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Deep Conductive Structures of the Frontal Belt of the Garhwal Himalaya and Their Seismotectonic Significance

B.R. ARORA AND C.D. REDDY
Indian Institute of Geomagnetism, Colaba, Bombay 400 005, India

Abstract

A two-dimensional geoelectric model is developed to summarise the signatures of electromagnetic response revealed by the two profiles of magnetometers providing coverage from the Indian shield into the Ganga-Yamuna Valley of the Garhwal Himalaya, NW India. A highly conducting mid-crustal layer beneath the Indo-Gangetic plains which dips-down at the Main Frontal Thrust and tends to be less conducting dominates the electrical conductivity cross-section across the frontal Himalayan collision zone. Noting that the top of the conducting slab correlates with the planar zone, along which lie the foci of most moderate earthquakes, and also defines the cut off depth of crustal microseismicity, metamorphic fluids trapped beneath the brittle-ductile transition zone are invoked as a source of enhanced conductivity. It is envisaged that this free water at the transition-zone may be a dominant physical factor in the development of thin extended detachment zone which may facilitate upward migration of fluids to account for the enhanced conductivity of the mid-crust beneath the Indo-Gangetic plains. Limitations of this mechanism are highlighted and role of graphite films at grain boundaries is invoked as an alternative source for the enhanced conductivity.

A narrow conductive zone, mapped in the epicentral track of the 1991 Uttarkashi Earthquake, is viewed as a shallow but extended fracture zone above an obducted crustal block. Movement in this fracture zone to readjust the compressive forces may explain the correlation of this conductive zone with Garhwal Lesser Himalaya Seismic Belt and with the recent Uttarkashi Earthquake.

INTRODUCTION

Magnetovariational studies is NW India, undertaken in recent years, in the form of regional and localised magnetometer arrays have begun to provide independent constraints on the tectonic framework of the frontal zone of Himalaya as well as of contiguous Indian shield (see the review by Arora, 1990; Arora and Singh, 1992). The Magnetovariational studies which provide a broad picture of the electrical conductivity distribution at depth manifest changes related to the sub-surface distribution of meteoric or metamorphic fluids, thermally included partial melt or that caused by the films of graphite or magnetite coating on grain surfaces (Gough, 1992). The electrical conductive structure so determined, in conjunction with seismic, gravity and other geophysical data, aid our understanding of the seismotectonic structures of the region. As a part of our ongoing research in this region, two more linear profiles of magnetometers were operated along the Ganga-Yamuna Valley of the Garhwal Himalaya. These surveys were especially designed to obtain the spatially well resolved electromagnetic response of the geoelectric structures associated with important lithotectonic boundaries of the Himalayan collision zone, free from the influence of the major Trans-Himalayan Conductor (THC) emerging out of Himalaya into the Indo-Gangetic plains along the Delhi-Aravalli trend (Lilley *et al.*, 1981; Arora *et al.*, 1982; Arora and Mahashabde, 1987). The present surveys had an additional goal to map the conductive structure, if any, associated with a narrow localized high seismicity zone (named Garhwal Lesser Himalaya Seismic Belt-GLHSB), indicated to exist little south of the MCT by a network of microearthquake stations (Gaur *et al.*, 1985; Khattri *et al.*, 1989). The study area also included the epicentre of the Uttarkashi earthquake of magnitude 6.2 that rocked the area on October 20, 1991. The initial results of the first profile centered around the MCT have already been discussed by Reddy and Arora (1992a,b). The present paper is an attempt to synthesize the induction features of both the profiles as a step to develop a two-dimensional (2-D) geoelectric model of the region. The seismotectonic significance of the mapped conductive structures is discussed with special reference to the Uttarkashi earthquake.

GEOLOGICAL SETTING AND LAYOUT OF MAGNETOMETERS

Profiles of recording magnetometers were set up perpendicular to the general strike of the Himalaya. Fig.1 gives the layout of the magnetometers in relation to the important tectonic units. The northernmost stations were located on the Higher Himalaya, beyond the Main Central Thrust (MCT). In their southern extension, magnetometer network provided coverage over the Lesser Himalaya, Siwalik folded belt and the Indo-Gangetic Plains (IGP), separated respectively by the Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT). The magnetometers were primarily confined to the Ganga-Yamuna Valleys. The recording of time-varying magnetic fields in the three orthogonal components (X, Y, Z) were carried out in two phases. During the first phase, magnetometer distribution was centered around the MCT and was designed to map structural features associated with the GLHSB. Seven of the nine magnetometer sites in this phase were common with the microearthquake recording stations operated by Gaur *et al.*, (1985).

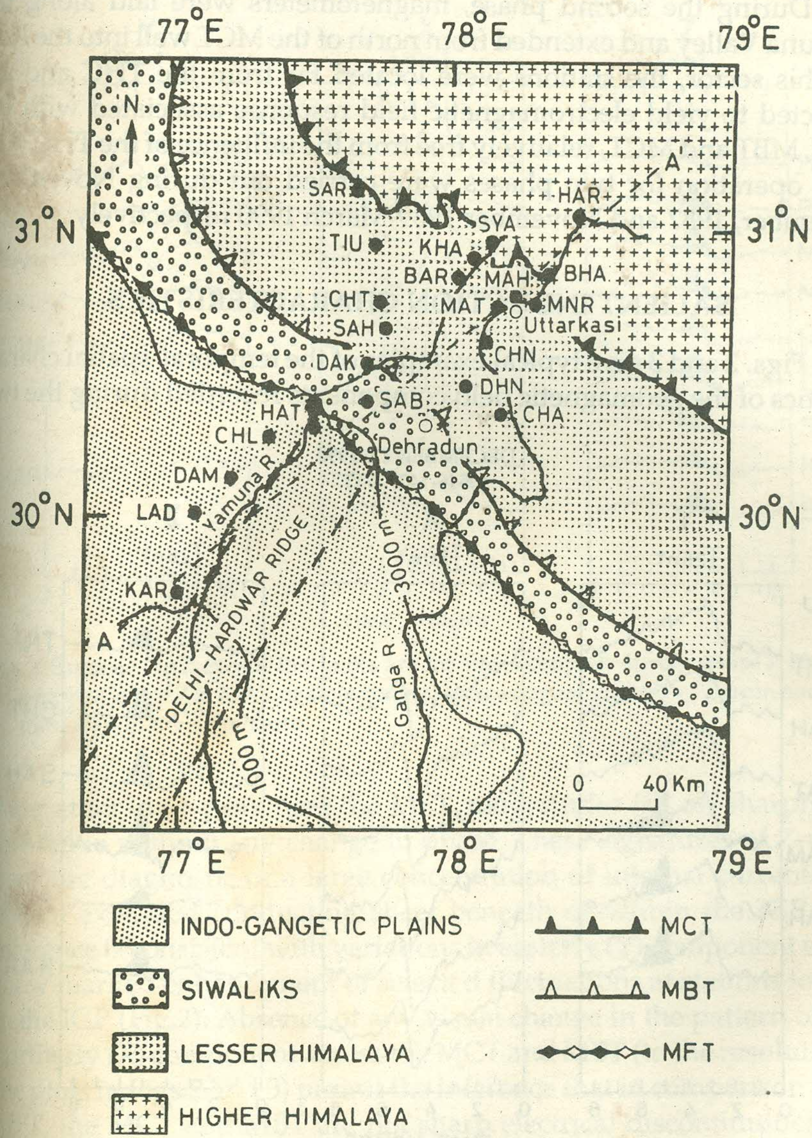

Fig. 1. Generalized geological map of the Garhwal Himalaya, NW India showing the location of magnetometer sites in relation to major tectonic boundaries. The field operations were carried out in two phases during 1987 and 1990. The Epicentre of 1991 Uttarkashi earthquake (*) is also marked.

In their disposition, magnetometers cut across the MCT and the GLHSB along two sectors, in the eastern part by a group of stations HAR-BHA-MNR-MAH-CHN and in the west by stations SYA, KHA and BAR.

Permanent magnetic observatory at Sabhawala (SAB) and another temporary station at DHN, covered in earlier survey helped to trace the behaviour of magnetic variations from the north of the MCT towards the MBT and MFT.

During the second phase, magnetometers were laid along the Yamuna Valley and extended from north of the MCT well into the IGP. On this sector, the stations were located far from the THC and are expected to yield electromagnetic field response associated with the MFT, MBT and MCT, relatively free from the influence of the THC. The field operation for two phases were carried out during November-December, 1987 and November 1989-March 1990 respectively.

SALIENT INDUCTION CHARACTERISTICS

Figs. 2 and 3 give typical examples of the temporal-spatial characteristics of the geomagnetic field components recorded during the two

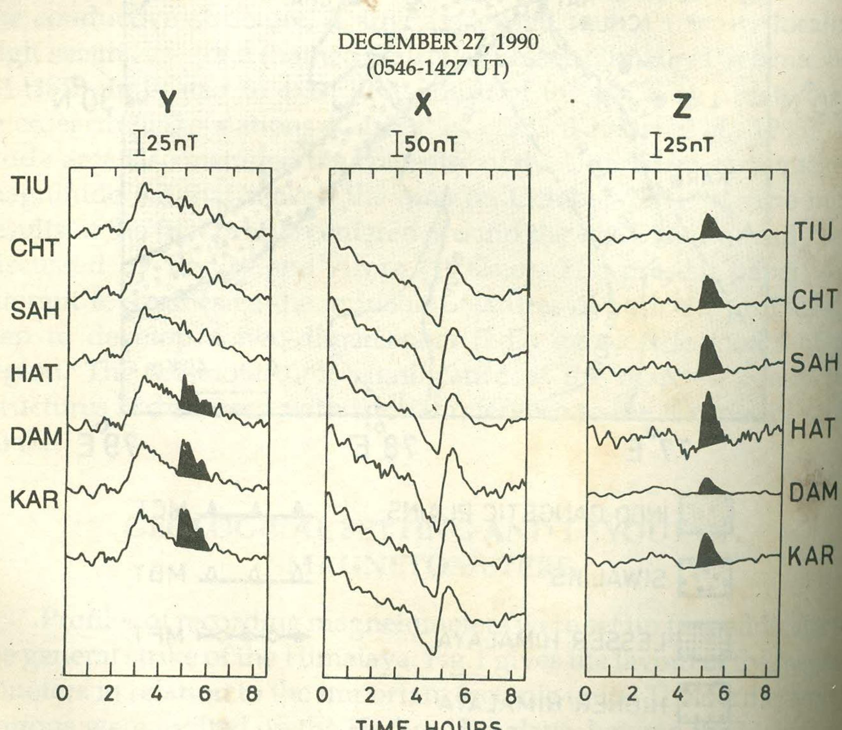

Fig. 2. Stacked plot of temporal variations recorded at the sites occupied in Phase II X, Y, and Z respectively represent variation in three orthogonal components directed along north, east and vertically downwards.

phases of field operation. The vertical field (Z) variations, which on physical consideration, are more prone to the sub-surface conductivity contrast, show systematic changes across the profiles. On the TIU-KAR profile, (Fig.2), the Z fluctuations show a gradual increase in their magnitudes from the northernmost site to the sites close to the MFT.

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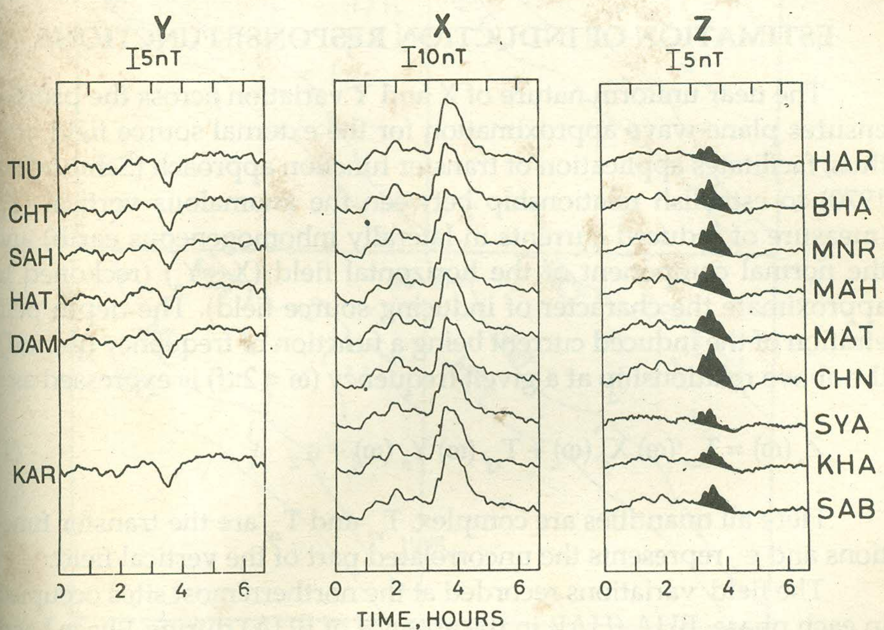

Fig. 3. Same as Fig.2 except that plots are for sites occupied during phase I. Note the suppression of Z at MAT against general increasing magnitude of Z from northernmost station towards south.

After attaining a peak near the MFT, magnitudes fall off sharply to a low value without any change in phase. These signatures of Z-variations are diagnostic of a large concentration of internal currents in a certain extended conducting sheet beneath or within the IGP. This inference is consistent with variations in easterly (Y) component which show marked enhancement of selected fluctuations at stations located in the IGP (Fig.2). Absence of any visual change in the pattern of Z or northerly (X) component across the MCT and MBT (to the resolution of the plots in Figs.2 and 3) permit the inference that in comparison to the MFT, the MCT and MBT are not sharp electrical discontinuities. The group of stations occupied in phase I is centred around MCT. These in conjunction with the data at SAB reveal a progressive increase in the magnitude of Z fluctuation with a conspicuous maximum at SAB, located in the vicinity of the MFT, both along the HAR-MAH-CHN-SAB and SAY-BAR-SAB sectors. A feeble but persistent feature, seen on many disturbance events is the suppression of Z fluctuations at MAT and KHA. This suppression indicates a localised concentration of induced currents beneath these stations. Enumerating in latter section, the persistence of these induction effects at different frequencies, a variety of signatures are synthesized to indicate a narrow conductivity belt, a little south of the MCT, associated with the GLHSB.

ESTIMATION OF INDUCTION RESPONSE FUNCTIONS

The near uniform nature of X and Y variation across the profiles ensures plane-wave approximation for the external source field and, thus, facilitates application of transfer function approach (Schmucker, 1970) to establish relationship between the anomalous vertical (Z_a) (measure of induced currents in laterally inhomogeneous earth) and the normal component of the horizontal field (X_n, Y_n) (reckoned to approximate the character of inducing source field). The depth penetration of the induced current being a function of frequency (period), the above relationship at a given frequency ($\omega = 2\pi f$) is expressed as:

$$Z_a(\omega) = T_{zx}(\omega)\, X_n(\omega) + T_{zy}(\omega)\, Y_n(\omega) + \epsilon_Z \tag{1}$$

Here all quantities are complex. T_{zx} and T_{zy} are the transfer functions and ϵ_z represents the uncorrelated part of the vertical field.

The field variations recorded at the northern most sites occupied in each phase, BHA (HAR in the absence of BHA) during Phase I and SAR (TIU) during phase II, were used to represent X_n and Y_n in eqn (1), as required in the statistical evaluation of transfer functions using the formulation of Schmucker (1970), detailed in Arora (1990) and Arora and Singh (1992). Vertical field variations recorded at each site were considered to be totally anomalous and, hence reckoned to be a measure of Z_a in Eqn (1). Some 15 events, similar to those shown in Figs.2 and 3, with varying source field polarizations were employed for the computation of stable transfer functions.

The information contained in the transfer function about the electrical conductivity distribution is presented in the form of a pair of induction arrows, corresponding to real and quadrature parts. These arrows by pointing at right angles to the lateral conductivity gradient, define the strike of geoelectrical discontinuity causing deformation and distribution of internal induced currents. The magnitude of the induction arrow and its spatial pattern hold information on the depth, geometry and conductivity contrast of the anomalous conductive body with respect to the host medium.

In the present work, about eight sets of induction arrows in the period range of 16-128 min were calculated. Based on their period dependence, the induction features can be divided into two major groups. In the period range of 85 min and above (Fig.4a), the induction

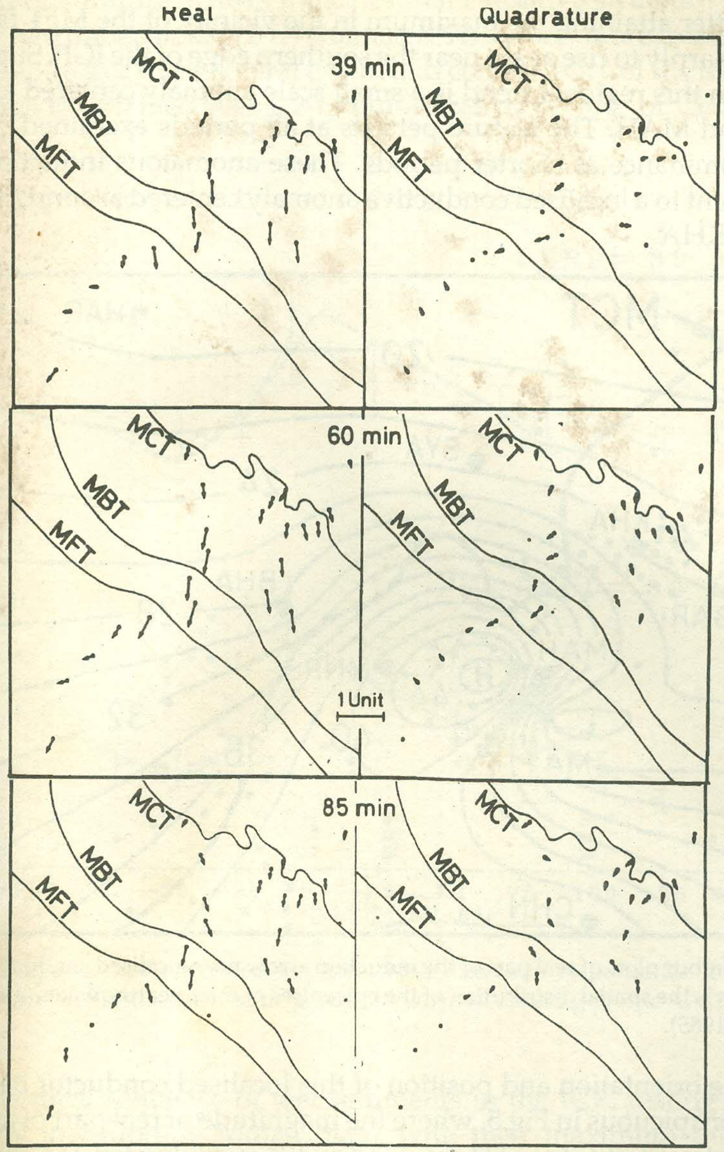

Fig. 4. The real (in-phase) and quadrature induction arrows at all recording sites corresponding to periods of 39, 60 and 85 min. The arrows have been reversed to point towards zones of internal current concentration.

arrows, particularly at sites located in lesser Himalaya, under the influence of the massive NE-SW oriented Trans-Himalayan conductor (Arora *et al.*, 1982, Arora and Mahashabde, 1987) have southeasterly orientation. However, below this period range, induction arrows exhibit southerly or southwesterly orientation and clearly bring out the control of lithotectonic boundaries following the trend of the Himalayan collision. In their spatial variation (also see Fig.6), the magnitude of the real induction arrows increases steadily from north to south which after attaining the maximum in the vicinity of the MFT falls off rather sharply to rise again near the southern edge of the IGP. Superimposed on this regional trend is a small scale anomaly centered around MAT and MAH. The feature persists at all periods examined, with a clear dominance at shorter periods. These anomalous induction features point to a localised conductive anomaly centered around MAT as well as KHA.

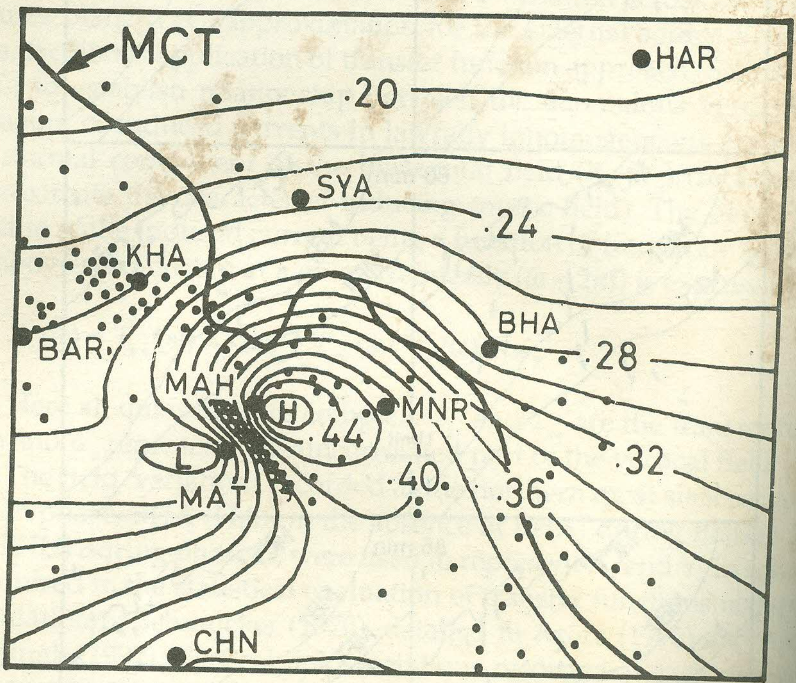

Fig. 5. Contour plots of real part of the induction arrow near localised conductive zone vis-a-vis the spatial distribution of the epicentres of micro-earthquakes (after Gaur *et al.*, 1985).

The orientation and position of this localised conductor becomes more conspicuous in Fig.5, where the magnitude of real part of anomalous vertical field $Zr = [T^2 zx_r + T^2 zy_r]^{1/2}$ is contoured for group of stations (Phase I) defining localised conductivity anomaly. The line separating regions of low and high magnitude of anomalous vertical field, mark the axis of localised conductive zone. The absence of the extension of this line, despite the observed suppression of vertical field at KHA may simply be the artifact of contouring due to the paucity of stations or their position with respect to the anomaly axis.

GEOELECTRIC MODELLING

The induction effects most evident in our observations suggest a highly conductive zone aligned with the MFT. The parallelism of the real and quadrature arrows indicates that causative structure is basically of two dimensional (2-D) character. Therefore, more information on the depth, thickness, lateral extent and conductivity of the involved structures is obtained using 2-D numerical modelling of Cerv *et al.* (1984).

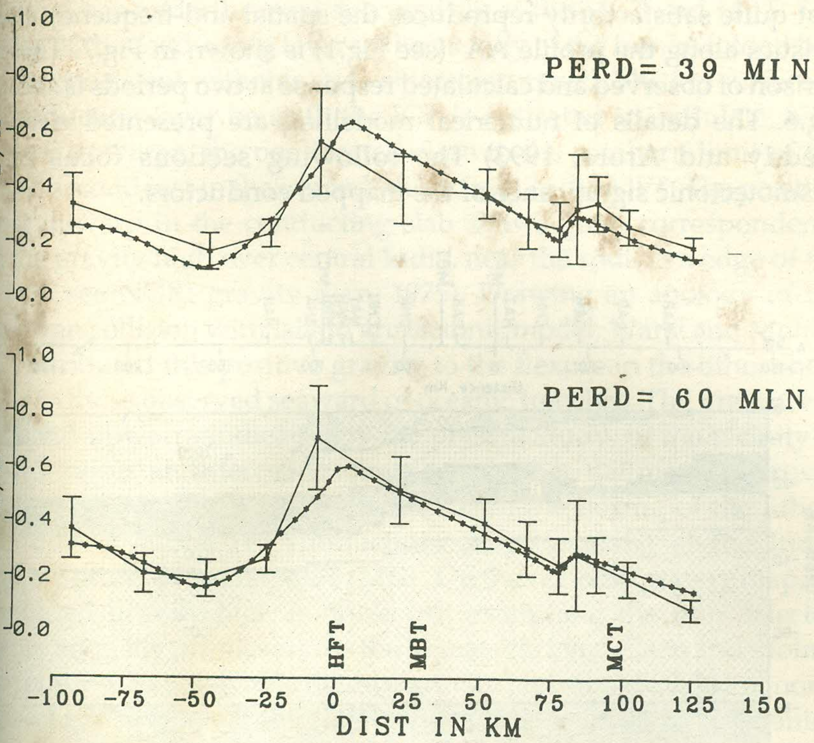

Fig. 6. Comparison of calculated in-phase (real) induction response for the model shown in Fig.7 with observed response for two periods along profile AA′ shown in Fig.1.

The thick sequence of wet sediments in the IGP, resting on the northerly low-dipping Indian plate, with their maximum thickness just south of the MFT, constitute natural seat for the concentration of induced currents. Initial test model calculations by Reddy and Arora (1992a, b) to account for the observed EM response considered only these sediments overlying a layered half-space. They showed that within the constraints on the thickness and resistivity, the induction in these sediments produce weak response in comparison to the observed, although in its spatial pattern a clear peak was seen at the MFT which falls off rather sharply on the SW than on the NE, similar to the observed pattern.

From the more systematic EM induction studies carried out on continental margin, it is apparent that at various geological times and locations, the processes of subduction has emplaced slabs of enhanced conductivity within the middle and lower crust of the subducting plate (*see* Jones, 1992). Consistent with this observation, a conducting layer was inserted at mid-crustal layer in a 2-D geoelectric model, the geometry of this layer was changed by trial-and-error method to produce response similar to the observed induction features. The final model that quite satisfactorily reproduces the spatial and frequency characteristics along the profile AA′ (see Fig.1) is shown in Fig.7. The comparison of observed and calculated response at two periods is shown in Fig.6. The details of numerical modelling are presented elsewhere (Reddy and Arora, 1993) The following sections focus on the seismotectonic significance of the mapped conductors.

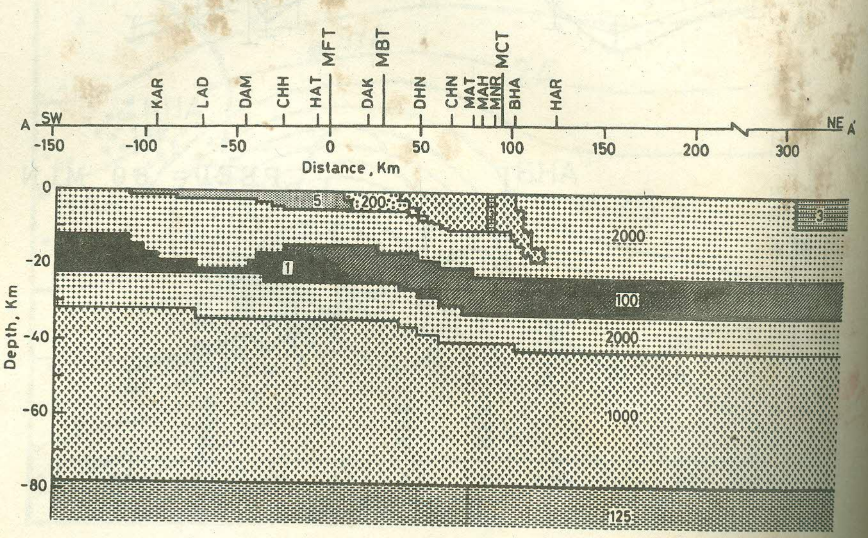

Fig. 7. Two-dimensional electrical resistivity model along the profile AA′ shown in Fig.1. Resistivities are in Ωm.

ORIGIN OF ENHANCED CONDUCTIVITY ZONES AND THEIR SEISMOTECTONIC SIGNIFICANCE

Mid-Crustal Conductor

The most important feature of the model in Fig.7. is a conducting slab at mid-crustal depth beneath the IGP which dips down under the Himalayan frontal belt. Under the IGP, the conducting layer with its undulating top roughly at a depth of 8-10 km varies in thickness of 6-10 km and has resistivity of 1 Ωm. Because of the principle of equivalence (Patra and Mallik, 1980, Jones; 1987, 1992), these parameters are obviously not unique. It is the integrated conductivity (product of conductivity and thickness) that is best resolved. Despite these constraints the model with the geoelectric and geometrical parameters provided here gives a reasonable fit to the observed response at different periods (Fig.6) and is consistent with the generalised tectonic model of the Himalayan collision zone in which following the cessation of the subduction along the Indus-Tsangpo Suture Zone, Indian plate dips down and has underthrusted successively at the MCT and MBT. The bending of the conducting layer in the vicinity of the frontal folded belt (Fig.7) is consistent with this style of tectonic model. The top surface of this conducting layer beneath the IGP is indicated to undulate, with two clear upwarps, the one located close to the southern limit of the IGP and second just in the immediate vicinity of the MFT. The position of first upwarp in the conducting slab shows good correspondence with the gravity high over central India, near the southern edge of the IGP (e.g. see NGRI gravity map, 1975). Drawing an anology of the Himalayan collision with Island arc tectonic model, Warsi and Molnar (1977) attributed this positive gravity to the flexure in the lithosphere similar to those observed seaward of oceanic trenches. The presence of the second upwarp, indicated by the present study, in the vicinity of the MFT raises an interesting question whether the mapped crustal upwarps are independent manifestations of the flexing of the lithosphere during successive subduction/underthrusting at the Indus Tsangpo Suture Zone and MCT/MBT. On the regional gravity map, no pronounced gravity high is noted but examining the four selected Bouguer anomaly profiles across the Himalaya, Lyon-Caen and Molnar (1985) observed a resolvable relative gravity high about 20-50 km north of the MFT. However, they interpreted this as due to substantial underthrusting of the sediments beneath the lesser Himalaya which, in turn, provided constraints on the extent of underthrusting.

Within the constraint provided by the modelling, an interesting feature of this mid-crustal conducting layer is that on its dipping part, north of the MFT, its conductivity is found to decrease from a value of 1 S/m to 0.01 S/m (i.e. resistivity changes from 1 Ω.m to 100 Ω. m). In this respect, the present model bears resemblance to the geoelectrical model for the Juan de Fuca plate as it subducts beneath North America (Kurtz *et al*, 1986; EMSLAB Group 1989). The interpretation of electromagnetic data from twenty-seven locations coincident with seismic reflection profile has provided convincing evidence of a dipping conductive zone with a resistivity of 30 Ω. m over its first 100 km of length and then attains a resistivity of the order of 100 Ω. m on its further extended part of approximately the same length (Kurtz *et al.*, 1986; Wannamaker *et al.*, 1989). It was suggested that the anomalous conductive zone which correlates spatially with a strong reflection zone was caused by the saline water drawn from the sediments down-going with the subducting oceanic plate or released from hydrated minerals at depth (Kurtz *et al*, 1986; Gough, 1992). For the fluids to be an effective mechanism for enhanced conductivity of mid-crustal layer in the model envisaged here for Himalayan collision zone, the most probable source may be the free water released at depth from a variety of prograde metamorphic dehydration reactions (Etheridge *et al.*, 1983 and Fyfe *et al.*, 1978). Bailey (1990), Hyndman (1988) and Jones (1987, 1992), amongst others have discussed the possible mechanisms for fluid generation, their mode of transportation and trapping beneath an impermeable cover as a possible source of enhanced conductivity at mid-crustal depths. Bailey (1990) has demonstrated that below the brittle-ductile transition, thermal activation of ductility is strong enough to facilitate the rapid evolution of porosity and consequently aqueous fluids, supplied by whatever mechanism at the base of the crust or deep within the crust, will infiltrate up quickly to the brittle-ductile transition. As a consequence, fluid overpressures resulting from the arrival of fluids at the brittle-ductile transition induce horizontal hydrofracturing, leading to fluid reservoir which in turn explains high conductivity and reflectivity at mid-crustal depths (Jones, 1992 and Hyndmann, 1988).

Stanley *et al.* (1990) noted that the brittle-ductile transition simulates onset of ductile behaviour in the crust and, thus, define the depth cut off for seismicity caused by crustal stress. They showed that in various tectonic regions, this depth limit varies between 15-20 km. Khattri (1990, 1992) noted that microseismicity in the present study area is confined to the upper crust of about 15-20 km. This correlation of the depth cut off of seismicity with the top of the underthrusted conducting slab supports our model in which the brittle-ductile transition that limits seismicity simulates zone of fluids beneath a cap of mineral disaggregation that causes the enhanced conductivity. Ni and Barazangi (1984) noted that foci of most moderate size earthquakes with epicentres south of the MCT are aligned along a linear plane, at about 10-20 km depth with an apparent northward dip of about 15°. In the tectonic model of Seeber *et al.* (1981), the planar zone coincides with the Basement Thrust Fault (BTF) separating Indian shield from the overriding wedge of the lesser Himalaya. It seems feasible to visualize that in such a horizontal compressional regime balancing to differential tectonic stress the upper and lower crust, due to the significant difference in the mechanical behaviour, may facilitate development of near horizontal thrust (detachment) at the transition zone (Bailey, 1990; Jodicke, 1992). The existence of such a detachment surface, coinciding with the top of the conducting layer, would also facilitate migration of fluids to the crust beneath the Indo-Gangetic Plains and would, thus, enhance the conductivity at the mid-crust indicated by the geoelectrical model in Fig.7.

Explaining this enhanced conductance of several thousand Siemens would, however, require prohibitively very high porosities (Hyndman and Shearer, 1989; Jodicke, 1992) which are hard to be substantiated by the petrology of middle crust (Yardley, 1986). In recent years, very small portion of graphite in the form of interconnected grain-boundary thin films are considered as promising candidates for producing high conducting layers at deeper levels of crust (Frost *et al.*, 1989; Jodicke, 1992). In the absence of any independent corroborating evidence, the feasibility of envisaging graphite films in the crust beneath the IGP is hard to discount. However, it is worth recalling that Chun (1986) based on shear wave velocity structure has indicated the anomalous character of the crust in the depth range of 10-20 km, coinciding with the depth and thickness of conducting slab in geoelectrical model of Fig.7.

LOCALISED MCT CONDUCTIVE ZONE

The second important feature of the geoelectrical model (Fig.7) is a narrow near vertical conducting zone south of the MCT, required to simulate small scale anomaly centered around MAT and MAH. Its shallow depth range is consistent with induction features which are most evident at the short periods examined. As seen on Fig.5, this localised conductive belt shows good correspondence with a concentrated belt of epicentres (GLHSB) located to the south of the surface trace of the MCT (Gaur *et al.*, 1985; Khattri *et al.*, 1989). Khattri *et al.* (1989) have estimated the width of the seismic belt to be of the order of 10-30 km with hypocentres of most earthquakes lying at depths of less than 13 km. It is interesting that the axis of mapped conductive zone (Fig.5), shows a good positional correlation with the southern edge of the high seismicity belt over its entire length from northwest of the Yamuna valley to southeast of the Alakananda valley.

On the gravity map of the region (Qureshy *et al.*, 1974), area of conductivity anomaly is characterized by a relative gravity high with axis of conductivity body coinciding with largest gravity gradient. The observed signature of gravity anomaly suggests that it may be related, in some way, to a high density linear intrusion, such as resulting from the obduction of detached crustal block from the overriding Asian plate onto the lithosphere of the underlying Indian plate above the plane of the MBT. In such a scenario, the shallow conductive zone may represent a fracture zone above the plane of obduction and may owe its high conductivity to the fluids brought to shallow levels by seismic pumping (Sibson *et al.*, 1975). Any movement along such fracture zone to readjust compressional forces arising due to the continued NE migration of Indian plate may explain high seismicity along the GLHSB in general and may emphasize its role in triggering Uttarkashi earthquake in particular.

CONCLUSIONS

In the 2-D geoelectrical model across the frontal Himalaya, the sedimentary sequence in the IGP is an important surface conductive feature but the dominant induction anomalies appear to be related with a conducting slab embedded in the underthrusting Indian lithosphere at the brittle-ductile transition zone. Incorporation of this subsurface features helps better understanding of space-depth distribution of the seismicity and bring out the role of fluids as a dominant controlling factor in the development of detachment zones.

The two crustal upwarps indicated beneath the IGP, particularly the one near the southern edge of IGP, is poorly constrained. In view of their significance in tracing the style of Himalayan collision process, more detailed investigations, preferably using magnetotelluric and contemporary geophysical methods are suggested. Seismic reflection surveys across the Himalayan collision zone, in addition to constraining the depth and geometry of the mapped structures, would provide clues on the likely source of enhanced conductivity, fluids or graphitic films.

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