the dirty water. It can be stated that water shortage is a site-specific problem and needs to be solved combining hydrological and management considerations.

Understanding the site-specific nature of the springs, their response to rainfall, land use, biotic pressure and sociological constraints and limitations of our knowledge with regard to revival of springs, the following areas of problem-solving research in this region may be suggested – (i) Water harvesting, conservation of spring sanctuaries, studying recharge and discharge pattern of springs, collection and analysis of hydrometeorological data (e.g. rainfall, runoff, evapotranspiration, water budget, etc.); (ii) traditional water conservation/ management systems; (iii) identification of plants which can help in augmenting ground water recharge; and (iv) strengthening water management system and role of technological inputs to check water misuse and losses.

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Recent crustal adjustments in Dehra Dun valley, western Uttar Pradesh, India

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The compression that was responsible for India–Asia collision and consequent formation of the Himalayan orogen, though subdued, has not yet ceased. A large number of earthquakes occurring between the Main Central Thrust (MCT) and Himalayan Frontal Fault (HFF) bear testimony to the continuing compressional stress regime. The present study provides evidence of recent crustal adjustments in Dehra Dun valley to the south of Main Boundary Thrust (MBT) in the form of tilted and deformed terraces, colluvial wedges, land subsidence and older rock sequences overriding the Holocene sediments. These neotectonic movements warrant detailed investigations using modern techniques in this seismotectonically sensitive area.

INDIA–Asia convergence that started about late Cretaceous, finally resulted in plate collision in early Cenozoic (45 ± 5 Ma). The deformation front successively propagated towards south. The rate of northward movement of the Indian plate relative to Siberia is estimated to be about 44–61 mm per year[1]. Of this, about 10–15 mm per year is absorbed in the frontal Himalayan region while the remainder is distributed across the Higher Himalaya, Tibet, Tein Shan and further north[2]. Some workers[3,4] visualize MBT as the current boundary of plate convergence. Neotectonic deformation in the foreland basin of Himalaya has been studied in the Nepal sector[5], Kumaun[6,7] and Garhwal[8].

The unusually wide sub Himalayan belt between the rivers Ganga and Yamuna is known as Dun re-entrant area. This area comprises of bedded Upper Siwalik sediments and Holocene Dun gravels and houses the densely populated township of Dehra Dun in the central part (Figure 1). This Dehra Dun valley has been the focus of attention since the 1905 Kangra earthquake that had one of its high intensity zones (secondary epicentre) around this city[9]. Currently this area is rising at the rate of 1 mm per year[10]. To map the active faults between the MBT and the HFF, a detailed geological mapping was carried out by the present authors in 1994–1995 (Figure 2).

The foreland basin in the outlined area comprises a basal sandstone succession with interbedded subordinate clays overlain by pebbly sandstone and boulder conglomerate. The boulder conglomerates exposed in the vicinity of the MBT show definite late Upper Siwalik affinity (V. Raiverman and A. C. Nanda, pers. commun.). In the field no tectonic or stratigraphic break was observed between these conglomerates and the underlying sandstone–shale succession. The entire sequence has thus been equated to Upper Siwalik subgroup exposed across Yamuna[11]. These sedimentary rocks are deformed into a major NW–SE trending syncline, flanked on either side by two parallel trending anticlines. The syncline is largely occupied by Holocene Dun gravels. In the northern range, four fault planes paralleling the MBT have been identified between Yamuna and Rispana rivers. The fault plane that lies immediately to the south of the MBT follows the axial zone of the northern anticline.

In the southern belt (part of southern anticline), a major zone of back-thrusting is identified between

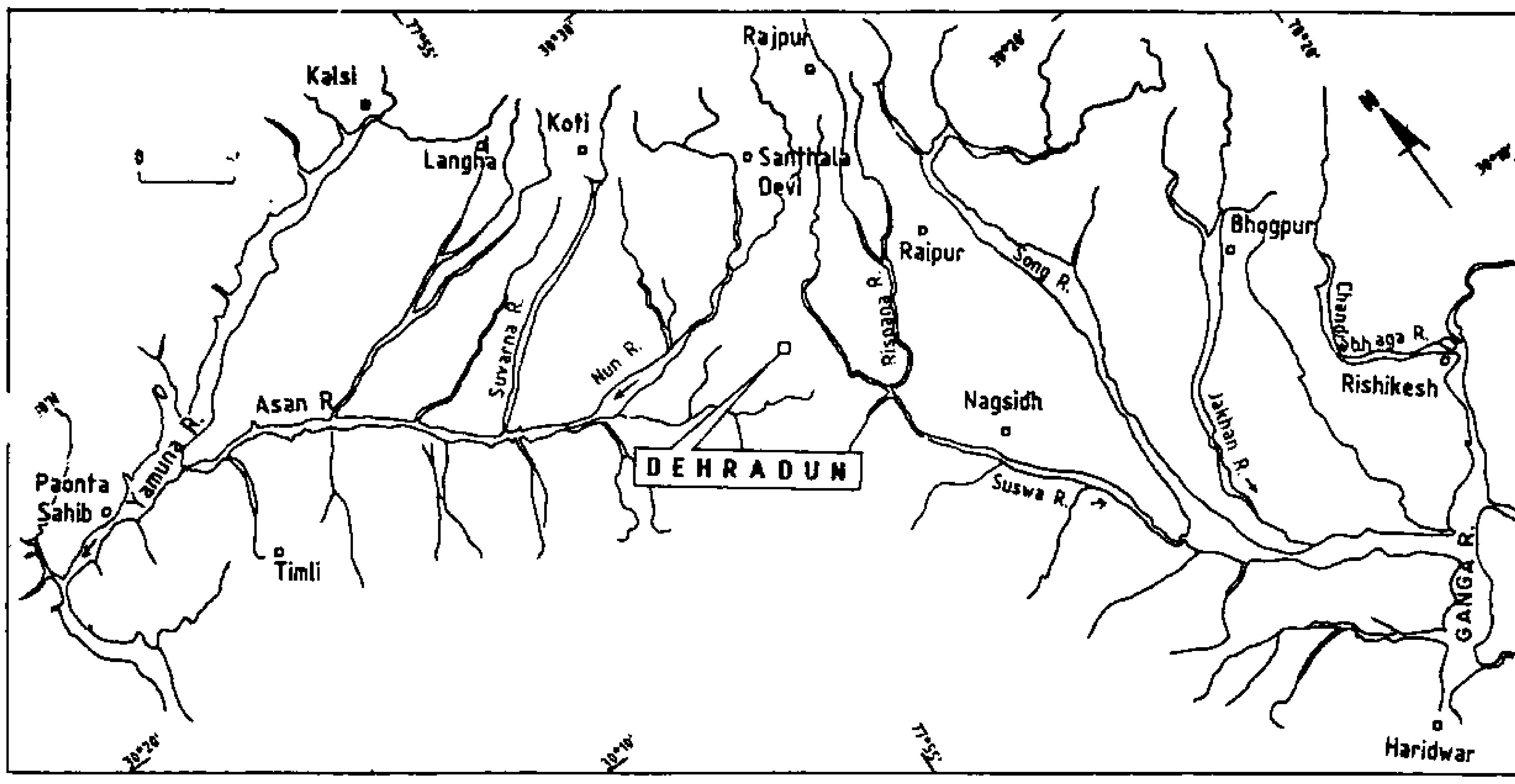

Figure 1. Location map of the area.

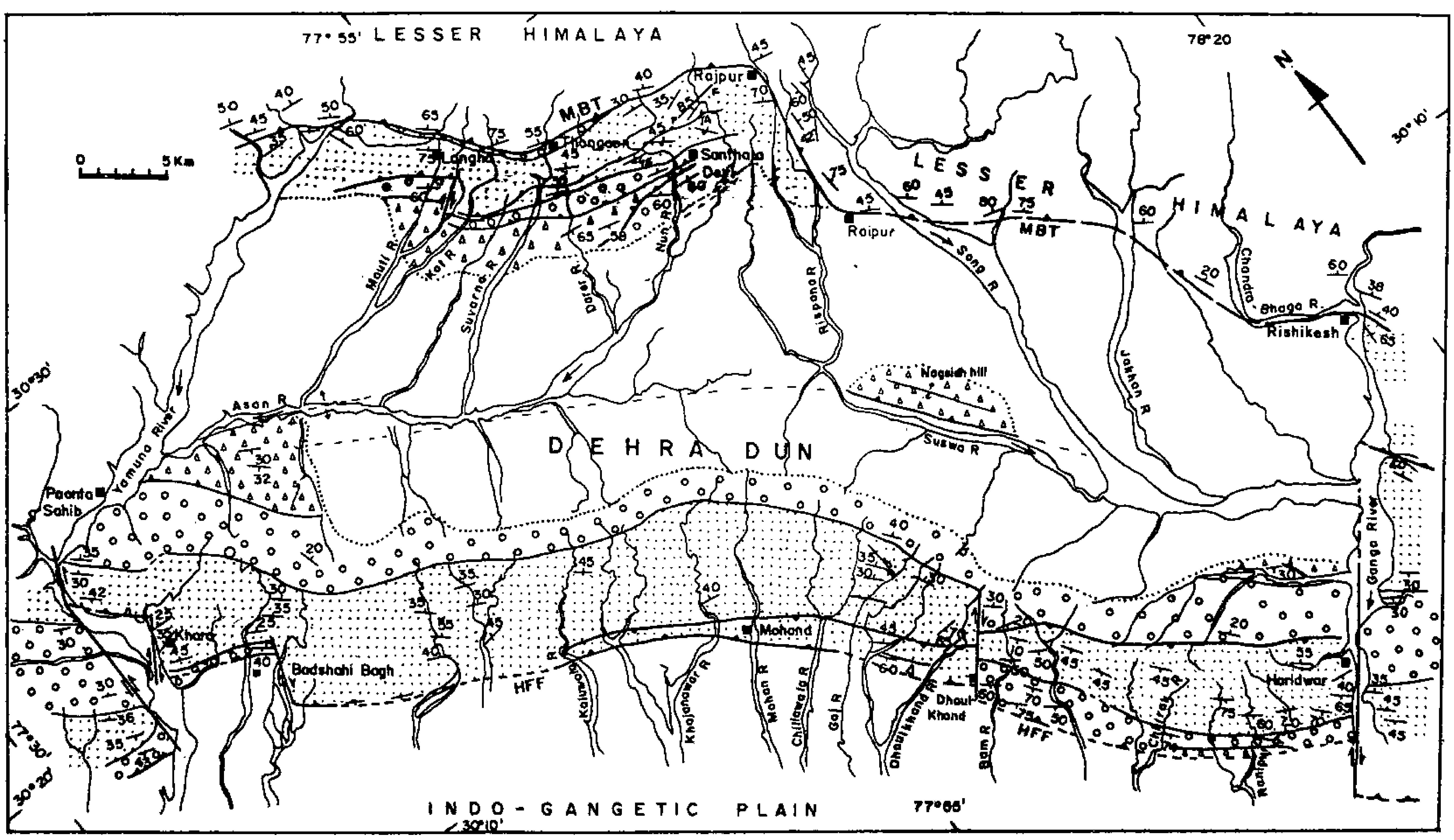

Figure 2. Geological map of the area. Indexed lithologies represent Upper Siwalik Formation. The dotted part indicates sandstone sequence with minor clay, siltstone and pebbly sandstone beds, the open circles indicate dominantly boulder conglomerates with occasional clay, siltstone and pebbly sandstone, the open triangles indicate the youngest Siwaliks deposited unconformably over the Upper Siwaliks and blank space in the central part indicates Holocene Dun gravels.

Kaluwala rao and Ganga. Three major zones of strike slip faulting have been mapped in this belt oriented along the rivers Yamuna, Dhaulkhand and Ganga with approximate lateral shifts of about 20 km, 2.5 km and 11 km respectively[12].

A close interrelation between the basement configuration and the structural set up of the area is worked out on the basis of the present studies. In the southern extremity an E–W vertical fracture is inferred in the basement along which the northern block has subsided. Arrest of the south-directed thrust movement against this vertical fracture initiated back-thrusting in the southern belt. Subsidence along this fracture increases towards east and hence the back-thrusting becomes increasingly pronounced in this direction. The observed back-folds (Figure 3*a*) overridden by back-thrusts

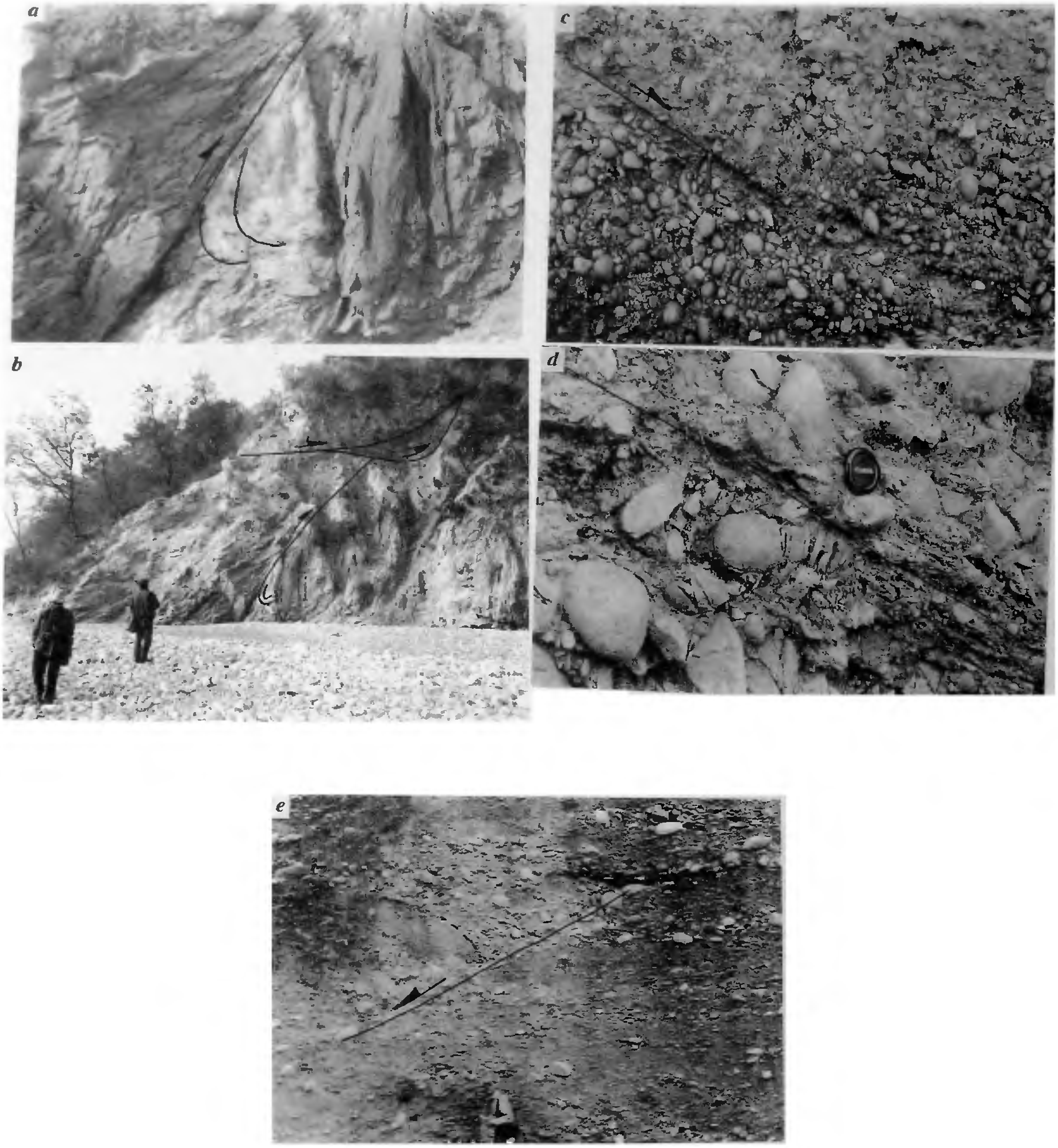

Figure 3. ***a***, Sandstone beds displaying a back fold structure in Khajnawar rao section. Camera views towards west. The southern limb (left hand side) of the fold is overturned; ***b***, The back fold is run over by back thrust pushing the thrusted slab towards the hinterland. View towards west; ***c*** and ***d***, A north dipping shallow plane cuts across the moderately north dipping boulder conglomerate beds near Rajauli in Kot river section. The pebbles and boulders in the zone are highly fractured. A stretched pebble oriented along the fault plane indicates normal faulting (camera facing west); ***e***, Thick column of un-endurated terrace sediments in Darer nala section near Manduwala showing north hading normal fault along which a colluvial wedge has developed (camera facing east).

(Figure 3 *b*) in this zone are the surface expressions of this subsurface fracture. Presence of the vertical fracture in the basement is also supported by the interpretation of the seismic profiles[13] across the area.

Our study shows evidence of ongoing tectonic activity in the form of tilted terraces, colluvial wedges, faulting in stream terrace, active land subsidence and the older rock sequences riding over the

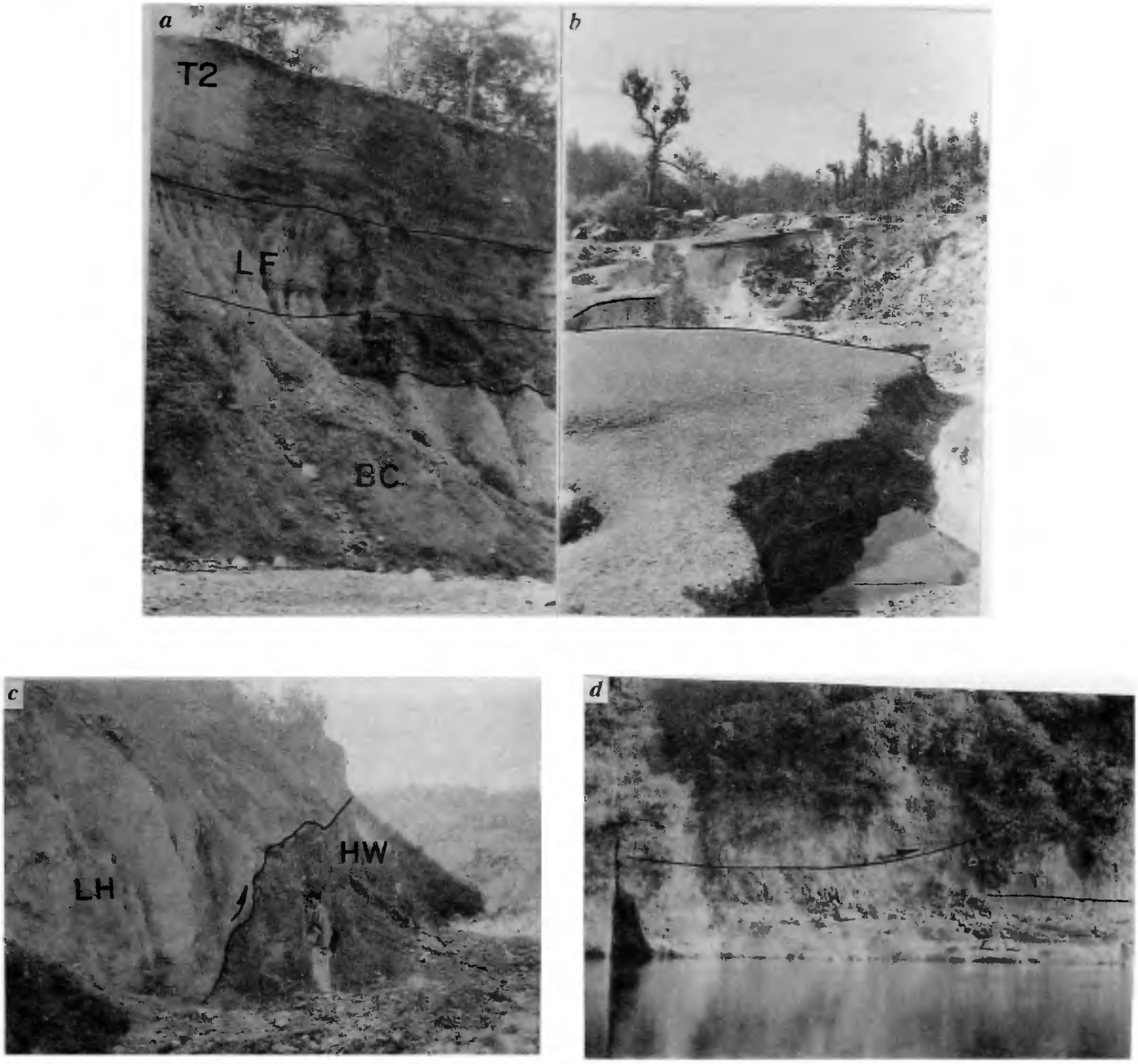

Figure 4. ***a***, In the upstream of Darer nala (north of Manduwala) north tilted terrace (T1) is seen resting over the vertically disposed boulder conglomerate formation (BC). The tilted terraces form the base for a nearly 3 m thick fine-grained lake fill deposits (LF), succeeded upwards by unassorted II terrace (T2) of about 5 m in thickness (view towards east); ***b***, Displaced terraces near village Khera indicate a zone of subsidence along a recently active fault zone (photograph taken towards west); ***c***, East of Rajpur along river Rispana SW directed thrusting along an en-echelon shear plane of MBT (lying in the north) is noticed. The Precambrian Simla Unit (LH) overrides the Holocene hillwash (HW) along this fault plane (photograph taken towards ESE); ***d***, SW directed thrusting close to MBT zone in Holocene river terraces near the Chandrabhaga–Ganga confluence in Rishikesh (photograph taken across Ganga on a left bank face).

Holocene sediments. These features are described below.

Tilted terraces are observed in Darer, Kot, Nun and Suvarna river sections. The tilt of the terraces varies between 15 and 25°. A shear zone is recorded in the Upper Siwalik conglomerates in the Kot river section. The conglomerate clasts are shattered and differentially displaced along the shear zones. One of the pebbles was found to be sliced (Figure 3 *c* and *d*). The sense of movement along this NE dipping shear plane is of normal type. The NE hading normal faults in this unit have been produced due to sudden upliftment of the footwall block and consequent collapse of the hanging wall.

In the Darer river section near Manduwala, a colluvial wedge is observed in a 20 m thick river terrace (Figure 3 *e*), suggesting normal faulting. The fault plane dips 35° towards NE. The terrace deposits are bedded, but poorly assorted and without appreciable breaks. The terraces are tilted towards the north, suggesting uplift in the Quaternary times along a sub-vertical fault parallel to the MBT. This relative uplift of the block caused local ponding in which the fine sediments were deposited

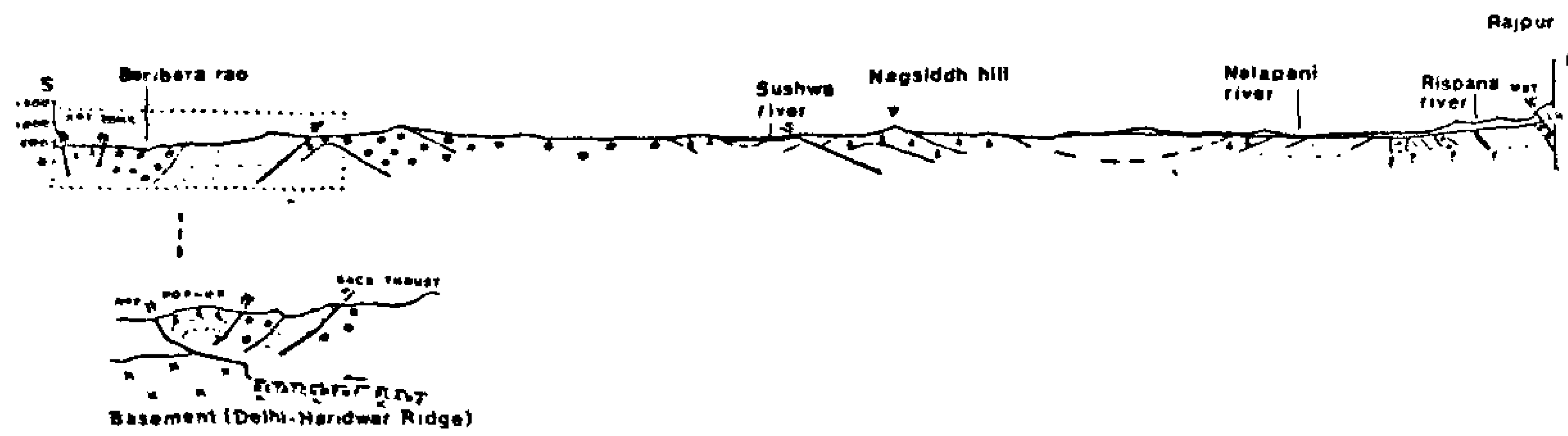

Figure 5. Geological cross-section along Ranipur–Motichur bypass road section in the southern Siwalik belt. The inset shows the pop-up structure in the HFF zone uplifting the Holocene sediments. Geology is as per Figure 2.

in the terraces (Figure 4 *a*). Northward tilted terraces are also observed along stream sections lying to the east of Nun river. A zone of subsidence occurs along a recently active fault to the northwest of Santhaladevi shrine. The land has subsided by about 5 m (Figure 4 *b*).

To the east of Rajpur along the Rispana rao section, an active en-echelon thrust of MBT is identified. Along this thrust, the Lesser Himalayan rocks are overriding the Holocene sediments (Figure 4 *c*). Friction clays and carbonaceous matter are observed along this contact. Similar activities have been noticed near Ganga–Chandrabhaga confluence (on the left bank of river Ganga), Rishikesh where southwest-directed thrusting along a shear plane is observed in the river terraces (Figure 4 *d*).

In the core of Dun syncline an E–W trending thrust has been identified along the southern border of Nagsiddh hill situated to the south of Raipur. This shallow N-dipping thrust plane brings a folded anticlinal structure in the youngest unit of the Upper Siwaliks (shown by open triangles in the map) over the Holocene gravels and boulders in the synclinal basin. The fault is not exposed towards Yamuna but an anticlinal structure delineated along Asan is indicative of its blind nature. In Dehra Dun city itself, prominent NW–SE (310°–130°) oriented fractures were observed in a large number of houses in a residential colony across river Rispana. These fractures are continuously opening up. The detailed studies are underway.

Evidence of neotectonic movements is also found along the HFF zone in the southern Siwalik belt between Chhirak rao and Ranipur rao. Here the youngest Upper Siwaliks containing unconsolidated, poorly stratified, boulder–pebble sequence in clay sand matrix display an open NW–SE striking anticline. This structure has formed within a pop-up setting between two thrust faults in the HFF boundary (Figure 5). In a nala section to the east of Bam rao, the displaced pebbles in the conglomerate unit along a SSW dipping shear plane suggest NE directed back-thrusting. Similar structures also occur in the Bam rao section. Neotectonic deformation is also reported in the Dhaulkhand strike-slip fault zone along the Gaj rao[8]. Neotectonic adjustment of the rocks here was shown to be responsible for the uplift of the river bed. From the presented evidence, three distinct neotectonically active domains have been identified: (i) the northern Siwalik belt experiencing active normal faulting, (ii) the central zone with south-directed thrusting and (iii) the southern belt with prominent back thrusting (north directed thrust movement).

Neotectonic movements show active ongoing movement related to the N–S compression responsible for Himalayan mountain building. This compression has not yet ceased and is causing strain in the foreland basin of Himalayas as manifested by the observed structures. Evidence of both SW-directed thrusting, NE-directed back-thrusting together with normal faulting recorded in the area suggests that the deformation is dominantly being controlled by the basement topography. The presence of active thrusting along an en-echelon shear of MBT and a thrust plane on the southern margin of the Nagasiddh hill in the eastern part of the area indicate that movement along HFF has almost ceased and currently some part of the strain is being released along these newly-formed shear surfaces.

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