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Contemporary tectonics of the Himalayan frontal fault system: folds, blind thrusts and the 1905 Kangra earthquake

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Abstract—The Sub-Himalayan fold–thrust belt consists of deformed late Cenozoic and older deposits south of the Main Boundary thrust (MBT). In Pakistan, east of the Indus River, the Sub-Himalaya comprises the Potwar Plateau and the Salt Range, which is thrust southward over the Jhelum River floodplain along the Salt Range thrust. Although an estimated 9–14 mm a^{-1} shortening has been taken up on the Salt Range thrust during the last 2 Ma, the range-front scarp does not show signs of recent faulting. Shortening may be shifting southward to the Lilla overpressured anticline, which rises from the Jhelum floodplain as a fault-propagation fold. Farther east, shortening is partitioned among several anticlines underlain by foreland- and hinterland-dipping blind thrusts. Southeast of the main deformation zone, the Pabbi Hills overpressured anticline is best explained as a fault-propagation fold. Throughout the Potwar Plateau and Salt Range, thrusts and folds rise from a basal décollement horizon in Eocambrian evaporites. The Pakistani part of the décollement horizon could generate large earthquakes only if these evaporites die out northward at seismogenic depths.

In India and Nepal, the Sub-Himalaya is narrower, reflecting the absence of evaporites and a steeper slope of the basement towards the hinterland. The southern boundary of the Sub-Himalaya is the Himalayan Front fault, discontinuous because part of the shortening is expressed at the surface by folding. Broad, alluvial synclinal valleys (dun valleys) are bounded on the south by rising barrier anticlines of Siwalik molasse. The 1905 Kangra earthquake (M8) produced uplift on the Mohand anticline and the Dehra Dun Valley, suggesting that this earthquake occurred on a décollement horizon above basement, downdip from the fold. If so, the Kangra event is the largest known earthquake on a blind thrust expressed at the surface as a fold.

INTRODUCTION

THE Himalaya is the result of continental convergence between the Eurasian and Indian plates at rates varying from 44 to 61 mm a^{-1} (Minster & Jordan 1978, Armijo *et al.* 1989). The present deformation front is at the foot of the Siwalik Hills of India and Nepal, where it is marked by the Himalayan Front fault (Nakata 1989), and at the foot of the Salt Range of Pakistan, where it is marked by the Salt Range thrust (Yeats *et al.* 1984) (Fig. 1). In India, Nepal and Pakistan, this deformation front is more subdued in its tectonic expression than are the great strike-slip faults of central Asia, and as a result the seismotectonic significance of this zone has been recognized only recently, starting with Nakata (1972).

In this paper we summarize the main characteristics of this zone in Pakistan relying on an extensive subsurface database of seismic lines and oil-exploratory wells. Subsurface data show that the fold-and-thrust belt of the Salt Range and Potwar Plateau of Pakistan (Fig. 2) is thin-skinned; the folds and thrusts ride on a cushion of salt and do not involve the basement (Yeats *et al.* 1984, Lillie *et al.* 1987, Baker *et al.* 1988, Pennock *et al.* 1989). We review these data, and we then extend our observations to the Sub-Himalaya of northwestern India, which reinterpret as a thin-skinned fold-and-thrust belt.

GEOLOGIC SETTING

The Indian–Eurasian collision occurred in early Tertiary time on the Indus suture zone. Subsequently, the thrusting shifted south, driving the northern edge of the Indian continental plate back onto itself along the Main Central thrust (MCT) and Main Boundary thrust (MBT), and uplifting the Himalaya (Le Fort 1975, Gansser 1981, Klootwijk *et al.* 1985). The convergence between India and Eurasia is taken up not only by thrusting at the front of the Himalaya, but also to the north, where E–W extension occurs on normal faults in southern Tibet (Armijo *et al.* 1986), and great crustal blocks move east out of the way of the Indian plate in western China and southern Siberia (Molnar & Tapponnier 1975, Armijo *et al.* 1989). Only about 9–14 mm a^{-1} convergence is taken up at the Himalayan frontal zone (Baker *et al.* 1988); the rest is taken up farther north (cf. Lyon-Caen & Molnar 1985).

Focal-mechanism solutions indicate that earthquakes in the southern foothills of the Himalaya are mainly thrust-type events, whereas those in Tibet are mainly normal-fault events; both regions have small subsets of strike-slip events (Baranowski *et al.* 1984, Ni & Barazangi 1984). Most of the earthquakes are concentrated in a zone 50 km wide between the MCT and MBT (Ni & Barazangi 1984). Seeber *et al.* (1981) suggested that these earthquakes occurred on a ramp, south of which the basal thrust is a décollement ('detachment') horizon between deformed Sub-Himalayan strata and Precambrian basement of the Indian shield, and north of which the thrust brings Precambrian crystalline rocks of the Great Himalaya southward over the deformed strata of the Lesser Himalaya. Seeber *et al.* (1981) additionally suggested that the 'detachment' extends south of the Himalaya beneath the Indo-Gangetic plain, but this suggestion is controversial (Molnar & Pandey 1989).

The 1905 Kangra earthquake (M8, an estimate based

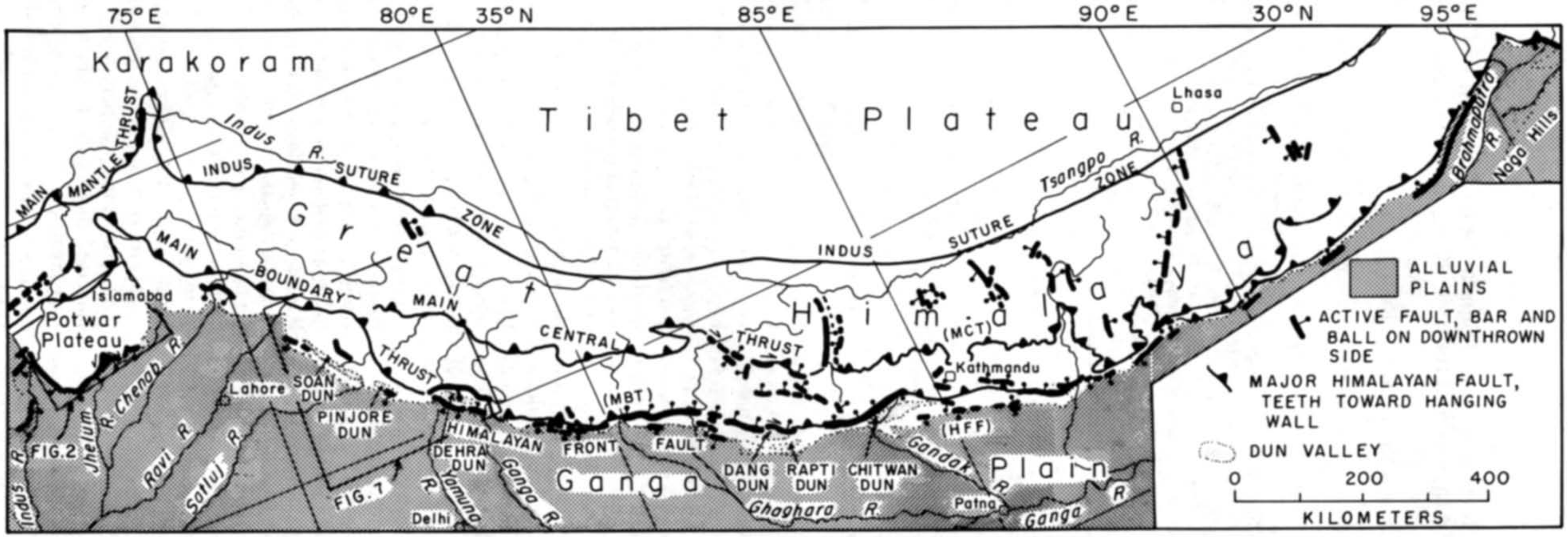

Fig. 1. Active-fault map of Himalaya, compiled by Himalayan Active Fault Subcommittee of IGCP 206 (R. Yeats, A. Farah, J. McDougall, M. Mirza, M. Fort, T. Nakata, M. Pandey and K. Valdiya).

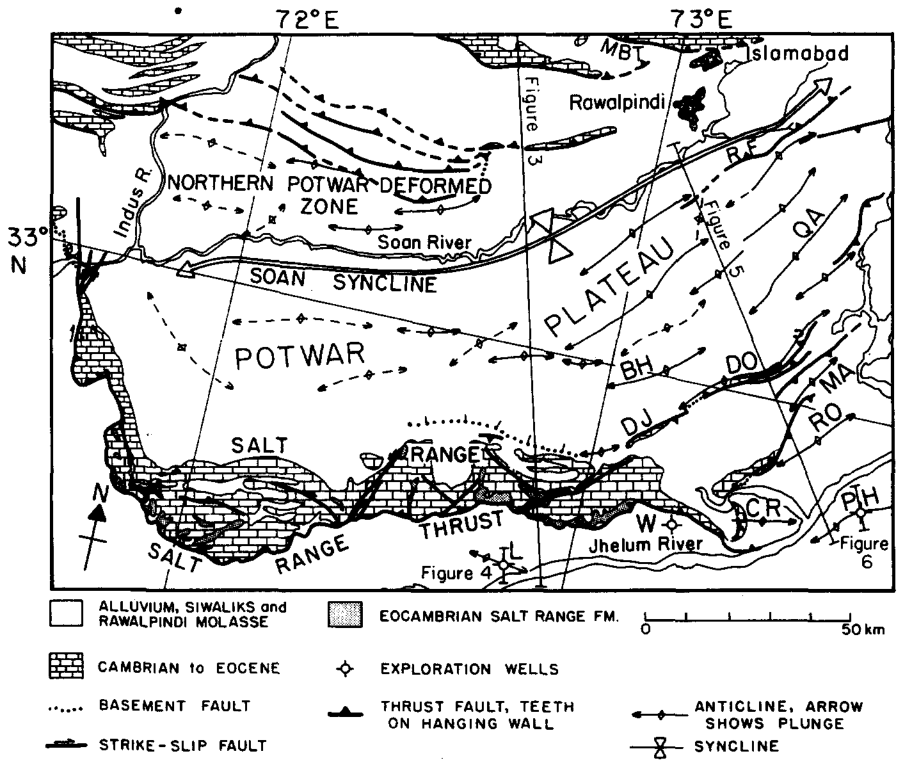

Fig. 2. Generalized geologic map of the Potwar Plateau and Salt Range. For location, see Fig. 1. BH, Bhubar anticline; CR, Chambal Ridge anticline; DJ, Dil Jabba thrust; DO, Domeli anticline and thrust; L, Lilla well and Lilla anticline; MA, Mahesian anticline; PH, Pabbi Hills well and Pabbi Hills anticline; QA, Qazian anticline; RF, Riwat fault; RO, Rohtas anticline; W, Warnali well. Dashed symbol denotes anticlines and faults documented only in subsurface.

on analysis of intensity data), the 1934 Bihar earthquake (M8.3) and the 1930 Dhubri earthquake (M7.1) shook the southern margin of the Himalaya. Seeber *et al.* (1981) suggested that these earthquakes occurred on the basal décollement thrust south of the MCT, an area now marked by low seismicity. Releveling in the Dehra Dun region showed major uplift south of the MBT (Middlemiss 1910) in the vicinity of a rising anticline in Siwalik strata. Damage reports for the 1934 Bihar earthquake suggested to Dunn *et al.* (1939) that the epicenter lay beneath the plains of northern India, but this report did not adequately take into account the damage in Nepal, which, when added to the Indian data, shows that the rupture zone was beneath the Lesser Himalaya (Pandey & Molnar 1988). None of these earthquakes resulted in any recognizable tectonic surface rupture.

The Precambrian Indian shield is overlain by Cenozoic molasse deposits of the Dharmsala Group and Siwalik Group, which consist of older versions of sediments deposited by the modern drainage system. The depositional axes of Siwalik molasse basins are parallel to the Ganga River but north of it; the molasse basins have been forced southward by the southward advance of Lesser Himalayan and Sub-Himalayan thrust sheets (Acharyya & Ray 1982, Yeats 1986). Farther north, beneath the Sub-Himalaya, marine Eocene strata occur, and still farther north these strata overlie a miogeoclinal sequence of Precambrian to Mesozoic age. In Pakistan, the Indian shield is overlain by Eocambrian evaporites and Cambrian redbeds, glauconitic shale and dolomite. This sequence is overlain unconformably by a sequence of Permian through Cretaceous strata that thicken westward across the Indus River, and these strata are overlain by Paleogene shallow-marine deposits. The molasse deposits (Murree, Kamlial and Siwalik) overlap southward over older strata as they do in India, but in Pakistan, they rest on the Cambrian and Eocambrian sequence, including salt deposits, whereas in India they rest directly on Precambrian basement.

The difference in stratigraphy has a strong effect on the style of folding and thrusting in the Himalayan foothills. In Pakistan, the fold-and-thrust belt overlies a décollement zone of Eocambrian salt, which causes it to have a narrow cross-sectional taper (angle between the forward topographic slope and rearward basement slope) of about 3° and a width of 100–150 km (Jaumé & Lillie 1988), as predicted by Davis & Engelder (1985). In India, Eocambrian salt is largely absent; consequently, the taper is larger, 5–7° (Davis *et al.* 1983, Jaumé 1986), and the fold-and-thrust belt is only 30–80 km wide, considerably narrower than in Pakistan. Seeber *et al.* (1981) suggested that the presence of salt beneath the fold-and-thrust belt in Pakistan might account for the absence of large, historical earthquakes, in contrast to India and Nepal.

We discuss two areas in Pakistan, the central Salt Range (Figs. 3 and 4) and the eastern Potwar Plateau–Pabbi Hills (Figs. 5 and 6), and then compare these areas with two areas in the northwestern Himalaya of India (Fig. 7), where subsurface well data are present. We conclude with a consideration of the seismic potential of both regions.

CENTRAL SALT RANGE

The central Salt Range was formed by the upward ramping of a décollement thrust sheet (Salt Range thrust) across a buried fault scarp in Precambrian basement (Baker *et al.* 1988) (Fig. 3). Folding and thrusting in the northern Potwar deformed zone ended about 1.9–2.1 Ma (Johnson *et al.* 1986), at which time the Phanerozoic strata of the southern Potwar Plateau and Salt Range began to move southward over basement, with the movement zone in Eocambrian salt (Baker *et al.* 1988). This southward displacement took place with relatively minor internal deformation. Balanced cross-sections suggest a minimum of 20–23 km of horizontal shortening in the last 1.6–2.1 million years (Baker *et al.* 1988). The basement slope toward the hinterland is 1–3°, and the overall topographic slope is essentially zero (Jaumé & Lillie 1988).

The faulted southern front of the Salt Range does not show evidence of Holocene activity. The range front is moderately embayed by late Quaternary alluvial fans, and the Salt Range thrust does not cut the youngest fans (Yeats *et al.* 1984). The Salt Range thrust has a relatively high slip rate; why does it appear to be relatively inactive in its geomorphic expression?

We suggest that the fault appears less active because thrusting is shifting farther to the south, to the Lilla anticline on the Jhelum River floodplain (Jaumé & Lillie 1988). Seismic lines show a broad, E-trending, doubly-plunging anticline in Phanerozoic strata (Fig. 4). Post-Siwalik overbank silts of the Jhelum River dip as much as 15°N on the north flank of this anticline. The Lilla-1 well, drilled on the crest of this anticline, bottomed in overpressured strata of the Eocambrian Salt Range Formation (Jaumé & Lillie 1988). Overpressuring is believed to be of tectonic origin because the nearby Warnali-1 well, not on an anticlinal structure, penetrated the same stratigraphic sequence with normal hydrostatic pressures (Jaumé & Lillie 1988).

In addition to folding of the Lilla anticline, shortening is being accommodated in another way, by E–W extension on strike-slip faults that extend northeast and northwest from the front of the Salt Range (Fig. 2). These faults, like the Salt Range thrust, do not involve basement. They have geomorphic expression because they form zones of weakness through which Eocambrian salt has welled up. The salt is weak and easily eroded into narrow gorges containing magnificent exposures of the Paleozoic sequence; these gorges are prominent on Landsat imagery. The structural result is escape-block tectonics on a small scale, involving only a single thrust sheet.

EASTERN POTWAR PLATEAU

The Salt Range thrust loses displacement in the eastern Salt Range (Yeats *et al.* 1984) and changes to a fold, the Chambal Ridge anticline (Fig. 2). The structure of the southern Potwar Plateau changes eastward from a gently N-dipping homocline to a series of folds bounded by thrusts (Pennock *et al.* 1989). Magnetic-reversal stratigraphy indicates that the southernmost of these folds, the Rohtas and Chambal Ridge anticlines, attained surface expression as a result of active folding only in the last few hundred thousand years (Johnson *et al.* 1979). Some of the anticlines have been drilled for oil, and the drill holes experienced tectonic overpressures (Jaumé & Lillie 1988), indicating that the fold belt is actively deforming.

Except for the Domeli thrust, most of the deformation observed at the surface is by folding (Martin 1962, Raynolds 1980, Pennock *et al.* 1989). However, seismic-reflection profiles show that the folds are underlain by blind thrusts that rise from a basal décollement horizon in Eocambrian salt (Pennock *et al.* 1989) (Fig. 5). These thrusts are both foreland-vergent (Domeli and Mahesian) and hinterland-vergent (Rohtas, Dil Jabba and Bhubar). The Salt Range thrust dies out eastward, and its displacement is partitioned among the Rohtas, Mahesian, Domeli and Bhubar thrusts. Although only the Domeli thrust reaches the surface, total shortening is still 17.8 km along and south of the Domeli thrust, not much less than the value obtained in the central Salt Range. If shortening began at the time of first surface expression of the Domeli thrust, that is, about 2.5 Ma (Raynolds 1980), the shortening rate would be 7 mm a^{-1} (Pennock *et al.* 1989). Because the salt is such an effective decoupling layer, the critical taper of the thrust wedge is less than 1° (Jaumé & Lillie 1988).

The Pabbi Hills anticline is an open, doubly-plunging fold southeast of the Jhelum River (Fig. 6). This anticline began to form less than 0.4 Ma ago (Johnson *et al.* 1979, Yeats *et al.* 1984); its growth may have diverted the Jhelum River around its southwestern end. A seismic line across this fold (Fig. 6) shows that the fold does not

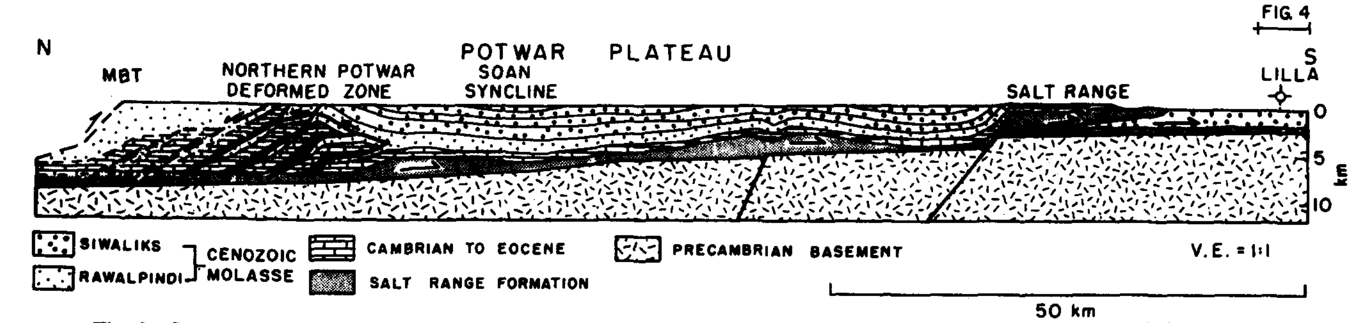

Fig. 3. Cross-section of the southern Potwar Plateau and central Salt Range, Pakistan modified from Baker *et al.* (1988). For location of section line, see Fig. 2.

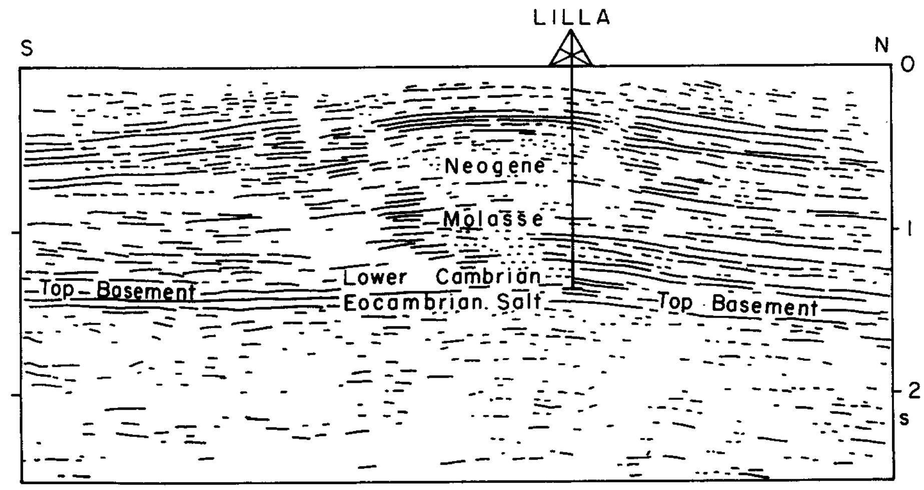

Fig. 4. Tracing of multichannel seismic line across the Lilla anticline in the Jhelum River floodplain. For location of line, see Figs. 2 and 3. Lilla well reached the Eocambrian Salt Range Formation.

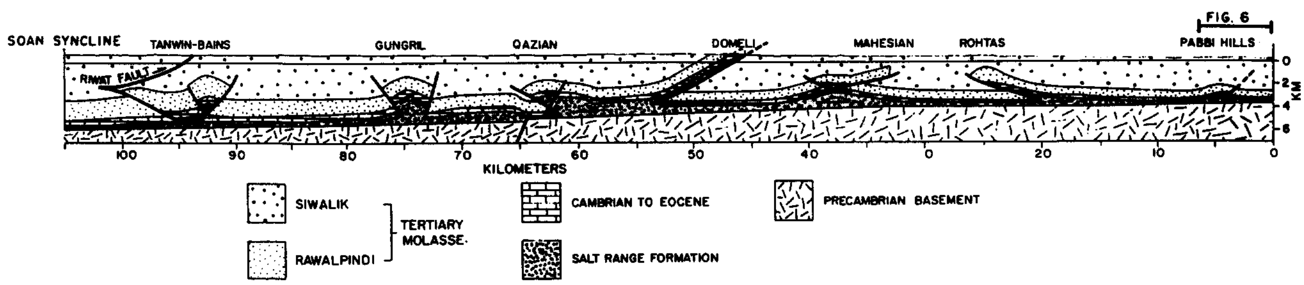

Fig. 5. Cross-section of eastern Potwar Plateau based on seismic-reflection profiles and well data. After Pennock *et al.* (1989). For location of line, see Fig. 2.

involve basement. The Pabbi Hills-1 well encountered tectonic overpressures in a molasse section more than 3 km thick (Jaumé & Lillie 1988), suggesting that the fold is still growing. We interpret the Pabbi Hills anticline as a fault-propagation fold controlled by a blind thrust rising from the master décollement horizon in Eocambrian salt.

NORTHWEST INDIA

East of the Kashmir syntaxis, the Sub-Himalaya is narrower due to the near-absence of salt (Davis & Engelder 1985, Jaumé & Lillie 1988) (Fig. 1), and the basement slope toward the hinterland is steeper than in Pakistan. The deformation front is the Himalayan Front

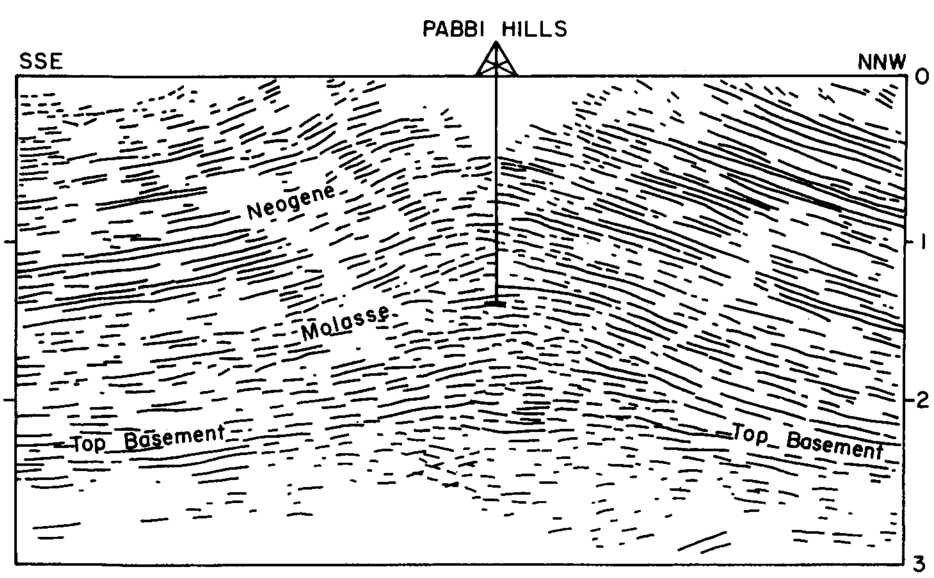

Fig. 6. Tracing of multichannel seismic line across Pabbi Hills anticline south of Jhelum River. For location of line, see Fig. 2. Pabbi Hills well was abandoned in overpressured molasse deposits.

fault (HFF) of Nakata (1972, 1989). Unlike the Salt Range thrust, the HFF is discontinuous (Fig. 1). Rising anticlinal ridges of Siwalik molasse are separated from the main range front by broad tectonic depressions called *dun valleys* (Nossin 1971, Nakata 1972, pp. 99–100) (Figs. 1 and 7). The MBT is inactive as a S-vergent thrust, but locally the surface trace of the MBT has been reactivated with different senses of surface displacement, north-side-down or right-lateral strike-slip (Nakata *et al.* 1984, Nakata 1989).

The structure of the Sub-Himalaya has been described by Karunakaran & Ranga Rao (1979), Acharyya & Ray (1982) and Raiverman *et al.* (1983), all of whom combine well data with surface exposures. The Sub-Himalayan anticlines are commonly bounded by reverse faults (Valdiya 1986), and the authors cited above assumed that these faults cut Precambrian basement. We have redrawn two of their cross-sections, the Janauri–Jawalamukhi transect between the Beas and Satluj rivers (Fig. 8) and the Mohand structure at Dehra Dun, between the Yamuna and Ganga rivers, (Fig. 9) to show the surface faults not cutting basement but merging downward into a décollement horizon, as they do in Pakistan.

The Beas and Satluj rivers are diverted around the northwest and southeast ends, respectively, of the Janauri anticline, which is separated from the rest of the Sub-Himalaya at Jawalamukhi by a dun valley (Soan Dun) underlain by a wedge of upper Siwalik strata (Fig. 7). Most of the trace of the syncline is occupied by the broad floodplain of the Soan River which flows into the Satluj River which also flows southeastward along the synclinal axis and from there around the southeastern end of the Janauri anticline. The Janauri well on the anticlinal crest penetrated pre-Vindhyan Precambrian marble directly beneath molasse (Acharyya & Ray 1982). In the plains southwest of the Janauri anticline, the Hosiarpur and Adampur wells also reached pre-Vindhyan basement directly beneath molasse. To judge from subsurface depths of the top of basement in these three wells, the basement slope is 3–4°. Figure 8 shows that the known structure can be drawn such that the folds and faults merge into a décollement above basement, as is the case for Pakistan, although in India the

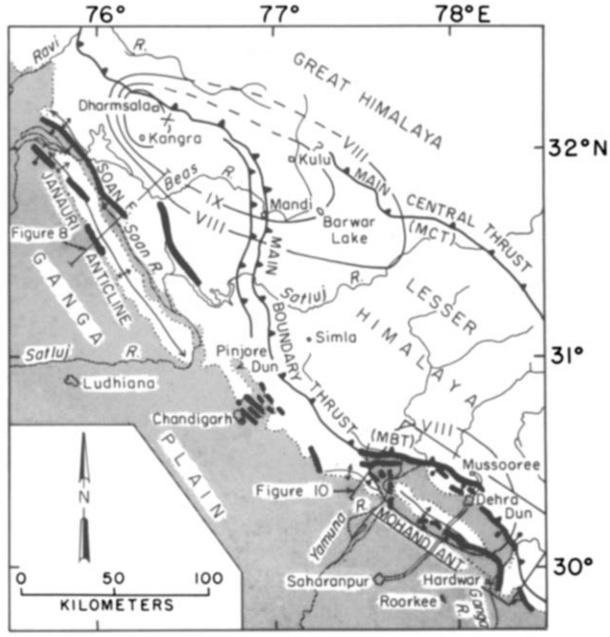

Fig. 7. Map of the Himalayan foothills of northwest India showing the largely inactive Main Boundary thrust (MBT) and the active folds and faults of the Himalayan front. For location of map, see Fig. 1. Active faults in heavy lines; bar and ball on downthrown side. Teeth in hanging wall of MBT. Alluvial plains in dot pattern, including 'dun valleys' (Soan Dun northeast of Janauri anticline, Pinjore Dun, Dehra Dun valley northeast of Mohand anticline). Double line shows leveling route between Saharanpur and Mussooree. Contours with Roman numerals are isoseismals (Rossi-Forel) of 1905 Kangra earthquake.

décollement level must be in shales of the middle Cenozoic Dharmsala molasse.

Farther southeast, the Dehra Dun valley is bounded on the north by the MBT, marking the main range front, and on the south by the rising Mohand anticline, where the Mohand well penetrated Siwalik molasse and went directly into basement (Acharyya & Ray 1982) (Fig. 9). The MBT cuts post-Siwalik fan gravel and is considered to be potentially active. However, on the basis of geodetic data discussed below, the youngest structure appears to be the Mohand anticline, cut on the south by the Foothill (Mohand) thrust which was crossed in the Mohand well. Figure 9 shows the structure of the Dehra Dun valley, interpreting the Foothill thrust (Himalayan Front fault of Nakata 1989) as rising from a décollement

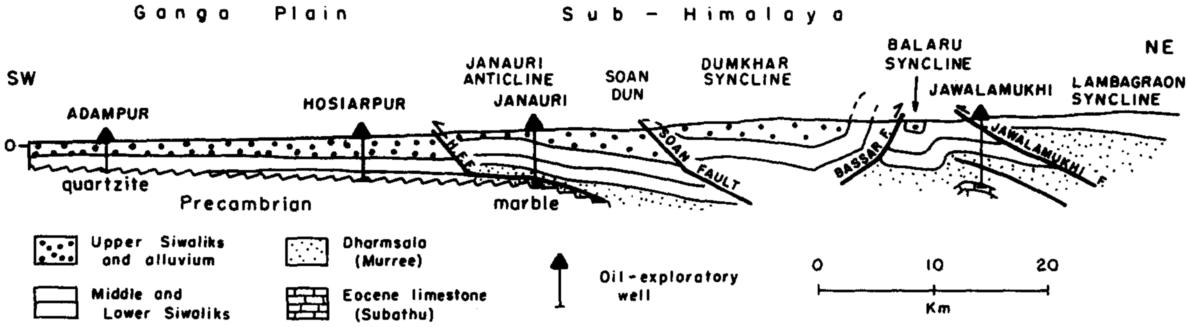

Fig. 8. Cross-section showing four wells extending from the Ganga Plain into the Sub-Himalaya reinterpreted from Acharyya & Ray (1982) and Raiverman *et al.* (1983) to show Sub-Himalayan structures as thin-skinned, that is, not involving Precambrian basement. HFF = Himalayan Front fault.

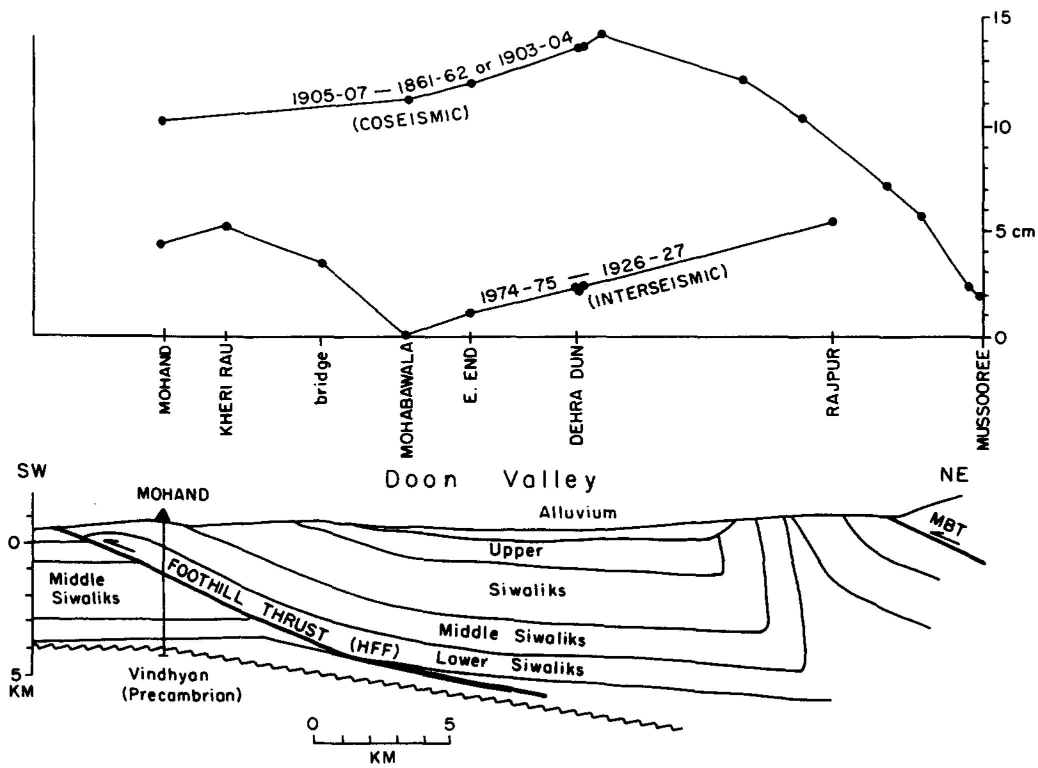

Fig. 9. Cross-section from Himalayan front across Dehra Dun valley to Main Boundary thrust, reinterpreted from Raiverman *et al.* (1983). Releveling data on road from Saharanpur (to left of section) to Mussooree, from Rajal *et al.* (1986) and Middlemiss (1910), projected onto structure section. Vertical displacements are relative to Saharanpur in the Ganga Plain, assumed to be stationary. Setting of leveling line shown in Fig. 10.

horizon in molasse deposits and not involving Precambrian basement.

The Foothill thrust is terminated on the west and east by the Yamuna and Dhal Khand tear faults, respectively. East of the Dhal Khand tear fault, the anticline is bounded on the north by the Bhimgoda hinterland-verging thrust, which is itself terminated on the east by the Ganga tear fault. This reversal of vergence is similar to that observed for the Dil Jabba and Domeli thrusts in the eastern Potwar Plateau (Pennock *et al.* 1989) (Fig. 2).

Other dun valleys farther southeast in Nepal (located on Fig. 1) appear to have a similar origin. The Dang Dun is a syncline bounded on the south by ridges of Siwalik molasse (Yamanaka & Yagi 1984) that have diverted the course of the Rapti River around the western, down-plunge end of the structure. Stream terraces on the north side of the Siwalik ridges are tilted northward toward the synclinal axis (Yamanaka & Yagi 1984). The MBT (Surkhet-Ghorahi fault) marks the northern edge of Dang Dun, but its modern displacement is down-to-the-north and right-slip (Nakata *et al.* 1984). The active Himalayan Front fault is only locally exposed along the south side of a Siwalik anticlinal ridge, suggesting that part of the displacement is taken up by folding.

EARTHQUAKE HAZARD: THE 1905 KANGRA EARTHQUAKE

On 4 April 1905, the Himalayan foothills of northwest India were struck by a large earthquake in which 20,000 people were killed (Middlemiss 1905). Intensities of X (Rossi-Forel) were observed in the Sub-Himalaya at Kangra and Dharmsala, and a secondary zone of intensity VIII (Rossi-Forel) damaged the Dehra Dun region (Middlemiss 1910, Quittmeyer & Jacob 1979). Observations in the region between the two zones of intensity VIII were so limited that the intensity VIII contours could connect through areas of low population in 1905 (Molnar & Pandey 1989). Alternatively, the two zones may reflect regions of high seismic moment release (cf. Thatcher 1990). The two zones of high intensity correspond to re-entrants in the MBT which show no corresponding re-entrants in the Himalayan Front fault, so that the Sub-Himalaya is unusually wide in these two areas (Middlemiss 1910) (Figs. 1 and 7). The length of the fault rupture was 100–150 km on the basis of the intensity distribution at Kangra, but if the secondary zone of intensity at Dehra Dun is included, the fault rupture length is about 250 km (Quittmeyer & Jacob 1979). Instrumental data suggest a magnitude M_s8 (Gutenberg & Richter 1954, Seeber *et al.* 1981), and the fault rupture plane is suggested to be a buried, gently-dipping thrust fault (Quittmeyer & Jacob 1979).

Despite a careful search, no evidence for surface rupture was found except for an area of secondary faulting at Barwar Lake (31.68°N, 77.30°E; Middlemiss 1910). However, a May 1904 leveling survey from Mussooree, north of the MBT, to Dehra Dun, south of the MBT, was repeated in May and October 1905. The releveling showed that Dehra Dun had risen more than 13.4 cm with respect to Mussooree during the earthquake (Middlemiss 1910, Rajal *et al.* 1986) (Fig. 9).

Middlemiss also reported that an 1862 survey from Dehra Dun to Saharanpur, on the plains south of the Himalaya, was releveled in 1906 and 1907 and showed that the Mohand bench mark on the Mohand anticline had risen 10.3 cm with respect to Saharanpur. To the north, the Mohabawala and Dehra Base Line East End stations had risen 11.4 and 12.2 cm, respectively, with respect to Saharanpur. This demonstrated that the area south of the MBT, including the Mohand structure, rose with respect to the main Himalaya during the earthquake (Fig. 10).

More recent surveys (Rajal *et al.* 1986) show a more localized uplift of the Mohand anticline with respect to the Doon Valley syncline and Saharanpur between 1926–1927 and 1974–1975. This showed uplift of the north flank of the syncline with respect to Mohabawala in the syncline (Fig. 9). A releveled line northwest of Kangra also showed 70 mm interseismic uplift of the area north of the MBT with respect to the area south of the MBT in the period 1960–1972 (Chugh 1974), with no discontinuity at the MBT itself (Seeber *et al.* 1981). Taken together, these surveys suggest movement on a buried thrust beneath and to the south of the MBT, not the MBT itself (Seeber *et al.* 1981). The interseismic southward tilting northwest of Kangra and northeast of Dehra Dun could be interpreted as strain buildup on the blind thrust.

We agree with Seeber *et al.* (1981) that the 1905 Kangra earthquake occurred on a blind thrust at the top of the basement. As demonstrated in Pakistan, the thrust front is migrating beyond the range front to newly formed anticlines in the plains south of the Himalaya. In northwest India, these are the Janauri and Mohand anticlines. Modern leveling lines should show growth of these anticlines, although the vertical displacement would be much smaller than the horizontal displacement. Mohand would be expected to move south toward Saharanpur. The Kangra earthquake, if formed on a blind thrust and expressed at the surface as a fold, would be the largest fold-related earthquake recorded in a continental area.

DISCUSSION

Comparison between Pakistan and India

The Himalayan front of Pakistan is underlain by evaporites and trends ENE, whereas the Himalayan front of India and Nepal is not underlain by evaporites and trends SE to E. However, there are many similarities between the two regions.

(1) Anticlines in the Siwaliks of the Sub-Himalaya and Potwar Plateau–Salt Range are relatively narrow and form ridges, whereas synclines are much broader and form broad alluviated plains (dun valleys) in India and Nepal.

(2) Anticlines are fault-propagation folds, the surface expression of blind thrusts. Some thrusts dip toward the foreland, and others dip toward the hinterland.

(3) Reflection seismic lines show that folds and thrusts do not involve the basement in Pakistan. Well and surface data in India, where seismic lines are not available, show that Sub-Himalayan folds and faults are best interpreted as décollement features, not involving basement. In India the zone of décollement is in Tertiary molasse deposits, whereas in Pakistan the décollement horizon is in Eocambrian evaporites.

Earthquakes along the Himalayan front

In northwest India, the 1905 Kangra earthquake, which produced no primary surface faulting, is best explained as an earthquake on a blind thrust beneath the Sub-Himalaya, expressed at the surface by growth of Sub-Himalayan folds. The Himalayan front farther

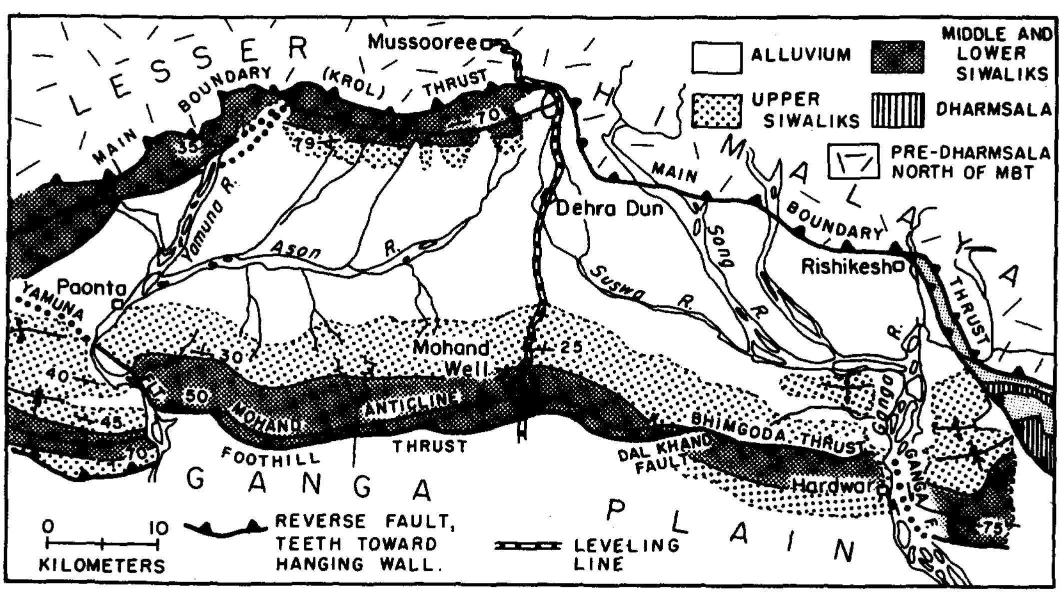

Fig. 10. Map of Doon (Dehra Dun) Valley, modified from Raiverman *et al.* (1983). For location see Fig. 7. Note drainage divide between Yamuna and Ganga rivers just west of Dehra Dun. Symbols as in previous figures.

southeast has been struck by several earthquakes, the 1934 Bihar earthquake (M_s8.3), the 1930 Dubri earthquake (M_s7.1) and earthquakes in 1803 and 1833 (Oldham 1882, Seeber *et al.* 1981). Seeber *et al.* (1981) suggested that the Bihar earthquake occurred on a blind thrust at the base of the sedimentary section, but an earthquake in 1988 close to the 1934 epicenter has a calculated depth clearly within basement, 70 km according to Maggs (1988), or 64 km according to Holt *et al.* (1989). The other earthquakes could possibly have occurred at the top of the basement, but a source within basement cannot be ruled out (Seeber *et al.* 1981). There is no question, however, that the Himalayan front has been seismically active along its entire length east of the Kashmir syntaxis in the last two centuries of record-keeping.

Role of salt

The absence of large earthquakes in the Potwar Plateau and Salt Range has been explained by the presence of salt in the décollement horizon (Seeber *et al.* 1981). If so, then the anticlines and faults near the deformation front (Lilla and Pabbi Hills) should be undergoing aseismic growth and fault creep. This has not been reported. Possibly fault rupture would initiate on the décollement surface farther north, in Hazara, where salt may be absent (see discussion by Seeber *et al.* 1981).

Middlemiss (1910) noted that the greatest damage caused by the Kangra earthquake occurred in a re-entrant of the MBT where the Sub-Himalaya is unusually wide, almost as wide as in Pakistan. It was stated above that there is no evidence of salt in the Precambrian basement beneath the Siwaliks, but the Shali schuppen zone north of Mandi contains highly tectonized rocks of the Precambrian Shali Group and includes salt (Srikantia & Sharma 1976). It is possible that the unusual width of the Sub-Himalaya in the area of the 1905 Kangra earthquake is due to the presence of salt at the décollement level, but if so, the salt did not prevent the accumulation of enough strain to generate the Kangra earthquake.

Segmentation

What limits the rupture zones of major thrust earthquakes in the Himalaya? The 1905 Kangra earthquake occurred along that segment of the northwest Himalaya marked by dun valleys (Soan, Pinjore and Dehra dun valleys), which themselves are controlled by Siwalik anticlines at the Himalayan front. Southeast of Dehra Dun and northwest of Soan Dun, the Sub-Himalaya is narrower and is characterized by imbricate thrusts cutting N-dipping Siwaliks rather than Siwalik anticlines. The presence of salt in the schuppen zone near Mandi on the MBT suggests that the 1905 Kangra mainshock may have ruptured a relatively weak segment of the décollement zone between two stronger segments where salt is absent. If so, the Sub-Himalaya northwest of Kangra and southeast of Dehra Dun may be accumulating strain for large earthquakes in the future. These two regions were struck by earthquakes in 1885 (Jones 1885) and 1803 (Oldham 1882), respectively, earthquakes which may have ruptured the basal décollement horizon. Farther southeast, that part of the Sub-Himalaya of the Nepal–India border region struck by the 1833 earthquake is characterized by dun valleys (Dang Dun, Rapti Dun and Chitwan Dun), indicating a structural style similar to that in the area of the 1905 earthquake. East of Chitwan Dun, the Sub-Himalaya is unusually narrow in the rupture zones of the 1934 and 1897 earthquakes, suggesting an absence of salt, (Seeber & Armbruster 1981, fig. 2).

Valdiya (1976) noted that the Himalaya is affected by NE-trending tear faults and basement ridges of the Indian shield. These basement features, when combined with changes in character of the Sub-Himalayan thrust belt, may allow the definition of segment boundaries of the décollement horizon that could be matched with rupture boundaries of earthquakes in the last two centuries based on intensity data.

Earthquake potential of folds and the 1905 Kangra earthquake

In California, the 1983 Coalinga earthquake (M6.5), the 1985 Kettleman Hills earthquake (M6.1) and the 1987 Whittier Narrows earthquake (M6.0) occurred at shallow depths beneath surface anticlines without accompanying surface rupture. However, geodetic surveys showed that the anticlines were uplifted during each event, suggesting that the anticlines themselves grew by a succession of moderate-sized earthquakes over a period measured in 10^5–10^6 years (Stein & King 1984, Lin & Stein 1989). Other larger earthquakes also appear to be fold-related, although they did produce surface rupture (Stein & Yeats 1989). These include the 1980 El Asnam, Algeria, earthquake (M7.3; King & Vita-Finzi 1981, Cisternas *et al*, 1982, Philip & Meghraoui 1983), the 1977 San Juan, Argentina, earthquake (M7.4; Baldis *et al.* 1979, Triep 1979, Introcaso 1987), and the 1988 Spitak, Armenia, earthquake (M6.9; Cisternas *et al.* 1989). In each case, the surface rupture and displacement gave a moment calculation much smaller than the seismic moment; the aftershock zone at Spitak was five times as long as the zone of surface rupture. All three earthquakes occurred beneath surface anticlines, and the anticlines at El Asnam and San Juan grew during the earthquake.

We suggest that the 1905 Kangra earthquake was expressed at the surface as a fold, thus accounting for the absence of surface rupture. Releveling surveys showed growth of the Dehra Dun valley and Mohand anticline with respect to the MBT and Lesser Himalaya during the earthquake. After the earthquake, the Mohand anticline continued to rise with respect to the Dehra Dun valley and Ganga Plain. Interseismic strain appears to be accumulating near and south of the MBT north of Dehra Dun and near Kangra. The Kangra earthquake, at M8, would be the largest fold-related earthquake known.

CONCLUSIONS

Subsurface data show that the anticlines and reverse faults of the Himalayan frontal fault system are consistent with a décollement origin, forcing a sedimentary wedge southward over an unyielding basement surface. The décollement origin is documented by seismic evidence in Pakistan and is inferred from surface and well data in northwest India. The Sub-Himalaya of India and Nepal has been struck by several large earthquakes in the last two centuries, and the 1905 Kangra earthquake in the northwest Himalaya of India is best explained as an earthquake on a blind thrust. The 1905 Kangra earthquake and the 1833 earthquake occurred on segments of the Sub-Himalaya characterized by dun valleys and by anticlines at the Himalayan front. The 1885, 1803 and 1934 earthquakes occurred on segments of the Sub-Himalaya characterized by imbricate thrusts and the absence of dun valleys and range-front anticlines. The transition between zones characterized by imbricate thrust and zones characterized by dun valleys and blind thrusts may represent segment boundaries within the basal décollement horizon. The boundaries may themselves reflect tear faults and basement ridges in the underlying Indian shield.

The absence of large earthquakes in the Potwar Plateau and Salt Range of Pakistan has been explained by the presence of salt at the décollement level, but this should result in aseismic growth of folds and movement on faults, which has not been observed. However, if the evaporites die out northward and are not present north of the MBT, the décollement surface may be locked as it is in India, building up strain for a large earthquake. If so, it is surprising that this region has not had a large earthquake in the past 2000 years of recorded history.

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