Strong-motion earthquakes in Himalaya: Geological perspective

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Large segments of boundary thrusts and wrench faults of the Himalaya are active, registering episodic or intermittent movements. The intersections of tear faults and of faults with thrusts are particularly seismogenic. This is evident from high seismicity in the areas cut by the multiplicity of tear faults.

Epicentres of earthquakes of magnitude ≥ 5 are located in a narrow belt just south of the Main Central Thrust, the hypocentres defining a simple planar zone at 10 to 20 km depth. These are related to underthrusting of the Lesser Himalaya under the Great Himalayan slab.

As the northward drifting Indian continental plate slides under the Himalaya along the Main Boundary Thrust, the subsurface basement ridges hidden under the sediments of the Indo-Gangetic Plains strongly press and prod the mountain arc. The areas in front of the prodding promontories or penetrating ridges are extraordinarily strained and the stresses are accumulating phenomenally. Segments which have not been able to relax strains continually for a long period would release the accumulated stresses suddenly and violently in the form of great earthquakes.

Evolution and tectonic design

THE convergence and eventual collision of the Asian and Indian continental plates some 50 m.y. ago resulted in the evolution of the Himalaya (Figure 1). The junction of the two crustal plates is known as the Indus–Tsangpo Suture[1]. As the moving Indian plate lurched northwards, its leading edge, made up of the Precambrian basement rocks and thick Phanerozoic sedimentary pile, was warped up, bent, compressed and severely deformed (Figure 2) Violent renewal of convergence about 20–18 m.y. ago culminated in the tightening of folds and successive breaking up of the Himalayan crust by deep faults. Stacking up of the resulting crustal slabs, and uplift and southward thrust of the blocks culminated in the emergence of the mountain ranges such as the Himadri, Pir Panjal, Dhauladhar, Mahabharat, etc. Known as Trans-Himadri Fault (T-HF), Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Himalayan Front Fault (HFF), these deep faults now delimit boundaries of the four geological provinces or terrains of the Himalaya, namely the Tethys Himalaya, the Great Himalaya, the Lesser Himalaya, and the Siwalik (Figures 3 and 4).

The breaking up or detachment of the Phanerozoic sedimentary cover from its foundation of Precambrian crystalline rocks gave rise to the T-HF. Strong and prolonged movements resulted in uprooting of even the foundation (of the crystalline rocks) along the MCT and their southward advance as vast sheets or nappes for tens to more than hundred kilometres. The thrust sheets have trampled and deformed the comparatively younger sedimentary rocks of the Lesser Himalaya. Repetition of convergence of plates and attendant tectonic upheaval (3.4 to 1.0 m.y. ago) caused severe folding, further uplift, and displacement of the southern front of the Lesser Himalaya and their translation along the MBT upon the Siwalik (Figure 4) made up of sediments deposited by rivers.

The belt of deformation has thus shifted south successively in the last 40 to 50 m.y. The Holocene movements in the last 11,000 to 4,500 years BP have caused the deformation of the Siwalik and its rupture along the HFF on the northern margin of the Indo-Gangetic Plain. This plain represents the foreland basin filled by great thickness of recent sediments deposited by myriads of rivers in their channels and flood plains (Figure 4).

State of tectonic conditions of boundary thrusts

As the convergence of Indo-Eurasian continents continues unabated at the rate of about 5 cm/yr, so do the ceaseless movements of crustal blocks and slabs that continue to occur along the boundary thrusts and faults, episodically when accumulating stresses reach a critical limit. All the boundary thrusts and faults and many intra-terrain faults and thrusts are thus active—registering movements in the geologically recent time. Since tectonic resurgence has been stronger, faster, and more frequent on the MCT, the Himadri (Great Himalaya) has attained great heights (≥ 7000 m). Likewise, the MBT has registered considerable movements in recent times giving rise to a ruggedly high (≥ 2500 m) mountain front overlooking the Siwalik (Figure 4). Between the MBT and MCT, the Lesser Himalayan terrain has been lifted up to its present height by three to six major pulses of uplift in the last 1.6 m.y.[2]. This is evident from the lateral and vertical displacement of recent and subrecent riverine

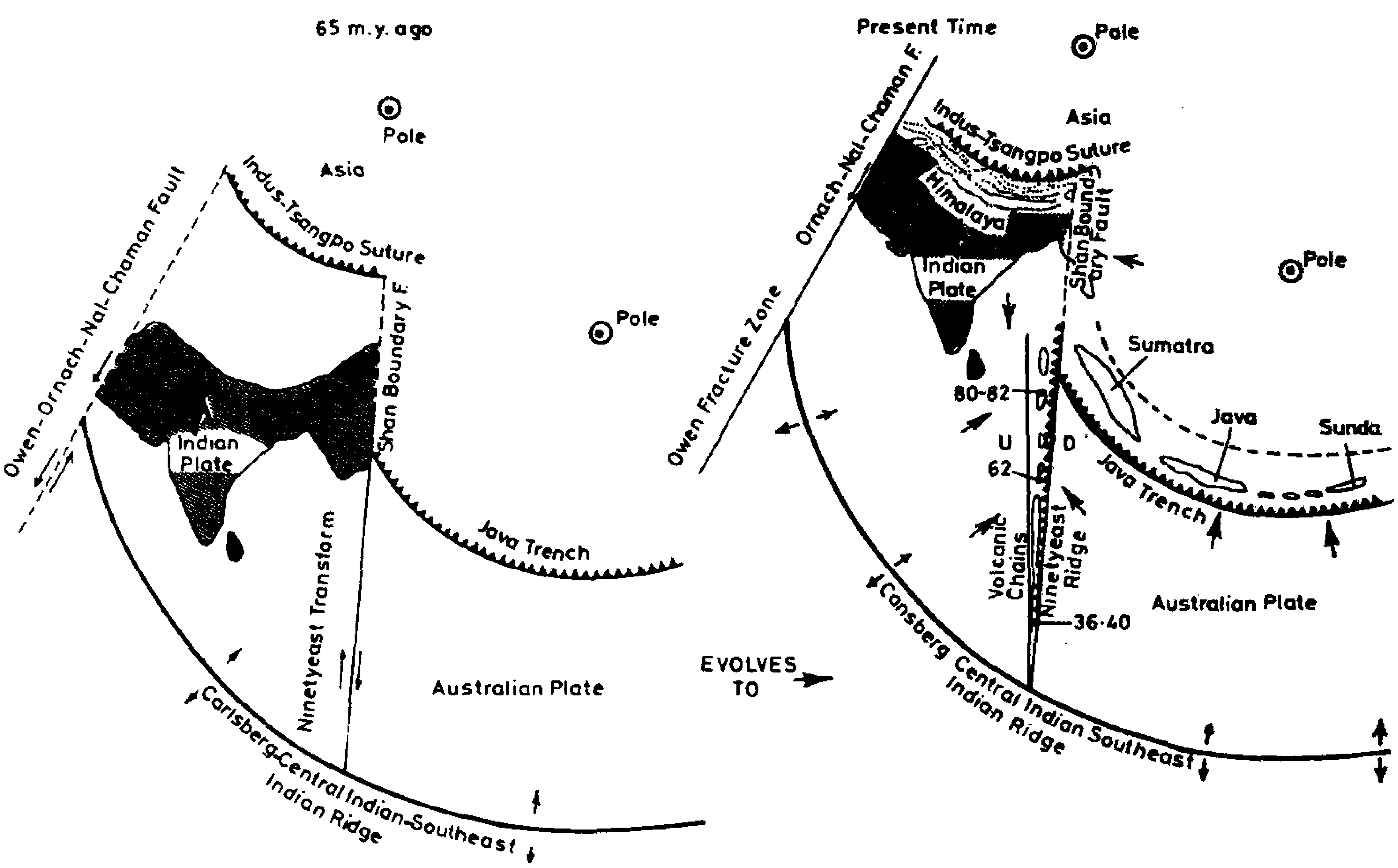

Figure 1. Himalaya arose as a consequence of collision of continents of India and Asia (after S. Chatterjee[40]).

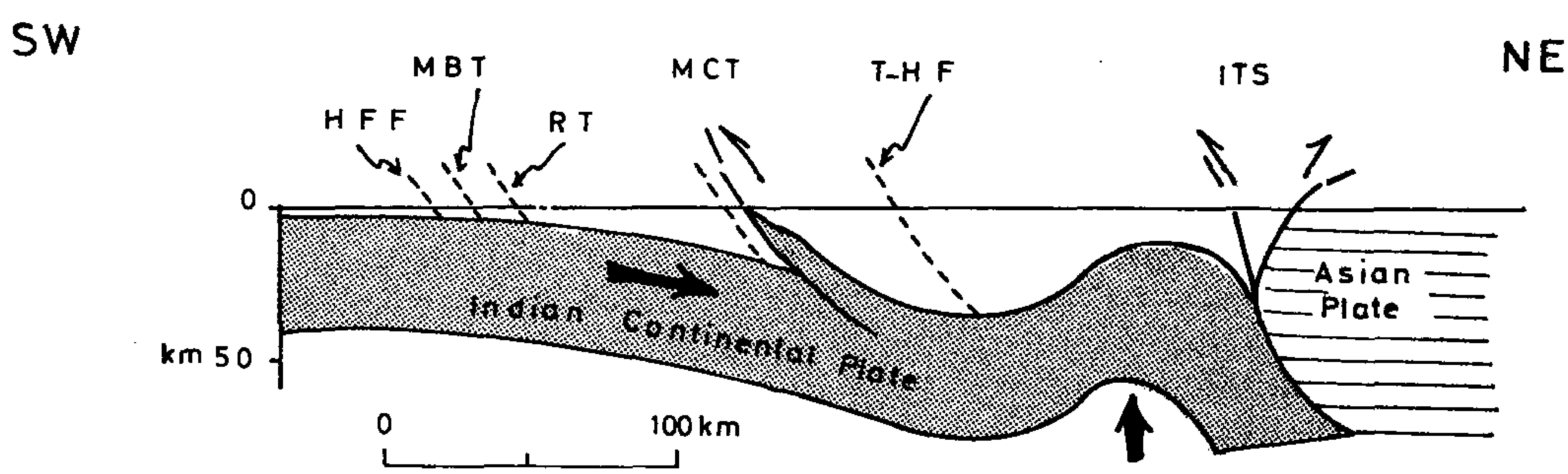

Figure 2. Leading edge of the Indian continental crust with its thick prism of Phanerozoic sediments was warped up, bent and successively split by deep faults such as Trans-Himadri Fault (T-HF), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Front Fault (HFF).

terraces and fans and cones of landslide debris, the trampling of recent debris by older rocks, extremely steep gradient of streams and occurrence of waterfalls in their courses, the tilting of lake deposits, the offsetting of streams and abandonment of old courses by rivers, etc[2-8].

Different parts of the Himalayan terrains have been rising up at different rates—the Nanga Parbat of the Great Himalaya at the rate of 5 mm/yr[9], the Pir Panjal of the Lesser Himalaya (Figure 4 *A*) at the rate varying from 3.5 to 10 mm/yr[10] and the Dehradun Valley in the Siwalik at the rate 1.0 mm/yr[11].

Latitudinal belt of high seismicity

Earthquakes are manifestations of sudden movements on active faults and thrusts. The epicentres of earthquakes of magnitude 5 and above (Figure 5) are located in a 50-km wide belt (just south of the MCT) all along the 1800-km length. Their hypocentres located in the 10 to 20-km depth (Figure 6) define a simple planar zone[12-15] that apparently dips 15° northwards—5° in the east and 30° in the west[16]. Its surface expressions, the active MBT and nearby subsidiary thrusts, however, did not register any displacement of rocks. Fault-plane mechanisms indicate predominant thrust movements, suggesting underthrusting of the Peninsular Indian plate beneath the Himalaya.

Parts of the movements associated with the MBT are bound to be relayed by subsidiary thrusts and faults in the southern front of the Lesser Himalaya (Figure 4). Likewise, the southerly movement of the Himadri will be transmitted in part to the thrusts of the schuppen

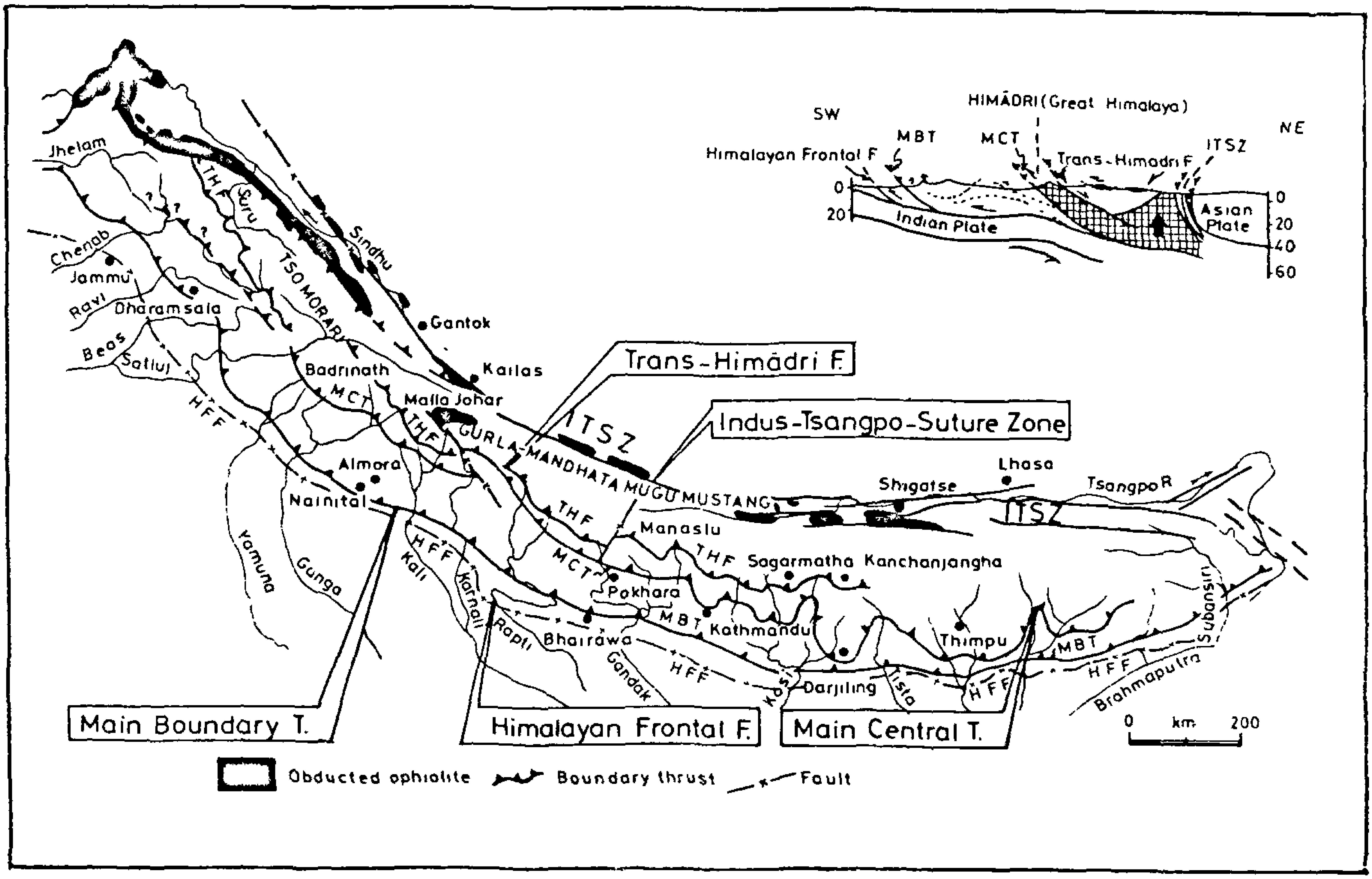

Figure 3. Trans-Himadri Fault (T-HF), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Front Fault (HFF) define the boundaries of the four geological terrains, namely the Tethys Himalaya, the Great Himalaya, the Lesser Himalaya and the Siwalik.

zone related to the MCT. This explains the epicentral distribution in a narrow belt just south of MCT (Figure 5).

Terrain-tearing faults

The Himalayan terrains are torn by myriads of transverse and oblique faults[17–21] trending NNE/N–SSW/S and NNW–SSE (Figure 7). Constituting a conjugate system, these faults were formed as a result of wrenching of differentially advancing (overthrusting) piles of rocks. Strong and persistent compression of fold mountains not only causes the rock masses or nappes to move bodily along the thrust planes, but also their tearing apart at arcuate edges, differential horizontal advance and attendant wrenching (Figure 8). The conjugate system of faults has released compression and simultaneously caused shortening of the Himalayan crust. Reactivation of old basement faults may also be responsible for tear faulting[18].

Both vertical (as much as 100–300 m) and horizontal (as much as 20 km) movements have taken place in the subrecent to recent times on these tear faults[2–4, 7, 8, 22]. Where vertical movements due to local crustal extension have taken place, grabens or rift valleys have originated, such as the 60-km long, 1000-m deep Takhola graben in north-central Nepal and the Yadong–Gulu graben north-east of Sikkim (Figures 9 and 10). The NW–SE trending faults, such as the Kopili–Bomdila F in eastern Himalaya have, by and large, registered right-lateral strike-slip movements and the NE–SW oriented ones (like those of northern Darjeeling–Sikkim), seem to have sinistrally displaced the rock masses. The NNW/NW–SSE/SE oriented faults are commonly more seismotectonically active than others. This is not to say that NNE/NE–SSW/SW trending faults are inactive.

Significantly, the Himalayan transverse faults and fractures demonstrate notable parallelism with those of the northern part of Peninsular India. Rather, in a large number of cases these fractures seem to be continuous across the terrain boundaries (Figures 9 and 10).

Pockets of high seismicity

There are over half a dozen areas of high seismicity (Figure 5) in terms of frequency of earthquakes (of $M \geq 5$). These are the areas where the terrains are cut by multiplicity of tear faults and thrusts. Superim-

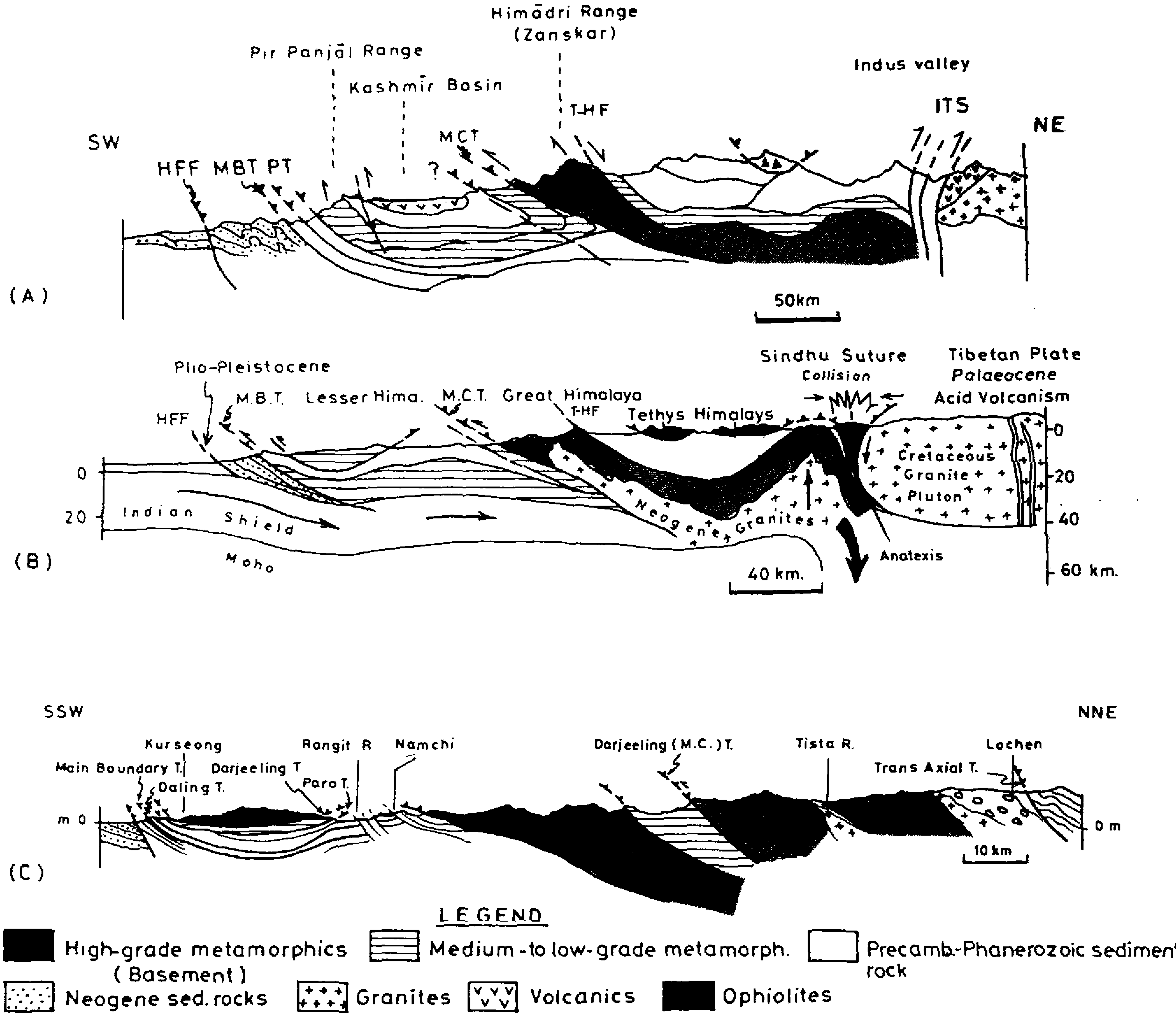

Figure 4. Diagrammatic cross-sections of the Himalaya showing major tectonic and lithological units, and illustrating the tectonic design of the mountain. (A) Western sector—Kashmir Himalaya (after Burbank and Johnson[10]) (B) Central sector—Kumaun Himalaya (after Gansser[1]). (C) Eastern sector—Darjeeling–Sikkim Himalaya (after Acharyya[41])

position of quantitative seismicity map[23] on the map of transverse faults brings out the fact that higher seismicity—in terms of frequency—is related to movements on these tear faults[3, 17, 18, 24]. The clusters of intense seismicity in eastern Himalaya (Figures 5 and 9) are likewise associated with the transverse faults and fractures forming rhombic blocks[20, 21]. Fault-plane solution of earthquakes indicate strike-slip motion on the transverse faults in Arunachal Pradesh, Sikkim and Nepal (Figure 10). According to Ben-Menahem *et al.*[25], the great earthquake of 15 August 1950 originated on the NW–SE trending Lohit Thrust as a result of interplate wedge motion. Two events located close to the MCT of November 1980 in northern Sikkim, for example, yielded left-lateral shear solutions on the NE–SW oriented faults which lie in the line of the Yadong–Gulu graben characterized by many N–S and NE–SW striking fault-scarps of Quaternary age[14]. Strike-slip movements on the Dangsi, Judi, Samea, Karnali and Tanakpur faults in Nepal (Figure 10) have likewise given rise to earthquakes[7, 8, 18, 20, 21]. The 1970 and 1975 earthquakes in central Nepal have been attributed to strike-slip motion[26] and the 1980 event in NW Nepal originated as a consequence of movement on the NW–SE trending Bajaura Fault[7].

The Bajang–Dharchula region in northwestern Nepal and adjoining northeastern Kumaun has been shaken repeatedly by moderate earthquakes, and exhibits the highest seismicity anywhere in the Himalaya—in terms of frequency of earthquakes of magnitude 5 or above (Figures 5 and 11). The strongest event so far of

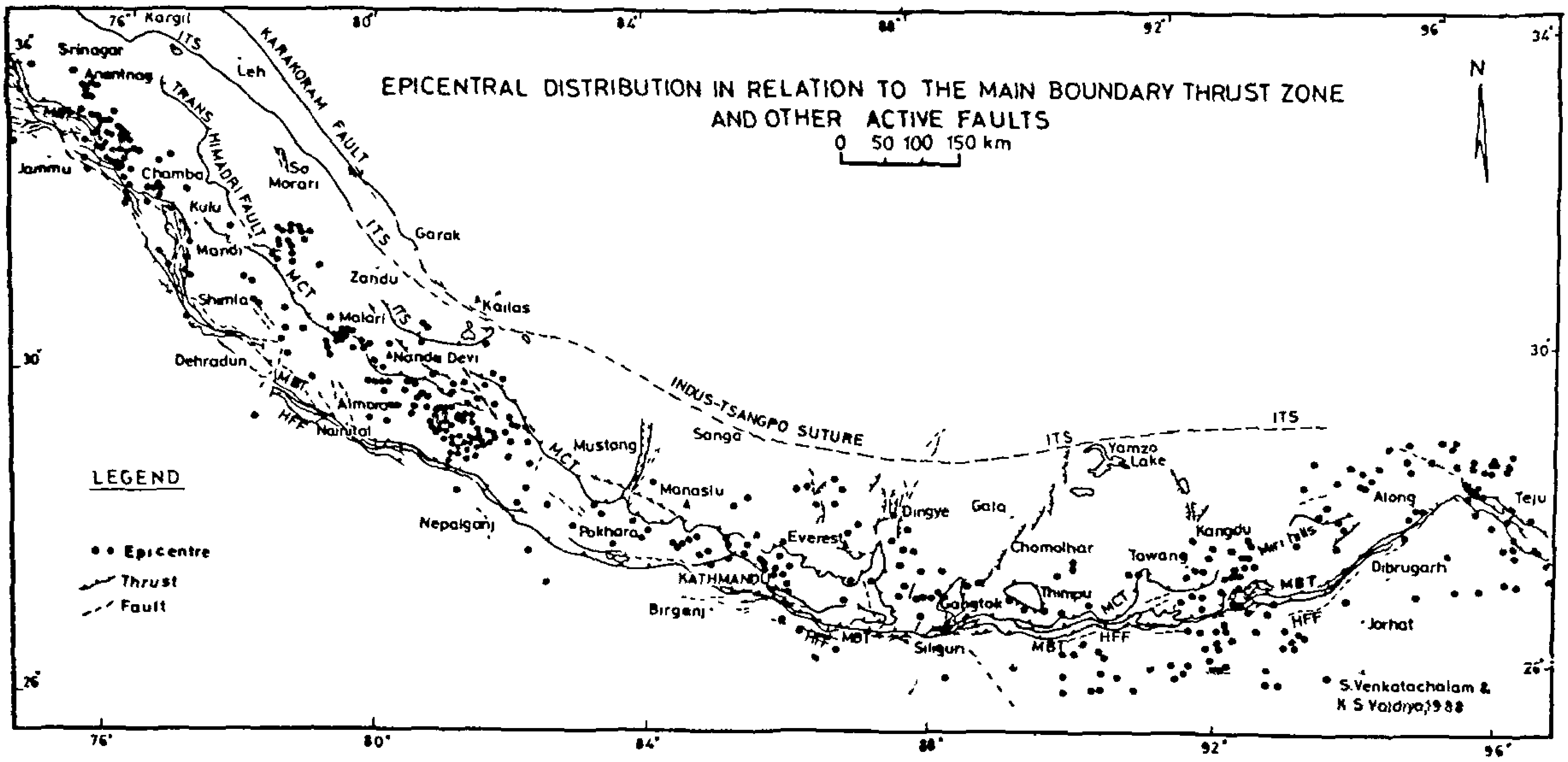

Figure 5. Distribution of epicentres of earthquakes of $M \geq 5$. There are half a dozen regions of high concentration of epicentres. (Structural map by K. S. Valdiya, epicentral distribution by S. Venkatachalam of NGRI, Hyderabad.)

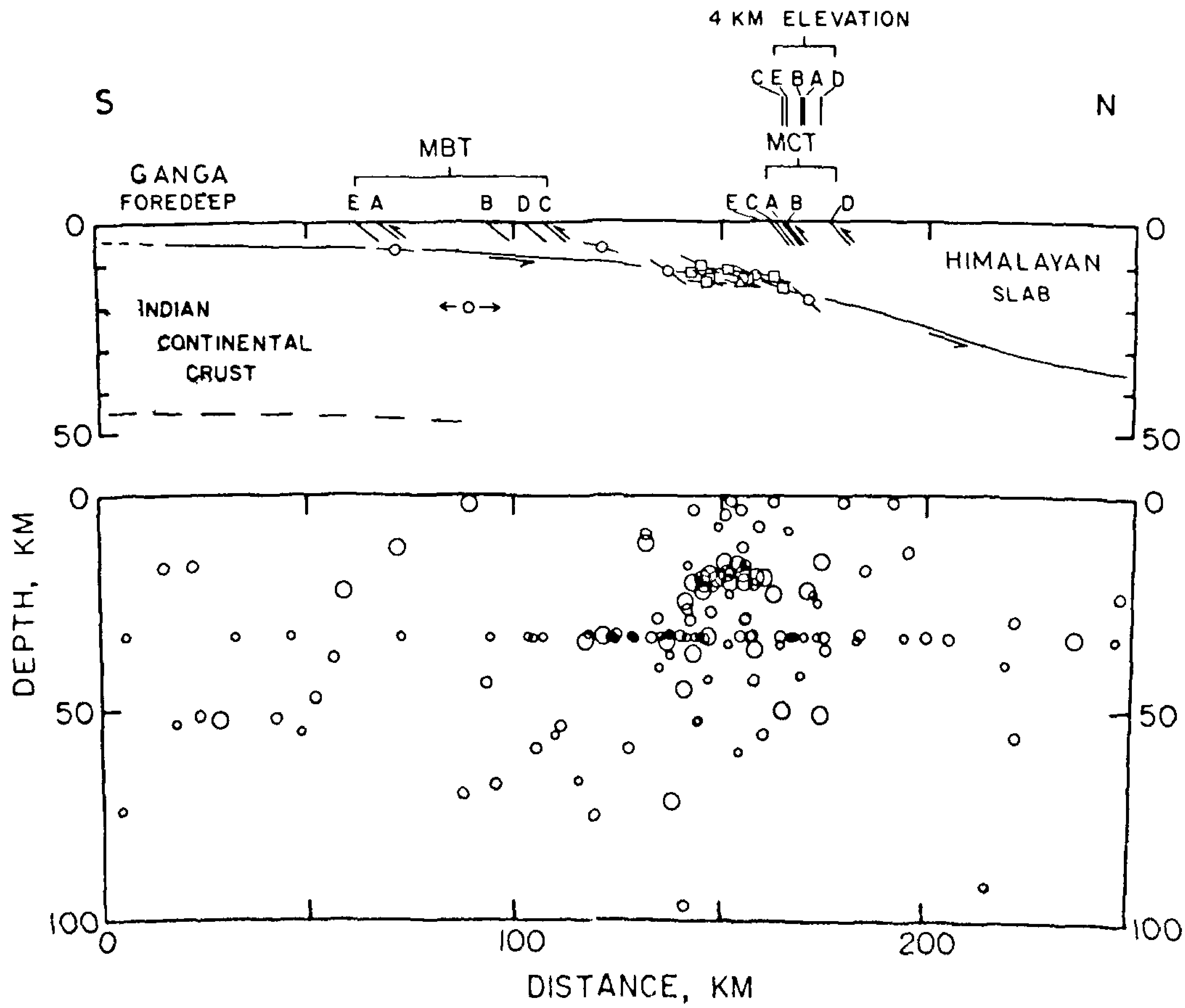

Figure 6. Planar surfaces of detachment (nodal plane) at the depth 10–20 km below the surface are found to be the loci of medium size earthquakes (after Ni and Barazangi[14]).

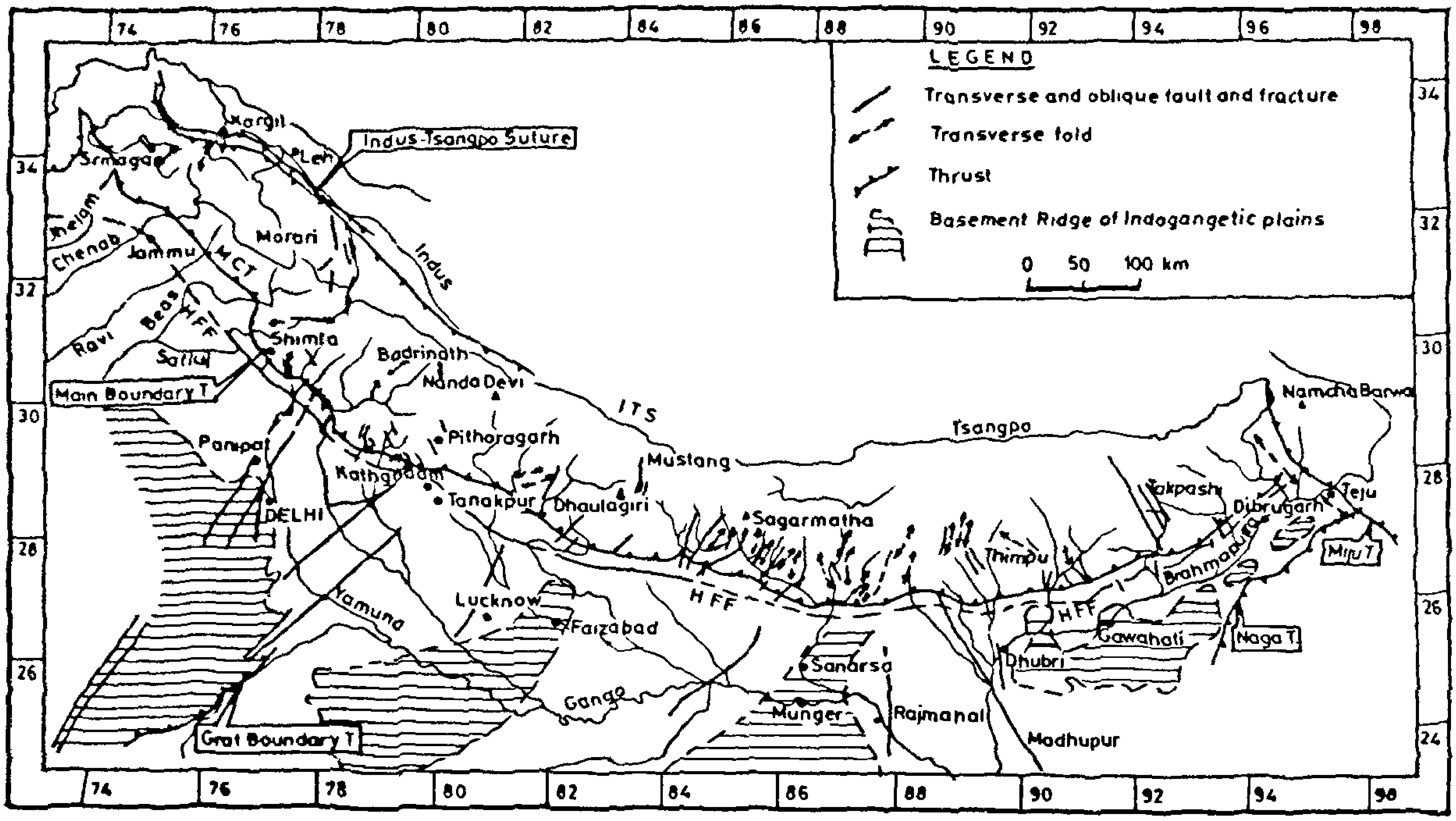

Figure 7. Transverse tear faults in the Himalaya bearing remarkable parallelism with the subsurface basement ridges or highs and faults of the Sindhu–Ganga Basin (Valdiya[18]).

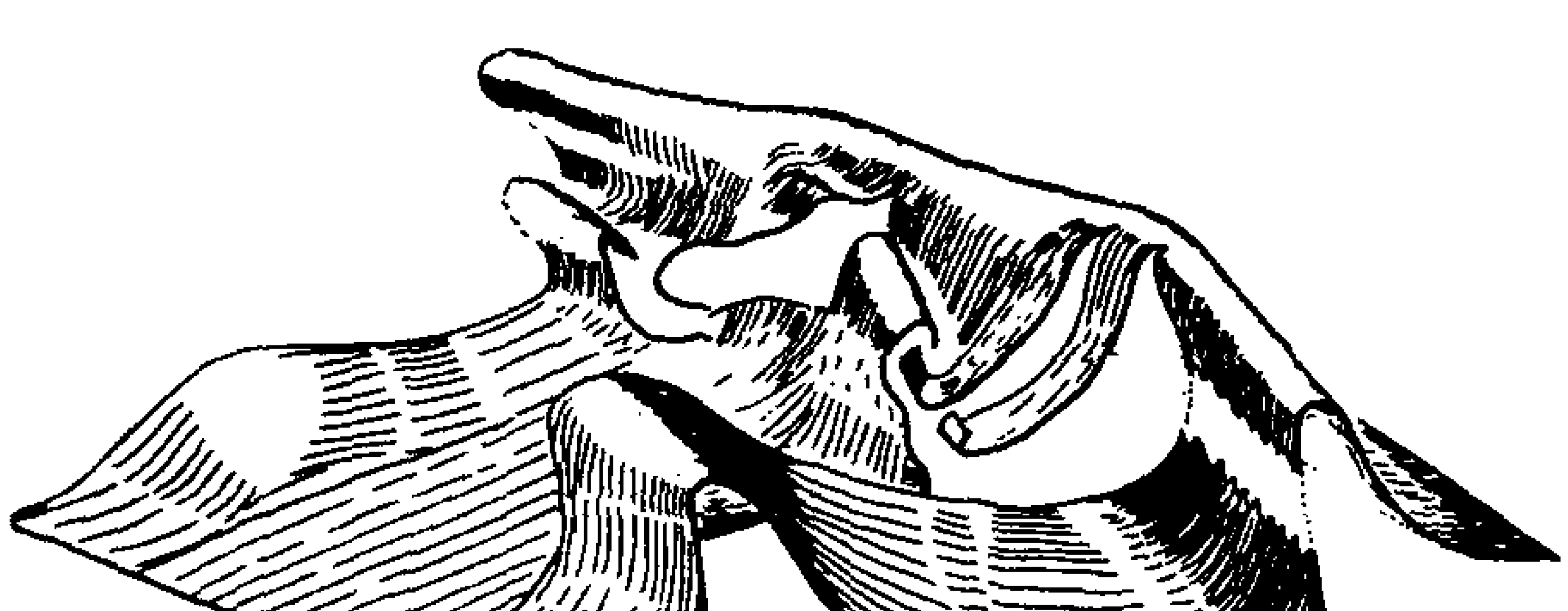

Figure 8. Tear faults developed in mountains of strong folding and thrusting due to translation of the folded masses. (J. Goguel, 1962, *Tectonics*, Freeman, San Francisco.)

M 7.5 occurred on 28 October 1916 (in Bajang) and the 27 June 1966 earthquake originated from a fault that registered strike-slip movement[27]. The location of hypo-centres in vertical planes is suggestive of tear movements on transverse faults such as the Baram–Baikot F and Baluwakot F[3,18]. Significantly, the December 1966 event of Dharchula badly shook the towns of Pilibhit and Muradabad in the Indo-Gangetic Plain. It may be pointed out that the Dharchula–Bajang area lies directly in the line of the subsurface active Muradabad Fault of the Ganga Basin. The fault-plane solutions of all other events, however, indicate thrust movements in this region[28,29]. The 29 July 1980 earthquake at Dharchula had the NNE–SSW trending axis of isoseismals parallel to the Muradabad Fault[30] even though the fault-plane solution indicated thrust faulting.

The microseismicity monitoring in the Uttarkashi–Chamoli districts in Garhwal (Figure 11) revealed concentration of epicentres in a 30-km wide belt. More than 95% earthquakes occurred in depths shallower than 15 km, and 62% were located in the upper 7 km crust[31,32]. The earthquakes of the belt between the Yamuna and Bhilangana are attributed to strike-slip movement in the E–W direction presumably related to the Uttarkashi Fault[33] and those between the Bhilangana and Alaknanda indicate thrust faulting[32] in the Bhatwari schuppen zone of the MCT[3]. The epicentre of the 20 October 1991 Uttarkashi earthquake of *M* 6.6 was located at the intersection of the MCT with the WNW–ESE striking Uttarakashi Fault[33].

To the northwest, in the lower reaches of the Spiti River (Figure 11) the 19 January 1975 event (*M* 7.5) and aftershocks of *M* 7.0 indicated movements on the NNW–SSE to N–S trending normal Kaurik–Chango Fault[27,34]. Further west, the seismically most active region lies to the northeast of the Dalhousie–Dharamsala area. The earthquakes of 14 June 1978 (*M* 5.0) and 26 April 1986 (*M* 5.7) have been related to left-lateral tear fault in the Ravi Valley west of Dalhousie[30]. The high microseismicity (monitored in the period 1966–1989) implies that the region ravaged by the great Kangra earthquake of 1905 (*M* 8.6) continues to experience

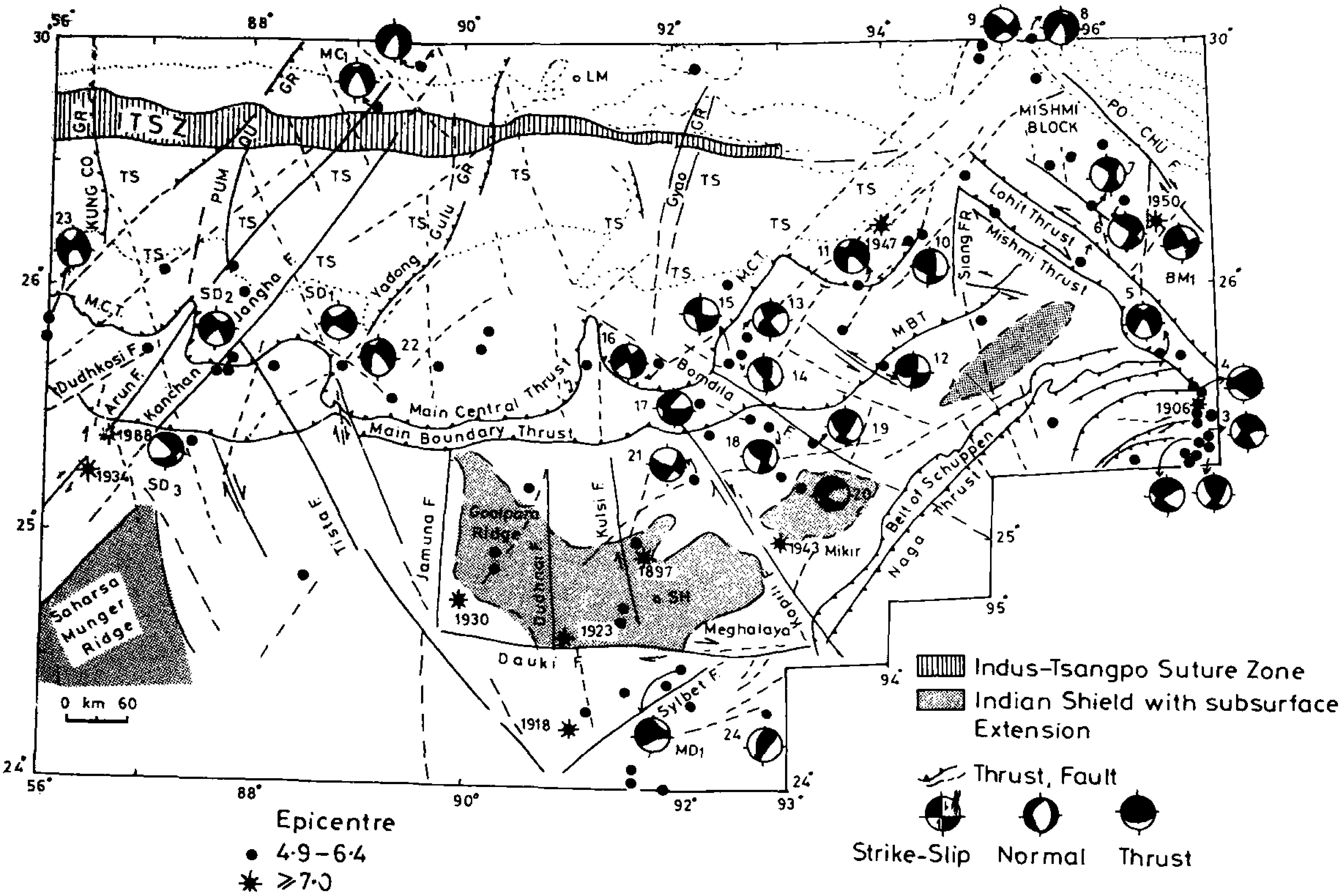

Figure 9. Transverse faults and fractures and fault-plane solutions of earthquakes in the Eastern Himalaya (modified after Nandy and Dasgupta[20]).

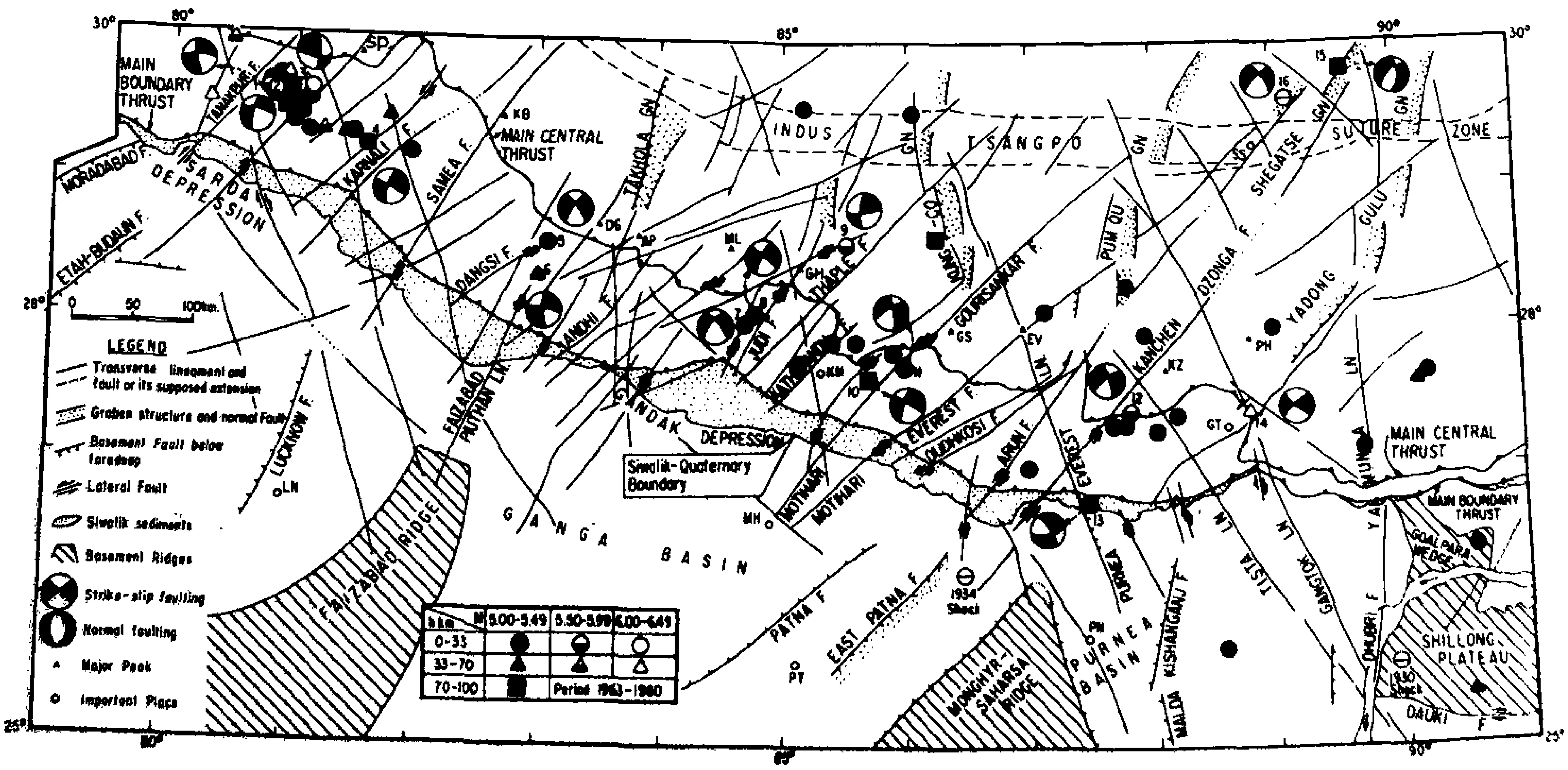

Figure 10. Transverse faults in Nepal Himalaya and fault plane mechanisms of earthquakes (from Dasgupta *et al*[24])
Tectonic map for the Nepal–Sikkim Himalaya and their foredeep superposed on seismicity data along with results of the focal mechanism study. Geologic and tectonic data are adapted from references cited in text, and from Figure 2. Other symbols are the same as in Figure 2. Intersecting lineament patterns are envisaged as rhombic fault blocks bounded by conjugate shear planes which slice the leading edge of the Indian plate at the Himalayan collision front; rhombic fault blocks possibly move as a mosaic. High peaks: *SP*—Saipal, *KB*—Kanjiroba, *DG*—Dhaulagiri, *AP*—Annapurna, *ML*—Manaslu, *GH*—Ganesh Himal, *GS*—Gauri Sankar, *EV*—Everest, *KZ*—Kanchendzonga, *PH*—Pauhunri. Prominent towns: *PN*—Purnea, *GT*—Gangtok, *SS*—Shigatse, *KM*—Kathmandu, *MH*—Motihari, *PT*—Patna, *LN*—Lucknow. *F*—fault, *LN*—lineament, *GN*—graben.

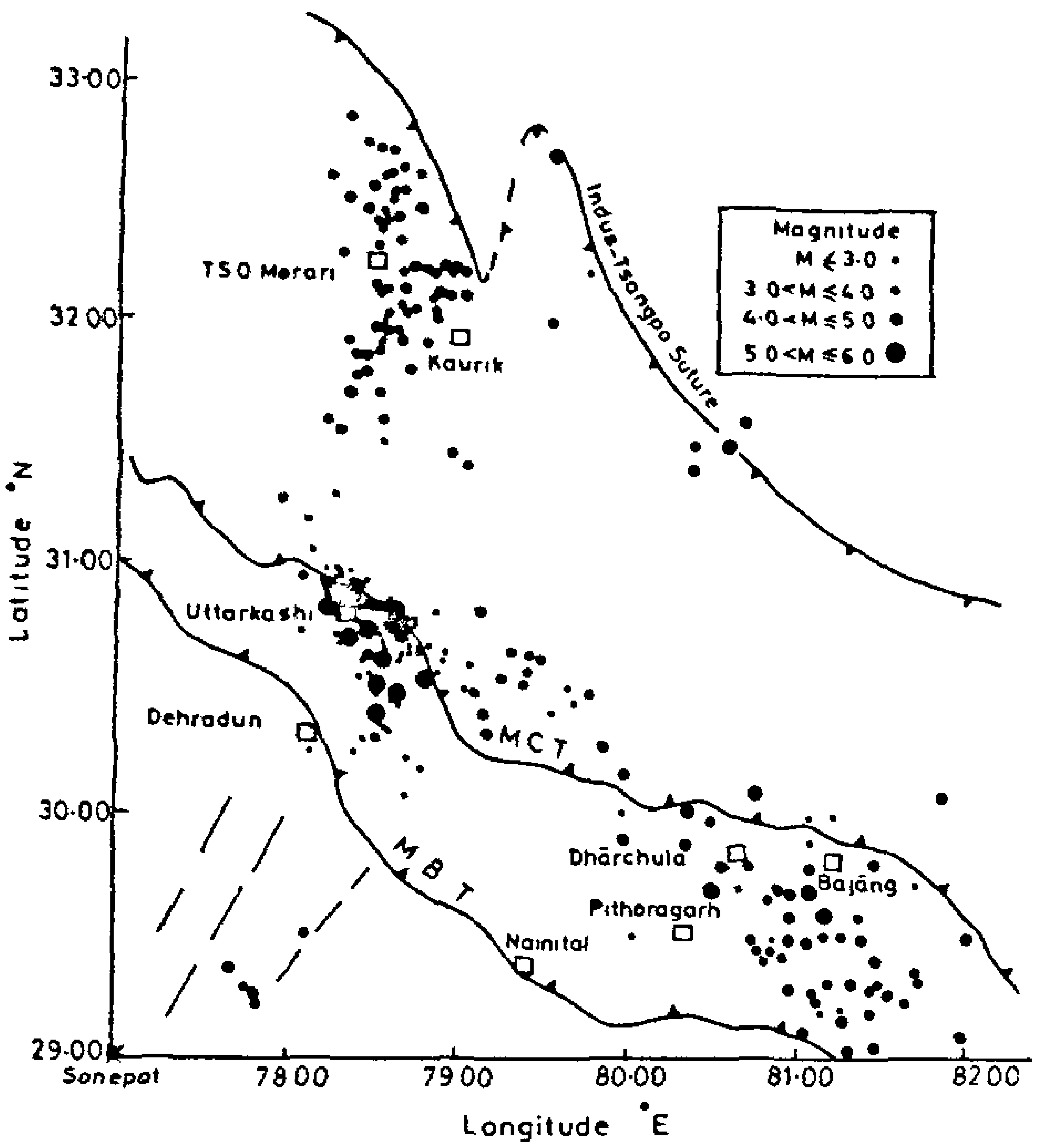

Figure 11. Epicentral distribution of moderate earthquakes in Kumaun, Garhwal and Eastern Himachal (Khattri[32])

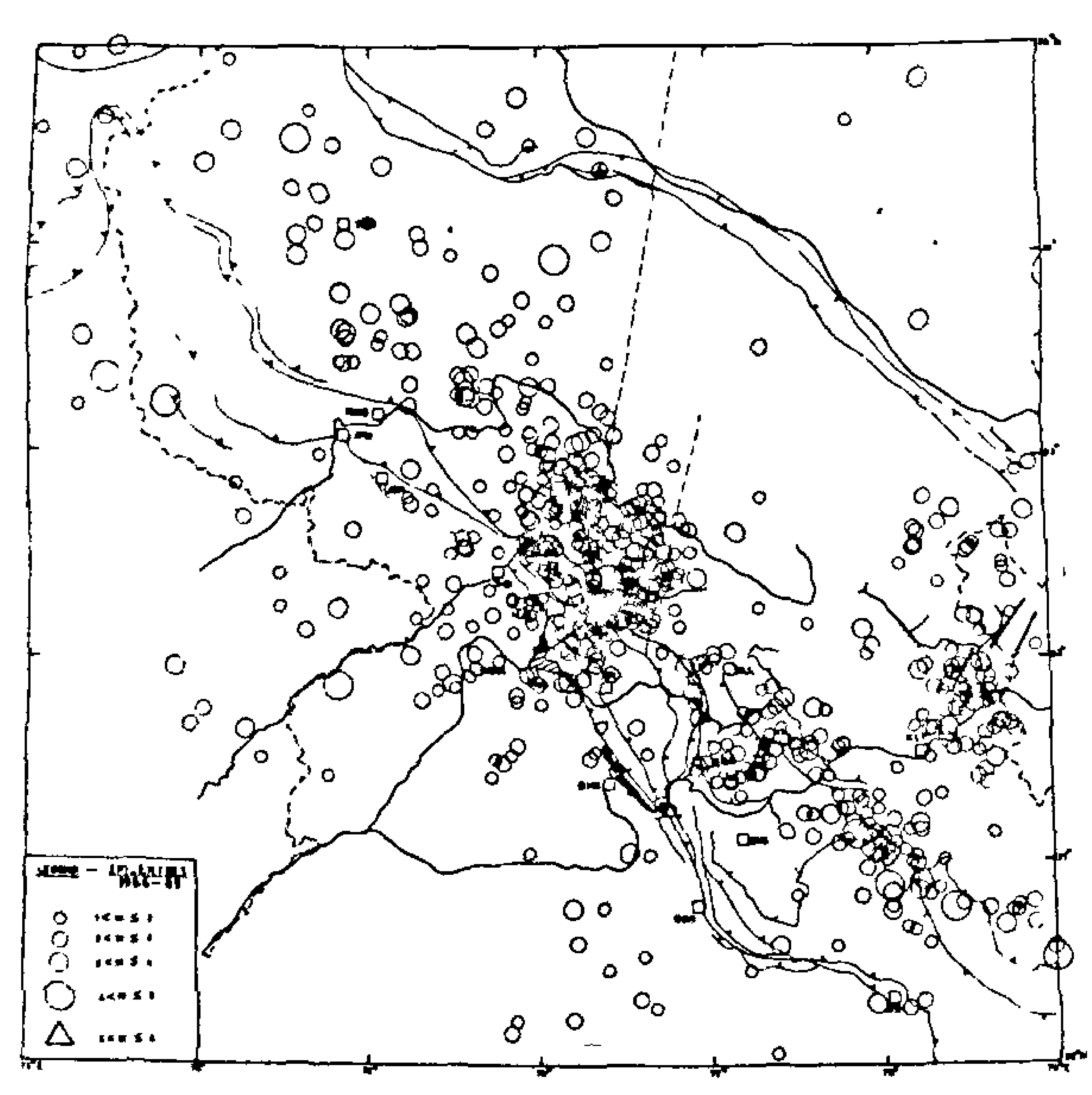

Figure 12. Microseismicity during the period 1986–1989 in western Himachal Pradesh—the region which was ravaged by the great 1905 Kangra earthquake (M 8.6) (Chatterjee and Bhattacharya[35])

stress buildup[35].

Morphostructural zoning on the basis of epicentral distribution and intersecting lineaments indicates many blocks and knots (Figure 13) of high potential of strong-motion earthquakes[36]. Out of the total number of 97 knots formed by intersection of transverse fractures/faults, 48 are found to be seismically potential for the occurrence of earthquakes of M 6.5 (including the area of 1991 Uttarkashi earthquake of M 6.6), and 36 knots are potential areas for the events of M 7.0 (ref. 36).

Obviously, the terrains dissected by transverse and oblique tear faults—which are presently locked—are potential sources of strong-motion earthquakes.

Subsurface ridges in the Sindhu–Ganga Basin

Geophysical probing of the Indo-Gangetic Plain has revealed subsurface extension northwards of the hill ranges of the Peninsular India (Figures 7 and 14). Having strong magnetic anomaly, many of these ridges are wedge-shaped.

As the northward drifting Indian continental plate slides under the Himalaya along the MBT, these hidden ranges strongly press and prod the mountain arc[33]. The Aravali (Delhi–Hardwar) Ridge seems to have even penetrated the underbelly of the Himalaya. This is manifest in the anomalously transverse structural trend in Garhwal[37], skewed distribution of sedimentary facies in the Spiti Basin[38], plutonic events and development of topographic eminences in the northern belt[39], very high concentration of epicentres in the lines of these ridges[17,18] and development of E–W trending tensional stress producing strike-slip faulting in the Uttarkashi region which has been upwarped by the presumed extension of the Delhi–Hardwar Ridge[16].

The clustering of seismic activity in areas of impingement of the basement highs with the subduction zone has been described as 'peg effect' by Raval[39] and compared with similar phenomena occurring in the oceanic subduction zones due to the presence of aseismic ridges, plateaus, chains of seamounts/swells, etc.

Naturally, the areas in front of the prodding promontories or penetrating wedges are bound to be extraordinarily strained as a result of terrific compression (Figure 15) as the Indian continental plate persistently presses northwards at the rate of 5 cm/yr. The phenomenally accumulating stresses naturally are released in the form of earthquakes. Segments which are not able to relax their strains continually for longer period, release the accumulated stresses suddenly and violently in the form of great earthquakes, such as the 1905 Kangra event (M 8.6) in front of a second-order basement high branching off from the Lahore–Sargodha Ridge, the 1934 North Bihar earthquake (M 8.1) in the line of the Munger–Saharsa Ridge, and the 1950 Arunachal event (M 8.7) in front of the Mikir–Upper Assam basement high (Figures 7 and 14). The moderate events of Uttarkashi (M 6.6) and of Jaisalmer (M 5.6) are likewise

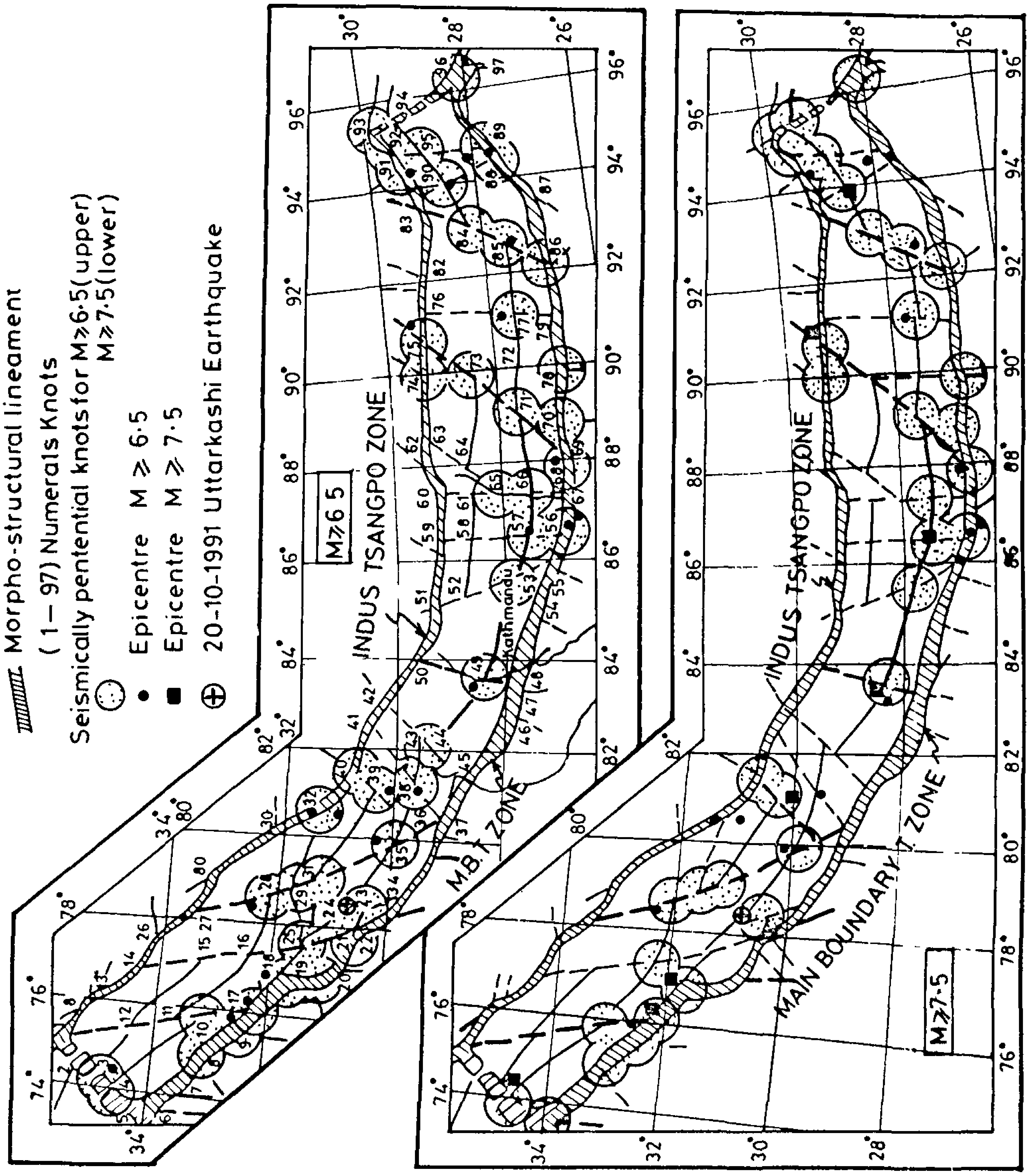

Figure 13. Morphostructural zoning on the basis of epicentral distribution and intersecting lineaments has revealed many blocks and knots of high potential for strong seismicity (Bhatia *et al*[36]).

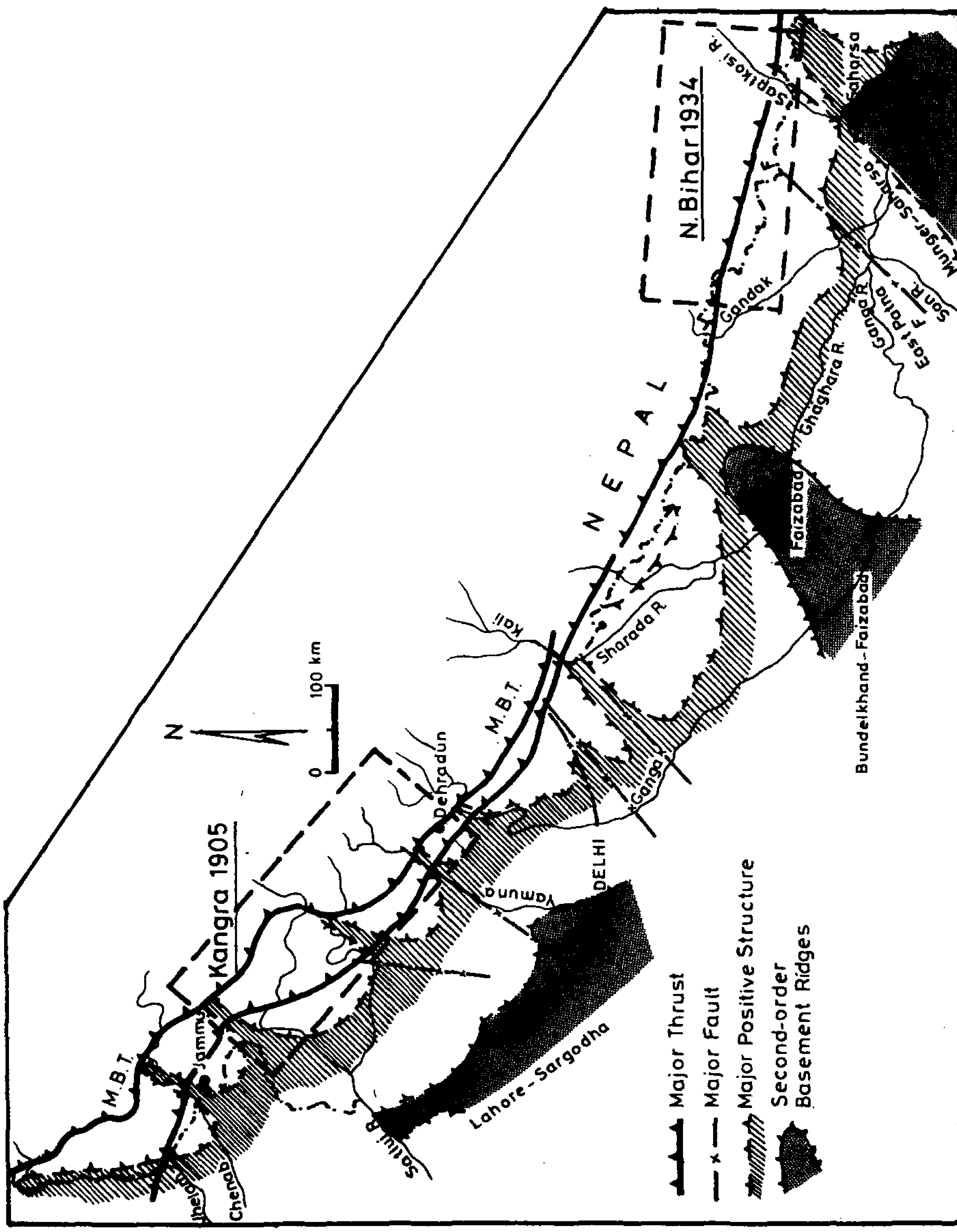

Figure 14. Major and second-order 'hidden ranges' or basement highs in the Sindhu–Ganga Basin exhibiting notable parallelism with the transverse structures of the Himalaya (based on Raiverman *et al.*[42]).

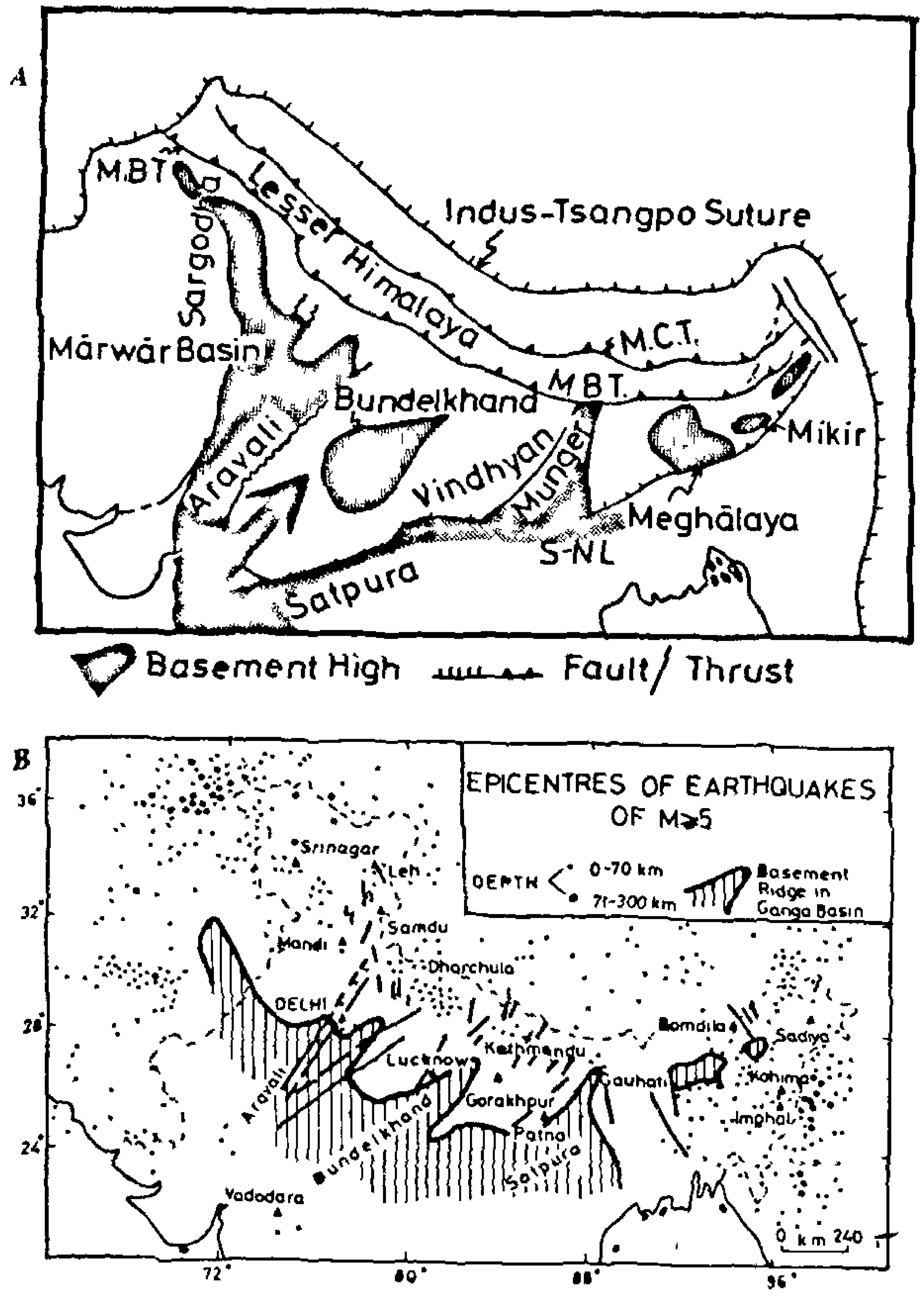

Figure 15. (*A*), Fronts of promontories prodding and penetrating the mountain arc must be generating terrific strains and stresses in the body frame of the Himalaya (*B*), (after Valdiya[2]).

related to the subsurface extension of, respectively, the Delhi–Hardwar Ridge and the Jaisalmer–Jacobabad Ridge[39]. Compression and squeezing up of Himalayan rocks by the prodding promontories must be releasing large volumes of fluids, which would reduce shear strength of the faulted rocks and thus precipitate failures and attendant earthquakes[39]. These are the areas, in my perception, which will not only be rocked severely but frequently also.

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