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The Himalayan Frontal Fault System

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Abstract

The Himalayan Frontal Fault System marks the principal present-day tectonic displacement zone between the stable Indian plate and the Himalaya, with a convergence rate of 10-15 mm/yr, about one-fourth of the convergence rate between the Indian and Eurasian plates. The Himalaya rides over the Indian plate on a décollement fault that does not cut basement. The surface expression of this fault is the discontinuous Himalayan Front fault (HFF) between the Sub-Himalaya and Indian plains and a set of anticlinal ridges and synclinal valleys (duns) that accommodates slip on the buried décollement fault by folding. In addition to the HFF, displacement occurs on more interior faults which reactivate the Main Boundary fault (MBF) mainly as dip-slip, down to the south faults, but locally as down-to-the-north faults with strike-slip components, principally in Nepal. Reactivated segments of the Main Central thrust (MCT) are right lateral strike slip, down to the north. Instrumental seismicity is concentrated along a zone about 50 km wide in the Lesser Himalaya south of and close to the MCT. Great earthquakes have struck the Himalayan Foothills in 1897, 1905, 1934 and 1950, leaving large seismic gaps between the 1934 and 1905 events and west of the 1905 event. Smaller seismic gaps were at least partially filled by smaller earthquakes in 1803, 1833, 1869, 1930, 1943, 1947 and 1991. None of these earthquakes resulted in primary surface faulting, although uplift accompanying and following the 1905 earthquake is consistent with a low-angle blind thrust.

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INTRODUCTION

The Indian-Eurasian collision took place in Paleogene time, with the collision zone marked by the now-inactive Indus suture zone of Tibet and India and the Main Mantle thrust zone of Pakistan (*fig. 1*). South of the collision zone, a Precambrian crystalline slab (High Himalaya) and a relatively complete cover of Phanerozoic rocks (Tethyan Himalaya) were thrust southward over a more discontinuous sedimentary sequence of Proterozoic and younger age (Lesser Himalaya) along the Main Central thrust (MCT) of Nepal and India. In Pakistan, a Precambrian to Mesozoic sequence, including crystalline Paleozoic and Precambrian rocks, was thrust southward over relatively unmetamorphosed Mesozoic and Cenozoic strata along the Khairabad thrust of YEATS & HUSSAIN (1987) or Panjal thrust of CALKINS et al. (1975). The sequence beneath the Khairabad and Panjal thrusts is itself thrust southward over a molasse sequence of early Tertiary to Pleistocene age (Sub-Himalaya) along the Main Boundary fault (MBF) (*fig. 1*).

Most of these south-verging structures are inactive today, although some parts of them, most particularly the MBF, have been reactivated by younger deformation accompanying the Himalayan Front fault (HFF) of India and Nepal and the Salt Range thrust of Pakistan. This active zone of deformation between the Sub-Himalaya and the Indian plains is here called the Himalaya Frontal Fault System. We describe this system between two major syntaxes

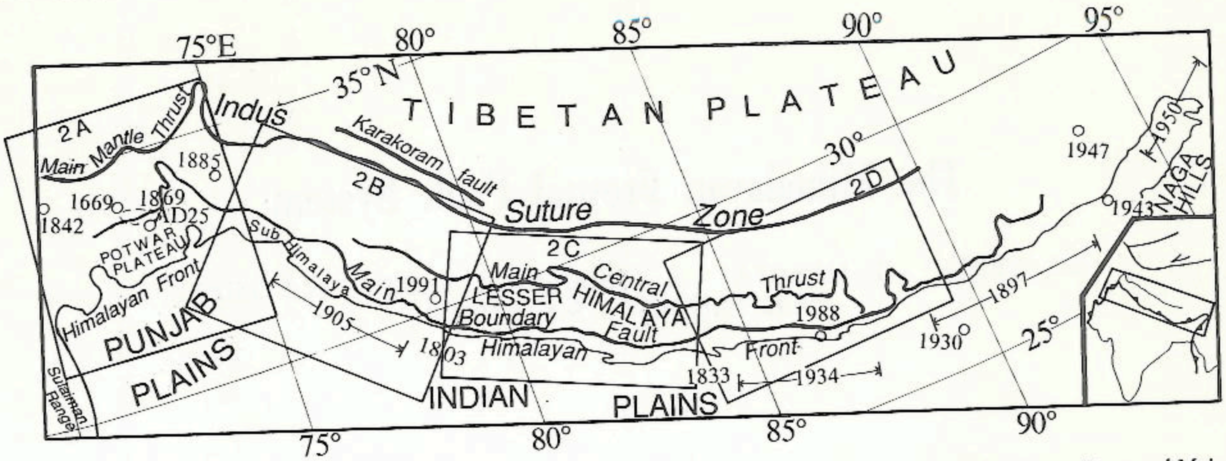


Fig. 1 - Major subdivisions of the Himalaya. Tethyan Himalaya and High Himalaya lie between Indus Suture Zone and Main Central thrust. Dates identify large earthquakes that have affected the Himalayan foothills. The earthquakes of 1897, 1905, 1934, and 1950 were M≥8. Based on earthquakes of the last two centuries, seismic gaps occur between the 1803 and 1833 earthquakes, between the 1869 and 1905 earthquakes, and possibly between the 1934 and 1897 events and between the 1897 and 1950 events. *Figure 2a-d* locations shown.

at the Brahmaputra River on the east and near the Indus River on the west, recognizing that a zone of active deformation extends beyond both of these syntaxes. Our map of this fault system (*fig.* 2) does not extend east of 89.5° E because we know of no modern mapping of active fault traces east of Bhutan. For a discussion of the MBF in this area, see VALDIYA (this volume).

The Himalayan Frontal Fault System marks the principal tectonic displacement zone at the northern boundary of the stable Indian plate. In northern Pakistan, this zone takes up 9 to 14 mm/yr of convergence (BAKER et al. 1988), and in India and Nepal, the estimated convergence rate is 10 to 15 mm/yr (LYON-CAEN & MOLNAR 1985). These values are only slightly lower than the rate of underthrusting of India beneath the Himalaya of 18 mm/yr based upon the slip on large earthquakes in the twentieth century (MOLNAR & DENG 1984). This is only part of the 44 to 61 mm/yr convergence rate between the Indian and Eurasian plates (MINSTER & JORDAN 1978), indicating that the remainder of the convergence is taken up farther north.

The Himalayan foothills have long been known to be seismically active (*fig. 3*). Part of the foothill zone of India and Nepal was ruptured by a series of seven devastating earthquakes beginning in 1803 and ending in 1950 (OLDHAM 1882; SEEBER & ARMBRUSTER 1981; SEEBER et al. 1981). The most recent damaging earthquake in India occurred in October, 1991. No surface faulting has yet been identified from any of these events. Active faulting in the Himalayan foothills was first described in India by NAKATA (1972), in Nepal by NAKATA et al. (1984), and in Pakistan by YEATS et al. (1984). The active-fault map presented here is compiled from these sources as well as KAZMI (1979), FORT et al. (1982), McDOUGALL (1988), ARMIJO et al. (1986, 1989), NAKATA (1989), YEATS & HUSSAIN (1989), SHRODER et al. (1989), MADIN et al. (1989), NAKATA et al. (1991) and VALDIYA (this volume).

CHARACTERISTICS OF THE HIMALAYAN FRONTAL FAULT SYSTEM

Structural geology

The boundary between the Sub-Himalaya and the Indian plains is marked by a discontinuous zone of reverse faulting called the Himalayan Front fault (HFF) by NAKATA (1975, 1989). The sub-Himalaya itself is marked by anticlinal ridges faulted on their flanks; growth of these anticlines appears to be taking place at the same time as movement on the HFF. The anticlinal ridges (and accompanying synclinal valleys to the north) occur in the northwest Himalayan front between the Sutlej and Ganga rivers and in the central Himalayan front between the Ghaghara and Bagmati rivers. In

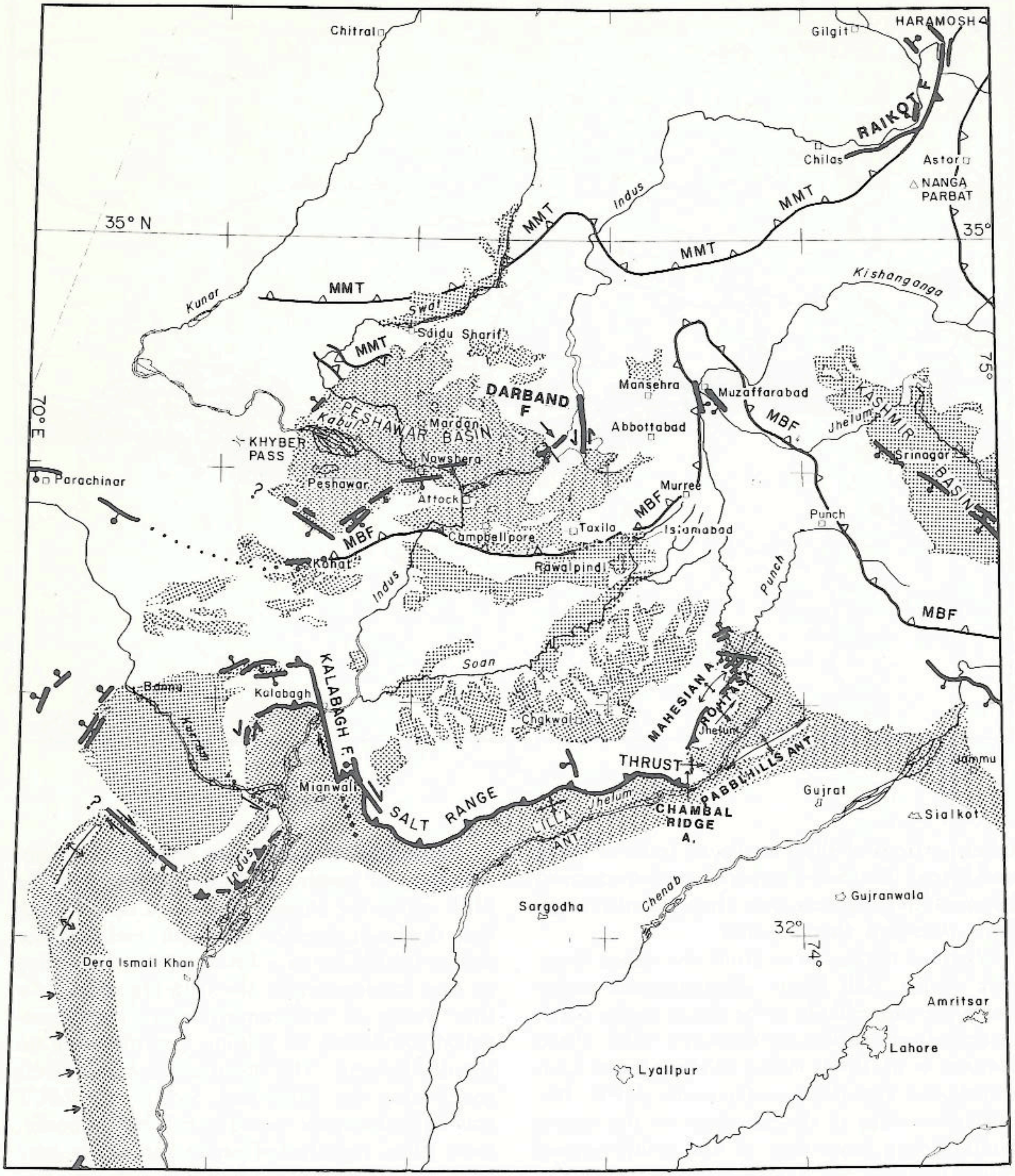
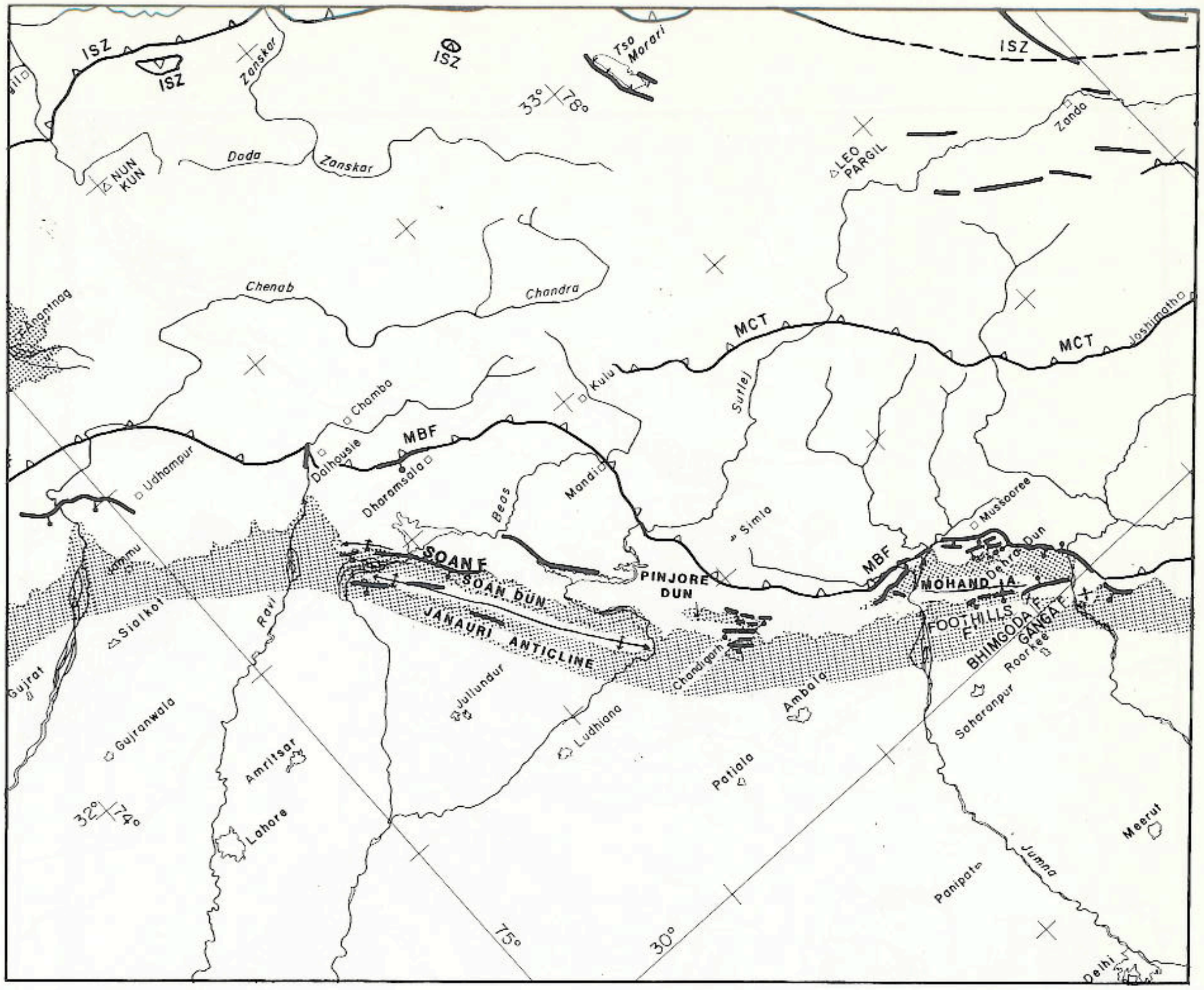


Fig. 2 - Active faults and folds of the Himalaya. (a) Pakistan Himalaya and Kashmir, (b) Northwest Himalaya, (c) Central Himalaya, (d) Eastern Himalaya. Active faults shown by heavy line; bar and ball on downthrown side, filled barb symbol on hanging wall of active thrust. Lighter lines show major faults of the Himalaya (generally inactive) with open barb symbol on hanging wall. MBF = Main Boundary fault, MCT = Main Central thrust, MMT = Main Mantle thrust, ISZ = Indus suture zone. Shaded pattern denotes areas underlain by late Quaternary sediments.



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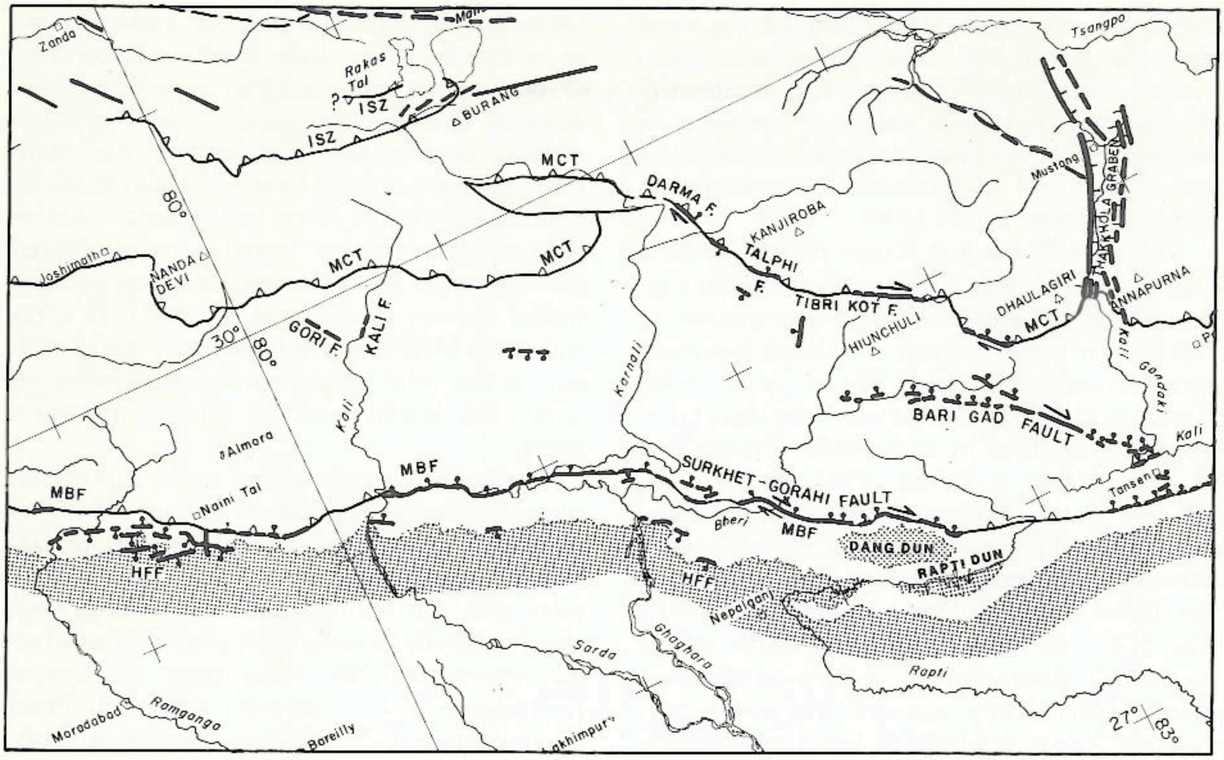
other portions of the Himalayan front of India and Nepal, the Sub-Himalaya is characterized by north-dipping imbricate thrusts rather than folds (VALDIYA this volume).

Farther north, away from the range front east of the Kali River, discontinuous active faults are more likely to be down-to-the-north or right-lateral strike slip (NAKATA 1975, 1989; NAKATA et al. 1984). Many of these faults have reactivated the down-to-the-south MBF. Because the sense of displacement of the active faults differs from that of the south-verging thrust bringing the Lesser Himalaya over the Sub-Himalaya, NAKATA (1989) prefers the name MBF (Main Boundary fault) in place of MBT (Main Boundary thrust) to emphasize the point that this fault may not now be acting as a thrust.

Subsurface cross sections through the Sub-Himalaya of northwest India suggest that the HFF marks the surface trace of a décollement that does not involve basement rocks of the Indian shield (YEATS & LILLIE 1991). According to this interpretation, the Sub-Himalaya is a thin wedge of sedimentary rocks being propelled southward by folding and thrusting on the décollement. The down-to-the-north faults reactivating the MBF and, locally, the MCT may be backthrusts rooted in this basal décollement. The right-lateral strike-slip faults may represent transfer zones between different segments of the HFF (YEATS & LILLIE 1991), or they may reflect a southeastward propagation of the right-lateral Karakoram fault into the Lesser Himalaya and Sub-Himalaya of central Nepal (Talphi fault and Bari Gad fault of NAKATA


Zanda
Rakas Tal
ISZ
BURANG
MCT
DARMA F.
KANJIROBA
Mustang
THAKKHOLA GRABEN
Joshimath
NANDA DEVI
TALPHI F.
TIBRI KOT F.
DHAULAGIRI
ANNAPURNA
GORI F.
KALI F.
HIUNCHULI
Karnali
Kali
Gandaki
BARI GAD FAULT
Almora
MBF
SURKHET-GORAHI FAULT
Naini Tal
Tansen
Bheri
DANG DUN
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Ramganga
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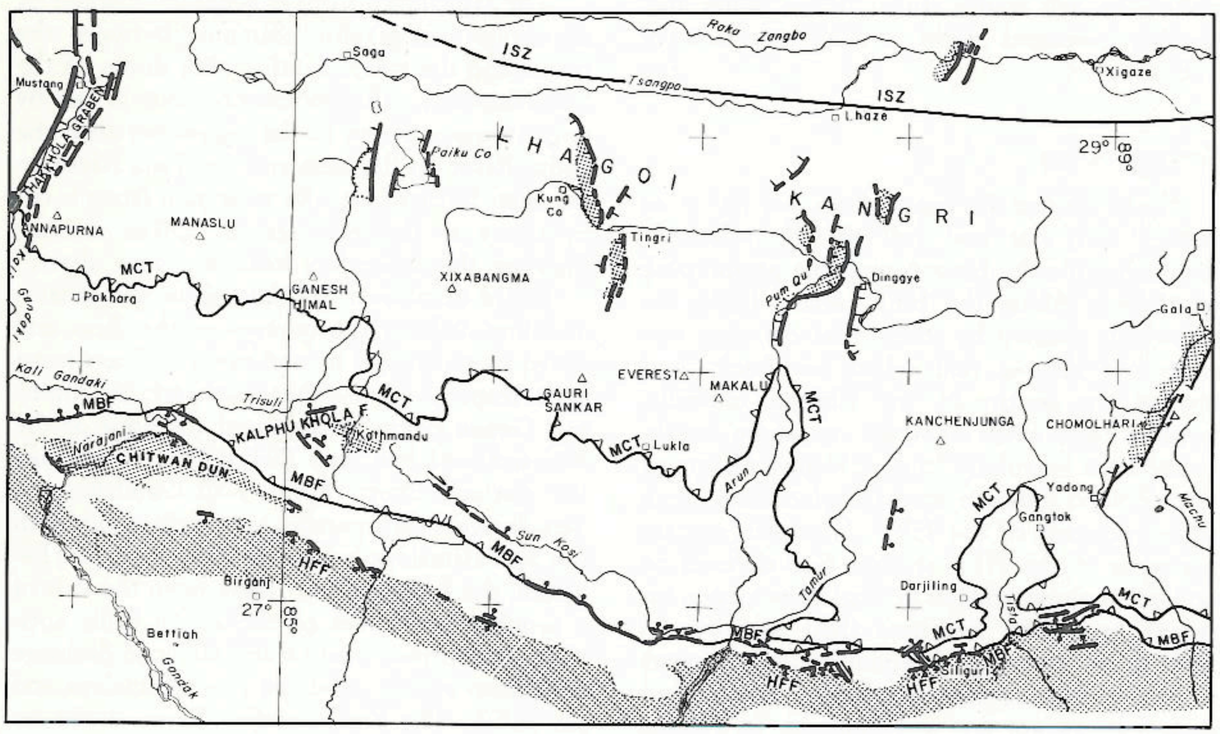
Raka Zangbo
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MANASLU
MCT
GANESH HIMAL
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GAURI SANKAR
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Kathmandu
Lukla
KANCHENJUNGA
CHOMOLHARI
CHITWAN DUN
Narajani
MBF
Arun
Yadong
Gangtok
Sun Kosi
HFF
Birganj
Tamur
Darjiling
Tista
Bettiah
Gandak
Siliguri

2d

1989). ARMIJO et al. (1989) dispute the view that the Karakoram fault propagates southeastward into Nepal. However, it is noteworthy that normal faults with east-west extension in southern Tibet are found northeast of the Karakoram fault and its southeastern projection in Nepal (NAKATA et al. 1990).

In Pakistan, the Salt Range thrust is a more continuous structure bringing Eocambrian evaporites and a Phanerozoic cover over molasse of the Jhelum plain without involving basement rocks of the Indian shield (YEATS et al. 1984; BAKER et al. 1988). To the east, the thrust dies out and is replaced by active folds (PENNOCK et al. 1989; YEATS & LILLIE 1991). To the west, the Salt Range thrust terminates at the Kalabagh right-slip fault, west of which active thrusting is present at the foot of ranges west of the Indus river (MCDOUGALL & KHAN 1991). The MBF, as much as 150 km north of the active Salt Range thrust, underwent displacement 2.1 to 1.8 m.y. ago, and it is now largely inactive (YEATS & HUSSAIN 1987) with the exception of discontinuous segments near Parachinar (*fig. 2a;* NAKATA et al. 1991). Farther north, a set of discontinuous north-side-up reverse faults in the southern Peshawar basin is marked by a zone of instrumental seismicity; unlike the Salt Range thrust, these faults may involve basement rocks (YEATS & HUSSAIN 1989).

Geomorphology

Faults shown in heavy lines on *fig. 2* as active, with bar and ball on the relatively downtrhown side, have prominent geomorphic expression. Along the HFF, active faults are commonly marked by scarps that cut river terraces and alluvial fans which are back-tilted toward the north. In the Bhutan foothills, streams have been dammed up along north-facing fault scarplets. In east Nepal, offsets of terrace risers indicate lateral displacement along some segments of the HFF. However, certain segments of the HFF are not well defined by faulted features, though geological evidence for recent movement confirms their activity. In some areas, warping of fluvial surfaces appears to be a surface expression of blind thrusts, but such features are not well mapped. In Pinjore Dun and Dehra Dun in west India and the Darjeeling foothills in east India, surface traces of imbricate thrusts of the MBF are reactivated as south-facing fault scarplets cut on alluvial fan surfaces. On the other hand, in the Nepal Himalaya, reverse-fault scarplets on the MBF along the foot of steep Lesser Himalayan slopes indicate separation down to the north. Active fault traces are rather straight, and elongated pressure ridges are common even across younger fluvial terraces (NAKATA et al. 1984). In areas where the MBF has a northwesterly strike oblique to the relative plate motion, right-lateral strike slip is observed by offsets of terrace risers.

Evidence for right-lateral strike-slip displacement includes right-lateral stream offsets of tributaries of the Bari Gad River in central Nepal. A fault exposure in terrace gravels indicates that the faulting has been taking place along vertically-dipping fault planes. North-facing reverse scarplets along these reactivated fault segments are commonly observed. From Landsat imagery, the Karewa Terrace in Kashmir is dislocated, and south-facing fault scarps are well-defined along NW-SE striking fault segments. Satellite imagery suggests that active faults in much of the northwestern Himalaya are yet to be mapped in the field.

The Himalayan front is generally marked by an abrupt topographic boundary between the plains and the steep, south-facing slopes of the Sub-Himalaya. This mountain front is cut by only 16 major rivers in the region between the Indus River on the west and the Tista River on the east; farther east, the mountain front is cut by rivers at shorter intervals. Other streams draining the mountain front are very short.

In the northwest Sub-Himalaya, the Janauri anticline deflects the courses of the Beas and Sutlej rivers around its northwest and southeast ends, respectively. Farther southeast, the Jumna and Ganga rivers flow around the ends of the Mohand anticline near Dehra Dun. In Nepal, the Karnali, Bheri, Rapti, Kali Gandaki, and Trisuli rivers flow parallel to anticlinal ridges in the Sub-Himalaya before crossing them. In Pakistan, the Jhelum River flows down the axis of a syncline northwest of the Pabbi Hills anticline. In contrast, major rivers show no drainage deflection as they cross the High Himalaya and the MCT. The Kali Gandaki River shows no drainage deflections as it carves one of the

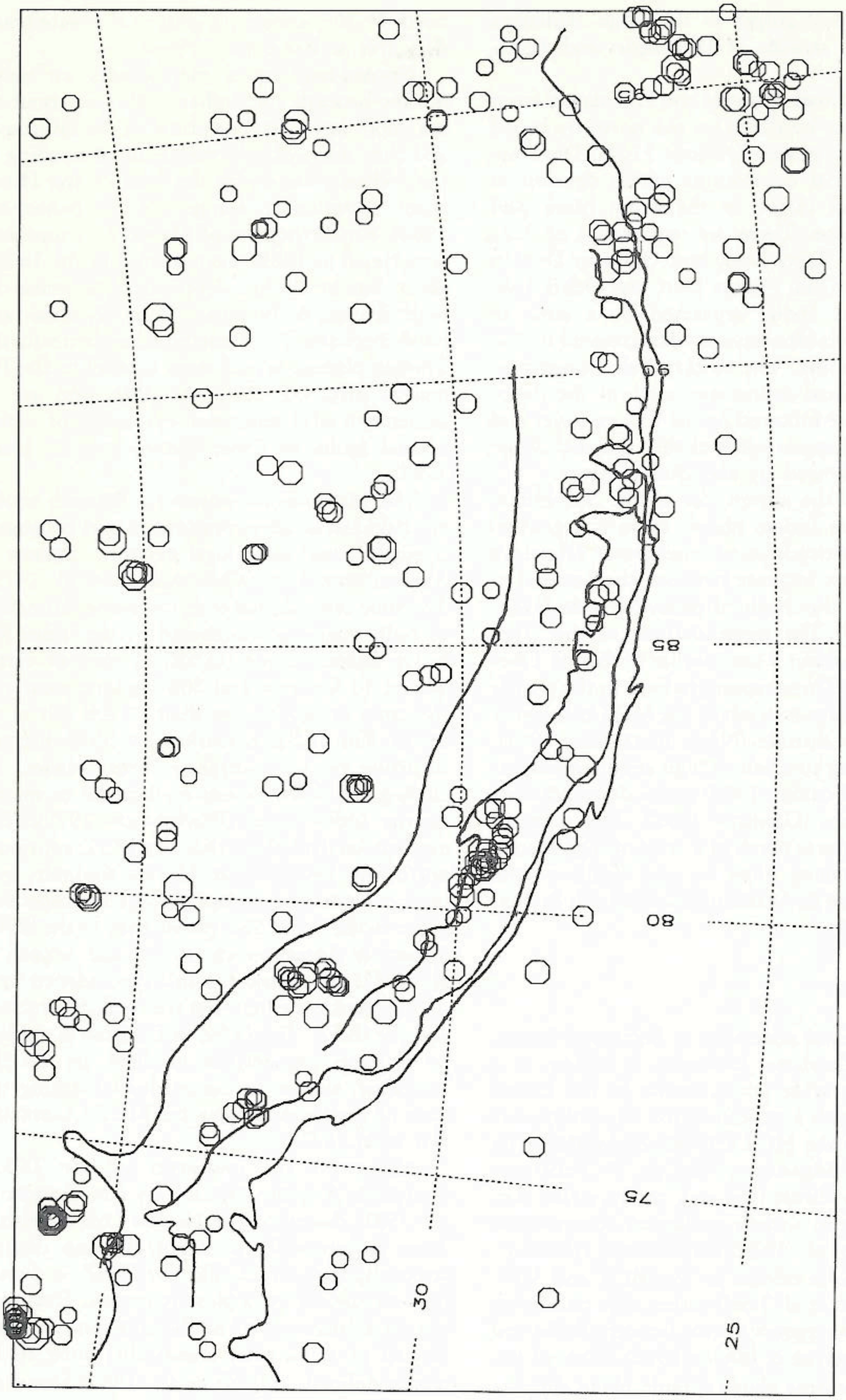

Fig. 3 - Seismicity ($m_b \geq 5$) of the Himalaya from January, 1964 to September, 1986 from ISC and USGS-PDE catalogues. Smallest octagon m_b5; largest octagon m_b7. Lines mark major subdivision boundaries identified in *fig. 1*. Seismicity map prepared by John Nabelek, Oregon State University.

world's deepest gorges in the High Himalaya between the massifs of Dhaulagiri and Annapurna.

The anticlinal ridges at the Himalayan front are commonly bordered on the north by broad plains known as *duns* (NOSSIN 1971). Duns are broad synclinal depressions which develop as the anticlinal ridges to the south block and divert drainage. There are two groups of duns (Dang Dun, Rapti Dun, and Chitwan Dun in Nepal; Soan Dun, Pinjore Dun, and Dehra Dun in northwest India) separated by a zone in which the Sub-Himalaya is characterized by imbricate thrusting. The eastern Salt Range contains a synclinal depression north of the Pabbi Hills anticline followed by the Jhelum River and another depression north of the Chambal Ridge anticline followed by the Bunha River.

North of the abrupt rise of the Sub-Himalaya from the Indian plains, there is a gradual increase in altitude across the Lesser Himalaya and an abrupt increase between the Lesser Himalaya and the High Himalaya (NI & BARAZANGI, 1984) The mean altitude of the High Himalaya is about 5 km, similar to that of Tibet (BIRD 1978). The steepest gradient in the profile of the Himalaya is north of the MCT between 4 and 5.2 km altitude (NI & BARAZANGI 1984), corresponding to a belt of high stream gradients (SEEBER & GORNITZ 1983) and a sharp gradient in uplift rates (GANSSER 1982). This zone of steep gradients is north of a zone of high instrumental seismicity close to and south of the MCT (SEEBER & ARMBRUSTER 1981; NI & BARAZANGI 1984).

Seismicity

Instrumental seismicity in India and Nepal, based on teleseismic locations, is highest in a zone 50 km wide across strike in the Lesser Himalaya, with a concentration of earthquakes just south of the MCT (SEEBER & ARMBRUSTER 1981; NI & BARAZANGI 1984; *fig. 3*). Focal mechanisms are thrust type and, rarely, strike slip, confirming the surface-geological observations of NAKATA et al. (1984) and NAKATA (1989). P-axes tend to be normal to the MCT and MBF (BARANOWSKI et al. 1984) rather than parallel to the plate-convergence vector between India and Eurasia (MINSTER & JORDAN 1978). Most of the focal mechanisms show a fault plane dipping north 5°-30°, apparently part of the plate boundary (NI & BARAZANGI 1984).

Normal-fault focal mechanisms of earthquakes beneath the Indian plains at about 20 km depth have T-axes normal to the Himalaya, and they are probably the result of bending of the Indian plate under the load of the Himalayan accretionary wedge (NI & BARAZANGI 1984). An earthquake of $Ms = 6.6$ in southeastern Nepal in 1988 also occurred in the Indian plate, but at 57 km depth along a strike-slip fault (PANDE & NICOLAS 1991). Normal-fault focal mechanisms of earthquakes beneath the Tibetan plateau have T-axes parallel to the Himalaya (MOLNAR & CHEN 1983) and are in agreement with east-west extension of active normal faults in Tibet (ARMIJO et al. 1986, 1989).

The instrumental seismicity beneath northern Pakistan is more complex, in part because it is partly based on a local network (SEEBER & ARMBRUSTER 1979; QUITTMEYER et al. 1979). The zone of earthquakes in the Lesser Himalaya of India continues northwest as the Indus-Kohistan Seismic Zone (IKSZ), a zone of earthquakes 10 km wide and 100 km long mostly in the crust at depths less than 25 km (NI et al. 1991). The IKSZ is marked by SSW-directed thrusting on north-dipping thrust planes, including the 1974 Pattan earthquake of $m_b = 6$ on the Indus River (PENNINGTON 1979). The earthquake data show that the IKSZ continues northwest beyond the Hazara-Kashmir syntaxis, whereas the surface geology indicates vergence to the S and SSE rather than to the SSW. SEEBER & ARMBRUSTER (1979), and SEEBER et al. (1981) accounted for this discordance by a décollement zone between the surface structure and the IKSZ. The IKSZ in Pakistan is marked by a steep topographic gradient up on the northeast, similar to the gradient marking the zone of earthquakes near the MCT (ARMBRUSTER et al. 1978).

About 60 km southwest of the IKSZ, SEEBER & ARMBRUSTER (1979) and SEEBER et al. (1981) described the Hazara Lower Seismic Zone as primarily a steeply-dipping dextral strike-slip fault which, like the IKSZ, is discordant to surface geological structure. Examination of a larger set of earthquake data (3 years instead of 6 months) shows this zone to be poorly defined, and NI et al. (1991) found no evidence that this seismic zone was a major fault breaking the Indian plate. The seismicity and gravity data suggest that the Indian plate dips northward at 5°-8°, steepening at the IKSZ (NI et al. 1991). The décollement is lubricated by Precambrian salt beneath the Potwar Plateau, but the seismicity farther north suggests that the salt may not continue as far north as the IKSZ.

Still farther south is a zone of seismicity in the plains south of the Salt Range, including the Kirana Hills, a possible WNW continuation of the zone of seismicity in India south of the Himalaya. Earthquakes south of the Salt Range have largely strike-slip focal mechanisms (SEEBER et al. 1981), in contrast to normal-fault mechanisms on the Indian continuation of the zone (NI & BARAZANGI 1984).

In contrast to the zone of intermediate-size earthquakes below the Lesser Himalaya of India and Nepal, the largest earthquakes of the last two centuries occurred farther south, with great shaking as far south as the Indian plains (OLDHAM 1899; DUNN et al. 1939). These earthquakes are described briefly from west to east. Modified Mercalli (MM) intensities are given unless otherwise stated.

The Himalayan foothills region of northern Pakistan is commonly assumed to have had no large destructive earthquakes in the last few centuries, an observation attributed to the presence of salt in the basal décollement (SEEBER & ARMBRUSTER 1981). However, QUITTMEYER & JACOB (1979) reported an earthquake of intensity IX-X at Taxila in the northern Potwar Plateau in AD 25, an earthquake of intensity VIII-IX at Attock on the Indus River on June 23, 1669, and an earthquake of intensity VII-VIII on December 20, 1869, at Campbellpore and Rawalpindi in the northern Potwar Plateau (located on *fig. 1*). The earthquake of February 19, 1842 of intensity VIII-IX was centered to the west in Afghanistan, although damage and loss of life occurred in Peshawar (OLDHAM 1882). These little-studied earthquakes cast doubt on the reduced seismic risk assigned to the Pakistan sector of the Himalayan Frontal Fault System and suggest that the décollement may be as subject to major earthquakes there as it is farther east in India.

On May 30, 1885, an earthquake of maximum intensity IX-X struck the Vale of Kashmir with the zone of maximum damage 25 km west of Srinagar (JONES 1885; QUITTMEYER & JACOB 1979; *fig. 1*). More than 3,000 people were killed, and the earthquake was accompanied by landslides and liquefaction of sediments. JONES (1885) guessed that the mainshock depth was about 12 km. Unlike other large historical earthquakes to the east, this event occurred in an intermontane basin, close to the IKSZ. OLDHAM (1882) reported large earthquakes in Kashmir in 1669, 1780, and 1828, the last resulting in the deaths of 1,000 people.

The April 4, 1905 Kangra earthquake with $M_s = 8$ based on instrumental data (KANAMORI 1977) struck the foothills of northwest India with maximum intensity of X or greater at Kangra and a secondary center of maximum intensity VII to VIII at Dehra Dun (MIDDLEMISS 1910; QUITTMEYER & JACOB 1979; *figs. 1* and *3*). If both zones of high intensity are connected by a single fault plane, the rupture extended for as much as 300 km along the Himalayan foothills (SEEBER & ARMBRUSTER 1981). Except for a local area of secondary rupture, no evidence of surface faulting was found by MIDDLEMISS (1910). This, together with geodetic changes reported by MIDDLEMISS (1910), led SEEBER & ARMBRUSTER (1981) to conclude that the 1905 fault-rupture plane was a shallow-dipping blind thrust, an interpretation supported by releveling data (CHANDER 1988). SEEBER & ARMBRUSTER (1981) suggested that there may be a seismic gap between the 1905 Kangra and 1885 Kashmir earthquakes. However, the Kashmir earthquake occurred beneath an intermontane basin 140 km north of the Himalayan mountain front, and it may be better compared with the 1842 earthquake in eastern Afghanistan, which also occurred beneath an intermontane basin. The meizoseismal area of heavy damage of the 1905 earthquake is more than 300 km east of the next foothills earthquake, the 1869 Rawalpindi event with an area of heavy damage less than 100 km in length.

The Mathura-Badrinath earthquake of September 1, 1803 (OLDHAM 1882) with maximum intensities VIII-IX (QUITTMEYER & JACOB 1979; *fig. 1*) may have produced a rupture that adjoined the 1905 rupture on the east (SEEBER & ARMBRUSTER 1981). This same region was struck by a destructive earthquake on October

19, 1991). Preliminary results from a few stations (S. JAUMÉ pers. comm. 1991) gave Mw = 6.8, $M_s = 7.1$, and a depth of 11.5 km on a thrust plane dipping gently north.

A poorly documented earthquake in 1833 abuts the 1934 Bihar-Nepal earthquake on the west. Both the 1833 and 1803 events may be décollement earthquakes (SEEBER & ARMBRUSTER 1981), although the poor documentation of rupture zones makes it difficult to determine whether a seismic gap lies between them.

The January 15, 1934 Bihar-Nepal earthquake (*figs. 1* and *2*) ruptured the foothill zone for a distance of 200 ± 100 km (MOLNAR & PANDEY 1989) although SEEBER & ARMBRUSTER (1981) estimated the rupture length to be 300 km. According to KANAMORI (1977), $M_s = 8.3$ and $M_w = 8.1$. PANDEY & MOLNAR (1988) showed that the intensity contours of DUNN et al. (1939) did not adequately consider damage in Nepal reported by RANA (1935). CHEN & MOLNAR (1977) assumed the earthquake was produced by a thrust fault, although there are not enough P-wave first motions to produce a fault-plane solution. Zones of high intensity within the Indian plains south of the Himalayan front, including the «slump belt» of DUNN et al. (1939) where destruction was nearly total, led SEEBER & ARMBRUSTER (1981) to extend the rupture zone of their basal detachment southward beneath the Indian plains. On the other hand, MOLNAR & PANDEY (1989) question the extension of the rupture zone south of the Himalayan front, and they suggest that the zones of high intensity in the plains, including the «slump belt», may be due to local site conditions.

The rupture zone of the 1934 earthquake adjoins the rupture zone of the great Western Assam earthquake of June 12, 1897 (*figs. 1* and *2*). This earthquake may have had a rupture length of 550 km (SEEBER & ARMBRUSTER 1981), although MOLNAR & PANDEY (1989) estimate this rupture length to be 200 ± 40 km. The greatest damage occurred in the Shillong Plateau south of the Indian plains, and severe damage extended south of the Shillong Plateau across the Ganga delta, leading OLDHAM (1899) to conclude that the earthquake occurred on a reverse fault (Dauki fault) that dips northward beneath the Shillong Plateau. The northern extension of damage into the Himalaya is less clear, but SEEBER & ARMBRUSTER (1981) raised the possibility that the earthquake could have occurred on the décollement beneath the Himalayan foothills.

Farther east, the Eastern Assam earthquake of August 15, 1950 ($M_s = 8.6$, $M_w = 8.6$ estimated by KANAMORI 1977) had its epicenter in China northeast of the Brahmaputra Syntaxis (*fig. 1*), but at least part of its rupture zone underlies the Himalaya (RAMACHANDRA RAO 1953; MOLNAR & PANDEY 1989). The foothills were riddled by landslides that covered one-third of the surface over an area of 46,000 km^2 (L.P. MATHUR in RAMACHANDRA RAO 1953; SEEBER & ARMBRUSTER 1981). The focal mechanism solution is dip slip on a thrust fault dipping gently NW (CHEN & MOLNAR 1977). The rupture length was 300 km along strike according to SEEBER & ARMBRUSTER (1981) and 250 km according to MOLNAR & PANDEY (1989). The rupture zones of the 1897 and 1950 earthquakes leave a gap of 50-100 km, but a M = 7.2 earthquake in 1943 and a M = 7.7 earthquake in 1947 may have filled this gap (SEEBER & ARMBRUSTER 1981; *fig. 1*).

In summary, the eastern Himalayan foothills were ruptured by three great earthquakes in 1897, 1934 and 1950, with no major gaps. In contrast, the western Himalayan foothills were ruptured by only one great earthquake in 1905, leaving gaps to the east and west. Smaller earthquakes affected the northern part of the Potwar Plateau in Pakistan in AD 25, 1609 and 1869, and intermontane basins to the north in 1842 (Afghanistan) and 1885 (Kashmir).

The Dehra Dun Valley as a representative Himalayan frontal fault structure

The Dehra Dun Valley, location of the Wadia Institute of Himalayan Geology, is well mapped in both the surface and subsurface and contains intensity and geodetic data related to the great earthquake of 1905 (MIDDLEMISS 1910; NAKATA 1972; ACHARYYA & RAY 1982; RAIVERMAN et al. 1983; RAJAL et al. 1986; CHANDER 1988; GAHALAUT & CHANDER 1991). The valley is bounded on the north by the MBT, which brings Lesser Himalayan strata in thrust contact with fan gravels north of Dehra Dun (*fig. 4*). The valley itself is underlain by a southward-verging asymmetric syncline flanked

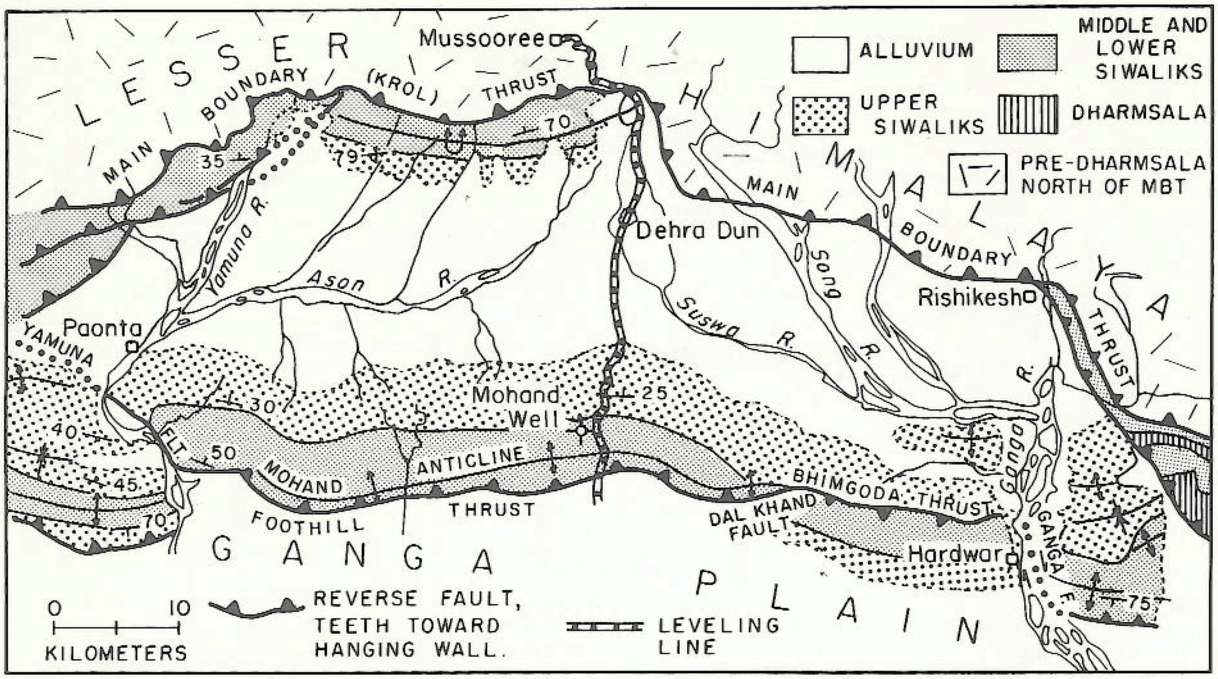

Fig. 4 - Map of Doon (Dehra Dun) Valley from YEATS & LILLIE (1991). Note drainage divide between Yamuna (Jumna) and Ganga rivers in the valley west of Dehra Dun. Modified from RAIVERMAN et al. (1983).

on the north by an overturned anticline in Siwalik molasse NW of Dehra Dun (*fig. 5*). The Siwaliks reach the surface south of the valley in the Mohand anticline, which is bounded on the south by the Foothill thrust, the local representative of the Himalayan Front fault (HFF) separating the Sub-Himalaya and the Indian plains. To the east, displacement appears to shift to a north-verging backthrust, the Bhimgoda thrust, and there is no evidence of the HFF to the south near the Ganga River. The Yamuna and Ganga rivers flow around the ends of the Mohand anticline, possibly following tear faults (Yamuna and Ganga faults), and the drainage divide between these two rivers is within the valley west of Dehra Dun. The Mohand well reaches Precambrian basement, and it may cut the Foothill thrust. YEATS & LILLIE (1991) show this thrust as a décollement, not involving basement.

MIDDLEMISS (1910) mapped an isolated zone of intensity VIII around the Dehra Dun valley as part of his study of the 1905 Kangra earthquake. A geodetic line from Saharanpur in the Indian plains to Mussooree north of the MBF was surveyed before the 1905 earthquake and immediately thereafter (MIDDLEMISS 1910). This line was also surveyed in 1926-27 and 1974-75 (RAJAL et al. 1986). The results of those surveys are shown in *fig. 5*.

We modeled the geodetic observations under the assumption that the fault length, or strike, is much greater than its down-dip dimension. Furthermore, we held no point fixed; that is to say, a constant can be added to all values of elevation change. This model (*fig. 6*) fits the geologic and geodetic observations reasonably well. The top of the coseismic rupture lies beneath Dehra Dun and extends at least 15 km downdip (to the northeast) with a dip of about 15°. If we assumed that the fault length was 100 km, the geodetic moment M_o would be 1.5×10^{26} dyne-cm, equivalent to $M_w = 6.75$. Doubling the fault width raises M_w to 7. The coseismic slip is consistent with the location of Dehra Dun, close to the SE edge of the area strongly affected by the earthquake, and supports the suggestion of MOLNAR & PANDEY (1989) that the intensity VIII contours could connect with the larger damaged area at Kangra. If so, the high-intensity contours may be controlled by site conditions in alluvium, as

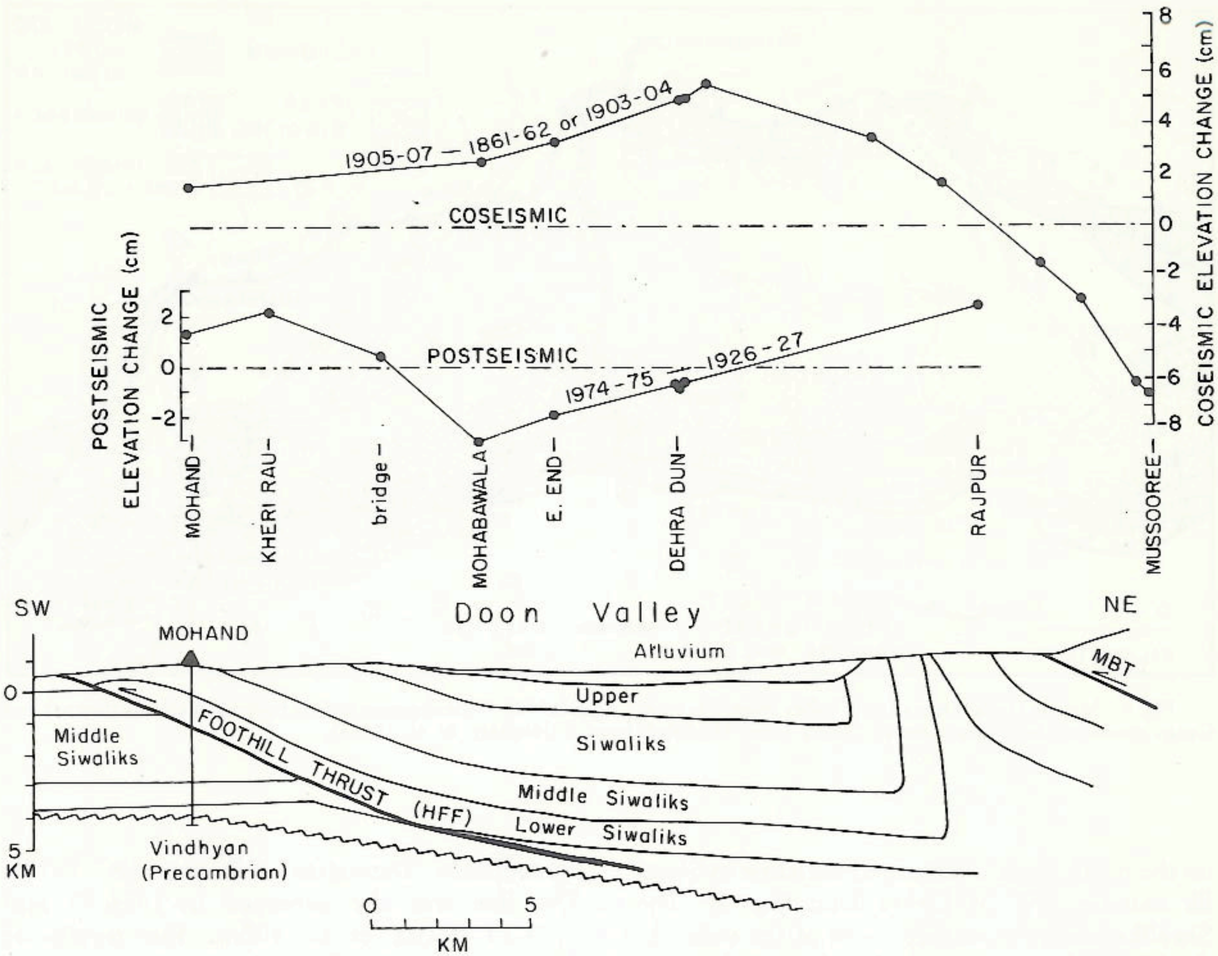

Fig. 5 - Cross section from Himalayan front across Dehra Dun Valley to Main Boundary thrust. Releveling data on road from Saharanpur (located on *fig. 2*) to Mussooree (line located on *fig. 4*) from RAJAL et al. (1986) and MIDDLEMISS (1910), projected onto structure section. Vertical displacements are relative to Saharanpur in the Indian plains, assumed to be stationary. Modified from YEATS & LILLIE (1991).

suggested for the «slump belt» in the Indian plains produced by the 1934 Bihar-Nepal earthquake. The post-seismic data for 1926-1975 are consistent with about 15 cm of slip on an isolated up-dip extension of the Foothill thrust (*fig. 6*). It is possible that the fault surface between the coseismic rupture and the 1926-1975 rupture underwent post-seismic slip in the period 1907-1926. The updip migration of post-seismic displacement is similar to the geodetic pattern following the 1983 Coalinga, California, earthquake (STEIN 1985; STEIN & YEATS 1989). These conclusions are in general accord with an independent study by CHANDER (1988) and GAHALAUT & CHANDER (1991), who also pointed out that the Kangra earthquake did not involve displacement on the Main Boundary fault.

SUMMARY

The Himalayan Frontal Fault System extends from the Indus River across Pakistan, India, Nepal, and Bhutan to the Brahmaputra River in eastern Assam. Instrumental seismicity in India and Nepal is concentrated in a zone 50 km wide in the Lesser Himalaya south of the MCT, although in Pakistan, where local network data are available, the seismicity pattern is more complex. Great earthquakes ruptured most of the eastern section of the fault system in 1897, 1934 and 1950 and part of the western section in 1905. Major seismic gaps are present between the 1905 and 1934 earthquakes and west of the 1905 earthquake. The Pakistan sector has been assumed to be aseismic due to the absence of great earthquakes

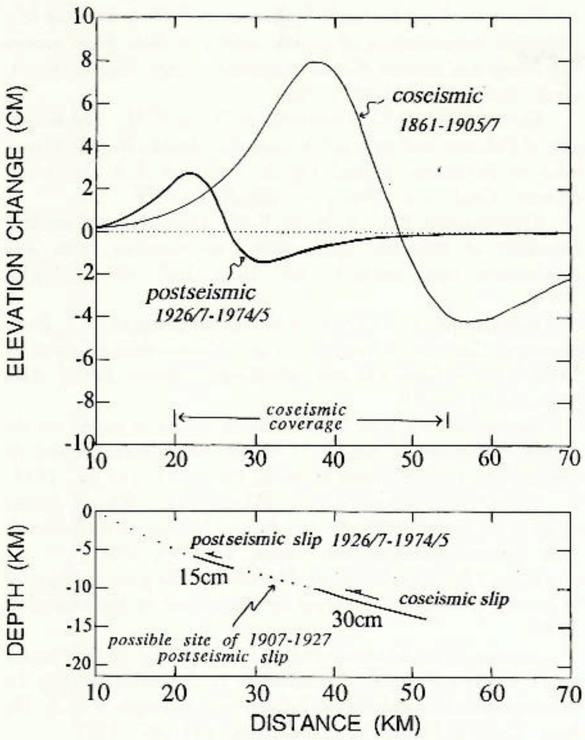

Fig. 6 - Two-dimensional model of coseismic (MIDDLEMISS 1910) and post-seismic leveling changes produced by low-angle thrust fault. Model assumes that there is no fixed zero datum and that the length of the fault is greater along strike than down-dip.

in the last two centuries and the presence of salt beneath the basal décollement. However, the absence of aseismic creep on the Salt Range thrust (YEATS & LILLIE 1991) and the presence of destructive earthquakes in the northern Potwar Plateau in AD 25, 1669 and 1869 cast doubt on that assumption, at least for moderate-size earthquakes.

The great earthquakes of the last two centuries produced no evidence of primary surface faulting. There is geological evidence for a discontinuous zone of thrusting at the base of the Sub-Himalaya (Himalayan Front fault and Salt Range thrust); this zone is discontinuous because much of the shortening is taken up by active folding. Anticlinal folds appear ahead of the range front and block out synclinal zones known as duns. Other active faults with various senses of displacement occur north of the range front across the Sub-Himalaya and Lesser Himalaya; these may be secondary structures related to the main décollement.

The Himalayan Frontal Fault System is best explained as a thrust that does not involve the crystalline rocks of the Indian shield, which are moving north with respect to the sedimentary cover of the Lesser Himalaya and Sub-Himalaya. Earthquake focal mechanisms and limited geodetic data suggest that earthquakes may be generated at seismogenic depths along this thrust. Thrust motion may not reach the surface but may, instead, be expressed at the surface by folding. Therefore, for a full evaluation of seismic risk of this region, active folding must be taken into consideration as well as active faulting.

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