Deep Crustal Electrical Signatures of Eastern Dharwar Craton, India

K. Naganjaneyulu and T. Harinarayana

National Geophysical Research Institute, Hyderabad 500 007, India, E-mail: kasturi_kasturi@rediffmail.com

(Manuscript received January 11, 2003; accepted June 8, 2004)

Abstract

Wide band magnetotelluric (MT) investigations were carried out along a profile from Kavali in the east to Anantapur towards west across the Eastern Ghat Granulite Terrain (EGGT), Eastern Dharwar Craton (EDC) and a Proterozoic Cuddapah Basin. This 300 km long profile was covered with 20 stations at an interval of 12-18 km. The MT data is subjected to robust processing, decomposition and static shift correction before deriving a 2-D model. The model shows a resistive crust (~10,000-30,000 ohm-m) to a depth of 8-10 km towards west of the Cuddapah basin. The mid crust is less resistive (about 500 ohm-m) and the lower crust with a slight increase in resistivity (about 1,500 ohm-m) in the depth range of 20-22 km. The resistivity picture to the east of the Cuddapah basin also showed a different deep crustal structure. The resistivity of upper crust is about 5,000 ohm-m and about 200 ohm-m for mid and lower crust. The sediment resistivity of Cuddapah basin is of the order of 15-20 ohm-m. MT model has shown good correlation with results from other geophysical studies like deep seismic sounding (DSS), gravity and magnetics. The results indicate that the lower crustal layers are of intermediate type showing hydrous composition in Eastern Dharwar Craton.

Key words: Eastern Dharwar Craton, Cuddapah basin, crustal structure, electrical resistivity, magnetotellurics.

Introduction

The South Indian Shield Region (SISR), due to its strategic location, plays a vital role in geological reconstruction of East Gondwana, with Madagascar and Africa on the west, and Sri Lanka, Antarctica and Australia in the east (Crawford, 1974; Katz and Premoli, 1979; Windley et al., 1994; Yoshida and Santosh, 1996; Meert and Van der Voo, 1997; Janardhan, 1999; Meert, 2003 and references therein). The SISR can be divided into three regions – the low- to medium-grade granite-greenstone terrain of Dharwar Craton (DC) towards north, the region of granulite facies rocks of Southern Granulite Terrain (SGT) towards south and another granulite facies region, Eastern Ghat Granulite Terrain (EGGT) towards east. An important feature of the SISR that separates DC and SGT is the prograde metamorphic Transition Zone (TZ), which follows an E-W trend across the regional structural fabric. The TZ is 60 km in width at places (Naqvi and Rogers, 1987 and Newton, 1990 and references therein).

The geology of the SISR (SGT, EGGT and DC) is well studied compared to geophysical studies and several tectonic models were proposed for this region. For example, subduction models (Drury et al., 1984; Rai et al., 1993), terrane accretion models (Nutman et al., 1989; Gopalakrishnan et al., 1990) and collision models (Rogers, 1986; Newton, 1990). However, geophysical studies are known to be helpful in understanding the deep crustal signatures and are capable to throw more light on the evolutionary history of the shield regions.

As we consider the available geophysical studies, gravity and aeromagnetic observations have reasonably well covered in the SISR (discussed later). A few seismic refraction/wide angle reflection profiles were available in Dharwar Craton. But there exist “gaps” in the knowledge of seismic velocity parameter in the south of Dharwar Craton and the deep crustal resistivity picture is “poorly understood”. Further more, there is no change in scenario since Hjelt (1988) stressed the need for new MT field-works to modeling studies in the southern part of the Indian Peninsula.

In a global context, knowledge about the deep structure, composition and evolution of the region could contribute immensely to our understanding of the various geological processes like: accretion, deformation, uplifts and other dynamics associated with the lithosphere. They are fundamental to model the formation of continents at large. In the case of SISR, the structural and evolutionary models and the tectonic signatures associated with few shear zones, for example, the Moyar-Bhavani Shear Zone (MBSZ) and the Palghat-Cauvery Shear Zone (PCSZ) are not known till recently. The Department of Science and Technology, under Deep Continental Studies (DCS) program has
provided the necessary grant-in-aid for undertaking detailed integrated geological and geophysical studies along Kuppam-Palani geotranssect. As a part of integrated geophysical studies consisting of coincident reflection, refraction/wide-angle reflection, gravity, magnetics and magnetotelluric (MT) studies were carried out in the SGT. In addition, MT surveys were carried out along part of the well-known seismic profile, the Kavali-Udipi profile (Kaila et al., 1979) (Fig. 1).

The major tectonic units covered in the present study are part of EGGT, EDC and a Proterozoic sedimentary basin, the Cuddapah basin. Thus the present study is aimed to construct a deep crustal resistivity model and compare with available geophysical models of the largest expanse of unexplored continental lithosphere of SISR.

**Previous Geological and Geophysical Studies**

The Indian shield consists of the geological history of more than 3.2 Ga and distinct geological provinces (Naqvi et al., 1978; Drury et al., 1984; Radhakrishna, 1989). Dharwar Craton is one among them. The Dharwar Craton is divided into Western Dharwar Craton (WDC) and the Eastern Dharwar Craton (EDC) separated by eastern boundary of Chitradurga supracrustal belt. The WDC and EDC comprise of Archaean supracrustal belts, schist belts...
surrounded by Archaean gneisses and granites. The gneisses and supracrustal units developed between 3.4 Ga and 2.5 Ga where as rocks >3.0 Ga seem to be restricted to the WDC. Oldest crustal nuclei of the craton is recognized around the Holenarsipur Supracrustal Belt, which preserves the gneisses of 3.33 Ga and supracrustal rocks of similar age (Bhaskar Rao et al., 2003).

While Dharwar Craton can be divided into two distinct regions, the SGT is divided into three major crustal blocks—northern, central and southern blocks—based on differences in lithology, tectonics, radiometric ages (Yoshida et al., 1999) etc. The northern block is covered by the transition zone (Rameshwar Rao and Narayana, 1996). The exposure of many crustal-scale deep faults (Grady, 1971) and the important tectonic lineaments (Naha and Srinivasan, 1996; Chetty and Bhaskar Rao, 1998), for example, the MBSZ, the PCSZ and Achankovil Shear Zone (AKSZ) makes the history of the terrain more complex. These shear zones are assumed to have developed during Neoproterozoic period (Drury and Holt, 1980). As observed before, the SGT is made up of horst and graben-like structures and were rejuvenated and uplifted during the Neogene period (Radhakrishna, 1993; Valdiya, 1998).

The present profile traverses through Eastern Ghats on the east and Eastern Dharwar Craton (EDC) on the west including Proterozoic Cuddapah basin in the middle. Earlier and recent geophysical studies in this region include deep seismic sounding (Kaila et al., 1979; Reddy et al., 2000 and references therein), aeromagnetic studies (Archuta Rao et al., 1970), gravity and magnetic surveys (Glennie, 1932, 1951; Kailasam, 1976) and seismic tomography (Rai et al., 1993; Srinagesh and Rai, 1996; Kumar et al., 2001; Gupta et al., 2003; Sarkar et al., 2003).

Aravamadhu et al. (1970) estimated that for South India below the 16th parallel the average crustal thickness is of 30 km and prepared an isostatic anomaly map of South India. A correlation between surface geology and gravity anomalies along the 14th parallel in South India is observed (Qureshy et al., 1967) and opined that the Dharwar schistose rocks which are having relatively high gravity values. The Bouguer gravity map (Fig. 2a) shows a low Bouguer gravity values from east to west over the eastern margin of the basin with a gradient of more than 2 mgal/km and a distinct gravity low over the east-central part of the basin to the west of the eastern boundary. The major part of the decrease of the gravity values over the eastern margin is attributed to the faulted and overthrust eastern boundary (Kailasam, 1976). The negative gravity field over the Cuddapah basin is attributed to crustal down warping. An overlapping of the densities of the Archaean gneisses and granites with Cuddapah rocks is also observed (Reddi et al., 1967). The regional field brought a broad gravity low caused by crustal thickening in the western part of the craton covered largely by greenstone belts, while towards the east and north the moderate gravity high over the Closepet granite and gneisses suggest probable crustal thinning.

The aeromagnetic studies (Archuta Rao et al., 1970) in the southern part of the Cuddapah basin have identified three types of signatures—broad anomaly with negative and positive parts of amplitudes over 100 gamma corresponding to western part of the Cuddapah basin, a central flat zone in the central and eastern part of the Cuddapah basin and a zone of oscillatory trend on the EGGB.

The DSS studies (Kaila et al., 1979) have revealed the detailed crustal cross section (Fig. 2b). They have identified two low-angle thrust faults situated at the eastern margin of the Cuddapah basin and central part of the profile. Moho is mapped in the entire region and is continuous. The crustal thickness estimated varies between 35 km to 42 km and the thickest part is situated below the Cuddapah basin. Reddy et al., (2000) brought out significant velocity variations in the eastern and western Dharwar Cratons. The WDC has a low average velocity, thick crust with Moho lying at a depth of 40 km whereas higher average velocity and thin crust characterize the EDC with Moho at a depth of 37 km. The upper mantle velocity for the WDC and the EDC are 8.4 km/s and 7.9 km/s respectively.

Arora (1971) obtained a two layer crustal model with layers of 16 km and 19 km thickness with corresponding velocities of 5.7 km/s and 6.5 km/s followed by 8.0 km/s substratum in the Dharwar Craton based on Gauribidanur seismic array. 3-D seismic tomographic studies (Rai et al., 1993) reveal distinct differences in crustal and lithospheric thicknesses between EDC and WDC. Tomographic studies (Rai et al., 1993) also revealed higher velocities in the Dharwar Craton (1–3%) while the SGT has low velocities (~1 to ~3 %). From this it is inferred that the crust beneath the SGT is thicker by about 2 km than Dharwar Craton. Srinagesh and Rai (1996) have reported the results obtained from 11 (vertical-component) seismic stations covering Dharwar Craton and the SGT. The results imaged the correlation between the surface geology with the velocity image in the upper mantle to a depth of about 180 km. The Dharwar craton is characterized by 1–2% higher mantle velocity where as the SGT has a low velocity down to a depth of 177 km. Recent tomographic studies (Gupta et al., 2003; Sarkar et al., 2003) have revealed more thicker crust in the WDC compared to EDC—in consistence with Kaila et al. (1979). A simple crust with Poisson ratio of about 0.25 is estimated (Gupta et al., 2003; Sarkar et al., 2003).

As can be seen from the above discussion, it can be concluded that the Dharwar Craton is a well-studied region both geologically and geophysically, where as the SGT is...
less studied, especially regarding the geophysical signatures, till recently. The region has recently been investigated by detailed DSS and gravity along with MT. The DSS study (Reddy et al., 2003) revealed variation in crustal thickness and have shown a five-layer model consisting of a thick, mid-crustal low velocity layer in the region. Average thickness of the crust is estimated as 45 km. The gravity study (Singh et al., 2003) shows large variation in Bouguer anomaly with 'highs' and 'lows'. MT studies (Harinarayana et al., 2003; Naganjaneyulu and Harinarayana, 2003) also gave an evidence for the steeply dipping anomalous conductive features near the shear zones (PCSZ, MBSZ, and SASZ). Based on the spatial correlation of seismic reflectors, gravity values and conducting features juxtaposition of blocks due to continent-continent collision is proposed (Naganjaneyulu and Harinarayana, 2003).

**MT Survey, Processing and Modeling Results**

The MT method (Cagniard, 1953) is a frequency domain technique and facilitates probing the earth from shallow to deep crustal depths by employing a suitable frequency range. The location of MT stations along with tectonic map of the study area is shown in figure 1. MT data was acquired in the frequency range of 8192-0.001 Hz using GMS-05 units of M/s Metronix, Germany along a 300 km profile from Kavali to Anantapur with 21 stations. The data at station 4 is noisy and hence, we have considered the data of 20 stations only. The Cuddapah basin is covered with 9 stations and to the west of the basin with 5 stations and to the east of the basin with 6 stations. The station interval is in general is about 15 km. The coverage of the basin is so planned that the Cuddapah basin and related features on either side of the basin can be studied. The magnetic field components (Hx, Hy and Hz) were measured using induction coil magnetometers and a set of Cd-Cd Cl2 porous pots were used as electrodes for telluric field measurements (Ex and q). The electrode separation is about 90 m. The data are subjected to robust processing, decomposition and static shift corrections before deriving a 2-D model.

The impedance tensors were investigated to study for distortion effects and dimensionality. The observed increase in skew values with increasing period indicates deviation from 2-D nature of the subsurface structure. However, in the present study 2-D modeling is carried out. To estimate the regional TE and TM responses from the derived impedance tensor, McNeice and Jones (2001) multisite, multifrequency MT tensor decomposition code is used in the present study. This code is based on the galvanic distortion decomposition of Groom and Bailey (1989). It detects and partially removes the effects caused by local near surface inhomogeneities. Parameters obtained from the analysis are regional 2-D geoelectric strike, twist and shear at each site. A mean value of 17° for strike is obtained and it coincides with the regional geological strike of Cuddapah basin in southern part.

---

Fig. 2. Bouguer anomaly along the profile (a) Seismic section, (b) showing deep seated faults in the region (after Kaila et al., 1979).
the three parameters viz., strike, twist and shear are fixed. Figure 3 shows the apparent resistivity and phase in measured direction for a station 3 and in figure 4 the decomposed apparent resistivity and phase are presented.

Modeling exercise has been carried out using Rapid Relaxation Inversion (RRI) technique (Smith and Booker, 1991). The following steps have been followed in 2-D modeling. At first, the distortion corrected TE and TM apparent resistivity and phase data were undertaken using RRI technique. Neither structural features nor resistivity discontinuities are imposed during the inversion. To accommodate the possible static shift effects, we assigned error floors of 10% for the apparent resistivities and 5% for phase in the data set so as to decrease the weight of the apparent resistivities in the inversion process. Such a procedure is followed by earlier workers (for example, Brasse et al., 2002). The RRI inversion approach determines the resistivity model with least structure most consistent with the data. The 2-D model obtained in the inversion scheme after 41 iterations with an RMS error of 1.42 is shown in figure 5. The apparent resistivity pseudosections for observed and computed data in TE and TM modes are shown in figure 6. Comparisons between the phase data and model responses are shown in figure 7 for individual stations.

The results from the model are summarized here. The depth of the basin varies from west to east with a maximum thickness of sediments is about 10–12 km and

Proterozoic Cuddapah basin is demarcated with low resistivity. The model (Fig. 5) show a resistive crust (~10,000–30,000 ohm-m) to a depth of 8–10 km towards west of the Cuddapah basin. The mid crust is less resistive (about 500 ohm-m) and the lower crust with a slight increase in resistivity (about 1,500 ohm-m) in the depth range of 20–22 km. The resistivity picture to the east of the Cuddapah basin also showed a different deep crustal structure. The resistivity of upper crust is about 5,000 ohm-m and about 200 ohm-m for mid and lower crust. The sediment resistivity of Cuddapah basin is of the order of 15–20 ohm-m. No attempt has been made in the present study to map and/or distinguish different sedimentary rocks of the basin, as resistivities observed are very low. The deep crustal structure of the basin is not well resolved in the present study due to lack of penetration of signals.

Discussion

The MT model has revealed a distinct variation on either side of the Cuddapah basin when compared to it with anomalous electric resistivity in both horizontal and vertical directions i.e., all along the profile and also at the upper, middle and lower crustal depths. The results have also shown correlation with other geological and geophysical studies as discussed below.

The Cuddapah basin region is characterized by low resistivity values. The section shows resistivity values of
less than 20 ohm-m up to a depth of 10-12 km. As can be seen from the figure 2, two major faults - 7 and 9 - are bounding the low resistivity zone. Presence of dolerite dykes and sills characterize the region between the faults 8 and 9. A broad gravity high of 45 mGal is observed in the Cuddapah basin region with the peak between the faults from 8 and 9. The resistivity values observed in this region are very low, coupled with a broad gravity high and a broad magnetic anomaly, it can be concluded that the source could be of basic/ultra basic in nature, which is in conformity with the surface geology. The variation in resistivity is much low as such no attempt has been done to distinguish between different types of sediments within the basin in the present study.

Towards the east of the Cuddapah basin, earlier gravity studies indicated deepest Moho at about 41 km and updip of the Moho is indicated (Kaila and Bhatia, 1981). The model consists of a thin crust and a high density body in the EGGB region. Several anorthosite bodies all along the EGGB are present. Similar to western part of the Cuddapah basin, one would expect resistivity low in this region. The upper crust over Dharwar Super Group has shown less resistivity (~3,000 ohm-m) and the estimated thickness is around 6-8 km. The result has shown a good correlation with upper crustal density layer of about 8 km in this region.

The stations on the west to the Cuddapah basin have shown characteristics of a shield region i.e., high resistive upper crust, low resistive mid crust and a resistive lower
crust. So for comparison and/or characterization of the EDC, we have taken the model obtained in this region. The low resistive mid-lower crust is a normal feature, which appears in several parts of the shield regions (Jones, 1992 and references therein). Figure 8 shows an excellent correlation between electrical resistivity and seismic velocity parameters. In the absence of information on velocity variation, estimating the possible source for this low resistivity (high conductivity) is complicated as low resistivity can be explained in terms of presence of partial melt, fluids or minerals like graphite, sulphides etc. Based on velocities in the upper most mantle, Black and Braile (1982) predicted Moho temperatures. Reddy et al. (2000) reported $P_n$ velocity in EDC as 7.8 km/sec and estimated Moho temperatures above 800°C. Hence the possible source, which explains $P, P_n$ velocities and low resistivity, is attributed to local partial melting and fluids in the deep crustal depths.

Fig. 7. Comparison of Phase: For data and model response both in TE and TM modes.

Gondwana Research, V. 7, No. 4, 2004
Based on the variation of parameters viz., seismic velocity, Poisson's ratio and electrical resistivity values Jones (1981) classified the Precambrian shield regions and have shown that it is possible to identify rock types in the lower crust. Gupta et al. (2003) have estimated an average Poisson's ratio of 0.24-0.27 for SISR and interpreted felsic to intermediate granulitic composition. The low Poisson's ratio (–0.25) indicates abundance of Quartz in the crust or a more felsic upper crust with a Poisson's ratio lower than 0.25 and a mafic lower crust with a Poisson's ratio of above 0.25 (Sarkar et al., 2003). Such a composition will show a change in P-velocity models. Based on the typical Poisson's ratio around 0.25, transition of seismic P-wave velocity from 6.7 to 7.0 km/s at a depth of 20 to 37 km overlain by a mid crust with a velocity range of 6.2–6.7 km/s. The Moho is observed at 37 km. The resistivity structure (Fig. 5) shows 10,000–30,000 ohm-m for upper crust up to about 8–10 km underlain by a conductive (<600 ohm-m) mid crust up to a depth of about 25 km followed by a resistive (about 1,500 ohm-m) lower crust. A schematic electrical resistivity section (Fig. 8) for EDC (west of Cuddapah basin) based on the present study is showing good correlation with seismic velocity model (Reddy et al., 2000) of the region.

(2) DSS studies indicate depth to the basin decreasing progressively to 7–8 km towards the western margin where the basement faulted down to the west between the intervening steep faults. The Moho is also affected by the intervening faults cutting through the crust. The major faults within the basin maintained its steady gradient towards westward side. High conductive feature that indicating thick pile of sediments (about 12 km thick) is seen between the stations 10 and 15. It seems the deep faults 7 and 9 might have controlled the sedimentation process.

(3) The regional gravity and magnetic profile shows a marked decrease in gravity values of more than 80 m Gal towards the eastern part of the basin indicating a thrust with an estimated throw of the order of 12–14 km (Kaila and Bhatia, 1981). The depth to the basin at its eastern margin delineated from the present study is about 12 km, in conformity with the depths deduced from the gravity and seismic data. The thickness of conductive sediments seems to be more on the western side as compared to the eastern part.

Conclusions

MT studies were carried out using wideband MT systems across the Cuddapah basin along a 300 km long profile extending from Kavali in the east to Anantapur towards west in an ENE–WSW direction. Gravity and magnetic investigations, regional and detailed, supplemented by deep seismic sounding profiles in the Cuddapah basin have brought out the deep structural features of the basin, including the Moho. The major features from Kavali-Anantapur part of the Kavali-Udipi profile cutting across the southern part of the Cuddapah basin are shown in figure 2. The geology, tectonics and geophysical studies in the region have indicated more complex nature of the eastern end compared to western side of the Cuddapah basin. The present study has brought out the details of the basin as well as the deep crustal signature.

The details of the electrical resistivity, velocity and structural features and their relevance are described below:

(1) The velocity structure in EDC (Reddy et al., 2000) shows an increase in an upper crustal velocity from 5.9 km/s at surface to 6.2 km/s at a depth of 5–8 km. Lower crust has a velocity of 6.7–7.0 km/s at a depth of 20–37 km overlain by a mid crust with a velocity range of 6.2–6.7 km/s. The Moho is observed at 37 km. The resistivity structure (Fig. 5) shows 10,000–30,000 ohm-m for upper crust up to about 8–10 km underlain by a conductive (<600 ohm-m) mid crust up to a depth of about 25 km followed by a resistive (about 1,500 ohm-m) lower crust. A schematic electrical resistivity section (Fig. 8) for EDC (west of Cuddapah basin) based on the present study is showing good correlation with seismic velocity model (Reddy et al., 2000) of the region.
upper crust up to a depth of about 10 km underlain by conductive (<500 ohm-m) mid-lower crust.

(5) Integrated studies with major contributions from DSS indicate that the region consists of a number of fault blocks involving the crust, with a substantial relief in the Conrad, Moho and other discontinuities showing a layered structure in the horizontal direction and a block structure in the vertical direction.

(6) Poisson’s ratio around 0.25, seismic P-wave velocity from 6.7 to 7.0 km/s at the lower crustal depths and moderate electrical resistivity indicates that the lower crustal rocks are of intermediate composition in the Eastern Dharwar Craton.

Acknowledgments

The Department of Science and Technology, Government of India supported this work under the Deep Continental Studies (DCS) project. We would like to thank the Director, NGRI for all his encouragement and permission to publish this work. Participation in field work by Mr. V.T.C. Kumaraswamy, Mr. T. Srinivasulu and Mr. C. Manoj is acknowledged. We acknowledge the help given by Dr. Sharana Basava, Mr. Prasanth and Mrs. Aruna in preparing the figures.

References

Glennie, E.A. (1932) Gravity anomalies and structure of the Earth's crust. Prof. paper, Survey of India, No. 27.
Geophys., v. 66, pp. 158-173.