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Magnetotelluric Studies in Some Seismically Active Regions of India

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Abstract: This paper describes the principles underlying the magnetotelluric techniques with some case studies from seismically active regions in the Indian region.

Studies in the Rohtak region have delineated a deep rooted NS aligned fault zone at depth of 500 m extending up to the bottom of the upper crust (14-16 km). This fault seems to mark the western edge of the epicentral clusters in the Rohtak-Jhajjar region. Most of the deep (with focal depth of 15-20 km) earthquake foci seem to be located in close proximity of this fault zone whereas, the foci on the eastern part of this cluster seem to be shallow. The fault has a NS extension of at least 50 km between Bahadurgarh-Jind region. On the north of Jind, it seems to bend along the NW direction over the Sargoda ridge. The extension of this fault zone on the south of Bahadurgarh could not be ascertained. In the Latur earthquake affected region, two conductive dykes were delineated about 10 km SW and 5 km NE of the epicentral region (Killari-Talni). The Deccan traps were thinner (300 m) in the region of maximum devastation compared to the thickness of 500 m in the surroundings.

INTRODUCTION

Information on the deep geoelectric structure of the earth is of paramount importance in understanding the various tectonic and crustal evolutionary processes as well as in the commercial exploitation of geological resources, such as the 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 geological studies, being based on the direct observations give reliable and accurate description of the shallow strata from which the crustal evolutionary processes can be deciphered. Absence of the structural information on the deeper formations however is invariably a handicap in these interpretations. Magnetotelluric technique is a geoexploration tool, based on the study of the earth's response to the naturally occurring electromagnetic (EM) wave. Here the time variations of the electric and magnetic field components of the naturally occurring EM field are measured on the surface of the earth and using these values the impedance tensor and then the apparent resistivity and phase of impedance are computed. The penetration of the EM wave in the interior is controlled among the other parameters by the frequency of the EM wave under consideration. High frequencies penetrate only the shallow layers and, as the frequency of sounding is decreased, the penetration increases. Thus, the frequency variation of the apparent resistivity and phase of impedance are used for obtaining the depth resistivity profiles using the suitable inversion schemes. In short, the impedance tensor is related to the electric and magnetic component variations through the vector relation:

$$E = Z * H, \text{ or,}$$

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

where, E = (Ex, Ey), is the electric field vector H = (Hx, Hy), the magnetic vector and Z is the impedance tensor. The components Ex, Ey, etc., are measured along the magnetic north and south respectively.

In addition to the depth variations, the earth's resistivity may also show lateral variations. This problem is addressed to by the rotation of the impedance tensor in the spatial co-ordinates. In the case of a horizontally stratified earth, the diagonal elements of the impedance tensor Zxx and Zyy are zero and the off-diagonal elements, Zxy and Zyx, are equal in magnitude and are opposite in sign for all the rotations of the impedance tensor. In the two dimensional case, where the measurements are made in the close vicinity of a long vertical resistivity contrast, such as the sea coast or a long lineament separating two different formations, etc., the impedance tensor elements in general are non zero. However, with a proper rotation of the impedance tensor, the diagonal elements (Zxx and Zyy) can be reduced to zero, when the co-ordinates of the measurement axis coincide with the strike of the two dimensionality. The off-diagonal elements in this case are, however, not equal. In the case of three dimensional crust, as encountered over magma plugs or cris-crossing of faults in different directions, it is not possible to reduce the diagonal components to zero by any rotation of the co-ordinates.

Once the dimensionality information is obtained, the apparent resistivity and phase curves are rotated parallel and perpendicular to the geoelectric strike. The apparent resistivities 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, shall have 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. 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 more complex 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 non-uniqueness 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 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 properties 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 non-uniqueness and thus evolving a geophysical model, which is closer to the true structure.

Over the past decade, 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 inhomogeneities, 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 inhomogeneities 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. Thus, the geologists commonly observe that there are patches of red laterite soil in a black cotton soil terrain, or vice versa, and various hard rock exposures in sedimentary basins. From MT point of view, these manifest themselves as localised conductive patches on an otherwise resistive crust or vice versa. These surface inhomogeneities have strongly distort the Z matrix at all the periods of measurements, leading to erroneous estimates of the geoelectric structure. These inhomogeneities, being shallow (very thin compared to the effective skin depth at the highest frequency of easurement) contribute in terms of a scalar multiplier to the elements of the Z matrix thus, Z = C * Z', where C is the matrix of real numbers without any significant imaginary part (Unity matrix, if no shallow inhomogeneities) 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 the scalar multiplier, 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. However, some practical techniques are employed for this purpose.

There are several 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 logged data are available in the vicinity of the survey profile. In the spatial filtering approach, the surface inhomogeneities 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, ρa = 100 +/- 10 ohm-m, Rokityanski, 1982). This is because the resistivities of the mantle and core are devoid of any major lateral resistive inhomogeneities and are reasonably homogeneous world over. The apparent resistivity curves are thus shifted such that, the low frequency asymptote passes through this point. One or more of these techniques are used for correcting the static shift, depending upon the nature of the geoelectric sub structure and availability of information.

The seismic activity is a result of relative displacement of crustal blocks across the fault zones or it may also be the result of reactivation of dormant faults or formation of new faults. In all the cases, the frictional forces over the large contact surfaces may lead to heat generation. The fractured regions in the presence of mineralised water, increase their conductivity in relation to the surroundings. Again, the conductivity normally increases with the increase in temperature. For these, as well as various other reasons, there is a close link between the electric conductivity and the seismic activity. The magnetotelluric studies thus assume importance in such regions. The MT group of the Indian Institute of Geomagnetism has conducted magnetotelluric studies in various seismically active regions.

The studies in the Latur (1993) earthquake affected region and Rohtak, where seismic swarms were reported, have been conducted under the aid from the world bank, extended to the institute through the Department of Science and Technology, Govt. of India. The results obtained in these regions are discussed here under:

RESULTS OF STUDIES IN SEISMICALLY ACTIVE REGIONS AROUND ROHTAK

Over the past 30 years, 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 earthquakes 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 into three clusters: the first on the west of Delhi in the Rohtak-Jhajjar region, the second south west 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 large magnitude seismic events. Most of the epicenters in this region are located in a 50 x 25 km rectangular block a shown in Fig.1. The solid circles denote the MT survey stations.

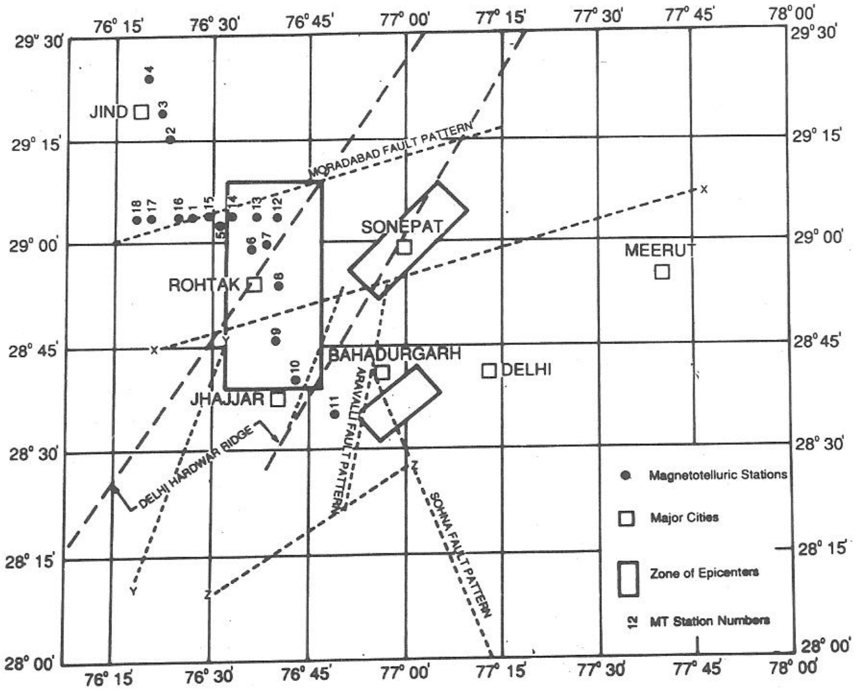

Fig.1. Major tectonic features in the Rohtak region. The rectangles are the regions of epicenter clusters and numbered solid circles are MT survey sites.

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, Sohna fault, etc. 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 Tertiery sediments and thus it is difficult to delineate the faults by the conventional geological methods. The geophysical studies are, therefore, necessary for a better understanding of the tectonic processes. The region has been explored using e gravity and aeromagnetic studies and the 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 contrasts, discussed later in this section, which could be delineated better with a E-W survey profile. Hence, it was decided to change the profile and thus additional data were collected over the E-W profile along the latitude, 29^0 5'E. The data were collected at seven stations on this profile.

The MT studies on the NS profile showed a strong influence of a conductivity contrast below the entire profile with a strike direction along either NS or EW. However, the spatial resistivity variations along the NS profile did not show any indication of an EW aligned resistivity contrast. Hence, it was assumed that the strike of the conductivity contrast may be NS. In order to verify this fact and to get more information on the nature of this contrast, an EW profile was chosen. Seven stations were surveyed over this profile approximately along the 29^0E latitude. The spatial variation of resistivity are shown in Fig.2 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 inversion program and a

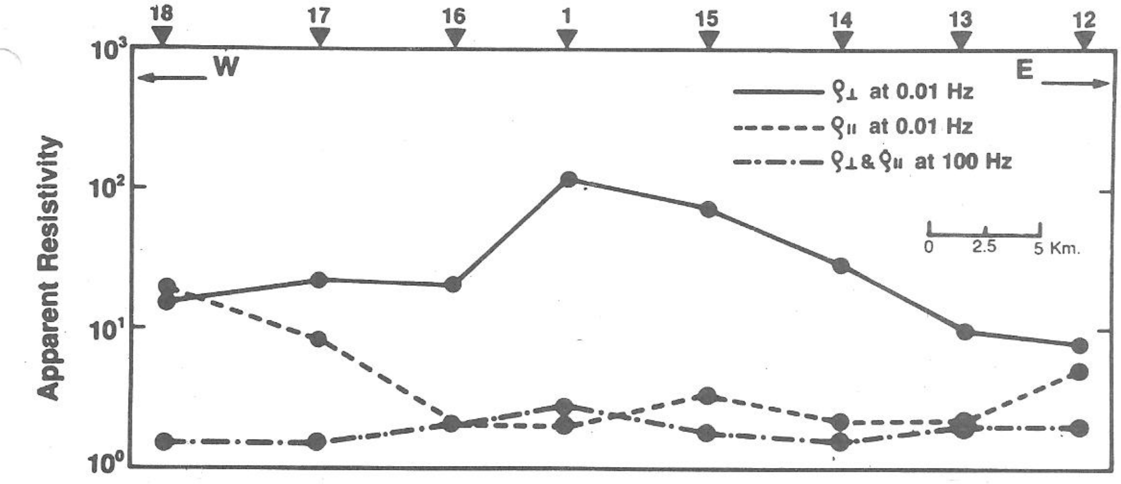

Fig.2. Spatial variation of apparent resistivity over the EW profile in Rohtak region.

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.3 (shallow structure) and Fig.4 (deep structure).

The magnetotelluric technique essentially senses the conductance of conductive 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) and some of the readers (Saini and Gupta, 1998) pointed some discrepancies over the thickness of the sedimentary layer (third layer, with resistivity 3.6 ohm-m) between the MT results and the well logged results (Thussu,1995). 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 the depth to the bottom of the resistive layers 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 was 25-60 m and had 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 was delineated. All these layers seem to be due to the Varanasi older alluvium with different degrees of calcretisation, thus leading to different resistivities. Below these sediments, a resistive layer (100 ohm-m) was delineated, extending up to depths of 3500-4500 m, overlying a thin conductive layer. This sequence was due to the metamorphosed basement overlying the crystalline basement separated by an unconformity. The crystalline basement had a resistivity of 3000 ohm-m and extended up to 14-16 km. A deep crustal conductor was 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 were attributed to the presence of a deep vertical conductive structure located below stations 1 (Lajwana Khurd) and 15 (Mehrara). This NS oriented feature was about 5 km wide extending up to the bottom of the Upper crust at depths of 14 km. The surface manifestations were not clear from the MT studies alone because the conductivities of the conductive feature were similar to those of the tc sedimentary layers. The lateral extent in the NS direction was not directly evident from this EW MT profile. However, the influence of this conductor is seen throughout the NS 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 (Badli, about 10 km west of Bahadurgarh) on the NS profile. The data at station 4 showed a rotation axis along either NE or NW. (a right angle ambiguity which could not be resolved due to lack of stations further north). Thus the observed conductive feature either terminates at station 4 or bends either in the NE or NW directions. From the tectonic elements reported by Balakrishnan (1998), it seems that this may be taking a NW turn to coincide with the Sargoda lineament.

LATUR EARTHQUAKE AFFECTED AREA

The Latur earthquake of September, 1993 is one of the rare seismic event in the sense that this earthquake of magnitude 6.5 on the Richter scale occurred in the stable continental shield. The region of epicenters here is located on the south eastern periphery of the Deccan volcanic province. The geophysical studies prior to the earth quake in and around this region were limited to the gravity and some satellite imageries. In some parts, DC resistivity and magnetotelluric studies were conducted.

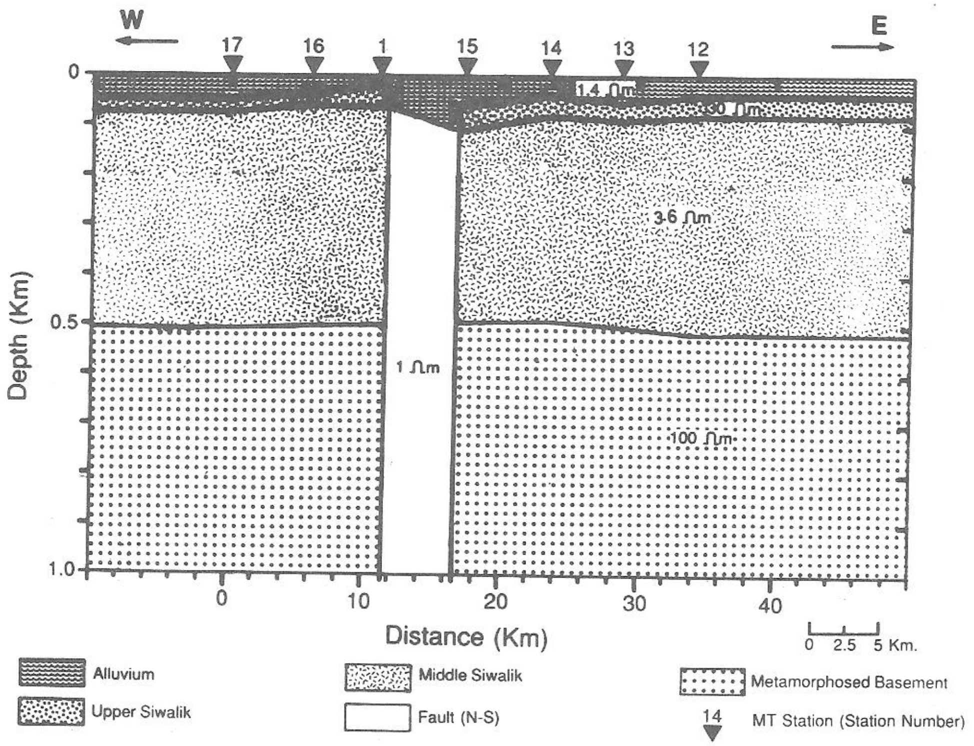

Fig.3. Geoelectric structure below the EW profile in Rohtak region (Shallow section).

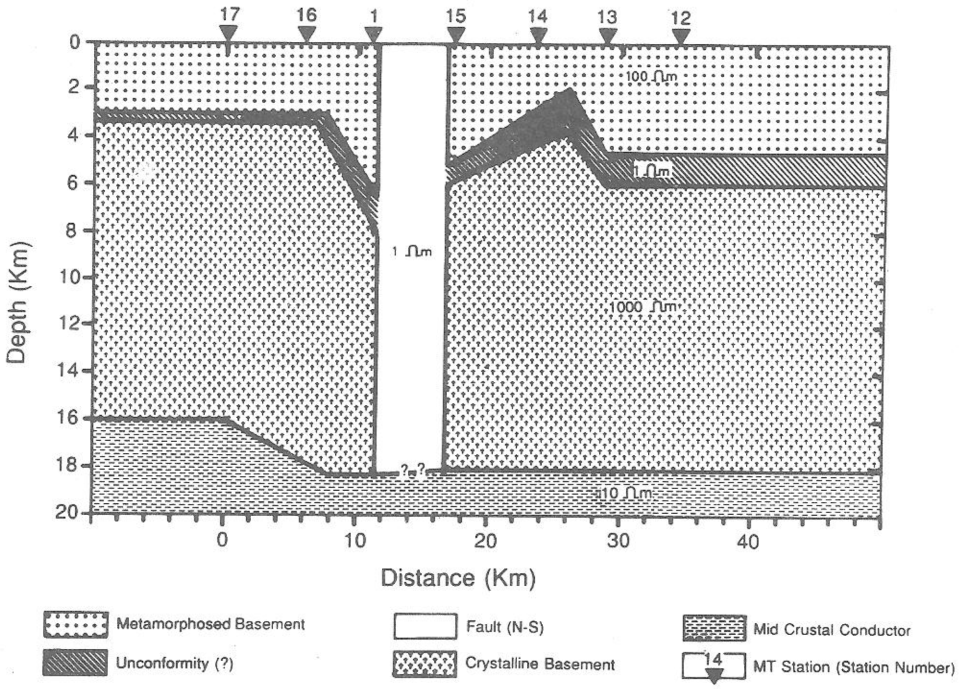

Fig.4. Geoelectric structure below the EW profile in Rohtak region (Deep section).

Subsequent to the Latur earth quake, magnetotelluric studies were conducted in and around the earth quake affected areas during January - March, 1994. Since there was no clear idea about the possible fault structure in this region at the time of commencement of the MT studies, some test stations were surveyed in the close vicinity of the epicentral region around Killari and the geoelectric strike in the survey area was determined to be along NW-SE. Based on this observation, the survey profiles were chosen along NE-SW direction (perpendicular to the observed geoelectric strike). Data were collected on three parallel profiles along the NE-SW direction (Fig.5); one between Ashta (AST) and Jawli (JAW), passing through the zone of epicenters, NW and SE of this profile, between Kilaj (KLJ) and Tungi (TUN) on the NW and between Gunjoti (GUN) and Dhanora (DHA) on the SE. Data were collected at 18 stations over

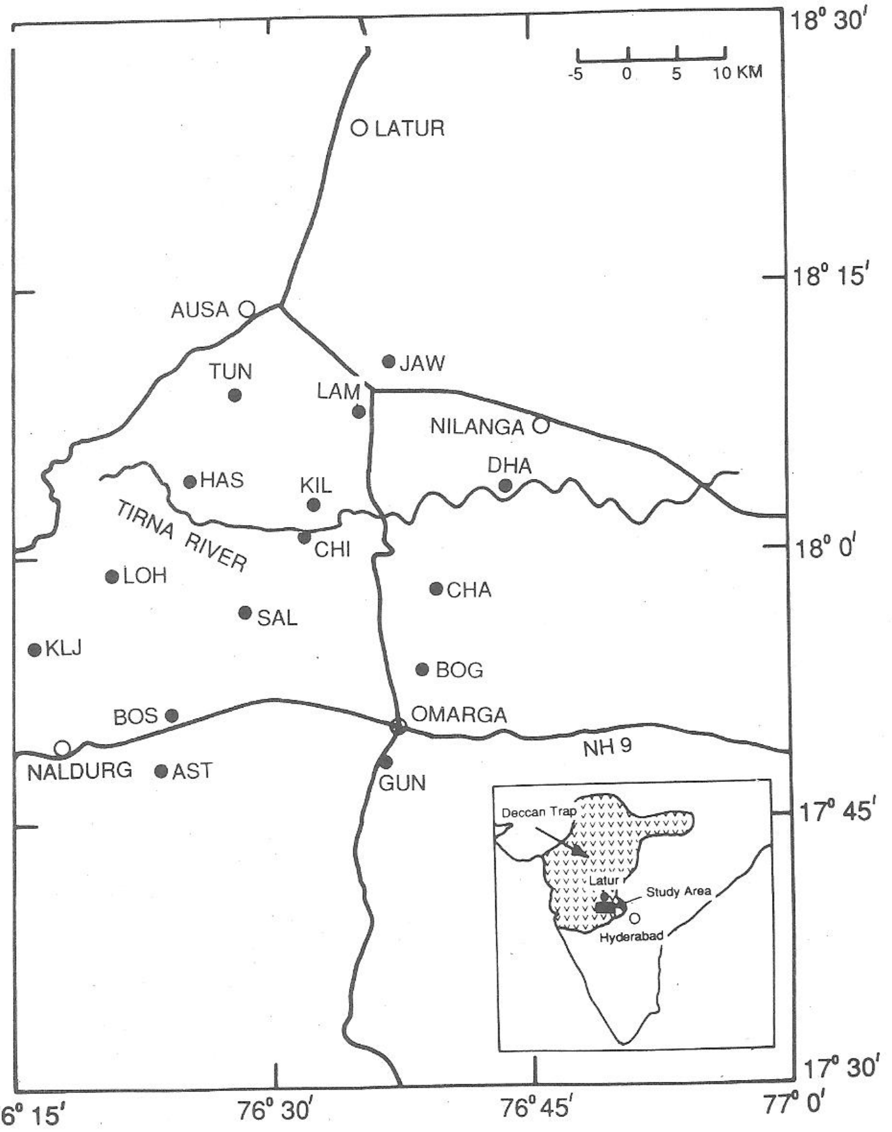

Fig.5. Location map of the MT stations in the Latur earthquake affected region.

these profiles in the frequency range, 100 - 0.01 Hz, using a five component magnetotelluric system.

Skew of the impedance (S) was less than 0.1 at all stations, indicating that the geoelectric structure is either one or two dimensional. The rotation of the impedance tensor showed weak two-dimensional effects at some stations with ratio of major to minor resistivities less than 5 with the geoelectric strike approximately aligned along N 30^0 W-S 30^{0}E direction. The spatial variations of the apparent resistivities at 0.1 Hz over the three profiles are shown in Fig.6. Here the three blocks are aligned such that the vertical line through the blocks is aligned with the strike direction. Thus, the stations HAS, SAL and GUN are located on a N30^{0}W-S30^{0}E line. The E-pol data over the central stations show a broad dip near SAL and CHI and another narrow dip below LAM. The H-pol data indicate a weak

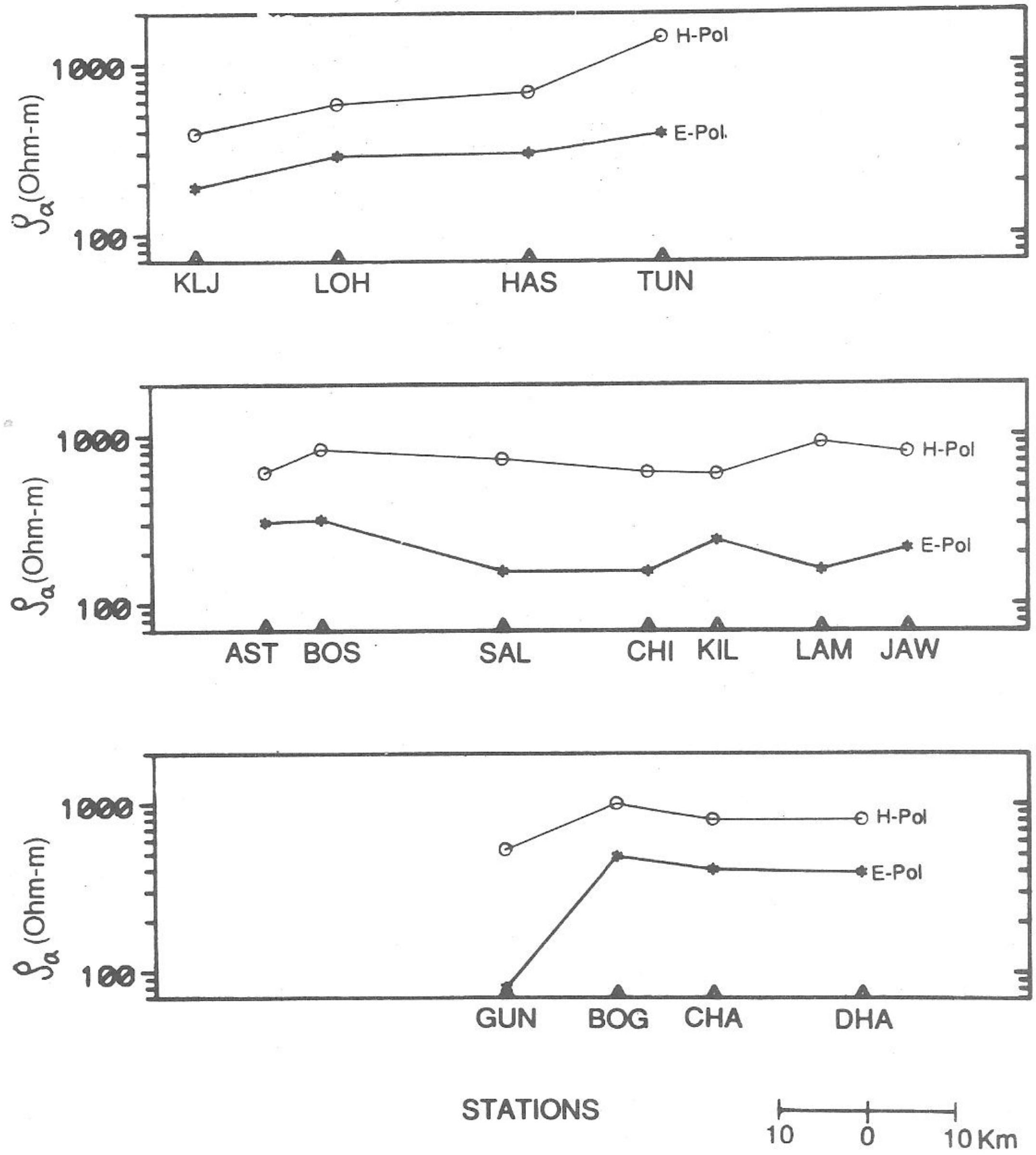

Fig.6. Spatial variation of apparent resistivity over the three profiles in and around the Latur region.

increase corresponding to the dips in the E-pol clearly indicating two vertical conductive dykes below these stations.

The apparent resistivities over the central profile were inverted using a one dimensional Marquardt inversion scheme to obtain the preliminary geoelectric cross section, which was further refined using a two-dimensional modelling program based on the finite element method. The refined geoelectric section is shown in Fig.7. The geoelectric structure shows about 300-500 m thick Deccan basalts throughout the survey region, overlying the granitic upper crust. A mid-crustal conductor was delineated at depths of about 15 km. The lower crust below the deep crustal conductor had a resistivity of 500 ohm-m.

Two vertical conductive dykes were delineated below the stations, SAL and LAM, extending in depth from about 2 km- 15 km and were located on either side of the epicentral region. These 3 km wide features were aligned along the N30°W-S30°E direction and had a conductivity of 30 ohm-m. Surprisingly, there was no change in the conductivity in the epicentral region (station KIL on the central profile) and both the conductive features were about 5-10 km on the NE and SW of this region.

The variation in the thickness of the Deccan traps is shown in Fig.8. The Deccan traps are

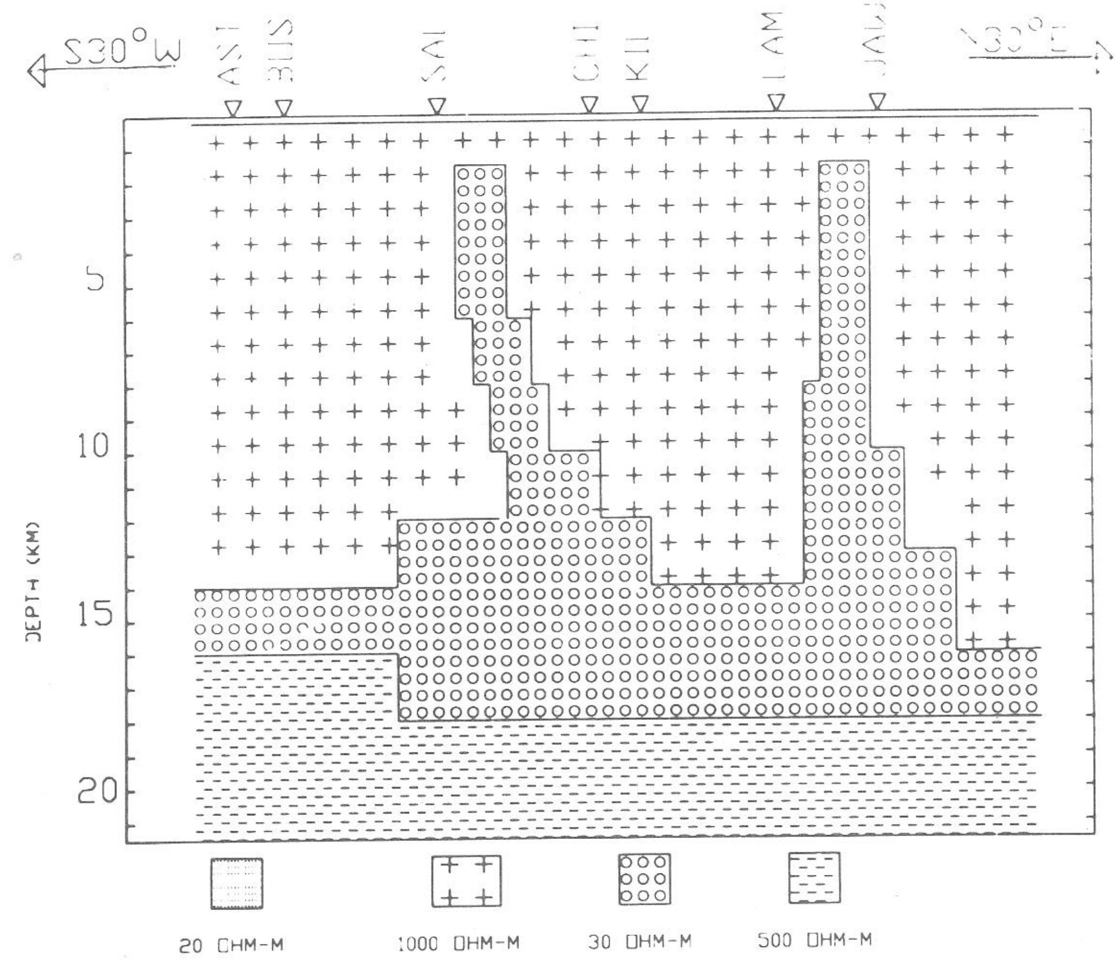

Fig.7. Geoelectric structure below the central profile in the Latur region.

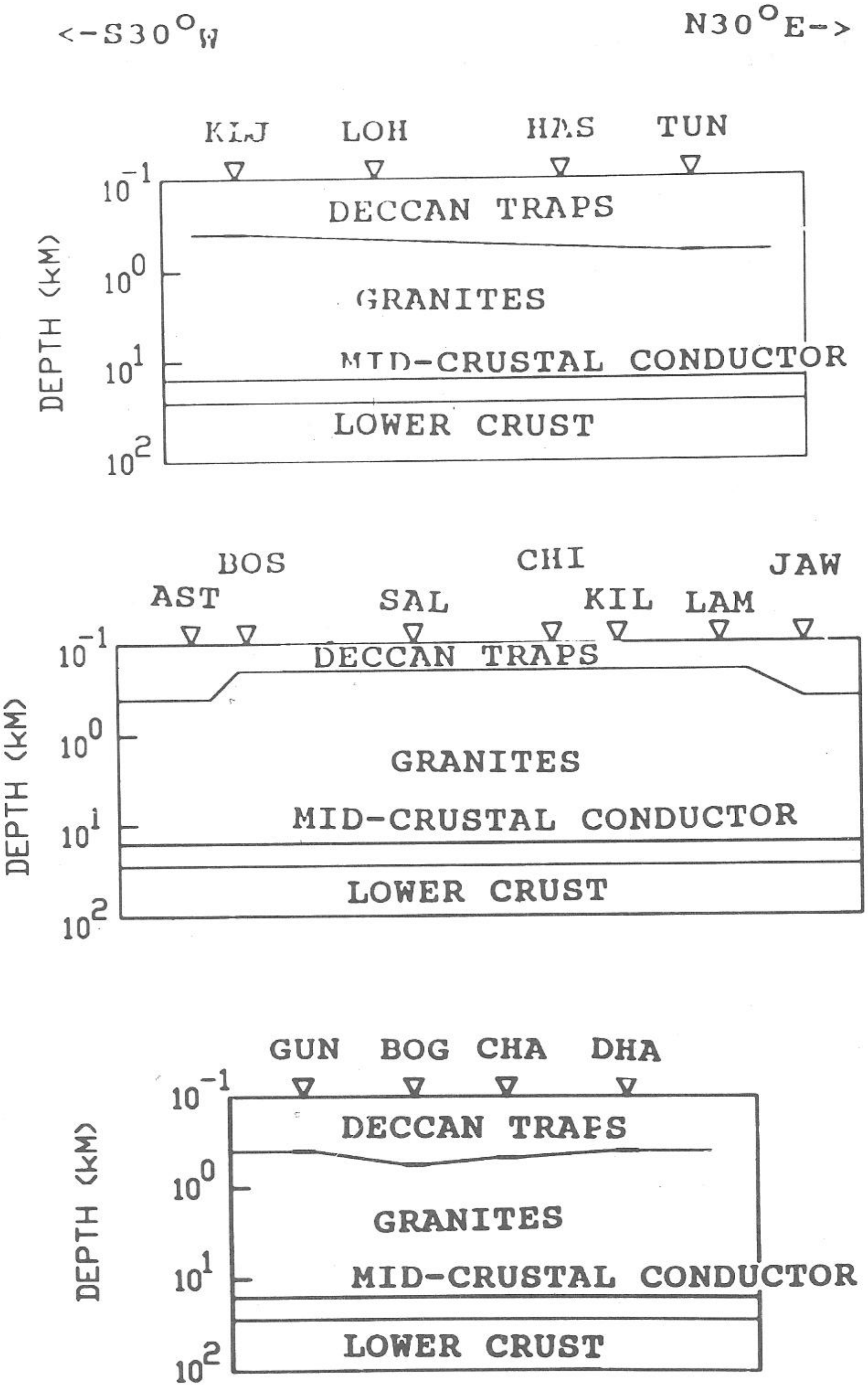

Fig.8. Thickness of Deccan traps over the three profiles in the Latur region.

thin (about 300 m) between the stations SAL and LAM with the thickness increasing to about 500 m below BOS (Bosga) and JAW (Jawli). Further, the thickness of the Deccan basalts is 500-800 m at all the stations on the SE-NW profile. The studies in the Kurduwadi region about 80 km west of this region also report about 500 km thick Deccan traps (Gokarn et.al., 1992). It is interesting to note that the maximum devastation falls in the regions where the Deccan basaltic cover is thin. This also suggests of a 200 m high hill in the topography prior to the Deccan volcanic episode. The present day topography does not indicate any such feature and, thus, the causes responsible for this structure were active in the pre Deccan trap era. The 5 mGal Bouguer anomaly maps (Kailasam, et.al., 1972) show rather unsystematic gravity variations. However, the detailed gravity mapping (Mishra, et.al., 1994) indicate two local gravity highs of 5 - 7 mGal, one near SAL and the other near LAM due to thicker Deccan volcanics in this region.

SUMMARY AND CONCLUSIONS

The results of the magnetotelluric studies in two seismically active regions, Rohtak and Latur have been discussed in this paper. The studies in the Rohtak region delineated a NS aligned fault zone extending from near surface through to the bottom of the upper crust. The conductive feature marks the western boundary of the epicentral clusters. A closer observation showed that the deeper foci in this cluster were located in close vicinity of this body. It is thus concluded that the conductive body represents a deep rooted seismically active fault zone. The signatures of this fault zone in the near surface region (at depths less than 500 m) were not clear in the present studies because of the weak conductivity contrast of this feature with the surrounding conductive alluvium and the Tertiaries.

The studies in the Latur earthquake affected regions showed thinner Deccan basalts (300 m) in the region of maximum devastation as compared to basaltic thickness of 500 m in the surrounding region indicative of possible Precambrian tectonic activity. Two conductive dykes were delineated, one about 10 km SW and the other 5 km NE of the epicentral region.

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