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Possible role of Delhi–Haridwar subsurface ridge in generation of Uttarkashi earthquake, Garhwal Himalaya, India

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Himalayan orogen, a product of continued NE-SW compression, has certain zones in its foreland, which frequently experience seismicity. Geophysical and aeromagnetic data suggest extension of Peninsular rocks as NE-SW trending ridges in the Himalaya in these zones. The epicentral zone lying above the ridge end, has generated many NE-SW extensional structures within the NE-SW compressional field. As the Himalayan orogeny has not yet ceased and the compression continues, the resultant geological phenomena are manifestation of basement-cover interaction. The authors visualize a structural high at shallow depth at the ridge end. The release of stresses, retained by such structures under elastic strain causes seismicity in the Himalayan belt.

FORELAND topography plays a leading role in shaping the tectonic features in the frontal zone of the advancing thrust sheet. The pronounced subsurface irregularity in the form of 'ridge'-like features, generate distinct deformational structures in the overriding thrust mass. The extensive geological, geophysical and aeromagnetic investigations in the Indo-Gangetic plains (Himalayan foreland basin) have revealed continuation of the Peninsular rocks across the strike of the outer hill ranges under the thick alluvium[1–4]. One such feature named as Delhi-Haridwar Ridge, buried at shallower depth in the western part of Uttar Pradesh (UP) hills, has produced distinct deformational structures in the overlying thrust sheets due to the resistance offered by the underlying base during the thrust movement. The subsurface features in this area therefore are important in moulding the tectonic features of the overriding nappes. The terminal zone of the Delhi-Haridwar Ridge behaved like a buttress for the impinging south-directed thrust sheets, ever since the thrust sheets translated southward. The release of the stress[5] accumulated under elastic strain may be the prime cause of the Uttarkashi earthquake of 20 October 1991. The present communication discusses some of the structural observations made along this ridge in the overriding thrust sheets specially near the terminal zone and explains the cause of the earthquake.

The Delhi-Haridwar Ridge is a linear, NE-trending aeromagnetic anomaly[6–9] marking the western boundary of the Ganga basin. This is an offshoot of the Aravalli orogenic range. The Ridge has very gentle slope towards NE and thus striking at right angle to the Siwalik belt as well as the Lesser Himalayan and Central Crystalline thrust sheets. The maximum thickness of the Neogene and Holocene sediments near the frontal Lesser Himalaya[10] is about 4 km but reduced to less than 3 km on the ridge as indicated by the subsurface contours (Figure 1). The ridge extends presumably up to beneath Pala Dam site at 4 km NE of Bhatwari in the Bhagirathi valley. This conjecture is based on geophysical studies carried out by a number of workers[4,8,9,11,12] and the structural features recorded by present authors. Considering 1° average palaeoslope of the Ridge, as calculated between Delhi and Mohand in the foothills and assuming its further extension towards NE, the terminal point of this Ridge must be at the depth around 8 to 10 km in the zone of crystalline rocks. This depth corresponds with the seismological data which restrict the focus of majority of earthquakes in this zone[11,13] at 10 to 12 km. Similar basement configuration of the Peninsular rocks is reported along Gola valley in Amritpur area, Kumaun[14,15] as inferred from the upthrow of about 10 km of the basement rocks along the Main Boundary Thrust (MBT), thus suggesting shallow depth of the basement. Gravity low in Bhatwari-Harsil area[12] suspected as representing depth wise extension of granitic and gneissic rocks of the Central Crystalline belt, as compared to a gravity high with positive isostatic anomaly in the southern Lesser Himalaya possibly implies Aravalli rocks extending underneath and not the Central Crystallines lying in the north at tectonically higher

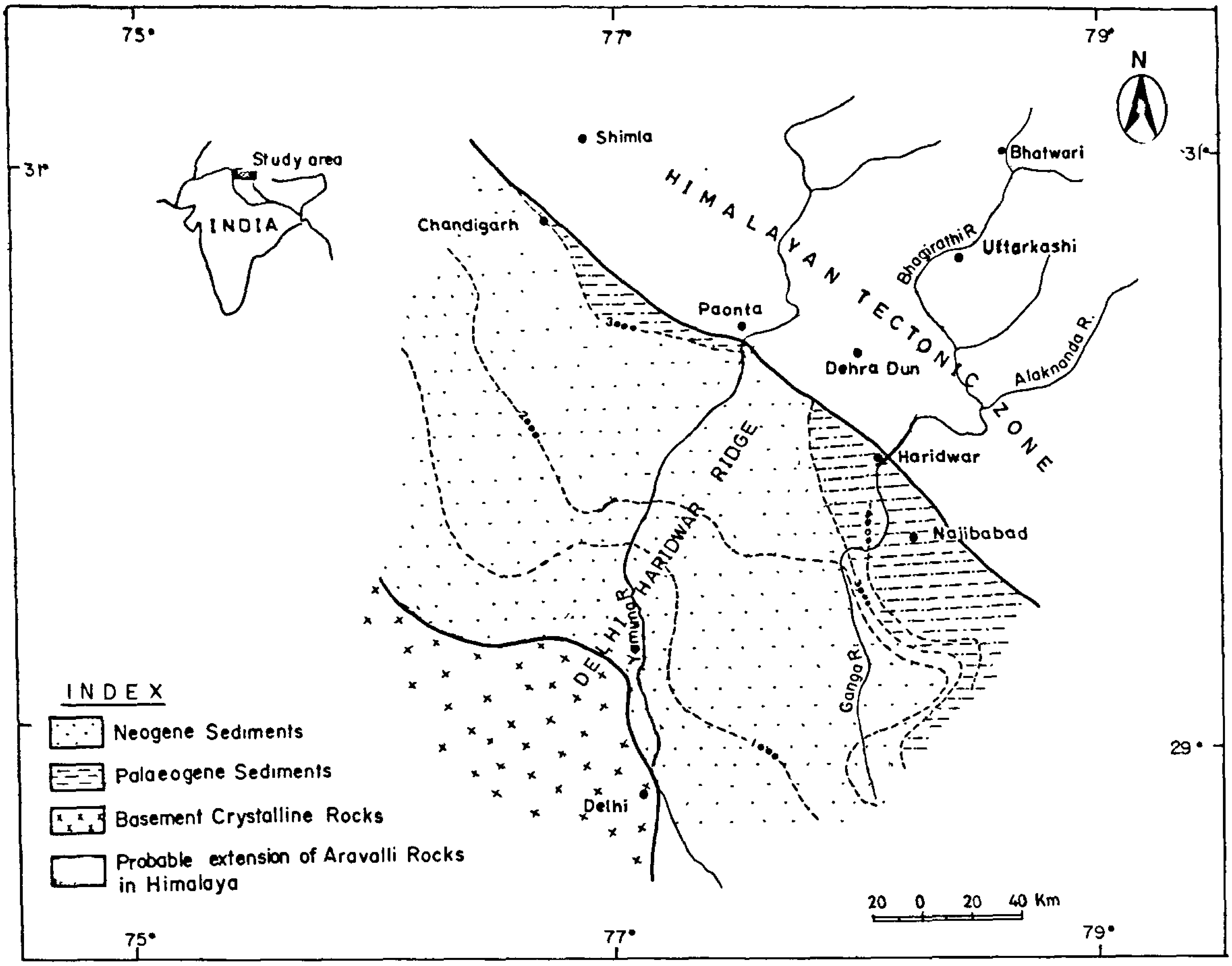

Figure 1. Subsurface geological map of the Siwalik foreland basin SW of Dehra Dun (based on Ray[2] and Eremenko and Negi[1]).

level. The assumed thickness of the load at the terminal point of the Ridge may be around 8–10 km.

The Neogene sedimentary belt in the foreland basin overrides the Holocene sediments to the south along the Himalayan Frontal Fault (HFF), in response to the continued NE-SW compression. The differential resistance offered by the uplifted basement produced strike-slip dislocations on its two sides in the overriding masses. Left-lateral strike-slip fault such as the Yamuna Tear Fault passing through Paonta, is the surface manifestation of the western boundary of the Ridge, whereas eastern boundary is defined by the right-lateral Ganga Tear Fault[16,17]. The most significant Doon re-entrant[18–21], which offsets the MBT or Krol Thrust and juxtaposes the Krol-Tal sequence against the Siwalik is undoubtedly related to this subsurface feature. The strike-slip movement along Yamuna Tear Fault[22] is measured $\simeq$ 20 km, while along the Ganga Tear Fault[19,23] the movement is of the order of 11 km. Considerable strain has probably been accommodated by the Dhaulkhand Fault, Doon re-entrant and many other minor-scale strike-slip faults across the Krol Thrust in the east. Upturned Upper Siwalik Boulder Conglomerate beds against Holocene sediments in the HFF zone indicates that the post-thrusting, NE-SW compression, is still active in Himalaya since lower Pleistocene. The Neogene sediments in the foreland basin, the Lesser Himalayan and Central Crystalline rocks of the Main Central Thrust (MCT) zone, lying over the Ridge indicate compressional stress field evidenced by closely-spaced NW-SE regional folds and NE-SW strike-slip faults (Figure 2). The southerly swing of the direction of fold-hinge lines and locally their rotation along the sides of the strike-slip faults suggest uplift of basement arch.

Mesoscopic structures as dilational fractures and SW-hading normal faults (Figure 3) indicating strong NE-SW

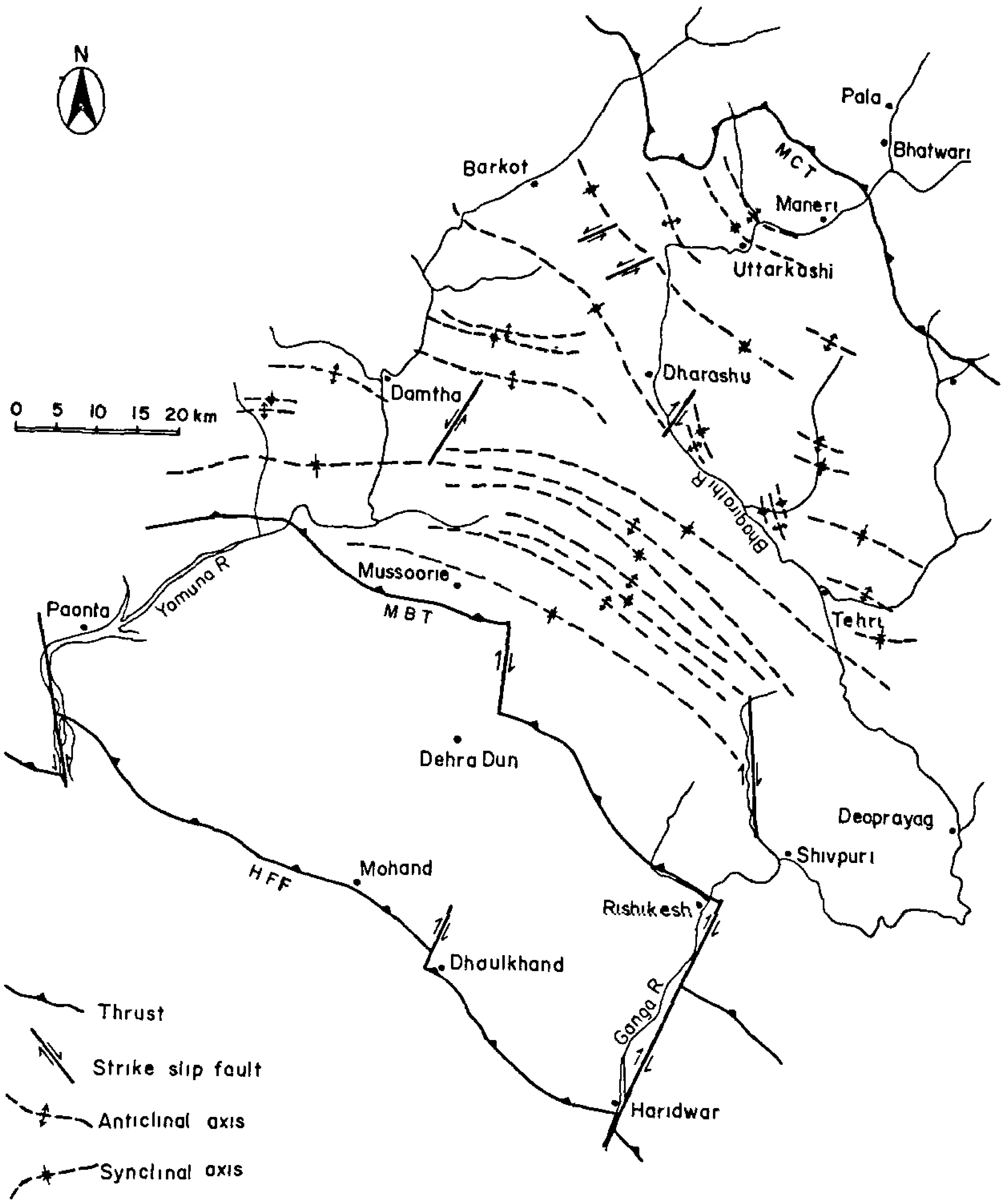

Figure 2. Structural map of Dehra Dun–Uttarkashi area showing trends of major fold axes and strike slip faults (after Valdiya[19]).

extensional regime have been recognized in the vicinity of the MCT zone between Maneri Dam and Pala Dam sites. These features are clustered mostly around Bhatwari and Pala Dam site. These extensional features are not related to the ductile MCT tectonics but their brittle nature suggests a post-thrusting origin. On the basis of available surface and geophysical data collected by the Oil and Natural Gas Commission (ONGC), the Geological Survey of India (GSI) and other agencies, a schematic model is proposed (Figure 4). The diagrammatic sketches illustrate the development of tensile field in the prevailing strong compression. It can be easily visualized that the terminal zone of the Ridge accumulated strong compressive stress ever since the beginning of thrusting along MCT; and within the limits of elastic strain it produced a large flexure at the ridge end and initiated strike-slip faulting along the sides of the Ridge. The flexure caused bulging up of the rock mass, and the buoyant force exerted by flexure initiated NE-SW extension in the enveloping rocks. This process produced many NW-SE to WNW-ESE trending brittle failures and SW-hading normal faults. Field study has recorded ample evidence in support of the postulations. The flexure which caused upliftment, triggered massive landslides in the overlying rocks and the morainic material critically resting on the mountain slopes in the MCT zone. The major landslide of 4 August 1978 near Gangnani[24], which blocked the Bhagirathi river course indicates this activity.

Earlier a fault carved rigid block passing into a plastic material at depth in the subsurface[11] was visualized. It was envisaged that within the field of local compressive stresses, which arise primarily from the relative motions of the Indian and Eurasian plates, the block would

Figure 3. ***a***, NW-SE trending extensional fracture in NE-dipping quartzites, 2 km north of Maneri Dam (camera facing NW). ***b***, SW-hading normal fault in augen gneisses–magmatites near Pala Dam site (view from SE). Sense of movement indicated by the foliation trails ***c***, Secondary extensional fractures produced in a block caught up between the two parallel, SW-hading normal faults. The fanning pattern indicate base to top path of strain release Photograph taken near Pala Dam site (camera facing NW). ***d***, Within the ongoing NE-SW compression some of the extensional fractures also reactivated with back thrusting, near one and a half km north of Pala Dam site (view from SE)

adjust itself continually and would evolve thrust-type relative motion accompanied by strike-slip movements, both sinistral and dextral, on its sides, The possibility of normal faulting elsewhere was also speculated[11]. The NW-SE trend of the Kedarnath-Askot high, paralleling the trend of MCT[4] takes southwesterly turn towards the planes enclosing Delhi-Haridwar Ridge and the Moradabad Fault. The transversely aligned feature with respect to Himalayan trend was suspected as responsible for the seismicity in the area[5]. The model proposed by the present authors indicates that the collapse of the flexed structure was the cause of the earthquake that rocked the zone lying above the termination of the Ridge. The large fissures and cracks produced during the quake range in length upto 2 km and width 2 m, oriented NW-SE to WNW-ESE. It has been found that these structures are oriented parallel to the extensional features recorded by the present authors. Some of the fractures aligned NE-SW were also found but the strike-slip component associated with these features cannot be recorded. The model also visualizes that the hypocentre of this earthquake lay somewhere near the termination of Ridge located at depth between 8 and 10 km. Earlier studies carried out in the area also indicated hypocentre of the smaller magnitude earthquakes[11] at less than 10 km. However the India Meteorological Department, New Delhi (1992), indicated 12 km focal depth for the present earthquake[25].

It is assumed that the MCT zone along which crustal shortening was accommodated during the formation of Himalaya, has been reactivated and is the prime cause of the Uttarkashi earthquake of 20 October 1991. Studies by the present authors have recorded no such reactivation in the MCT zone. Instead, many NE-SW extensional features were found in the zone. Secondly, the extensional features are present only in the localized sector of the Bhagirathi valley and not found in other sections of the MCT zone in the adjoining valleys. The frequent seismicity recorded immediately south of the MCT led some to conclude that though the MCT is inactive,

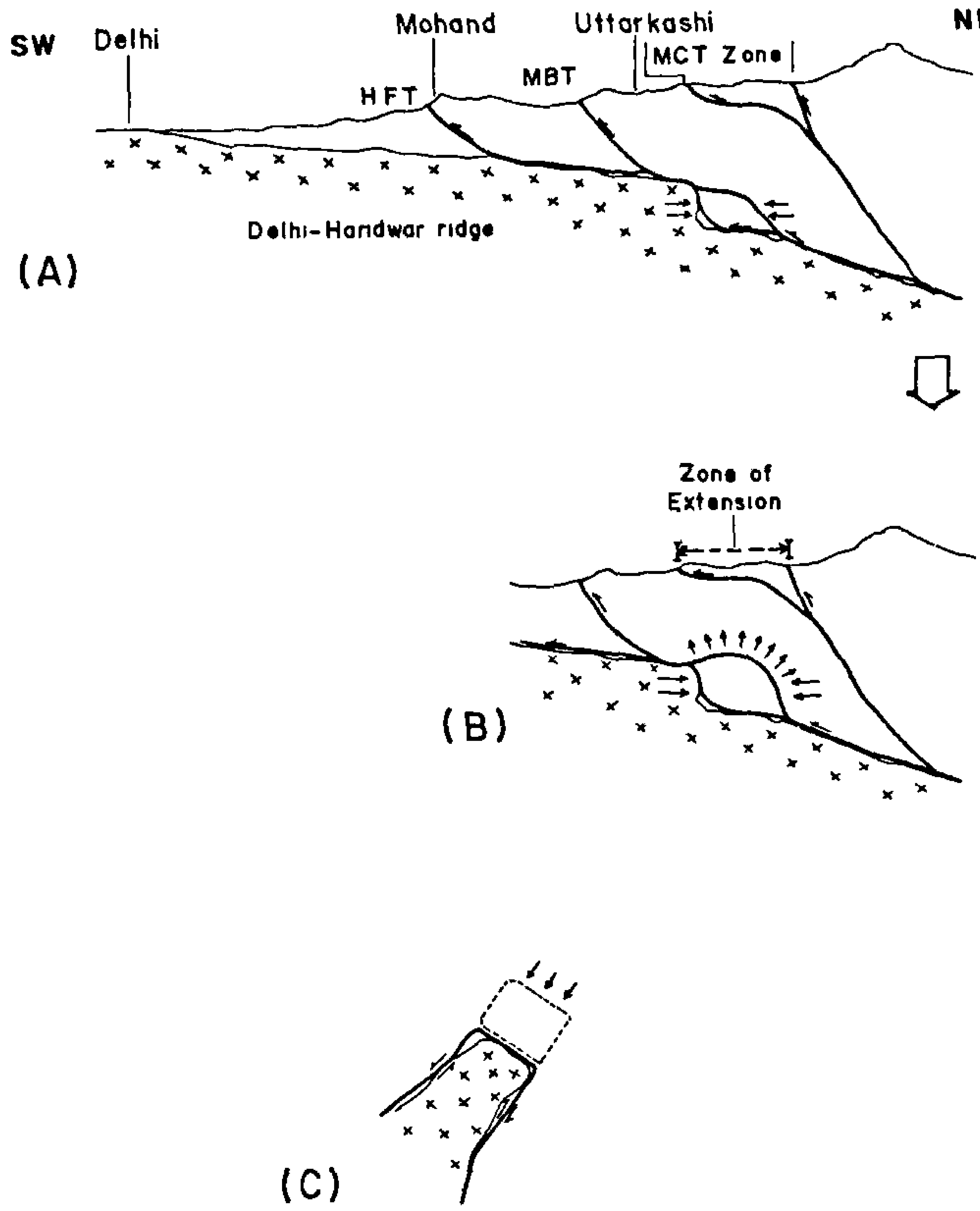

Figure 4. Diagrammatic sketches illustrating development of extensional field within the field of compression. *a*, Accumulation of stress in the enclosed compressional zone since post-thrusting *b*, Formation of a large domal flexure to accommodate extensive stress. The flexure exerted buoyant force on the overlying rocks besides overall uplift in the zone. It produced many NW-SE to WNW-ESE trending extensional structures on the ground. *c*, Behaviour of the stress at the ridge end, i.e. (1) accumulation of the compressive stress within the enclosed zone and (2) strike-slip dislocation along the sides of the ridge.

considerable activity immediately SW of the MCT cannot be ruled out[11]. Considering continental convergence along the MBT[26] the zone was marked as more active compared to MCT. MBT and HFF have been considered most active[7,27] which is evident from the fast rate of uplift of the Siwalik rocks bounded by these two structural features[7], however absence of coseismic slip along the MBT[28] is also significant. On the other hand contemporaneous origin of MCT and MBT[29] recalled the MCT, most active, MBT and other blind thrusts south of the MCT are believed to be very active[13,17,30] and neotectonic activity along some of the local thrusts paralleling to MBT[31] is responsible for seismicity in the Himalaya.

In Himachal area, the normal faulting during the 1905 Kangra earthquake, was in response to the stresses induced by a NE-extending salient of Precambrian Aravallis[32]. Similarly, between Yamuna and Bhagirathi valleys in Garhwal, the Aravalli salient named as the Delhi-Haridwar Ridge, seems to be responsible for generation of the driving force that modified the earlier thrust stress regime to strike-slip due to NW-SE flexing of the rocks around this Ridge[13]. The fault-plane mechanism solution data, which indicated definite strike-slip movement as the major operating process in the focal zone, was also interpreted on the surface as strike-slip movement along NW-SE trending MCT[13]. Detailed geological mapping in the MCT zone along Bhagirathi and Bhilangana river valleys revealed no such deformational structures supporting strike-slip movement. Secondly, considering the thickness of the rock column between the focus and the epicentre and rheology of the rocks at various depth levels, it is very ambiguous to find replica of the processes operating at the focus in the epicentral zone. The present model, proposed by the authors, support the fault-plane mechanism solution data indicating both NE-SW strike-slip movement along the sides of the Ridge-front and SW-directed thrust faulting on the main ridge in the focal zone.

Besides these two ridges it has been found that the Himalayan foreland basin has many similar basement features which have normal or angular relationship with the trend of the Himalayan orogen. The Faizabad Ridge in north-central Uttar Pradesh-western Nepal border, the Monghyr-Saharsa Ridge in Bihar-Nepal border and the basement metamorphics of Assam Plateau in Assam valley-Arunachal Pradesh are some of these features which make the overlying areas seismic prone. As the Himalayan orogeny has not yet ceased, the terminal zone of the basement ridges is accumulating stresses and releasing them in the form of cyclic seismic tremors. In the past most of these areas have already experienced massive earthquakes and they would do so in future. The WNW-ESE trending fracture zone with 'slump belt' of about 316 km produced on 15 January 1934 Bihar and Nepal earthquake[33] and various NW-SE to E-W fractures and cracks developed due to seismicity in the Dharamshala area[31,34] are oriented normal to the direction of the maximum principal compressive stress, similar to the features in the Bhagirathi valley.

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Camptonite dyke from the Pikkili alkaline complex, Dharmapuri District, Tamil Nadu

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A camptonite dyke (25 × 3 m) occurs within the leucocratic nepheline syenites of the Pikkili alkaline complex. It is a melanocratic, fine to medium-grained rock with porphyritic to panidiomorphic texture. The dyke rock is composed of phenocrysts of clinopyroxene (aegirine-augite), amphibole (hastingsite) and olivine set in a relatively fresh ground mass comprising plagioclase, orthoclase, pyroxene, amphibole, nepheline, sodalite and traces of opaque oxides, apatite and calcite. The alkaline character of the dyke is suggested by its petrochemistry and norm. The camptonite represents the last phase of alkaline activity in the pikkili alkaline pluton.

LAMPROPHYRES associated with alkaline (or sub-alkaline) massifs have been described from Kishangarh in Rajasthan[1], Purimetla[2], Settupalle[3], Uppalapadu[4], Elchuru[5–7] and Kellampalle[8] from Andhra Pradesh. The Pikkili area in Tamil Nadu is another example of the association of lamprophyre with the alkaline complex. The Pikkili alkaline complex (12° 9′–12° 21′ N and 78° 0′–78° 06′ E) in Tamil Nadu is composed of theralite, melanocratic-, mesocratic-, and leucocratic-nepheline syenite, nepheline syenite pegmatite, alkaline lamprophyre (camptonite) and dolerite dykes[9]. The alkaline rocks were intruded into a group of Precambrian amphibolites, granulites and charnockites (Eastern Ghats).

The dyke (25 × 3 m) occurs within leucocratic nepheline syenites, south of Anjaneyar Koil (12°13′ N and 78°05′ E). It makes sharp contacts with the host and