Reactivation of terrane-defining boundary thrusts in central sector of the Himalaya: Implications

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The central sector of the Himalaya is under very strong compressive strain. Almost all thrusts that define the boundaries of lithotectonic terranes of the Kumaun Himalaya are active, though variably, for much of their extent. The fault reactivation is expressed in different geomorphic developments and drainage responses. In the north, neotectonic movements along the fault zone, that caused detachment of the Great Himalayan crystalline foundation from the Tethyan sedimentary pile, have resulted in formation of lakes upstream of points of the fault crossings and in the development of deep gorges downstream. Confined to the inner Lesser Himalaya in the middle of the Himalayan domain, are stepped terraces lining valleys upstream of the reactivated Almora Thrust, implying commonly three pulses of uplift in the late Quaternary time. The synclinal nappe of the crystalline rocks bound by the Almora Thrust is an active fold. In the south, reactivation of faults of the schuppen zone of the Main Boundary Thrust is evident from the pronounced dextral swing of antecedent rivers, the truncation of colluvial cones and fans in the fault zone, and the valley-fills upstream of points of the faults that cross them. In the foothills, Holocene movements along the Himalayan Frontal Fault have considerably uplifted and tilted the late Pleistocene-to-early Holocene gravel deposits covering the Siwalik terrane.

The boundary thrusts merge with the plane of decoupling or detachment thrust along which the pile of Himalayan rocks was uprooted from its foundation. Earthquake hypocentres at depths of 15 to 25 km below the surface define this plane and imply ongoing movements on the detachment thrust. Continuing uplift related to active faults is related to the movements on this thrust plane.

THE understanding of past behaviours of active faults provides keys to the evaluation of seismic and landslide hazards. The major thrusts and faults that delimit the boundaries of Himalayan physiographic–lithotectonic terranes were therefore studied by the author at crucial spots in the Kumaun Himalaya. Realizing that geomorphic features record tectonic events, the changing profiles of landscape and the drainage deflections were kept in the focus of investigation. Significantly, almost all terrane-defining thrusts bear testimony to tectonic movements in the late Quaternary time – the Precambrian or older rocks ride over young fluvial terraces or colluvial fans, quite many streams are beheaded and deprived of their headwater, some recent terraces are tilted or elevated discernibly, and many of the larger rivers rush down the overly steepened gradients. As a result of movements on active faults, streams and rivers got ponded upsteam of the points of fault crossings. As the uplift of the mountains intensified the pace of erosion, the lakes that were formed due to river impoundments were rapidly filled up with sediments, resulting in the formation of flat stretches in the otherwise rugged terrains. The flat stretches of fluvial and lacustrine sediments are intensively used for agriculture and settlement, and account for very high population density. The lake deposits also provide records of tectonic movement that took place subsequent to the formation of lakes, and of the climate changes documented by fossil spores and pollens.

Progressive strain build-up

The central sector of the Himalayan arc that embraces eastern Himachal Pradesh, Uttaranchal (Kumaun Himalaya) and western Nepal, is persistently pressed underneath by the northwardly-oriented ridges of the Indian Shield

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hidden under the sediments of the Indo-Gangetic Plains (Figure 1). Magnetovariation studies unequivocally demonstrate extension right up to the interior of the Kumaun Himalaya of the Aravali orogen, represented by a magnetic transconductor[1]. The convergence of India towards Asia is causing considerable strain build-up in the framework of the Himalaya, particularly where the hidden ridges of the Indian Shield impinge on the orogen.

The strain build-up in the central sector of the Himalaya is relaxed periodically by earthquakes of generally moderate intensity (Figure 2). The major seismic events of 1803 ($M \geq 7.5$), 1816 (M 6.8), 1916 (M 7.5), 1945 (M 6.5), 1958 (M 6.2), 1964 (M 6.2), 1968 (M 7.0), 1979 (M 6.5), 1980 (M 6.5), 1991 (M 6.6) and 1999 (M 6.8) were among the larger earthquakes occurring preponderantly in north-eastern Kumaun and north-central Garhwal regions (Figure 2). Large-to-moderate in magnitude, these earthquakes individually could not have sufficiently relaxed the amount of strain generated by the India–Asia convergence at the rate of 58 ± 4 mm/yr (ref. 2). The central sector, so far unruptured in any great earthquake ($M \geq 8$), is therefore a seismic gap[2–5].

Accommodation of continental convergence

Only about 30% of the India–Asia convergence is absorbed across the Himalaya[6], the average rate of accommodation derived on the basis of slip rates of great earthquakes being ~ 17.7 ± 2 mm/yr (ref. 7). The slip at depth below Tibet occurs at the rate of 20 ± 3 mm/yr (ref. 8). The seismic slip on the detachment plane underneath the Lesser Himalaya south of the Himadri or Great Himalaya (Figures 3 and 18) at the longitude of Kathmandu in Nepal, is taking place at the rate of ~ 5 mm/yr. Evidently, the central sector of the Himalayan arc seems to be presently locked; and minor deformation that is discernible is insufficient to release more than a third (i.e. 18 ± 2 mm/yr) of the convergence velocity (ref. 3). It is noticed that there is a westward decrease in the accommodation rate – from 18 mm/yr in Nepal to 10 mm/yr in Pakistan (ref. 9).

In the Kumaun Himalaya, no systematic geodetic levelling has been carried out, and the GPS geodesy is as yet incomplete. There is therefore no way of estimating the continuing movements that must be taking place on the active faults in this sector. Interestingly, the GPS measurements during the period 1995–1999 in the adjoining parts of far-western Nepal indicated that the Simlikot–Dopho and Dopho–Jomosom belts register a vertical velocity of 15 ± 2 mm/yr and 12 ± 3 mm/yr, respectively, while they move parallel to the chain at the rate of 4.5 ± 3.5 mm/yr (ref. 10). The geodynamic situation being not different, the continuous north-eastern Kumaun Himalaya is experiencing deformation presumably at the same rate.

Geological setting

The Himalaya is divisible into four lithotectonically and physiographically distinct domains or terranes (Figures 3 and 4). The dividing surfaces are thrusts of regional dimension and varying tectonic activity. The Indo-Gangetic Plains in the extreme south are separated by the Himalayan Frontal Fault (HFF) from the ruggedly youthful Siwalik Hills (900–1500 m) made up of late Tertiary to early Quaternary molasse. Delimited against the Siwalik by the Main Boundary Thrust (MBT), the Lesser Himalaya is made up of middle and later Proterozoic to early Cambrian sedimentary rocks that are overthrust by vast and thick sheets of early Proterozoic metamorphic rocks with granites dated 1900 ± 100 Ma and 500 ± 25 Ma.

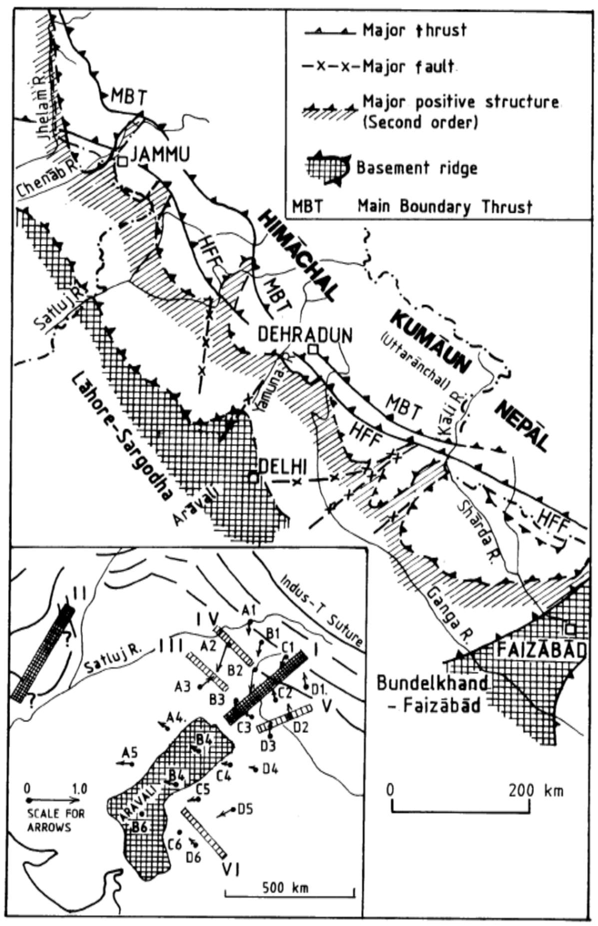

Figure 1. NNE-oriented ridges of the Indian Shield hidden under the sediments of the Indo-Gangetic Plains extend northwards and impinge on the underbelly of the Himalaya (modified after Raiverman *et al.*[64]). *Inset*: Extension up to the interior of the Kumaun Himalaya of a magnetic transconductor representing the Aravali orogen (modified after Arora[1]). MBT, Main Boundary Thrust; HFF, Himalayan Frontal Fault; A1, Rampur; A2, Chandigarh; A3, Hisar; A5, Jodhpur; B1, Uttarkashi; B2, Roorkee; B3, Delhi; B5, Udaipur; C1, Gopeshwar; C2, Muradabad; C5, Kota; D1, Champawat; D4, Gwalior; D6, Ujjain; S, Sabhawala.

Rising to the elevation of 500 to 2500 m above sea level, the Lesser Himalayan terrane exhibits a comparatively mild and mature topography. North of the Lesser Himalaya the Main Central Thrust (MCT) demarcates the lower boundary of the extremely rugged and youthful 6500- to 7000-m high Great Himalaya (or *Himadri*) – a complex of high-grade metamorphic rocks intensively injected with and migmatized by mid-Tertiary anatectic granites. Further, north, the Trans-Himadri Fault (T-HF) marks the tectonic boundary between the Great Himalayan crystalline complex and its thick late Proterozoic-to-late Cretaceous sedimentary cover of the Tethys domain. Representing the distal continental margin of the Indian Shield and having an extremely rugged physiography, the Tethyan terrane ends against the Indus–Tsangpo Suture (I–TS) which marks the junction of the Indian and Asian continental masses.

Neotectonics of Himalayan thrusts and faults

Neotectonic investigations in the Kumaun Himalaya (Figure 4) have shown that the thrusts and faults defining the lithotectonic–geomorphic terranes such as T-HF, MCT, MBT and HFF (Figure 3) and the transverse faults that cut through the four terranes have been quite active in the late Quaternary, including the Holocene[11–21]. Forming right stepping echelon pattern, the NNW-SSE to NW-SE trending tear faults registered dextral displacement with the throw to the north, while the less common NNE/N-SSW/S-oriented faults were characterized by sinistral movements. The WNW/W-ESE/E trending faults caused dip-slip to oblique-slip displacements. The characteristics of the active faults of western Nepal are also similar[22,23]. The rate of uplift on the E-W trending faults of the MBT Zone in Nepal has been 3 to 4 mm/yr during the last 4,00,000 to 50,000 years, while the rate of lateral displacement along a NW-SE-oriented fault in the MCT Zone about 1.2 mm/yr (ref. 23).

Reactivation of the Trans-Himadri (detachment) Fault

The steeply-hading extension fault (Figures 3 and 6 *a*) that brought about detachment (through dip-slip movement)

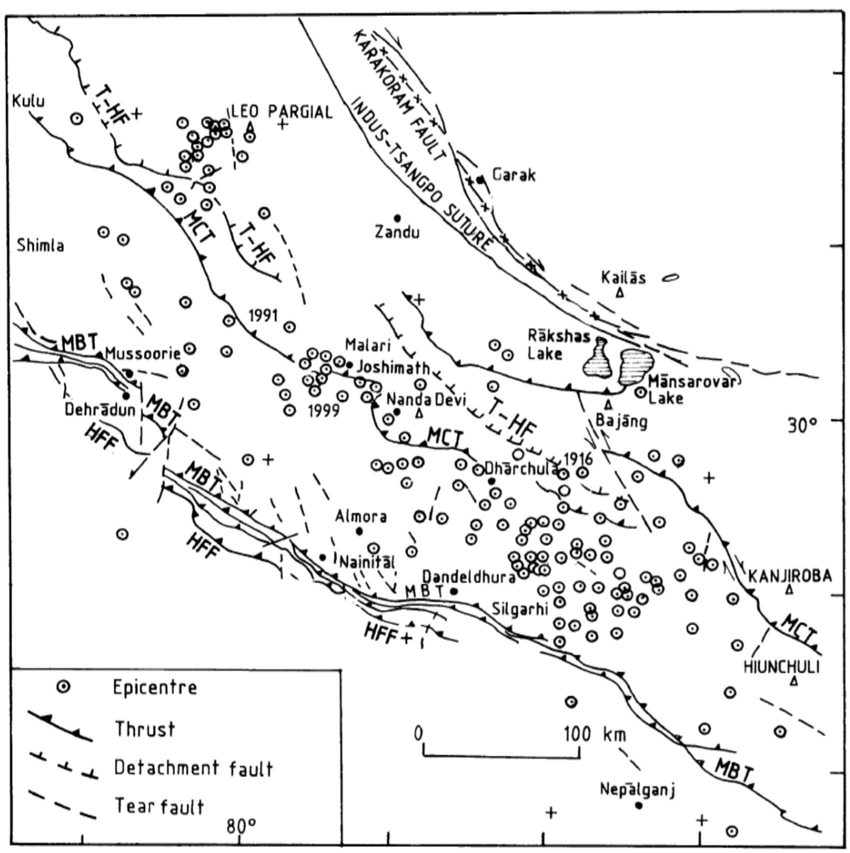

Figure 2. Distribution of epicentres of large and moderate magnitude earthquakes in relation to major active faults and thrusts in the central sector of the Himalaya (modified after Valdiya[11]). Note the concentration of epicentres in the much-faulted north-eastern Kumaun and north-central Garhwal.

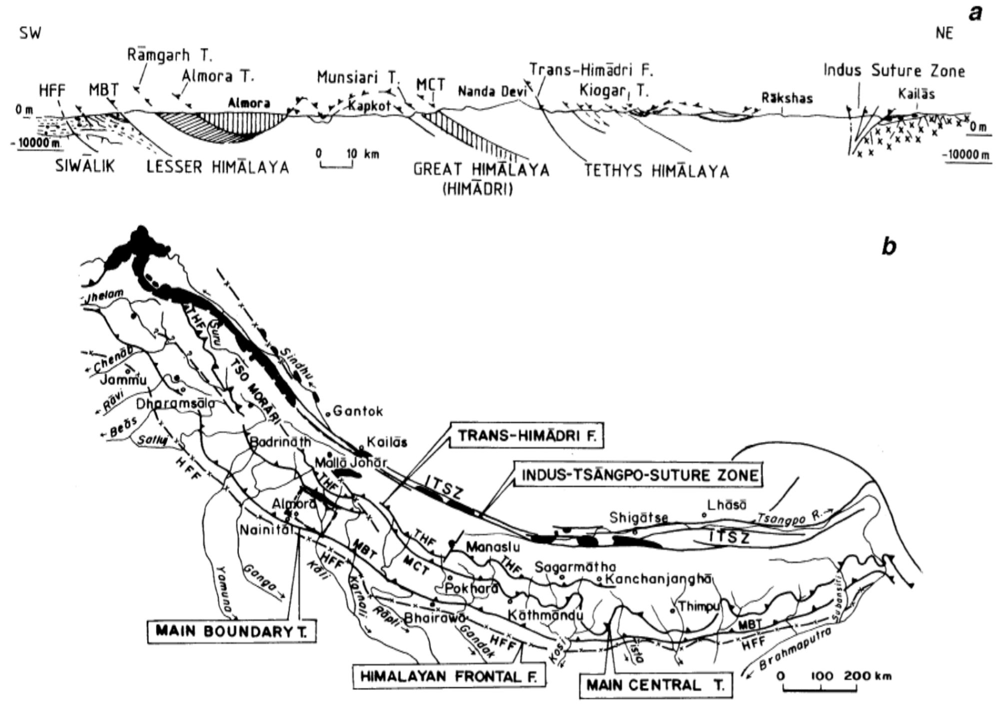

Figure 3. ***a***, Cross-section across the Kumaun Himalaya showing major tectonic planes that define the boundaries of its lithotectonic–physiographic terranes (modified after Gansser[43]). MCT, Main Central Thrust; ***b***, Lateral extent of the terrane-defining boundary thrusts of the Himalaya.

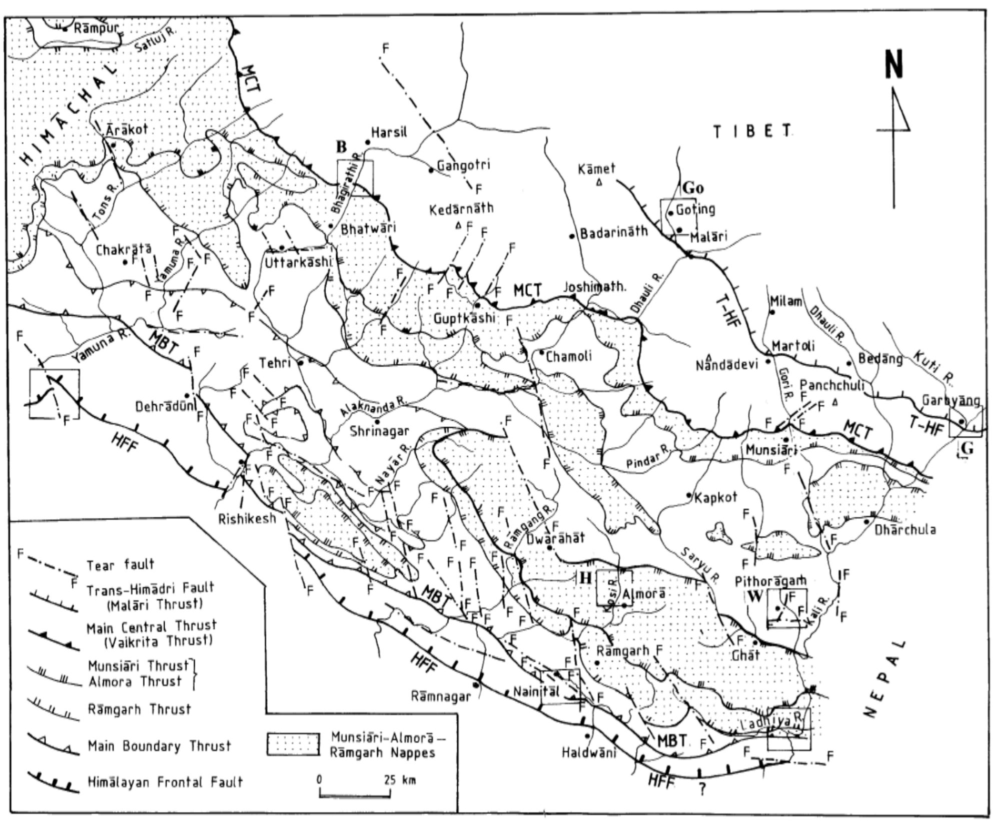

Figure 4. Sketch map showing major thrust faults that define the lithotectonic–physiographic terranes in Kumaun Himalaya and the transverse tear faults (modified after Valdiya[12,24]). Boxes show the locations of the study areas discussed.

of the Tethyan sedimentary pile from its basement of the Great Himalayan complex, was first identified and described as the Malari Thrust by Valdiya[12,13,24–26] and later redesignated as the Trans-Himadri Fault[20,27,28]. Its extension (Figure 3 *b*) in Nepal is known as the South Tibetan Detachment System[29–33] or as the North Himalaya Shear Zone[34]. The T-HF extends northwest into Himachal (Figure 3 *b*), where it has been described as the Tethys Thrust[35–37] and as the Zanskar Shear Zone[38–40]. The T-HF exhibits pronounced dip-slip movements in the Himachal and Kumaun sectors but dominant dextral displacement in Nepal, where it caused lateral extension of the northerly Tethys domain[31,33,34]. In the Sagarmatha massif in north-eastern Nepal, there is offsetting of the order of 35 to 40 km along this thrust[41]. Gravitational collapse structures characterized by backfolding and backthrusting are the hallmarks of the T-HF[27,28].

Downstream of the points of crossing of the T-HF, the wide valleys of the Tethys domain abruptly become narrow gorges that are characterized by vertical to convex walls (Figure 5). A significant development related to the T-HF is the past ponding of rivers upstream of its crossing the valleys (Figure 6). In the Kali valley, the Garbyang terraces (Figure 7) made up of gravels and 'varvities', represent the palaeolake that evolved in the Quaternary[24,42,43]. In the Darma (Eastern Dhauli) at Bedang and in the Gori at Burphu (Figures 6) fluvial terraces represent river-bed gradient decrease and sediment accumulation upstream of the trace of the T-HF. The Western Dhauli (Figure 8) was ponded about 40 ka BP, as

Figure 5. ***a***, Kali gorge near Budhi, downstream of the point of the crossing of the T-HF (Courtesy: S. K. Paul); ***b***, Canyon of the Western Dhauli river in proximity to Trans-Himadri (Detachment) Fault near Malari; ***c***, River Bhagirathi was ponded near Harsil (on the way to Gaumukh) upstream of the fault that crosses the valley. Box B in Figure 4 locates this spot.

borne out by radiocarbon dating of the carbonaceous material in the varvite of the Goting palaeolake[44]. The blockage of the Kali and the Dhauli has been attributed to the advance of glacial moraines[42,44]. However, I attribute the development of impoundment to the reactivation of the T-HF. This phenomenon resulted in the uplift of the downstream (footwall) block, culminating in the river impoundment.

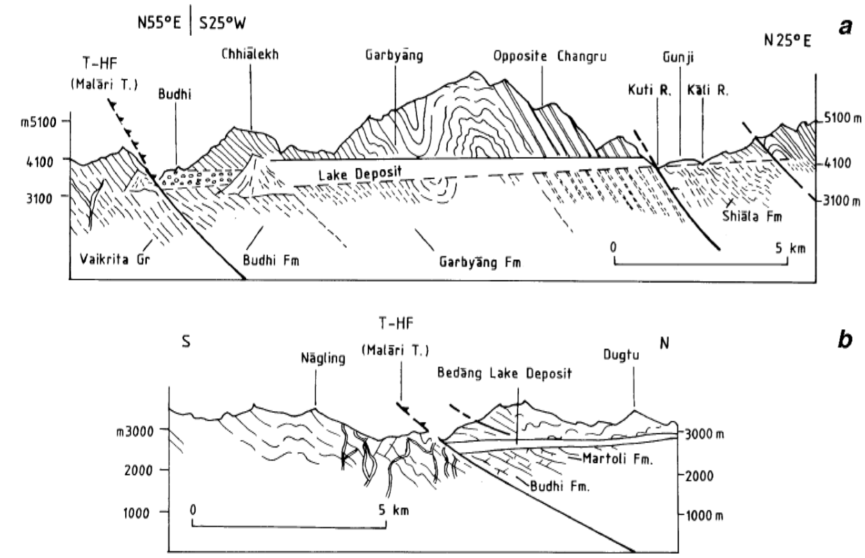

Figure 6. Cross-sections of the Tethys domain in north-eastern Kumaun showing the position of the active Trans-Himadri Fault and the resultant formation of lakes that are today represented by fluviolacustrine deposits in (*a*) Kali valley and (*b*) Darma (Eastern Dhauli) valley (modified after Valdiya[24]). (Location of study area as box G in Figure 4).

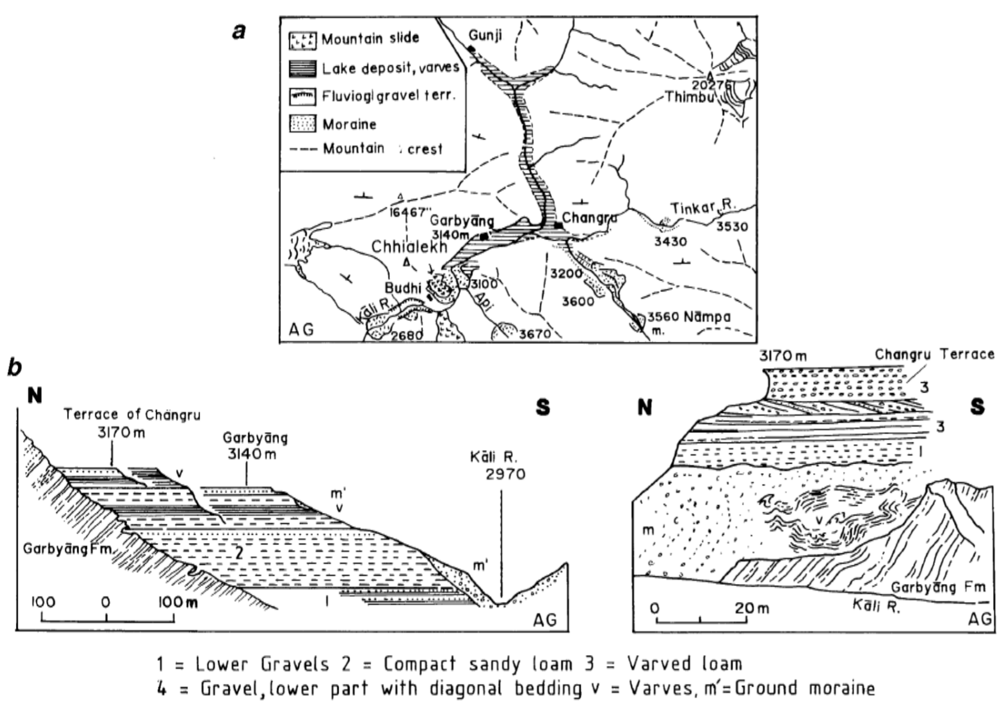

Figure 7. *a*, Extent of the Garbyang palaeolake in the Kali valley; *b*, Lithological succession of the Garbyang palaeolake; *c*, Deformation in the clay beds in the lower part of the Garbyang succession, interpreted here as indicating movements along the fault subsequent to the formation of the lake (after Heim and Gansser[42]).

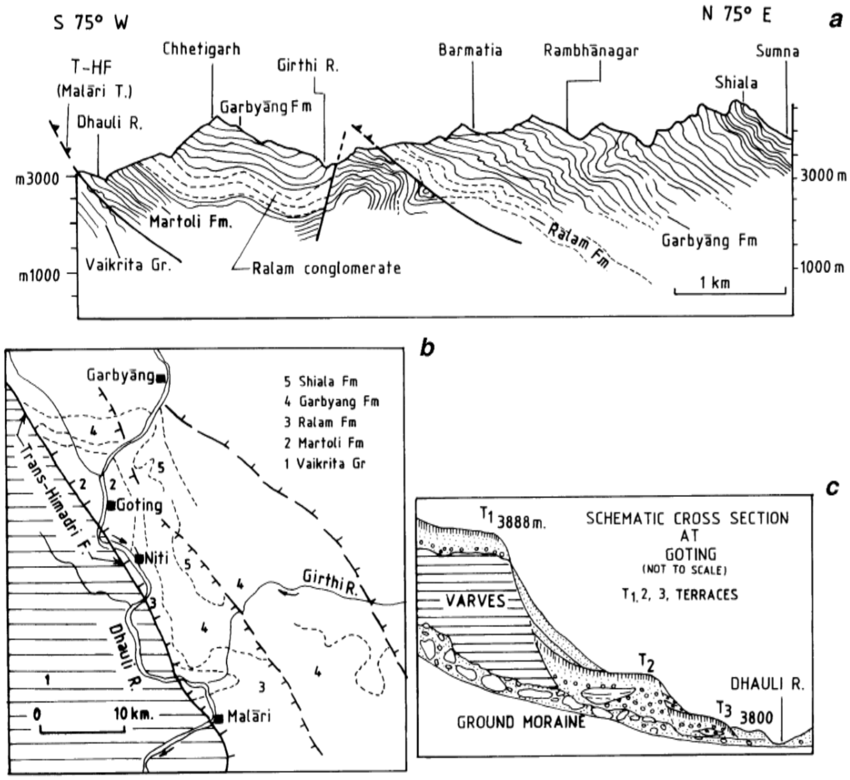

Figure 8. ***a***, Cross-section of the Tethys domain along the valley of the Girthi, a tributary of the Western Dhauli (modified after Valdiya[24]); ***b***, Simplified geological map of the Dhauli valley in which the Goting palaeolake formed upstream of the point of crossing of the T-HF (modified after Pant *et al.*[44]); ***c***, Lithological successions of the Goting palaeolake and the younger fluvial terraces, (after Pant *et al.*[44]). (Location of study areas as box Go in Figure 4).

Knick points and the Main Central Thrust

All through the thrust-delimited Himadri (Great Himalaya) terrane, rivers flow through very narrow deep valleys with nearly vertical slopes. The knick points in the beds of rivers that have deeply cut their courses across the Great Himalaya mark breaks in their gradient – representing more than ten-times increase in the normal gradient (Figure 9). These are related to the crossing of the MCT[45]. These knick points imply uplift on the fault plane delimiting the base of the Himadri terrane.

The MCT Zone is characterized by imbricating thrust planes and severe shearing and shattering of rocks. The deformation of recent lake sediment at Takula in the Tons Valley[20] in northwestern Garhwal and the 34–103 m uplift of fluvial deposits coupled with drainage deflections in the Loharkhet area in southern Kumaun[21] indicate that the faults of the schuppen zone related to the MCT are very active.

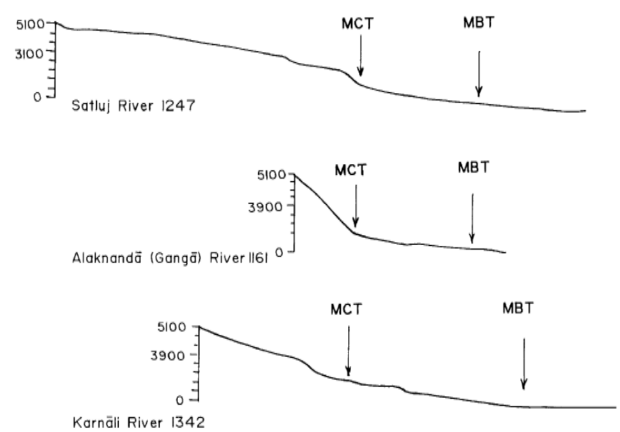

Figure 9. Knick points in the river beds marking the crossing of the Main Central Thrust in the Great Himalaya domain (modified after Seeber and Gornitz[45]).

Reactivation of synclinally folded Almora Thrust

In the Lesser Himalaya, the overthrust nappe of metamorphic and granitic rocks is concordantly folded with the underlying Precambrian sedimentary succession (Figure 4). The delimiting Almora Thrust (AT) is thus folded synclinally, and the nappe is split into a number of sheets by the folded thrust planes. The autochthonous sedimentary succession is likewise faulted – quite severely in the proximity of the AT and its analogues in western Garhwal.

The most conspicuous – and socio-economically extremely useful – feature of the Lesser Himalayan physiography are the terraces that line the valleys, in pairs or otherwise. In the *inner* Lesser Himalaya domain between the MCT and the AT (and its analogues like the Shrinagar Thrust), the valleys of practically all rivers and major streams are lined by these terraces. Most of these terraces are products of sediment deposition following decrease in river-bed gradient. Commonly, there are three levels of terraces. Locally, in the vicinity of certain faults, there may be as many as six. The sharp ending of these stepped terraces at the points of the crossing of the thrust/fault implies that their development is related to the reactivation of the fault[16].

In central Kumaun, where the Kosi river has cut its channel across the synclinal Almora Nappe (Figure 4), an extraordinary development has taken place in the core of the syncline. A 10-m thick, red clay and mud succession atop the fluvial gravel forms the uppermost terrace, constituting a discontinuous rim of sorts (Figures 10 and 11 *b*). The clay–mud succession represents a lacustrine deposit resulting from ponding of the Kosi between the limits of the folded Sitlakhet–Kasun Thrust. The peculiarity of the configuration of the clay deposit implies that the thrust reactivation must have uplifted the footwalls above the river-bed gradient[16,19]. Recent vertical movements on the Sitlakhet–Kasun Thrust are borne out by the narrowing of the old Kosi valley to an approximately 15-m wide canyon (with convex walls) at the point of the crossing of the Kasun Thrust (Figure 11 *a*). Similar development is associated with the Sitlakhet flank of the thrust (Figure 11 *c*). Occurrence of fans of debris-flow deposits adjacent to the active thrust all along its extent in the northern part and the pronounced stream incision in the basin close to the thrust zone, further corroborate the activeness of this thrust.

In eastern Kumaun, the faulting up of the downstream block on an E-W oriented fault that parallels the Almora Thrust (Figure 4) caused ponding of streams and formation of a large lake – the Wadda palaeolake (Figure 12). This palaeolake is represented by a 7–13 m thick succession of black clay intercalated with brownish mud and debris-flow deposits in the upper part. Radiocarbon

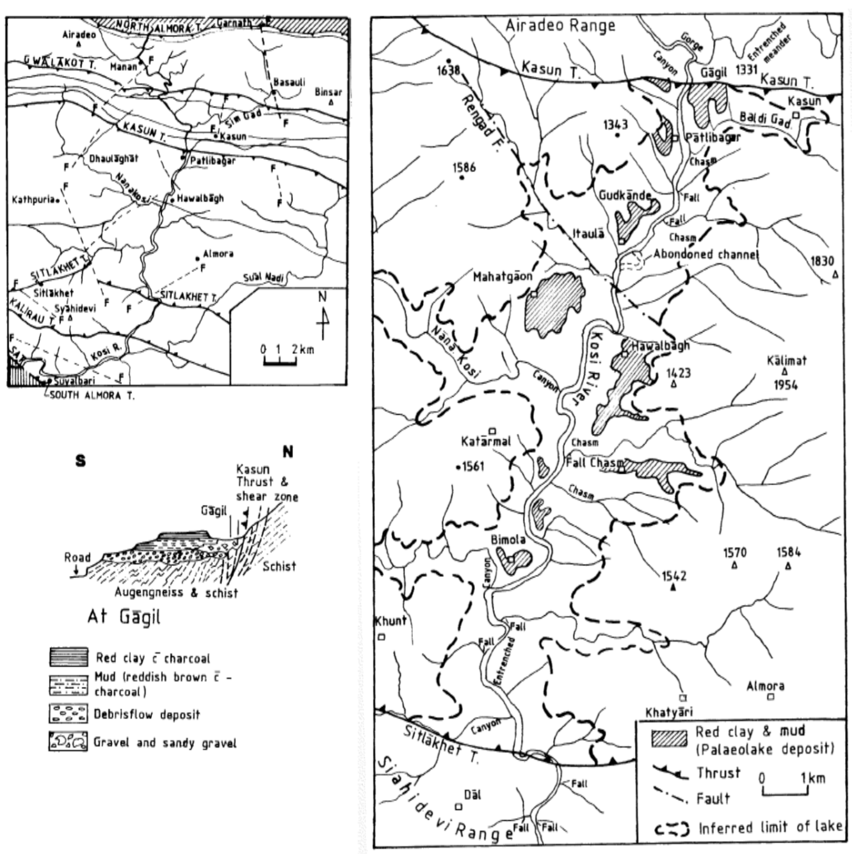

Figure 10. Hawalbagh palaeolake confined to the Kosi valley bound by the synclinally folded Sitlakhet–Kasun Thrust (upper left inset). It is represented by a 10-m thick, red mud–clay succession in the type area (lower left Inset). (Location of the study area shown as the box H in Figure 4).

dating of the black clay shows that the lake originated ~ 36 ka and dried up ~ 2 ka (ref. 46).

The reactivation of the AT and its subsidiary thrusts such as the Gwalakot–Kalirau Thrust and the Kasun–Sitlakhet Thrust (Figure 10, inset) that split the nappe is attributed to horizontal compression of the Lesser Himalayan terrane due to the underthrusting of the Indian plate beneath the Himalaya (Figure 13).

Active faults of the Main Boundary Thrust Zone

The abrupt rise of the outer ranges of the Lesser Himalaya that overlook the 900–1500 m high Siwalik Hills to the heights greater than 2500 m, implies uplift of the former on any of the multiplicity of faults in the MBT Zone (Figures 3 and 4). Thermoluminescence dating of the fault gouges of the MBT near Nainital indicates its reactivation at 70 ± 17 ka (ref. 47, 48). Vertical displacement of the order of 10–30 m in south-eastern Garhwal and 30–40 m in south-central Kumaun of the late Pleistocene to early Holocene fluvial terraces, truncation and uplift of the toe of subrecent colluvial fans (Figure 14 *a*), and the ponding of the rivers upstream of the crossing of the faults of the MBT Zone testify the neotectonic movements[11,17,18]. The river impoundments have since been filled up with gravel and converted into flat stretches in the rivers flowing through the terrains of extreme ruggedness (Figure 14 *b*, *c*).

Not only the MBT but also the faults that are parallel to or branch off from it were responsible for stream ponding and formation of lakes that survive in the high

Figure 11. ***a***, Abrupt narrowing of the old Kosi valley to an approximately 15-m wide canyon with convex walls at the point of crossing of the Kasun Thrust; ***b***, Downstream of the above point the dissected valley of the Kosi is very wide, with gentle slopes that are lined with multiple terraces; ***c***, Kosi gorge just after the crossing of the Sitlakhet flank of the active Kasun–Sitlakhet Thrust.

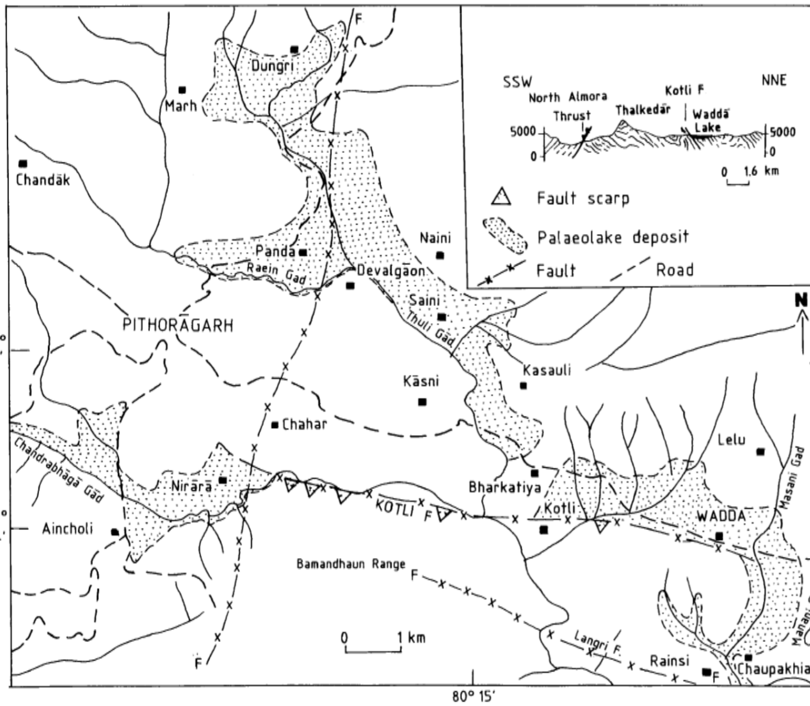

Figure 12. Extent of the Wadda palaeolake that stretches upstream of the active E–W-oriented fault. Parallel to the northern flank of the Almora Thrust this fault caused the downstream block to rise up and block the passages of the streams. (Box W in Figure 4 shows the location of the study area).

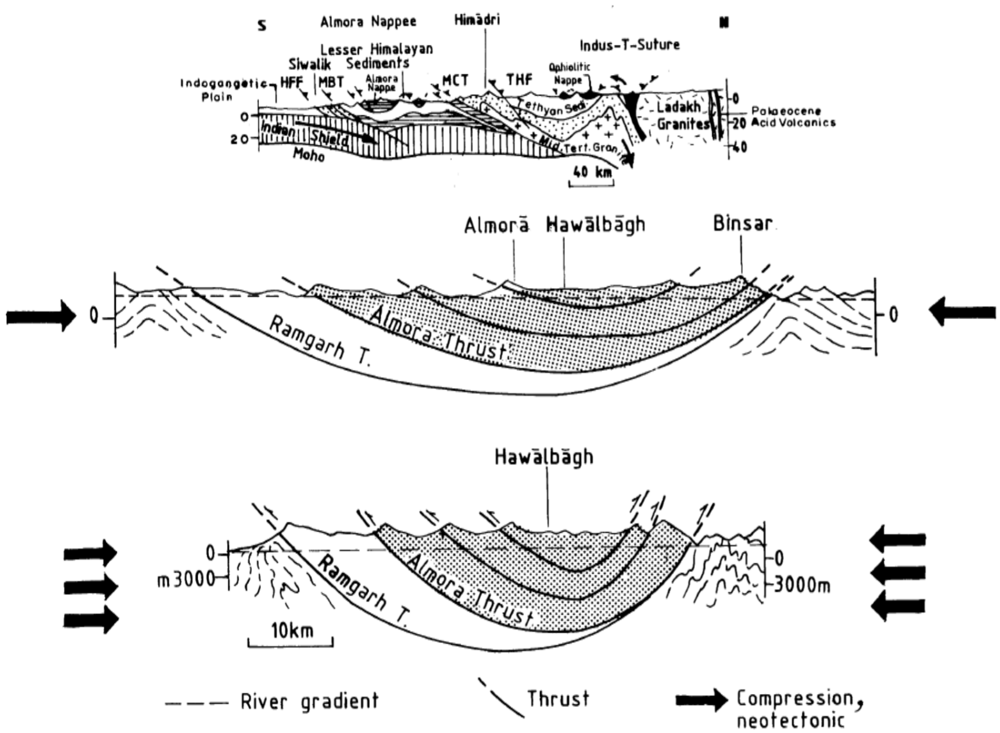

Figure 13. Reactivation of the Almora Thrust and the subsidiary thrusts and faults is attributed to the compression experienced by the Almora Nappe due to the underthrusting of the Indian plate beneath the Himalaya. The upper section, after Gansser[43], shows the structure of the Himalaya and the dynamics of the Indian plate sliding under the Himalaya.

mountain terrain (Figure 15). The Naini*tal* and the Bhim*tal* in south-central Kumaun, and the Renuka*tal* in south-eastern Himachal (*tal* means lake) provide examples of the neotectonic lakes that originated in this manner ~ 40 ka (40 ± 8 to 36 ± 5 ka) ago, as thermoluminescence dating suggests[47,48]. Radiocarbon dates of the bottom sediments of the Bhim*tal* corroborate this age deduction[49]. Mild deformation of the modern sediments in the Naini lake suggests very slow ongoing movements on the causative fault[50].

Figure 14. ***a***, SE of Nainital, a late Pleistocene to early Holocene fluvial terrace T along with younger colluvial cone has been cut and uplifted on the MBT; ***b***, Ponding of the Ladhiya river and rapid sediment filling of the resultant lake upstream of the MBT near Chalthi, south-eastern Kumaun; ***c***, Gravel-filled Ladhiya river at Shim at the Indo-Nepal border, where a fault of the MBT zone has cut the gravel pile and uplifted nearly 70 m.

Holocene uplift of the Siwalik front

The Siwalik front in the Kotabagh area in south-central Kumaun is characterized by a wide apron of gravels of late Pleistocene to early Holocene age. The gravels fill the synclinal basins as well and are known as the Dun Gravel. The Dun Gravel rises 60 to 90 m abruptly above the Indo-Gangetic Plains, is tilted 6–15° northward[11,18,51] or locally folded (Figure 16) and is characterized by triangular facets on its southerly spurs. The streams that drain the Siwalik terrain are deeply incised and locally exhibit conspicuous entrenched meandering as they cross the Himalayan Frontal Fault (HFF). These developments are related to the reactivation of the HFF, first recognized and described by Nakata[51]. In the Dun Valley to the north-west, the reactivation of the faults of the HFF zone[52–53] is associated with the growing folds, uplift of the Siwalik and drainage restriction within the Siwalik terrane[56,57].

In the Yamuna valley, a fluvial terrace forming the apron of the Siwalik foothills (Figure 17) is exposed 20 to 30 m above the stream bed, due to uplift along the HFF at the rate of ≥ 6.9 ± 1.8 mm/yr. The top of the terrace contains 3663 ± 215-yr-old carbonaceous matter[58]. Obviously, the uplift occurred sometime in the later Holocene. The horizontal shortening across the HFF has taken place at the rate of ≥ 13.8 ± 3.6 mm/yr in the Yamuna valley[58], compared to 21 ± 3 mm/yr in southern Nepal[59].

Implications

It is evident that all the terrane-bounding thrusts/faults are active. The faults of the Himalayan front in the south are more active than others. For, it is along this belt that the strains generated by the subducting Indian plate under the Himalaya are being relaxed periodically (Figure 18). Over 96% of the hypocentres of small earthquakes are confined to the crustal level shallower than 15 km, 62% occurring within the upper 7 km (ref. 4). The hypocentral depths of larger earthquakes are 15 to 20 km. The confinement of the hypocentres of earthquakes at depths of 15 to 25 km below the surface implies continuing movements on the Basement Detachment Thrust (BDT)[60–63] (Figure 19). This is the plane along which the pile of Himalayan rocks was uprooted from its foundation (basement) and is prone to decoupling and displacement due to continuing northward push of the Indian plate. The boundary thrusts and faults such as T-HF, MCT, MBT and HFF merge with this BDT, so that the movements along the BDT are propagated to the boundary thrusts. It may be emphasized that the boundary thrusts are locked in some sectors and are active in other parts, as evident from the pattern of

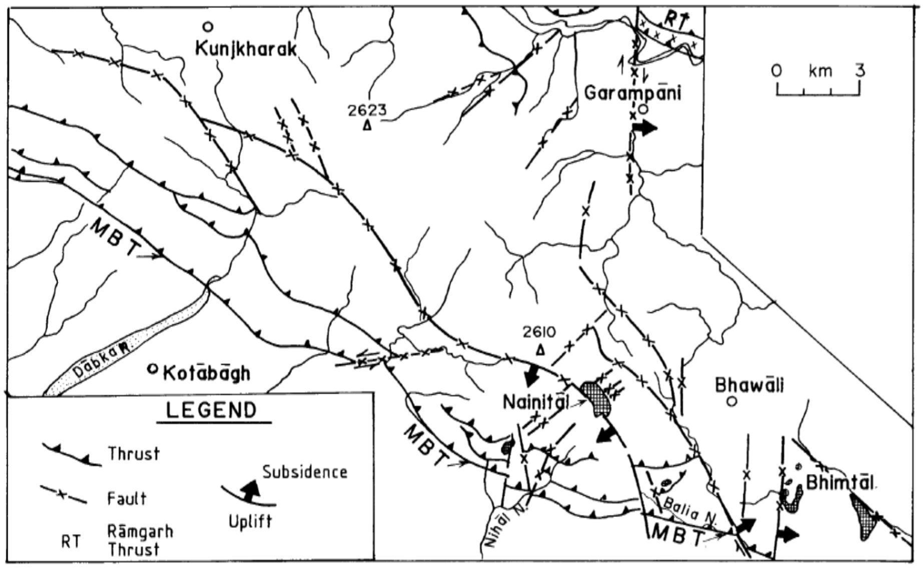

Figure 15. Reactivation of the faults related to or branching off the MBT was responsible for the origin of lakes due to stream ponding in the very high mountains of the outermost Lesser Himalaya (modified after Valdiya[15]).

Figure 16. South of Kotabagh in south-central Kumaun, the late Pleistocene to early Holocene gravel bed is (*a*) tilted 6–15° northwards, and (*b*) folded in the proximity of the HFF.

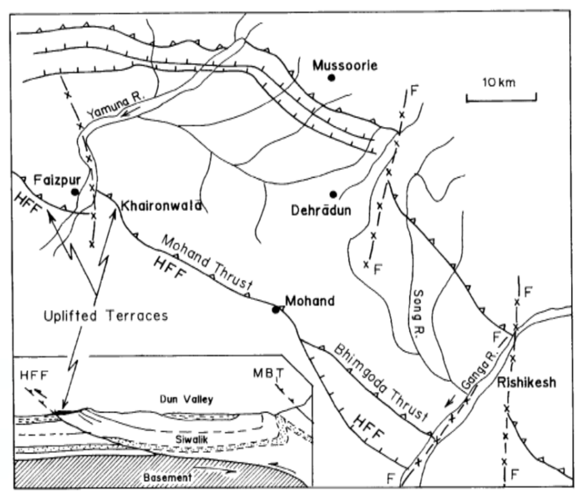

Figure 17. Left-lateral tear fault along the Yamuna river has offset the Siwalik of the Dehradun region. *Inset*: 20–30 m uplift of the fluvial terrace (that contains 3663 ± 215-yearr-old carbonaceous matter). Arrows point to the places where uplifted terraces are seen (modified after Wesnousky *et al.*[58]). The box in Figure 4 gives the location.

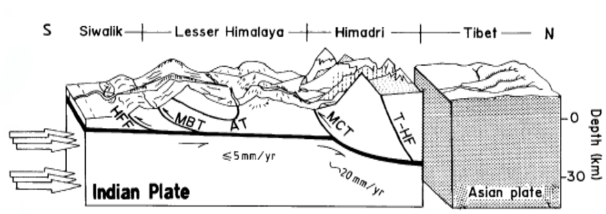

Figure 18. Block diagram showing the joining of the terrane-defining thrusts and faults with the Basement Detachment Thrust. The Himalayan rock pile is detached from its foundation (basement) owing to the continued push of the Indian Plate. (Numbers give the approximate rate of sliding in the present time; modified after Jackson and Bilham[60].)

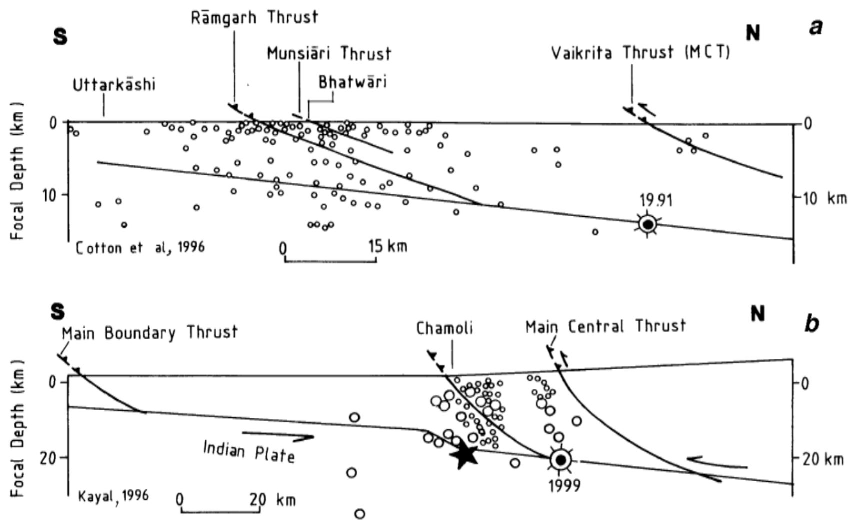

Figure 19. Hypocentres of small and moderate earthquakes in the Uttarkashi and Chamoli areas in Garhwal are confined to 15–25 km below the surface, and define the plane of decoupling and displacement due to continuing northward push of the Indian Plate. ***a***, After Cotton *et al.*[61]; ***b***, After Kayal[63].

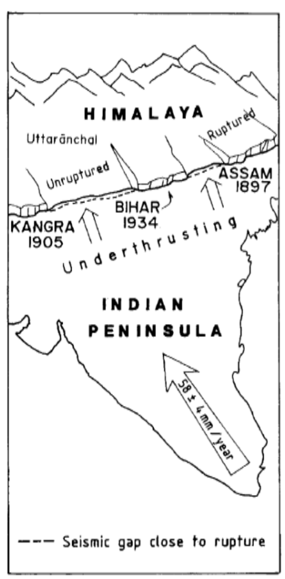

Figure 20. Kumaun Himalaya (Uttaranchal) sector of the Himalayan arc has not ruptured so far in any great earthquake for nearly two hundred years – not since the 1803 event ($M \geq 7.5$) (after Gaur[5]).

seismicity. The whole of the Kumaun Himalaya sector has not been ruptured in any great earthquake ($M \geq 8$) for nearly two-hundred years – not since the 1803 event ($M \geq 7.5$) in Garhwal (Figure 20).

Noting that the sliding rate in the southern front of the Himalaya is of the order of 18 ± 2 mm/yr and that the previous longest known interval between the great events of 1833 AD and 1905 AD was 72 years; it is significant that the Kumaun seismic gap has not been ruptured in any great earthquake ($M \leq 8$) since 1803 (Figure 20). This calls for special attention regarding hazard preparedness in the central sector of the Himalaya.

The continuing uplift related to active faults has kept the four Himalayan terranes in a very youthful state characterized by extreme ruggedness of their terrains, despite the great antiquity of rocks. Repeated movements in the late Quaternary time are responsible for the high elevation of the mountain ranges delimited by active faults. In the central sector of the Himalayan arc, accelerated erosion and slope failures in the fault zones, and rapid silting-up of lakes behind tectonic or debris dams, are the consequences of the resurgent tectonism in the Holocene.

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