JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.50, Dec. 1997, pp.697-708

Deep Geoelectric Structure in the Rohtak Region using the Magnetotelluric Studies

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Abstract: Magnetotelluric studies conducted in the seismically active regions around Rohtak over two linear profiles showed a predominantly two dimensional behaviour with major and minor rotation directions along the E-W and N-S respectively, indicative of strong influence of an approximately N-S aligned conductive feature. The geoelectric structure indicates a 25 m thick surface layer with a resistivity of 1.4 ohm-m corresponding to the alluvium. The thickness of the second (30 ohm-m) and third (1.2 ohm-m) layers were 50m and 150m respectively. These are interpreted to be due to the Siwalik sediments below alluvium. The fourth layer is 3000-4500m thick and has a resistivity of 100 ohm-m. This is presumably the metamorphosed basement and is separated from the granitic basement by 500-1500m thick highly conductive (1 ohm-m) layer, which presumably is the unconformity between the metamorphosed and granitic basements.

A N-S oriented vertical conductive zone was delineated extending from near surface to depths of atleast 18 km. This conductive body is about 5 km wide (along E-W) and has a resistivity of 1 ohm-m. The vertical conductor is indicative of a N-S aligned active fault or fracture zone transverse to the strike of the Himalayan collision belt. The epicentral distribution of the earthquakes indicates that this fault may be of significance in understanding the seismicity of this region.

Keywords: Geophysics, Magnetotelluric studies, Himalaya, Indo-Gangetic foredeep

INTRODUCTION

Over the past 30 years, the region around Delhi has been experiencing sporadic seismic activity with tremors of magnitude up to 5 on the Richter scale. There are a large number of faults in this region, the prominent ones being the Delhi-Hardwar ridge, Moradabad fault and the Datagang-Tilhar fault. Fig.1 shows a tectonic map of the study region along with the location of these faults. The region surrounding Delhi has experienced a moderate seismic activity as indicated by the 1720 earthquake (magnitude 6.5) near Delhi and the 1803 earthquake (magnitude 6.5) near Mathura (Verma et al. 1995a). A large number of earthquakes were experienced in the Delhi-Sonepat region during 1963, subsequent to which the India Meteorological Department, Govt. of India, set up a chain of microseismic stations in this region. In the following ten years about 1000 shocks were recorded and the results (Kamble and Chaudhury, 1979) indicate that the epicenters causing the seismicity in this region can be broadly grouped into three clusters, the first to the west of Delhi in the Rohtak-Jhajjar region, the second near Sonepat to the NW of Delhi and the third near Bahadurgarh, SW of Delhi. Epicenters reported by these authors are enclosed in the three rectangles shown in Fig.2. The solid circles with numbers are the magnetotelluric (MT) survey stations. The epicentral cluster in the Rohtak-Jhajjar region seems to be rather active in terms of the density of the epicenters and also the number of large magnitude shocks. Most of the epicenters in this cluster are located in a 50x25 km rectangle surrounding Rohtak and Jhajjar.

The region of interest is in the Punjab plains located in the SW part of the Indo-Gangetic foredeep with a thick cover of alluvium, Tertiaries and Siwalik sequences making it

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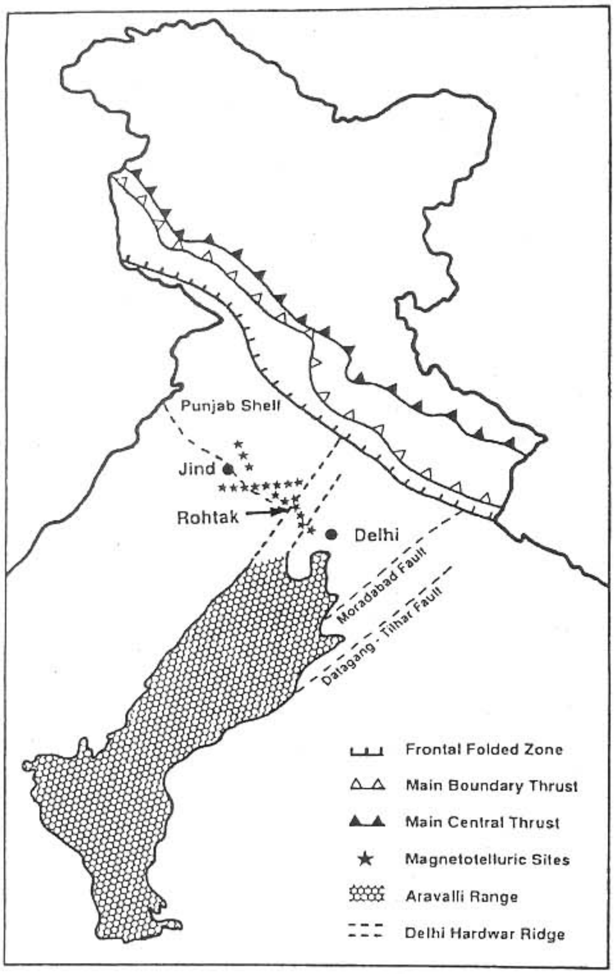

Fig.1. Map showing the major tectonic elements in and around the magnetotelluric survey region. The asterik symbols denote the magnetotelluric stations.

difficult to delineate faults in the subsurface based purely on geological methods. The region has earlier been investigated using gravity, aeromagnetic and seismic techniques. The Bouguer anomaly map (NGRI, 1975) shows irregular gravity contours in this region. Aeromagnetic studies (Agocs, 1956, Ahmed and Alam, 1978, Karunakaran and Ranga Rao, 1979) have indicated the depth to the basement of 500-1000m on the west of the epicentral region and about 2500-3000 m on the east. There is no clear indication of depth to basement in the epicentral region.

Magnetotelluric studies were undertaken in the region NW of Delhi with the intention of determining the geoelectric sub-structure in the zone of epicenters in and around the Rohtak region which could be of help in identifying possible deep seated faults. Data were first collected over a linear, approximately NS trending profile between Jind and Bahadurgarh. Field observations at 11 stations on this profile indicated a possible NS oriented conductive feature. To investigate this feature in detail, a 50 km long EW-trending linear profile was surveyed along the Latitude, 29° 15'. Data were collected at 7 stations over this profile with an interstation spacing of 5-10 km. The detailed location map of the magnetotelluric stations is shown in Fig.2.

GEOLOGY AND TECTONICS

The study area is located in the Punjab plains situated in the vicinity of the Himalayan frontal folded zone. Surface geology indicates that this region is covered by Siwalik sediments deposited during the Middle Miocene to Early Pleistocene period, directly over the crystalline basement (Sastri et al. 1971, Wadia, 1983, Aditya et al. 1976, Verma, 1991). The entire region is covered by a thick layer of recent alluvium. The isopach maps of the Siwalik formation and the alluvium in the region of epicenters shows basement at a depth of about 500m.

Most of the faults identified so far in this region show a predominantly NNE-SSW orientation which is transverse to the strike of the Himalayan collision belt. Valdiya (1976) has reported the possibility of the existence of N-S aligned faults below the Siwalik sediments in the Punjab plains. Some of the prominent lineaments in and around the study region are shown in Fig.1. The NE-SW oriented Delhi-Hardwar ridge is known to be a horst associated with a regional gravity high (Verma, 1991 and Sati and Nautiyal, 1994). The Sohna fault with an approximately N-S orientation is known to be seismically active in recent times as is evident from the large number of earthquake epicenters observed along this fault zone (Kamble and Chaudhury, 1979).

Field Survey and Data Analysis

Four component magnetotelluric data were collected at 18 stations in the survey region with an interstation spacing of 5-10km in the frequency range, 320.0-0.0005 Hz during December, 1995 using the Phoenix V-5 magnetotelluric system. The NS and EW components of the magnetic field variations were measured using induction coil magnetometers whereas the lead-lead chloride electrodes with an interprobe spacing of 80-120 m were used for measuring the electric field components in the NS and EW directions. The data were analysed using a combination of the fast Fourier transforms and cascade decimation techniques as described by Wight et al. (1977) and Bostick and Smith (1979) to obtain the signal amplitudes and the auto and cross power spectra were determined. The apparent resistivities and phases were then computed using the classical techniques described by Vozoff (1972).

RESULTS AND DISCUSSION

Surveys were undertaken on an almost N-S profile between Jind and Bahadurgarh. The response functions (apparent resistivity and phase variations with frequency) at all the stations showed a two dimensional behaviour with the major and minor axis along E-W direction and perpendicular to it respectively, indicating that the source of the observed two-

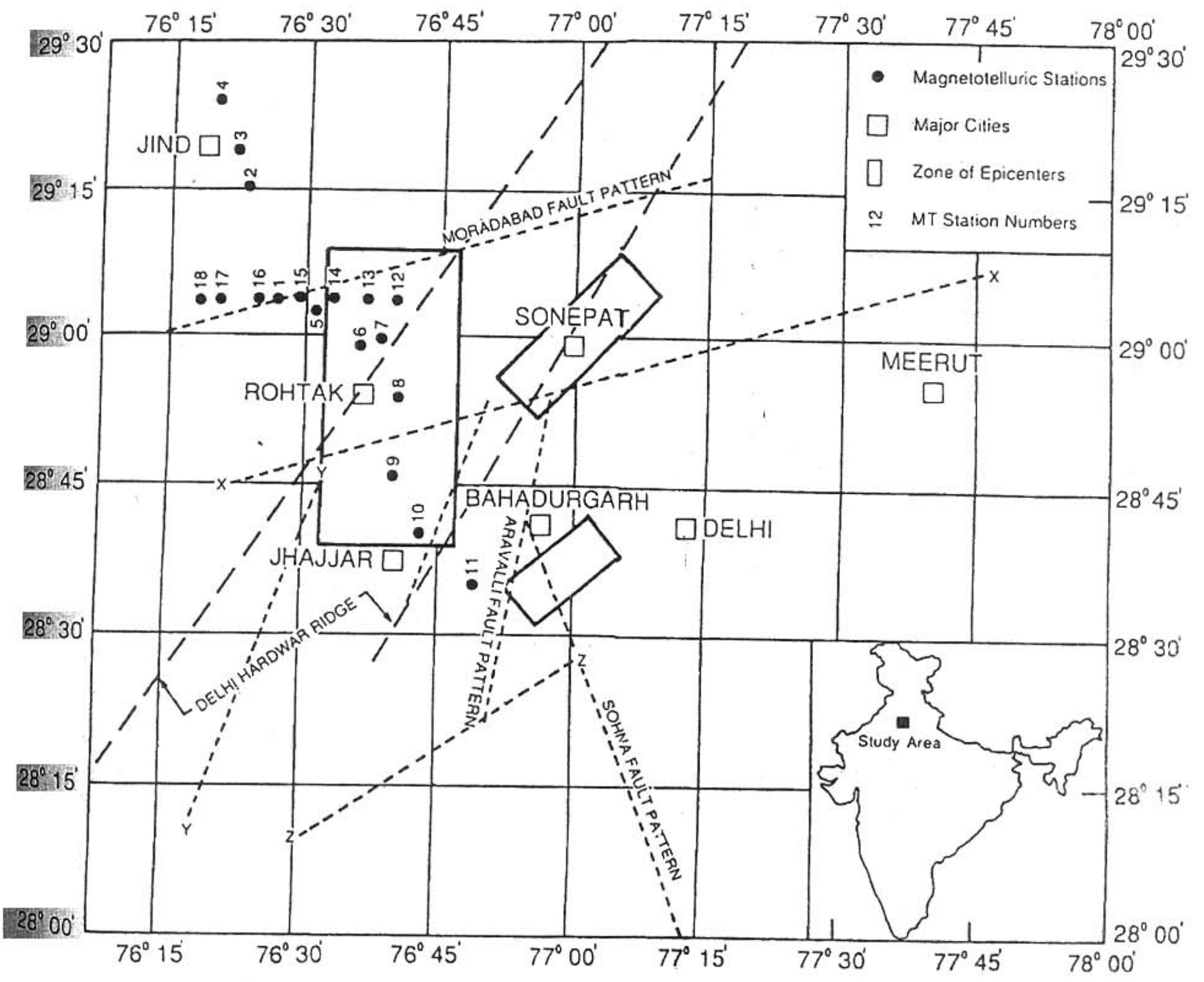

Fig.2. Lineament map of the Delhi and surrounding region showing the regions of epicentral zones and the magnetotelluric stations

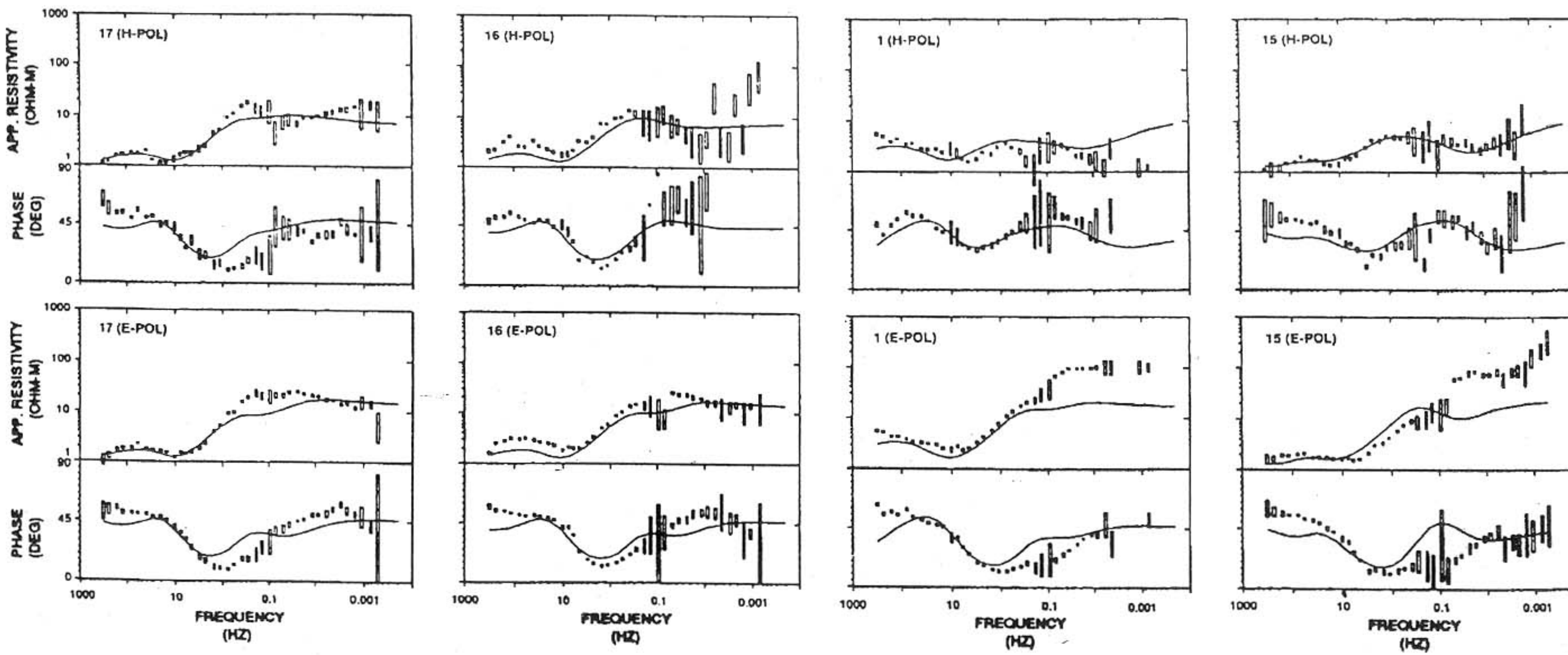

Fig. 3a. Rotated response functions over the E-W profile. The rectangular legends represent the observed apparent resistivity and phase. The height of the rectangles represents the measurement error in the estimates. The solid curves through the observed data points are the responses obtained by forward modelling the proposed geoelectric structure (shown in Fig.5).

dimensionality is either along N-S or E-W direction. However, the observed weak spatial variations along the the NS direction indicated the absence of any major E-W oriented resistive inhomogeniety in the survey region. Thus, the two dimensional effects were attributed to a possible N-S oriented resistivity contrast. In order to confirm this fact and to get a clear picture of the resistive inhomogeniety, an E-W profile (perpendicular to the expected resistive inhomogeniety) was identified for further investigations along the latitude, 29°15', where the dimensionality effects were most prominent.

The response functions at all the stations on the E-W profile indicated major and minor rotations along the E-W and N-S directions respectively. In view of the observed N-S resistive inhomogeniety, the apparent resistivities along this direction were assumed to be the E-polarisation (E-pol) values and those in the E-W direction, the H-polarisation (H-pol) values. The response functions in the E- and H-pol at all stations (except the station 18) on the E-W profile are shown in Fig.3a. and 3b. Here the rectangular legends represent the apparent resistivity and phase and their height indicates the error of measurement. The solid line through the experimental points is the forward modelled response of the proposed 2-D structure to be discussed in a later paragraph. Due to some strong cultural noise at station 18, data at this station were not used for analysis. The spatial variation of the apparent resistivity at 100 and 0.01 Hz. is shown in Fig.4. It is observed here that there is no appreciable spatial variation in the apparent resistivity at 100 Hz. Further, both the E- and H-pol values are similar at this frequency at all stations. At frequency of 0.01 Hz, rather strong spatial variations are observed in both the E- and H- pol resistivities. The apparent resistivity in the E-pol was 15 ohm-m at station 18 on the west and decreased systematically to about 2 ohm-m at the station 1. Further east, this value increased to about 7 ohm-m at the station 12. In the H-pol, the apparent resistivity was about 12 ohm-m at station 18 on the west and systematically increased to about 200 ohm-m at station 1 and further east, it decreased to about 9 ohm-m. The apparent resistivity in the H-pol at this frequency was about 2 orders of magnitude larger than the corresponding E- pol value in the central stations (Station 1 and 15). This difference decreases gradually on either sides of these stations on the E-W profile, indicating that the response functions may be strongly influenced by the presence of a N-S oriented conductive feature located between stations 1 and 15. The apparent resistivities did not show any significant spatial variations at higher frequencies (100 Hz) and also the E- and H-pol values were similar at all the stations at this frequency. It seems that the proposed conductive feature may not be exposed to the surface, but may be submerged below the alluvial cover at the stations 1 and 15. It is also possible that due to the presence of highly conductive alluvial cover, the surface manifestations of this conductive zone may be obscured in the present studies.

The preliminary depth resistivity profiles were obtained by using an Occam's one dimensional inversion scheme. In view of the strong two dimensional influence observed at all stations on the E-W profile, the results of the one dimensional analysis may be misleading to the general readers and hence these results are not shown here. However, the spatial variation of apparent resistivities shown in Fig.4 clearly bring about the extent of the two dimensionality in the region. The geoelectric structure obtained from the one dimensional studies was utilised to construct the starting model which was further refined by using a two dimensional forward modelling scheme based on the finite element technique (Wannamaker et al. 1987) procured from M/s Interpex Ltd. of USA. The shallow and deep geoelectric cross sections are shown in Fig.5a and Fig.5b respectively.

The geoelectric structure shows a five layer sequence overlying the resistive upper crust

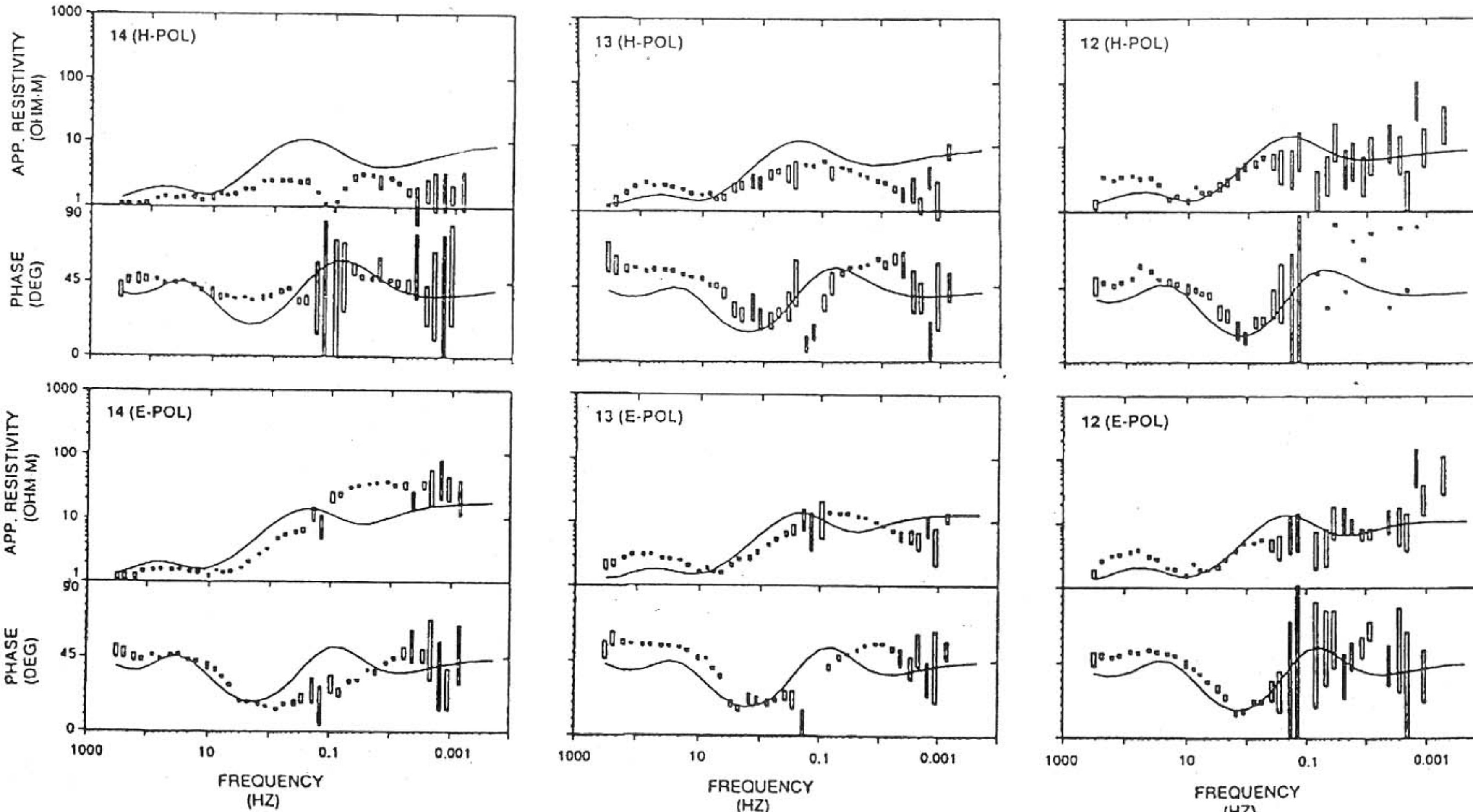

Fig. 3b. Rotated response functions over the E-W profile. The rectangular legends represent the observed apparent resistivity and phase. The height of the rectangles represents the measurement error in the estimates. The solid curves through the observed data points are the responses obtained by forward modelling the proposed geoelectric structure (shown in Fig.5).

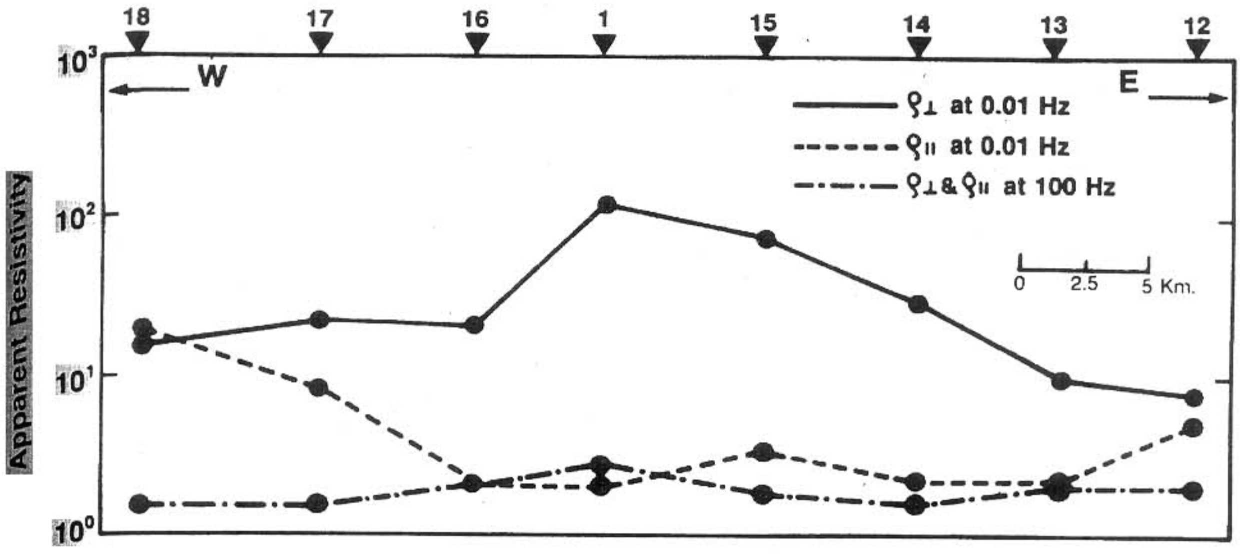

Fig.4. Spatial variation of the apparent resistivity at 100 and 0.01 Hz over the E-W profile.

delineated at depth of about 3.5 km. The top layer of the alluvium was 25-60 m thick and had a resistivity of 1.4 ohm-m, overlying a resistive (30 ohm-m) sedimentary layer with a thickness of 25-50 m. Underlying this, a 150 m thick conductive layer was delineated with a resistivity of 1.2 ohm-m. Both these layers seem to be due to the Siwalik sedimentary sequences. The Upper Siwaliks were deposited in fresh water conditions and are thus more resistive than the underlying Middle Siwaliks which are essentially the brackish water deposits. There was no indication of the Lower Siwalik sequences. These may either be absent or could not be distinguished from the Middle Siwalik sediments. It may be noted here that both Middle and Lower Siwaliks were deposited in the brackish water environment and thus may have similar resistivities. The borehole studies (Ahmed and Alam, 1978) about 200 km NW of our study area have indicated the absence of Lower Siwalik sequences in the Zira borehole which has a basement configuration almost identical to the one expected in the present study region. Below this sequence a resistive layer was observed with a resistivity of 100 ohm-m and a depth extent of 3000m on the western part of the profile. This layer was thicker (4500 m) on the eastern part of the profile. Underlying this was a 500-1500 m thick conductive layer with a resistivity of about 1 ohm-m. There are reports of metamorphic rocks below the Siwalik sediments (Karunakaran and Ranga Rao, 1979) in some parts of the Punjab plains which are separated from the underlying granitic upper crust by an unconformity. In view of this the 100 ohm-m layer was interpreted as the metamorphosed layer overlying a conductive unconformity. The granitic upper crust was delineated at depths of 3500-4500 m.

The thickness of the sedimentary sequences was estimated to be about 200 m which is much lower than the values of 500 m reported from the isopach maps (Verma, 1991) and airborne magnetic surveys (Agocs, 1956) in the region north of the present survey area. However, there are no clear indications of the estimated depth to the basement in the present survey region. Some of the earlier studies (Sastri et al. 1971, Wadia, 1983, Aditya et al. 1976, Verma, 1991) have reported crystalline basement below the Punjab plains. The presence of a conductive layer at depths of 3500-4500 m however indicates that the basement below the sedimentary sequences may not be crystalline. In view of the reports on the possibilities of a metamorphosed basement in some parts of the Punjab plains (Karunakaran and Ranga Rao,

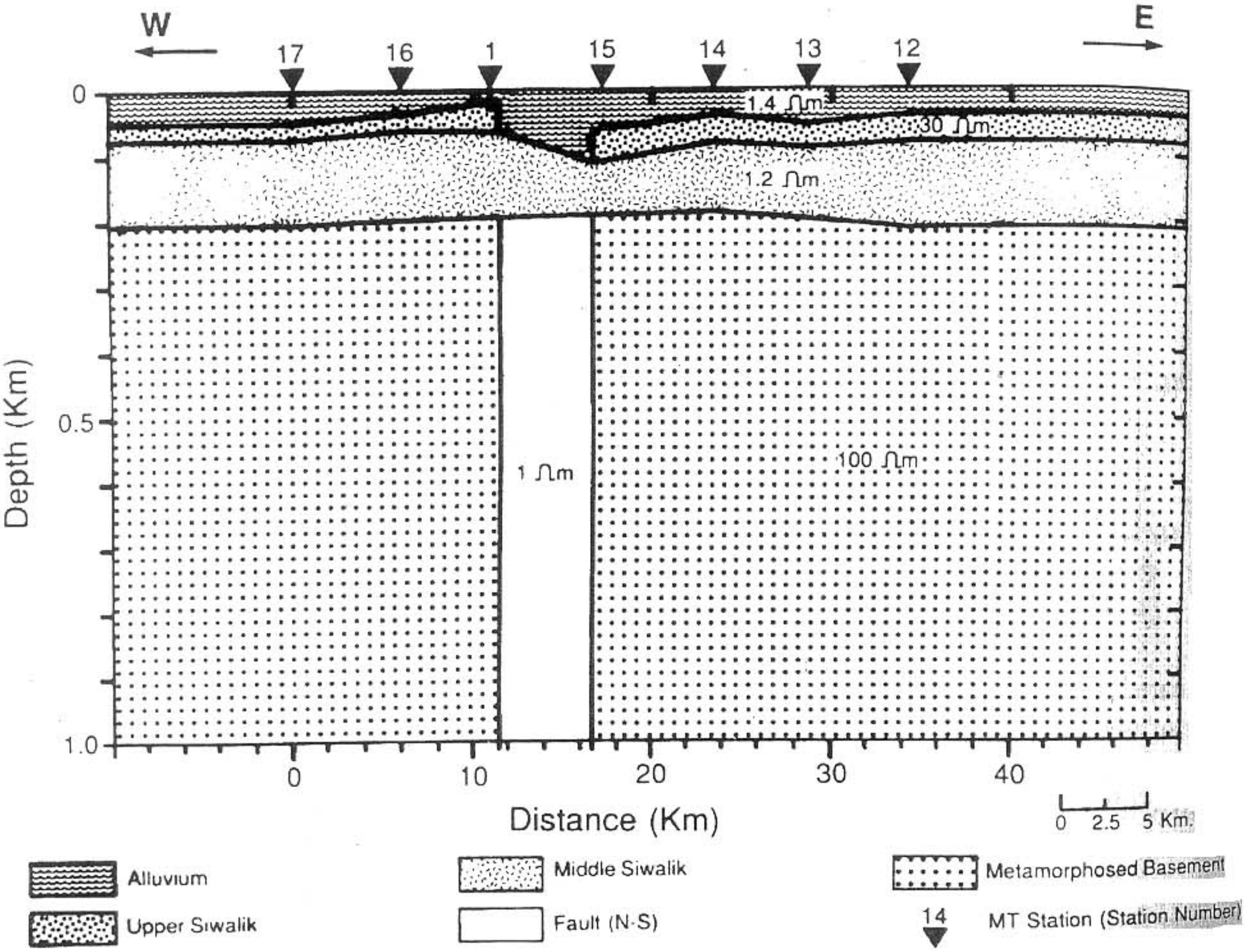

Fig.5a. Two dimensional geoelectric model (Shallow section) proposed from the present magnetotelluric studies.

1979), the present studies expect a metamorphosed basement below the sedimentary sequences which is separated from the crystalline basement by a conductive unconformity at depths of 3000-4500 m.

A high conductivity layer was delineated below the upper crust at depths of 16-18 km corresponding to the normally observed mid-crustal conductor. The conductivity of 10 ohm-m at these depths is somewhat higher than the normally observed value of 30 ohm-m.

The Delhi-Hardwar ridge is a well known feature in the survey region. The response functions showed a weak signature of this feature in the form of a different rotation angle at measurement frequencies in the vicinity of .1 Hz at the stations, 7 (Bamhanwas) and 9 (Barana). However, the electrical manifestations of this ridge were not sufficiently strong for any quantitative interpretation. Further the signatures of the Delhi-Hardwar ridge were overwhelmed by the strong two dimensional effects of the NS oriented conductive body. It may be inferred that the MT survey profile crosses western edge of the Delhi-Hardwar ridge between stations (7) and (9).

Two Dimensionality of the Data

The observed two dimensional effects discussed earlier were related to the presence of a vertical conductive structure delineated below the stations 1 (Lajwana Khurd) and 15 (Mehrara). This feature had a resistivity of 1 ohm-m and extended from shallow depths of less than 25 m to about 18 km. The sensitivity studies of this vertical contrast indicated that this feature may be extending even beyond the

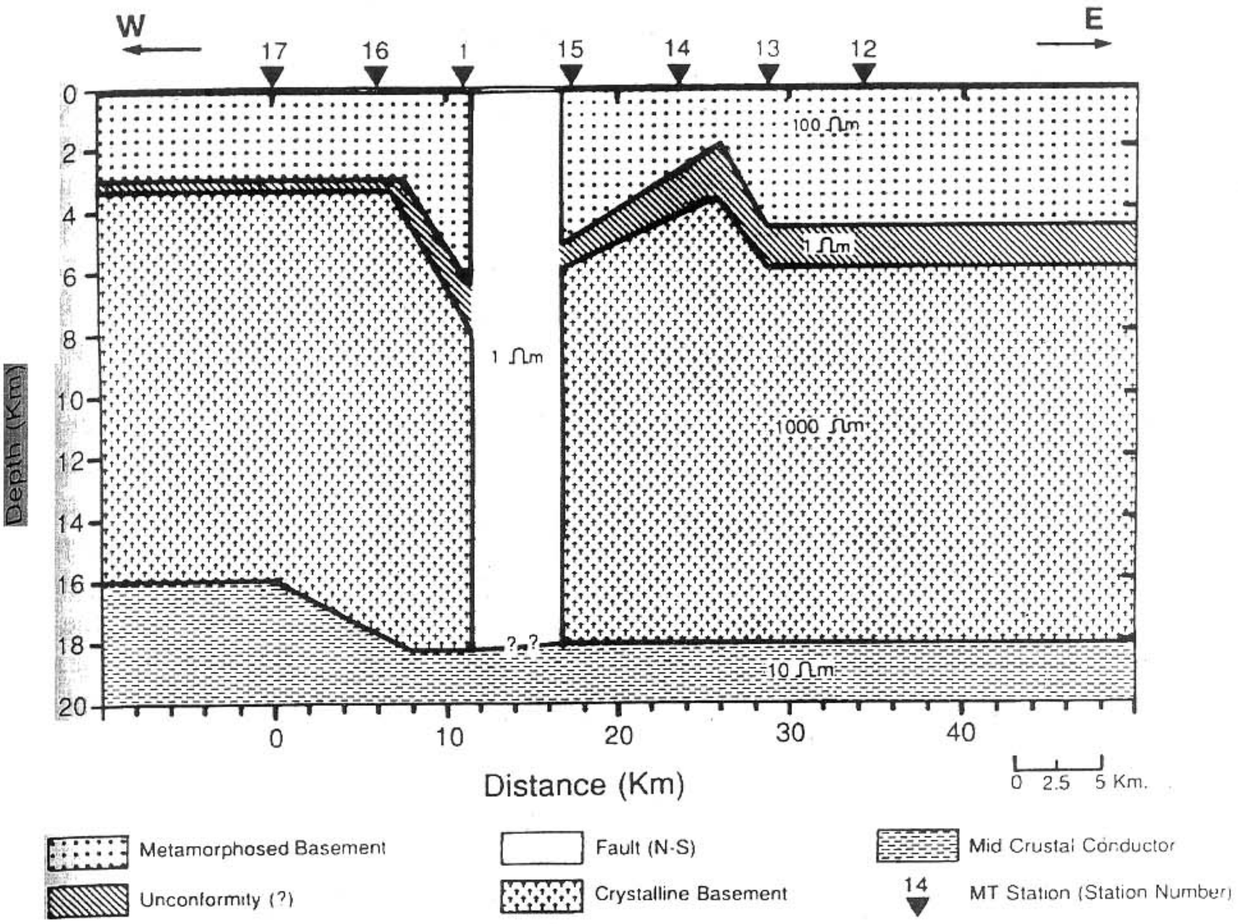

Fig.5b. Two dimensional geoelectric model (Deep section) proposed from the present magnetotelluric studies.

depth of 18 km reported here. This structure with a width of 5 km is aligned almost NS. The apparent resistivities and phases observed at the stations on the NS profile show that the rotation angles at all the stations on the southern part of this profile are influenced by the presence of this conductive feature. However, the rotation angles at the station 4 (near Jind) do not show any such trend. Thus it is felt that the conductive feature may be truncated in the vicinity of Jind or alternatively it may have changed the direction near this station. The southward extension of the conductor could not be exactly estimated. It can however be concluded that this feature extends beyond the southernmost station (station 11, near Bahadurgarh). The microseismicity studies (Kamble and Chaudhury, 1979) have shown that the epicenters in the Rohtak region are located in a 50 x 25 km rectangular block. Further most of the deep seated (5-15 km deep) earthquake foci show an approximately N-S alignment along the conductive feature reported here. The recent work on the seismicity (Verma et al. 1995b) indicates a predominant N-S alignment in the distribution of the earthquake epicenters in Rohtak region. This line is located within a distance of 20 km on the east of the conductive fault observed here. It is thus felt that this fault zone is rather active and may be of significance in understanding the seismicity of this region. Reports exist on the fault zones in the Siwalik and Indo Gangetic Plains which are transverse to the strike of the Himalayan collision zones (Valdiya, 1976).

Possible Limitations of the Present Interpretation

The existence of a N-S aligned vertical conductive structure as discussed earlier was strongly indicated by the magnetotelluric data in this region beyond any traces of doubt. This is evident from the spatial variation of the apparent resistivity shown in Fig.4. However, some comments regarding the possible limitations of this structure are pertinent here as rightly suggested by the referee of this paper. Due to the predominantly two dimensional nature of the problem, the conductive feature was modelled by a two dimensional refinement of the starting model. About 150 variations of the starting model were attempted before arriving at the two dimensional geoelectric structure presented here (Fig.5a and 5b). The misfits between the computed and observed response functions are shown in Table I. A large misfit in the E- pol data is observed at the stations 1 and 15. Further as observed from the Figs. 3a and 3b, the misfit occurs at the frequencies corresponding to the boundary of the metamorphosed and crystalline basements. It is felt that some weak three dimensional effects may have resulted in the observed misfit. This is indicative of a non-uniform topography before the deposition of the Siwalik sedimentary sequences below the stations, 16, 1 and 15 which are in the vicinity of the fault reported here. This may also be indicative of the possible strong tectonic movements during the Eocene era which could lead to strong undulation in the pre-sedimentation topography.

Table I. Misfits between the observed and 2D forward modelled response functions (Apparent resistivity and phase shown in Fig. 3a and 3b)

Station No.	Percent misfit in	
	E-pol	H-pol
12	45.2	49.6
13	50.3	62.3
14	73.7	86.4
15	126.6	27.8
1	105.7	30.8
16	35.6	49.3
17	44.0	41.3

The conductive feature is represented as a 5 km wide vertical zone with a rectangular cross section, extending from near surface to depths of about 18 km. The surface expressions of the fault corresponding to this conductive feature were obscured by the alluvium at the top which has resistivity similar to that of the conductive feature(1 ohm-m). The depth extent was estimated to be 18 km. In the electromagnetic studies, the induced electric currents tend to have a higher concentration in the top part of the conductive body and the current density decreases at deeper parts even when the resistivity of the conductor is same. Thus the signatures of the depth extent of the conductive bodies tend to be weak. In view of this fact, the conductive feature may have depth extent of more than 18 km reported here.

As observed from the Fig.4, the spatial variations of apparent resistivity are not symmetric on either side of the maximum H-pol value (stations 1 and 15). This shows that the causative conductor may not be exactly vertical, but may be having a westward downthrow at deeper strata. However, the deviation from the verticality does not seem to be significant. Different inclinations were attempted to take care of this aspect, but there was no appreciable improvement on general fit.

There is inherent non-uniqueness associated with the electromagnetic techniques in estimating the exact shape and size of the conductive bodies. The conductive feature was represented by a 5 km wide and 18 km deep rectangle with a resistivity of 1 ohm-m. It is possible to obtain the same results by varying the width and resistivity of the feature, keeping the areal conductance (cross sectional area times the conductivity) constant. Thus for example, a 2.5 km wide and 18 km deep body with a resistivity of 0.5 ohm-m may lead to responses similar to those observed here. Thus possibility exists that the conductive feature is narrower than the distance between the stations 1 and 15. The conductivity of 1 ohm-m was selected on the basis of the preliminary interpretation which indicate that the conductivity of this feature is possibly due to the presence of mineralised water in the fractures in the region of the fault. Experience suggests that such geological features usually have a resistivity of not less than 1 ohm-m.

The conductive feature was modelled as a vertical body with a rectangular cross section which may not be the case. Any deviations from the verticality and the rectangular shapes assumed in the modelling may also lead to some three dimensional contributions to the magnetotelluric response functions. The misfits at the stations (1) and (15) (Table I) discussed earlier may be indicative of this fact.

Within the constraints imposed by the above limitations, which are inherent to the electromagnetic techniques, the proposed structure is not significantly different from the "true geoelectric model" of this region.

CONCLUSIONS

Magnetotelluric studies in the Rohtak region have delineated a N-S aligned conductive feature along the longitude, 76°30', extending in depth from 25 m to more than 18 km. This feature is atleast about 100 km long and has a width of about 5000 m in the EW direction. The granitic upper crust was delineated at a depth of 3500-4500 m underlying about 25 m thick alluvials, 175 m thick Siwalik sediments and a 3 km thick layer of metamorphic rocks. An unconformity was observed between the metamorphosed rocks and the granitic upper crust.

ACKNOWLEDGEMENT

The authors thank the Department of Science and Technology (DST), Govt. of India for the financial support. The keen interest shown by Dr. R.K. Midha, Joint Advisor, DST, is gratefully acknowledged. Thanks are also due to Prof. R.K. Verma, University of Delhi, Dr. V.P. Kamble, India Meteorological Department, Govt. of India and Prof. D.R.K. Rao, Indian Institute of Geomagnetism for their encouragement. The excellent co-operation of Mr. C. Selvaraj and V.R. Balasubramaniam in the field work is gratefully acknowledged. Thanks are also due to Mr. B.I. Panchal for drafting and photography of the diagrams.

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(Received;25 June 1996; Revised form accepted: 17 March 1997)