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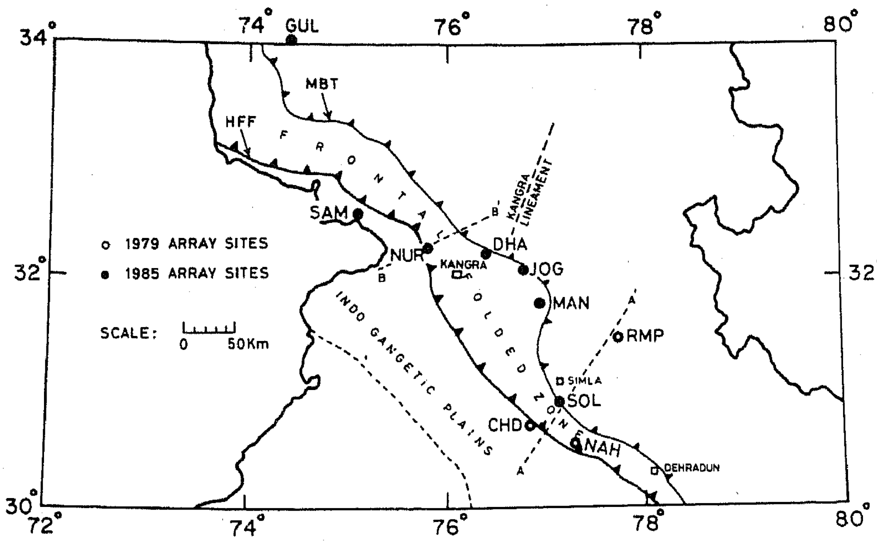

Figure 1. Map showing observing sites of Kangra magnetometer array in relation to the main boundary thrust (MBT) and Himalayan frontal fault (HFF) of Himachal Pradesh-Kumaun-Himalaya. Solid circles mark the sites occupied in 1985 and open circles denote sites occupied during earlier arrays (see text).

delimit the Siwalik folded formations, predominantly consisting of freshwater molasse-like sediments. The Tertiary and older sequences of lesser Himalaya lie to the north and the thick pile of the Pleistocene to subrecent alluvial deposits in the Indo-Gangetic Plains to the south. Although the choice of the stations was to some extent constrained by the terrain and logistics, their present distribution was expected to map the effects of the conductivity anomaly associated with the Kangra lineament, in addition to providing information on the geoelectrical configuration of the HFF and the MBT.

3. Data treatment

The field operations were carried out between May and December 1985. During this interval of 1 min. Figure 2 gives an example of transient variations in the northward the transient variations in the three geomagnetic field components with a sampling interval of 1 min. Figure 2 gives an example of transient variations in the northward (X), eastward (Y) and downward directed vertical (Z) components. This and seven other events were Fourier-transformed to evaluate the inter-station type of transfer functions, at the selected frequencies, that best satisfy:

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

where X_n and Y_n are the Fourier transform (FT) parameters of the normal field at the frequency in question and were approximated by the averaged values of the respective FT parameters over all stations, except Gulmarg. Assuming a uniform source field, the measured vertical variation was considered to be totally anomalous and used to compute Z_a. Solutions to expressions, similar to equation (1), in respect of the anomalous horizontal fields, were also obtained. From among the eight sets of induction arrows, constructed from the vertical field transfer functions, over the period range of 10–120 min, two sets corresponding to the periods of 46 and 82 min

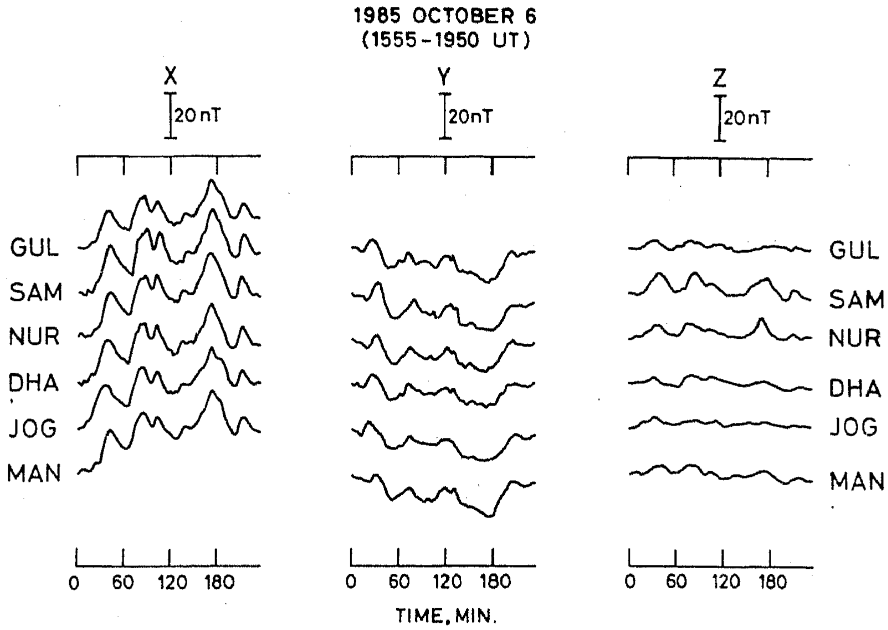

Figure 2. Magnetic disturbances, as recorded by the Kangra array stations. X, Y and Z refer to the northward, eastward and downward magnetic field components.

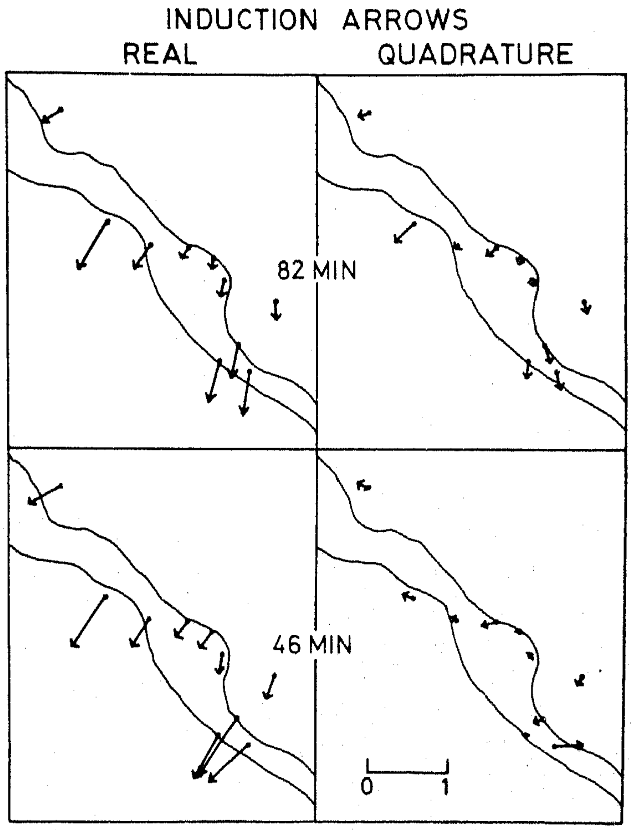

Figure 3. Reversed real and quadrature induction arrows for all stations of the Kangra array. In their present notation, arrows point at right angles towards region of high electrical conductivity.

are given in figure 3. Induction arrows for the four stations from earlier arrays are also included. By the application of hypothetical event analysis (Bailey *et al* 1974) on the vertical and the horizontal transfer functions, real and imaginary parts of anomalous

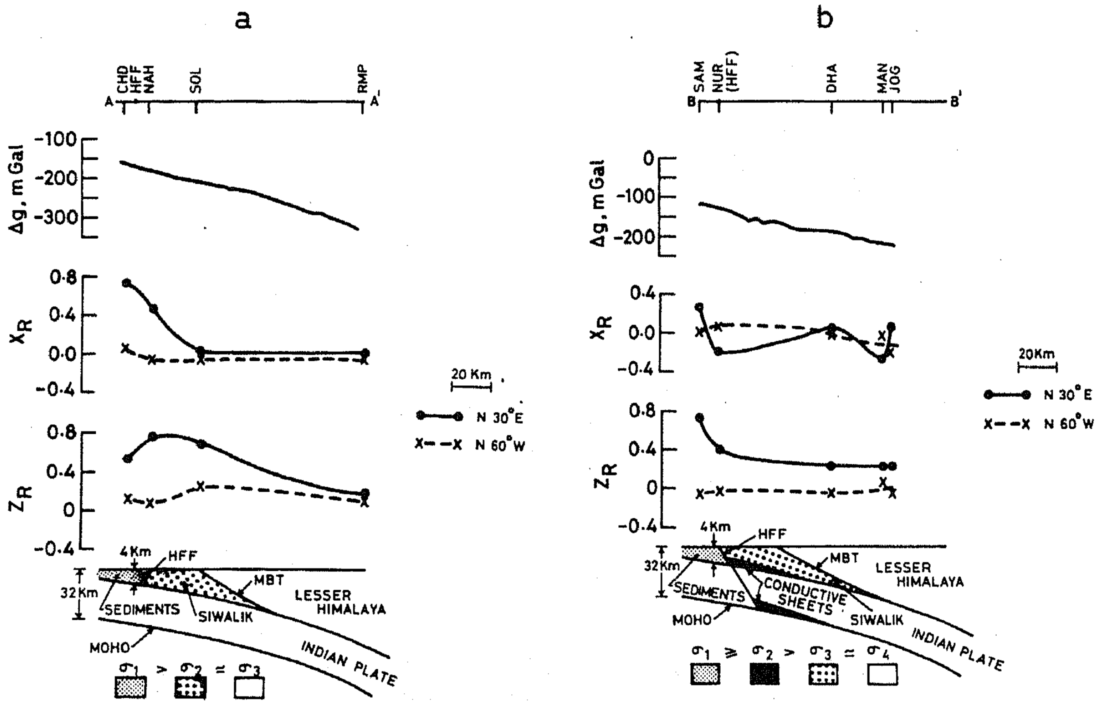

Figure 4. Spatial variation in the real part of the predicted anomalous horizontal (X_R) and vertical (Z_R) field along the traverses (**a**) AA′ and (**b**) BB′ for two polarization of horizontal inducing field. Lower panels give the inferred distribution of electrical conductivity in the schematic geological cross-section. Also shown are the Bouguer gravity anomaly variations.

field associated with a horizontal inducing field of a unit amplitude and specified polarization were worked out. Figure 4 gives the spatial behaviour of the real part of the vertical, Z_R, and the horizontal, X_R, anomalous field along two hypothetical traverses running across the strike of the HFF. It is shown below that induction anomaly is primarily associated with a two-dimensional conductivity boundary coincident with the HFF and, therefore, its strength at various stations will be the function of distance of the stations from the HFF. The traverses referred to as AA′ and BB′ in figure 4 are formed by combining respectively the old and new groups of stations. The locations of the stations on the traverses are marked in relation to their vertical distance from HFF. Lower panels in figure 4 give distribution of the inferred electrical conductivity in the schematic geological cross-section along the traverses. Also included in figure 4 is the Bouguer anomaly variation derived using data from Dass *et al* (1979) and that from NGRI gravity map.

4. Results and discussion

4.1 *Conductivity structure along the HFF*

First evidence on the presence of a large electrical conductivity contrast across the foothills is quite obvious from figure 2, where Z variations show marked enhancement from JOG to SAM. A close scrutiny also reveals a little larger amplitude of X fluctuations at SAM. Examination of several such disturbance events suggests that the enhancement of X and Z fluctuations at SAM is much more conspicuous and stronger when horizontal field has dominant northeast polarization. In figure 3 the real induction arrows point at right angles to the MBT/HFF and their amplitude attain large values in the close vicinity of the HFF. The quadrature arrows with significant magnitudes also depict these features, which is well marked at the period of 82 min and warrants the inference that associated conductivity structure has more resistive response, such as that caused by the surface sediments. For periodicities of < 46 min, quadrature arrows present a much more scattered picture, perhaps due to the very localized concentration of the currents in the isolated near-surface sedimentary structures. From figure 4 one observes that when the horizontal field is polarized at right-angles to the HFF/MBT, it produces a strong anomalous field, whereas orthogonal polarization excites practically no response. This polarization dependence is one indication that the induction effect can be interpreted in terms of a two-dimensional structure. Further that the anomalies, both in Z_R and X_R attain their largest value close to the HFF suggests that induction effects are associated with some electrical discontinuity aligned with the foothills of the Himalaya.

The sedimentary strata in the Indo-Gangetic Plains constitute an asymmetric prism of sediments with its axis of thickest deposition running close to the Siwalik foothills. Here the undisturbed sedimentary strata sitting over the northerly dipping Indian Shield attains a thickness of 3–4 km (Raiverman *et al* 1983). The resistivity log data from the Indo-Gangetic Plains indicate values of the order of 15 ohm.m for sedimentary strata (Vozoff 1984). Thus, the HFF separating the thick conducting sedimentary strata of the Indo-Gangetic Plains from the more resistive formations of the Siwalik folded belt and the lesser Himalaya does provide a large conductivity contrast across it and induction along such a junction would be expected to influence the transient geomagnetic variations. The geoelectrical cross-section across the HFF is similar to that found across the coastline. Here, the sea water is replaced by the wet conducting sediments in the Indo-Gangetic Plains. Thickening of the crust beneath Himalaya, in accordance with the isostatic model, provides step-like structure in the mantle, similar to those found on the coastline. The electromagnetic response of the geoelectrical cross-section across the coastline has been investigated by several workers (Menvielle *et al* 1982). Many salient features of geomagnetic coast effect are quite evident on the anomaly pattern observed on the present traverses. The anomalous Z variations register a large value at NAH, CHD and SAM, *i.e.* at the stations located close to the edge of the thick sediments of the Indo-Gangetic Plains. Persistence of high value of Z_R at SOL as compared to NUR will be discussed in the next section but consistent with the expected coast effect, the anomalous horizontal component is also found to be large at NAH, CHD on the traverse AA′ and SAM on the traverse BB′, which fall off very sharply to a very low value at SOL and NUR on the resistive side of electrical discontinuity. This broad agreement of the observed features with those expected along the coastline suggests that the nature of observed induction anomalies along the traverses can be atleast qualitatively explained in terms of the edge effect of the sheet current induced in the thick conducting sediments of the Indo-Gangetic Plains.

4.2 *Conductivity structure beneath the Siwalik belt*

Figure 4 shows that the stations CHD and SAM, nearly equidistant to the south of the HFF have comparable Z_R. To the north, Z_R on the traverse BB′ falls off rather more sharply to a relatively low value than along AA′. This difference in the spatial characteristics of Z_R persists irrespective of the manner in which the normal field components are defined in equation (1). X_R variations along traverse BB′ reveal a small wavelength anomaly around MAN and JOG, perhaps related to the rock salt deposits exposed around MAN and known to exist in the form of bedding in the sub-surface (Srikantia and Sharma 1972). The distance up to which induction effect associated with the HFF would persist north of the HFF would depend upon the effective conductance of the sediments in the Indo-Gangetic Plains and/or upon the deep conductivity structure. No significant difference in the depth and the extent of the overlying sediments along the two traverses can be inferred from the basement depth map of the Indo-Gangetic Plains (Raiverman *et al* 1983). Tentatively it can be surmised that the cause for the varying induction pattern along the two traverses must be related to deeper conductivity structure rather than to the variation in conductance of the sediments. Drawing an analogy with similar differences in the geomagnetic coast effect across stable and tectonic shield margin (Cochrane and Hyndman 1970), the attenuation of Z_R at stations located over the Siwalik folded belt along profile BB′ is interpreted to indicate the concentration of induced currents in association with some conducting sheet at a certain depth beneath the folded belt. As the induction arrows even for stations on the Siwalik belt of traverse BB′ are directed towards the HFF, the overall conductance of the envisaged conductive sheet or depth integrated conductivity of the Siwalik block would be sufficiently lower than that of the sediments in the Indo-Gangetic Plains. Perhaps due to the presence of dominant sediment effects, the frequency dependence of induction pattern does not help to resolve the likely depth of the conductive sheet beneath the Kangra folded belt. However, from geological consideration, it seems possible to envisage probable locations of the conducting sheet. Further correlation with other geophysical data has been able to place constraints on the likely seat and causes of enhanced conductivity, which include partial melting, presence of conducting solid minerals, conducting fluids in fractured rocks or free water released from dehydration process.

The salt-bearing Sahli belt of the Himachal Pradesh falls within the ambit of volcanic belt running parallel to the MBT from Mandi to Daral (just west of Dharmashala). Discussing the origin and source of the volcanic belt, Taron (1979) reported that volcanic magmas were derived from the partial melting of the upper mantle. The effect of melting on the conductivity of rocks is well established (Shankland and Waff 1977). It may be argued that frictional heating at the crust-mantle zone as a consequence of continued under-thrusting of the Indian plate beneath the Eurasian plate might initiate and retain the magma in the state of partial melt. Counter-thrusting or obduction of such magma along the crust-mantle boundary can offer seat for the zone of high conductivity required to explain the features of geomagnetic induction along the traverse BB′. But the heat flow values that prevail over the Siwalik belt do not support thermal origin of the high conductivity required beneath traverse BB′. On the heat flow map, compiled by Ravi Shankar (1988), the area of Siwalik folded belt is characterized by heat flow values in the range of 40–70 $mW.m^{-2}$. These values are not sufficiently high to initiate or sustain partial melt at crust-mantle boundary (Adam 1978). The mechanism related to the accumulation of conducting minerals also seems unlikely as to our knowledge there is no reported occurrence of graphite or magnetite in the Siwalik sequence. A more likely source may be associated with the electronic conduction in hydrated rocks. The overall decreasing trend in gravity field from SW to NE along both traverses in figure 4 indicates general thickening of the crust beneath the Himalaya (Dass *et al* 1979). The absence of a sharp increase in the Bouguer anomaly from the plains to the lesser Himalaya led Lyon-Caen and Molnar (1985) to suggest that the boundary between sedimentary fill in the Indo-Ganetic Plains and more dense rock of lesser Himalaya is not sharp and vertical. Instead, it appears that relatively light sediments have been subducted beneath the Siwalik and lesser Himalaya along with the underthrust plate. They, however, further noted that the extent of sediment underthrusting is variable along several sectors. Furthermore, among the various latitudinal litho-tectonic provinces of the Himalaya, the frontal zone is tectonically most active at present (Nakata 1986). Geomorphological and geodetic measurements indicate that the Siwalik block bounded by the MBT and the HFF has been locally uplifted. Valdiya (1986) notes that vertical movements have been variable from sector to sector and have caused northward tilting and development of many intrabasinal thrusts and faults. These oscillatory vertical movements of the Siwalik block can result in the opening of new cracks. Their exposure to the saturated sediments of the Indo-Gangetic Plains can lead to increased hydration of certain sedimentary layer of the Siwalik block, providing a zone of enhanced conductivity. The concentration of induced currents in such a layer or in subducted sediments may account for the attenuation of Z over the frontal folded belt. The differences in the depth integrated conductivity along traverses AA′ and BB′ may also arise from the variable amount of free water released during the process of dehydration at the boundary between amphibolitic and granulitic facies (Berdichevsky *et al* 1972).

All these suggestions regarding the seat of conductive zone and its position on the geological cross-section of figure 4b, are quite speculative and hence no geological significance is claimed. However, these ideas provide the necessary background material for the numerical modelling to be undertaken to estimate the likely depth and conductance of the conductive sheet beneath the frontal folded belt. The proposed magnetotelluric soundings would provide further bounds on the models to be tested, and would enhance the geological significance of the observations. It is worthy of note that the area covered by the magnetometer array included the epicentral zone of destructive Kangra earthquake of 1905. The most remarkable features of the isoseismal map was the peculiar distribution of high intensity. Middlemiss (1910) identified two zones of high intensity; a major one with a maximum near Kangra and Dharmshala and extending to Mandi (area covered along traverse BB′) and a minor one centred around Dehradun. Molnar (1987) showed that these high intensity belts marked the dual rupture zone in conjunction with this great earthquake. The intervening zone extending from SW of Mandi to Simla (area corresponding to traverse AA′) was characterized by low intensity. The difference in the geomagnetic induction pattern along traverses AA′ and BB′ shows good correspondence with high and low intensity zone and, thus, may argue for the geological significance of the results reported here.

5. Conclusion

The nature of induction anomalies across the HFF can be qualitatively explained in terms of the edge effect of sheet currents circulating preferentially in the thick and conducting sediments of the Indo-Gangetic Plains resting against the more resistive formations of the lesser Himalaya. The implication of a good conductor beneath the Siwalik folded belt of the Kangra suggests the existence of a layer of water-saturated sediments.

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