

## Seismotectonics of the Frontal Himalaya through the Electrical Conductivity Imaging

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**Abstract.** The geomagnetic induction response functions as deduced from the number of geomagnetic deep sounding experiments in the frontal Himalaya and contiguous Indian shield have been used to map geoelectrical structures of the Frontal Himalaya. The anomalous induction features have shown presence of an elongated conductive structure embedded in high seismicity zone emerging out of the Himalaya. The nature of electrical conductivity distribution along a profile extending from the Indian shield to higher Himalaya shows evidence of a mid-crustal conductor beneath the Indo-Gangetic Plains. This conducting layer dips down at the Main Frontal Thrust and underthrusts the Himalaya as low-angle dipping plane. Beneath the frontal Himalaya, top surface of the mid-crustal conductor correlates with a plane defined by hypocenters of moderate earthquakes. It also defines the cut-off depth of crustal micro-seismicity. It is suggested that conducting zone represents a thermal/metamorphic boundary below which fluids, driven off from the down-going sediments or produced by the dehydration reactions, are trapped. While the presence of fluids can account for the high conductivity, the fluid saturated slab at mid-crustal depth tends to simulate onset of ductile behaviour and hence defines the cut-off depth of the crustal seismicity. Presence of fluids along the thrust planes or detachment plane can reduce the sliding resistance and, hence, focus tectonic deformations along a linear plane, as evidenced by the alignment of the foci of moderate earthquakes. Consideration of the space-time pattern in seismicity, in relation with the high conductivity zone, permits to infer that the nature of electrical conductivity distribution could be a sensitive pointer of the reactivation of the sub-surface structures that lead to earthquakes.

### 1. INTRODUCTION

Knowledge of sub-surface structures in any seismically active zone and their characterization in terms of geophysical properties is a key to understanding the physical processes causing earthquakes. A better understanding of the seismogenic structures can also help to update the seismic zonation map of the given region. Therefore, delineation and mapping of the seismogenic structures was one of the primary objectives of the All India Co-ordinated program on the seismicity and seismotectonics of the Himalayan region. The program was launched and sponsored by the Department of Science & Technology, Government of India. Towards achieving these objectives, number of Geomagnetic Depth Sounding (GDS) studies, in the form of large and local magnetometer arrays, were undertaken in the frontal parts of the Himalaya and contiguous shield region. The GDS, which

permits to image deep structures in terms of the electrical conductivity distribution, was adopted for two important features. First, GDS using wide band of natural geomagnetic variations has the capacity to map large-scale structures that are fundamental to track the tecto-evolution model of the orogene. Second, given the strong dependence of electrical conductivity on temperature and fluid contents, the nature of electrical conductivity distribution can be a sensitive pointer of currently operative geodynamic processes (Gough, 1989).

In this paper, we give an overview of GDS investigations that have mapped number of electrical structures and have helped to update the tectonic model of the frontal parts of the Himalaya and contiguous Indian shield region. The distinctive features of the mapped conductive structures that have direct bearing on the seismotectonics of the region are highlighted.

## 2. MAGNETOMETER ARRAY NETWORK

The basic input data used in GDS to infer conductivity distribution are obtained by operating array of magnetometers that record simultaneously the time-varying geomagnetic fields in three components at 1 min interval. First regional NW India array was operated as early as 1979 that covered part of Lesser Garhwal Himalaya and adjoining Indo-Gangetic Plains (IGP) and extended into the shield region where Aravalli range is exposed at the surface (central panel of Fig. 1).

This array led to the discovery of a major deep-seated conductive structure beneath the Ganga basin and number of shallow structures, which in some way appeared to be related with the nature of sedimentation in the IGP (Lilley *et al.*, 1981; Arora *et al.*, 1982). In continuing attempt to explore the deep geoelectric configuration of the mega-thrusts of the Himalaya, namely MCT, MBT and MFT, the magnetometer coverage has been progressively increased to cover Garhwal, Kangra, Ganga-Yamuna valley and U.P. Nepal sectors of the Himalaya and contiguous IGP. The total magnetometer coverage, obtained by supplementing the NW India array, with a series of small overlapping arrays is shown in Fig. 1. As compared to the inter-station spacing of 100–150 km in NW India array, the local arrays had inter-station distances of 20–30 km. Therefore, in addition to constraining the induction response of regional structure mapped by NW India array, local arrays mapped number of localized conductive structures.

The magnetovariational fields recorded at each site were reduced to frequency-dependent transfer functions as a diagnostic of lateral conductivity distribution at varying depths. In most cases, the vertical field transfer-functions summarizing the relation between anomalous vertical and normal horizontal field components were computed for 10 period bands from 6 to 128 min. The nature of conductivity distribution near the vicinity of measuring sites is inferred by presenting the transfer functions in the form of induction arrows. These arrows by pointing at right angle towards the lateral conductivity gradient help to locate the strike and extent of the geoelectric discontinuity controlling the distribution of internal induced currents (Schmucker, 1970; Gough and Ingham, 1983).

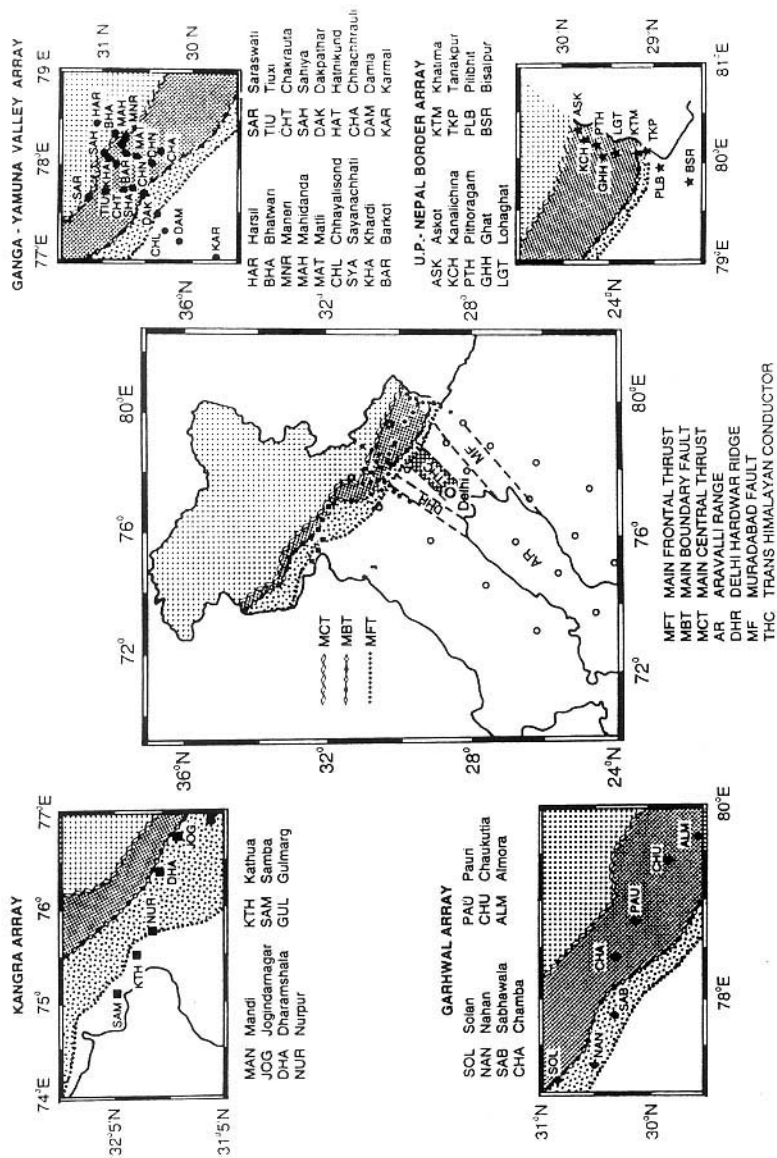


Fig. 1. Map of northern India showing layout of magnetometer sites occupied in Regional NW India array and the locations of the magnetometer sites covered in various small arrays in relation to the litho-tectonic boundaries of the Himalaya.

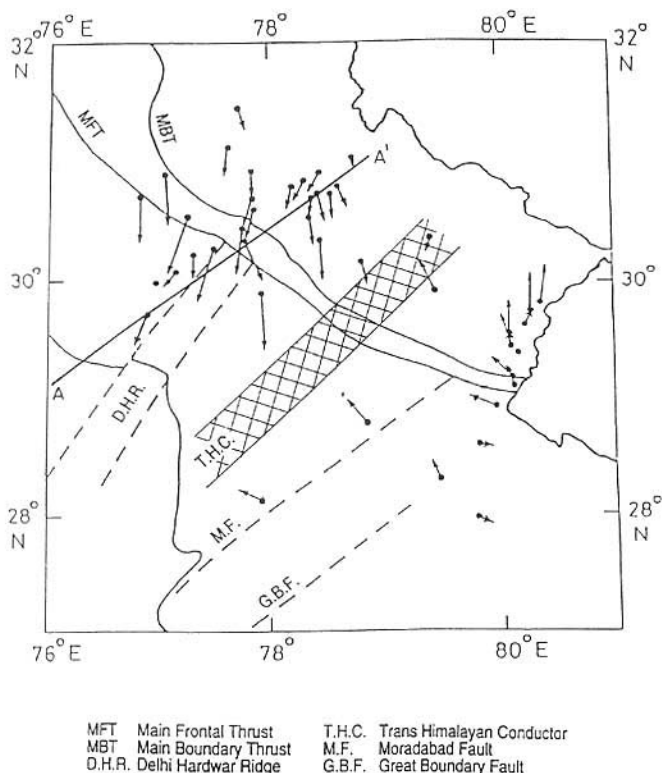


Fig. 2. The real induction arrow corresponding to period of 85 min for all the sites shown in Fig. 1.

The magnitude of the induction arrow and its spatial pattern hold information on the conductivity contrast, geometry and depth of anomalous structure that is extracted by recourse to numerical modeling (Arora, 1997). Figure 2 gives the composite picture of the real induction arrows corresponding to the period of 85 min for the central sector of the Himalaya and adjoining shield region. By way of their orientations and spatial pattern, induction arrows bring out evidence on the number of conductive structures. The following sections give the characteristics of two first-order conductive structures, running transverse and aligned with the strike of the Himalaya, and highlight their seismotectonic connotations.

### 2.1 Electrical structure transverse to the Himalayan collision zone

The most dominant induction feature transverse to the Himalayan collision belt are evidenced by oppositely directed induction arrow pattern in the upper central part of Fig. 2. This NW-SE directed arrow pattern marks the presence of a roughly NE-SW oriented elongated structure beneath the Ganga basin (Lilley *et al.*, 1981). The structure, following the trend of Aravalli range, is found to run

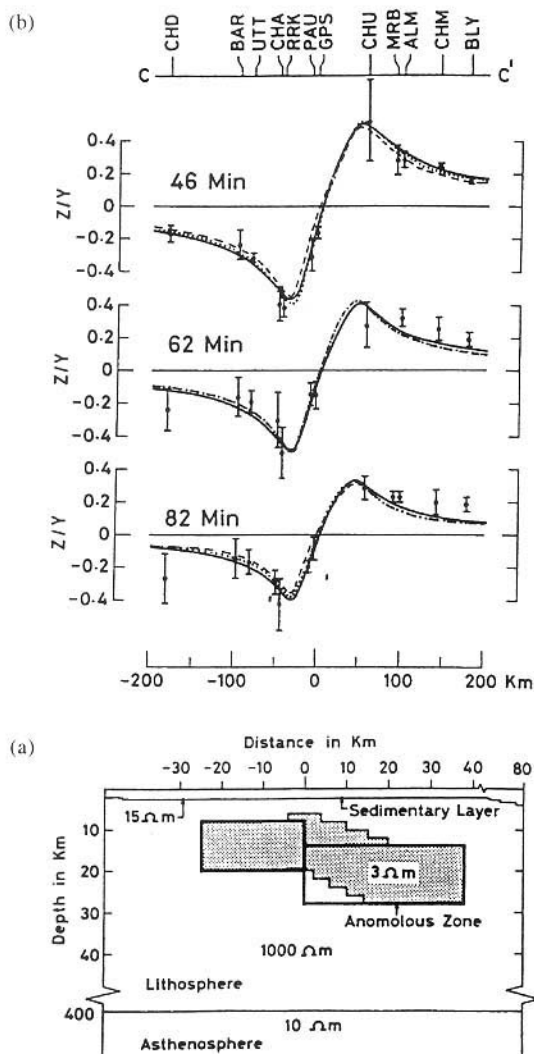


Fig. 3. (a) Cross-sectional view of the geoelectrical model for the THC along a vertical plane perpendicular to the strike. (b) The comparison of calculated and observed in-phase response at different periods. The solid lines denote the calculated response when the structure is approximated by the tabular blocks whereas broken lines represent response for stripped zone. Dotted line mark the response when an additional conducting layer simulating sediments in the IGP is also included.

into the foothills of the Himalaya. The structure marked by very high conductivity contrast has been named Trans Himalayan Conductor (THC). It constitutes one of the major induction anomalies mapped by the natural source electromagnetic method (Arora *et al.*, 1982; Gough, 1989). The continuation of the THC beneath

the Lesser Himalaya was confirmed by subsequent linear Garhwal magnetometer array (Arora and Mahashabde, 1987). Numerical modeling of observed induction functions suggested that salient spatial and frequency (period) characteristics could be accounted for by the induction in two tabular blocks (Fig. 3). Partial modifications of these block structures, as shown by strippled zone in Fig. 3, reproduce the sharp gradients in the response functions near the center. In a vertical section across the strike, the overall geometry of the structure can be visualized as an asymmetric domal upwarp at mid-crustal depth.

Noting the alignment of mapped conductive structure with the Aravalli range, Lilley *et al.* (1981) interpreted it as a continuation of the Aravalli belt being thrust down by the collision of India and Asia. The existence of number of traverse faults and fracture zones that dissect the lesser Himalaya rather extensively has been known for quite sometime and their relation with sub-surface structures of the north Indian plains has been discussed by Valdiya (1976). Drawing on the contrasting gravity (Sivaji *et al.*, 1992) and shear-wave velocity structure (Chun, 1986) beneath the Indo-Gangetic Plains, Arora (1993) concluded that the THC represents an accretion zone between crustal blocks of contrasting geophysical properties. He suggested that upwarped domal geometry of the THC might result from the Quaternary reactivation of the accretion zone in response to stresses generated during the locking in of the Indo-Eurasian plates. The metamorphic dehydration coupled with the invasion of mantle derived CO<sub>2</sub> fluids, resulting as a consequence of collision and attendant crustal interstacking, are the likely cause of enhanced conductivity in the inferred tectonic scenario. Presence of fluids along the THC is also corroborated by the P-wave travel time residuals. Mohan and Rai (1992) found that P-waves approaching Delhi from the ESE have large negative residuals, while at Dehradun, only 225 km away in NE, the residuals are found to be close to zero. A localised low velocity region between Delhi and Dehradun coincident with the THC is thus inferred.

From the point of view of seismotectonics, it is important that the THC coincides with a localized zone of high seismicity striking across the Himalayan arc. Khattri (1990) has shown that seismicity in Indian shield exhibits a well-defined system of block-tectonics. Figure 4 shows blocks of active tectonics as outlined by concentrated belts of epicenters. Map shows profuse activity all along the Himalayan arc. However, a narrow elongation extending into the IGP is also well marked. Suggestion of a transverse zone of high seismicity emerging out of the Himalayan range towards the Delhi in south is also seen on the quantitative seismicity map prepared by Kaila and Narain (1976). This transverse zone is bounded by Delhi Hardwar ridge on the northwest and Moradabad fault in the southeast. The close positional correspondence of the THC with this transverse high seismicity zone perhaps signifies the control of structural discontinuity associated with the THC in triggering weak seismicity in this part of the Indo-Gangetic plains. It is envisaged the clustering of the most recent shallow earthquakes in the THC, may signify the periodic activation of the ancient structure in this part of the shield due the locking and anti-clockwise rotation of Indian plate with respect to the Eurasian plate.

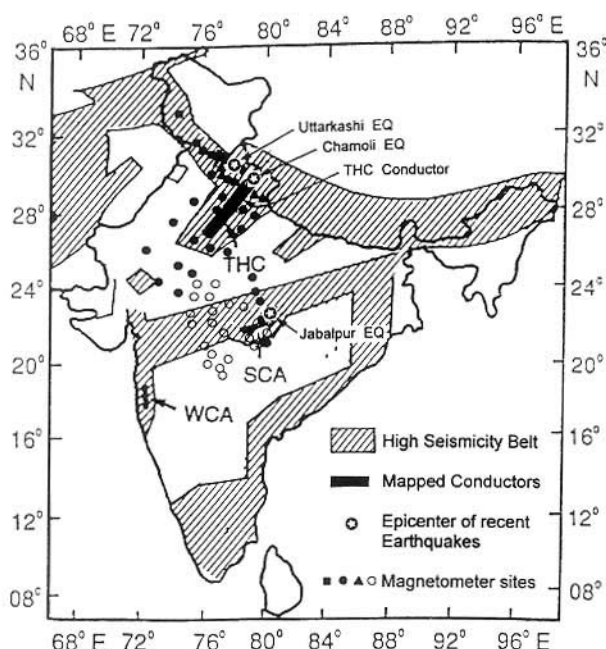


Fig. 4. Blocks of active tectonics as defined by the distribution of epicentres (redrawn from Khattri, 1990). The locations of conductors mapped by GDS studies as well as location of recent Earthquake are also marked.

## 2.2 Electrical structure parallel to the Himalayan collision zone

Away from the influence of the THC, the induction arrows on the western part along the Ganga-Yamuna valley have persistent southwesterly orientation. The magnitude of the induction arrows increase steadily from the northern locations (higher Himalaya) towards the southern sites. After attaining maximum in the vicinity of the MFT, magnitude of the arrows fall off sharply to a very low value but increase (rise) again near the southern edge of the IGP. Such spatial variation in the arrow pattern, without any major change in orientation, identify MFT separating the thick alluvial sequence in the IGP from the Siwalik fold belt, as a major electrical discontinuity. The initial numerical calculations showed that within the constraints on the resistivity of sediments, the concentration of induced currents in the conducting sediments resting on the dipping Indian plate, with their maximum thickness just south of MFT, produce induction effects similar to the observed trend but much weaker than the observed signatures. The 2-D geoelectrical model that accounts for the salient induction features seen on the profile extending from the shield region into the Himalaya along the Ganga-Yamuna valley (Reddy and Arora, 1993). The 2-D electrical model is shown in Fig. 5(a), whereas the generalized tectonic model drawn incorporating the

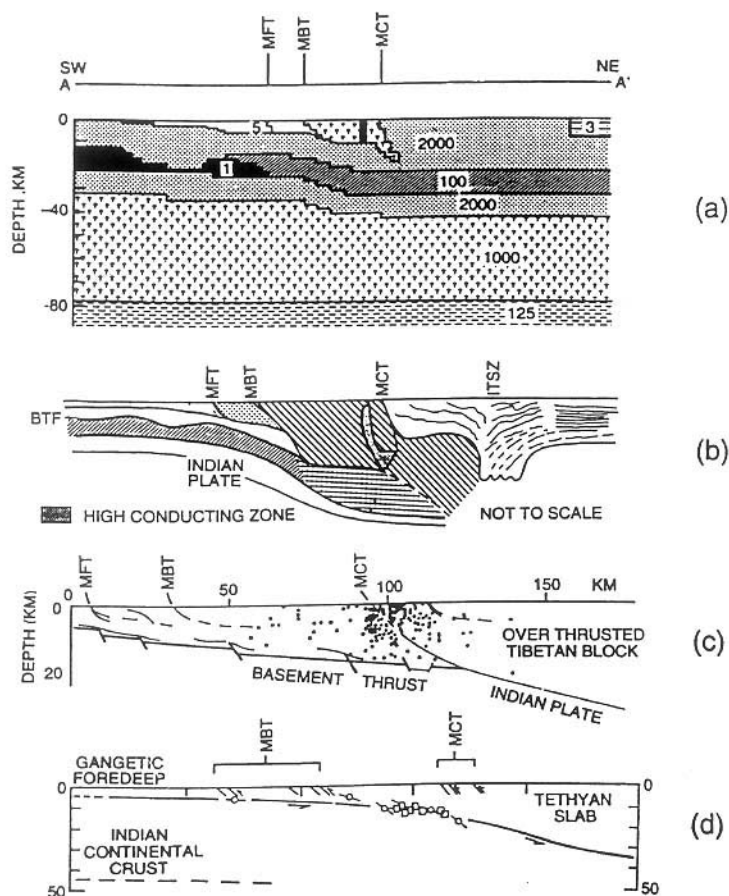


Fig. 5. (a) Depth-section of electrical conductivity distribution along profile AA' (Fig. 2) and (b) equivalent tectonic model across frontal Himalaya. (c) Depth distribution of micro earthquakes in the frontal Garhwal Himalaya (adopted from Khattri, 1990). (d) Alignment of hypocenters of moderate earthquakes along northward dipping linear plane (modified from Ni and Barazangi, 1984).

features of mapped conductivity structures is shown in Fig. 5(b). An important feature of the model is a conducting layer beneath the IGP at mid-crustal depths. This highly conducting layer ( $1 \Omega\text{m}$ ) is found to undulate with two clear humps, one near the MFT and other near the southern edge of the IGP. Consistent with the tectonic-collision model of the Himalaya, this highly conducting layer dips down and underthrusts with the down-going Indian plate as a moderately less conducting slab ( $100 \Omega\text{m}$ ).

It is noteworthy that the top of the modeled mid-crustal conducting layer beneath the Himalaya appears to correlate with a planar zone along which the foci

of medium size earthquakes are located (Ni and Barazangi, 1984). These authors noted that foci of most moderate earthquakes with epicenters south of the MCT are aligned along a linear plane, at about 10–20 km depth, with an apparent northward dip of about  $15^\circ$  (Fig. 5(d)). This planar zone may also symbolize the Basement Thrust Fault (BTF) separating the Indian plate from the overriding sedimentary wedge of the Lesser Himalaya (Seeber *et al.*, 1981). The top of the underthrust slab also appear to define the cut off depth of microseismicity (Fig. 5(c)) caused by crustal stresses that has been shown to be restricted to crustal section above 15–20 km in this part of the Himalaya (Khattri, 1990).

Electromagnetic surveys carried out across the Juan de Fuca plate and elsewhere in similar compressional regimes have shown that dipping conductive slabs, intimately related to the downgoing plates, are the general attributes of the subduction zones (Kurtz *et al.*, 1989; EMSLAB, 1989). It has been suggested that this zone represents a thermal/metamorphic boundary below which fluids, originating from the down-going sediments or produced by devolatilization reactions, are trapped. The fluid saturated zone tends to simulate onset of ductile behaviour in the crust and, thus, define the depth cut off for the seismicity caused by crustal stresses (Stanley *et al.*, 1990). In the frontal Himalaya, this depth cut off correlates with the underthrust conducting slab. Further, it also seems possible that in a horizontal compression regime of the Himalaya, adjusting to differential tectonic stresses, the upper and lower crust due to their rheological differences may facilitate development of a thrust (detachment) at the brittle-ductile transition (Bailey, 1990; Jodicke, 1992). It can also be conceptualized that the frictional heating associated with underthrusting processes may produce favorable conditions for the generation of free water from dehydration reactions (Fyfe *et al.*, 1978). The free water produced by such process or driven off from the down going sediments may act as a lubricant, causing substantial reduction in the sliding resistance of rocks along the thrust and detachment zones (Blanpied *et al.*, 1992). The reduced sliding resistance along the thrust plane may focus the tectonic deformation to such linear planes. The noted alignment of the foci of moderate earthquakes along a single planar zone beneath Lesser Himalaya favors such postulation. The development of thin extended detachment zone may also facilitate upward migration of fluids to the crust beneath the IGP and may account for the enhanced conductivity at mid-crustal depth (Arora and Reddy, 1995), as indicated by the goelectrical model (Fig. 5(a)).

Yet another important feature of the goelectrical model across the Himalaya (Fig. 5(a)) is a near vertical conducting zone south of the MCT. This localized narrow conducting zone simulates small wavelength induction anomaly observed centered around south of the MCT (Reddy and Arora, 1992). The large vertical extent of the conductive structure is consistent with the observed induction response that persists at all period bands examined but with clear dominance at shorter period. Reddy and Arora (1992) noted that this conductivity anomaly striking parallel to the MCT defines the southern edge of the Garhwal Lesser Himalaya Seismicity Belt (GLHSB), mapped between Ganga-Yamuna Valley by a network of micro earthquake stations (Gaur *et al.*, 1985; Khattri *et al.*, 1989).

Noting the positional correspondence with the GLHSB, the localized conductive zone was analogously termed as Garhwal Lesser Himalaya Conductivity Anomaly (GLHCA). Interestingly, the hypocenter of the 1992-Uttarkashi earthquake was rooted in the GLHCA. On the gravity map (Qureshy *et al.*, 1974), the area of the GLHCA is marked by a relative gravity high, while its axis matches with line of largest gravity gradient. This feature indicates that generation of the GLHCA may be related in some way to the high density and linear intrusion, such as resulting from the obduction of the detached crustal block from the overriding Asian plate onto the crust of underthrusting Indian plate. Consistent with this visualization, in the tectonic model of the frontal Himalaya (shown in Fig. 5(b)), the GLHCA is represented as a narrow fracture zone above the level of obduction block. The fracture zone may owe its high conductivity to the fluids brought up by seismic pumping (Sibson, 1975). Any movement along such fracture zone to readjust compressional forces due to the continued NE migration of the Indian plate may explain high seismicity along the GLHSB in general and may emphasize its role in triggering Uttarkashi earthquake in particular.

### 3. FLUIDS: POSSIBLE LINK BETWEEN HIGH CONDUCTIVITY AND HIGH SEISMICITY

The above examples are clear illustrations of the close connection between high conductivity and high seismicity zones. The THC and the GLHCA are clear examples of this correlation. Similar correlations are also seen along the Narmada-Son Lineament of central India. This lineament has shown recurrent seismicity over its entire length (see Fig. 4). The GDS studies carried out across the Narmada-Son belt do not demarcate this belt as a continuously enhanced zone of conductivity. Only a section of this belt (Satpura) was identified as a high conductivity zone (Arora *et al.*, 1993, 1995). Significantly, the 1995-Jabalpur earthquake was rooted in this section, coincident with the high conductivity zone. It is also note worthy that GDS studies across the MCT of Himalaya have identified small segment between Ganga-Yamuna valley to be major electrical discontinuity. Interestingly only this part is seismically active and formed the seat of 1992-Uttarkashi earthquake. Such examples coupled with the noted correspondence of hypocenters in relation to the conductive detachment plane beneath the frontal Himalaya indicate that conductive zone in certain cases may signify reactivation of a sub-surface feature that creates physical conditions favorable for triggering earthquakes. Perhaps, fluids provide the common link, such that formation of high conductivity zone and occurrence of earthquakes mark different but sequential manifestations of the physical influence of the fluids. The generation and trapping of fluids can produce high conductivity zones while their lubricating influence can cause softening/stability of fault planes. The relationship of the high pore pressure fluids and seismicity is yet another area of active research (Keller and Loaiciga, 1993). When the pore pressure exceeds the confining pressure plus the tensile strength of the rocks, the fluids from deep crust may hydro fracture mineral grains, triggering seismic activity (Stanley *et al.*, 1990). The present observation that hypocenter of the October 22, 1992-Uttarkashi

earthquake was rooted in the GLHCA anomaly may reemphasize the role of high-pore pressure fluids migrating from greater depths.

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