Evidence of active tectonics along oblique transverse normal fault in the Kosi River valley around Betalghat, Kumaun Lesser Himalaya, India

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We report evidence of offsetting in the Quaternary sediments along the NNE–SSW trending oblique transverse normal fault from Betalghat area, Nainital District, Uttarakhand, Kumaun Lesser Himalaya, India. The area is located in a broad, active tectonic valley of Kosi River sandwiched between three major tectonic planes; the Main Boundary Thrust and the Ramgarh Thrust in the south and the South Almora Thrust (SAT) in the north. The Quaternary sediments occur as part of the erosional remnants of terrace-cut fan deposits, consisting of an unsorted mixture of boulders and pebbles set in a sandy and silty matrix. Distinct silty clay layers occur within the sediments, which act as a marker horizon for fault movement. An offset of ~1.5 m in the Quaternary sediment by the NNE–SSW trending transverse fault has been observed. The dip component in the silty clay layers and the nature of displacement indicate both compressional and extensional tectonic activity. The NNE–SSW trending fault being youngest displaces major Himalayan structural grains, suggesting that the transverse fault trending NNE–SSW is active due to oblique convergence of the Indian plate beneath the Eurasian plate.

Keywords: Active tectonics, alluvial fans, Quaternary sediments, transverse fault.

GEOMORPHIC evolution of the Himalaya is attributed to northward push and underthrusting of the Indian plate. The reactivation of intracrustal boundary thrusts and faults at different times formed Quaternary basins in the Himalaya, and differential uplift of the orogen influenced sedimentation in these basins[1]. The Himalaya in general have risen to great heights, implying their uplift and reshaping due to progressive and ongoing neotectonic movements; however, changes in the landscape of the Lesser Himalaya are attributed to Holocene uplift[2,3]. The geomorphic evidences cited for recent movements along thrusts and faults are sudden change in the stream courses, deep gorges, huge fans and debris avalanches, entrenched meanders and uplifted fluvial terraces[2]. Tectonic activity in the southern front of the Lesser Himalaya has been linked to repetitive movements along the Main Boundary Thrust (MBT)[4]. In the southern part of the seismically active Kumaun Himalaya, 3–6 pulses of uplift during the Quaternary have been envisaged[2,4–7].

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Active tectonics in the Kumaun Himalaya has been observed proximal to the intracrustal boundary thrusts, viz. the Main Central Thrust (MCT), Krol Thrust (KT) or MBT and the Himalayan Frontal Thrust (HFT). Recently, out-of-sequence thrusts (OSTs) and erosion leading to isostatic adjustments have been invoked to address active tectonics in the hinterland part of the Nepal Himalaya by Wobus *et al.*[7]. A similar hypothesis was proposed in the Garhwal Himalaya; abnormal incision was attributed to OST-related, erosion-driven deformation[8]. It has been surmised that neotectonic activity is concentrated along MBT and HFT in Kumaun Himalaya[2–4]. However, in the present study, we have documented that the transverse faults displacing the longitudinal thrusts in parts of the Kumaun Lesser Himalaya are equally active, and the geomorphic development along the Kosi River valley testifies to the recent movements along these faults (Figure 1).

Betalghat area of Nainital District, Uttarakhand, Kumaun Lesser Himalaya is located in a wide Kosi River valley sandwiched between three major tectonic planes; namely the MBT and the Ramgarh Thrust (RT) in the south, and the South Almora Thrust (SAT) in the north. The area around Betalghat is studded with NW–SE trending RT and NNW–SSE trending Garampani and Betalghat faults[2,4]. The area forms the southeastern extremity of the Krol belt between Nainital syncline and Kosi anticline (Figure 1). The rocks of the area belong to the Bhimtal Formation, Blaini Formation of Baliana Group, Ramgarh and Almora Groups (Figure 1). Towards the north, Precambrian metamorphics of the Ramgarh Group are thrusted over the Bhimtal Formation along RT. The Ramgarh Group of rocks is in turn thrusted over by the Almora nappe along SAT (Figure 1).

The thick (~15 m) Quaternary successions are seen overlying the shale, slate, phyllite and limestone of

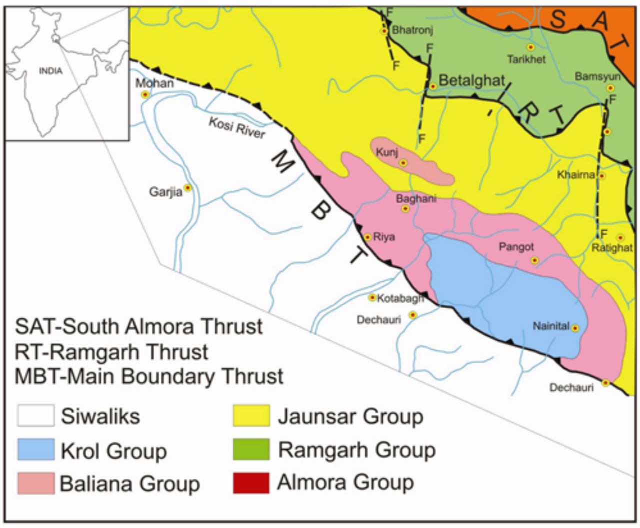

Figure 1. Geological and structural map of the study area. (Inset) Location of the study area.

Betalghat Formation of Ramgarh Group (Middle Proterozoic). The sequence starts with a sandy horizon containing angular rock fragments (size 1–2 cm) of phyllite and quartzite overlain by sub-rounded to rounded imbricated clasts of quartzites (size 5–15 cm) set in a silty to gravelly matrix (coarse : fine :: 70 : 30). The thin sand layers occur in pockets deposited in minor trough or ponds developed within the broad fan sediment layers. The gravelly clasts are mainly of quartzite, sandstone and dolomite. Sedimentary structures and textural attributes suggest that these were deposited as alluvial or colluvial fans which were subsequently modified into terraces by the fluvial processes. Lithology is dominated by a matrix-supported assorted mixture of boulders and pebbles of quartzite of the Bhimtal Formation and limestone of the Betalghat Formation.

Around Betalghat (Kosi Valley), four levels of terraces can be observed that have been formed by the fluvial modification of colluvial and alluvial fan deposits (Figure 2). These terraces are made up of gravels, rock fragments, sand, silt and clay. The river has a wide valley and has at places incised >3 m into bedrocks. A NNE–SSW trend gorge can be found in the upstream section. Based on the distribution pattern of the linear features, it can be suggested that the Kosi River course is structurally controlled probably by the longitudinal thrusts which seems to have been displaced by the NNE–SSW trending transverse faults. The NNE–SSW displacement is geomorphologically expressed in the longitudinal profile of the river as knick points.

In order to generate alluvial fans, one needs to have appreciable sediment supply on the mountain slopes. A study in the adjoining Alaknanda valley suggests that moderate to steep slopes riddled with streams and seismically active MCT and local NW–SE and N–S trending faults were responsible for the generation of sediment cover on the slopes. These sediments are transported valley in the form of alluvial fans which are subsequently modified into terraces by the fluvial process[9]. In the present case we envisage that fan sedimentation in the study area was caused due to faulting and rapid uplift along the transverse faults and KT. The most striking evidence of active tectonics recorded is the offsetting in the Quaternary fan sediments on the left bank of Kosi River at the Betalghat–Khairna road section (Figure 3). The near-horizontal bedded Quaternary sediments have been offset by an oblique transverse normal fault[10–13] trending NNE–SSW, registering a vertical displacement of about 1.5 m (Figure 3).

Evidence of faulting in the study area is marked by sagging of displaced beds, alignment of pebbles, shearing and formation of gauge. The warping of Quaternary sediments is seen at the Khairna–Betalghat road section. Faulting and warping in the Quaternary sequences in the Kosi Valley are indicative of both compressional and extensional tectonic activity. Crudely laminated scree/talus material has also been found displaced by normal

Figure 2. A view of the broad Kosi River valley showing well-developed terraces on either side represented by T_1–T_4. Note the deep gorge formed in the upstream trending NNE–SSW (near Betalghat).

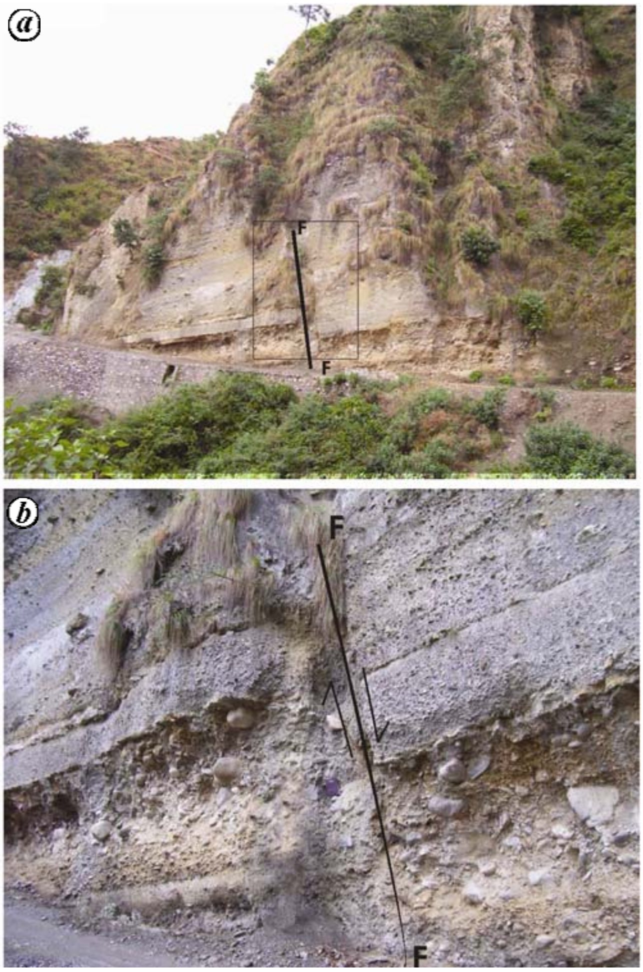

Figure 3. ***a***, A normal fault (F) offsetting the alluvial fan sediment sequence by about 1.5 m near Betalghat. ***b***, Closer view of the alluvial fan sediment sequence clearly depicting the displacement (1.5 m) in the indurated clays alternating with cobbly and pebbly gravel horizons at Betalghat.

Figure 4. A distinct NNE–SSW trending pressure ridge comprising Quaternary fan sediments. This is the direction of active tectonics observed in the valley (near Dhaniyakot).

strike-slip fault, indicating that the movement is still continuing. Another evidence of active tectonics in the Kosi Valley is well depicted in the form of down fan movement, steep fan scarps, uplifted terraces, pressure ridge (Figure 4) and landslides along the cliff surface of the Quaternary sediments. The faults trending NNE–SSW being the youngest, displace all the structural elements of the area. The NNE–SSW trending faults recorded in the Quaternary sediments indicate that these faults are also active besides longitudinal faults/thrusts.

Thus Quaternary sequences developed in the Kosi Valley around Betalghat have provided ample evidence of active tectonics. The uplifted and truncated fluvial terraces, tectonic landforms and offsetting in the Quaternary sediments along transverse faults indicate that the Kumaun Lesser Himalaya is tectonically active. Although preliminary in nature, the available field evidences as discussed above indicate that the transverse faults have developed on account of oblique convergence of the Indian plate under the Eurasian plate. However, a more definitive inference should await a detailed morphotectonic study of the area.

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Intense deep convective mixing in the southeast Arabian Sea linked to strengthening of the northeast Indian monsoon during the middle Pliocene (3.4 Ma)

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The climate of the Indian Ocean is dominated by monsoon reversals, influencing hydrography and biogeochemistry of the Indian Ocean as well as land vegetation through changes in precipitation. During summer or southwest monsoon season, intense upwelling zones driven by Ekman spiral appear in the western and eastern parts of the Arabian Sea that enhance surface primary production and thus proliferation of distinct fauna and flora. During the winter season, northeast monsoon winds cause deep convective overturning (mixing) that injects nutrients to the surface ocean and increases surface production. As a result, the primary production in the Arabian Sea has bimodal annual distribution. The present study analyses 5.6 Ma

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