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Magnetotelluric Techniques

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Abstract: Over the past three decades, magnetotelluric techniques (MT) have proved useful in studying the depth and lateral variation of the electric resistivity in the earth's crust and mantle. The physical principles underlying these techniques and the strong and weak points associated with them are discussed. Shallow inhomogenieties have been found to distort the MT data at all frequencies, thus leading to erroneous interpretations, which need to be corrected. The normally used methods of correction of the effects of near surface inhomogenieties are also discussed here. Some case studies from the Indian region are included. In the Satpura range, two distinct sets of Basaltic flows have been delineated. The top 12 flows are conductive, presumably due to the sporadic weathering observed in them. The lower 15 flows are devoid of any such weathering effects and thus are manifested as a high resistivity layer. A deep crustal intrusive has been delineated under the anomalous crust of Satpura. In the Deoli-Jhalawar region, a deep rooted fault was delineated near Kota, burried under about 2 km thick Vindhyan sediments, extending from this depth to almost the lower crustal depths of 18 km. The SE inclination of this fault is in good agreement with the similar throws of the other features in this Precambrian shield. The magnetotelluric studies in the Damoh-Mandla region could delineate the lower crustal intrusive rising SE from below Jabalpur into the upper crust leading to the Tikar gravity high. The Rohtak region west of Delhi is covered by about 500 m thick alluvial and Tertiary cover. The substructure here could be investigated using the MT studies and a deep rooted NS aligned fault zone could also be delineated below this sedimentary cover.

INTRODUCTION

The information on the deep geoelectric structure of the earth is of paramount importance in understanding the various crustal evolutionary processes as well as in the commercial exploitation of geological resources such as petroleum, minerals, etc. The tectonic details are also important for the planners and developers in deciding the locations of the major dams, bridges, nuclear projects, sewerage disposal sites, etc. The surface geological studies, being based on the direct observations give reliable and accurate description of the shallow strata from which the crustal evolutionary processes are conjectured. The absence of the structural information on the deeper formations, however, is invariably a handicap in these interpretations.

There are various tools available for the investigation of the earth's interior such as the gravity and magnetic studies, seismic and deep seismic sounding studies, surface heat flow studies, electromagnetic induction studies, etc. All these techniques are termed *"indirect"* or *"interpretational"* techniques because they rely on one or the other physical property of the rocks in the earth's interior which is interpreted to obtain the possible layering of the deeper strata. Thus, gravity studies are dependent on the variation of the density of the sub-structural formations whereas the magnetic studies are based on the variations in the residual magnetic moment of the rocks. The seismic and DSS techniques depend on the variation in the velocity of the mechanical wave and the reflections at the boundaries of heterogeneous densities. The heat flow studies are based on the thermal conductivity distribution of the rocks as well as the state of the thermogenic bodies in the deep interior. The electromagnetic (EM) methods are based on the electrical properties of the rock formations in the deep interior. The magnetotelluric (MT) technique, which is the topic of discussion, is one of the electromagnetic exploration tools.

THEORETICAL BASIS OF THE NATURAL SOURCE EM TECHNIQUES

The electromagnetic studies consist of measuring the electrical and magnetic field components on the surface of the earth, be it natural or artificially generated. These measurements are used for obtaining the information on the lateral and vertical resistivity variations in the earth's interior. In the natural source EM techniques, the earth's electromagnetic field is used as the source field, whereas in the artificial source EM techniques, the electromagnetic field is generated using either an electric current dipole or a large magnetic field loop which are the source of the EM field. The theoretical treatment of the problem in the two approaches is different because in the natural source EM studies, the source can be assumed (within reasonable limits of error) as infinite in extent and located at infinity, whereas in the artificial source EM studies, this assumption does not hold good. In the following pages, natural source EM techniques are discussed.

The earth's EM field induces electric currents in the crust, the mantle and the core with a variable distribution. The current density distribution is governed by various factors, the important among them being the electrical resistivity distribution and the effective skin depth for the frequency of the EM wave under consideration. These currents develop electrical voltages on the surface of the earth. The EM techniques essentially use the magnetic and the electric field components on the surface of the earth to determine the details of the sub-structure.

The earth's magnetic field has a small varying component (about 1 % of the total field). These variations are a result of various atmospheric, solar and cosmic phenomena. At high frequencies (>1 Hz.), the lightening activity, which occurs in some part of the globe for atleast 250 days in a year, makes major contribution whereas in the mid-frequency ranges (1 - 0.001 Hz) a major contribution comes from the micropulsation activity, magnetic storms as well as the polar sub-storms. In the low frequency range (<0.001 Hz) the diurnal variations, the lunar variations, etc., contribute to the EM spectrum of the earth.

The theoretical treatment in both cases is based on the assumption of a plane EM wave incident on the surface of a horizontally layered earth's surface, which diffuses downwards. In reality the EM waves, which are generated in the earth's atmosphere, reach the surface of the earth from all possible directions. However, the above assumption is still valid because the air has a very high electrical resistivity, well in excess of giga ohm-m which is very large compared to the resistivities of the solid earth and are less than 100 k ohm-m. Thus, the EM waves get refracted at the surface of the earth and diffuse in the direction normal to the surface of the earth. Further, the earth is not always horizontally startified as assumed. Generally, there are some vertical resistive contrasts. One of the commonly encountered vertical contrasts is in the coastal regions, where the highly conductive sea water (.25-.5 ohm-m) is contrasted against the more resistive continental land-mass, thus affecting the electric current distribution in the coastal regions (known as the coast effect in EM studies). Although this violates the assumption of a stratified earth, the theoretical treatment based on the above assumptions forms a good starting point.

There are two major variants of EM techniques used in the geoexploration: (i) the magnetovariational (MV) methods, where the three magnetic field components are measured and (ii) the magnetotelluric (MT) studies, wherein the two horizontal components of the electric field are also used.

The MV techniques measure the three components of the magnetic field variations along the magnetic NS, EW and the vertical (denoted as Hx, Hy and Hz, respectively). As discussed earlier, the EM field on the surface of the earth is essentially horizontal (the vertical

EM components are zero). However, in the presence of any conductive zones in the sub-structure, strong electric currents are induced in this zone, which lead to the secondary magnetic field surrounding the conductive body. Being localised in nature, these magnetic fields lead to a non-zero vertical component. Thus, from the simultaleous measurements of the horizontal and vertical magnetic field variations over a linear or rectangular array of stations, the location and approximate depths of these conductive bodies can be determined from the MV studies.

In the magnetotelluric studies, the horizontal electric field (along magnetic NS and EW denoted as Ex and Ey, respectively) is measured in addition to the three magnetic components (Hx, Hy and Hz). It should be noted here that the measurements of the electric and magnetic field variations are time synchronised. In the case of a horizontally layered earth, devoid of any vertical inhomogenieties, the electric current is induced in a direction perpendicular to the inducing magnetic field, i.e, Ex is caused by Hy and Ey by Hx. With this information, impedance tensor (Z) is computed. The mathematical formulations of the problem is detailed in Vozoff (1972) and Kaufman and Keller (1981). Impedance tensor is a 2 X 2 matrix and is related to the EM components through the relation,

$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} Zxx & Zxy \\ Zyx & Zyy \end{bmatrix} \begin{bmatrix} Hx \\ Hy \end{bmatrix}$$

Where the tensor element, $Zxy = Ex / Hy$. Similar relations are used to compute the other elements of the impedance tensor. In general, $Zab=Ea/Hb$ where, $a,b = x, y$

Impedance tensor is the central parameter around which the magnetotelluric interpretations revolve and has all the sub-structural information which is obtained from the MT technique. The apparent resistivities are then determined from the known values of Z using the relation:

$$\rho_a^{(xy)} = 0.2\,T\,|Z_{xy}|^2 \text{ , and}$$

$$\rho\,(a)\,yx = 0.2\,T\,|Zyx|^2$$

where $\rho_a^{(xy)}$ and ρ (a) yx are the apparent resistivities in the NS and EW directions respectively.

The adjective "apparent" is used because the measured quantity is not the true resistivity but is some sort of integrated resistivity of the crust as apparent from the surface of the earth up to a depth, which is determined from the effective skin depth. The depth control also comes through the skin effect considerations, wherein the high frequencies penetrate only the shallow strata and as the frequency is decreased, the depth of penetration increases. The depth of penetration is also controlled by the sub-surface resistivity and at a fixed frequency, it varies from place to place. In the regions of conductive sedimentary covers, longer periods are required for significant depths, whereas in the older exposed basement rocks, which normally have very high resistivities, large depths can be penetrated using not so low frequencies. It is generally difficult, if not impossible, to quote the depth to which one can obtain the information. However, with a frequency band of 100 -0.0001 Hz, normally known as the conventional MT wide band, the crust and a part of the upper mantle can be generally studied in most of the regions on the surface of the earth. Most of the lateral inhomogenieties of interest to the geoscientists in the earth's interior are located in the crust and thus this frequency range suffices for most of the MT studies. In recent times, need is felt for lower frequency studies especially in the regions in Himalayas and the Tibetian plateau, where the crustal thickness may be in excess of 70 km and thus the conventional band quoted above may not be adequate for probing the crustal depths. Similar need is felt in the exploration of the Indo-Gangetic plains, where the thick high conductive alluvials and the Tertiaries limit the depth of penetration in the conventional frequency band to less than 30 km.

As discussed earlier, the earth is assumed to be horizontally layered which is seldom the case. Apart from the coast effect mentioned earlier, there are many faults cris-crossing the continental regions. Due to the presence of mineralised water in the fractures associated with these faults, conductive structures appear in many parts of the continents. Some of the lineaments may also have markedly different resistivities on either side of them, as in the case of the Narmada-Son lineament, which separates the conductive Vindhyan sediments on the north from the predominently resistive granitic material on the south, or the great boundary fault of Rajasthan, separating the Vindhyans on the SE from the Aravallis on the NW (Details of these examples form part of the case studies to follow). In all these cases the assumptions of horizontally layered earth are violated and thus the geoelectric structure becomes two or three dimensional.

In the magnetotelluric studies, the above dimensionality problems are identified from the Z-matrix. When the geoelectric structure is one dimensional, the elements in the principal diagonal, Zxx and Zyy are both zero and the off diagonal elements, Zxy = -Zyx. This is evident from the fact that in such cases Ex is controlled by Hy completely and is independant of Hx. Thus, ratio of Ex and Hx is zero. Again by the cylindrical symmetry of the problem, Zxy and Zyx are equal in magnitude. The sign difference exists because the basic problem has a cylindrical symmetry and is being treated in the Cartesian co-ordinates.

When the sub-structure is two dimensional, Ex depends on both Hx as well as Hy and thus Zxx and Zyy are in general non zero. However, if the axes of the two dimensionality and measurements coincide, the dependance of Ex on Hx will reduce to zero. In other words, in the case of two dimensional earth, it is still possible to rotate the impedance tensor in the spatial co ordinates so as to reduce Zxx and Zyy to zero. However, the Zxy and Zyx are not equal any more because the resistivities "seen" by the currents parallel and perpendicular to the strike are not the same. The geoelectric strike is either parallel or perpendicular to the rotation angle. This can be uniquely fixed from the studies of the vertical magnetic field. Some times, the general trends of the various surface geology results are also useful in identifying the direction of the geoelectric strike.

When the resistivity distribution is more complex and varies in all the directions as in the case of a magma plug or other intrusive structures, (three dimensional earth), it may not be possible to identify a spatial rotation angle along which Zxx and Zyy become zero. One important derivative of the impedance matrix, which is often used for the determination of dimensionality, is skew of impedence (S),

$$S = |Zxx + Zyy| / |Zxy - Zyx|$$

Skew is a rotationally invariant parameter and is zero in the one and two dimensional cases. In the three dimensional cases, this is not zero. The importance of the skew comes from the fact that since this is rotationally invariant, the dimensionality of the geoelectric structure can be gauged even without rotating the impedance tensor.

Once the dimensionality information is obtained, the apparent resistivity and phase curves are rotated parallel and perpendicular to the geoelectric strike. The apparent resistivites and phases parallel to the geoelectric strike are known as the E-polarisation values and those perpendicular to the strike, the H-polarisation values. These curves are then checked to provisionally identify the possible number of layers as well as the possible locations of the conductive / resistive vertical contrasts. An experienced interpreter then has a reasonably good idea about the possible geoelectric structure of the region. He knows whether the structure is in one of the above catagories, or "some where in between", e.g., is it a weakly two dimensional or strongly two dimensional with weak three dimensional effects, etc. In any case it is a good idea to obtain the preliminary one dimensional models which are useful in formulating a starting model for the further modelling / inversion. The suitable one or two dimensional inversion schemes are then used and the final geoelectric structure is then derived with the help of computer programs. The three dimensional inversion schemes are available at present but are normally not very commonly used because of the inherent nonuniqueness associated with the inversion problem, which becomes serious with the increase in dimensionality. Also, these are expensive in terms of computer resources as well as time. The geoelectric structure thus obtained is then correlated with the available geological and geophysical data from other techniques - normally, the surface geology and tectonics, gravity magnetic DSS and heat flow studies. The discrepancies (if any) between the results of the various techniques pose a difficult and interesting challenge for the interpreter. As mentioned earlier, the various techniques are based on the study of different physical property of the earth's crust such as, the density, porosity, fluid inclusions, seismic velocity, etc. Also, different techniques have their own strong and weak points as well as non-uniqueness of the results to varying extent. Thus, a combined interpretation of the results of different techniques helps to reduce the degree of nonuniqueness and thus evolving a geophysical model which is closer to the true structure.

Over the past decade, the experimental as well as some of the theoretical modelling studies on the MT response functions brought about some interesting features of the MT studies. It was established that the near surface inhomogenieties, which are commonly encountered on the surface of the earth, have strong influence on the Z matrix to the extent of entirely changing the geoelectric models even at deeper strata. It was also noted that the presence of these distortions do not in any way obliterate the information on the deeper structures and the data can still be interpreted after the effects of the distortions caused by the near-surface inhomogenieties are removed. Thus, the importance of identifying and correcting the effects of these near-surface distortions was realised.

The earth's exposed crust is subject to various weathering and sedimentation processes which alter the surface selectively. The geologists thus commonly observe that there are patches of red laterite soil in a black cotton soil terrane or vice versa, and various hard rock exposures in sedimentary basins, etc. From the MT point of view, these manifest themselves as localised conductive patches on an otherwise resistive crust or vice versa. These surface inhomogenieties strongly distort the Z matrix at all the periods of measurements, leading to erroneous estimates of the geoelectric structure. These inhomogenieties, being shallow (very very thin compared to the effective skin depth at the the highest frequency of measurement) contribute in terms of a scalar multiplier to the elements of the Z matrix and thus in the measured quantity Z has the form:-

$$\begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} = \begin{bmatrix} C_1 & C_2 \\ C_3 & C_4 \end{bmatrix} \begin{bmatrix} Z'_{xx} & Z'_{xy} \\ Z'_{yx} & Z'_{yy} \end{bmatrix}$$

$$\text{or} \quad \mathbf{Z = C * Z'}$$

where C is the matrix of real numbers without any significant imagimary component resulting from the effects of the surface inhomogenieties (Unity matrix if no shallow inhomogenieties) and Z' is the undistorted impedance matrix.

In order to remove the contribution from C, the impedance tensor is decomposed using modified Pauli spin matrices and the twist and skew are removed and thus the undistorted Z' is obtained in the form, g Z', where g is known as the site gain or more commonly as the static shift factor. The theoretical treatment of the tensor decomposition procedure was developed by Groom and Bailey (1989). There are no analytical methods to rid the impedance tensor of the static shift factor. However, some practical techniques are employed for this purpose.

There are many empirical methods employed to correct for the static shift, such as the key layer approach, spatial filtering, global curve matching, etc. In the key layer approach, (suggested by Jones,1988) the depth to one of the resistive interphases is assumed to be known from some other technique, (e.g, well logging) at one of the points on the survey profile. The model parameters are constrained using this information and the regional structure is obtained. Normally, the depth to the bottom of resistive layers is a good constraining parameter, because it is well resolved parameter in the MT studies. Normally, the bottom of the conductive layers is not accurately resolved. This approach is possible only when the well-log data are available in the vicinity of the survey profile. In the spatial filtering approach, the surface inhomogenieties are assumed to be randomly distributed and thus the static shifts also are expected to be random. Thus, the apparent resistivities in the high frequency end of the available spectrum at all the stations are spatially filtered to remove the short wavelength spatial features. The correction factors obtained at high frequencies are then applied to the entire frequency band and the corrected data are interpreted. The global curve approach is based on the fact that all the MT sounding curves in the horizontally layered (isotropic) crustal regions, when extended to very long periods (> 10000 s), the apparent resistivities at any place on the globe have similar values. (e.g, at 10000 s, a = 100 +/- 10 ohm-m, Rokityanski, 1982). This is because the resistivities of the mantle and core are devoid of any major lateral resistive inhomogenieties and are reasonably homogeneous world over. The apparent resistivity curves are thus shifted such that the low frequency asymptote passes through this point.

All the techniques used for static shift correction are empirical in nature and the data set has to be properly understood before deciding on the method to be used. In this way, the global technique can spell a disaster in the regions with strong two or three dimensionality. The spatial filtering techniques may be dangerous if the assumption on the random distribution of static shift fails. The success of the key layer method depends upon the confidence limits on the values of the key layer. The well logged data is essentially a "spot value" of the depth and may not be representative of the "spatially averaged" value, which is sensed by MT techniques. A proper consideration of these factors while correcting for the static shift help in quantitatively correcting the static shift effectively and also in coming out with a judicious geoelectric structure.

ADVANTAGES AND LIMITATIONS OF MT TECHNIQUES

All the interpretational tools of exploration are invariably nonunique in one form or the other. The deep structure obtained from any particular technique is, therefore, the model of the earth as "seen" by the particular property under consideration and some degree of nonuniqueness is normally associated with such techniques. It is, therfore, essential for any interpreter to understand the strong and weak regimes of each of these techniques so as to obtain a model which is as close to the real earth as possible.The magnetotelluric technique has its own strong and weak points which should be remembered at the interpretation stage.

The magnetotelluric technique is a fast inexpesive method of exploration for obtaining the sub structural resistivity. The response functions essentially sense the vertical conductance (thickness conductivity product, S) in the true sense. Thus, even the thin high conductivity layers are more clearly "seen" in the response functions because of their higher conductance. The resistive layers are easily screened, unless they are thick enough to have a sufficiently high conductance. Conductive sedimentary layers below the basaltic layers can easily be delineated but in places such as the Indo-Gangetic plain or the Cambay basin, where there is a thick sedimentary overburden, the inlying resistive layers may go undetected.

Normally, the bottom of resistive layers and conductance of conductive layers are the well determined parameters in the magnetotelluric responses and are constrained better in the final interpretation. However, the thickness of conductive layers or their individual resistivities may not be accurate. Similarly, the resistivity of the resistive layers is an insensitive parameter. In some cases MT can play a leading role in deciding the sub-surface structural features, whereas in some other cases, MT technique may effectively complement the results obtained from the other techniques. The depth of exploration can range up to about 150 km. However, the MT results normally do not delineate the Moho discontinuity, which is an important parameter in the deep seismic sounding techniques. This transition does not seem to be associated with any significant change in the electrical resistivity, and hence is not delineated from the MT studies.

With all the limitations discussed above, the MT technique provides good support for enhancing our understanding of the crustal evolutionary processes as will be evident from the case studies below.

CASE STUDIES

Satpura Range

Satpura range is the horst block flanked by the Tapti-Purna graben on the south and the Narmada graben on the north and extends almost about 300 km in the EW direction. The Bouguer free air and isostatic anomalies are positive over this region as against the expected negative values for the horst structures. The deep seismic soundings indicate a crustal thickening under the Satpura horst block, which again contradicts the observed positive anomaly observed in the gravity studies. In order to explain these contradictory observations, Verma (1985) proposed a possibility of higher density rocks below the Satpura horst block on the grounds that the crust in this region has different evolutionary history from the crust in the surrounding region.

Magnetotelluric studies were undertaken along a 100 km long profile between Torni and Purnad with an interstation spacing of 3 - 10 km. Five component MT data were collected in the frequency range, 100-0.01 Hz. The locations of the MT stations over this profile are shown in Fig.1. along with the major tectonic features. The entire survey profile is located over the Deccan trap region. The response functions generally showed a two dimensional behaviour with a regional strike direction along N 60° W direction, which shows good correspondence with the regional strike of the Narmada and Tapti lineament. Some of the stations showed static shift which was corrected by the key parameter technique discussed earlier.

The geoelectric structure (Fig.2.) shows a 100-150 m thick conductive (40 ohm-m) layer overlying a more resistive (150 ohm-m) second layer, which is about 2000 m thick in the central part of the profile (between SUK and BAS) and decreases on either side of the profile to about 300 m on the north and about 1000 m on the south. Both these layers seem to be the Deccan basalts, which differ from each other in the physical and chemical nature. The studies of the basaltic outcrops in the Mandaleshwar-Pipaljopa region about 50 km west of this area have identified 28 flows of Deccan basalts of which the 12 flows on the top with a total thickness of 100 m show sporadic weathering. This weathering is absent in the lower flows (Sreenivas Rao et.al,1985). Pal and Bheemashankaram (1976) have delineated 27 flows at Asirgarh (the station, ASR in the figure). However, there are no reports on the composition or the physical state of these flows. In view of these reports, it seems reasonable to assume two different types of basalts. The top basaltic layer is conductive presumably because of the sporadic weathering, which leads to increased electrical conductivity due to the presence of mineralised water.

Below the Deccan basalts a conductive layer (200 ohm-m) was delineated with thickness varying between 200 and 2000 m, which is due to the Gondwana sediments. The granitic upper crust had a resistivity of 300 ohm-m and thickness ranging between 10 and 12 km. The strong variations in the thickness of the second (basalts) and third (Gondwana) layers possibly reflects on the long history of the tectonic

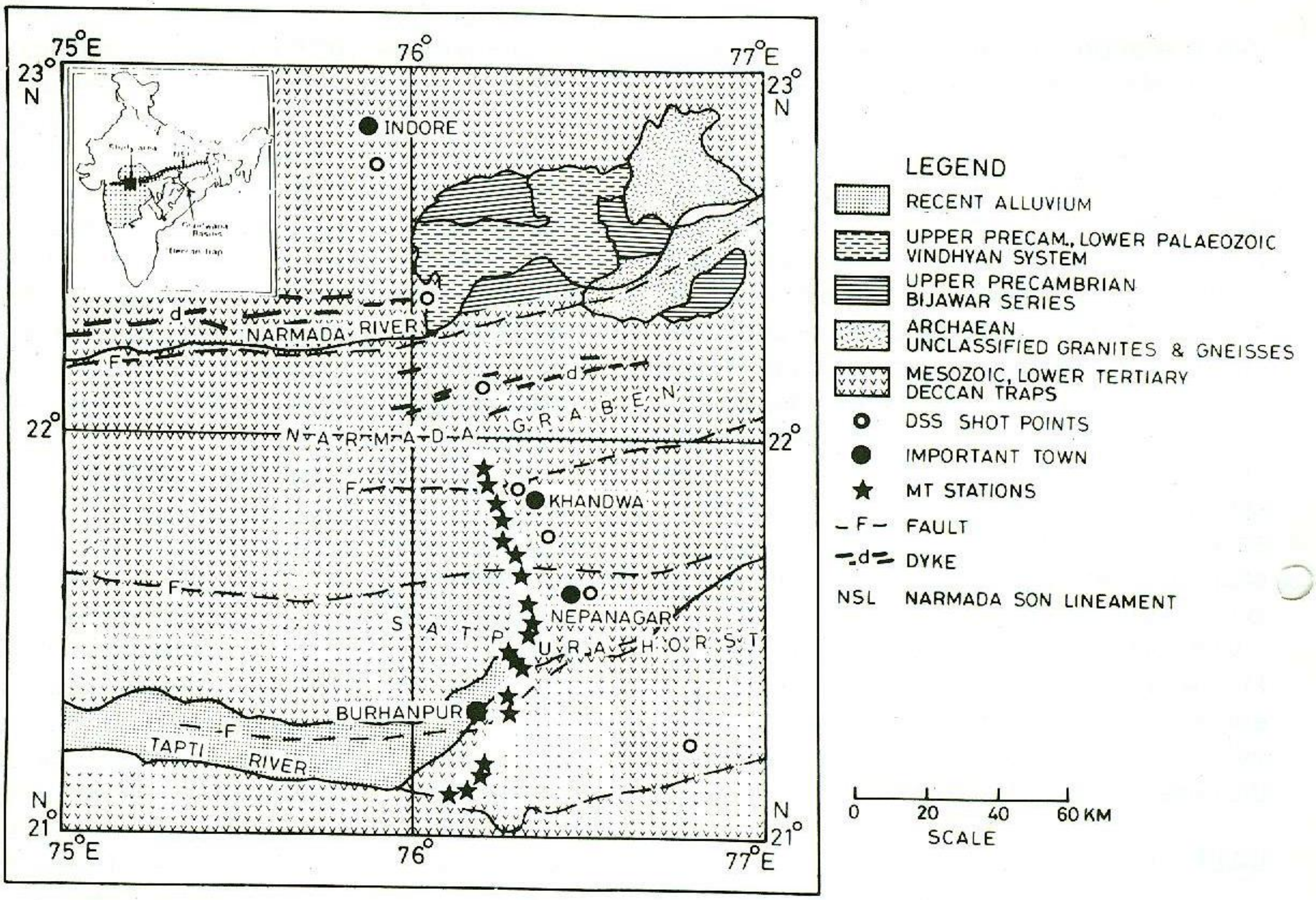

Fig.1. Geological map of the Satpura horst region showing the locations of MT stations.

movements in this region. The top basaltic layer is reasonably uniform.

Two vertical resistivity contrasts were delineated, one below the stations CHE and MOK (coinciding with the Khandwa lineament) and second near BAS and ZAI (coinciding with the Burhanpur tear). As discussed earlier in the section, advantages and limitations of the MT technique, these two conductive zones are associated with a good degree of nonuniqueness and thus it may not be appropriate to draw conclusions on the electrical nature of these lineaments based on the present studies alone. However, the high conductivity zones at these stations is clearly indicated in the MT data and the nonuniqueness is regarding the shape of the conductive features.

A prism shaped conductive feature, having a resistivity of 20 ohm-m, was delineated below the stations RUS and DAH. The top of this body was 8 km wide extending between ASR and DAH and is located at depths of 3.5 km from the surface. At its base, 14 km below the surface, this conductive feature is about 40 km wide. This feature seems to be composed of two conductive zones rising from the lower crustal depths converging towards each other at shallow depths and is associated with a high heat flow in the range, 100-180 mW/sq.m, (Ravishankar, 1988). However, there are no detailed heat flow studies in this region. This feature is also associated with a negative Bouguer anomaly as shown in the Fig.2 and may be a lower crustal low density magmatic intrusive.The results are discussed in more detail in Rao et.al, (1995).

Deoli-Jhalawar Profile

This work is a part of our studies in the

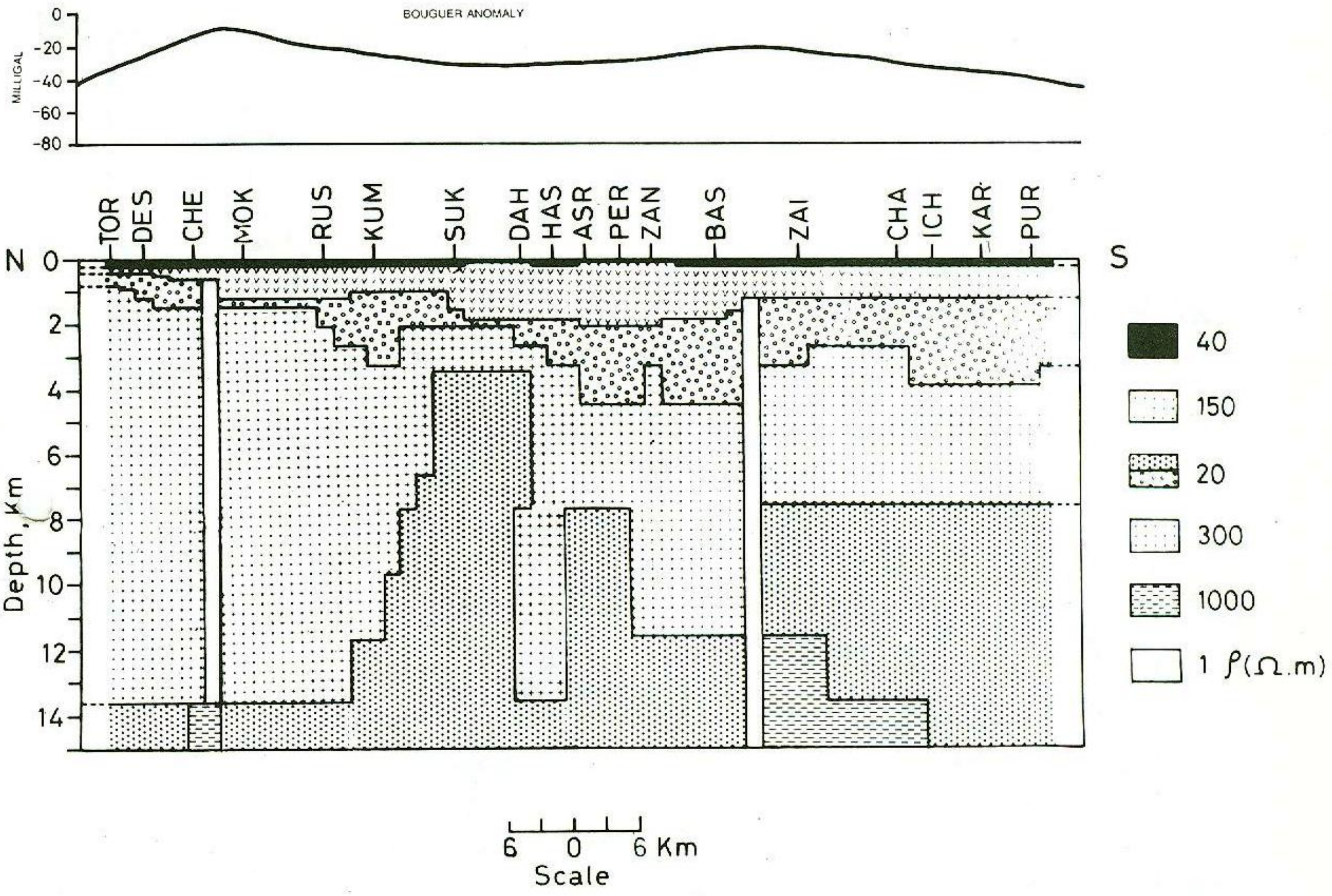

Fig.2. Geoelectric structure in Satpura region.

Nagaur-Jhalawar corridor and was carried out under the financial support from Department of Science and Technology, Govt. of India. The geological map of this region is shown in Fig.3 along with the location map of the stations occupied for the magnetotelluric data collection. The surface geology of this region shows the deep crustal exposures of the banded gneissic complexes, also known as the Sandmata-Mangalwar complexes near Deoli and Tikar, separated from the Vindhyan sediments on the SE by the great boundary fault (GBF). Immediately NW of the GBF, the Hindoli volcanosedimnetary formations are present with embedded exposures of the Jahazpur granites. This region has been explored by the other geophysical studies, such as gravity, magnetic as well as the deep reflection profiling studies (Results presented in the first three papers in this volume).

Broad band magnetotelluric studies were conducted in this region covering a frequency range of 320 - 0.0005 Hz. Four component (Hx, Hy, Ex and Ey) MT measurements were carried out at 19 stations on this 200 km long linear profile with an interstation spacing of 10-12 km. The data showed a fair amount of two dimensionality with the major axis along the NW-SE direction at all stations on the NW of the GBF, whereas on the SE, the two dimensional effects were some what weaker (due to the higher sub-structural conductivity in this region). The data were interpreted using a two dimensional modelling technique, wherein the initial model obtained from the one dimensional inversion by plotting together the

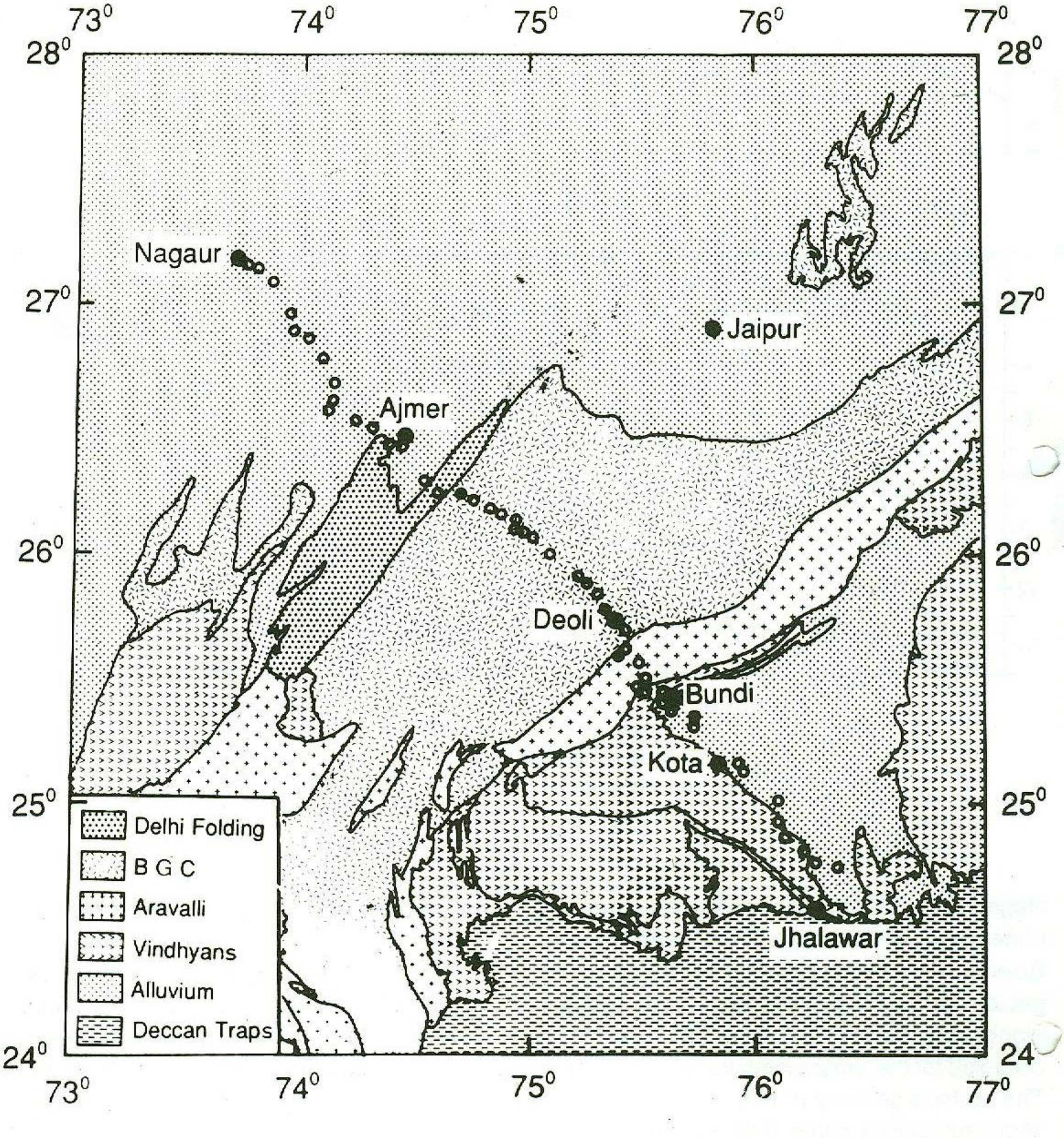

Fig.3. Location map of the Nagaur-Jhalawar MT profile. The results over the Deoli-Jhalawar region are discussed in the text.

depth sections at the individual stations, was refined further using a finite element two dimensional modelling program. About 150 variations of the initial model were necessary to arrive at a reasonably good geoelectric model presented in Fig.4.

The geoelectric model indicates a resistive crust on the NW of the GBF with a 50- 100 m thick relatively conductive layer (100 ohm-m, not seen clearly in the figure) overlying a 20 km thick block with a resistivity of 2000 ohm-m. corresponding to the Sandmata Mangalwar complexes. A 1 km thick deep crustal conductor was delineated at depths of 20 km and had a resistivity of 50 ohm-m. The lower crust and upper mantle had a resistivity of 500 ohm-m. In

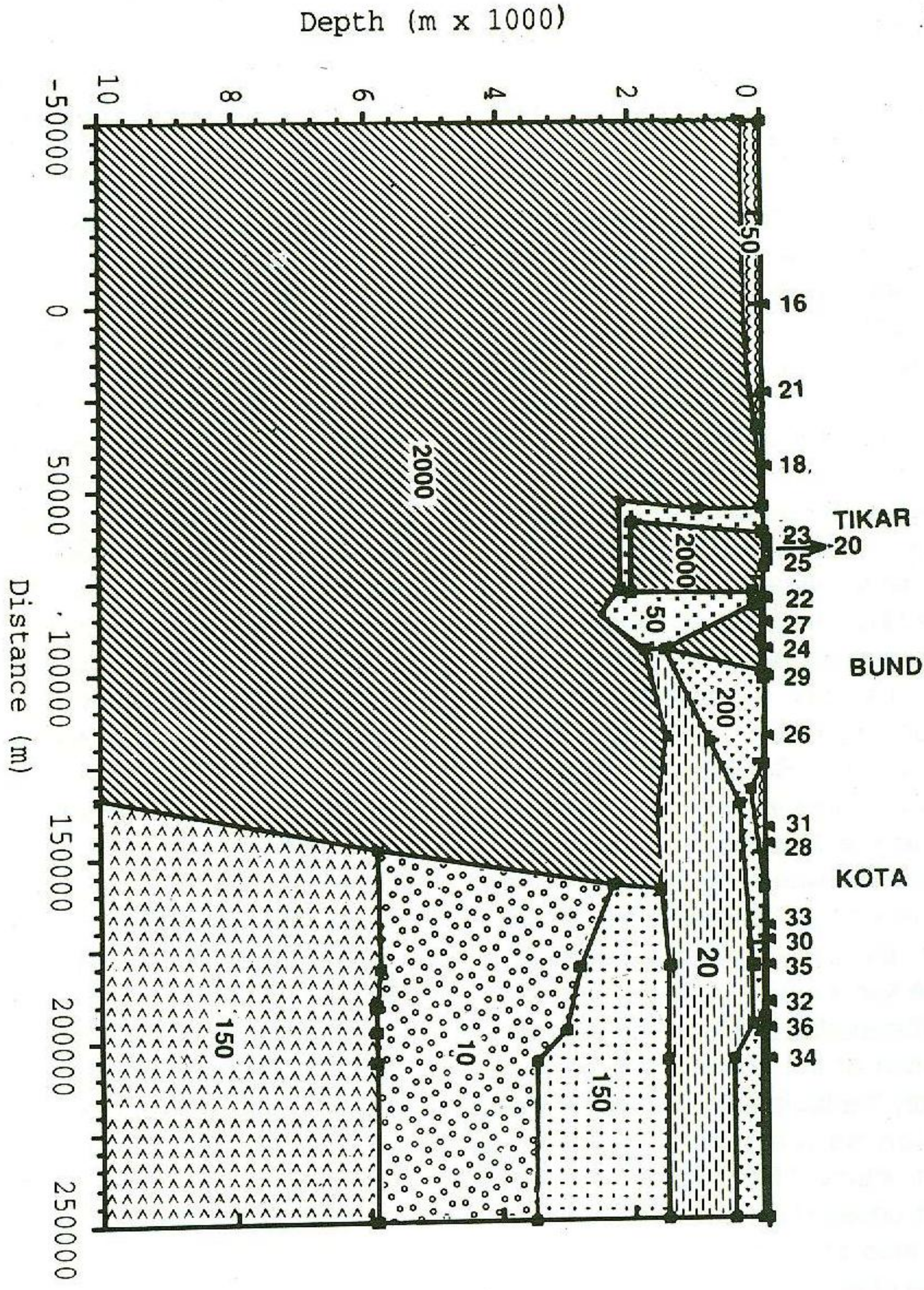

Fig.4. Geoelectric structure in the Deoli- Jhalawar region.

the vicinity of the GBF between Tikar and Bundi, a conductive block extending in depths to about 1 km was delineated between Bundi and Tikar embedding a resistive block of Jahazpur granites. A major dislocation zone is reported along the Banas river (Banas dislocation zone) near Tikar in Fig.4. The signatures of this dislocation zone are not clear in the MT studies. Perhaps, there are no conductivity changes associated with this zone.

The 800 km long GBF is a well established feature on the geological map separating the

Vindhyan sequences on the SE from the Aravalli formations on the NW in the region of interest and passes through Bundi. The magnetotelluric studies confirm the presence of such a divide but the conductivity changes associated with this deep fault zone are not obvious. In the SE of the GBF between Bundi and Kota, the Upper and Lower Vindhyan sequences were delineated with a total thickness of about 2 km, which increases to about 2.5 km on the NW near the GBF. On the SE of Kota, the thickness of the Vindhyans increased abruptly to about 3 km and the upper crust was anomalously conductive with a resistivity of about 150 ohm-m. Another conductive layer (10 ohm-m) was delineated below the Vindhyans in this region. The geological nature of this conductive layer could not be ascertained at present. The deep crustal conductor was present in this region also but was more conductive than on the NW.

A deep seated fault zone was delineated below the Vindhyan sequences at depths of 2 km near Kota. This seems to be a major SE inclined fault zone extending through the upper crustal depths to about 18 km. Between this fault and the GBF, the Vindhyans are directly deposited over the Sandmata-Mangalwar complexes. Further, a prominent upwelling is observed in the lower crust which is at 18 km near the deeper part of this fault, as against the estimated depth of 20 km in the surrounding region. The deep reflection profiling studies in this region suffered heavy absorption of the seismic energy and could not identify this fault region. However, the weak reflection patterns do show some indication of structural differences on the NW and SE of the proposed fault zone. The residual gravity maps also provide some supporting evidence to this effect.

Damoh-Jabalpur-Mandla Profile

The geological map of the study area is shown in Fig.5. along with the stations occupied for the collection of the magnetotelluric data. The Damoh-Jabalpur-Mandla profile passes through the Vindhyan sequences on the NW between Damoh and Katangi. On the SE, recent alluvials are encountered overlying the Jabalpur horst block between Katangi and Jabalpur. Further SE, the profile passes through the Deccan volcanic formations. On the SE of Mandla, the granites are exposed. The gravity studies indicate a positive Bouguer anomaly of about 40 mGal between Jabalpur and Mandla. This region is also characterised by a high heat flow of about 130 mW/sq.m. (Ravishankar, 1988).

The magnetotelluric studies were conducted at 20 stations on this NW-SE aligned linear profile with an interstation spacing of about 10 km. Here also, the four component data were collected in the frequency range, 320-0.0005 Hz. The MT data analysis indicates a two dimensional behaviour at all the stations. Thus, a preliminary geoelectric cross section was formulated using the one dimensional inversion method which was further refined using two dimensional finite element program. The geoelectric structure is shown in Fig.6.

In the segment between Damoh and Katangi, the Vindhyan sediments had a total thickness of about 4 km, with the 700 m thick Upper Vindhyans with resistivity of 100 ohm-m, overlying the Lower Vindhyans (80 ohm-m.). A thin unconformity was delineated separating the Upper and Lower Vindhyan sequences. The region of unconformity had a resistivity of about 10 ohm-m. The entire sequence of the Vindhyan sediments was underlain by a 1000 m thick conductive layer which was attributed to the Bijawar sediments, deposited in the Vindhyan basin before the Vindhyan sedimentation commenced. The upper crust beneath had a resistivity of 2000 ohm-m and extended up to depths of 15 km, overlying the lower crust. The deep crustal conductor was not delineated in this region.

On the SE, the Jabalpur horst block was delineated and which is separated from the Vindhyans by a vertical conductive zone coinciding with the Katangi fault. The Jabalpur block had a resistivity of 700 ohm-m. Further SE, about 30 m thick layer of Deccan volcanics was observed, extending up to Mandla, overlying

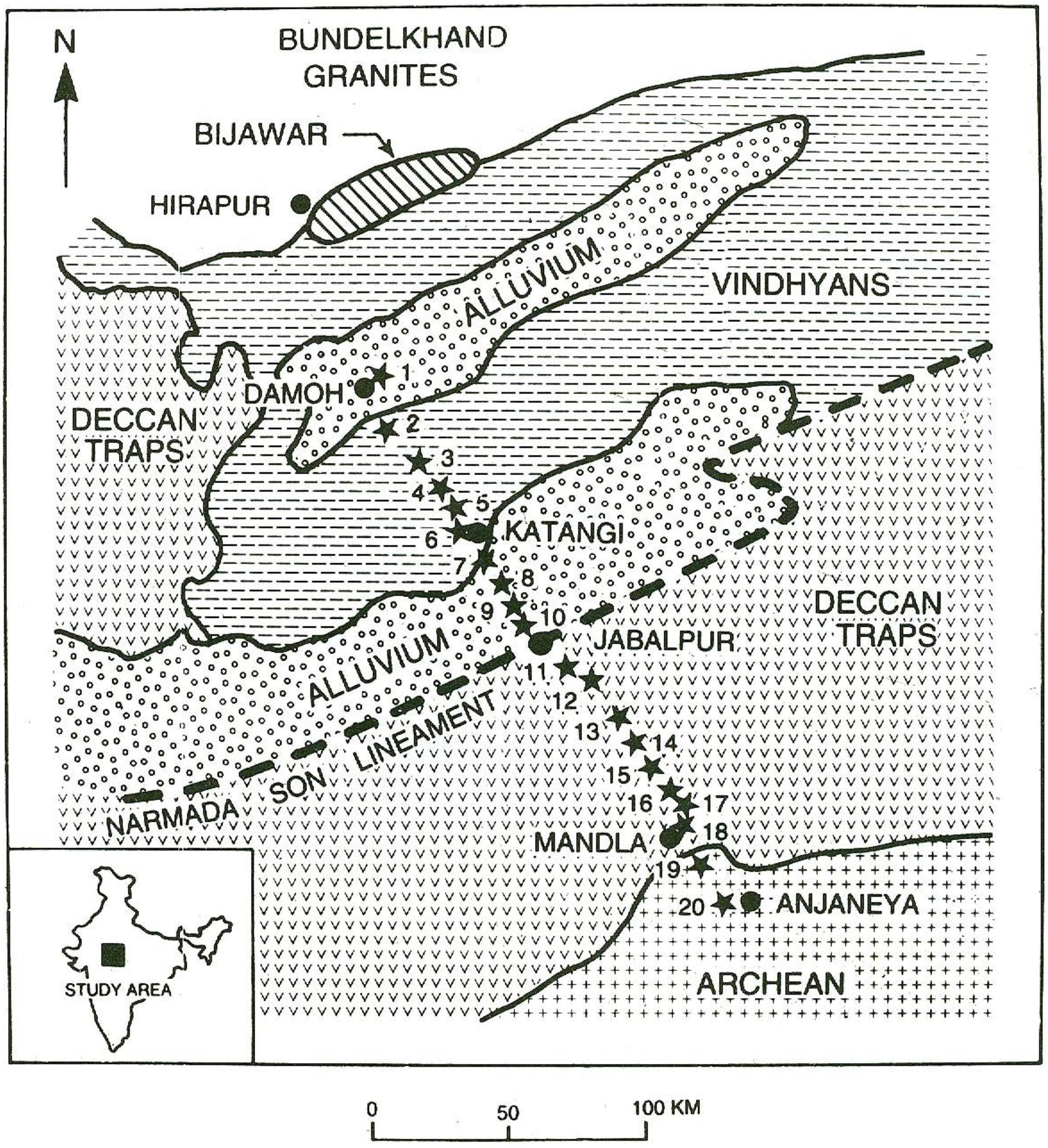

Fig.5. Geological map of the Damoh-Jabalpur-Mandla region. The star symbols denote the magnetotelluric stations.

a thin conductive layer of 10 ohm-m which was assumed to be due to the possible presence of the Gondwana sediments. The upper crust below is about 16 km thick and has a resistivity of 2000 ohm-m. separated from the lower crust by a deep crustal conductor.

The MT results indicate a basaltic intrusive rising from below Jabalpur in the SE direction. This intrusive seems to be rising from the lower crustal depths (15 km) and consolidated between stations 13-14 in Fig.5. The presence of this resistive intrusive is also characterised

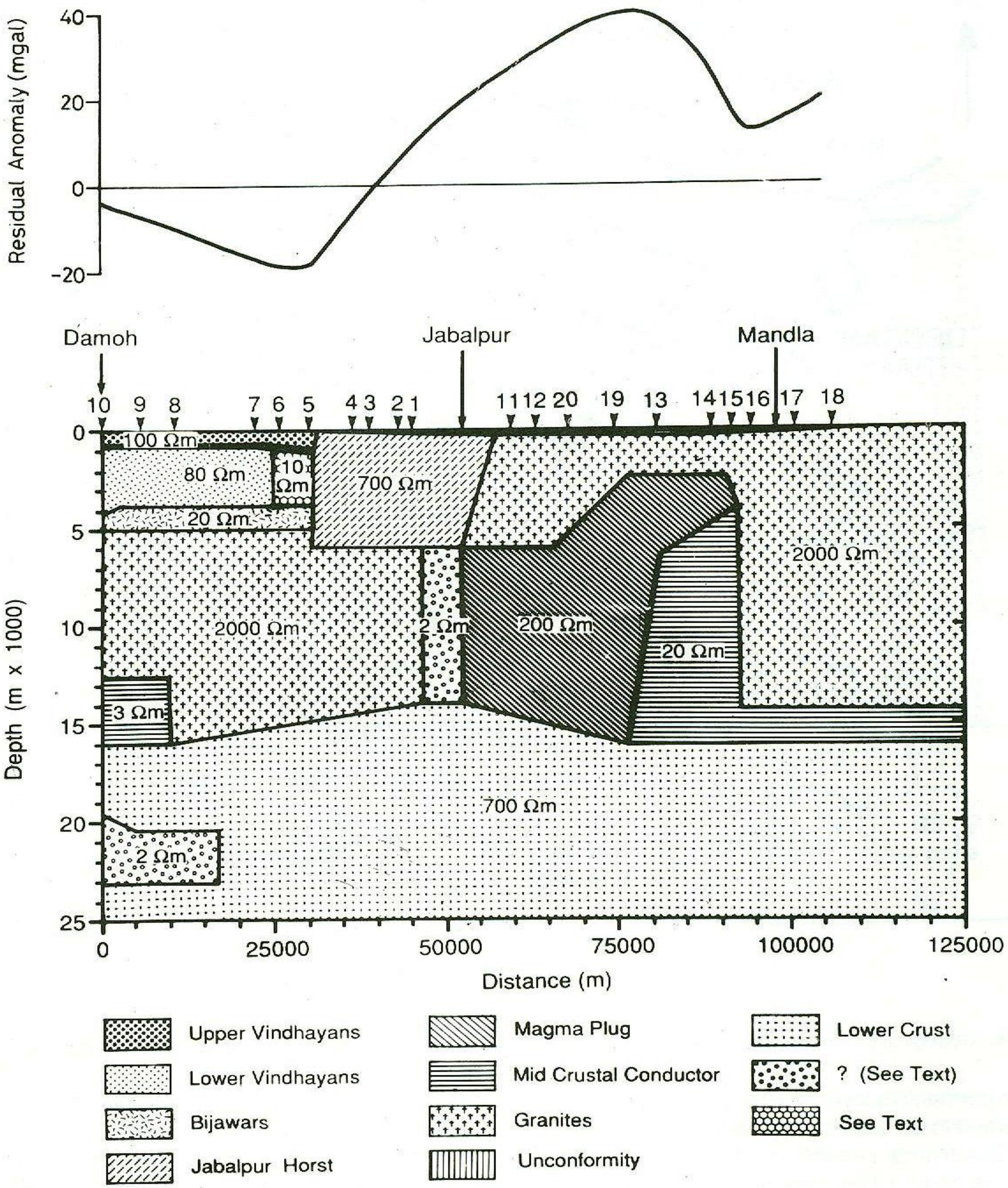

Fig.6. Geoelectric structure in the Damoh-Mandla region.

by a gravity high of about 40 mGal and the heat flow studies also indicate higher heat flow in this region (130 mW/sq.m). These facts support the intrusive hypothesis, because such intrusives from deep below have a high density thus leading to positive anomalies and since they have risen from the high temperature domains, lead to local heat flow highs.

The proposed intrusive has a resistivity of 200 ohm-m in a granitic upper crust having a resistivity of 2000 ohm-m. Thus, a resistive contrast of only one order of magnitude exists between the intrusive body and the surroundings. Such weak contrasts are normally difficult to delineate in the MT studies. However, the intrusive reported here seems to have a conductive sheath covering from all sides, presumably due to the presence of fluids evolved in the process of its rising to lower temperature regime in the Upper crust. These fluids might have remained trapped in the region surrounding the intrusive. Although the counductive cover over this intrusive could not be completely incorporated in the two dimensional modelling, its existence is clear in the MT response functions.

Seismically Active Regions of Rohtak

Over the past 30 years, the Delhi and its surrounding regions were rocked by many low intensity earthquakes. This region has a history of seismic activity as is evident from the 1720 earthquake of magnitude 6.5 near Delhi and the 1803 earthquake of Mathura with a similar magnitude. Thus, the outburst of the weak activity during 1963 in this region was taken serious note of and the India Meteorological Department set up a chain of microseismic stations. In the following ten years, about 1000 shocks were recorded with magnitudes of 2-5 on the Richter scale (Kamble and Choudhury, 1979). The epicenters of the earthquakes could be broadly grouped in to three clusters, the first on the west of Delhi, in the Rohtak- Jhajjar region, the second SW of Delhi in Bahadurgarh region and the third, on the NE, near Sonepat. The epicentral cluster around Rohtak and Jhajjar seemed to be the most active in terms of the density of seismic shocks as well as the number of the large magnitude seismic events. Most of the epicenters in this region are located in a 50-25 km rectangular block as shown in Fig.7.

A large number of faults are documented in the crust below Delhi and its surroundings, the major ones being, the Delhi Hardwar ridge, Moradabad fault, Dataganj-Tilhar fault, etc (Fig.7). Most of the faults identified so far are along the NNE-SSW orientation, perpendicular to the strike of the Himalayan collision zone. Valdiya (1976) has reported a possibility of many more faults aligned in the NS direction in this region. The entire region is covered by a thick pile of the alluvials and Tertiary sediments and thus it is difficult to delineate the faults by the geological methods. The geophysical studies are, therefore, necessary for a better understanding of the tectonic processes. The region has been explored using the gravity and aeromagnetic studies and need for more geophysical exploration is felt for a better understanding of the sub-surface tectonics.

In order to study the epicentral block in the Rohtak-Jhajjar area, magnetotelluric studies were planned to cover an approximately N-S, Jind-Sohna profile. However, the in-field analysis of the data collected at 11 stations between Jind and Bahadurgarh indicated a possible N-S oriented conductivity contrast (discussed in detail in the next paragraph). Hence it was decided to change the profile and thus further data were collected over an EW profile along the latitude, 29° 05'. The data were collected at seven stations on this profile.

The MT studies on the N-S profile showed a strong influence of a conductivity contrast below the entire profile with a strike direction along the N-S or E-W. However, the spatial resistivity variations along the N-S profile showed the absence of any E-W contrasts. Hence, it was assumed that the strike of the conductivity contrast may be N-S. In order to verify this fact

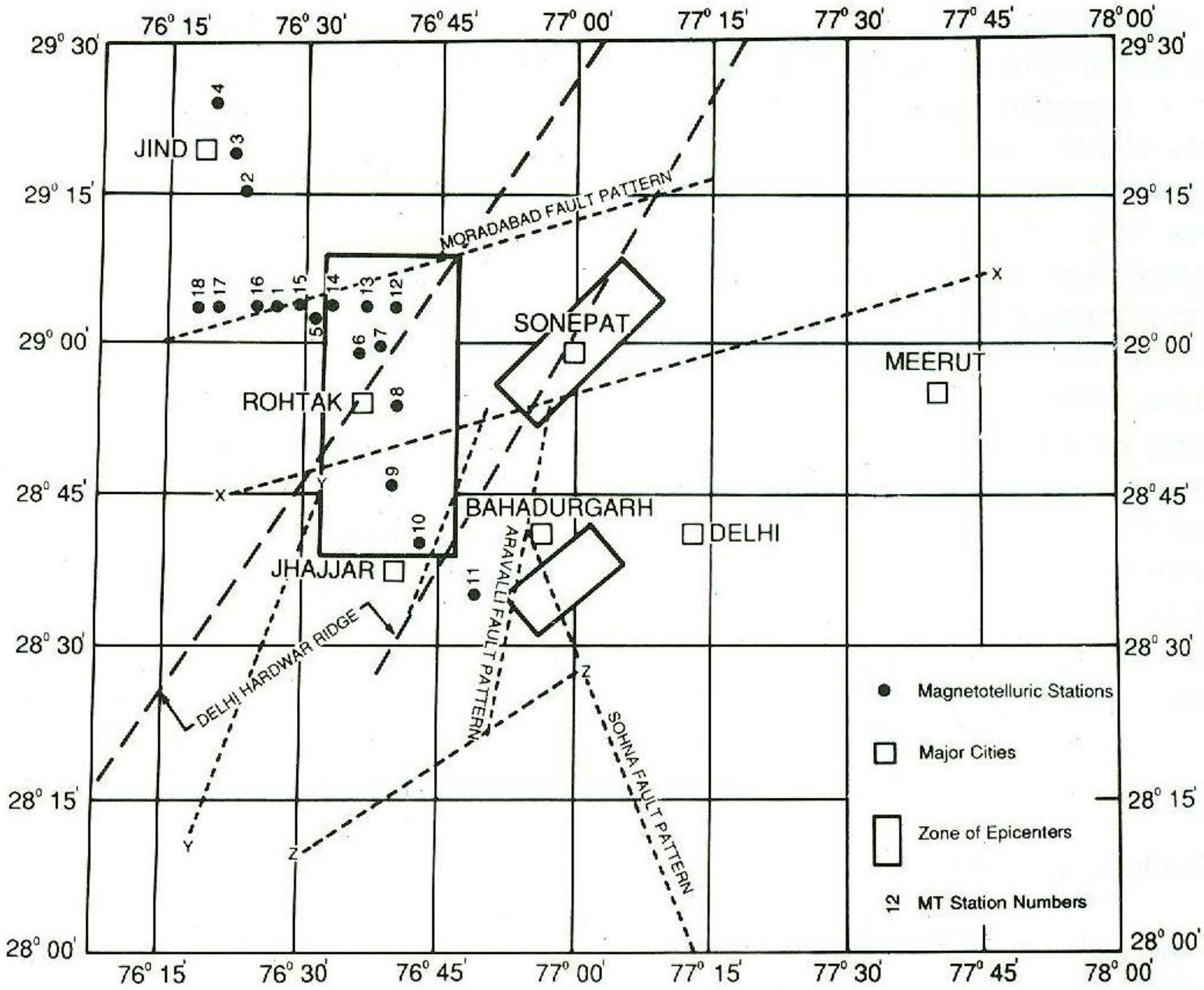

Fig.7. Location map of the Rohtak region. The rectangular blocks are the regions of the epicentral clusters (after Kamble and Choudhury,1979). The solid circles are MT stations

as well as to get more information on the nature of this contrast, an E-W profile was chosen. Seven stations were surveyed over this profile approximately along the 29 degree latitude. The spatial variation of resistivity is shown in Fig.8. at frequencies of 100 and 0.01 Hz. It is observed here that the apparent resistivity at low frequency (0.01 Hz.) in the E-polarisation (electric field measured parallel to the strike) show high values of 15 and 7 ohm-m at stations 18 and 12 respectively on either extremes of the profile with a low of 1-2 ohm-m at the central stations (1 and 15), whereas at the same frequency, the H-polarisation resistivity shows low values of 12 and 9 ohm-m on the extremes with a high of 150-200 ohm-m at the central stations. This behaviour clearly indicates the presence of a high conductive vertical feature located between the central stations (1 and 15). At high frequencies, the apparent resistivities were similar in both the polarisations and did not show any significant spatial variations. The apparent resistivities were inverted at all the stations on the EW profile using the Occam

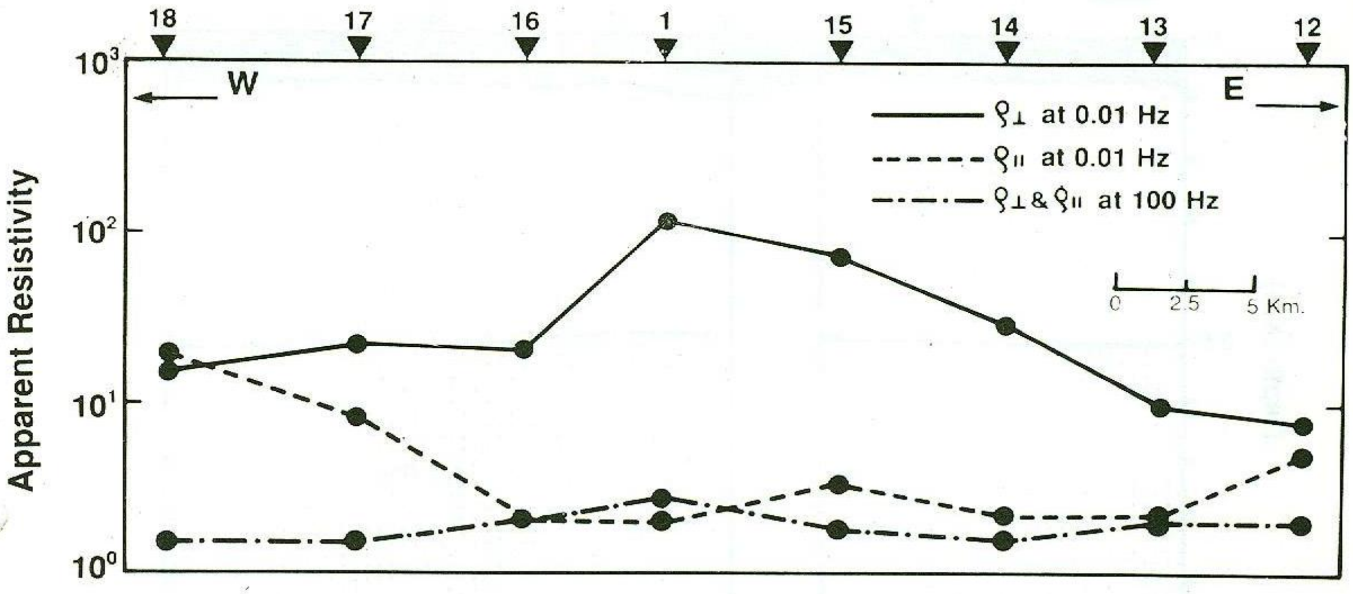

Fig.8. Spatial variation of the apparent resistivity along the EW profile in the Rohtak region.

inversion program and a preliminary one dimensional geoelectric model was formulated. In view of the strong two dimensional influences on the model, which may be confusing to the general readers, this model is not shown here. However, this was used for constructing the initial model for a two dimensional modelling program based on the finite element method. After about 150 variations of the starting model, the two dimensional geoelectric structure is shown in Fig.9. (shallow structure) and 10 (deep structure).

As discussed in the section on Advantages and Limitations of MT techniques, the magnetotelluric technique essentially senses the conductance of the sub-structural layers and not the individual thicknesses and conductivities. Some times constraints have to be imposed on the individual thicknesses to obtain realistic geoelectric models. The results of the two dimensional modelling were published earlier (Gupta, et.al., 1997). Some discrepancies over the thickness of the sedimentary column (third layer, with resistivity 4.8 ohm-m) between the MT results (Saini and Gupta, 1998) and the well logged results (Thussu,1995) have been pointed out. On the basis of these observations, the geoelectric model presented here was constrained using the observed well logged results so as to maintain the thickness of the sedimentary cover at 500 m. This, however, in no way affects the depths to the bottom of the next (resistive) layer because this is a well determined MT parameter.

The geoelectric structure shows a five layer sequence overlying the resistive upper crust.delineated at depths of about 3.5 km. The top layer of alluvium is 25-60 m and has a resistivity of 1.4 ohm-m overlying a 150 m thick resistive (30 ohm-m) layer. Below this a 350 m thick conductive layer with a resistivity of 3.6 ohm-m. All these layers seem to be due to Varanasi older alluvium calcretised to varying extent, thus leading to different resistivities. Below these sediments a resistive layer (100 ohm-m) is delineated extending up to depths of 3500-4500 m, overlying a thin conductive layer. This sequence is understood as due to the metamorphosed basement overlying the crystalline basement separated by an unconformity. The crystalline basement has a

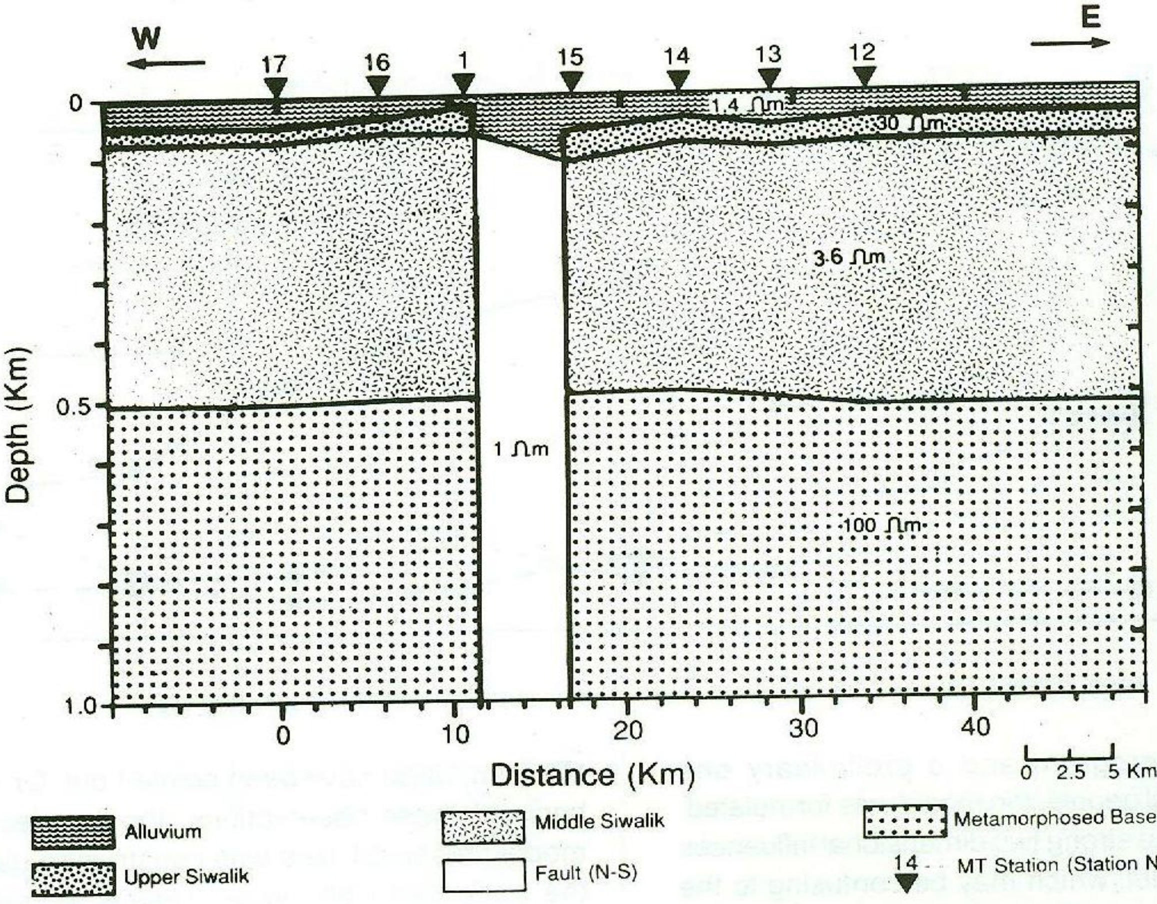

Fig.9. Geoelectric structure in Rohtak region over the EW profile (Shallow structure).

resistivity of 3000 ohm-m and extended up to 14-16 km. A deep crustal conductor is delineated at 14-60 km depths with a resistivity of 10 ohm-m. It was not possible to obtain information on the deeper strata because of the high conductive overburden, which limits the penetration of the EM waves.

The two dimensional effects discussed earlier are related to the presence of a deep vertical conductive structure located below stations 1 (Lajwana Khurd) and 15 (Mehrara). This N-S oriented feature is about 5 km wide and extends through to the bottom of the Upper Crust at depths of 14 km. The surface manifestations are not clear from the MT studies alone because of the similar conductivities (1-4 ohm-m) of the conductive feature as well as the top sedimentary layers. It is thus not clear whether this feature is exposed at these stations or burried deep under the alluvial cover. The lateral extent in the N-S direction was not directly evident from this E-W MT profile. However, the influence of this conductor is seen throughout the N-S profile, except at the station 4 on the north end. It may thus be concluded that this feature extends at least up to the southern most station on the N-S profile. The data at station 4 show a rotation axis that was along either NE or NW (a right angle ambiguity which could not be resolved due to lack of stations). Thus the observed conductive feature either terminates at station 4 or bends either in the NE or NW directions.

SUMMARY AND CONCLUSIONS

The main objective of this article is to outline the magnetotelluric technique and highlight its usefulness in the field of the geoexploration. The MT technique is a geophysical exploration

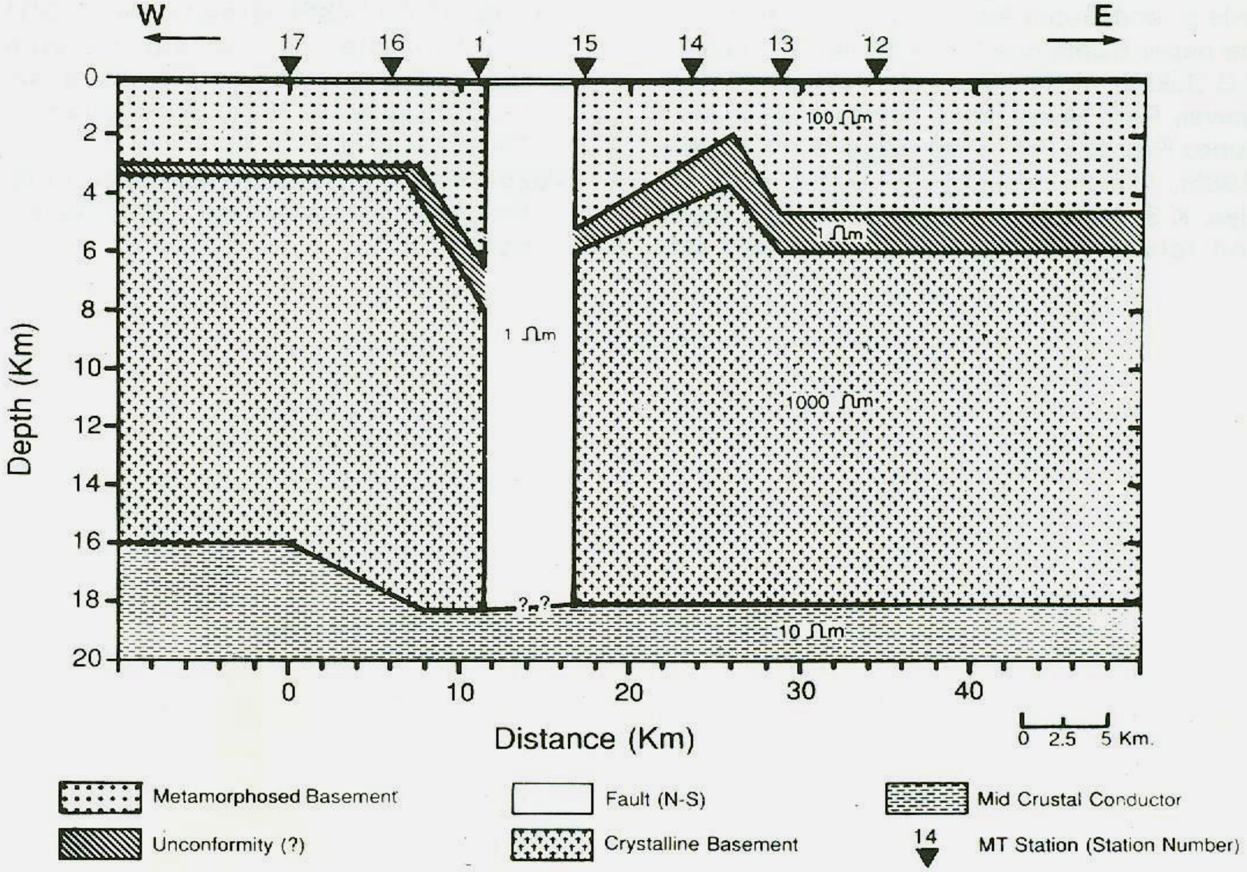

Fig.10. Geoelectric structure in Rohtak region over the EW profile (Deep structure).

tool which uses the electrical resistivity as a parameter for obtaining the structure of the crust and mantle. Case studies, which demonstrate the usefulness of this technique in retrieving the deeper information that may not be directly evident from other techniques, are presented. It should, however, be emphasised that as is the case with any other interpretational technique, the role of MT technique may be decisive in some cases or may be complementary in some others.

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