Reactivation of Himalayan Frontal Fault: Implications*

K. S. Valdiya

Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore 560 064, India

Youngest of the five terrane-defining faults, the Himalayan Frontal Fault (HFF) is a series of reverse faults that demarcates the boundary of the Siwalik front of the Himalayan province with the alluvial expanse of the Indo-Gangetic Plains. Originated about 1.6 million years ago, it has truncated and attenuated the Siwalik domain. Over large tracts, it is either concealed under younger sediments or has as yet not reached the ground surface and is therefore a blind fault. The nature of this frontal fault varies along its length. Where the hidden ridges of the Indo-Gangetic basement impinge the Himalaya, the mountain front is ruptured and the HFF is repeatedly reactivated. In the sectors intervening these ridges, it is not expressed on the surface, but the ground of the adjoining Indo-Gangetic Plain is sinking, the rivers are shifting their courses and a large tract of the land is waterlogged and characterized by marshes or ponds and by strong seismicity. The northern part of the Indo-Gangetic Plains in the proximity of the ruptured mountain front is also experiencing buildup of tectonic stress. The HFF traces the frontal line of the detachment plane along which the Indian plate is sliding under the Himalaya and generating earthquakes.

Himalaya–Indo-Gangetic Plains boundary

THE nearly 2400-km long line of broadly *en echelon* faults that demarcates the boundary of the Himalaya and the alluvial expanse of the Indo-Gangetic Plains is the youngest of the five terrane-defining faults of the Himalayan province (Figure 1). It was first recognized and named Himalayan Frontal Fault (HFF) by Nakata[1] in southern limit of the Dehradun domain. Nearly at the same time, Talukdar and Sudhakar[2] pointed to the existence of a thrust at the southern edge of the Himalaya in the Ganga Valley near Haridwar.

The HFF had originated in the Later Pleistocene between 1.5 and 1.7 Ma when the foreland basin in front of the emergent Himalaya was intensely compressed, resulting in its breaking up into the rising hilly Siwalik domain and the subsiding Sindhu–Ganga–Brahmaputra depression[3]. The entire Siwalik domain from Potwar in northern Pakistan to the Dihing Valley in Assam was overwhelmed by excessive influx of gravels and muddy debris flows from the fast-rising Himalaya. Understandably, the mountain front was affected by a very strong tectonic upheaval that triggered massive landslides and debris flows on the slopes of the destabilized mountain. This happened about 1.6 million years ago[3].

The boundary fault of tremendous import that remained undetected (and untraced) until quite recently, has been described by different names by different workers—as Foothill Fault by Karunakaran and Ranga Rao[4], and Thakur[5]; as Main Frontal Thrust by Gansser[6] and as Himalayan Foothill Boundary by Raiverman *et al.*[7]. I would adhere to the nomenclature proposed by Nakata[1] who first recognized and characterized it in southwestern Uttaranchal Himalaya between the rivers Ganga and Yamuna (Figure 2).

Nature and geomorphic expression

The HFF is not a continuous fault. Rather, it represents a series of reverse faults that have brought about attenuation of the Siwalik terrane, truncating its fold and faults and placing the Tertiary assemblage of rocks of the Siwalik against the Quaternary sediments of the Indo-Gangetic Plains (Figure 3). While the Siwalik terrane is more than 350 km wide in the Jammu region, it is attenuated to less than 100 km in the Brahmaputra Valley. The Siwalik in the west comprises three structural units, and just one (northern) unit east of Kaladhungi (79° long.) all through the extents of the Siwalik up to the Brahmaputra[8]. This situation is attributed to the truncation of the Siwalik terrane by movements on the fault bounding it against the Indo-Gangetic Plains.

It may be noted that over large tracts, the HFF is either concealed under the gravel deposits of the piedmont zone or has as yet not reached the ground surface (Figure 3).

The nature of the HFF varies along its length from east to west. In the Arunachal Himalaya foothills (Figure 3 *c*) a reverse fault demarcates the Upper Siwalik from the Brahmaputra alluvial plain. In the Nepal (Figure 3 *b*) sector there is no clear expression of the HFF. In the tract between the Sharada and Ganga rivers, it is of the nature of a thrust (Figure 3 *a*). Between the Ganga and Ravi Valleys the reverse fault is of variable inclination, and is affected by strike-slip movements. In the foothills of the

*Dedicated to Prof. S. Ramaseshan on his 80th birthday.

e-mail: nehrucen@jncasr.ac.in

Kashmir Himalaya between the Ravi and Jhelam valleys (Figure 3 *a*), the faulting is not clearly expressed—it is either concealed under the cover of young sediments or is a blind fault, yet to reach the surface of the ground.

According to Raiverman *et al.*[7], the variation of the nature and attitudes of the HFF is due to the strong influence of transverse structural elements (hidden ridges and faults) in the floor of the Sindhu–Ganga–Brahmaputra Basin (Figure 4).

The strongly negative gravity anomaly (up to – 150 mgal) near the foothills of the Siwalik is indicative of a great thickness of the Quaternary sediments adjacent to the boundary between the two domains. This implies considerable sinking of the floor of the Ganga Basin beneath the mountain front.

In the type area in southwestern Uttaranchal (Figure 2), the HFF is a low angle (~ 30°) thrust. Holocene movements on it have lifted up the gravely terraces dated older than 3663 ± 215 yr BP to 20–30 m above the stream level[9]. The uplift (at the rate of ≥ 6.9 ± 1.8 mm/yr and the resultant slip at the rate of 13.8 ± 3.6 mm/yr) is geomorphically expressed in the development of scarps. Slope failure is quite common on their scarps as seen west of Mohand (Figure 5 *a*). According to Yeats and Lillie[10], the HFF is a blind thrust, a part of which is expressed at the surface by anticlinal fold near Mohand, and the down-dip part becoming a decollement horizon. The 1905 Dehradun earthquake ($M \sim 8.0$) is attributed to the reactivation of this decollement plane. The township rose up a few centimetres due to the earthquake.

In the foothills of southcentral Kumaun, the HFF is related to a 60–90 m high escarpment (Figure 5 *b*) having very low sinuosity, and locally broken by triangular facets that are devoid of rills and gullies. On the scarps are exposed the Late Pleistocene Dun gravel grading upwards into younger fluvial gravel deposit, as clearly seen between Kalagarh and Kamola. At Sawalde, Himmatpur and Bailparao, the southward tapering mantle of the gravel is appreciably deformed (Figure 6 *a*). At the mouths of streams and rivulets the younger deposits are lifted 8 to 20 m above the stream level[11,12]. The Dun Gravel is tilted 10–15° northwards in the Ramnagar–Jim Corbett National Park region as clearly discernible along the Kosi Valley (Figure 6 *b*). Significantly, the subrecent gravel terraces, though horizontal, indicate two pulses of uplift subsequent to the tilting of the Late Pleistocene Dun Gravel. In the southern periphery of the Jim Corbett National Park small streams crossing the outer Siwalik range have carved canyons, and are deeply entrenched[11]. Clearly, the outer range of the Siwalik delimited by the HFF has risen up recently.

In the far east in Arunachal Pradesh, the entire outer hill range from west of Itanagar to southwest of Pasighat is made of the Siwalik, overlain by very thick mass of

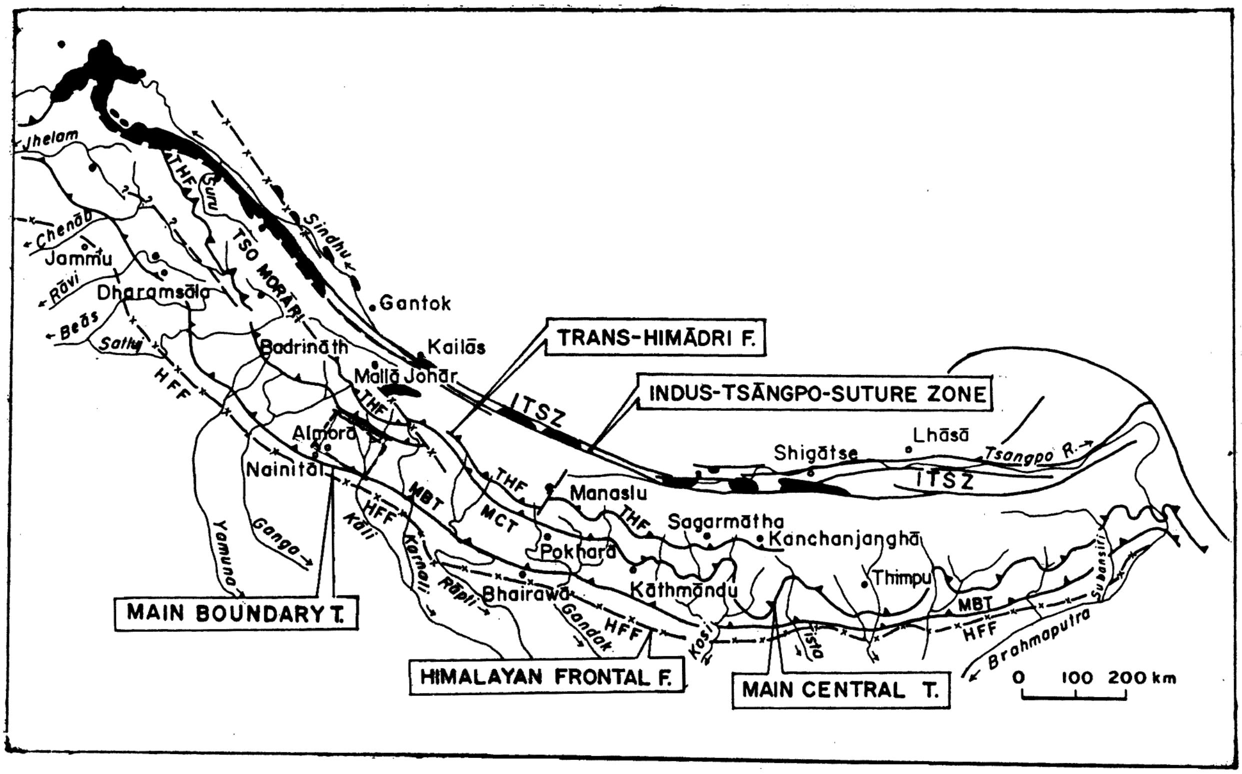

Figure 1. Himalayan Frontal Fault, the youngest of the five terrane-defining faults, delimits the boundary of the Siwalik front with the Indo-Gangetic Plains (From Valdiya[3]).

extensive gravel deposits emplaced by streams and debris flows. The elevation of the young deposits, considerably higher than the Brahmaputra Plain, indicates the extent of uplift related to the frontal fault.

To the northwest, the HFF defining a scarp near Chandigarh is right-laterally offset by a tear fault along the Ghagghar River (Figure 7 *a*). The fault-riven hill is presently experiencing ground subsidence, slope failure and ground swelling, presumably due to reactivation of the HFF. Further, northwest in District Hoshiarpur, the Middle Siwalik of the Soan Valley is thrust upon the Older Terrace along a gently inclined thrust (Figure 7 *b*). Not only has the young terrace been uplifted by 10 m, the sub-recent clay deposit at Hazipur is also pushed up by 2 m (ref. 2).

Impact on Indo-Gangetic Plains

The northern part of the Indo-Gangetic Plains could not have escaped the upheavals related to the reactivation in

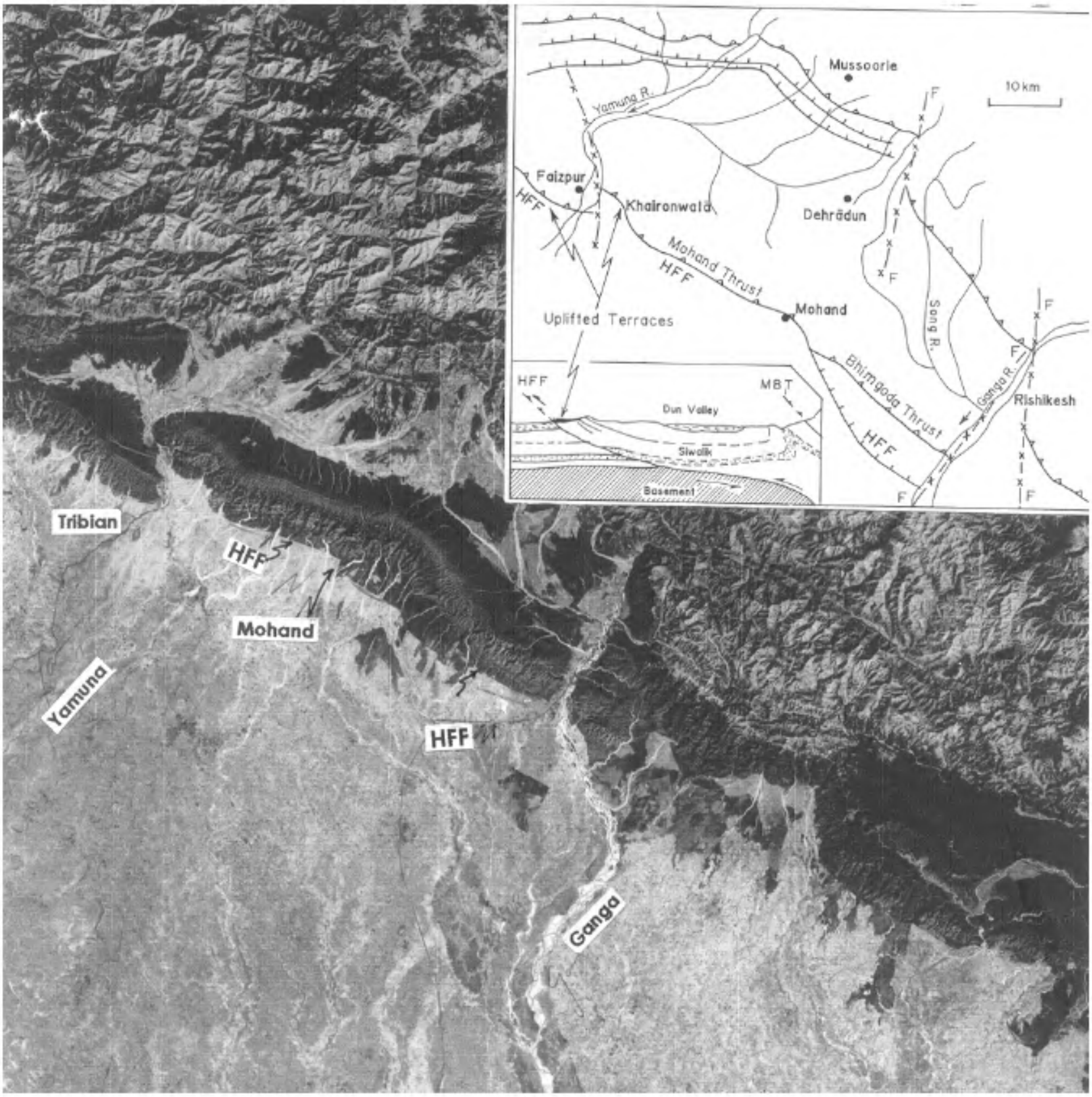

Figure 2. Satellite imagery shows the HFF as a remarkably sharp, nearly linear boundary of the Siwalik with the alluvial expanse of the Ganga–Yamuna rivers. Dark grey tone shows the forested Siwalik front, and the light grey-white part represents the apron of gravel fans at the foothill. The inset shows simplified structural map of this area, based on Yeats and Lillie[10] (Courtesy: NRSA, Hyderabad).

the recent time of the HFF. This is manifest in the development of ridges and depressions in the flat expanses of the Plains. In the foothills of central Bhutan (Figure 8) the ground just south of the foothill has subsided, and a little south risen up 30–35 m, giving rise to an E–W ridge[1]. The depression is characterized by ponds, lakelets and marshes, due to impeded drainage.

In the Sikkim–Darjiling sector the ground surface has been lifted up 80 m along an E–W fault to the east of the Chel River (Figure 9) while there is upwarping and southward tilting in the west[1].

The Nepal foothills (Figure 10) does not show any manifestation of the geomorphic development related to faulting. However, over 180-km long stretch between the Rapti and the Saptkosi, the ground is subsiding at a rapid rate[13]. The ground subsidence has resulted in impeded drainage and ponding of streams on a large scale. The result is the development of marshes that remain under water for eight months in a year (Figure 10). Another result of the ground subsidence and its tilting is the continuing shifting of rivers. The Gandak, for example, has shifted eastward by 105 km over its mega fan in the period

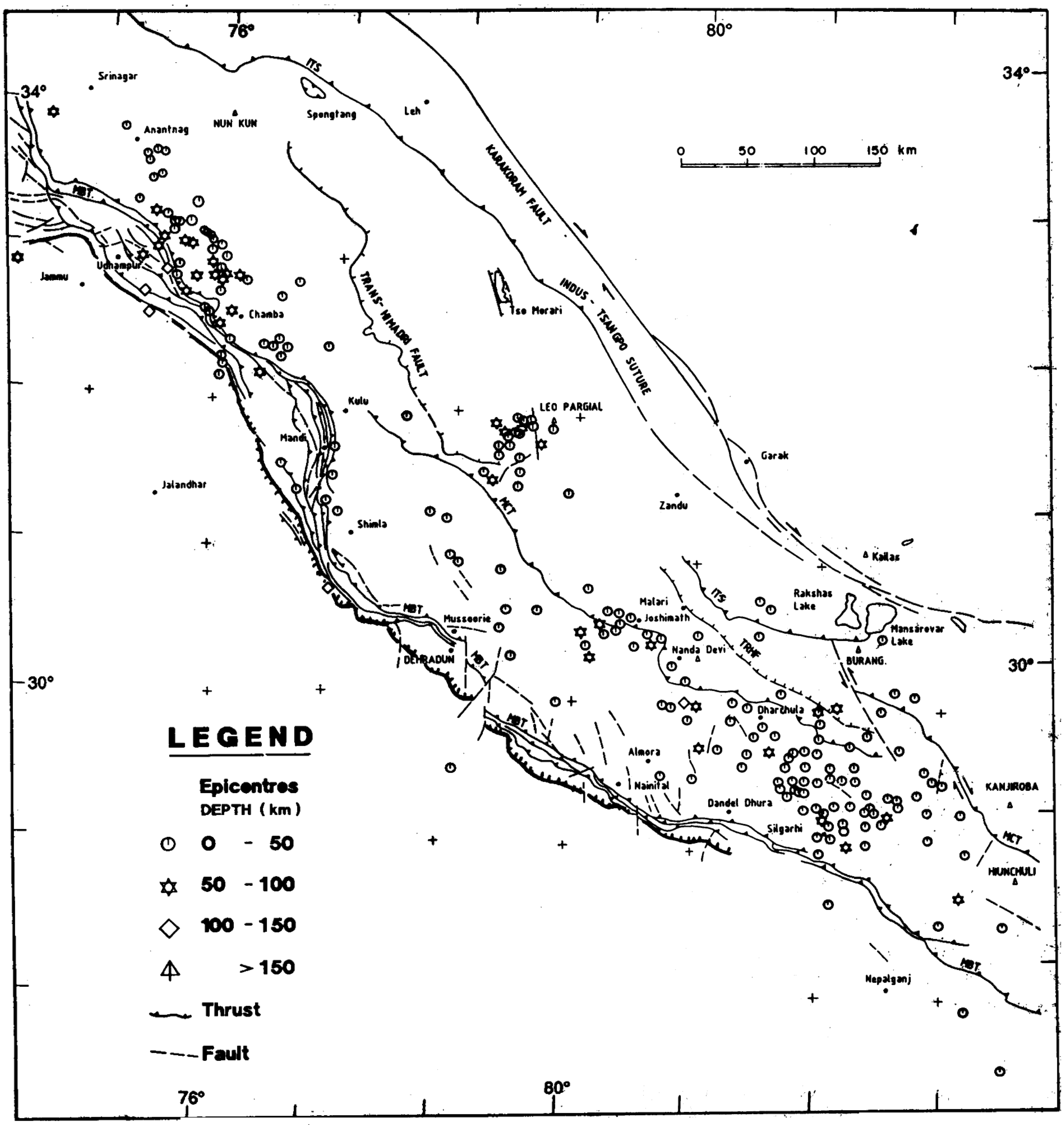

Figure 3 *a*.

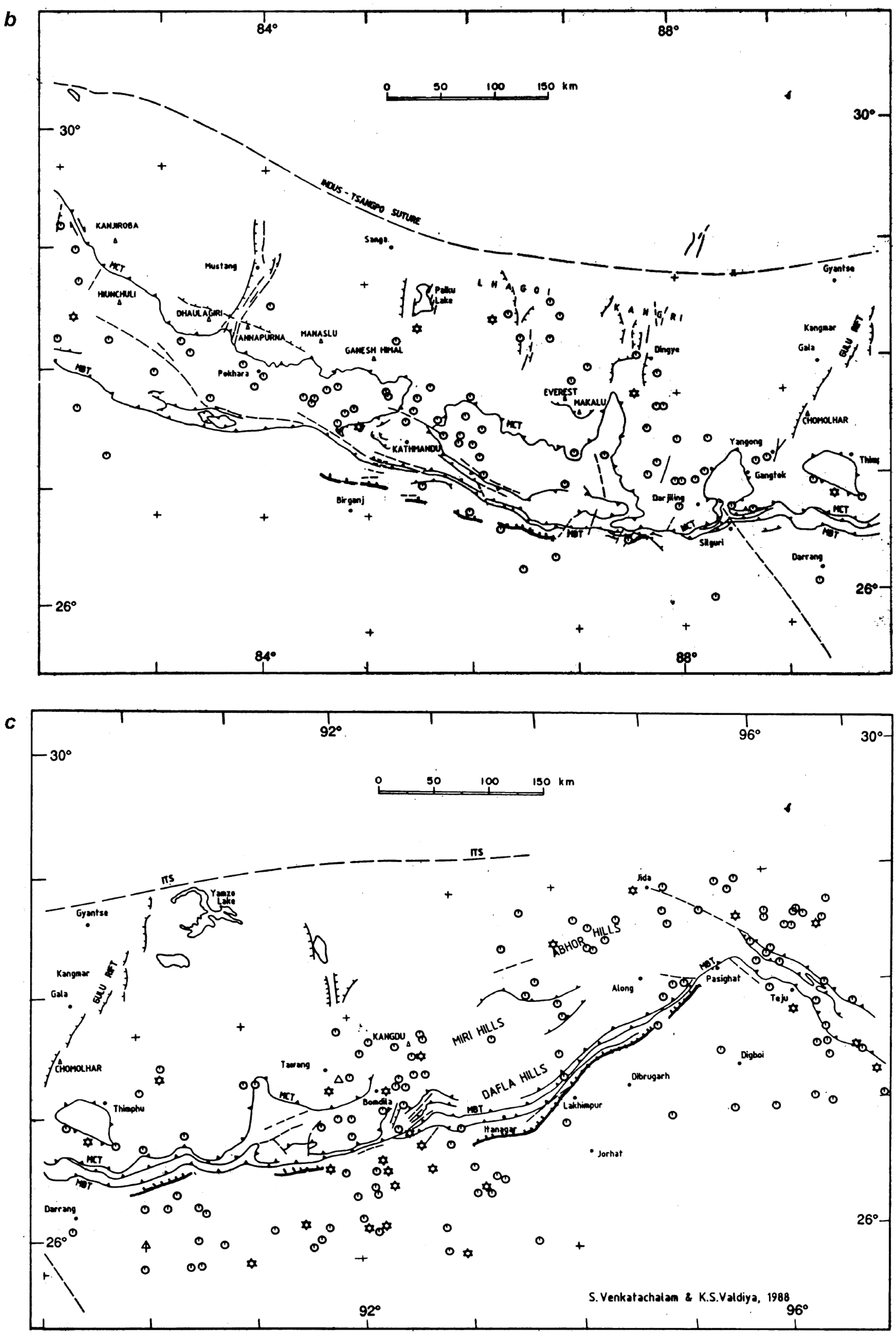

Figure 3. Delineation of the Himalayan Frontal Fault (in three pieces—of western, central and eastern sectors) by the author (Valdiya[11]) on the basis of published works of a number of workers. Note the distribution of epicentres of earthquakes of magnitude $M \geq 5$. There is practically no seismicity in the proximity of the HFF in the central and western sectors.

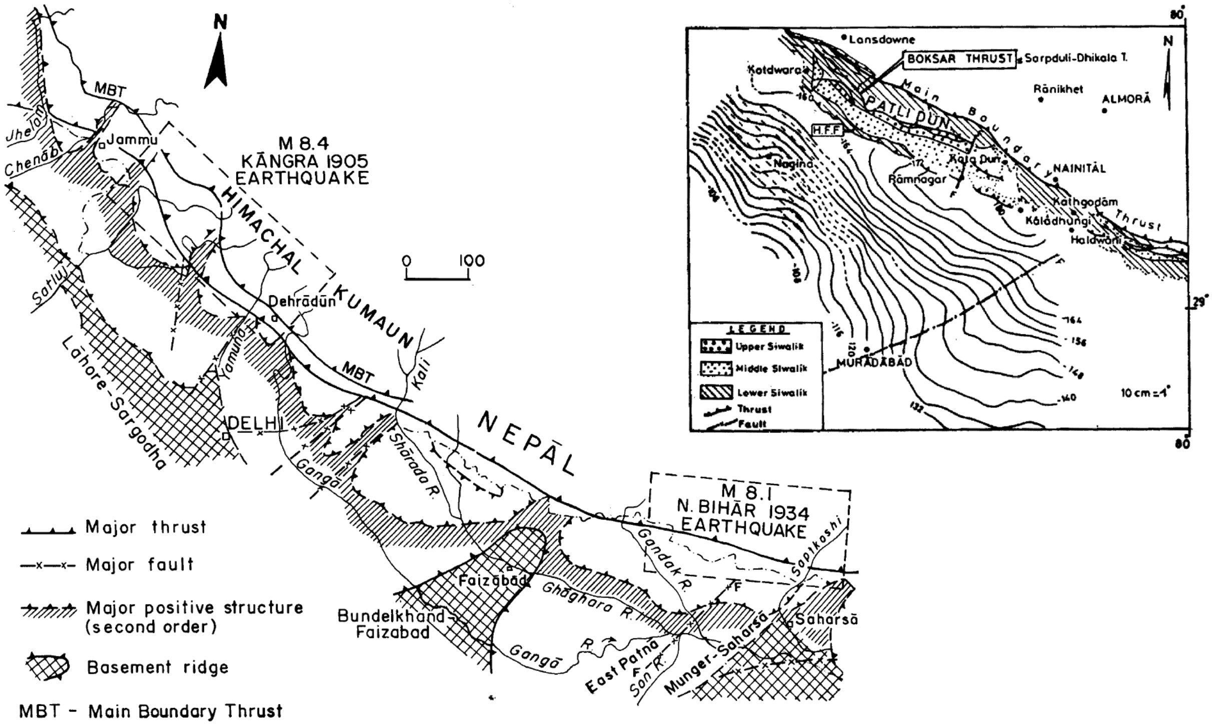

Figure 4. Uncovering of the thick mass of Quaternary sediments would reveal northward extension of the Precambrian ridges, faults and intervening depressions in the basement of the Indo-Gangetic Basin. The inset shows extension of the subsurface Moradabad Fault towards central Kumaun Himalaya (After Raiverman *et al.*[7]).

1935–1975 (ref. 13), and the Kosi moved 112 km in the span of 228 years (1736 to 1964)[14]. The subsidence of the ground has forced the rivers to migrate (through avulsion and cut-off and extensive overbank flooding), resulting in the development of back swamps and lakes[15].

In southcentral Kumaun foothills where the HFF is untraceable, the Gaula flowing past Haldwani is deeply incised into the 15–56 m thick mass of fluvial and debris flow deposits[16]. This implies mild continuing uplift of the piedmont zone. Similar situation is witnessed in the west. As the Ganga enters the Indo-Gangetic Plains, it passes through a zone of erosion, where the soil development is in a poor state. The degree of soil development increases from north to south, implying the rise of the northern part[17]. Significantly, the tilting of the ground is testified by progressive shifting of the Ganga and Yamuna rivers (Figure 11), and the variations in the degree of soil development[17].

On either side of the Yamuna River, there is a pronounced geomorphic development related to ground swelling. The Dehradun–Roorkee road shows one such bulge between Mohand and Chhutmalpur. West of the Yamuna, a 9-m high scarp in the E–W direction, cutting through the alluvial gravel, is manifest in the shifting of a petty stream[9].

Tectonics of fault reactivation

While India converges towards Asia at the rate of 58 ± 4 mm/yr, only one third of the convergence is accommo-

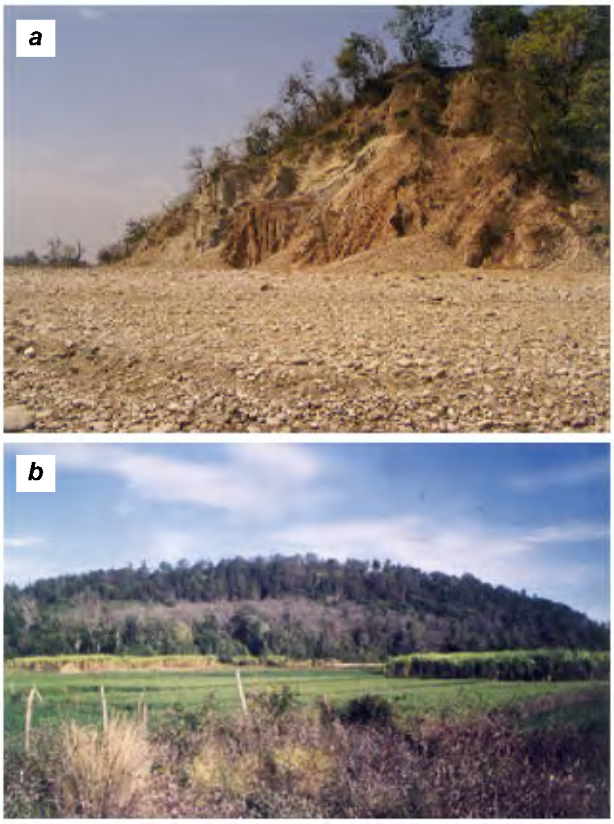

Figure 5. ***a***, Triangular facets on the scarp face of the Siwalik related to the HFF, seen west of Mohand on the Dehradun–Roorkee road. ***b***, Between Ramnagar and Kaladhungi in southcentral Kumaun, the 60-m high scarp exposing Late Pleistocene gravel deposit is a result of the reactivation of the HFF.

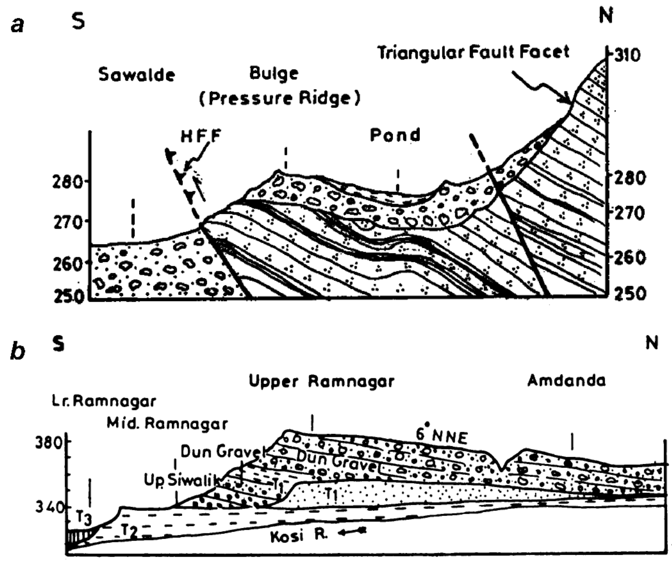

Figure 6. ***a***, Deformed fluvial gravel of sub-recent age (resting on the Siwalik) at Sawalde, west of Ramnagar. ***b***, Dun Gravel of Late Pleistocene age is tilted 10–15° northwards in the Kosi Valley. However, the younger gravel terraces, indicating two pulses of uplift, remain horizontal (From Valdiya[11]).

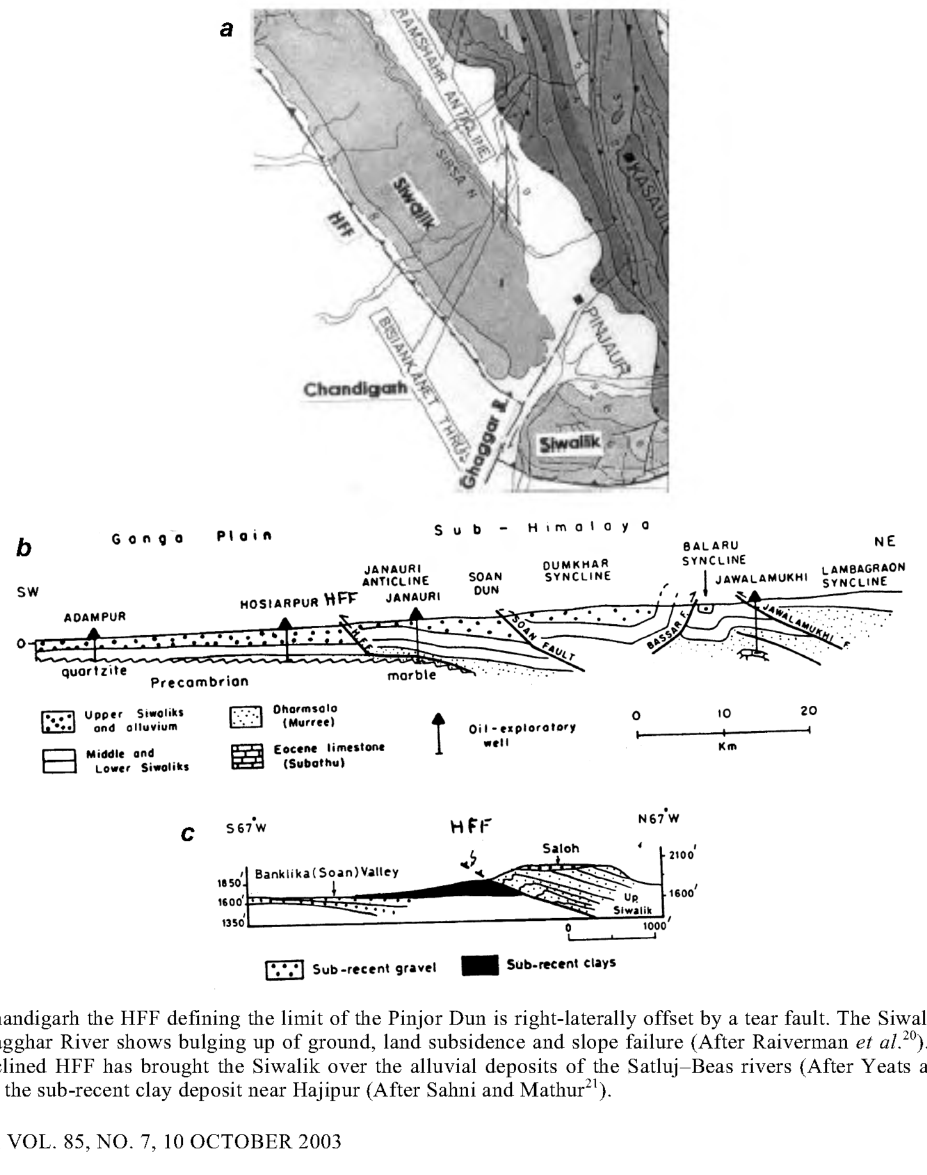

Figure 7. ***a***, Near Chandigarh the HFF defining the limit of the Pinjor Dun is right-laterally offset by a tear fault. The Siwalik hill on the left side of the bank of the Ghagghar River shows bulging up of ground, land subsidence and slope failure (After Raiverman *et al.*[20]). ***b***, In the Hoshiarpur District, the gently inclined HFF has brought the Siwalik over the alluvial deposits of the Satluj–Beas rivers (After Yeats and Lillie[10]). ***c***, Upper Siwalik is pushed over the sub-recent clay deposit near Hajipur (After Sahni and Mathur[21]).

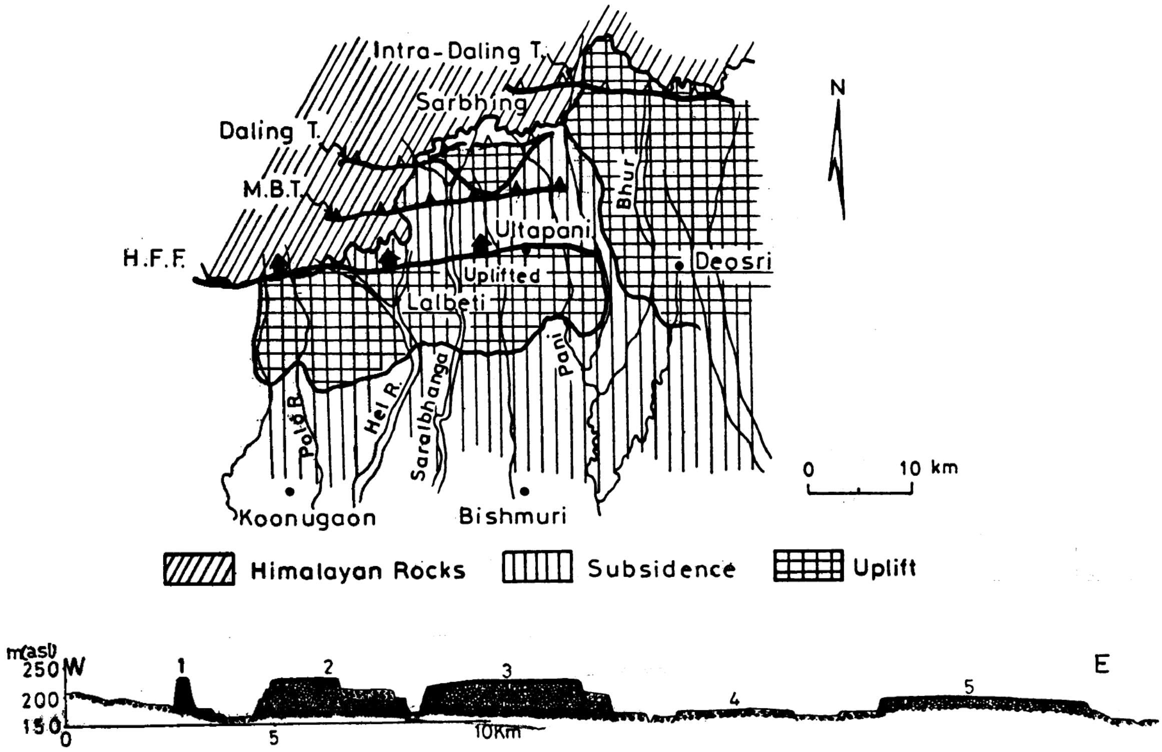

Figure 8. Foothill belt of central Bhutan Himalaya is characterized by ridges and depressions resulting from uplift and subsidence of the ground surface, as the cross section clearly shows (After Nakata[1]).

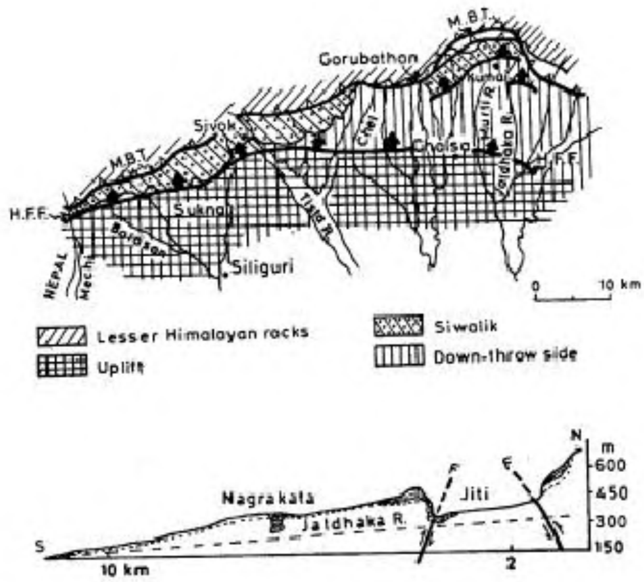

Figure 9. South of the mountain-plains boundary in the Sikkim–Darjiling sector, the ground surface is lifted up, forming a horst and depressions (After Nakata[1]).

dated by the zone of the Main Boundary Thrust. In other words, the Indian Plate, with the prisms of Siwalik and Indo-Gangetic sedimentary assemblages, is sliding under the Himalaya at the rate of 20 ± 4 mm/yr along the Siwalik–Himalaya boundary plane. Understandably, some proportion of the remainder of the convergence is being accommodated by other faults south of the Main Boundary Thrust, including the HFF and others within the Indo-Gangetic domain. Most parts of the faults in the latter domain are either untraced or hidden under the pile of younger sediments. Surely, the reactivation of these faults is responsible for the various physiographic changes taking place in the north Indian plains.

As already pointed out, the foothill belt is not behaving uniformly all through its extent. Some parts are ruptured and resurgent tectonically, others are showing signs of tectonic turmoil, and some others remain quiet and unaffected. It seems that where the ridges in the basement of the Indo-Gangetic Basin[7] such as the Aravali–Haridwar High, the Satpura–Munger–Saharsa High, the Meghalaya–Mikir High (Figure 4) impinge the Himalaya, the mountain front is ruptured (Figure 3 *a* and *c*) and the HFF is repeatedly reactivated. In the intervening sectors between these hidden ridges, the HFF is not expressed—at least not on the ground surface (Figure 3 *b*). Presumably the frontal boundary is a blind fault in these sectors, and the ground is sinking owing to its reactivation deep underground. This is particularly evident in northern Bihar where the ground has subsided maximally and continues to sink at the rate of 0.2 to 0.3 mm/yr (ref. 15), the rivers are continually changing their courses, and the land is recurrently ravaged by floods. It is here that the thickness of the sedimentary accumulation is maximum (> 7000 m),

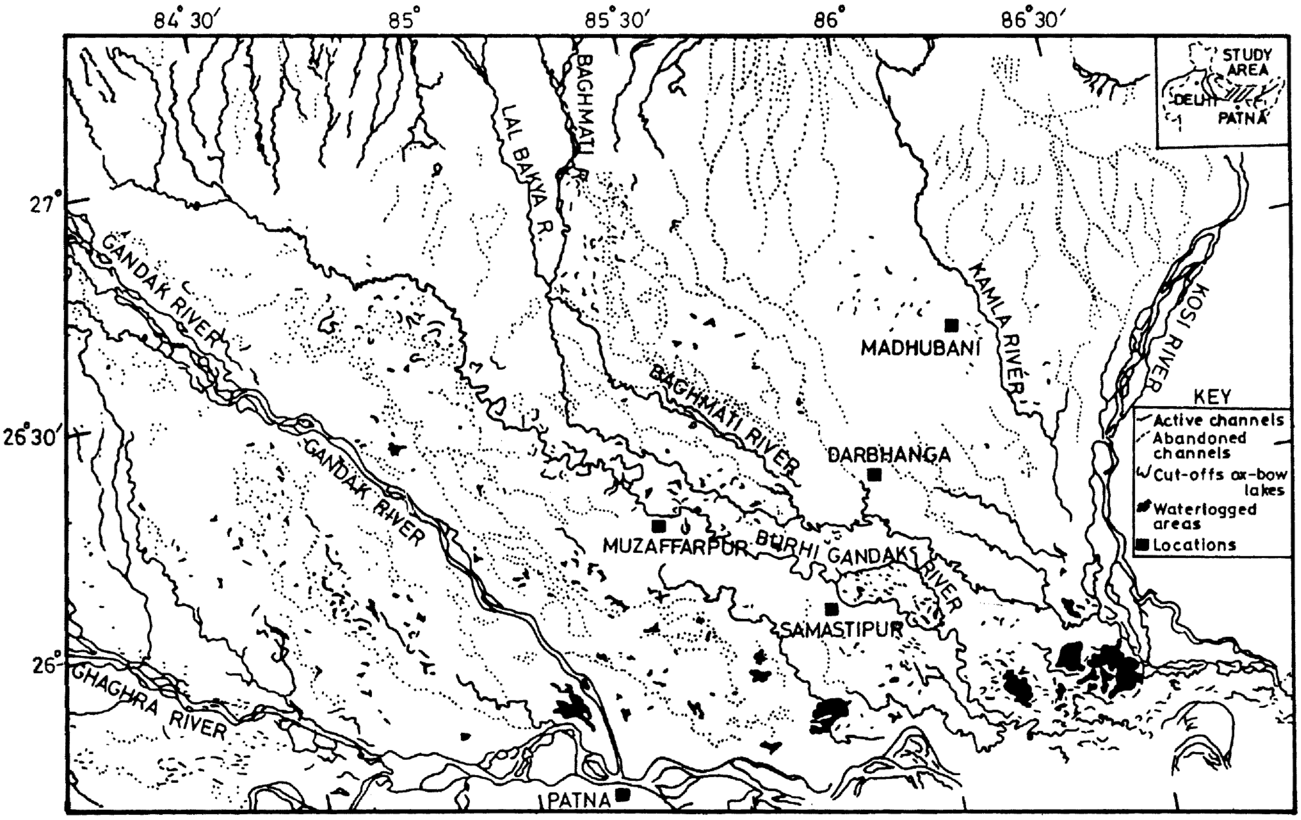

Figure 10. Gravel surface of northern Bihar is subsiding resulting in progressive shifting of rivers and development of waterlogging, swamps and lakes due to impeded drainage (From Sinha[14]).

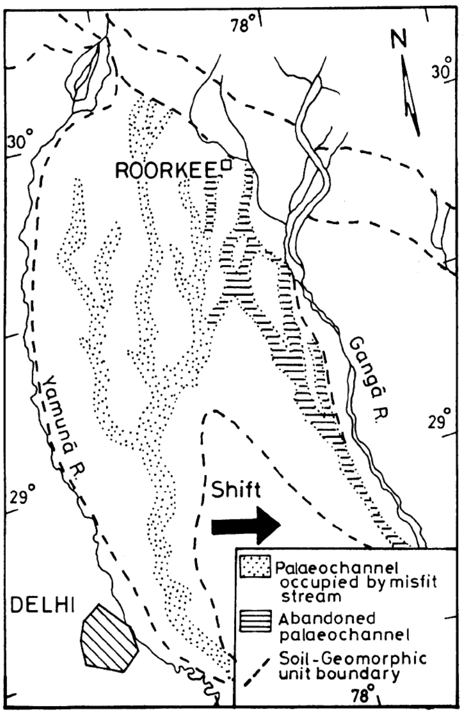

Figure 11. Shifting channels of the Ganga and Yamuna rivers owing to tilting of the ground surface close to the HFF (From Kumar *et al*[17]).

the Quaternary alone accounting for 1500–2500 m. The regions have served like depocentres, and are known as Sharada and Gandak depressions (Figure 4).

Palaeoliquefaction studies in the Motihari–Sitamarhi–Madhubani region in northern Bihar show that in addition to the recorded 1883 and 1934 great earthquakes ($M \geq 8.0$), there were two more seismic events of equal magnitude—one between 1700 and 5300 yr BP and the other earlier than 25,000 yr BP[18]. This seismically active region covering more than 12,000 km^2 area, is known as the 'slump belt'.

Analysis of electrical conductivity data indicates extension northwards beneath the Himalaya of the mid-crustal conductor[19]. The conductor dips down gently at the HFF, its upper surface correlating with the plane defined by the hypocentres of moderate earthquakes and the limit of microseismicity. It is obvious that the HFF traces the frontal line of the detachment plane separating the crystalline basement (Indian plate) from the pile of the Himalayan rocks (Figure 12). It is this plane along which sudden, swift movements generate earthquakes. The logical surmise is that whenever unlocking of the part stuck for a period of time takes place along this detachment plane, there is an earthquake (Figure 12). The longer the

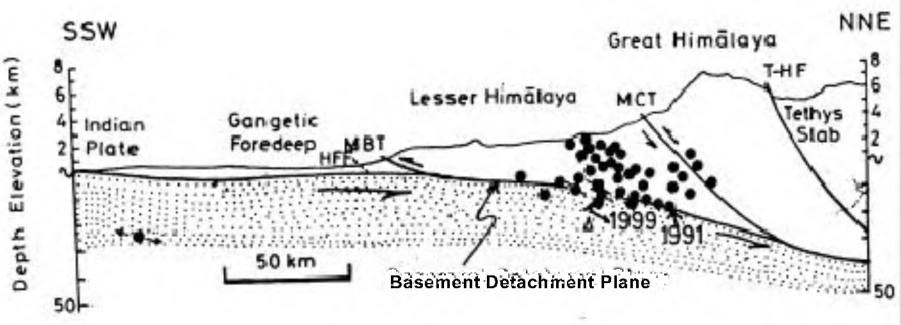

Figure 12. HFF traces the front of the Basement Detachment Thrust—the plane along which the Indian plate is sliding under the Himalaya. Movements of this plane generate earthquakes.

period of locking of movement, the greater is the magnitude of the earthquake.

The corollary of this surmise is that the identification of the sectors where strain buildup is taking place would require intensive monitoring in the zone of the HFF of geomorphic changes, drainage deflection and impediments, and of geophysical variations.

The study of the HFF reactivation has, therefore, great bearing on hazard management.

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