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UNLOCKING OF ACTIVE FAULTS IN THE HIMALAYA AND ITS FORELAND

K S VALDIYA, FNA

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

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Larger parts of the active faults dissecting and delimiting the Himalaya have remained locked most of the time in the Recent epoch. These faults in the recent past had registered significant uplift—at the average rate of 3 to 7mm/yr of the Lesser Himalayan terrain and considerably more than 5.5mm/yr of the Great Himalayan domain—with attendant displacement, deformation and modification of landforms and sediment accumulations.

The continuing convergence or northward movements of India towards Asia is thus being stored progressively as elastic strains in the stressed rocks of these faults zones. This is particularly pronounced in the zone of the Main Boundary Thrust along which the Indian Shield is being shoved under the Himalaya, and also along transverse faults tearing the framework of the Himalaya into differentially loaded blocks. Since no great or moderately high magnitude earthquakes have occurred regularly or even periodically in the last few hundred years in the central sector of the mountain arc, and as the aseismic slip on the postulated rupture surface beneath the Lesser Himalaya is not more than 30% of the total convergence rate of 18 ± 7mm/yr, the stored strains are likely to be released suddenly with attendant drastic topographic changes including uplift, subsidence, landslides, etc. in this central sector between rivers Satluj and Kosi.

Unable to make easy penetration under the weighted Himalaya, the front of the Indian Shield buckled down into a progressively subsiding basin—now filled up into the Indo-Gangetic Plains. It continues to subside in certain areas such as northeastern Uttar Pradesh, northern Bihar and northeastern Bangladesh. The depressed areas experience recurrent uncontrollable hazards of floods and waterlogging. The upwarped backside of the northward pushing Indian Shield—such as the Chhotanagpur-Vindhyan belt—and the fault-lined Aravali ranges, has been rising concomittently. The slow uplift of the Aravali has deflected and shifted the courses of rivers like Satluj, Yamuna and Kosi and caused disappearance of the legendary Saraswati that flowed through Haryana and northwestern Rajasthan during the Harappan period. Distribution of epicentres of earthquakes and displacement of geomorphic features demonstrate that the Aravali, Satpura and Meghalaya defined by the active Narmada-Son-Dauki Fault deep down are experiencing tectonic turmoil.

Key Words: Unlocking; Active Faults; The Himalaya; Lesser Himalayan Terrain; The Great Himalayan Domain; Tectonic Turmoil

Rapid Rise of The Himalaya

The Himalaya is rising very rapidly, and its ranges are gaining height despite the furious pace of denudation (Fig. 1). While the uplift rate of the Siwâlik is

Fig 1 Great height of the Himadri (Great Himalayan) peaks is due to repeated, strong and recent movements on the active Main Central Thrust and other thrust faults. A majestic peak in Kumaun Himalaya with its more than 3000m high nearly vertical scarp (Photo Anup Sah)

nearly 1mm/yr, the Lesser Himalayan terrain is moving up at the rate varying between 3 and 7mm/yr[1-3]. The Great Himalayan domain in the northwest is rising at the rate considerably more than 5.5mm/yr, and the southern frontal ranges of the Lesser Himalaya, such as the PirPanjal-Dhauladhar and Mahabharat, have gained their soaring elevations at the rate 10 to 12mm/yr[2,5].

The mountain ranges delimited by and related to active faults demonstrate more pronounced upliftment. Active faults are those along which up-and-down and/or sideway movements have taken place in the Quaternary period—in the last 1.6 million years. Evidently, their greater elevation and rapid rise are due to stronger, repeated and more recent (in the last 11,000 years) movements on the active faults (Fig. 2).

Buckling and Breaking of The Himalayan Crust

The headlong collision of the northward drifting India with Asia—some 65 m.y. ago—not only caused the buckling or doming up of the leading edge of the Indian plate (Fig. 2), but also the breaking off successively of the crust behind the upwarp. Periodic revival or accelcration of the convergence of continents manifests in the forward lurch of the Indian landmass and reactivation of

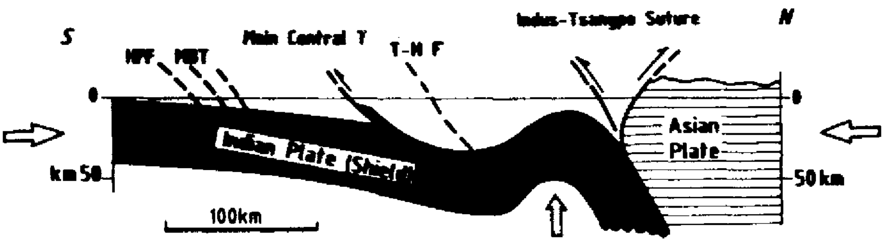


Fig 2 Unable to slide easily under the Asian landmass, the leading edge of the buoyant Indian plate buckled up at its front and broke off successively behind the upwarp

the boundary faults like the Trans-Himadri Fault (T-HF), Main Central Thrust (MCT), Main Boundary Thrust (MBT), Himalayan Frontal Fault (HFF), etc. (Fig. 3).

Frontal Ranges: Movements on Active Faults

Geomorphic, structural and geodetic studies indicate repeated movements in the Pleistocene and Holocene epochs—in the last 1.6 m.y.—on the T-HF, MCT, MBT, HFF and other faults and thrusts. It is the MBT and its sympathetic subsidiary faults which have registered the strongest and repeated movements in the Holocene. The MCT was extremely active in the Pleistocene. The movements on the active faults were by and large episodic—of the order of 20-40 to 70m in the Lesser Himalaya[6-13] as borne out by displacement of riverine terraces and landslide debris cones and fans (Fig. 4). These movements have taken place even in the historical times—in the Kushan period 2nd to 4th centuary A.D.[11].

Landslides and Excessive Influx of Sediments

Episodic, possibly spasmodic, uplifts of the mountains were accompanied by earthquakes, with attendant landslides on stupendous scales on the slopes of the abruptly elevated mountains. This is apparent from fans and cones of debres in the foothills (Fig. 5), as well as from excessive influx of sediments in the Ganga Basin and connected Bengal Sea. The transverse prolongation of the debris fans have pushed the Ganga and Brahmaputra rivers to take the very southerly course (Fig. 5).

There were many episodes of voluminous input to the sea of finer detritus resulting from accelerated erosion due to rapid Quaternary uplift of the Himalayan terrain in tectonic turmoil. The dramatic increase in the rate of sediment accumulation in the Bengal Sea from 20-70m/m.y during the Late Miocene-to-. Early Pleistocene to more than 200m/m.y very suddenly about 800,000 years BP[14] indicates that the Himalaya—particularly its Great Himalayan domain—rose up extremely rapidly to great height less than a million years ago[14]. It was possibly at this juncture that the Himalaya acquired its gigantic dimension.

Accumulating Strains and Locked Segments of Active Faults

The pattern of distribution of epicentres indicates that the Himalayan earthquakes are related to movements on the MBT, and to the tear faults[11,15] or to the subsurface extension of the MBT as a rupture zone within the Himalayan province. Four times in the last hundred years, the Himalayan arc has been ruptured by great earthquakes of magnitude above 8.0—Kangra (M 8.4) in 1904, southcentral Nepal (M 8.1) in 1934, northern Meghalaya (M 8.7) in 1897 and northeastern Arunachal (M 8.7) in 1950 (Fig. 6).

However, quite large parts of the very active MBT remain locked or struck since quite a few hundred years. The northward movement or push of the Indian plate continues—the Indian Shield pushing the Himalaya persistently and strongly. This movement is being converted into elastic strain, and

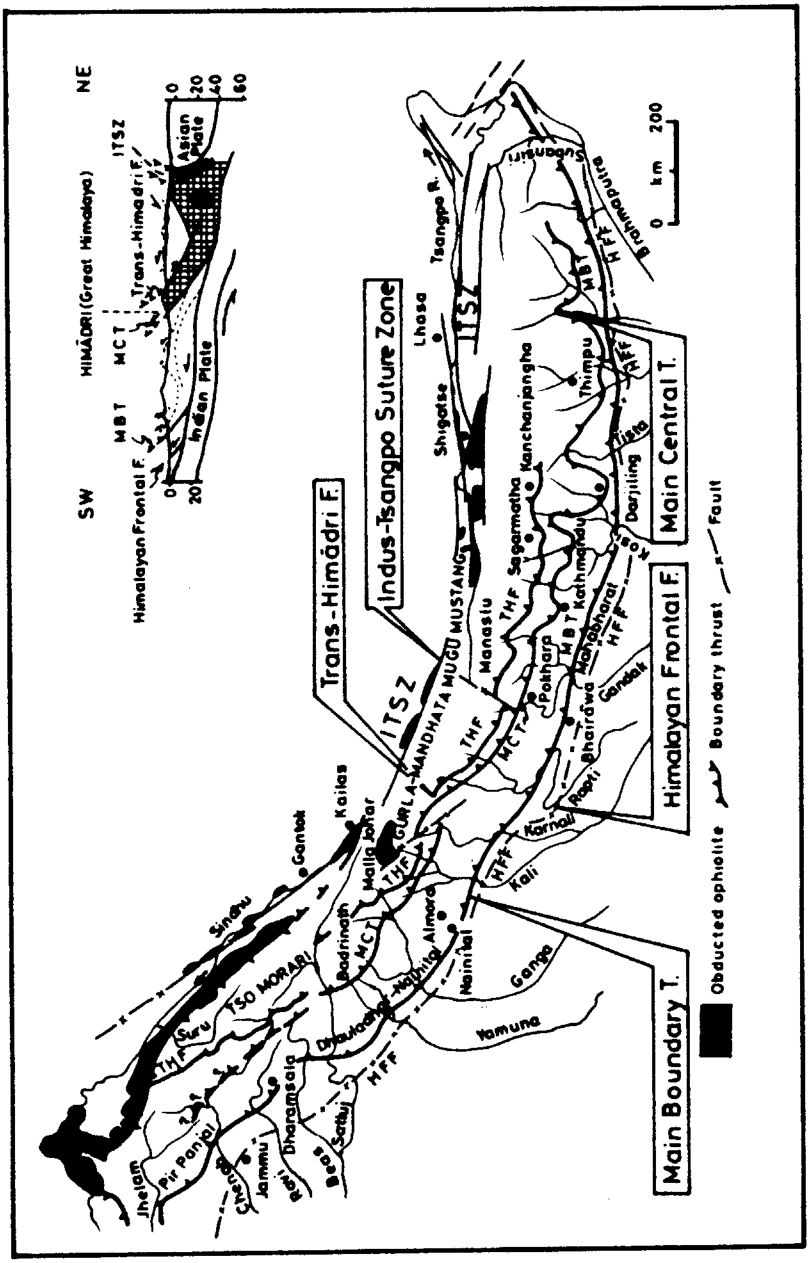


Fig 3 Major thrusts dividing the Himalayan province into lithologically, tectonically and geomorphically contrasted domains or terranes (Siwalik, Lesser Himalaya, Himadri and Tethyan) *Inset:* diagramatic section through the Himalaya showing positions of active boundary thrusts/faults).

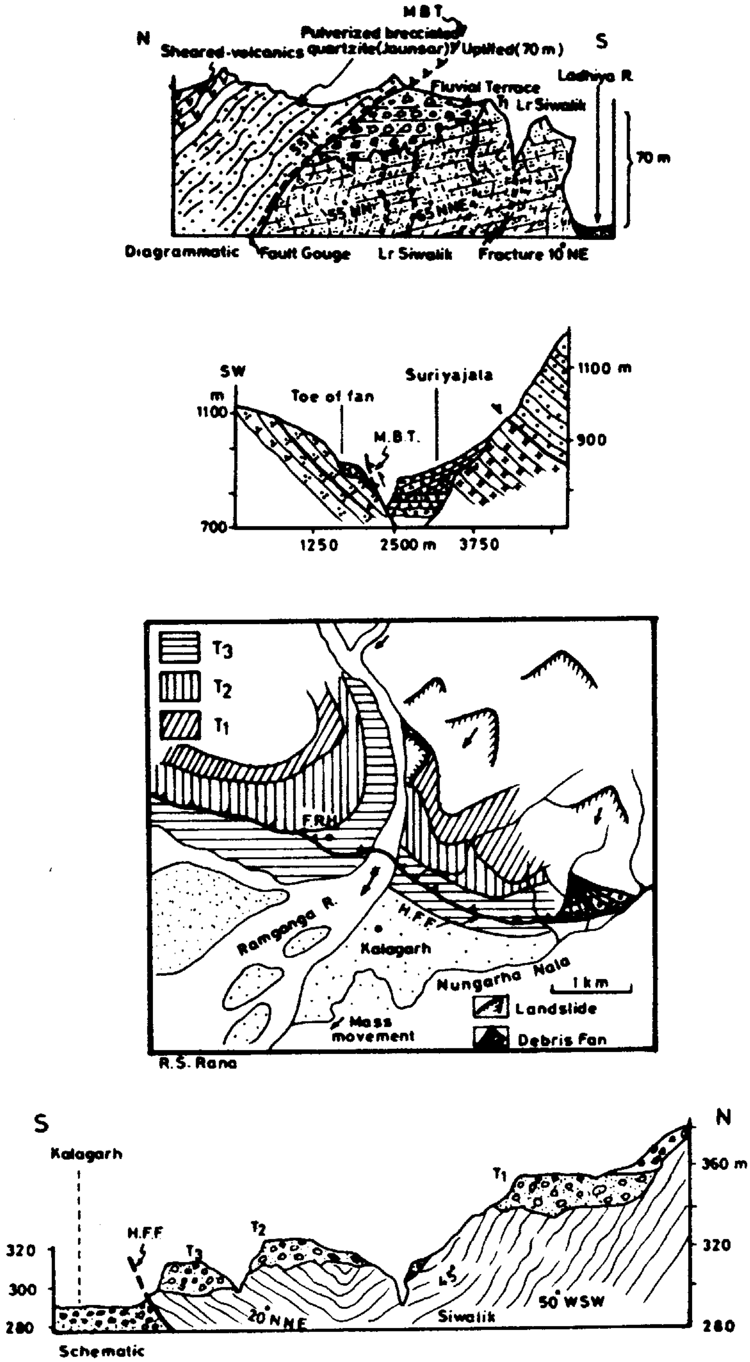
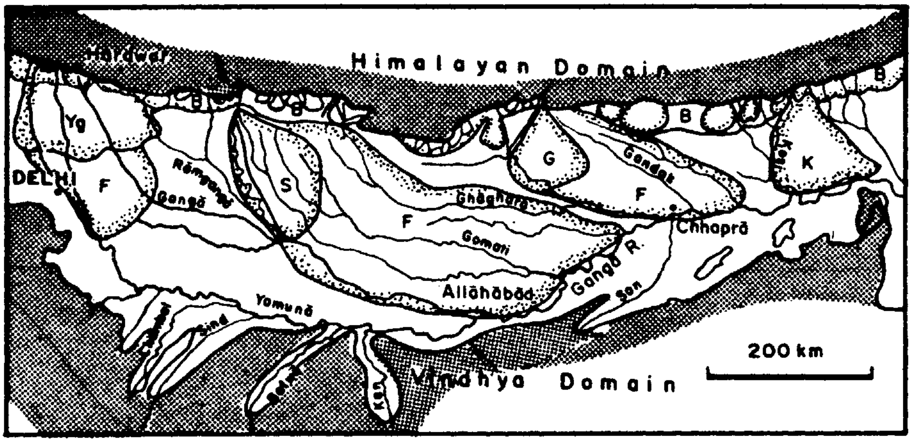


Fig 4 Displacement, dismemberment or deformation of Holocene landforms like riverine terraces and cones and fans of landslide debris indicate neotectonic movements on the active MBT and HFF in south-central Kumaun.



B- Bhabhar fans, Yg-Yamuna Ganga megafan, S-Sharada fan, F-Megafan G-Gandak fan, K-Kosi fan

Fig 5 Stupendous volumes of debris generated by landslides formed huge fans in the foothills, and the floodplains of the Ganga Basin, forcing the Ganga River to flow along a very southerly position (Based on I B Singh, 1995)[40].

stored progressively in the rocks of the zones of active faults, particularly the MBT. Despite continued strain build-up, the segment between the Satluj and Kosi rivers has so far not ruptured by great earthquakes, which alone could sufficiently release the enormous strain energy accumulated in the last few hundred years. It may be emphasized that no great earthquake has occurred within the more than 1000km long central sector since the Kathmandu earthquake of A.D. 1255. The devastating earthquake of 1833 of central Nepal was of magnitude $M > 7.5 < 7.9$ occurring close to the rupture of the 1934 earthquake[17] of M 8.1. Practically the same seismotectonic situation obtains in the Garhwal segment[18] characterized by very active faults[6,11,15]. Quite a part of the estimated convergence is causing accumulation of recoverable elastic strain in the upper crust[18]. Significantly, minor or moderate earthquakes are not occurring regularly or periodically as one would expect in an extraordinarily stressed belt.

It is evident that strains have been building up in the central sector (Fig. 6), characterized by very active faults for quite a long period of time, and must have attained a very high level, if not close to the threshold value. The amount of creep recorded in the Nepal sector is so insignificant[17]—almost negligible—that aseismic accommodation of the convergence between Nepal and Indian Shield can be safely ruled out. From these facts it is obvious that the sector between Satluj and Kosi is a seismic gap, where movements on the MBT have got stuck[19-21].

Unlocking of the active faults accompanied by sudden release of the stored strain energy will certainly shake the region violently and destructively once that happens. One does not know when this unlocking will take place, but it will happen surely someday in future.

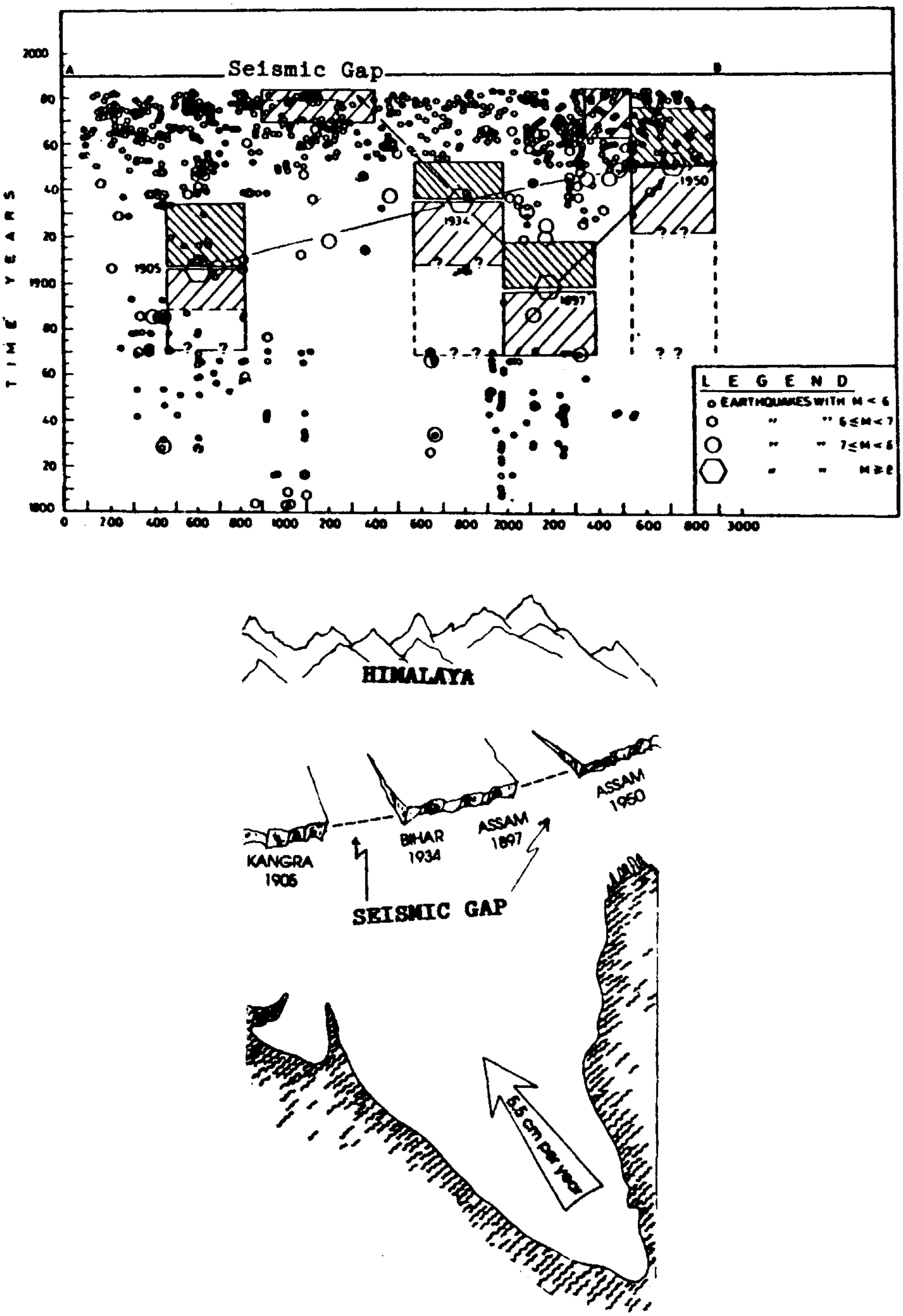


Fig 6 Four great earthquakes of magnitude higher than 8.0 have ruptured the mountain front in the last about one hundred years. Unruptured parts represent seismic gaps where no great earthquakes (of $M \geq 8.0$) have occurred in the last few hundred years. *Upper*: Khattri, 1987; *Lower*: Gaur, 1993)[19,21].

Pressing Promontories

Uncovering of the Indo-Gangetic Plains would reveal the hill ranges of the Indian Shield such as the Satpura and Aravali, extending transversely towards the Himalaya (Fig. 7). As the Indian Shield is shoved under the Himalaya, the basement ridges press hard or prod the body of the mountain, thus generating

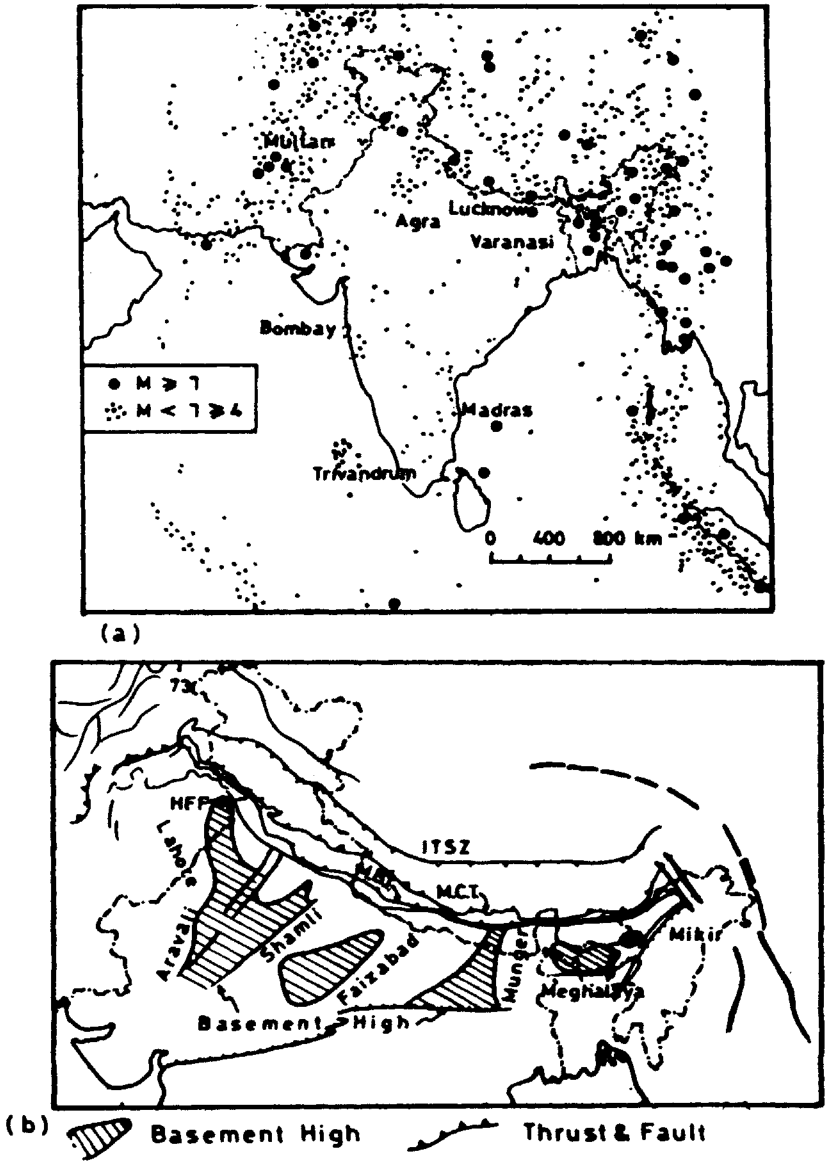


Fig 7 Mountains of Precambrian antiquity extend towards the Himalaya as ridges hidden under the sediments of the Indo-Gangetic Plains. As and when the Indian Shield is shoved underneath the Himalaya, these transverse ridges press hard and prod the siant frame of the mountain, thus creating areas of very high compression and strains in the zones of impingement.

terrific compression and resultant strains in the areas of impigement[22]. This is manifest in the clustering of epicentres in these areas (Fig. 6). The Uttarkashi earthquake of 1991 (M 6.6) occurred in front of the Aravali-Delhi-Hardwar Ridge, the Kangra event (M 8.4) of 1904 was related to a promontory branching off fron the Lahore-Sargodha Ridge, the northern Bihar earthquake (M 8.1) of 1934 was located in the line of the Satpura-Murger-Saharsa Ridge and the 1897 seismic disaster of M 8.7 can be attributed to the prodding of the Meghalaya promontory (Fig. 8).

The segments which have as yet not ruptured by great earthquakes are more vulnerable to seismic hazards in the areas pressed persistently or prodded periodically by the basement ridges[22].

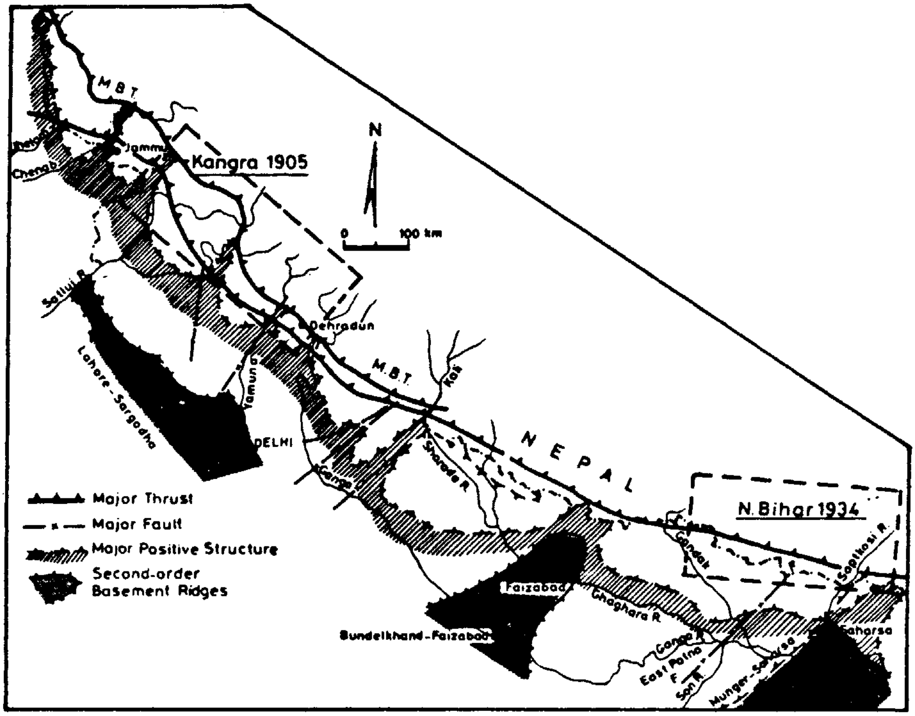


Fig 8 In addition to major basement ridges there are minor or secondary promontories, pressing hard at the underbelly of the mountain (Raiverman *et al.*, 1983).[38]

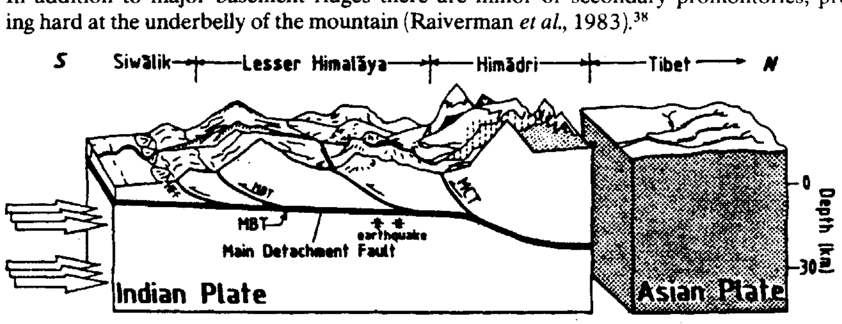


Fig 9 Postulated rupture surface beneath the Himalaya registers slips which are not more than 30% of the convergence of Indian Shield and southern Tibet (Jackson and Bilham, 1994)[3].

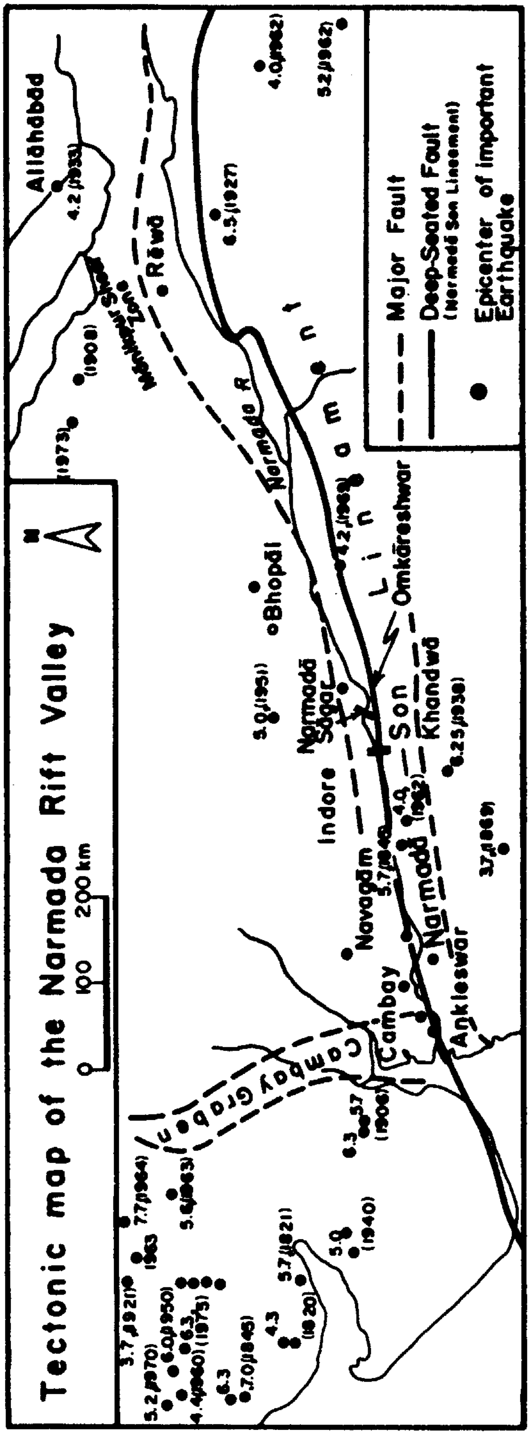


Fig 10 Seismicity in the Narmada-Son Lineament belt—a rift exhibiting neotectonic movements and high heat flow (After Jain *et al*, 1984)[28].

Strain Build-up within Indian Shield

The rate of convergence of the Indian Shield (Peninsular India) and southern Tibet is 18 ± 7mm/yr, that is between 20% and 50% of the total convergence of the Indian and Asian plates[23]. About 15 ± 5mm/yr of this slip is taking place on the MBT itself in the Indian sector (Figs 3 and 9). This leaves a residual convergence of about 13 ± 8mm/yr[3]. The present author believes that this (residual) amount—or a considerable fraction of it—is absorbed by the active faults within the Indian Shield such as the Narmada-Son-Dauki Fault (Figs 10 and 11) in northern India and the Moyar-Attur Fault in southern India[24].

The high seismicity of the Dauki belt south of Meghalaya and of the Narmada valley bear testimony to this postulation (Figs 10 and 11). Occurrence of moderate to small earthquake of the magnitude 5.7 (100 km east of navagam in 1945), 6.25 (at Khandwa in 1938), 6.5 (SW of Rewa in 1927), 5.8 (at Bharuch in 1970) point to the building up of strains in the Narmada-Son fault zone. Its easterly extension, the Dauki Fault (Fig. 11) is even more tectonically and seismically active (Fig. 11B). A zone of high heat flow (290 ± 50mW/m^2 exists in the Sarguja-Tattapani belt in Bihar[25]. The Narmada-Son Zone exhibits eloquent evidence of neotectonic movements such as the 20-25° tilting of Pleistocene terraces between Harda and Jabalpur[25], the 10-15m of vertical displacement of riverine terraces at Navagam[26], the sharp easterly swing of north-flowing tributaries of the Narmada[27] and the 25-30m offsetting of the Narmada rift itself by cross faults[28].

Undoubtedly, the Satpura Range, adjoining the Narmada rift, has been rising and possibly slipping westward relative to the Malwa Plateau in the north. As a matter of fact, the Meghalaya massif has moved right-laterally nearly 240km eastwards along the Dauki Fault since the late Jurassic times from its original position north of the Rajmahal Hills in eastern Bihar[29]. The Meghalaya massif continued to rise up vertically, so that it stands more than 2000m high, while the adjoining Sylhat plain in Bangladesh has sunken to a level no more than 2 to 3m above the mean sea level—it sank 10-15m just in the last 100 years[30]. The subsidence of the Sylhat terrain has resulted in the derangement of the rivers like Meghna, Surma and Brahmaputra leading to abandonment of old courses, development of marshes and lakes and to the inexorable deluge of the plains invariably every rainy season (Figs 11 and 12).

Subsidence of Indo-Gangetic Foreland: Flood Hazards

As already pointed out, the Indian Shield is sliding under the Himalaya along the MBT (Figs 3 and 9). Unable to slip easily into the underbelly of the heavily weighed edifice of the orogen, the northern front of the Indian Shield gradually buckled down, giving rise to the Indo-Gangetic Basin. This progressively deepening foreland basin has been completely filled up with sediments brought by rivers from the rising and wasting Himalaya. The parts of the floor between the Bundelkhand-Faizabad and Satpura-Saharsa ridges (Figs 7 and 8) have greatly subsided to the depth more than 7000 to 8000m forming the Sharada and Gandak Depressions (Fig. 12).

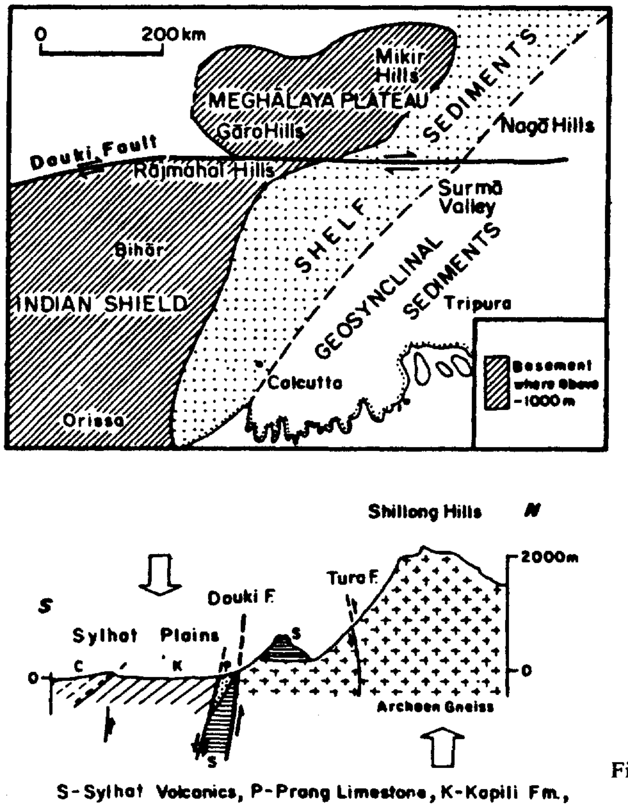


Fig 11A

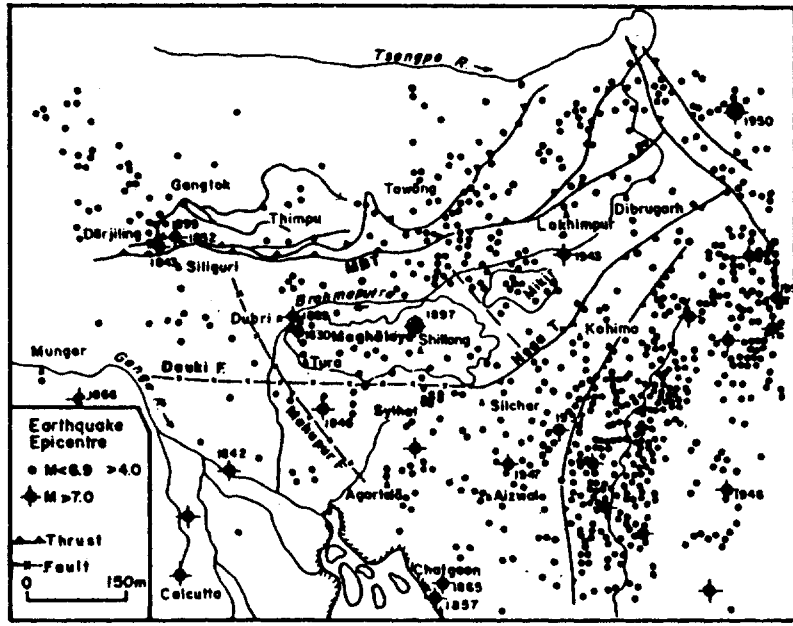


Fig 11B

Fig 11A & B While the Meghalaya massif (>2000 m high) is rising, the adjoining Sylhat plain)2-3 m above , m.s.l.) is subsiding rapidly. (After Murthy *et al.*, 1969)[30].

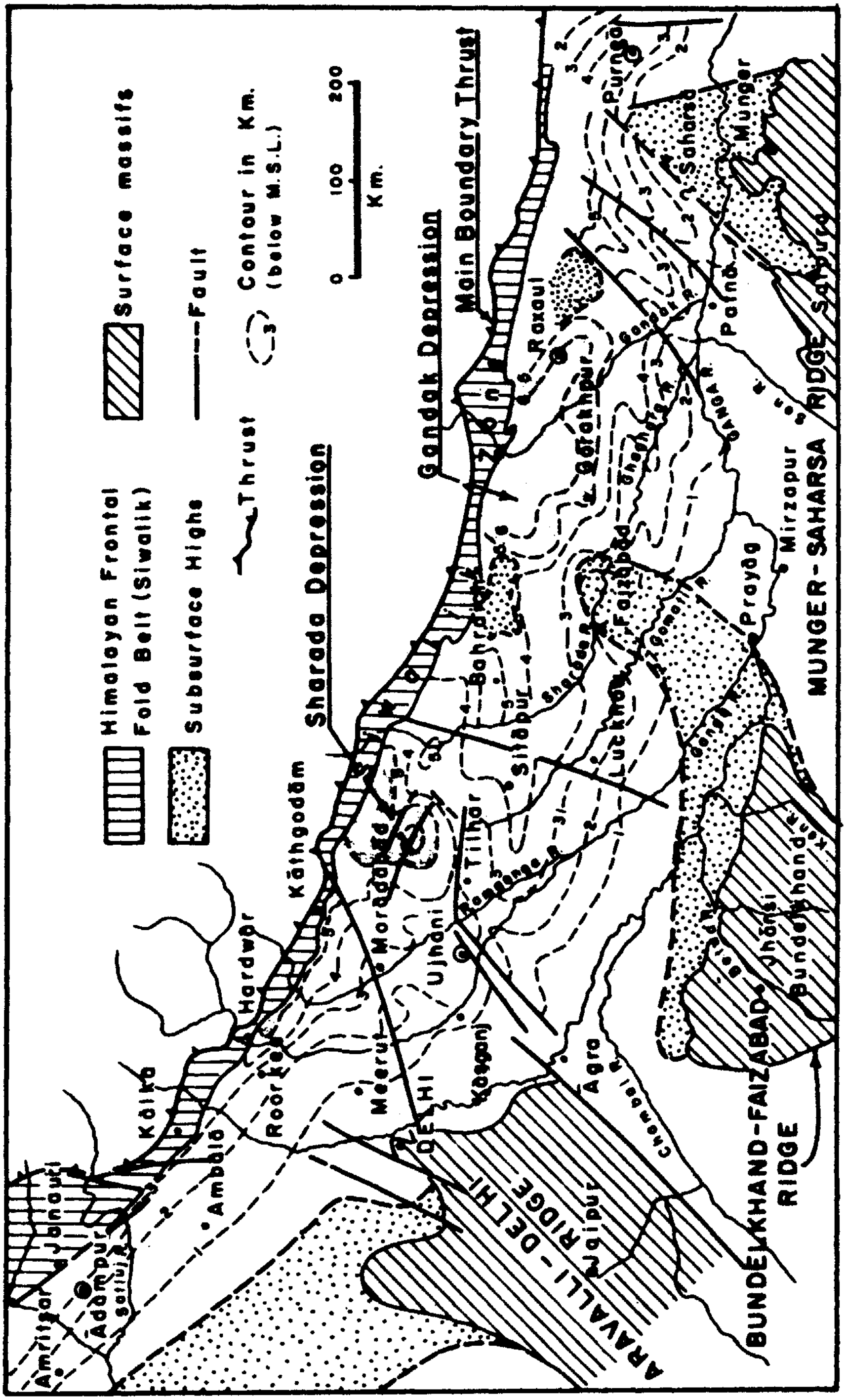


Fig 12 Floor of the Ganga Basin has subsided to the depth more than 7000 to 8000m between the basement ridges, as evident from the thickness of the sediments (After Raiverman *et al.*, 1983)[38]

The progressive subsidence of the Survey of India bench marks in these areas[31] indicates that the subsidence is continuing. This is further borne out by the phenomenal shift westward of the wayward Kosi River—120km in the last 250 years (Fig. 13), and also the eastward migration of the tributaries of the Ganga (Fig. 14).

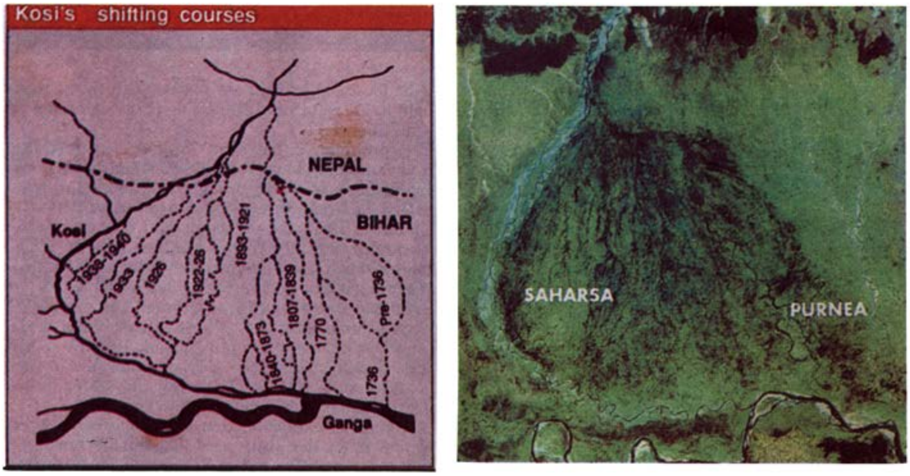


Fig 13 Nearly 120km westward shift of the Kosi River in 250 years on its own megafan, as a consequence of continuing subsidence of the Gandak Depression to the west. Satellite photo from *Down to Earth*, November 1992 issue.

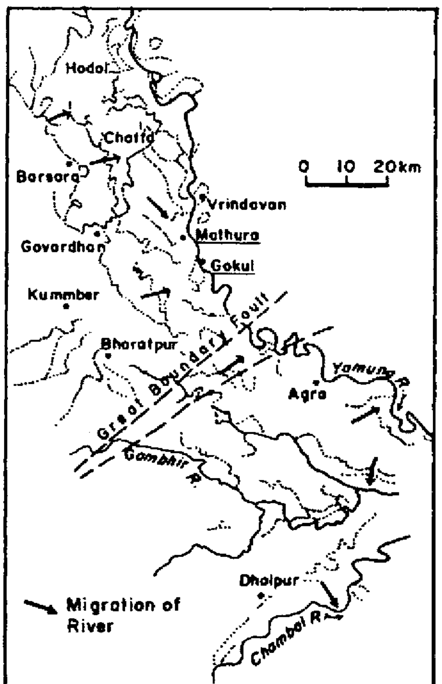


Fig 14 The Yamuna has migrated 10 to 40km east towards the Sharada Depression in the east since the time of Lord Krishna 3000 to 3500 years BP (Bakliwal and Sharma, 1980)[32].

The Yamuna moved 10 to 40km eastward in the past 3000 to 3500 years (Fig. 14)[32]. The progressive subsidence of the ground coupled with the brisk influx of great volumes of sediments from the Himalaya has resulted in the river beds being at higher level than the plain through which the rivers flow (Fig. 15). The result is recurrent, uncontrollable, disastrous deluges every time the rivers Gandak, Narayani, Kosi, etc. are in spate (Fig. 16).

One other consequence of the subsidence of the tract is the serious waterlogging due to canal irrigation. There is no outlet for the rising groundwaters in these depressed and subsiding sub-basins.

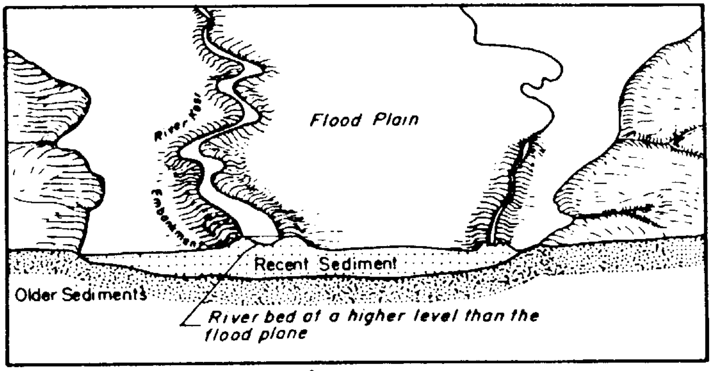


Fig 15 Bed of the Kosi is at a higher level than the flood plain through which it flows.

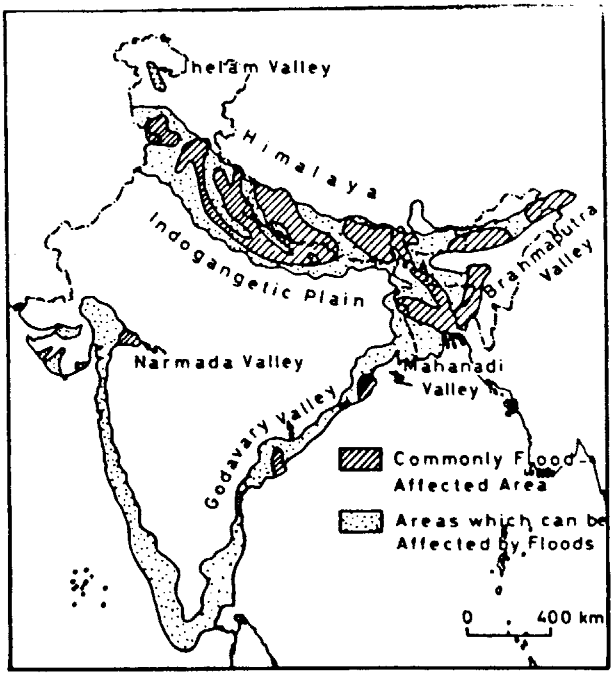


Fig 16 Recurrently flood-affected areas of the Indian subcontinent. Northeastern U.P. and adjoining Bihar—the rigion subsiding progressively—is ravaged inexorably and uncontrollably by devastating deluges year after year, despite tremendous measures of flood control and protection.

Disappearance of the Legendary Saraswati

The fault-lined Aravali horst has been rising, atleast since the Mahabharat times 3000 to 3500 years B.P. This is obvious from recurrent earthquakes in the Delhi Ridge (Aravali) belt (Fig. 17).

The uplift of the Aravali is quite pronounced in its southwestern part[4], which rises abruptly against the Gujarat plains. The gently westward flowing streams draining the mature terrain of Mewar suddenly descend through deep gorges and ravines in the western flank of the mountain, delimited by faults and are characterized by entrenched meanders. Many tributaries of the Luni river have cut incised valleys and show development of terraces on their banks (Fig. 18), before abruptly swerving across active faults[33-36].

The uplift of the Aravali forced the Yamuna River to migrate eastward while the Satluj was deflected westward[8]. Earlier, the Yamuna flowed southwestwards through what are presently the channels of dry streams Chautang and Ghaggar (Figs 19 and 20). Joining the Satluj at Shatrana (25km south of Patiala) the Yamuna formed the legendary Saraswati River[37].

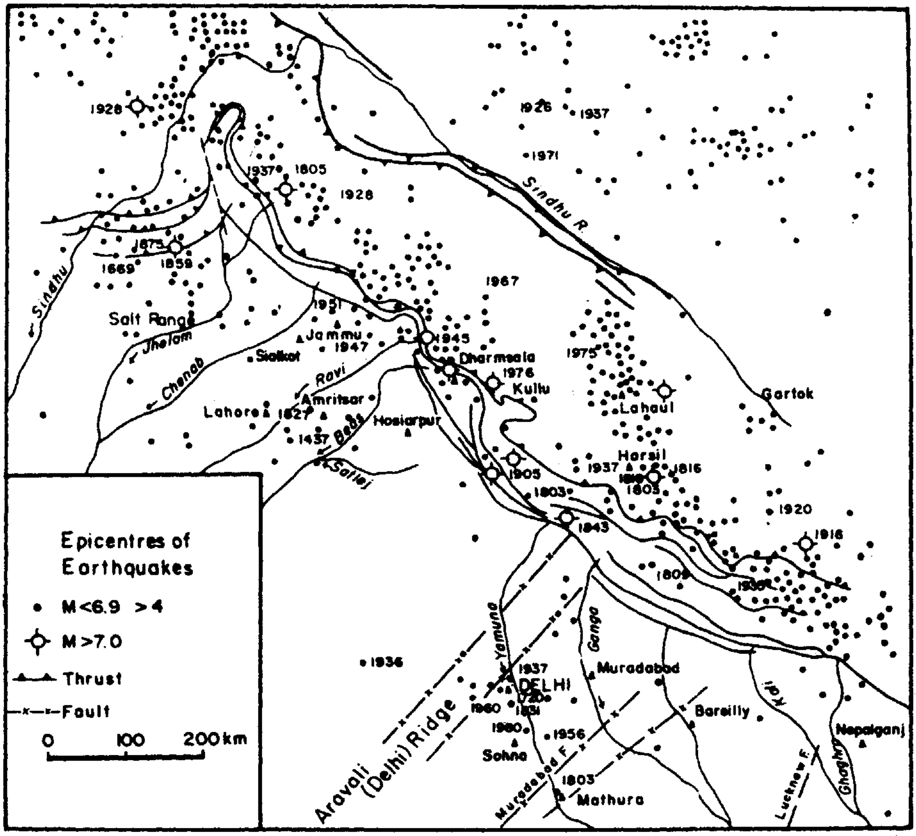


Fig 17 Seismicity in northwestern Himalaya and its foreland (After Verma, 1991)[39]. The distribution of epicentres may be seen in the context of promontories of hidden ridges underground, shown in Figure 8.

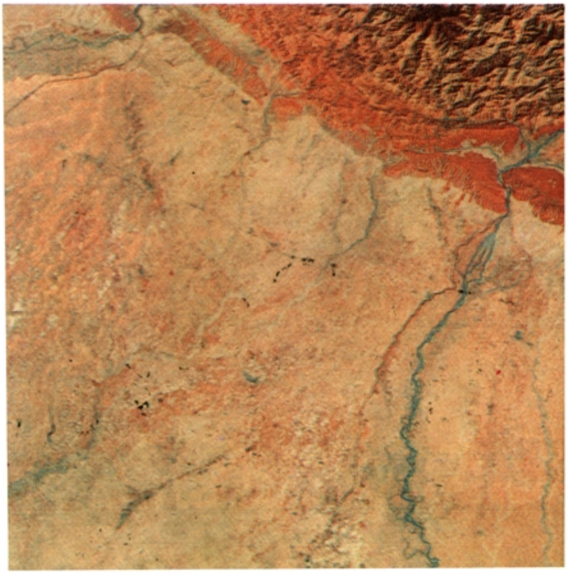


Fig 18 Evidence of uplift of southwestern Aravali in the upper reaches of the Luni River.

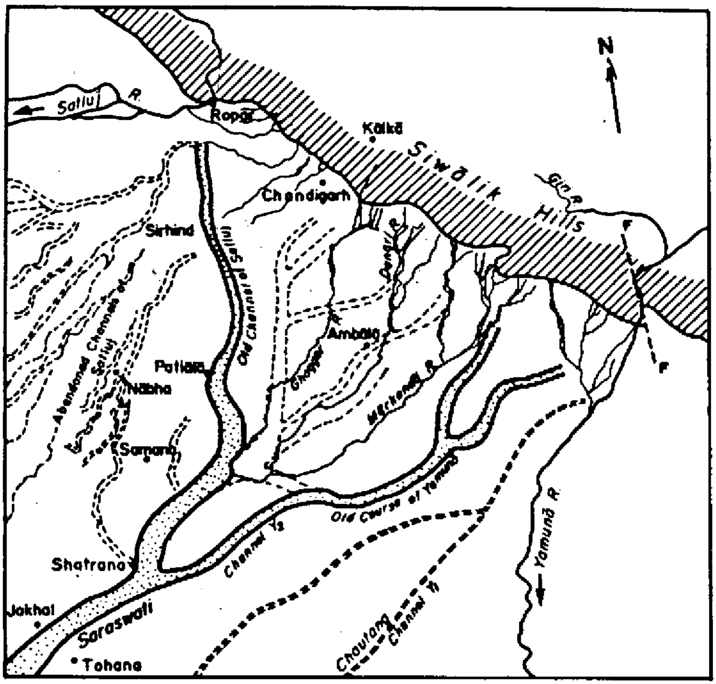


Fig 19 Upper reaches of the Saraswati in the Harappan time, 2200-1700 years BP (Yashpal *et al.* 1980)

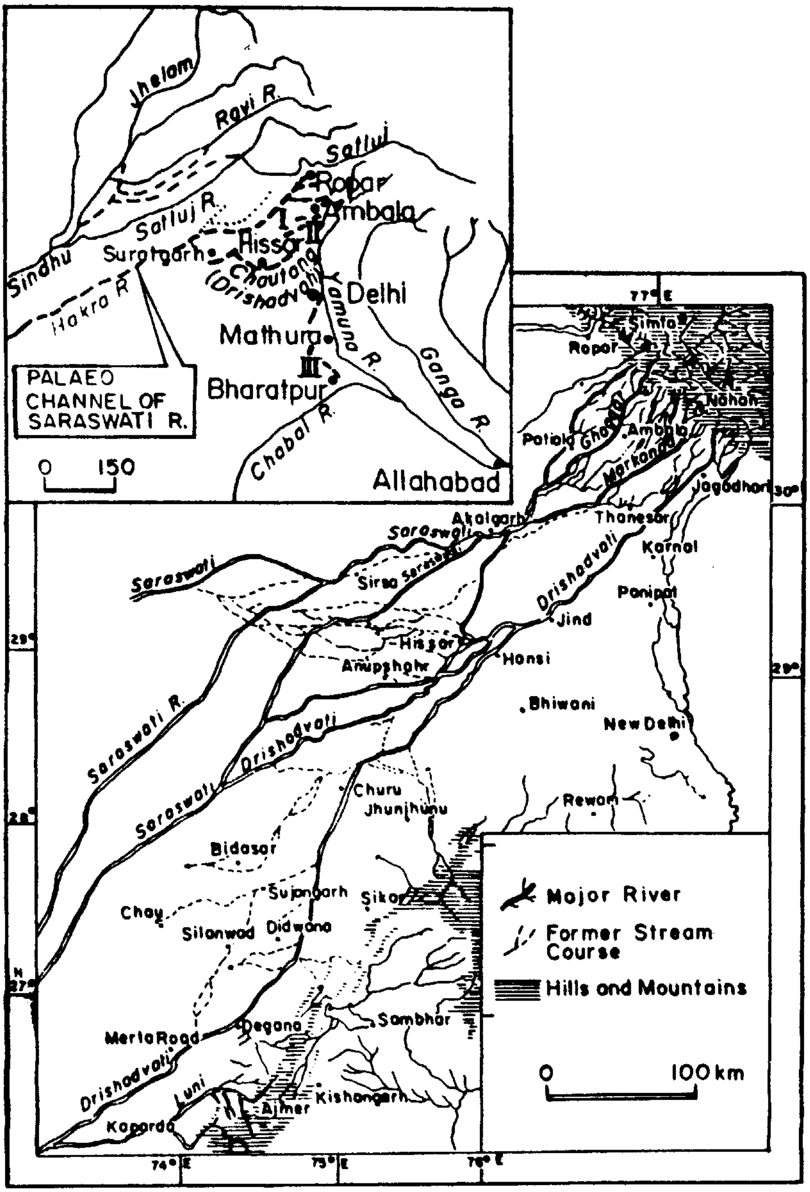


Fig 20 Legendary Saraswati—one of the three great rivers of India during the Harappan period—has now vanished. Its abandoned channels are known as Ghaggar, Chautang, Hakra, Nara etc. The Satluj (Shatadru) and the Yamuna—which were its primary feeders—changed courses due to uplift of the Aravali horst (After Kar, 1993 and Valdiya, 1984)[34,8].

The Saraswati was a great river—6 to 8km wide downstream of the confluence of the Satluj and the Yamuna near Shatrana—and prosperous towns of the Harappan civilization (4600 to 4100 years B.P.) were located on its banks. It flowed through northern Marwar and emptied itself in the Gulf of Kachchh.

The rise of the Aravali by more than 20m caused eastward deflection of the Yamuna (which joined the Ganga) and westward swerving of the Satluj (which became a tributary of the Sindhu). The Saraswati was left high and dry. Its courses are presently represented by the dry channels of Chautang (the Drishadvati of the Mahabharat times), Ghaggar, Hakra, Nara, etc. It was the neotectonic movements in the foreland of th Himalaya, which brought about the demise or disappearance of one of the greatest rivers of the Indian subcontinent.

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