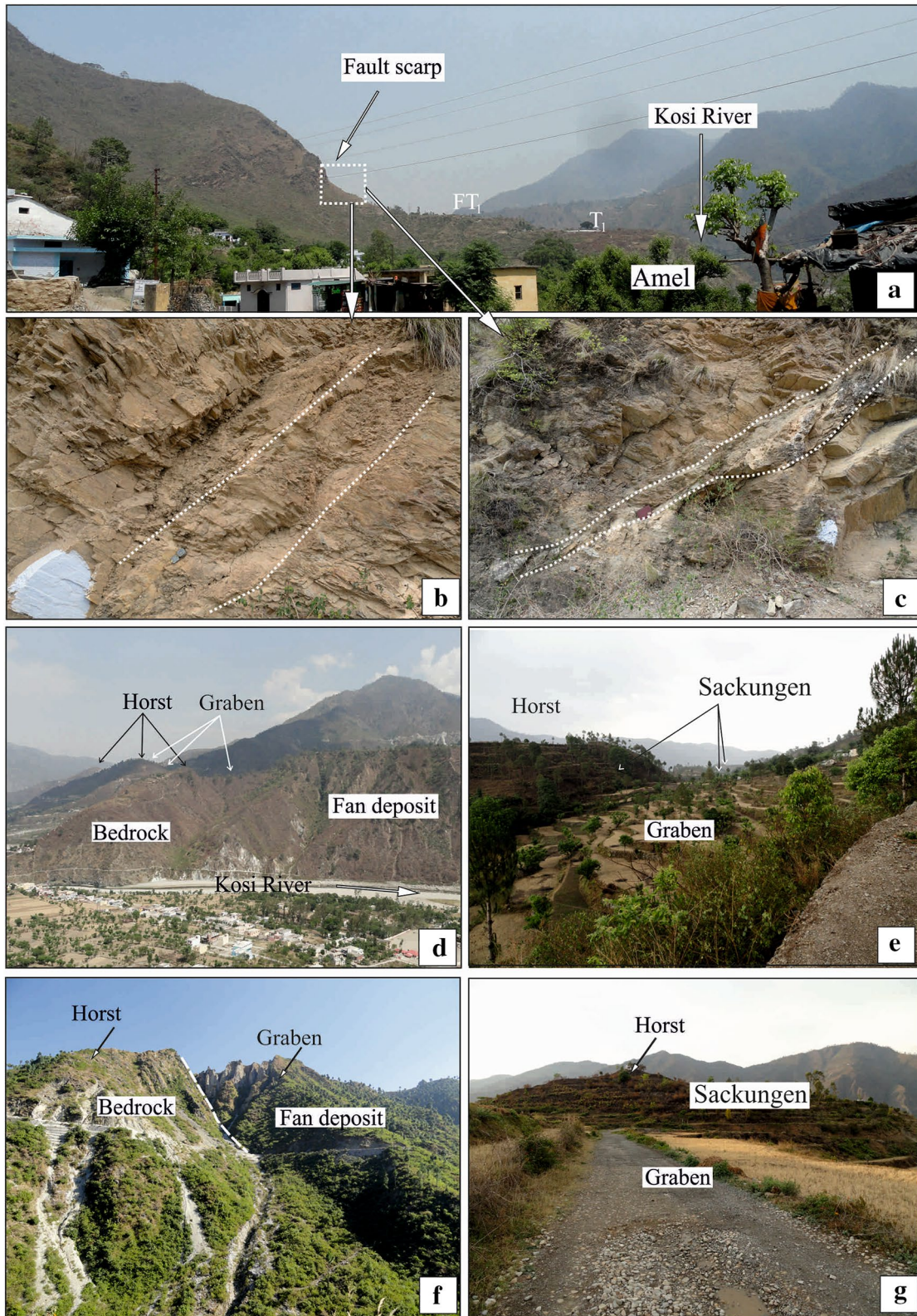
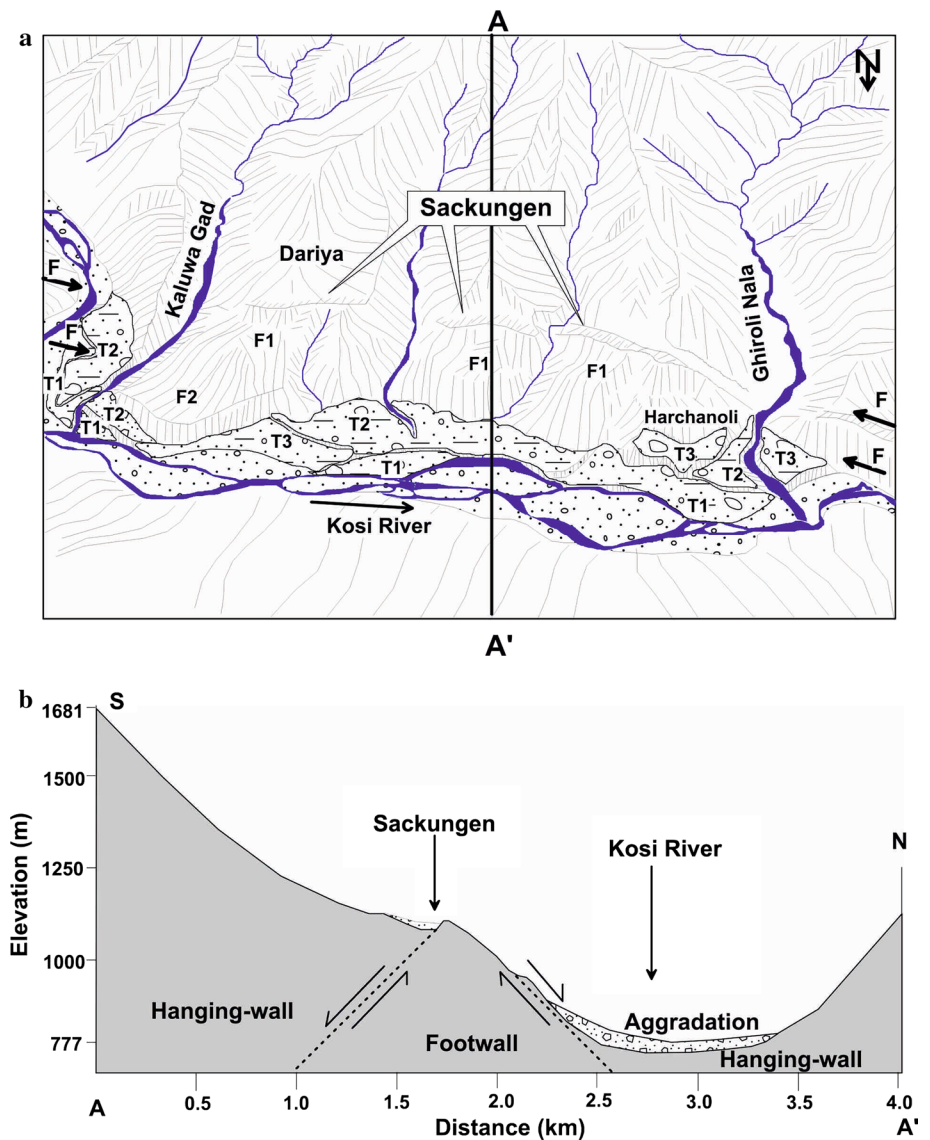


Fig. 9 a Fault scarp of Amel Fault observed near Betalghat and the formation of fault terrace. b, c Moderately north dipping bedrock faulted by normal faults. Fault zone characterized by fault gouge cemented by carbonates. d–g Field photographs showing horst and

graben. Horst characterized by thin sediment cover while graben filled by huge thickness of sediments. Linear discontinuous sackungen marked the slope facing fault scarp

Fig. 10 **a** Schematic diagram generated from Topomap and SRTM. **b** Cross section showing the development of wide Kosi River valley in the fault zone



the Kosi River in the area due to vertical movements along deep fault resulting in mini-horsts and mini-grabens. Kosi River becomes wide within the fault zone that gave space for the deposition of sediments in the hanging wall of fault (Fig. 10). During the initiation of the normal faulting, huge landslides occurred in the north-facing slopes as evident from the thickness of the fan sediments.

The faulting mechanism-related activity generated enormous amount of debris where the depressions are filled with significantly thick fan deposits (Fig. 10b). Sediments are deposited episodically as evident from mud/clay sediments in between the debris fan deposits indicating blockade of streams. The sediment deposited in the subsided block of the normal faults is more than 100 m thick as observed near Ochakot. Normal fault traces are observed trending E–W. The once continuous linear horst has been furrowed by a number of streams cutting across. At present, the horst is

represented by isolated linearly arranged small ridge. The small ridge is also characterized by hill slope facing fault scarps (Sackungen) as illustrated in Fig. 10. The maximum height of the fault scarps of ~40 m is observed at Ghiroli-Pali and Ochakot areas.

Field evidence supports that this view is the sudden narrowing down of the Ghiroli Nala at the horst from more than 300-m-wide channel to about 35-m-wide canyon near Harchanoli. This is also corroborated by sudden narrowing down of the active channel of Kosi valley from about 600 m at Harchanoli to about 45 m at Betalghat as is cut across the horst. Fault scarp measuring about 450 m in length and 130 m in height is observed between Betalghat and Amel. In this area, normal faulting has formed a fault terrace (Fig. 9a). The fault zones are characterized by highly sheared rocks and breccias cemented by carbonates. The authors are of the view that the present channel of the Kosi River

is flowing in the subsided block. Recent tectonic activity along AF and B–BF is characterized by faulting of the Quaternary debris fan deposits and is observed at two sites. The attitude of the faults in the bedrock and Quaternary deposits is consistent with each other. From the thickness of the deposits in the depression (graben), it is assumed that the displacement in bedrocks measures more than 100 m, while the maximum displacement observed in Quaternary deposits measures about 2 m.

The localized normal faulting in the study area is presumable by drag exerted by Bhikiyasain Fault, a strike-slip dextral fault (Valdiya 1980; Goswami and Pant 2008). Mukherjee (2014) has also described similar structures while reviewing the flanking structures. Goswami and Pant (2008) suggested that fault is steeply dipping ($>75^\circ$) extending beyond Amdali just south-west of Amel. The

displacement of the SAT and RT by this fault is ~ 2.5 and ~ 1.6 km, respectively (Valdiya 1976, 1980). The existence and strike-slip nature of the Bhikiyasain Fault and its role on the evolution of tectonic landforms are well documented by Goswami and Pant (2008). The drag exerted by the left-hand block of the fault on the right-hand block extended and subsided the rocks. Reactivations of the faults are also evident from the tilting of thick mud deposit. From the nature of tilting of the mud deposit and the horizontal bedding of the overlying fan deposit, it is inferred that the fault reactivated after the deposit of the mud. From field observations (Fig. 8) and Google earth image (Fig. 6), the width of the extensional environment measures about 700 m, which further east converges into a single fault. The valley occupied by the fan sediments is not the paleochannel of the Kosi River as the sediments lack typical fluvial deposit

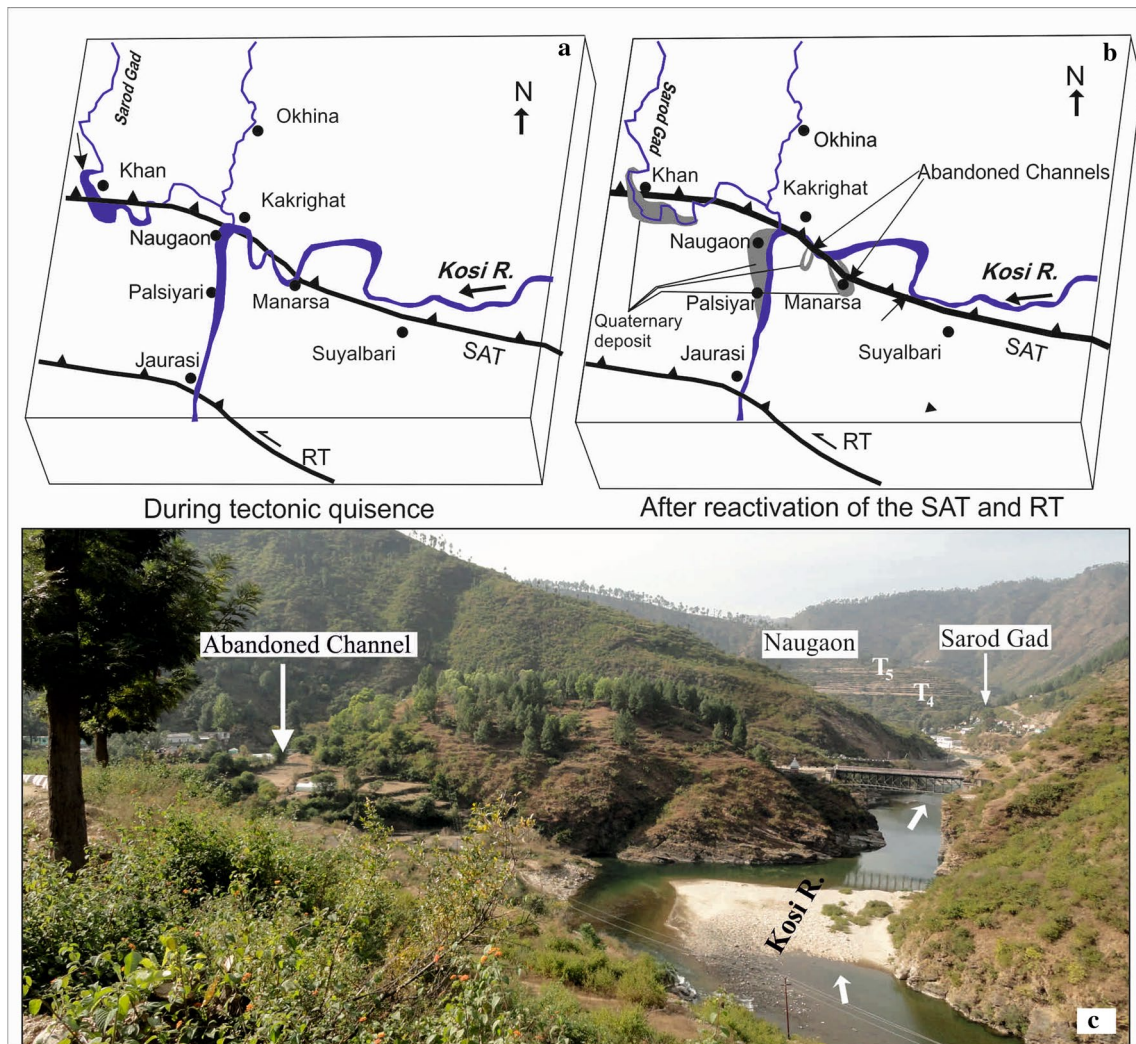


Fig. 11 a, b Schematic diagram representing deposition in tectonic quiescence followed by tectonic upheaval in the SAT and RT zones. c Geomorphic evidence of tectonic uplift in the South Almora Thrust

zone, abandoned channel, incision leading to formation of deep-cut V-shaped valleys

characteristics. Reworking of the sediment is observed but by tributaries and not the main Kosi River. The thick sedimentary pile can be explained in either way: by filling up the paleochannels or by filling up the subsided block. The authors believe that the huge thicknesses of sedimentary piles are due to extensional activity along the closely spaced normal faults and filling up the subsided block.

In contrast to the wide extensional environment observed between Amel and Basgaon, compressional environment is observed at Kakrighat area. During tectonic quiescence of unconstrained timing, the Kosi River and its tributaries maintain meandering pattern, as evident from the presence of aggradational landforms (Fig. 11a, b). Four to five levels of fluvial terraces are observed overlain by colluvial fan deposits (Fig. 11c). At present, not only the terraces but also the underlying bedrocks are incised. Abandoned channels and incised meandering reflect thrust tectonic rejuvenation of the area (Fig. 11c). Kosi valley in this section is much narrower than that around Betalghat–Basgaon. Moreover, aggradational deposits are observed in much localized area between Khairna and Manarsa. In Kakrighat area, maximum width of the Kosi River valley is around 95 m, which is much less than that of 850 m in the Betalghat–Badhani area. The thickness of sediment of the fans/terraces is much less than those between Betalghat and Dhaniyakot. In Kakrighat area, the sediment is ~20 m thick, while that in Betalghat–Dhaniyakot exceeds 100 m. The difference in nature of the valley is interpreted to be a direct consequence of the structures beneath the bedrocks. Tectonic activity along the SAT is also explained by temporary damming of a small stream that deposited of the 14-m-thick fluvio-lacustrine deposit at Manarsa. The base part of the mud deposit is tilted by 10° towards NE, indicating reactivation of SAT in the Quaternary time. The GF running NNW–SSE is morphogenic producing landforms associated with tectonic activity. Khairna Gad and Kuch Gad flows along this fault show prominent offset, indicating that the streams are structurally controlled.

Conclusions

An analysis of landforms along the Kosi River valley in the outer Lesser Himalaya shows signatures of both extensional and compressional tectonics recognized in the Quaternary landforms. South of the Ramgarh Thrust, normal faults indicate extensional tectonics that developed wide valleys forming basins for deposition of huge thickness of the Quaternaries. The deposits therein are affected by later phase of ongoing tectonics by faulting and tilting. While eastwards in the South Almora Thrust zone, the Kosi River has not only incised the sediment but also incised the uplifted bedrocks. This suggests neotectonic activity.

Structural details across thrust and subsidiary faults are necessary to interpret the neotectonics of the region with respect to the tectonics of fold–thrust belt.

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