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Reprinted from "Latur Earthquake"
Memoir 35, Geological Society of India, pp. 101-118

GEOLOGICAL SOCIETY OF INDIA
BANGALORE
1994

OIR GEOLOGICAL SOCIETY OF INDIA
No.35, pp.101-118

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Abstract

A knowledge of subsurface lithology and structure is one of the essential pre-requisites for an understanding of physical processes related to any seismicity and more so in the case of earthquakes in the stable continental regions such as the recent Latur earthquake. Keeping this in view, a wide band (10^3 Hz - 10^{-3} Hz) magnetotelluric study was carried out in and around the epicentral zone covering the area with a total of 16 MT soundings. Modeling results show that the Deccan Traps, which blanket the entire area, vary in thickness from about 300 - 450 m. One of the interesting findings of this study is the detection of a distinct and anomalously shallow electrical conductor in epicentral zone, embedded in an otherwise high resistive upper crust characteristic of shield regions. The conductive feature oriented approximately in a WNW-ESE direction lies in the depth range of 6-10 km in the epicentral zone, this observation assuming significance in view of the shallow focal depth (7 km) reported for the Latur earthquake. Interpreting the conductive feature as a fluid enriched zone in the upper crust, the role of such anomalous zones in the context of their possible relationship to the seismicity in stable continental regions is discussed. It is suggested that presence of fluid-filled fractured zones in the upper crust would weaken rock strength and aid in localization of stress concentrations around such zones, leading ultimately to rock failure as might be the case with the Latur earthquake.

INTRODUCTION

The recent Latur earthquake of September 30, 1993 provided yet another evidence against the popular belief that the Indian peninsular shield is basically stable and aseismic. Measuring a magnitude of Mw 6.1 on the Richter scale and with its epicentre located close to Killari (Lat.18.07°N; Long. 76.62°E) the earthquake released energy of about 1.5×10^{25} CGS units and claimed a heavy toll of an estimated 11,000 human lives besides causing extensive damage to property (Gupta *et al.*, 1993).

The Latur earthquake is the second largest seismic event recorded during the last three decades in the Deccan trap covered area of the

Indian peninsular shield. It is rated to be one of the ten significant earthquakes of the stable continental regions accompanied by surface rupture (Johnston, 1994) and thus occupies an unique place. An understanding of the physical processes underlying this seismic activity in an apparently stable shield area calls for, besides the studies related to monitoring of seismic activity, an investigation of subsurface structure. With this objective in mind we have initiated a magnetotelluric field study in the Killari area from 15th December, 1993.

MAGNETOTELLURIC FIELD STUDIES

Field Layout

The Latur earthquake area in Maharashtra falls in the Deccan trap region which constitutes a significant geological unit of peninsular India and is one of the major flood basalt provinces of the world. Probing of subtrappean lithology has been a long-standing problem. In

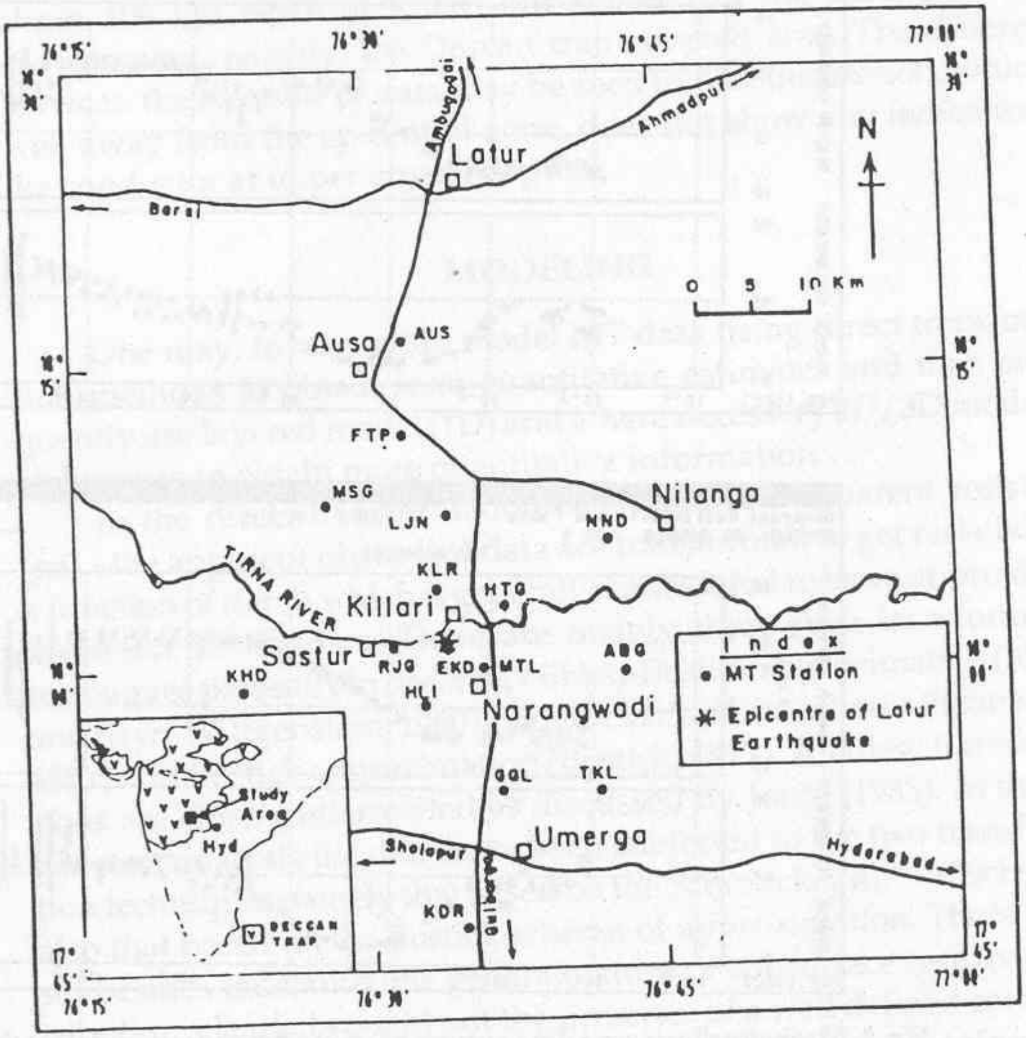

Fig. 1. Location map of MT stations - Latur earthquake area.

contrast to some of the conventional geophysical approaches such as gravity, magnetics and seismics for probing subtrappean lithology, the magnetotellurics (MT) works more effectively since the trap and the underlying subsurface present, in general, significant electrical resistivity contrasts (Kailasam *et al*. 1976; Sarma *et al*. 1992).

In the present programme of MT field studies, the region was covered by occupying two long profiles, one along a NS-traverse from south of Omerga to Ausa in north and another along a NE-SW traverse from Nilanga to Khed, besides occupying additional select sites in and around the epicentral zone (Fig. 1).

Data acquisition

Using a state-of-the-art wide band magnetotelluric sounding system (M/s Metronix, Germany), data were acquired over a wide frequency band (10^3 Hz - 10^{-3} Hz) to probe a broad range of depths extending from a few tens of metres from the earth's surface to as much as a few tens of kilometres. A dipole length of 150 m was used for telluric field measurements. Magnetic field was measured with magnetic induction coil magnetometers on three components, Hx(NS), Hy(EW) and Hz(vertical). The total equipment assembly was truck-mounted and a typical field set-up is shown in Fig 2. The entire system

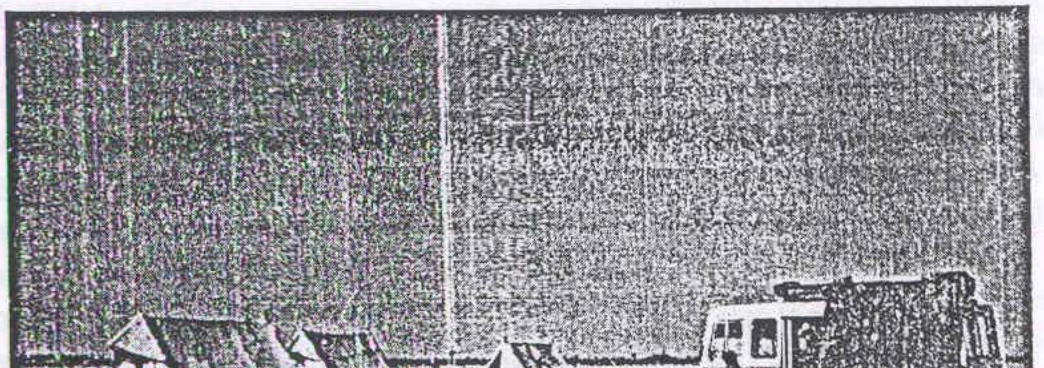

Fig. 2. A typical MT field camp.

is computer controlled and the system's software facilitates in-field data processing, evaluation and data quality control. Data were acquired at each field site over sufficiently long time, which on an average lasted for about 15 hrs duration. The data are acquired over three overlapping frequency bands - Low Frequency (LF), Medium Frequency (MF) and High Frequency (HF) - one band at a time. The data acquisition and analysis procedures are different from one band to the other and are described below.

Data analysis

In the low frequency (LF) band, the data are acquired in the 2^2-2^{-12} Hz range (i.e. 0.25-4096 sec) covering 10 octaves. The low frequency analog signals are sampled with a 16 Hz sampling rate and a 16 bit resolution. Real time processing is done using 'decimation-in-frequency' technique. In the medium frequency band the signals are sensed in the 4 Hz - 256 Hz range covering 6 octaves. The analog signals are digitized with a 1024 Hz frequency interval.

A linear trend removal is performed in the case of LF band for each data segment by fitting a straight line using least square method. After detrending, the data are multiplied by a Hanning Window in the case of LF band and by a Hamming Window in the case of MF band to remove effects due to finite record length. After conversion into frequency domain the complex Fourier amplitudes obtained are corrected for system response. From the raw-spectra, auto and cross power spectra are computed, and the conventional MT Parameters such as impedance, apparent resistivity, phase, multiple coherency, skew, azimuth, tipper, induction arrows etc. are obtained. The data are now checked for quality and the multiple quadratic coherency is used for this purpose and the data should cross a present threshold value of coherency for its acceptance. A threshold value of 0.85 in the case of LF band and 0.90 in the case of MF and HF bands have been set in the present study. All the accepted data sets are stacked.

In the HF band, which covers the audio magnetotellurics (AMT) band, the signals are sensed in the frequency range 16,384 Hz to 1 Hz covering four decades on a logarithmic scale. Unlike LF and MF band data analysis, the data in HF band are acquired and analysed sequentially, one frequency after the other. The digitization of the signals is carried out using heterodyne converters, which are based on synchronous detection principle. After obtaining the spectral amplitude and its phase for each component in the frequency domain, the usual auto and cross power spectra are computed, from which the other MT parameters are obtained as in the case of LF and MF frequency bands.

These procedures are so designed that a high quality data is assured and at the same time the data acquisition time is kept to a minimum. The data evaluation software of the system together with stringent criteria adopted during the field programme for selection of each MT site made it possible to maintain a high data quality. A few examples of MT sounding curves are shown in Fig. 3.

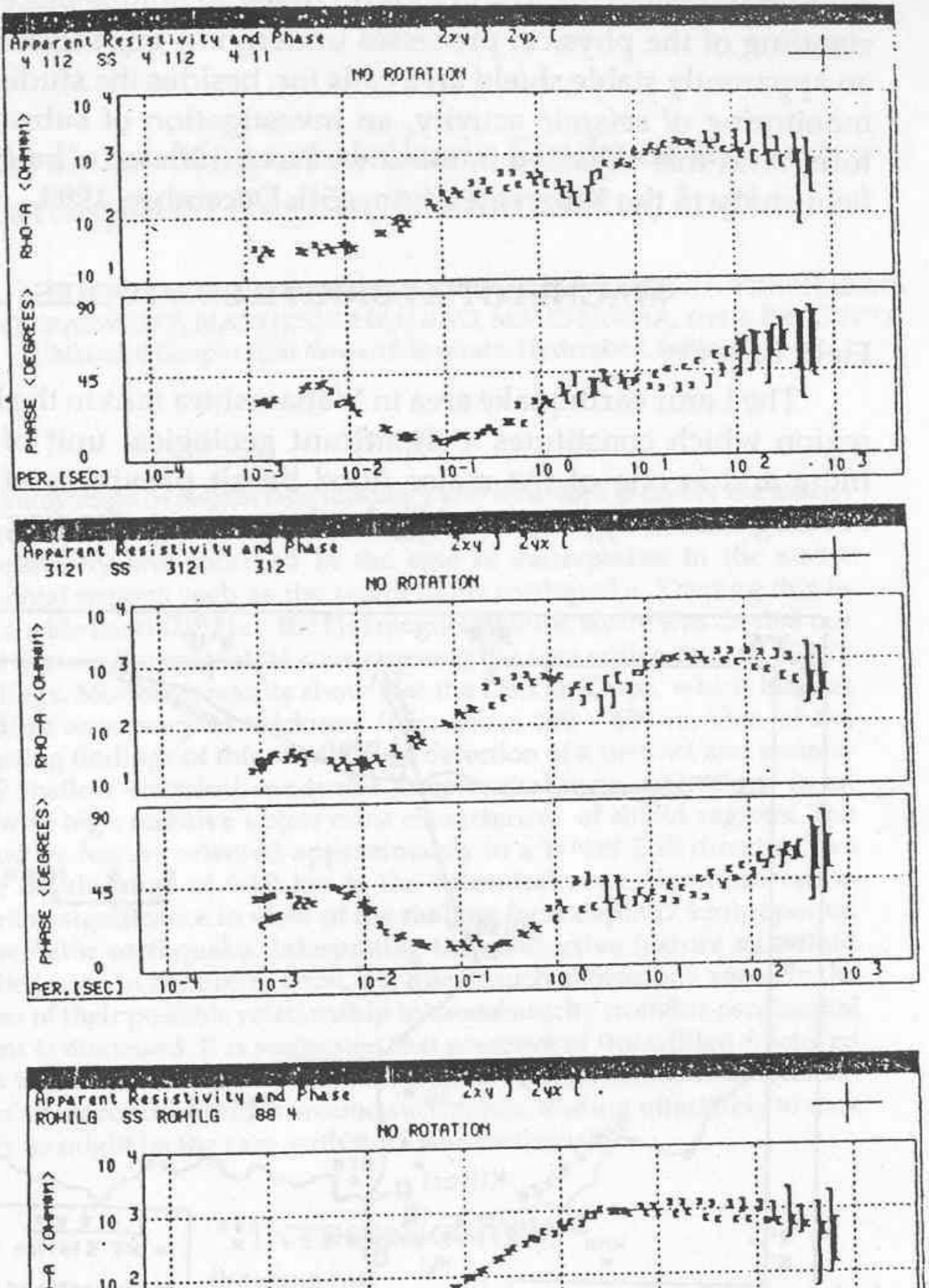

Fig. 3. Magnetotelluric sounding curves: ρ & ϕ as a function of period at the stations (a) Matola; (b) Ekondi (in the Killari area) and (c) Rohilgad (near Aurangabad).

MT sounding curves

The sounding curves from the Killari area in general show a four layered structure for the subsurface overlain by a top conducting soil cover. The Deccan traps show a moderate resistivity of about 30 to 100 Ohm-m. The traps appear to rest on a high resistive crust. This is followed by a low resistive subsurface tending to show up gradually at deeper levels corresponding to periods larger than 100 sec. One of the most impressive and interesting features that the data brings out is that the high resistive upper crust itself contains a distinct signature of a conductor, as shown by a clear depression in the apparent resistivity curves of the stations at Ekondi and Matola in the 1 - 0.1 Hz range (Fig. 3a&b). Though the sounding data at other stations also show a similar pattern of subsurface resistivity distribution, there exist perceptible change from station to station in the signature of the crustal conductor which could also be seen in the modeling results as detailed in the next section. Further, for purpose of comparison, also shown is the MT sounding curve obtained during 1987 at Rhohilgad (Fig.3c), a station about 100 km north of Killari but situated in the same geological environment, namely, the Deccan trap covered area. The difference between the two sets of data may be seen in that this station, which is well away from the epicentral zone, does not show any indication of the conductor at upper crustal depths.

MODELING

One may, to start with, model MT data using direct transformation methods to obtain semi-quantitative estimates and then subsequently use layered model (1D) and where necessary 2D/3D modeling techniques to obtain more quantitative information.

In the direct transformation technique, the apparent resistivity (ρa) - the apparent phase (ϕa) data are transformed to get resistivity as a function of depth which is generally considered to be an approximate inversion of MT data. There are mainly three such transformation techniques presently in use, viz., Niblett-Bostick approximation (Niblett and Sayn-Wittgenstein, 1960), Schmucker's ρ^* - z^* scheme (Schmucker, 1987) and Bostick approximation (Bostick, 1977). All these transformations are closely interrelated as discussed by Jones (1983). In the first phase of analysis the data have been subjected to the two transformation techniques namely that based on the Schmucker's ρ^* - z^* scheme as also that based on the Bostick scheme of approximation. These analyses besides indicating the general nature of subsurface resistivity distribution, clearly brought out the presence of a well defined conductor as could be seen from Fig.4 which shows the Bostick transformation curves. This figure also includes the results of 1D inversion.

The direct transformation analysis is followed by a more quantitative 1D inversion analysis using a linearized inversion scheme to get layered geoelectric sections at each of the stations. In the 1D-inversion analysis a starting model is necessary, in general, to initiate the inversion process. The subsurface section is divided into distinct layers with each layer having a definite resistivity and thickness. The layer parameters for the initial model can be chosen from the geology of the area (or) from the results of direct transformation techniques (Schmucker, 1987; Bostick, 1977) or from drilling results if available and/or from the nature of the observed curve itself. In the present case for the Killari area, a five layered structure viz., a conductive (10 Ohm-m) thin top soil cover, followed by traps with a resistivity of a few tens of Ohm-m, lying over a thick high resistive crust, in which a conductive layer of about 15-25 Ohm-m resistivity is embedded, has been chosen for the initial model. The linearized inversion scheme of Jupp and Vozoff (1975), has been used to invert the two invariants namely the Z-invariant (Berdechivisky and Dmitriev, 1976) and the ρ det (Ranga Nayaki 1984) of the MT data.

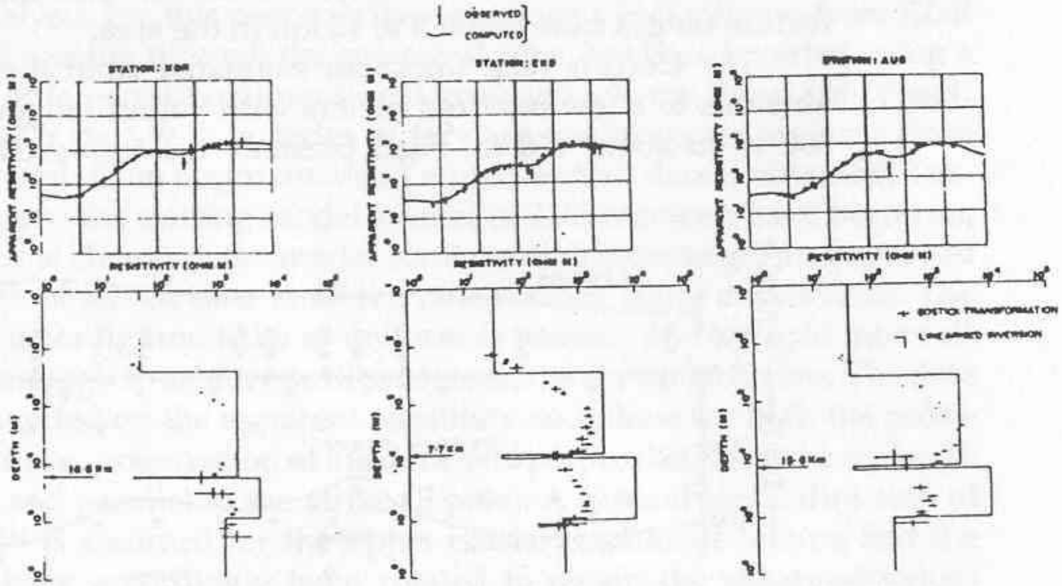

Fig. 4. 1D modeling results of Z-invariant data and Bostick's transformed resistivity at three stations - (a) KDR; (b) EKD and (c) AUS.

The geoelectric section obtained from 1D inversion corroborate well with those from the direct transformation technique. An example showing the geoelectric sections from 1D inversion for three of the stations, one located near the epicentre (EKD) and two others far away on either side of the epicentre is presented in Fig. 4 together with the transformed resistivity obtained using Bostick scheme. The results show that while the top layer representing the soil cover with a thickness of about a few meters has a resistivity of less than 10 Ohm-m, the resistivity of the Deccan Traps which underlie the soil cover comes to about 30-100 Ohm-m. The resistivity of the basement below the traps is very high amounting to about 10^4 Ohm-m indicating a hard dry granite-gneissic basement. It is within this highly resistive granitic rock, the "conductive feature" with a resistivity of about 10-20 Ohm-m is embedded. The one dimensional analysis indicates that the depth to this feature ranges from about 8 to 15 km in the area.

The Deccan Trap thickness estimated from the present study amounts to a few hundred meters with values ranging from around 300 m to about 450 m. Fig.5 presents the trap sections along two profiles, one along a N-S traverse from KDR, south of Omerga up to AUS north of Ausa and another an approximately E-W trending traverse from Khed (KHD) in the west to Ambulga (ABG) in the east. The trap appears to be relatively thinner at Ekondi (EKD) in the immediate vicinity of the epicentral zone and also at another station Lamjana (LJN), to the north.

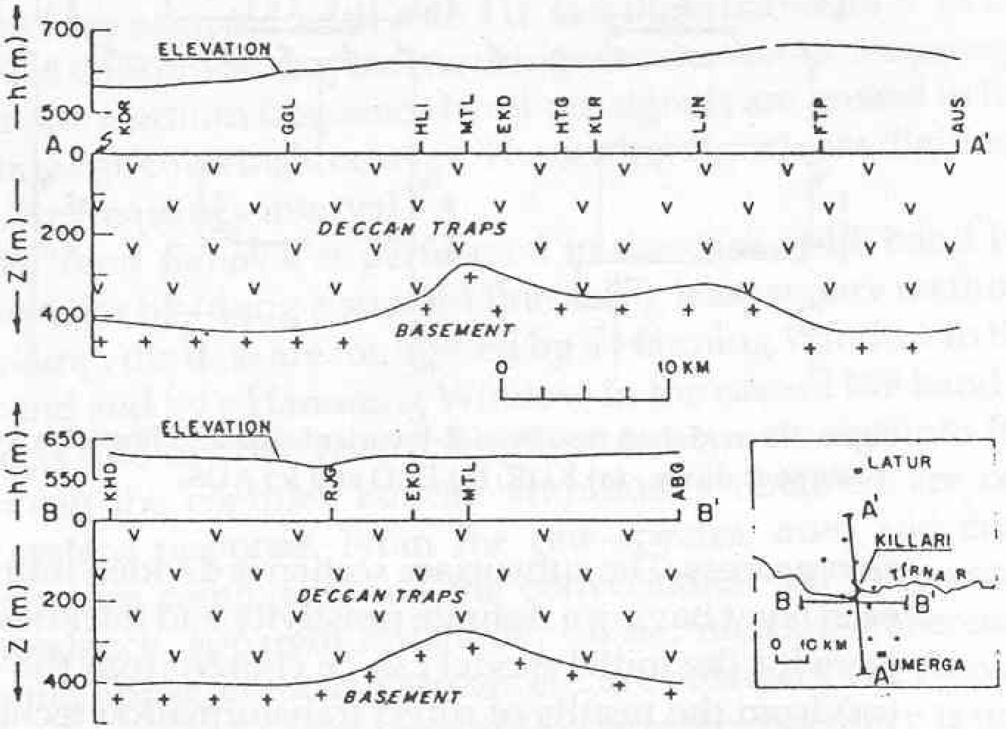

Fig. 5. Deccan trap thickness inferred from 1D-modelling of MT data along two profiles AA' and BB'.

The 1-D inversion results also indicate that the crustal conductor tends to become shallower at Ekondi, a station close to the epicentre, relative to that at the other two stations on either side of the epicentre (KDR on the south and HTG to the north). This tendency of shallowing of the conductor is also seen at the stations viz., Rajagaon (RJG), Ambalgaon (ABG) and Matola (MTL) relative to other stations in the area. This indicates that the crustal conductor becomes shallower, in general, in the epicentral zone. Though the station distribution is not uniform enough, nevertheless, in order to bring out the direction of the feature atleast in an approximate measure, a contour map based on the available values of the depth to the upper crustal conductor in the area obtained from 1D-analysis is prepared and presented in Fig.6. The map broadly indicates that this shallow feature (7 km) in the epicentral zone, tends to align approximately in a WNW-ESE direction.

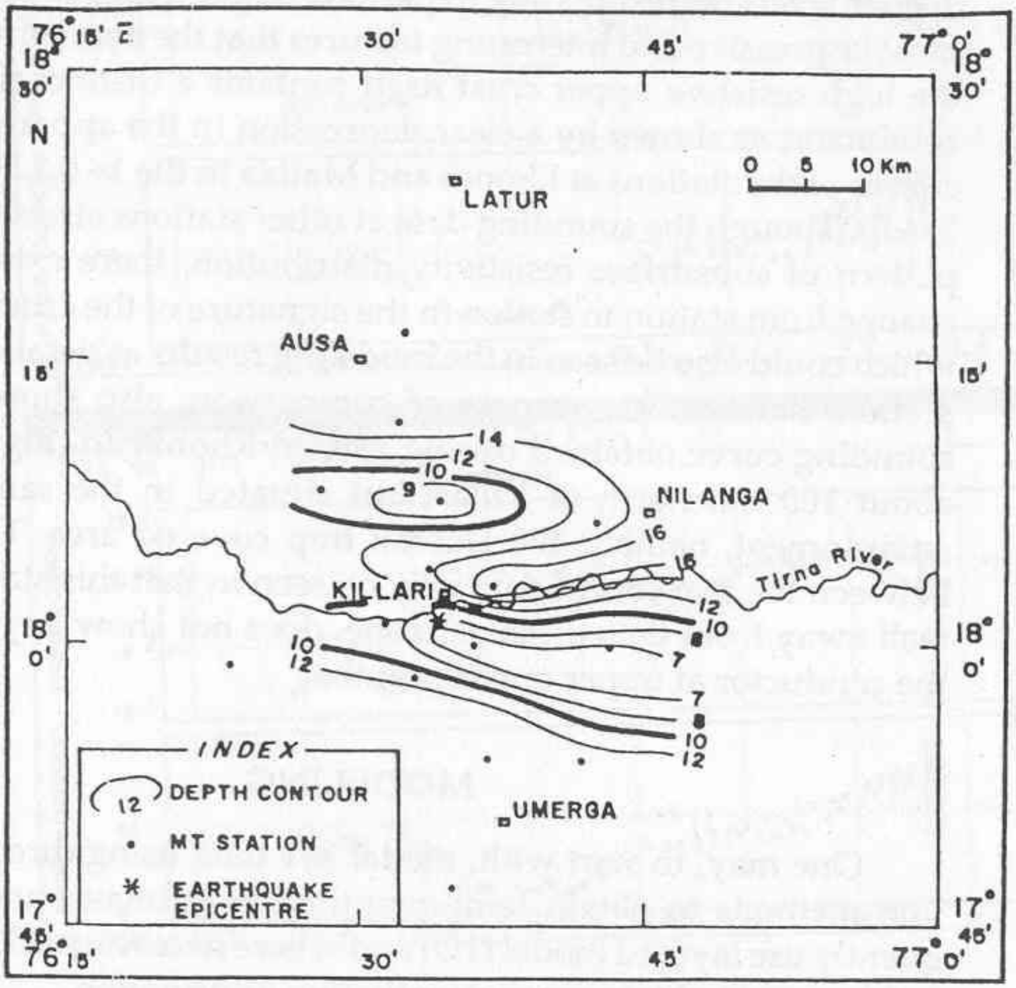

Fig. 6. Contour map of depth to the upper crustal conductor inferred from 1D-inversion of ρyx data. The numbers shown near the contour lines are in km.

Tipper Analysis

Another useful magnetotelluric response function we have examined is the "Tipper" parameter (Vozoff 1972). Fig.(7) shows the pseudo-section of Tipper distribution obtained along a N-S traverse from GGL to AUS. In this representation the depth coordinate is the Z* parameter (Schmucker 1987) corresponding to each of the frequency for which

"Tipper" value is plotted and these values are contoured. The section thus obtained is utilized to identify the presence of conductors, if any, through an examination of characteristic spatial pattern in the tipper magnitudes. Thus, the two minima (contours shown in dotted lines) in Fig.7 - one located near Ekondi-Matola stations and another at Lamjana - with each of these minima flanked on either side by relatively higher values (contours shown by continuous lines) - indicate presence of subsurface conductive features. The Tipper analysis providing an independent information, therefore, not only confirms the presence of the upper crustal conductor in the epicentral zone but also points out to its 2D-nature. The two dimensionality could probably be visualized as a manifestation of an upward local bulging, in the epicentral zone (and hence becoming shallower), of a regional conductive layer.

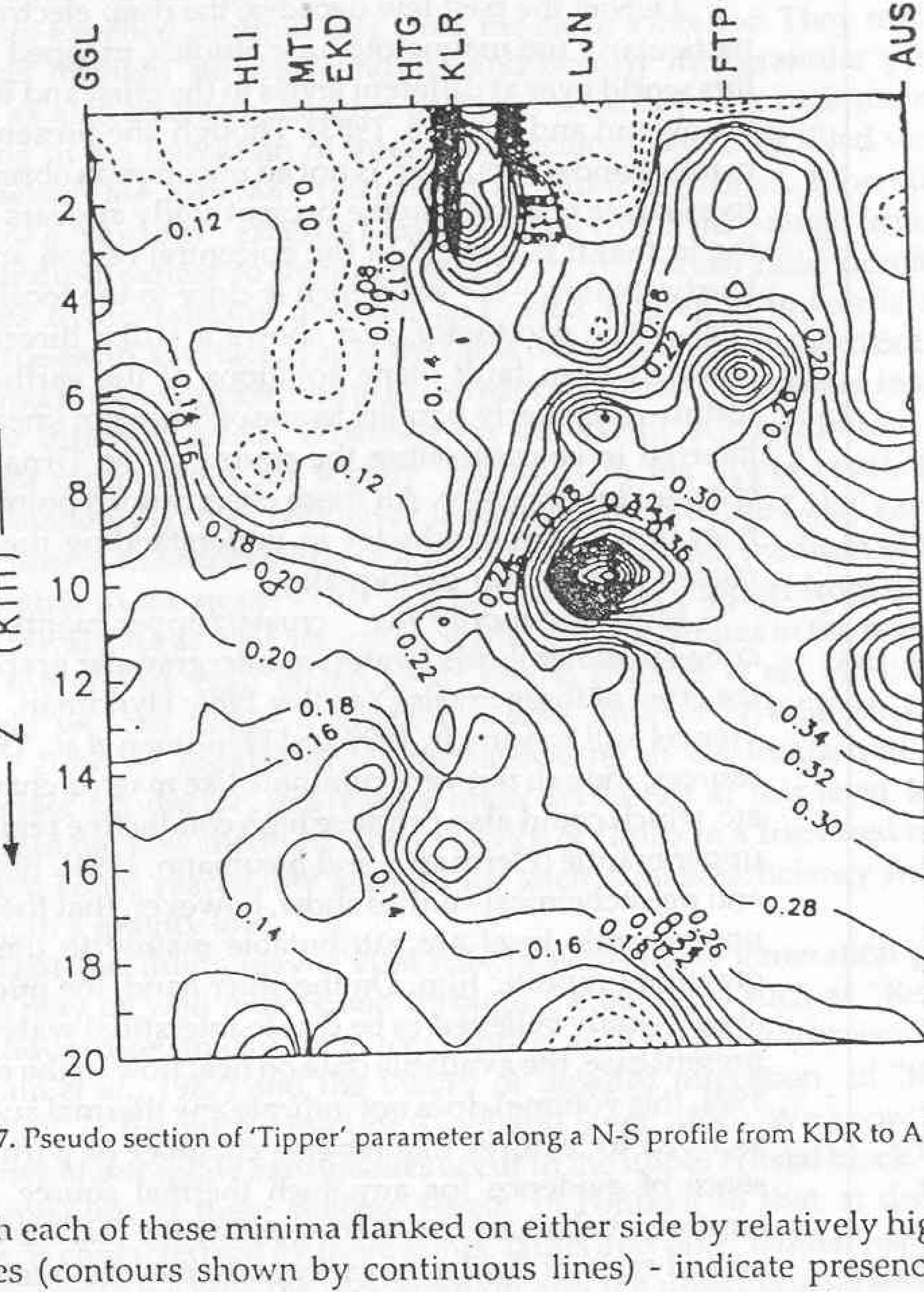

Fig. 7. Pseudo section of 'Tipper' parameter along a N-S profile from KDR to AUS.

2D INVERSION

While 1D analysis is sufficient for providing a reasonable estimate of the thickness of the Deccan Traps which may be assumed to be nearly horizontal, delineation of the configuration of deeper structure in the upper crust, however, can be made more realistically through a 2D analysis. For this purpose, the data along a N-S traverse from KDR to FTP passing through the epicentral zone, has been inverted using a finite difference two dimensional inversion scheme (Jupp and Vozoff 1977). To start with, a series of forward model responses have been computed till an approximate fit with observed data is obtained. Taking this as the starting model a series of 2D inversions have been run, each time changing the model configuration so as to get an improved fit with observed data at all the nine stations along the traverse. The mesh is configured to be as uniform as possible and the grid intervals close enough to achieve sufficient resolution in the structure. The data are inverted on the apparent resistivity and phase for both the polarizations i.e. polarization of incident field perpendicular to the strike (B-pole) and parallel to the strike (E-pole). A general strike direction of N75°W is assumed for the upper crustal conductive feature and the data have accordingly been rotated to obtain the observed values corresponding to E-pole and B-pole modes. The final model obtained after about 12 trials of inversion by changing the initial model for each trial, is shown in Fig.8. The computed and observed responses at each

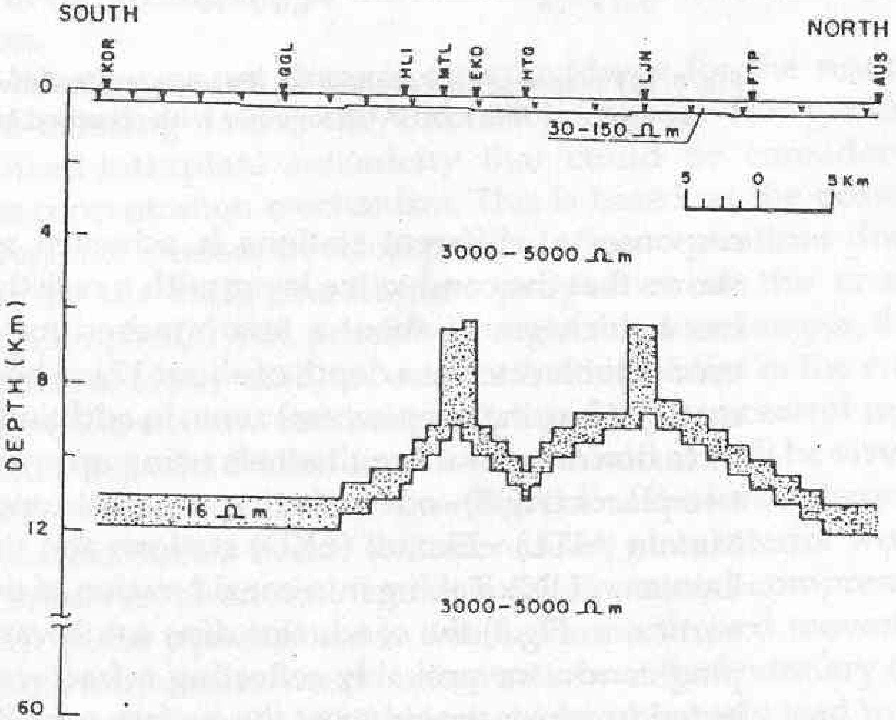

Fig. 8. subsurface section along the profile from KDR to AUS in the Latur earthquake area inferred from 2D modelling (B-pole) of MT data.

of the stations along the traverse for B-pole mode are shown in Fig.9 along the traverse. The overall fit between the model and observed

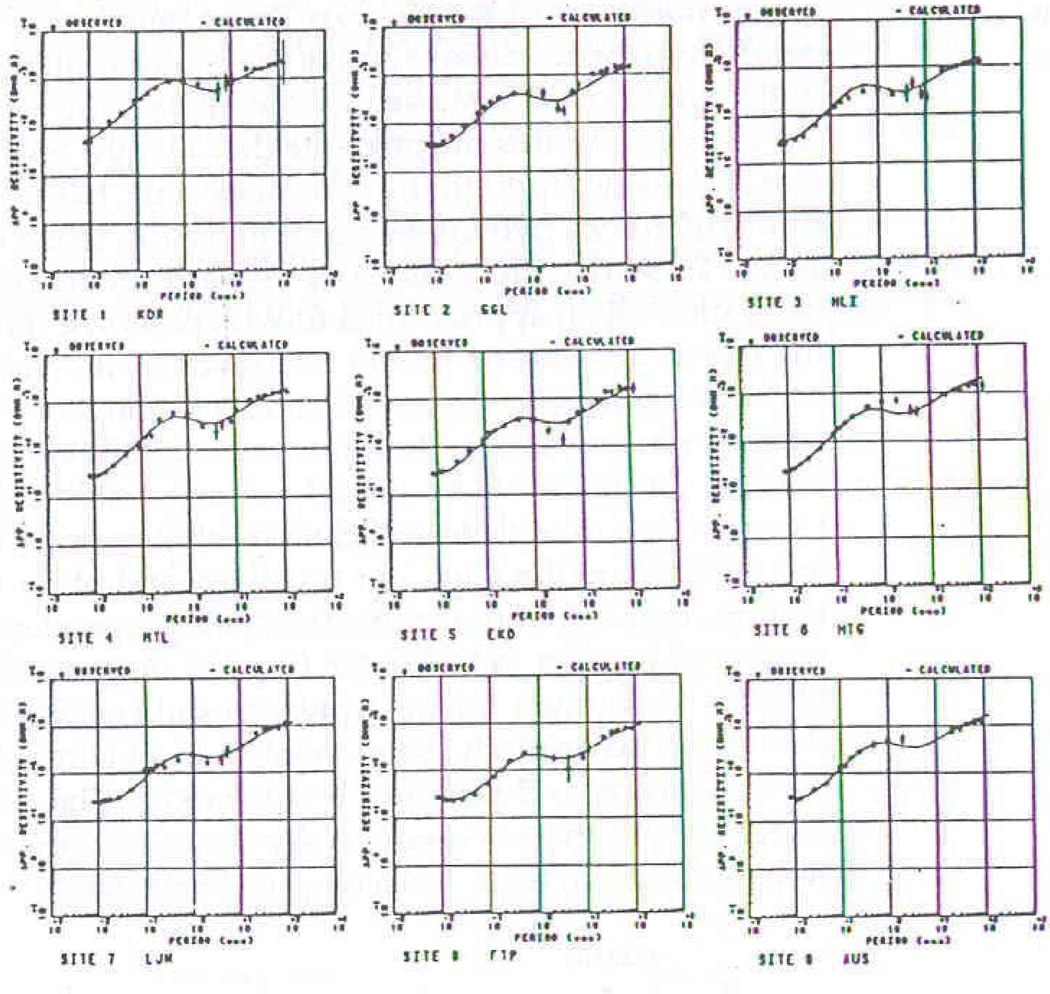

Fig. 9. MT response curves showing the apparent resistivity for the 2D model (B-pole) along the profile KDR-AUS together with observed MT data at respective stations.

responses at different stations is achieved within 22%. The model shows that the conductive layer with a resistivity of about 16 Ohm-m has a thickness of about a few hundred meters to a kilometer. The conductor located at a depth of about 12 km becomes shallow, approximately 7 km, in the epicentral zone. In addition, the model required the inclusion of conductive channels rising upwards from the conductor at two places (Fig.8) - one in the hypocentral zone of the earthquake, near Matola (MTL) - Ekondi (EKD) stations and the other north of it near Lamjana (LJN). Taking into consideration of the scales (horizontal and vertical in Fig.8) the conductor dips southwards. The southward dipping conductor probably reflecting a fracture/fault zone, when projected upwards would meet the surface near Killari. It is interesting to note that the surface ruptures with a length of about a kilometer associated with Latur earthquake and which showed exceptionally high helium anomalies (Rao *et al.*, 1994) is observed near Killari. The second feature near Lamjana may be visualized as a similar sympathetic fracture.

DISCUSSION

During the past few decades, the deep electromagnetic methods, particularly the magnetotelluric studies, mapped subsurface conductors world over at different levels in the crust and uppermantle (e.g. *see* Shankland and Anders, 1983). Though the presence of crustal/upper mantle conductors, thus, is not an uncommon observation, the conductive feature observed in the present study appears to be rather intriguing in that it is located in the epicentral region and becomes anomalously shallow ~6-7 km which is close to the focal depth of the earthquake. The conductor also shows a strike direction similar to that reported from fault-plane solutions of the earthquake. Further, the feature runs nearly parallel to one of the major lineaments of the region inferred to be controlling the course of the Tirna river which passes close to the epicentre. All these observations point out to a significant relevance of the conductor in understanding the physical processes related to the Latur earthquake.

More commonly the crustal/upper mantle conductors are ascribed to either fluids (water) or intergranular graphitic film present in the crust at these levels (Yardley 1986; Hyndman, 1988; Warner, 1990; Wenzel and Sandmeir, 1992 and Hyndman *et al.*, 1993). There are other sources, though not very common, like magma chambers, partial melts etc. which could also produce high conductive regions in the crust and upper mantle (Hermance and Neumann, 1991). Results of petrological and petrochemical studies show, however, that the deep conductors at uppermantle level are attributable mainly to the presence of intergranular graphitic film. On the other hand, the midcrustal conductors are generally believed to be due to interstitial water in the crust. In the present case, the available data on heat flow in the region (Sundar *et al.*, 1994, this volume) does not indicate any thermal anomaly that could be ascribed to features like magma chamber or partial melts. In the absence of evidence for any such thermal source and in view of its location at shallow depth the conductive feature detected in the epicentral zone of the Latur earthquake may be interpreted to be a fractured and permeable subsurface medium filled with fluids like H_2O in the upper crust.

Water in this conductive zone could have been derived from several ways - for example, the dehydration of hydrated minerals like Serpentine, zeolites etc. in the subsurface rocks (Jodicke, 1992) would release water at these levels. There also exists a reasonable possibility for contribution of fluids to the upper crust from surface as well as deeper sources. The gravity driven downward percolation of meteoric water to deeper levels of the earth's crust (Costain *et al.*, 1987) is an interesting possibility. On the other hand, we have deeper sources as well which send fluids upwards towards the earth's surface. It is widely believed that significant amounts of high pressure volatiles and fluids are expelled continuously from the earth's interior. They travel upwards through suitable conduits and occupy intergranular pore spaces as also fractures, fissures and microcracks in the rock matrix resulting in the formation of three dimensional networks filled with fluids which are generally referred to as "fluid domains". When the height of a "domain" exceeds a critical value which may range from a few hundred meters to as much as 10 km, the whole fluid domain becomes hydrostatically unstable and starts migrating upwards towards the earth's surface, due to the force of buoyancy (Gold and Soter, 1985) and thus could contribute to formation of fluid filled zones in the crust at different levels. Whatever be the extent of contribution of different mechanisms for supply of fluids in the upper crust, the interpretation that the conductive feature detected in the Latur earthquake area is a manifestation of a fluid-filled fractured medium of the rock matrix in the upper crust derives additional support from other geophysical data as well, for example, the gravity studies in the region. From the gravity map of the Latur region (Mishra *et al.*, 1994; this volume) we can notice a minor but well defined NW-SE striking gravity `low' of about 5 m.gal corresponding to the location of the subsurface conductor, implying a mass deficiency at this level with respect to the host medium. The presence of fluids in a fractured rock medium could reasonably account for such a mass deficiency manifesting in a gravity low.

That the fluids play a vital role in earthquake generation processes may be well understood through the concepts such as "Reservoir induced seismicity" (e.g. *see* Gupta *et al.*, 1992), "hydroseismicity (Costain *et al.*, 1987) and the theory of upward migration of "fluid domains" in the earth's interior (Gold and Soter, 1985). We know that majority of intraplate earthquakes occur in the upper crustal block. The rock medium at these shallow levels, in contrast to that at deeper levels, is characterized by more joints, faults and other similar features which would weaken the rock strength and the upper crustal block is thus generally considered to be pre-stressed to near failure conditions. If fluids enter into such a weak medium the increased pore pressure will further push the rock medium closer to the threshold of failure (e.g. see Costain *et al.*, 1987; Gold and Soter, 1985). In the light of the results obtained in the present study, which provide evidence for existance of fluids in the upper crust in the hypocentral region of the

Latur earthquake, we examine here the two hypotheses, namely, the one based on reactivation of a pre-existing fault (Sykes, 1978) and the other concerning the stress concentration mechanism (Long, 1976; Campbell, 1978) which are generally considered (for e.g. *see* Bowman and Dewey, 1991) for understanding intraplate seismicity and which are not mutually exclusive.

In the case of Latur earthquake, the estimated focal depth is about 7 km (Gupta, *et al.*, 1993) and with the presence of the conductive feature interpreted to be representing a fluid-filled zone located at very shallow depths of around 6 to 10 km, we have appropriate conditions for increase of pore pressure resulting in the creation of suitable stress environment for generation of rock failure. The presence of fluids weaken the strength of the rock, in general, and when they meet an already existing weak zone, say a fault they might activate the fault zone by reducing the effective stress normal to the fault plane by an amount equal to the pore pressure. The present geological knowledge of the Latur area, however, does not seem to indicate any direct evidence for a major pre-existing fault zone (Seeber, 1994) near Killari. But satellite imagery shows two major lineaments viz., one is a near E-W trending lineament passing close to Killari and aligned almost along the Tirna river and the other is a NNW-SSE trending lineament which cuts the former near Killari (Rao, *et al.*, 1993). These two mega-lineaments inferred from satellite data are the two known structural elements, which might have played some role in the weakening of the rock strength at shallow depths in this region.

Whether or not there is direct evidence for the reactivation of a pre-existing fault, the other hypothesis for generation of localized intraplate seismicity that could be considered is the stress concentration mechanism. This is based on the possibility that the regional stresses develop pockets of concentrations due to variations in the bulk rheological properties of the crust (Long, 1976, Campbell, 1978), possibly brought out, for example, through the presence of either 'stiff' or 'weak' intrusive bodies in the crust. In this context, the shallow conductive feature in the epicentral region interpreted to be a fluid-filled fracture zone could as well be visualized as a 'weak' inclusion in the hard granitic rock of the lithospheric plate. The presence of such a 'weak' inclusion in the plate interior would, under the influence of an ambient uniaxial horizontal compressive stress, which in the present case is due to the northward movement of the Indian Plate, creates stress concentrations at the boundary of the weak inclusion (Campbell, 1978) which might ultimately lead to nucleation of the fault fracture. The conditions for generation of such stress concentrations are more favourable in the present area in view of the inferred strike direction of the 'weak' inclusion i.e. the subsurface conductor, being in a near WNW-ESE direction tending to be nearly at right angles to the ambient stress direction of N 30°E as deduced from hydrofracturing measurements (Gowd *et al.*, 1992).

CONCLUSION

The magnetotelluric investigations in the Latur earthquake region has brought out the existence of a well defined upper crustal conductor in the epicentral region located at an estimated depth of 6-10 km. The data have been subjected to both one and two dimensional modeling schemes. The conductor which appears to be in the hypocentral region is interpreted to be a fluid enriched rock matrix. The presence of such fluids would weaken the rock medium and may help reactivating a pre-existing fault, if any. This fluid-filled rock matrix may also be visualized as a "weak intrusive" into a hard granitic rock medium and thus plays a significant role in developing stress concentrations around the feature ultimately leading to rock failure which might be one of the possible mechanisms underlying the Latur earthquake.

Because of its high resistive nature, the upper granitic crust in shield regions would provide an excellent electromagnetic window for probing the crust for subsurface conductors in the region. We suggest that detection and mapping of such electrical conductors particularly in the upper crust would be an effective strategy to gain valuable insights into the understanding of physical mechanisms responsible for seismicity in the stable continental regions, in general, and in the Indian peninsular shield in particular. An appropriate geophysical approach for detection of conductors representing such weak zones would be the electromagnetic imaging of the crust using magnetotellurics supported by gravity studies as also high resolution seismics, wherever necessary. Areas in the peninsular shield characterized by such upper crustal conductors would assume more significance and deserve further attention particularly when they are associated with some prior seismicity.

ACKOWLEDGEMENTS

We are grateful to Dr. H.K. Gupta, Director, N.G.R.I. for his keen interest in these studies and for permission to publish the results. We thank Prof. Keen Vozoff for providing modeling software. Thanks are due to Shri V. Sriramulu for typing the manuscript and Shri. M. Gopalakrishna for drafting the figures.

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