Electromagnetic imaging of magma across the Narmada Son lineament, central India

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Wide band magnetotelluric (MT) studies were undertaken over a 130 km long, approximately north-south profile in central India across the Narmada Son lineament (NSL) that runs through Indian peninsula in ENE-WSW direction and its contiguous region. The NSL and its contiguous zone in the study region consists of Narmada graben, Satpura horst and Tapti-Purna graben, which are arranged from north to south as this order within the zone. The obtained deep crustal resistivity structure shows two deep-seated conductive features, which locate below the Tapti River on the southern flank of the Satpura horst (South conductor) and below Dorwa on the Narmada graben (North conductor), respectively. Both conductive features have identical resistivities of 10–200 Ohm-m and extend from 7 km to about 50 km in depth. Integration with gravity, heat flow and the deep seismic reflection studies suggests that these conductive bodies may have different causative factors. The South conductor, which is embedded in a high heat flow and a negative Bouguer gravity anomaly area, seems to be due to magma intrusion into the crust leading to high heat flows in the region. On the contrary, the North conductor is not characterized by high heat flow however seismic reflectors in this region show a domal feature. It is thus conjectured that the north conductive feature may be caused by the tectonic activity and partially molten magma emplacement from the asthenospheric levels into the crust.
Key words: Magnetotellurics, resistivity, conductor lineament, magma, India.

1. Introduction

The central Indian crustal block has records the imprints of complex tectonic processes. These processes have being active since the Precambrian times, along the 1600 km long Narmada Son lineament (NSL) and its contiguous areas (Fig. 1). Some of the tectonic manifestations across this zone of weakness can be observed through seismicity, numerous gravity anomalies (Verma and Banerjee, 1992), the intense geothermal activity characterized by the high heat flow values, and hot water springs (Ravi Shanker, 1988). In spite of several systematic geophysical studies over the NSL, the tectonic processes and the crust mantle interactions in this region are rather poorly understood. Pascoe (1959) observes that at least the western part of the NSL has rift structure. The EW trending Satpura hill range is a prominent horst block extending over about 300 km and is flanked by the Narmada graben to the north and the Tapti-Purna basin to the south (Fig. 1) (Verma, 1986).

Under the project CRUMANSONATA, Geological survey of India conducted geological and geophysical studies for delineating the crust-mantle configuration in NSL region. Venkata Rao and Nayak (1995) indicated the dense basic bodies aligned ENE-WSW at a depth of 5 to 6 km are mantle derivatives to have ascended through tensional faults in the mid crustal layers based on the gravity studies carried under

this project. The deep seismic sounding results do not indicate any significant channel or crustal fracture zone for the magma chamber (Kaila *et al.*, 1985).

In order to obtain detailed geoelectric structure in this region and also to identify the presence of magmatic bodies within the crust, wide band magnetotelluric (MT) studies were undertaken over a 130 km long, approximately NS profile, between Barwa and Edlabad. The locations of MT sites along with the major tectonic elements are shown in Fig. 1. Also shown here are the traverses covered by deep seismic sounding (DSS) studies (Kaila *et al.*, 1985) and deep electrical resistivity studies (Venkata Rao, 1997). The MT profile passes through the Narmada basin in the north, the Satpura range and the Tapti-Purna basin in the south.

2. Geophysical and Tectonic Studies

The study region is located over the Deccan flood basalts with a thickness varying between 100 and 2000 m. These Deccan basalts are underlain by the Gondwana sediments (Permian and Mesozoic) to the south and the Vindhyan and Bijawar sediments (Proterozoic) to the north of Dorwa. The basement is delineated at depths varying between 800–3000 m beneath the sedimentary sequences. The Deccan basalts are overlain by a thin alluvial cover in small patches on the southern part of the profile. From DSS studies over the Ujjain-Mahan profile (Fig. 2), Kaila *et al.* (1985) have reported about 1000 m thick Deccan basalts to the south of Nepanagar, which thins down to about 400 m in the Tapti-Purna basin to the south and to about 100 m in the NSL re-
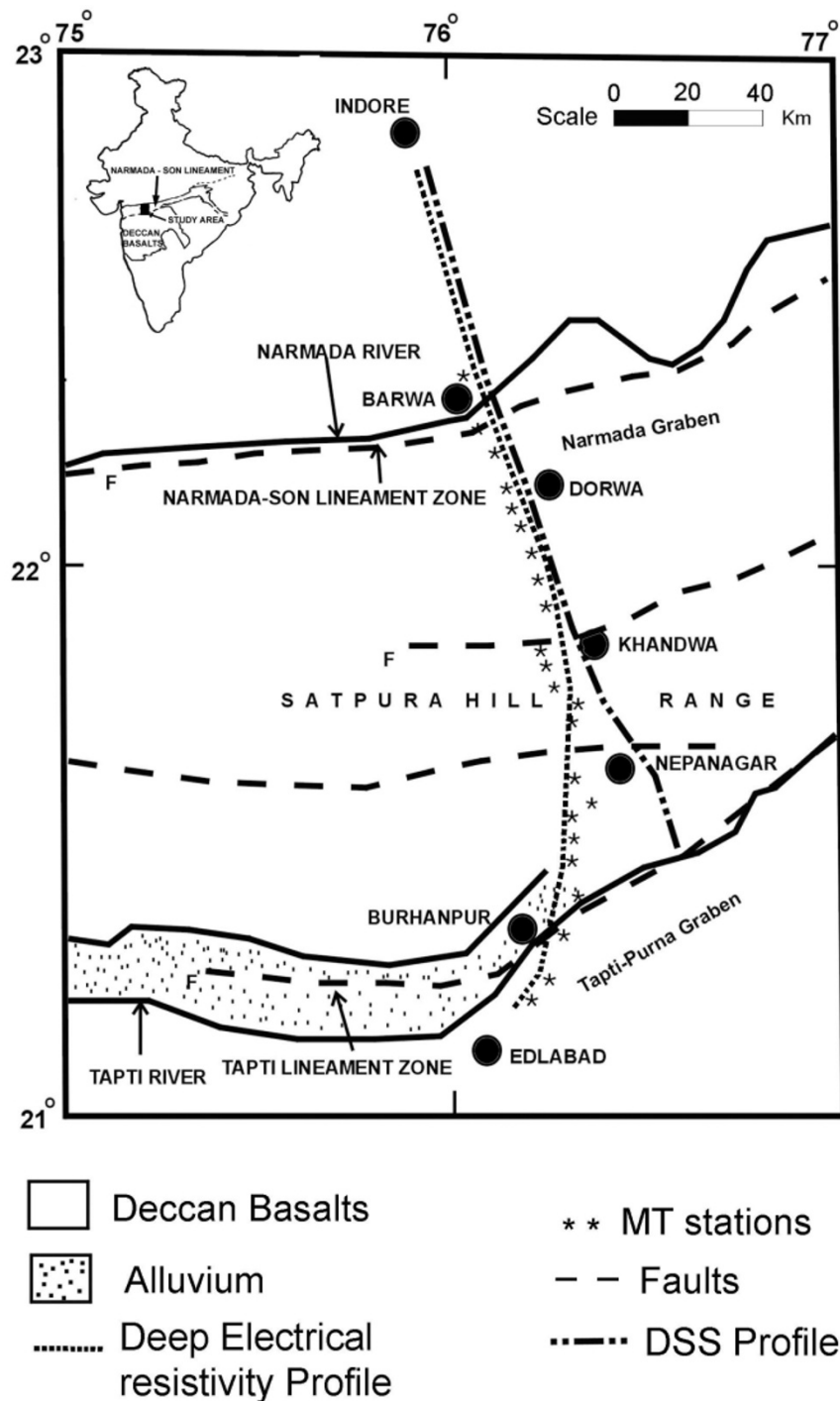
Fig. 1. Tectonic map of the Satpura region and surroundings, showing the locations of the MT sites. Profiles covered using the Deep seismic sounding studies (Kaila *et al.*, 1985) and Deep electrical resistivity studies (Venkata Rao, 1997) are also marked here.

gion to the north. Also shown on the top part of Fig. 2 are the observed and modeled Bouguer gravity values along the profile (Verma and Banerjee, 1992), which will be discussed later. Two deep-seated faults are reported from the observed deep crustal reflections, one below Dorwa and the second below Nepanagar. The Dorwa fault (Fig. 2) demarcates the Vindhyan and Bijawar sediments to its north from the Gondwana sediments to the south with thickness of Gondwana sediments varying between 300 and 1700 m. The Vindhyan and Bijawar sediments have a total thickness in the range of 500–800 m. Based on the deep crustal reflection

patterns obtained from the DSS studies, Kaila *et al.* (1985) have identified four tectonic blocks in the crust (marked in Roman numerals in Fig. 2) which may have exhibited vertical tectonic movements at different times in the geological past. The block III in the south of Dorwa may have moved upward during the Precambrian, thus forming the Vindhyan sedimentation over the block II. Subsequently, in the Gondwana period, the vertical movement may have occurred in the opposite direction, resulting in the sedimentation of the Gondwanas over the block III. The MT profile is located over the blocks II, III and IV as shown in Fig. 2.
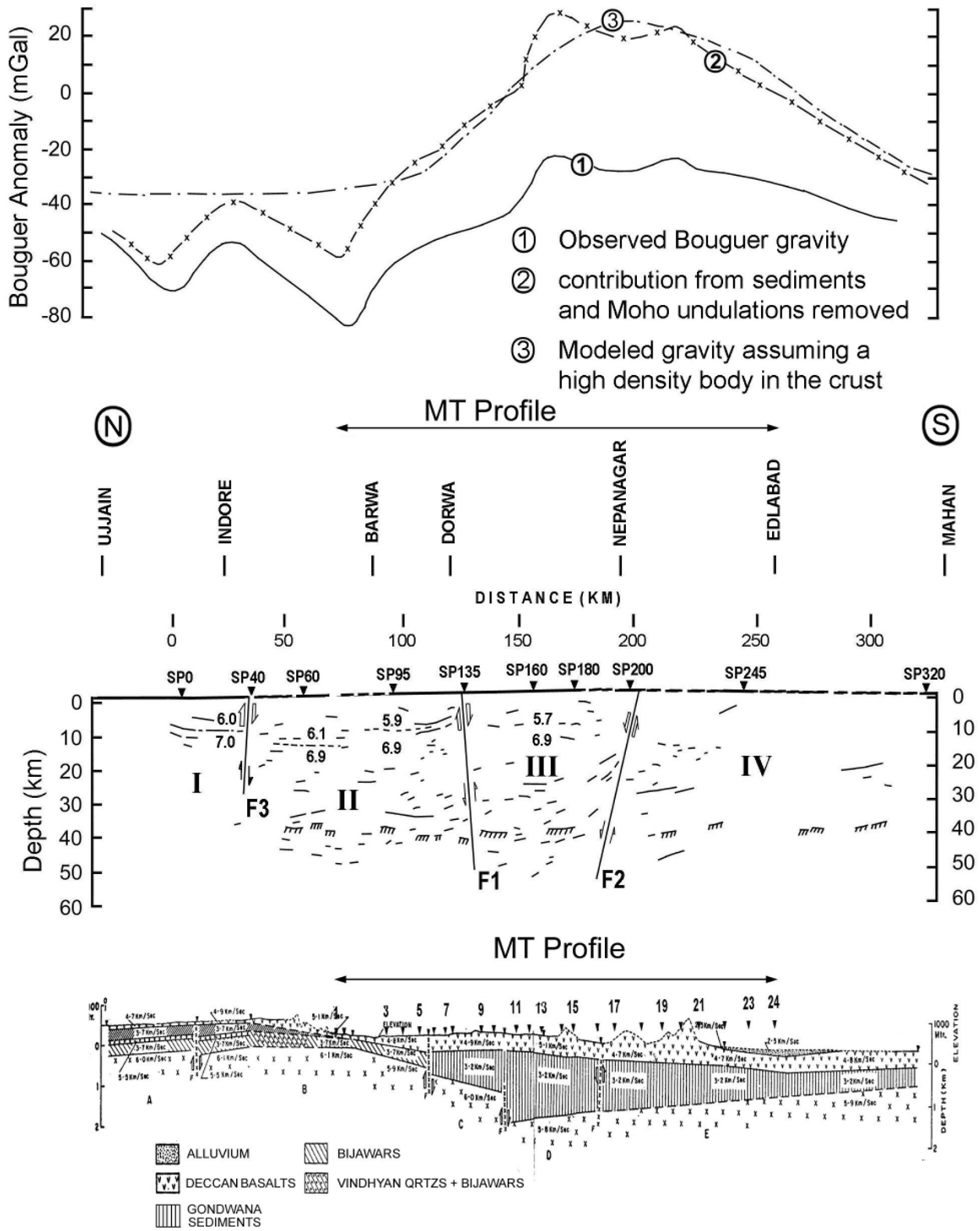
Fig. 2. Deep and shallow crustal structure obtained from the deep seismic sounding studies (redrawn from Kaila *et al.*, 1985). Also shown in top part of this figure are the observed and modeled Bouguer gravity values along the profile (redrawn from Verma and Banerjee, 1992).

The Bouguer gravity contours over the Satpura horst region (Kailasam, 1979) are shown in Fig. 3 along with the locations of the MT stations. The Bouguer gravity map shows a number of prominent gravity highs and lows. The different gravity highs and lows observed in Fig. 2 are indicative of marked zones of uplift and subsidence. The Bouguer grav-

ity shows a local high in the central part of the MT profile. Verma and Banerjee (1992) interpreted the Bouguer gravity high along this profile using the depth constraints from the DSS studies. These results are shown in Fig. 2. Here the curve (1) is the observed Bouguer gravity. Curve (2) is obtained after removing the contribution from the sedimentary
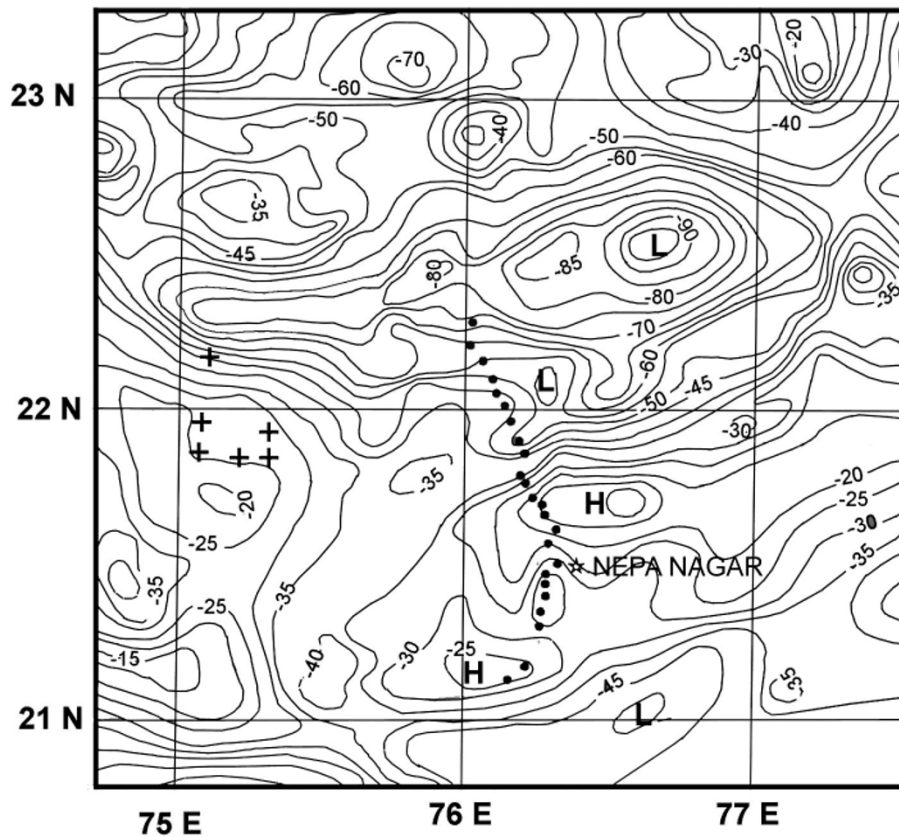
Fig. 3. Bouguer gravity over the Satpura region and surroundings (after Kailasam, 1979) and + symbol indicates thermal springs (Ravi Shanker, 1988).

layers as well as the Moho undulations. In order to get a reasonable fit to the observed data (denoted by the curve (3) in Fig. 2), a body with an average density of 2.95 gm/cm^3 considered by these authors. The velocity structure (Kaila *et al.*, 1985) indicates that crustal velocities corresponding to these depths are higher in this region i.e. in the blocks III and IV than those in the blocks II and I in the north. Based on these observations, Verma and Banerjee (1992) have proposed that the intermediate and deep crust in the Satpura block may be rich in the basic and ultra-basic materials such as the amphibolites and gabbro.

A close observation of the deep crustal reflections (Fig. 2) reveals several systematic trends in the crustal reflectivity pattern. The seismic reflections near the fault at Dorwa are dipping to the north at depths between 5 and 10 km. This band of reflectors seems to define the reflective top of a body at those depths. Similar trend is observed in the north and south of the fault at Nepanagar at depths between 15 and 25 km. This band of reflectors at Nepanagar shows a remarkable continuity to the north, almost up to the shot point 135 and it seems to extend to depths below Moho in several places between the shot points 135 and 180. Kaila *et al.* (1985) as well as Verma and Banerjee (1992) have not considered these trends in the dipping reflections in their interpretations.

The integrated geophysical studies conducted under the project CRUMANSONATA by Geological Survey of India, to decipher the crust-mantle interaction resulted in bringing up a model for the central Indian region. Venkata Rao and Nayak (1995) presented an integrated model for shallow crustal section using all available data. The authors showed

that the sedimentary thickness along the present profile is around 1–1.5 km. The basement structure inferred from resistivity surveys suggests an asymmetrical half graben. The quantitative analysis of gravity high observed along this profile (Venkata Rao and Nayak, 1995) indicated the causative feature for this anomaly to be at a depth of 5 km.

Based on the deep resistivity and residual gravity studies, Venkata Rao (1997) has proposed an alternate interpretation to explain the deep crustal processes in the Satpura horst region. He has provided an explanation for the high Bouguer anomaly in the Satpura horst region, based on magma emplacement in the upper crust in the form of dyke intrusions. The shallow structure obtained from the deep electrical resistivity studies is in reasonable agreement with the DSS studies. These studies indicate the electrical resistivities of the Deccan basalts and Gondwana sediments to be in the range of 50–100 and 20–150 Ωm, respectively and thus these two formations have overlapping electrical resistivity values. The Proterozoic sequences of the Vindhyan and Bijawar sediments are reported to have electrical resistivity in the range, 400–800 Ωm. Naskar *et al.* (2002), based on electrical resistivity surveys, identified a fault at the central part of Satpura horst with variable thickness of Deccan trap (61 m to 900 m) along the profile. The resistivities of different formations along the profile are similar to that of Venkata Rao (1997).

Nayak (1990) synthesized the results available from geomorphological, geological and geophysical data from the study region and interpreted the dipping seismic reflectors in terms of deep structural features. The viscous mantle material ascending through the crustal faults appears to have
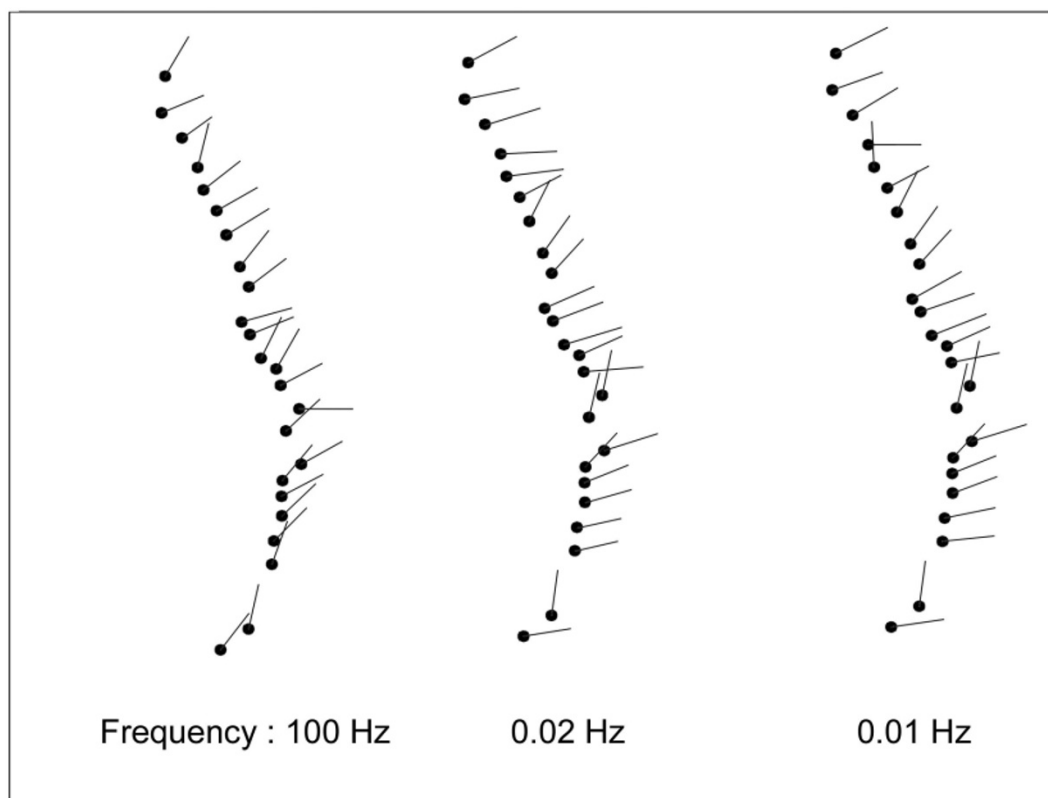
Fig. 4. Strike angles obtained from the Groom Bailey tensor decomposition at all stations at frequencies of 100 and 0.01 Hz.

collected at the base of the crust forming magma chambers.

Raval and Veeraswamy (2000) have observed that the NSL and adjoining regions form a zone of crustal weakness. The outburst of the Reunion plume on the western India landmass would have had strong effects on the geothermal state of the deep crust in the Vindhyan region. The geothermal studies (Ravi Shanker, 1988) over the NSL and adjoining regions indicate high heat flow values in the range, 100–130 mWm^{-2} over the Satpura horst block and the Tapti-Purna basin. The locations of the hot water springs (marked (+)) reported in the vicinity of the study area shown in Fig. 3 along with Bouguer gravity over the Satpura region and surroundings and MT stations.

Short period (100–0.01 Hz) magnetotelluric studies in the Satpura region (Rao *et al.*, 1995) delineated a prism shaped conductive feature (20Ω m) in the upper crust, which was related to a possible intrusion of mantle material in the shallow crust. In view of the subsequent developments in the data interpretation techniques and also for obtaining the electrical information in the deeper parts of the crust, this region was revisited with a wide band MT system and studies were undertaken over the Barwa-Edlabad region.

3.   Data Acquisition and Analysis

Magnetotelluric soundings were carried out over a 130 km long approximately NS profile between Barwa and Edlabad. Data were recorded at 24 stations with an inter-station spacing of 5–10 km in the frequency range, 320–0.0005 Hz using the Phoenix V-5 system. Here the electric field components were measured as the voltage between pairs of lead—lead Chloride electrodes, placed 80–100 m apart and the magnetic

field, using the induction coil magnetometers. Data were analyzed using a single site analysis procedure. The analysis was done using the robust processing technique (Jones and Jödicke, 1984) for obtaining the auto and cross power spectra required for computing the frequency variation of the apparent resistivity and the phase of impedance. The robust processing technique (Jones and Jödicke, 1984) using good remote reference data, does improve the magnetotelluric transfer function estimations. For noisy data, using good remote reference site, the data will be substantially improved in the frequency range of 10 Hz to 0.1 Hz and in other frequencies, the E-bias and H-bias is reduced.

The response functions (apparent resistivities and phases) at the individual frequencies were decomposed using the Groom and Bailey (1989) tensor decomposition procedure at all the stations. The unconstrained decomposition parameters indicated a stable shear at most of the stations. The shear value was fixed at its median value and the tensor decomposition procedure was repeated. This resulted in a reasonably stable frequency dependence of the twist and strike angle. The twist was then varied in the vicinity of its median value to further stabilize the frequency variation of the strike angle. The strike angles at all the stations in the high (100.0 Hz) and low (0.01 Hz) frequency range are shown in Fig. 4. The low frequency strike angles are reasonably stable at most of the stations and are aligned along the N20°W direction within about 10 degrees. It was thus assumed that the regional strike direction is either along the N20°W or perpendicular to it (N70°E). The prominent tectonic features and also the gravity contours show a predominantly ENE-WSW alignment in this region. In view of this fact, the geoelectric
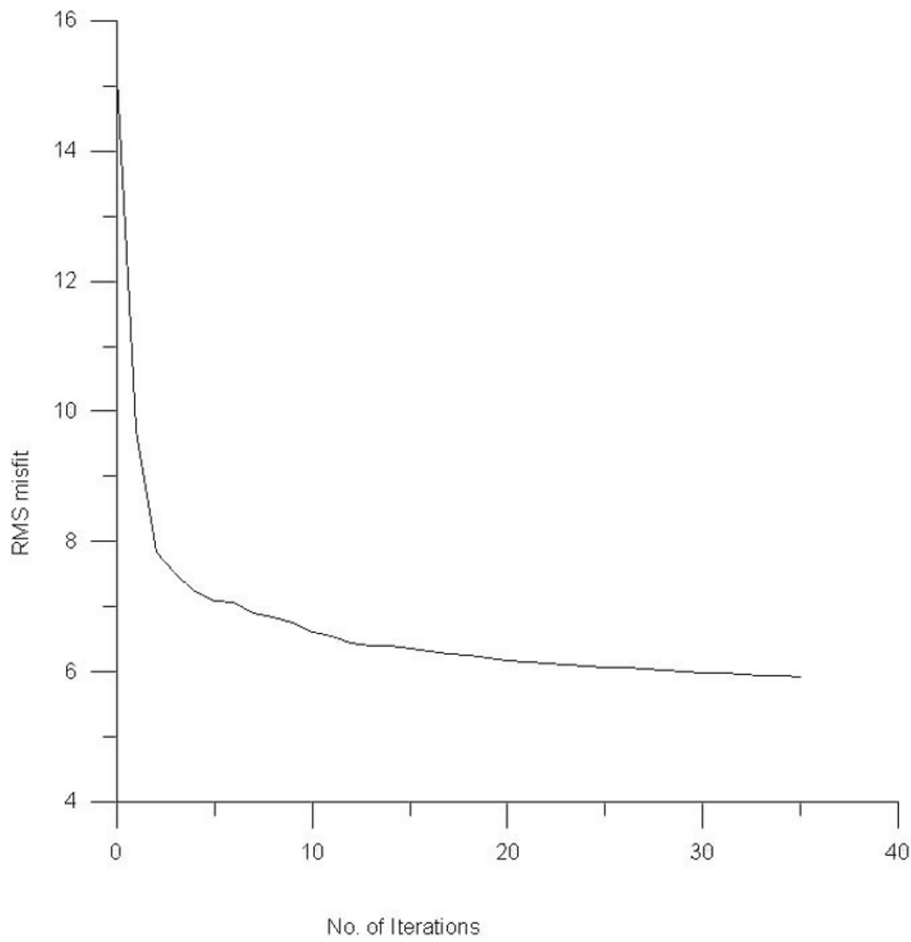
Fig. 5. RMS misfit of data after 2D inversion.

strike was assumed to be along N70°E. The response functions along this direction were assumed to be the TE mode values and that of perpendicular, the TM mode values.

3.1 Static shift considerations

As mentioned earlier, the study region is located on Deccan flood basalts, overlying the sedimentary sequences of Gondwana to the south and Vindhyan and Bijawar group to the north. The resistivity values of the Deccan basalts and Gondwana sediments are in the range of 50–100 and 20–150 Ωm with a significant overlap. Thus this parameter may not be appropriate to use as a key layer for the static correction (Jones, 1988; Ogawa, 2002). The depth to the basement of the sedimentary sequences is known from DSS as well as the deep electrical resistivity sounding studies. But the bottom of the conductive layer is not a well-constrained parameter in the MT response functions. Moreover, in view of the composite nature of the top conductive layer (Gondwana, Vindhyan and Bijawar sediments as well as the Deccan basalts), the conductance of the top layer is not suitable for the effective correction of the static shifts. Thus the available information on the crustal structure from the other studies was considered inadequate for the static shift correction.

Jones and Dumas (1993) have used a procedure based on the assumption that the low frequency MT responses show only smooth spatial variations. Under the assumption of a laterally uniform deep structure, they have shifted the TE apparent resistivities to the averaged low frequency value at all stations. But in the place like NSL region where there were intense vertical movements and tectonic activity, the procedure by Jones and Dumas (1993) may not be a good choice. Wu *et al.* (1993) have used a procedure based on the inversion of phase data to overcome the static shift. We followed the procedure similar to Wu *et al.* (1993). Here we included apparent resistivity data at all frequencies with error floor set at 100% in inversion. The error floor for phase data was set at 5% i.e. 1.45°. Inclusion of small amount of information is necessary to recover the complete resistivity response (Wu *et al.*, 1993). Thus we inverted TE and TM mode data with error floor of 5% using the 2D inversion program of Rodi and Mackie (2001). The RMS misfit is 5.92 after 35 iterations. Beyond this the RMS value remained constant (Fig. 5). The data fit of forward responses for TE and TM phase is shown in Fig. 6.

4. Interpretation and Discussion

4.1 Shallow crustal section

The shallow geoelectric cross-section in the top 5 km is shown in Fig. 7. The bottom of the Deccan basaltic layer and sedimentary sequences as delineated from the DSS studies are superposed on the geoelectric cross section for a comparative assessment. The geoelectric cross section shows a conductive top layer with resistivities in the range, 20–200 Ωm with a thickness ranging from 500–3000 m at most of the stations. The thickness of the conductive top layer is about 1.5
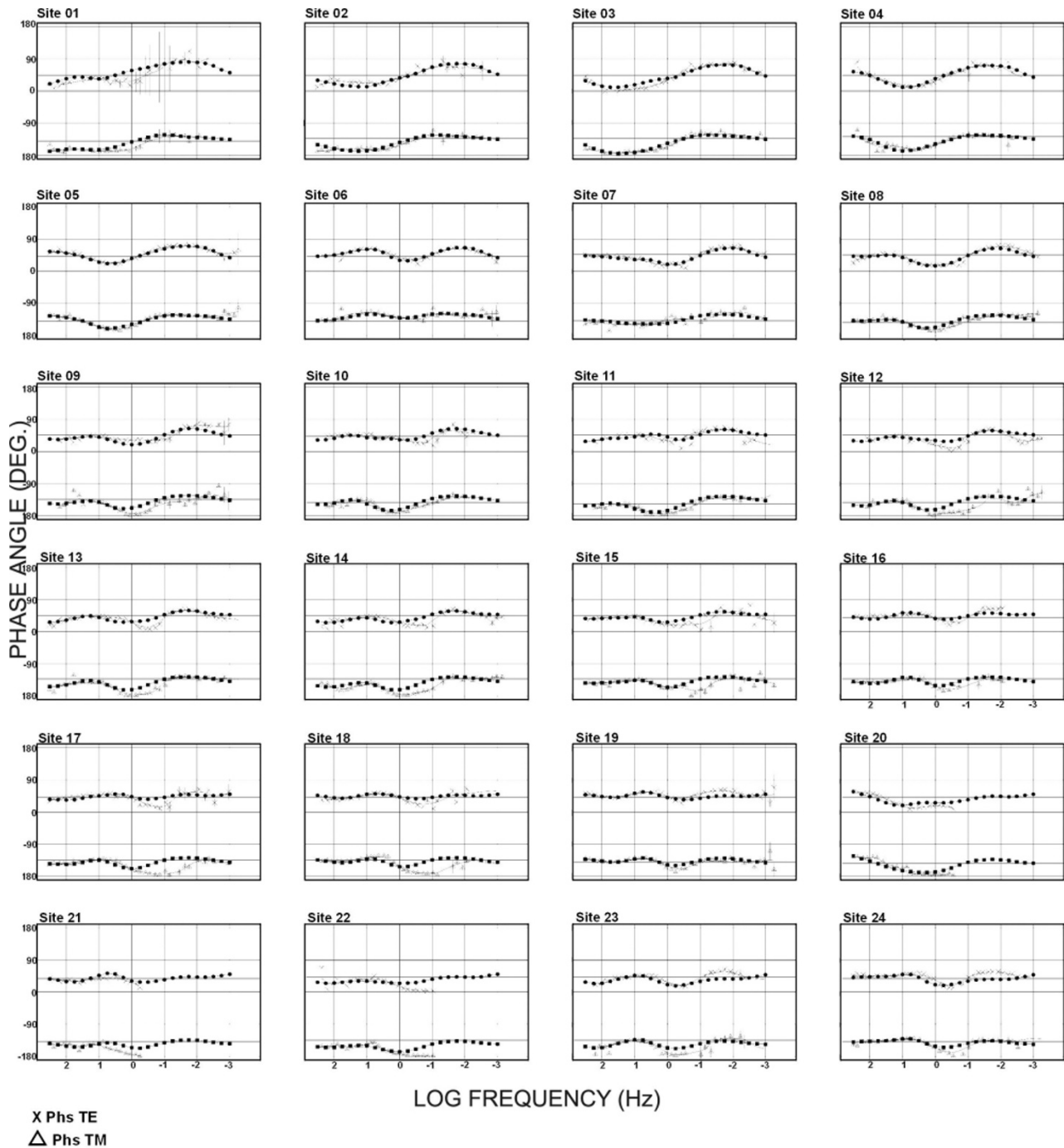
Fig. 6. Observed and modeled phase verses frequency curves for the TE and TM modes.

km at station 14 and gradually increases towards the south to about 2.5 km at station 19. Further south it decreases to about 1.5 km near station 24. These observations are in fair agreement with the total thickness of the Deccan basalts and Gondwana sediments estimated from the DSS studies (Kaila *et al.*, 1985) and also from the deep electrical resistivity studies (Venkata Rao, 1997; Naskar *et al.*, 2002). The 2D forward modeling of short period MT data (Rao *et al.*, 1995) corroborates the present results. Although a conductive layer is delineated in short period as well as in wideband MT surveys, it is difficult to differentiate between Gondwana and Deccan basalt formations due to overlapping of resistivities. Venkata Rao and Nayak (1995) identified the Gond-

wana sediments and Deccan basalts by judicious projection of exposed geological formations using combination of different physical parameters. The total thickness of basalts and sediments together along the profile closely matches with the resistivity section obtained from magnetotelluric studies. In the north of station 8, the high conductivity layer extends to a depth of more than 3 km, whereas the total thickness of the Deccan basalts and the sedimentary sequences in this region is known to be less than about one km. Thus the high conductivity feature seems to intrude deep into the basement. The upper crustal velocity in this region is about 5.9 km/s, but it is higher in the northern part with values of 6.0 and 6.1 km/s. It seems that the upper crust here may be fractured in this
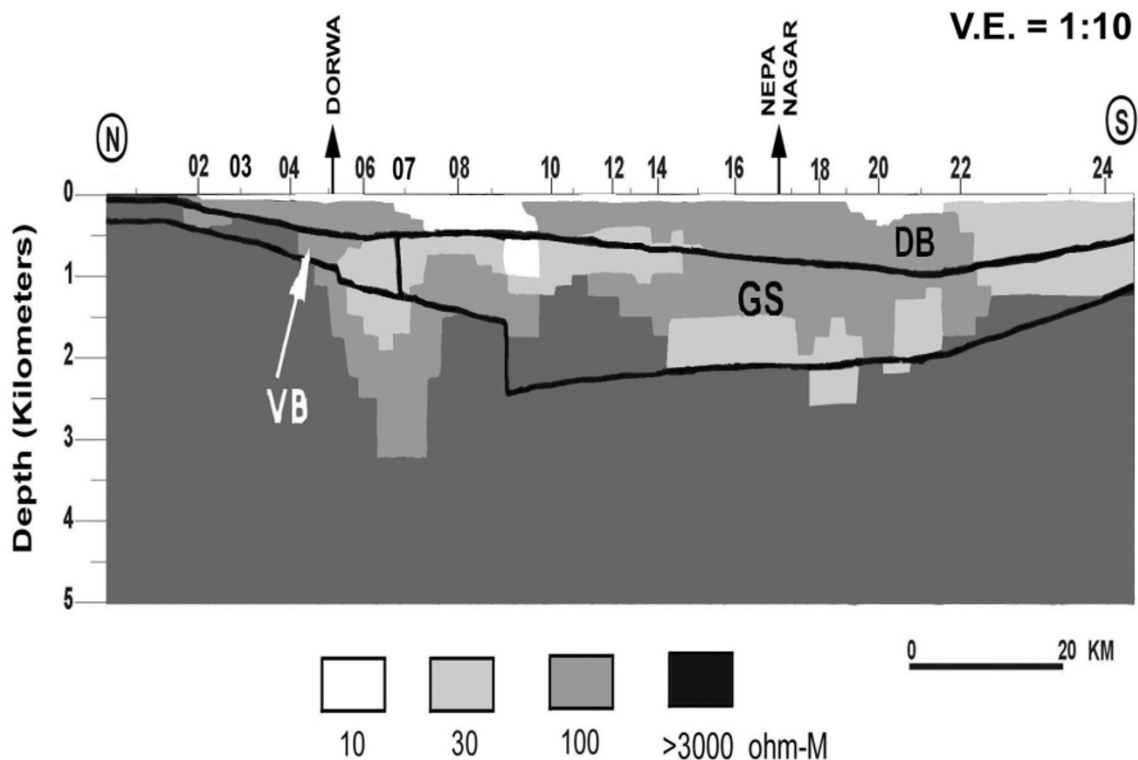
Fig. 7. Geoelectric structure for the shallow section. The Deccan volcanics and sedimentary layers obtained from the DSS studies (Kaila *et al.*, 1985) are overlain on the electric cross section for comparison sake. Here DB indicates the Deccan basalts, VB: Vindhyan and Bijawar sediments and GS: Gondwana sediments.

region, thus leading to the high conductivity and low seismic velocity. However this simple explanation does not hold good in the south of station 8, where the upper crust has a high electrical resistivity coincident with even lower seismic velocity of 5.7 km/s. It is evident from the seismic velocity structure (Kaila *et al.*, 1985) that the crustal blocks in the north and south of Dorwa (stations 7 and 8) have different configurations and possibly different chemical compositions (Verma and Banerjee, 1992). Again the geothermal and tectonic settings on the either side of Dorwa are different. Thus the reasons behind this discrepancy are not immediately apparent.

4.2 Deep crustal section

The deep geoelectric structure of the crust is shown in Fig. 8. Two deep-rooted conductive bodies are delineated here, one between the stations 3 and 7 and the second in the south between stations 18 and 21. In the discussion to follow, these conductive bodies will be referred to as the north conductor and the south conductor, respectively. Signatures of both conductive bodies are traced between the depths of about 7 km to almost about 50 km with a resistivity of about 10–100 Ωm. It is not clear whether these two bodies rise from a common source, although there are some indications at depths below 50 km. The crust in the other parts is resistive up to depth of about 20 km, with resistivity of more than 1000 Ωm.

In order to study the other geophysical manifestations associated with these conductive bodies, the deep crustal reflections obtained from DSS studies (Kaila *et al.*, 1985) are overlaid on the deep electrical structure, as shown in Fig. 8. The Bouguer gravity along the profile (Verma and Banerjee,

1992) is also shown on the top part of this figure. A discontinuous Moho is observed beneath the south conductor, between stations 16 and 20 and also further south between stations 22 and 23, indicating that either the Moho could not be delineated here or that it does not exist beneath this conductive feature. It may be noted here that the Moho is normally observed as a discontinuous layer in the seismic reflection profiles.

The top boundaries of the high conductivity of the south conductor show a close correspondence with the seismic reflectors and also with a local gravity low of about −15 mGal between stations 18 and 21. The heat flow measurements using the conventional drilling method as well as the geochemical method (Ravi Shanker, 1988) in close vicinity of the study region indicate that the southern part of the survey profile is located over high heat flow regime with heat flows in the range of 105–130 mWm^{-2}. The locations of the hotwater springs documented close to the survey region (Ravi Shanker, 1988) are marked in Fig. 3. From these observations, it is evident that the south conductor may be the result of the possible magma emplacement into the crust, thus leading to the high heat flows in this region. The partial melt and the evolution of the gases and fluids in the process of rising into the low-pressure regime of the shallow crust may be the cause of the high conductivity as well as the negative Bouguer gravity anomaly. The seismic reflection patterns observed at depth range of 10 and 20 km seem to be resulting from the solid-partial melt interface.

Based on the different seismic reflectivity patterns in the south and north of station 18, Kaila *et al.* (1985) proposed deep seated faults near the Tapti river and near Dorwa in
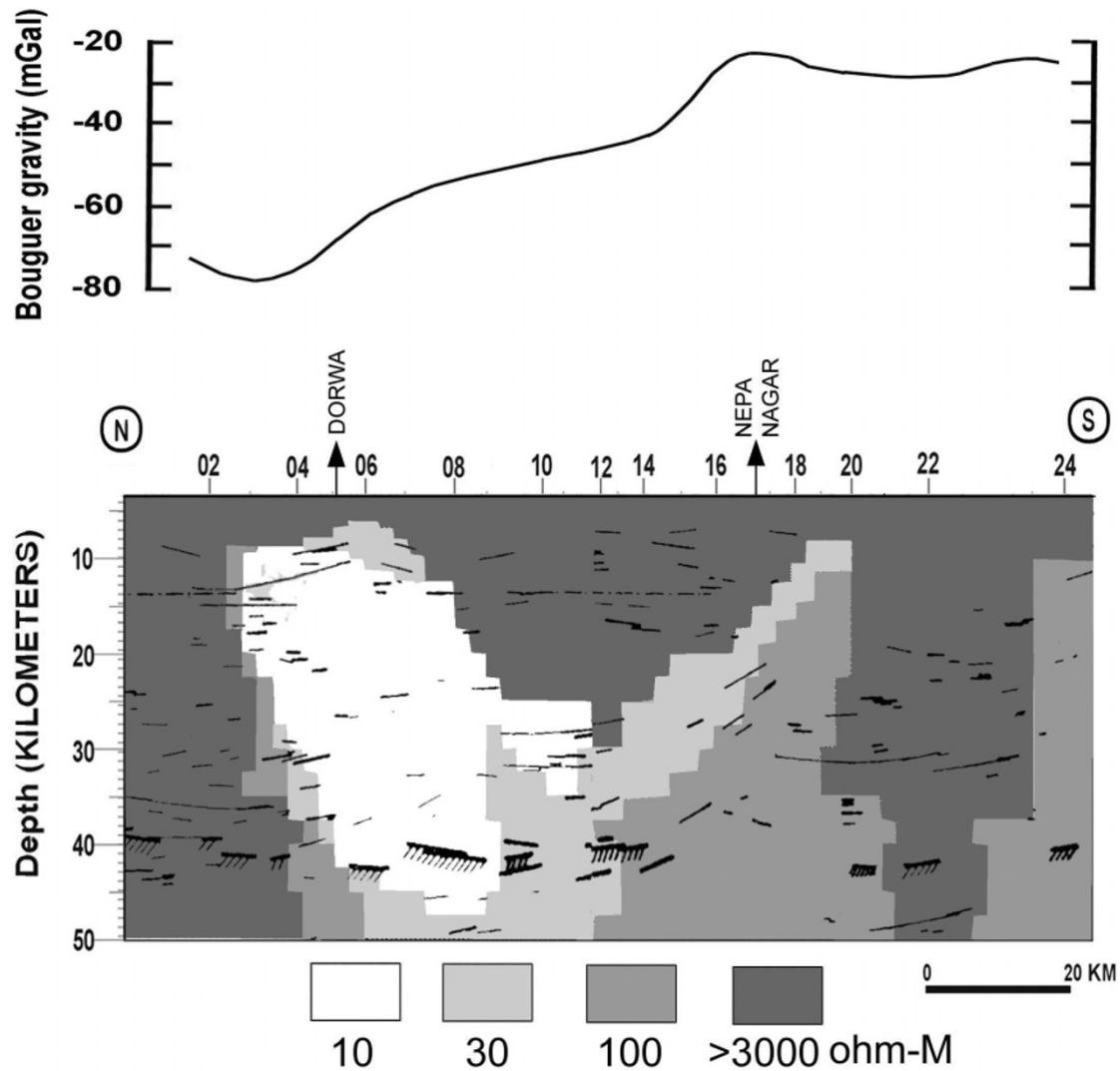
Fig. 8. Deep geoelectric cross section along with the crustal reflectivities obtained from the DSS studies (Kaila *et al.*, 1985). The Bouguer gravity variation along the profile is shown on the top part.

the close vicinity of the south and north conductors (Fig. 2). However, in view of the above discussion, it seems that the intrusive mantle material proposed here could adequately explain the geophysical observations. Again, the relatively undisturbed nature of the Deccan basaltic layer as well as the Gondwana sediments beneath the south conductor does not provide any support to the deep rooted fault here. The fault signatures are somewhat visible near north conductor. In Shallow section, the basement depth steeply increases towards south side of the station 4. This shows a fault indication, but in basement there is no change in the resistivity associated with this fault. The north conductor at a depth of 7 km again shows the fault signature.

The Moho level beneath the stations 6 and 7 indicates that the crust to the south of station 7 was uplifted by about 3–4 km relative to the crustal block to the north. The agreement between the observed reflectors and the top boundary of the conductive feature is good. The reflection patterns in the top 10 km show a domal shape in the crust beneath station 7. There are no hot water springs in this region. The interpolated heat flow values indicate that this region is located on the shoulder of the northward decreasing heat flow trend,

with a value of about 70 mW m^{-2} over this conductive body. The shallow structure discussed earlier indicated the possibility of intensely fractured basement in this region, as was inferred from the unusually low resistivities of less than 200 Ωm observed at the basement levels. The disturbed Moho discontinuity and the 3–4 km upward shift of the Moho in the southern block at stations 7 and 8 provide sufficient testimony to the intensity of the tectonic activity, which could result in a major fault extending to deep crust. Based on this observation, it may be reasonable to assume that the high conductivity in the shallow depths could be a result of accumulation of fluids in the fractured crust. The north conductor is located on the shoulder of the northward decreasing gravity trend and thus its manifestations in the gravity studies are not clear. Naik (1990) synthesized all the available data in the study region and showed that mantle derivatives from anomalous mantle reached the crust along the two crustal faults delineated from DSS studies (Kaila *et al.*, 1985). He also interpreted the continuation of mantle derivatives between these two faults. This result correlates well with our geoelectric section where the two conductors are connected. The short period MT studies (Rao *et al.*, 1995) reported a

prism shaped conductive feature composed of two distinct conductive zones, one at depth of 3.5 km and the other at 8 km depth from the surface with resistivity of 20 Ωm. The conductor at a depth of 8 km matches with the south conductor from the present profile. The depth of 3.5 km in earlier studies may be overestimated from 2D forward modeling in the process of obtaining a fit to resistivity data where the data quality is poor beyond 5 seconds.

The north conductor seems to extend even beyond the Moho depth, up to about 50 km. Again the lateral spread of nearly 30 km for this conductor does not justify the fault zone hypothesis alone. Thus the presence of fluids in fractured crust may not provide adequate explanation to the observed high conductivity here. As mentioned earlier, the reflection patterns in the vicinity of the south conductor show a northward continuation at depth up to and even beneath the Moho discontinuity. Based on the northward decreasing trend of the heat flow values (Fig. 3), it seems that the depth to the partially molten horizon decreases to the north. Thus it seems reasonable to assume that a significant contribution to this conductivity results from the partially molten magma emplacement from the asthenospheric levels into the crust.

5. Conclusions

Magnetotelluric studies conducted over the Satpura horst block and adjoining Narmada and Tapti basins have delineated two conductive features, one beneath Dorwa and the second to the south, below Nepanagar. Both these conductive features have resistivity of 10–200 Ωm and depth extent in the range between 7 and 50 km. Both the conductive features are similar in appearance. However, when viewed in the perspective of the deep seismic reflections, gravity and heat flows, it seems that the causative factors behind these conductive features may not be identical. The south conductor seems to be caused predominantly by the emplacement of magma from the deeper levels, which may exhibit a partial melting and fluid generation in the low-pressure regime of the upper crust. The north conductor seems to be a combined result of the fractured upper crust by the tectonic processes and the magma emplacement.

There are indications of possible deep crustal conductive bodies in the deep crust at station 24 to the south. However with the present station locations, this conductive feature could not be suitably constrained, and hence this is not discussed here.

The DSS studies (Kaila *et al.*, 1985) have delineated almost continuous reflections corresponding to the velocity transition to 6.9 km/s at shallow depth of about 10 km. The corresponding electrical resistivity in this region is higher than 3000 Ωm. Lower crustal resistivities at this depth are observed to be less than 1000 Ωm elsewhere in the south of NSL (Gokarn *et al.*, 2001) and also in the adjoining parts of Deccan volcanic province (Gokarn *et al.*, 1992). Thus the lower crust in the Satpura region seems to be anomalously resistive. Perhaps this region might have experienced several episodes of magma emplacement in the geological past. The magma may have subsequently cooled, thus leading to the high electrical resistivity concurrent with relatively higher seismic velocities in the crust beneath the Satpura horst block.

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