Comparison of Electrical Structure of the Deep Crust of the Central Indian Shear Zone, Narmada-Son Lineament, Deccan Traps, Southern Granulite Region and Eastern Dharwar Craton

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Abstract

As a part of the Deep Continental Studies programme initiated by the Department of Science and Technology, the National Geophysical Research Institute has taken up wide band magnetotellurics, besides other studies, to map the electrical structure of the deep crust on a regional scale. Long geotraverses have been covered in Southern Granulite Terrain (SGT), Deccan Trap (DT) region, Central Indian Shear (CIS) zone, Narmada-Son Lineament (NSL) zone and Eastern Dharwar Craton (EDC). It is observed that the upper and lower crustal character are different in these regions. Continent-continent collision tectonics is evidenced in SGT and lithosphere thickness of 100 km is estimated in DT. Distinct resistivity changes are observed across CIS; correlation of surface faults with deep crustal conductive features is seen in NSL region and in EDC. Additionally, these studies have brought out a relation between upper crustal rocks and the development of seismicity in the region. In the present paper, the deep crustal signatures of the five different regions are compared and their bearing on the properties of the upper crustal rocks is discussed to understand the seismotectonics of the region.

Key words: Electrical structure, cratons, deep crust, magnetotellurics, conductivity.

Introduction

Apart from mapping of the deep seismic structure of cratons and other tectonic features, electrical imaging is found to be important to understand the evolutionary history of the region. Major geotraverses in Europe, Canada and Asia were covered using both seismics and magnetotellurics, which paved the way for better understanding of the tectonics and gave an insight to the deep crust and upper mantle structure of those regions. Eurotraverse, Lithoprobe and Indepth profiles are some of the examples of such studies (Cermak and Bodri, 1986; Hammer and Clowes, 1997; Jessica et al., 2005).

As a part of the Deep Continental Studies project of the Department of Science and Technology the NGRI has initiated wide band magnetotellurics (MT) facilitating the mapping of the electrical structure of the earth from shallow to deep crustal depths along a few geotraverses (Fig.1). The traverses covered are Seoni-Rajnandgaon in the Central Indian Shear Zone, (Sarma et al., 1997, 1999) a few traverses in the Deccan Trap region of western India (Gokarn et al., 1992; Bhaskar Rao et al., 1995; Harinarayana et al., 2002a; Prasanta et al., 2005a, b), a profile cutting across Narmada-Son Lineament Zone from Edulabad to Khandwa in Central India (Harinarayana et al., 2002a; Prasanta et al., 2005a, b), Kuppam-Palani in South India (Harinarayana et al., 2006, 2003) and across Cuddapah Basin in eastern India along Kavali-Anantapur (Naganjaneyulu and Harinariana, 2004). These studies have shown distinct electrical resistivity character of the upper and lower crust and paved the way for better understanding of the lithosphere. They have also thrown light on the relation between seismotectonics of the region and upper crustal rocks. In this paper, deep crustal character along these six major traverses undertaken by NGRI (Fig. 1) are discussed and the relation between upper crustal rocks and the seimotectonics in Deccan traps region is presented.

Deep Continental Studies

Magnetotellurics (MT), a natural source electromagnetic method - provides information on the subsurface electrical resistivity. The source for the signals are generated through the interaction of Solar wind-ionosphere (1Hz to a few milli Hz) and worldwide thunderstorm activity in the Earth's ionosphere cavity (10 KHz-1 Hz). Following skin
The high frequency signals scan the earth to shallow depth, where as the low frequency signals provide information to a few tens to even couple of hundred kilometers and beyond. Excellent papers and reviews are available in the literature about its application to various geological problems (Vozoff, 1972, 1986; Kaufman and Keller, 1981). In the following section, the results of magnetotelluric investigations along the various transect outlined above are presented.

Central Indian Shear (CIS) Zone

A geotraverse across CIS with a profile length of about 350 km from Rajnandgaon towards south to Seoni towards north (profile-A in Fig.1) has revealed a crustal block structure with differing resistivity. High resistive upper crust is about 30 km thick over a conductive lower crust towards south and the upper crust became thin towards north. The CIS Zone is characterised by anomalously high conductive feature near BNP station (Fig. 2). Seismic signatures have shown different dipping reflectors across CIS (Reddy et al., 1996). Gravity low also coincides spatially with CIS (Fig. 3). These geophysical indicators have shown that CIS is a major tectonic zone in Central India apart from NSL (Sarma et al., 1997, 1999).

Narmada-Son Lineament (NSL) Zone

Magnetotelluric soundings were carried out along 130 km profile oriented in NNE-SSW direction along Edlabad in the south to Khandwa towards north (Profile-B in Fig. 1). The results obtained from 2-D modelling of the data have revealed four high conductive zones in the deep crust. These deep conductive features (A, B, C and D in the Fig. 4) seemed to have association with the Gavligarh Fault (GF), Tapti Fault (TF) Barwani-Sukta Fault (BSF) and Narmada South Fault (NSF) (Fig. 4). The high resistive upper crust is thick towards southern end and...
Fig. 2. Deep resistivity structure across Central Indian Shear (CIS) Zone from 2-D modeling of the MT data. Very high resistivity towards the south and relatively low resistive for upper crust is observed with shear zone as the boundary.

Fig. 3. Resistivity (bottom), Seismic structure (middle) and gravity profile (top) across CIS. Correlation of high conductive feature with dipping reflectors and small gravity low can be seen.
tends to become thinner towards the middle and northern part of the traverse. The lower crust is uniformly conductive along the profile. The presence of high heat flow values in the region with a characteristic gravity high and enhanced seismic velocity (Kaila et al., 1985) are well correlatable to the mid to lower crustal conductors. From these evidences, it is interpreted that the region has association with magmatic underplating of the crust (Harinarayana et al., 2002a; Prasanta et al., 2005a, b).

Deccan Trap Region

It is well known that Deccan volcanic province (DVP) with large thickness of basalts acts as a geological/geophysical barrier to understand the deep structure. From earlier geophysical studies (Kailasam et al., 1972; Qureshy, 1981), it is proposed that rift like structures lie buried below the trap cover. The magnetotelluric profile along Sangole-Partur (Profile-C in Fig. 1) showed a variation of Deccan trap thickness from 500 m towards southern and northern parts of the profile to 1000 m in the middle (Fig. 5) (Prasanta et al., 2005b). Steep conductive features observed in the basement are interpreted to be due to fracture zones filled with fluids (Fig. 5) (Gupta et al., 1996; Harinarayana et al., 2002a).

The Deccan Trap thickness map (Harinarayana et al., 2007) has been prepared based on magnetotelluric sounding results and also from other studies such as deep resistivity soundings and deep seismic soundings. The trap thickness along a few selected profiles are presented in figures 6 and 7. The map is very useful in understanding the seismotectonics of the region. It is known that Deccan trap – mainly basalt – is denser as compared to the basement rock, namely granite and granite gneiss. Changes in the thickness of Deccan trap cover or presence of basement faults play a major role in the development of seismicity in the region. In order to study the development of stresses in the region, trap thickness for a few profiles in NS, EW and NE-SW direction are presented in figures 6 and 7. A general variation in thickness of the trap is seen from east to west and north to south, where as uniform thickness is observed along NE-SW profiles. This indicates that the presence of basement faults and its orientation play a significant role for the development of seismicity in the region. The schematic diagram presented in figure 8 shows four different models. They describe the possible reason for the above argument on relation of trap thickness and seismicity. Model I shows uniform thickness of trap without basement faults or fracture zones. In this case, stress is uniform on the basement. Model-II shows non-uniform thickness of trap which may develop a weak zone in the basement. Model-III shows the presence of basement fault or fracture zone with uniform thickness of trap on the top. In this case, like Model-I, major stress may not be developed in the region. Model-IV shows non-uniform thickness of trap cover underlain by a fracture zone. In this case, the region may be prone to the development of major stress that may lead to seismic activity. From these models, it is clear that if the subsurface structure is close to Model-II or IV, it is likely that these regions are prone to seismic activity.

Geological and geophysical investigations of the earlier and present studies show major basement faults/fracture zones in Deccan trap region. The west coast fault (towards western part, oriented in north-south direction) and basement faults (in central part of DVP, oriented in NW-SE direction) are the prominent features. In such a scenario, relatively more seismic activity in western part and less seismic activity in central part of DVP and can be related to Model-II/IV and Model-III respectively (Harinarayana et al., 2002a).
Southern Granulite Region

A regional geotraverse from Kuppam to Palani has been covered by integrated geophysical methods with seismics, MT, gravity and magnetics and also deep resistivity soundings. Block structure with distinct resistivity character is evidenced with Moyar Bhavani Shear Zone (MBSZ) as the boundary separating Archean Dharwar towards north and granulite terrain towards south. Another block structure within the granulite terrain is also observed with Palghat-Cauvery Shear Zone (PCSZ) as the boundary. Shear zones in the region have shown anomalous high electrical conductivity.

Fig. 5. Deep resistivity structure in Deccan Traps region from SAN (Sangole) (sw) to LON (Partur); A,B,C,D,E and F are the anomalous conductive features embedded in an otherwise high resistive upper crust.

Fig. 6. Deccan trap thickness variation along various EW profiles for different latitudes from 17-21 degrees north.

Fig. 7. Trap thickness along NS for 74° and 76° longitudes and for NE-SW profile for the direction as shown. Relatively uniform thickness of the trap cover is observed.
High conductive feature at mid-crustal depths can be spatially correlated with distinct gravity high of about 20 mGal associated with Moho upwarp delineated from seismic studies. This has indicated that the region might have experienced intense crust-mantle interaction that might have resulted in large amount of mantle-derived fluids trapped at upper crustal depths (Harinarayana et al., 2002b).

Mettur Shear Zone (MTSZ) is observed to be the boundary between low- to high-grade metamorphics and the crust is high resistive (10000 Ohm.m) towards north and less resistive (3000 Ohm.m) towards south along the profile from Kuppam to Bommidi (Profile-E in Fig. 1). MTSZ exhibits anomalous conductivity (100 Ohm.m) at mid-lower crustal depths. Presence of fluids is one possibility for the high conductive character of MTSZ but the presence of graphite cannot be ruled out as old collision zones generally exhibit graphite rich zones (Harinarayana et al., 2006, 2002b).

Marked resistivity variation is also observed across MBSZ with 40,000 Ohm.m towards north and about 5000 Ohm.m towards south-eastern part as observed along profile-F in figure 1. Differing crustal reflectors are observed on either side of MBSZ from seismic study (Fig. 9). From these studies of distinct variation in electrical resistivity and also dipping reflectors from seismics, continent-continent collision tectonics in the region is inferred (Naganjaneyulu and Harinarayana, 2003).

Eastern Dharwar Region

Magnetotelluric study across Cuddapah Basin has been carried out in an EW direction (Profile-D in Fig. 1). It has shown a differing resistivity character for eastern and western part of the basin. Upper crust is very resistive (10000–30000 Ohm.m) towards west near Anantapur and relatively less resistive (500–1000 Ohm.m) towards east along Udayagiri-Kavali (Fig. 10). Crustal structure towards east is also conductive at mid to lower crustal depths. From the study of electrical resistivity, DSS profile results across Kavali-Udipi and also gravity it is inferred that the Eastern Ghats might have experienced intense tectonic activity and was thrust up and lies over and in juxtaposition with the upper Cuddapah sediments (Naganjaneyulu and Harinarayana, 2004). This is inline with the geological evidence.

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Lithospheric Thickness in the DVP

Since our studies covers major part of DVP with many MT stations, it is of importance to estimate the thickness of the lithosphere. To do such an exercise, data from 40 sites along the Sangole-Partur (SP) traverse is selected. Several estimates are available on the lithospheric thickness below the Deccan Trap region based on the scanty data for the region. For example, based on only a few heat flow measurements, estimations were made (Gupta et al., 1991). The thickness of the lithosphere for DVP is varying from 70–180 km (Mahadevan, 1994). To obtain reliable estimates for the thickness of lithosphere from the MT data, the following procedure is adopted. Firstly, Rho-phase det (Ranganayaki, 1984) for MT data is obtained, as it represents better invariant parameter with less distortion. Among the data, stations located near steep conducting features along the traverses are removed. This is necessary because near surface and lateral variation of subsurface structure distorts the data and masks the information of the deep structure. Additionally, simple 1-D modeling is not sufficient in such cases. Accordingly, the Rho-phase det parameter for all the stations along SP traverse and the corresponding Bostick transformation of the data showed a wide variation. Large variation for the lithosphere within a short distance is unrealistic. This is due to the effect of lateral inhomogeneities. The selected data and the simple Bostick transformation are shown in figures 11a and 11b respectively. From this data (Fig. 11a) an average MT curve devoid of any lateral inhomogeneities for all the stations are considered, averaged and presented in figure 12a. The MT average
Comparison of Deep Crustal Signatures in Different Regions

The data obtained provide us a 'regional MT curve for Deccan Traps'. This data may serve for comparison and helps any research worker doing investigations in the region using MT study. The data thus obtained has been subjected to modelling schemes using two different approaches to get a reliable estimate. Firstly, the results obtained from both Occam and Marquadt linearised inversion schemes gave consistent result for the lithosphere thickness. In figure 12b results obtained from Marquadt inversion scheme are presented. Thus the thickness of lithosphere based on magnetotelluric data along SP profile is about 100 km with an error limit of 5 km.

Comparison of Deep Crustal Signatures in Different Regions

The results obtained from wide band MT study of the deep electrical crust along five geotraverses, are compared...
Fig. 10. Deep resistivity structure across Cuddapah Basin along Kavali towards east of Eastern Ghat region and Anantapur towards the west. Anomalous conductive feature in the middle upper crustal region is due to the presence of sedimentary formations of the basin.

Fig. 11. (a) Magnetotelluric data of Rho-det parameter for a few stations of SP profile in Deccan Volcanic Province. (b) Simple Bostick depth transformation of the MT data presented in figure 11a showing resistivity variation as a function of depth (approx.).
in the following section. Table I provides average resistivity derived from MT study for the upper and lower crust. The table also provides the anomalous features in these regions.

**Conclusion**

Magnetotelluric studies undertaken by NGRI in different tectonic regimes of peninsular India have shown distinct nature for each region as evidenced from the electrical resistivity character. Identification of younger or older crust in relative sense can be judged based on the resistivity values (Haak and Hutton, 1986; Jones, 1992). The same type of older rock formation exhibits high resistivity values as compared to the younger ones. In our present study the upper crustal resistivity is very high, of the order of 30000–50000 Ohm.m, in southern Granulite and southern part of CIS regions as compared to other cratonic regions of peninsular India. Mid and lower crust are in general less resistive, however, their resistivities seem to be relatively high for SGT and south of CIS regions. The marked high resistive upper crust

**Table I. Average Resistivity (Ohm.m) of upper and lower crust in different regions**

<table>
<thead>
<tr>
<th>Crust</th>
<th>CIS region</th>
<th>NSL region</th>
<th>Deccan Trap region</th>
<th>Southern Granulite region</th>
<th>Eastern Dharwar region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper crust</td>
<td>South</td>
<td>North</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20000-50000</td>
<td>10000</td>
<td>5000-10000</td>
<td>5000-8000</td>
<td>10000-30000</td>
</tr>
<tr>
<td>Mid-lower crust</td>
<td>10000</td>
<td>250-500</td>
<td>500-1000</td>
<td>500-1000</td>
<td>1000-3000</td>
</tr>
<tr>
<td>Anomalous features</td>
<td>Near CIS</td>
<td></td>
<td>NSL zone is more conductive with sediments</td>
<td>Features of anomalous conductors with 50 Ohm.m at mid crustal depth</td>
<td>100-500</td>
</tr>
<tr>
<td>Remarks/ Observations</td>
<td>Central Indian Shear Zone seems to be boundary between sharp variation of resistivity in the upper-lower crust</td>
<td>High conductive features are the deep crustal signatures of the exposed faults</td>
<td>Resistive lower crust is seen. Anomalous conductive features at mid-lower crust represents crustal scale faults/fractures</td>
<td>Anomalous conductors are the deep crustal signatures of shear zones and resistive lower crust is seen</td>
<td>Basement of Cuddapah Basin is less resistive as compared to Dharwar region</td>
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<td></td>
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<td></td>
<td>Eastern Dharwar Craton is characterised by less resistive for the mid-lower crust</td>
</tr>
</tbody>
</table>

Fig. 12 (a) Average magnetotelluric data of rho-phase-det parameter considering all the data shown in figure 11a. (b) Simple 1-D model results based on the data shown in the figure 12a using Marquardt inversion.
indicates that the crust from CIS region towards south upto about SGT marked by MTSZ can be considered as major cratonic structure. On the other hand the region south of MTSZ has shown distinctly different upper crustal signature that might have originated in a different geological scenario. Average electrical lithosphere thickness for DVP is about 100 km.

The electrical signature of the anomalous conductive features of the crust relate as (1) major shear zone in the CIS region, (2) surface faults in NSL region, and (3) extension of the shear zones to deep crust in SGT. Electrical resistivity at mid-lower crust strongly depends on the temperature. Interpretation of anomalous conductivity at these depths involves compositional variations within the crust, for example presence of increased amount of fluids or free carbon (graphite?). Although these geotraverses provide us information to understand the deep crustal structure, the western Dharwar region needs to be mapped in more detail to get an overall picture of peninsular India. It is particularly more important in view of a thick lithosphere indicated by recent seismic tomographic studies. The anomalous conductive features at crustal depths in all the regions studied indicate that the geological structures such as faults, fracture zones and shear zones have association with the deep crust. Variation in the thickness of upper crustal rocks and the orientation of the underneath faults seems to be responsible for the development of high seismic activity as compared to other regions.

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