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Deep crustal structure in central India using magnetotelluric studies

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SUMMARY

Magnetotelluric studies over the Damoh–Jabalpur–Mandla–Anjaneya profile in central India have delineated Vindhyan sediments which are about 5 km thick in the Damoh–Katangi region. The crust below the Vindhyan sediments shows the characteristics of lower crust, as observed from the relatively lower resistivity of about 200 Ω m and high seismic velocities (*P*-wave velocities of 6.5 km s^{-1} compared with 5.8–6.2 km s^{-1} in the surrounding region). It is conjectured that the upper crust may have been completely eroded in the uplift and erosion process and thus the Vindhyan sedimentation has occurred directly over the lower crust. An anomalous conductivity is observed at depths of 10–12 km in the Vindhyan crust. The conductance of more than 1200 S observed here may be due to either the serpentinization of the mafic and ultramafic rocks or the presence of grain boundary graphites. The thickness of the Deccan traps is about 100 m near Jabalpur and decreases near Mandla. On the south of Mandla, the Archaean crust is exposed. Two crustal conductors are delineated below the Deccan volcanics with a resistivity of about 30 Ω m. The first on the immediate south of Jabalpur seems to mark the southern boundary of the Jabalpur horst block. The second conductor was delineated about 40 km southeast of Jabalpur, coincident with a positive gravity anomaly of about 30 mGal. Deep seismic sounding studies do not show any significant density contrast associated with this conductive feature. It is proposed that the gravity high may be due to the upwarp of the Moho. The high electrical conductivity is attributed to the fluids in the upper crust.

Key words: Deccan Traps, electrical conductivity, magnetotellurics, Narmada Son lineament, Vindhyan Basin.

1 INTRODUCTION

The Narmada Son lineament (NSL) is a major tectonic feature in the Indian subcontinent, characterized by a long history of crustal movements from the Precambrian era to as recent as Eocene times. Different parts of this 1600 km long ENE–WSW-trending lineament have been tectonically active at different times. Some of the characteristic geophysical manifestations over this zone of weakness are the intense seismic activity (Verma & Banerjee 1992), the relatively high heat flow values and the presence of hot water springs (Ravi Shanker 1988).

The NSL forms a divide on the Indian peninsula with predominantly higher Bouguer anomalies on the southern side than on the northern side (Verma & Banerjee 1992). There are numerous gravity highs and lows on either side of the NSL, indicating complex substructural formations. In spite of the extensive geophysical studies, the evolutionary aspects of this lineament are rather poorly understood. The complexity in the crustal structure seems to have arisen mainly as a result of the multiple crustal evolutionary processes of different tectonic origins, active at different geological times. Pascoe (1959) observed that at least the western part of the NSL has a rift structure, although there is sufficient evidence of the vertical tectonic movements as seen from the various horst and graben formations throughout the 1600 km length of this lineament. West (1962) has observed that the NSL is a major line of divide, separating the Vindhyan rocks to the north from Gondwana sediments to the south, and inferred that the crust on either side may have undergone intense differential vertical movements over extended periods in geological history.

Our studies represent an effort to understand the crustal structure in the region of the NSL over a 190 km long NW–SE-trending Damoh–Jabalpur–Mandla–Anjaneya profile using magnetotelluric (MT) studies. The study profile is shown in Fig. 1 along with the regional geology of the survey area. The region under consideration is located over the collision belt resulting from the Early Proterozoic collision between the Bundelkhand Protocontinent (BP) to the north and the Dharwar

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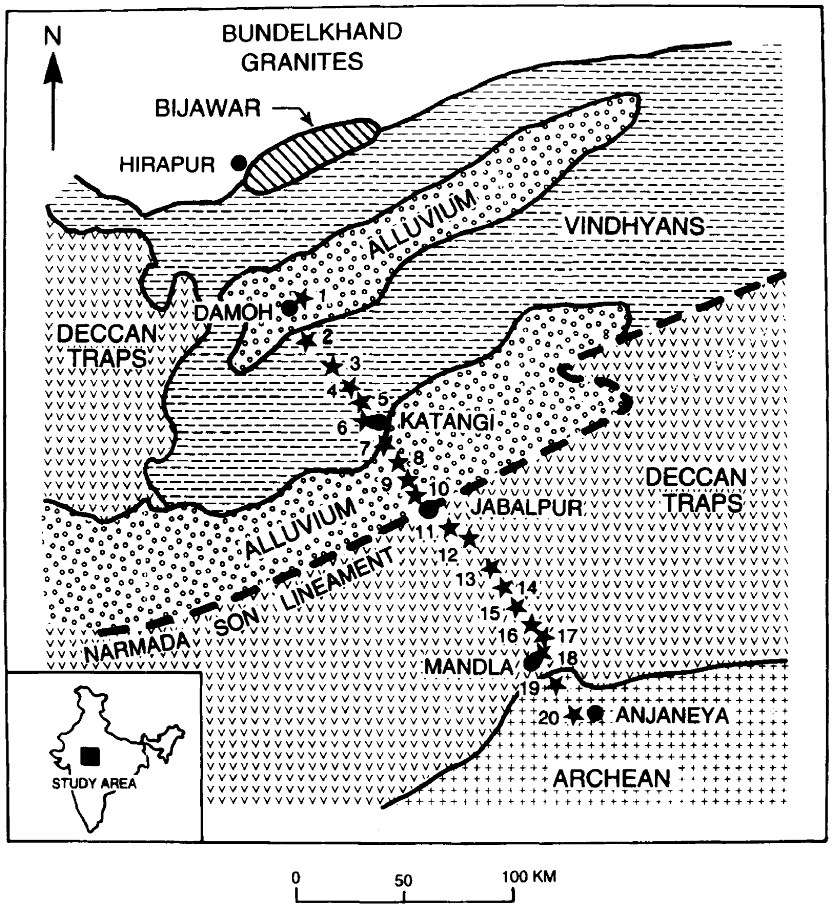

Figure 1. Geological map of the study area showing the locations of the MT stations over the Damoh–Jabalpur–Mandla–Anjaneya profile.

Protocontinent (DP) to the south (Yedekar *et al.* 1990), which resulted in the underthrusting of the BP below the DP. This suture, known as the Central Indian Suture, is located about 100 km south of Mandla. Thus the MT survey profile is located over the interface between the suture zone and the foreland basins.

2 GEOPHYSICAL STUDIES AND TECTONICS

The Vindhyan Basin is known to have formed as a result of the uplift and erosion of the pre-Vindhyan crust, which subsequently resulted in the graben formation. This graben was the site for the deposition of the Precambrian Vindhyan sediments. The shallow crustal structure reported from the deep seismic sounding (DSS) studies by Kaila *et al.* (1989) over the Hirapur–Jabalpur–Mandla profile is shown in Fig. 2. The MT survey profile coincides with the DSS profile between Damoh and Mandla. These results show upper and lower Vindhyan sediments in Damoh–Katangi with *P*-wave velocities of 4.5–4.8 km s^{-1} and 5.4 km s^{-1}, respectively, with a total thickness of about 5 km near Katangi. On the southeast, the basement is exposed below Jabalpur, near SP 135. The basement velocities are relatively high (6.5 km s^{-1}) in the Damoh–Katangi region, compared to 5.8–6.2 km s^{-1} in the other parts of the profile. From the results of 2-D inversion of the observed traveltimes, Kaila *et al.* (1987) have reported the Moho as a discontinuous layer over the entire DSS profile, at depths varying between 35 and 45 km. The Moho seems to be shallowest between Damoh and Jabera in the Vindhyan region and in the vicinity of Tikaria below the Deccan volcanics.

Mall *et al.* (1991) have reported that the thickness of 900 m for the Deccan traps observed by Kaila (1988) is anomalously large compared to the value of 100 m in the northeastern parts of the Deccan volcanic province. Such a discrepancy can be explained by considering an additional high-velocity layer beneath this region, which could not be resolved from the overlying trappean layer, thus leading to the anomalously high thicknesses of the Deccan traps. These authors reinterpreted the DSS data with constraints from the gravity data and proposed a high-velocity layer at depths of 6–8 km between Jabalpur and Mandla.

The Bouguer anomaly map of the survey region is shown in Fig. 3, after Verma & Banerjee (1992), who estimated the densities of the various rock types and crustal layers from the seismic velocities. Based on subsequent gravity modelling, they interpreted the gravity high between Jabalpur and Mandla in terms of a high-density body in the upper crust with a density contrast of $+0.1$ g cm^{-3}. Das *et al.* (1996) applied 2-D matched filters to isolate the gravity anomalies associated with the Moho. Estimates of the variations in Moho depth are in good agreement with DSS values wherever reported. The absolute values, estimated from gravity studies, are lower by about 5 km throughout. Verma & Banerjee (1992) have identified the positive Bouguer anomaly as part of the NE–SW chain of gravity features aligned parallel to the NSL.

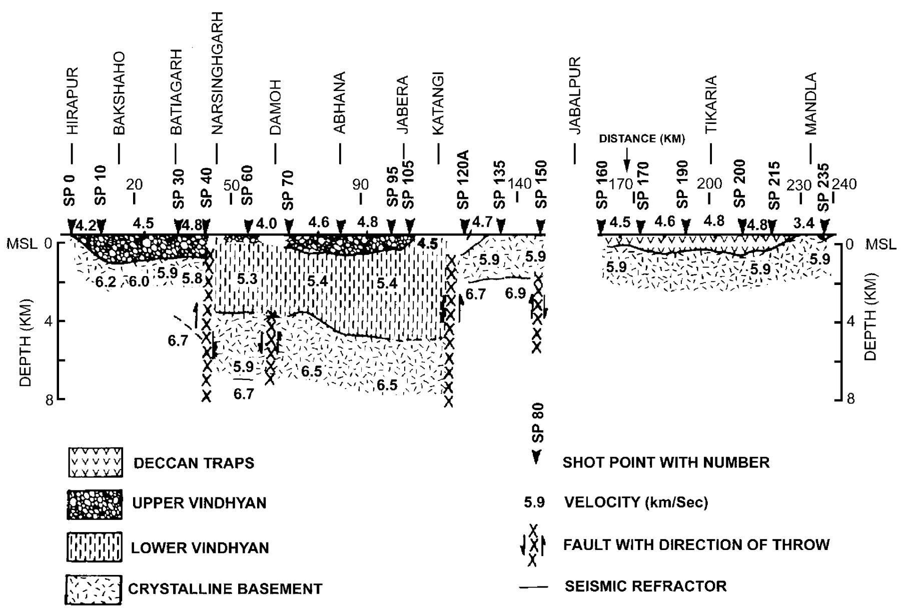

Figure 2. Crustal cross-section in the Hirapur–Jabalpur–Mandla region obtained from the deep seismic sounding studies (redrawn from Kaila *et al.* 1989).

From thin-sheet modelling of the geomagnetic depth sounding (GDS) data, Arora *et al.* (1995) have reported a conductive feature at a depth of 20–30 km, with a lateral extent of about 100 km below Jabalpur and Mandla, with a resistivity of about 5 Ω m. The position of this conductive feature corresponds to the high-velocity zone proposed by Mall *et al.* (1991) and the high-density body modelled by Verma & Banerjee (1992). GDS studies have delineated another conductive body on the north of Damoh, with a lateral extent of about 20 km, at a depth of 15–20 km.

No systematic heat flow studies exist over the region of interest here. However, this region is flanked on the east and

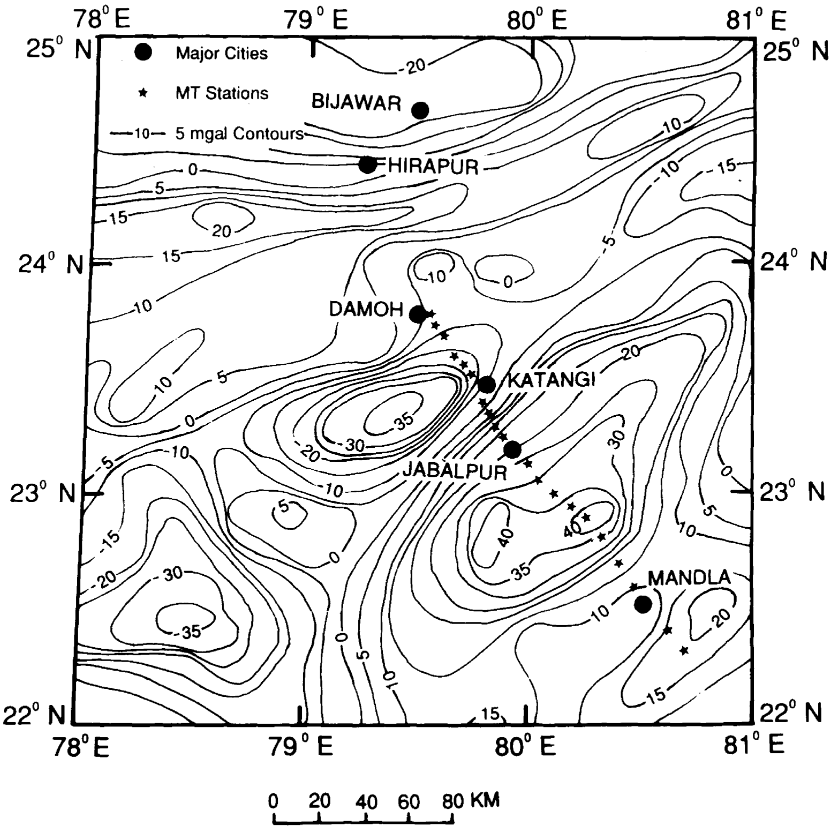

Figure 3. Bouguer gravity map of the study region (redrawn from Verma & Banerjee 1992).

west by the major thermal regimes of Tattapani and Salabardi, respectively, which are extensively covered by heat flow studies (Ravi Shanker 1988). Based on the averaged data interpolated over the present survey profile, the heat flows are expected to be about 130 mW m^{-2} in the Jabalpur–Mandla region, coinciding with the gravity high, and about 100 mW m^{-2} over the northern parts of this profile (Ramakrishna 1995).

In view of the observed high gravity anomalies, seismic velocities and electrical conductivities over the NSL region, Raval (1995) proposed that the region surrounding the NSL may be a mobile arm (Satpura mobile arm) between the stable cratonic nuclei of Bundelkhand to the north and the Dharwar to the south. Being relatively less rigid than the cratonic nuclei on either side, this region is vulnerable to the thermomechanical forces from deeper levels, making it the most likely area of uplift, doming, faulting and fracturing. The recent outburst of the Reunion plume at 65 Ma, about 700 km west, would have had strong effects on the geothermal state of the deep crust below the study area.

In order to obtain the geoelectric structure in this region, MT studies were undertaken in the Damoh–Jabalpur–Mandla–Anjaneya region. MT data were collected at 20 stations over the 190 km long NW–SE-trending profile, with a station spacing of 8–15 km (Figs 1 and 3). Two horizontal components of the magnetic field variations were measured using induction coil magnetometers, and the lead–lead chloride electrodes placed about 100 m apart were used for measuring the variations in electric field along the magnetic N–S and E–W directions. An air loop was used for measuring the vertical magnetic field variations. Data were collected in the frequency range 320–0.0005 Hz synchronously at two stations in the mutual reference mode using Phoenix V-5 MT systems.

The data were processed using the mutual reference procedure, wherein the horizontal magnetic field components measured at one station were used to eliminate the local noise at the other synchronized station and vice versa. A combination of fast Fourier transforms and cascade decimation techniques (Wight & Bostick 1980) was used to determine the auto- and cross-power spectra required for computing the frequency variation of the apparent resistivity and phase.

3 RESULTS OF THE MAGNETOTELLURIC STUDIES

The response functions at each site were decomposed using the tensor decomposition procedure (Groom & Bailey 1989). At most of the stations, the unconstrained decomposition at the individual frequencies indicated a reasonably stable twist, whereas the shear and strike directions were rather unstable. The twist was constrained to its median value. This resulted in a marked improvement in the stability of the shear and strike. The shear was then constrained and varied in the vicinity of its median value to obtain as stable a strike direction as possible, particularly at the low-frequency end (0.01–0.001 Hz). The rotation directions at stations 4–20 are along N50°E within about 15° (Fig. 4). The rotation angles at stations 1, 2 and 3 were unsystematic and did not show any preferred alignment. In view of the predominant ENE–WSW alignment of the geological features and also the gravity contours, N50°E was assumed to be the strike direction and the response functions along this direction were assumed to be the TE mode values and those perpendicular, the TM mode values.

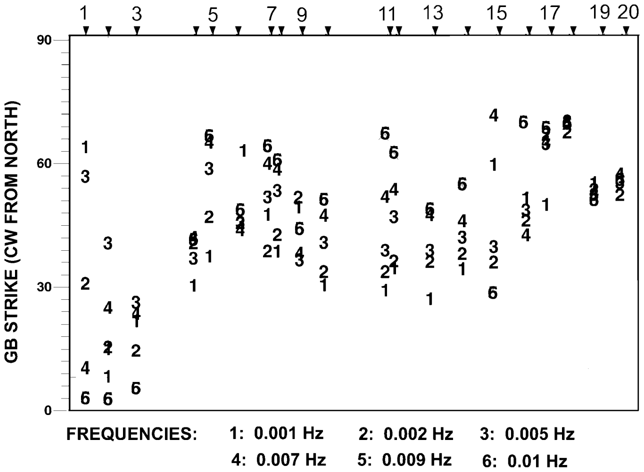

Figure 4. Rotation angles at low frequencies obtained after Groom–Bailey decomposition.

In order to correct the static shifts, the geometric average of the apparent resistivities in the TE mode in the low-frequency range (0.01–0.001 Hz) are obtained at all stations with similar deep resistivity structure. The apparent resistivity curves in the TE mode at the individual stations are then shifted on the logarithmic scale to coincide with the geometric average at the centre frequency (0.003 Hz) of the low-frequency band. The apparent resistivity curves in the TM mode are then tied to their corresponding TE counterparts at each station in the high frequency end (320.0 Hz). As mentioned earlier, the region under study is part of the foreland and suture between two Protocontinents. The correction of the static shifts thus needs to be made with some caution. On the basis of the observed phase pseudo-sections in the TE mode (Fig. 5b), the survey profile may be divided into two groups. The phases at all frequencies over stations 1–6 in the Vindhyan region show rather weak frequency and spatial dependences, indicative of weak vertical resistivity contrasts, whereas these variations are more prominent over stations 7–20 in the Jabalpur horst and Deccan volcanic regions. The crustal resistivity configuration seems to be different in these two blocks, which needs to be considered when correcting for the static shifts. Thus the MT stations were divided into two groups; Vindhyan group (stations 1–6) and the Jabalpur horst and Deccan volcanic group (stations 7–20), and the static shifts were corrected for in these two groups independently. The average resistivity levels for static corrections obtained from only six stations in the Vindhyan group, however, do not provide acceptable statistics. Thus the results of such corrections could lead to erroneous geoelectric sections and so have to be viewed with caution. This aspect will be further discussed later in Section 4.3.

The geometric average of the TE mode apparent resistivities in the Jabalpur horst and Deccan volcanic group was about 250 Ω m, and the TE resistivities at most of the stations show a decreasing low-frequency asymptote except at stations 8 and 9, where the asymptote is almost horizontal. In view of the fact that the survey region is located in the palaeosuture and foreland basins, it is interesting to note that this asymptote passes through the global resistivity curve (Rokityansky 1982). The phases in the TE mode in this region do not show any appreciable spatial variations at low frequencies, indicating that the deeper structure is devoid of any major vertical resistivity contrasts.

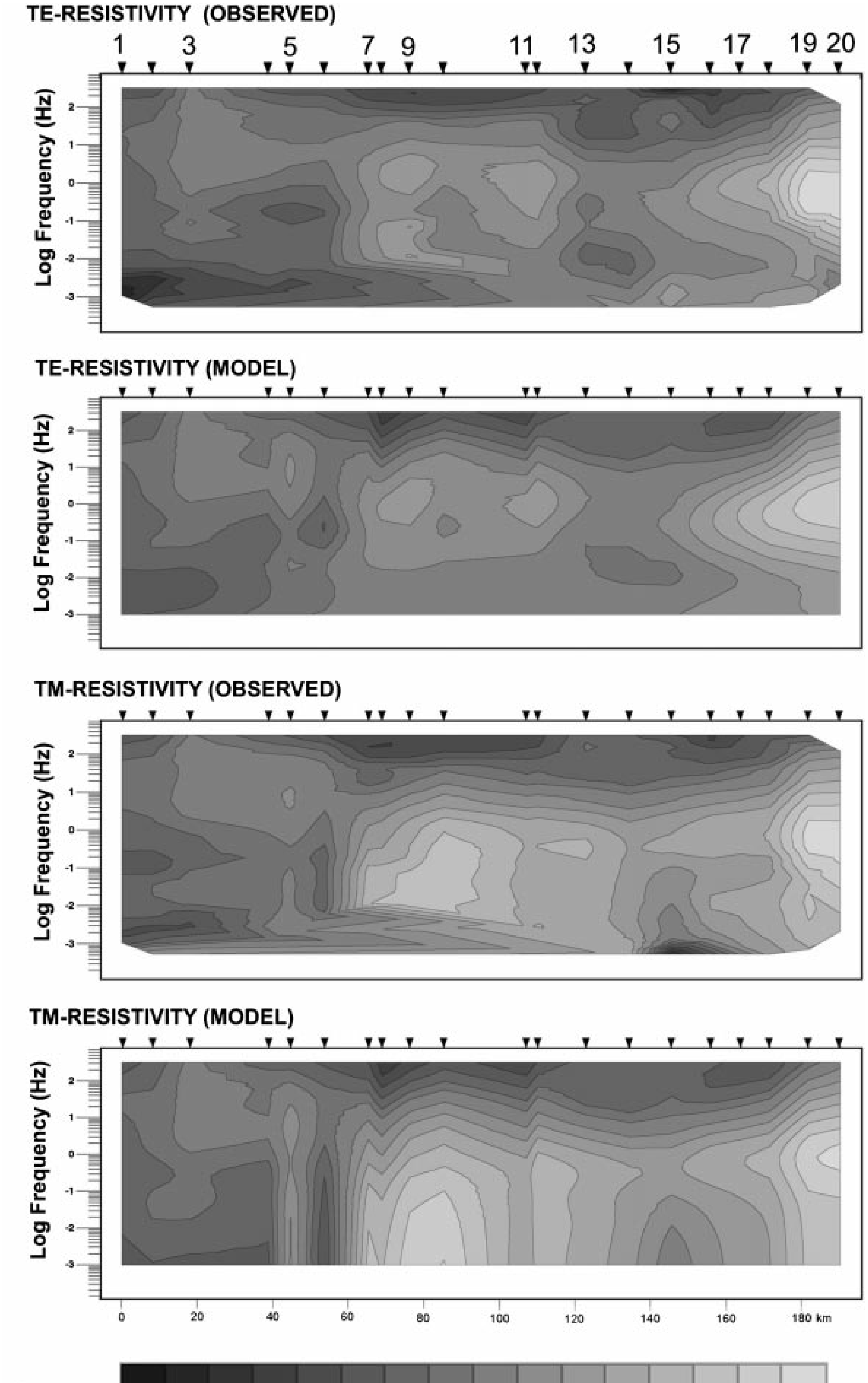

Figure 5 (a) Experimental (rotated) and modelled apparent resistivity pseudo-sections in the TE and TM modes. (b). Experimental (rotated) and modelled phase pseudo-sections in the TE and TM modes. Figs 5 and 6 may be viewed in colour in the online version of the journal (http://www.blackwell-synergy.com).

The geoelectric structure is obtained starting with a half-space with uniform resistivity of 100 Ω m, using a 2-D inversion scheme (Rodi & Mackie 1999). Both the apparent resistivity and phase in the TE and TM modes were used for the inversion. An error floor of 5 per cent was set for both the TE and TM mode data and the Tau parameter was set at 30. The resulting RMS error was 6.2. The substructural resistivity distribution thus obtained is shown in Fig. 6.

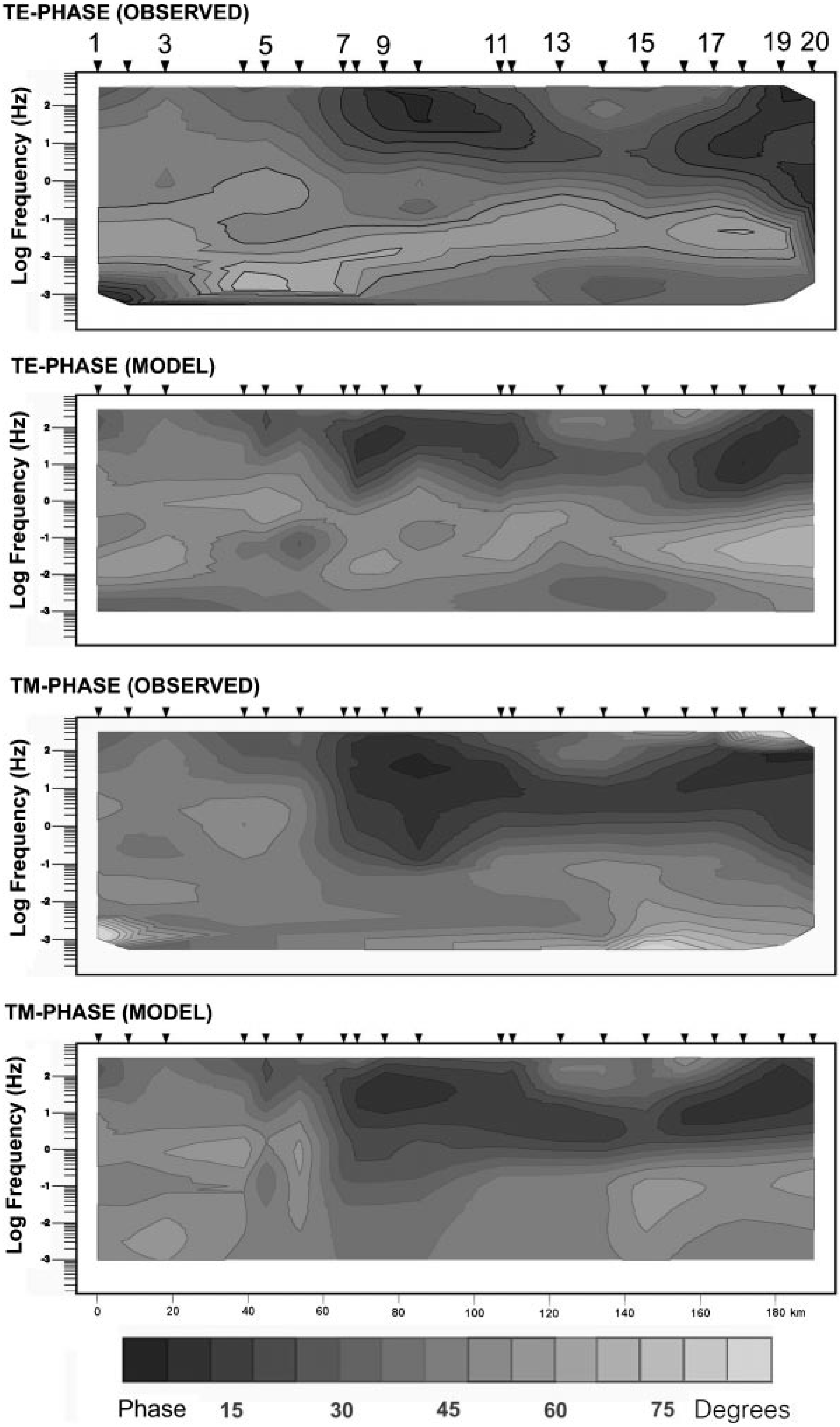

Figure 5 (*Continued.*)

4 DISCUSSION

For convenience, the survey profile is broadly grouped into four regions: the Vindhyan sequences between stations 1 and 6 in the northwest, the Jabalpur horst block between stations 7 and 10, the Deccan volcanic province between stations 11 and 18, and the Archaean exposures below stations 19 and 20. These are marked on the top of the geoelectric cross-section (Fig. 6).

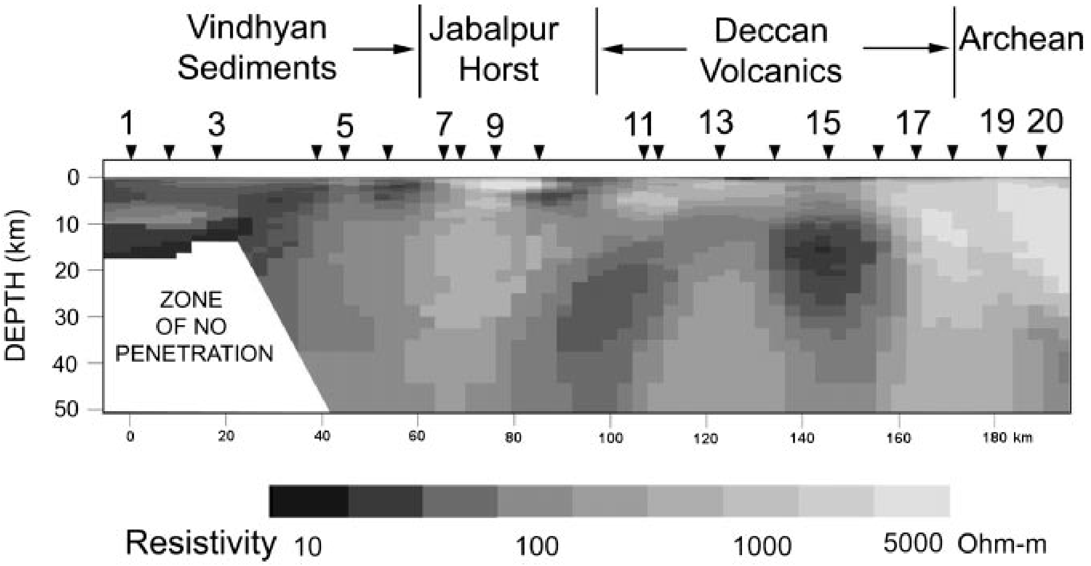

Figure 6. Geoelectric cross-section obtained from the 2-D inversion of the magnetotelluric data.

4.1 Vindhyan sequences

The crustal structure in the Vindhyan region shows approximately 5 km thick conductive sediments, with resistivities in the range 6–30 Ω m, overlying a resistive (200 Ω m) layer up to a depth of 10–12 km, corresponding to the pre-Vindhyan crust. The thickness of the sedimentary layer (between stations 1 and 6) agrees well with the value of 5.5 km obtained from the DSS studies. On the northern part of the profile near Damoh (below stations 1 and 2), the DSS results indicate a gradual decrease in the total thickness of the sediments to about 4 km. This variation was, however, not detected in the geoelectric model from the MT studies. The Vindhyan sedimentary sequences comprise the Upper and Lower Vindhyan sediments, separated by a structural unconformity (Kaila *et al.* 1989). The Upper Vindhyan sediments are fresh-water deposits, whereas the Lower Vindhyans were deposited in marine conditions and are thus expected to be more conductive than the Upper Vindhyans. However, this was not clear from the MT studies and thus it may be reasonable to assume that there is no significant difference in the resistivities of the Upper and Lower Vindhyan sediments in this region.

4.2 Crust below the Vindhyan sediments

The crust below the Vindhyan sequences has a resistivity of approximately 200 Ω m, which is rather a low value for the upper crust. The DSS results show higher *P*-wave velocities of 6.5 km s^{-1} in the basement below the Vindhyans, compared to 5.8–6.2 km s^{-1} in the surrounding regions. The Vindhyan Basin was formed as a result of uplift and erosion followed by graben formation. This was subsequently the region of Vindhyan deposition. The MT and DSS studies clearly indicate an anomalously high conductivity and a relatively high *P*-wave velocity (6.5 km s^{-1}) at a depth of 5 km below the Vindhyan sediments.

Vindhyan sedimentation was preceded by the deposition of the Bijawar sequences (Pant & Banerjee 1990) and thus these sequences may underlie the Vindhyan sediments. The DSS studies have, however, reported *P*-wave velocities of 4.8 km s^{-1} corresponding to the Bijawar outcrops and 5.4 km s^{-1} for the Bijawars (Kaila *et al.* 1987) located over the basement below the Vindhyan sediments. Thus, these sequences cannot explain the high *P*-wave velocity below the Vindhyan Basin. Studies on the exposed metasediments of the Mahakoshal group on the east of the MT profile show that these rocks have densities of 2.8 g cm^{-3}, which could lead to high seismic velocities and thus could be a possible candidate to explain the high *P*-wave velocity. The Bouguer and residual gravity studies (Venkat Rao *et al.* 1990), however, do not indicate any significant extension of the Mahakoshals below the Vindhyan Basin. It is thus proposed that the upper crust may have been completely eroded in the uplift and erosion process and the Vindhyan sedimentation may have occurred directly over the lower crust.

The deeper crustal exposures in the Kapuskasing uplift in Canada have been well studied using seismic and electromagnetic techniques amongst other geophysical and geological investigations. The seismic velocity structure here shows a monotonous increase in the *P*-wave velocities from 6.4 km s^{-1} at the top to 7.8 km s^{-1} at depths of about 40 km (Fountain *et al.* 1990). The *P*-wave velocities in the crust below the Vindhyan Basin, however, do not show any significant variation from the value of 6.5 km s^{-1} in the corresponding depth range (Kaila *et al.* 1987). In fact, these authors have observed that the 2-D model shows an improved fit with the traveltimes when a low-velocity layer was invoked at Moho depths. Thus, the *P*-wave velocities may decrease with depth. The interpolated heat flow data (Ramakrishna 1995) show that heat flows of about 100 mW m^{-2} may be expected below the Vindhyan sediments, corresponding to temperature gradients in the range 30–40°C km^{-1}, depending on the thermal conductivity of the crustal rocks. In the presence of such high temperature gradients, the *P*-wave velocities could decrease with increasing depth (Christensen 1979), which seems to be the case here. The exposed deep crust in Kapuskasing shows high resistivities of 10 000 Ω m (Kurtz *et al.* 1988), compared to values of 200 Ω m observed in the Vindhyan region. Jones (1992) has observed that the location of the lower crustal rocks has a greater influence on the electrical resistivities than their composition. Thus, the thermal state and presence of fluids in open pores may be more critical parameters than the composition in determining the electrical resistivity of rocks.

Subsequent to the deposition of the Vindhyan sediments in the Precambrian era, the region has been thermomechanically reworked between 2350 and 1600 Ma (Yedekar *et al.* 1990). The recent outburst of the Reunion plume about 700 km west of the survey profile (Raval 1995) would have strongly influenced the physical characteristics of the deep crust in the Vindhyan region. These processes could have resulted in substantial fluid generation in the deep interiors. These factors, along with the high heat flow values estimated for this region, are sufficient to explain the lower resistivity of the Vindhyan crust and the large discrepancies in the resistivities observed between the Vindhyan and Kapuskasing crustal blocks. In view of these observations, it seems reasonable to conjecture that the upper crust may be completely eroded and that the Vindhyan sedimentation occurred directly over the lower crust.

4.3 High conductivity in the deep Vindhyan crust

Anomalously high conductivity (resistivity less than 1 Ω m and conductance in excess of 1200 S) is present in the northwestern part of the Vindhyan Basin, below depths of 10–12 km at stations 1–3. The apparent resistivity and phase plots at station 3 are shown in Fig. 7. A decreasing trend is observed in the apparent resistivities, with values of less than 1 Ω m at the low-frequency end of the response functions, indicating that the causative body may have resistivities of less than this value. A similar trend is observed at stations 1 and 2 to the northwest. The resistivity of this layer shows an increase towards the southeast below station 3, and further southeast its signatures are absent. Because of the lack of stations to the northwest of Damoh, the lateral extent of this conductive feature to the north could not be ascertained. As discussed earlier, the static shifts at the stations over the Vindhyan sediments were corrected by obtaining the low-frequency averages of the apparent resistivities in the TE mode at six stations, which is not acceptable in terms of statistics alone.

Two points may be noted here. First, the thickness of 5 km estimated for the Vindhyan sediments is in reasonable agreement with the value reported from the DSS results. Second, the geomagnetic depth sounding studies (Arora *et al.* 1995) have delineated a conductive feature with a conductivity of less than 3 Ω m below Damoh at depths of 15–20 km, with a lateral extent of about 30 km along the present survey profile. The conductance of this layer is estimated to be about 1500 S. As a result of the shielding of the long-period electromagnetic energy by this conductive layer, its base is not observed in the

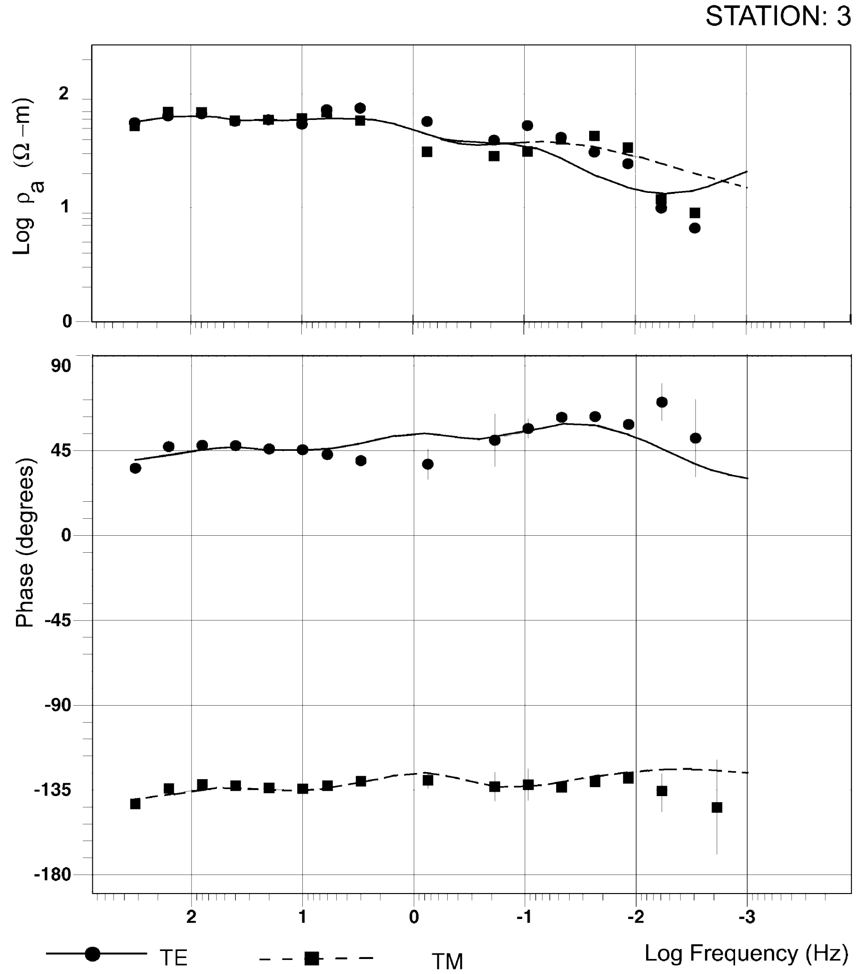

Figure 7. Response functions at station 3. The solid and dashed curves correspond to the forward responses of the geoelectric cross-section shown in Fig. 6.

MT response functions and hence its total conductance could not be determined. The conductance was estimated to be more than 1200 S, which is in good agreement with the GDS results. Because the GDS studies are based only on the magnetic field measurements, they are free of any static shifts that are associated with the electric field measurements.

The tectonic settings here are reminiscent of the Proterozoic suturing of the Archaean crustal blocks in the North American Central Plains (NACP), where a high conductivity of 0.1–0.5 Ω m is delineated at a depth range between 12 and 25 km from MT studies (Jones & Craven 1990). Among the different mechanisms proposed by various workers to explain the conductivity anomaly below the NACP, the grain boundary graphite in schistose rocks, the presence of saline water in porous rocks and partial serpentinization of the ultramafic rocks have been discussed in detail.

The high conductivity below the Vindhyan crust may not have a single explanation at this stage. The saline fluids in open pores are unlikely to cause such high conductivities at depths of 10–12 km; this process requires high porosity in excess of 12 per cent, which may not be possible at these depths. One possibility is the serpentinization of the mafic and ultramafic rocks of the oceanic crust in this region, which is located over the forearc and palaeosuture between the Bundelkhand and Dharwar cratons (Yedekar *et al.* 1990). Laboratory studies on the serpentinized rocks in the Indian ocean ridge have indicated resistivities of about 0.3 Ω m (Stetsky & Brace 1973). These authors have also reported porosities of about 14 per cent for these serpentinite samples. The high conductivity of serpentinites may be due to two causative factors: the porosity and the mineral conduction due to the presence of magnetite. The decrease in porosity leads to a decrease in its contribution to conductivity through the presence of saline fluids. On the other hand, the conductivity of the magnetite is a result of electron exchange between the divalent and trivalent Fe ions. Being a thermally activated process, this electron exchange leads to higher electrical conductivities at elevated temperatures. With decreased porosity, which could bring the magnetite particles closer to each other, serpentinites may exhibit a further increase in the conductivity of the deep crustal rocks. The presence of serpentinites thus provides an explanation for the observed deep-crustal conductivity.

Another possibility arises from the presence of grain-boundary graphite. The existence of Kimberlite pipes and diamond-producing mines in the Panna region (Wadia 1983) about 150 km east of Damoh provides sufficient evidence for the presence of carbon in the deep crust in the northern part of the Vindhyan Basin, which could crystallize as graphite at grain boundaries. There thus seems to be good justification to assume that the observed high conductivity in the deep crustal region is a result of grain boundary graphites.

4.4 Jabalpur horst

In the Jabalpur horst region (stations 7–10), a block with a resistivity of about 2000 Ω m is delineated extending up to a depth of about 30 km. The Jabalpur horst is covered by an approximately 25 m thick layer of conductive (1 Ω m) alluvium. The DSS studies show a 2 km thick top layer with a velocity of 5.9 km s^{-1} overlying a second layer with a velocity of 6.7–6.9 km s^{-1} in this region. A conductive feature seems to demarcate the southern boundary of the Jabalpur horst below station 11.

4.5 Deccan volcanics

The region southeast of the Jabalpur horst is covered by the upper Cretaceous Deccan basaltic flows. Approximately 100 m thick Deccan basalts are present here and their thickness seems to decrease to the southeast, up to the station 18. Beneath the basalts, the granitic basement is observed with resistivities of about 3000 Ω m; this is exposed to the southeast of station 18. The conductive top layer over the granitic exposures below stations 19 and 20 is perhaps the result of weathering of the exposed basement. There is no indication of any Gondwana sediments below the Deccan basalts. These are either absent or could not be distinguished from the basalts.

Two conductive features with a conductivity of about 30 Ω m are seen in the crust below the Deccan volcanics, one below station 11 and the second between stations 14 and 16. The first conductive feature is in the depth range 20–35 km and seems to mark the southern limit of the Jabalpur horst block. The second conductive feature extends from depths of 10 to 30 km. These features do not show any deeper roots and seem to be truncated at depths of about 35 km. GDS studies (Arora *et al.* 1995) have shown the presence of high conductivity to the south of Jabalpur. These studies could not resolve the two conductive features because of the large station spacing (25–50 km) used by these workers. The Bouguer anomaly map (Fig. 2) shows a gravity high of about +30 mGal, coinciding with the high-conductivity feature below stations 14 and 16. However, the DSS refraction studies do not show any significant change in the crustal densities associated with this conductive feature. It is thus evident that the gravity and conductivity anomalies may be due to different causative mechanisms. Spectral analysis of the Bouguer gravity data using 2-D matched filters (Das *et al.* 1996) has shown that the Bouguer anomaly observed over the Deccan volcanics could be adequately explained in terms of the upwarped Moho in this region. The Moho reported from DSS studies is discontinuous in this region. However, there are sufficient indications of a Moho upwarp corresponding to the gravity high.

From spectral analysis of the regional Bouguer gravity data, several workers (Venkat Rao *et al.* 1990; Agarwal *et al.* 1995; Balakrishnan 1997) have proposed that a fault zone in the crust below the Deccan volcanics coincides with the gravity high. It is proposed that the high conductivity below stations 14 and 16 may be due to the fluids present in the fractures associated with this fault.

5 CONCLUSIONS

The magnetotelluric studies in the Damoh–Jabalpur–Mandla–Anjaneya profile have shown a rather conductive crust (200 Ω m) beneath the Vindhyan sequences, associated with relatively high *P*-wave velocities. Based on these observations, it is conjectured that the upper crust may have been completely eroded in the uplift and erosion processes preceding Vindhyan sedimentation, and thus the present-day basement of the Vindhyans may be the lower crust. The total thickness of the Vindhyan sediments is about 5 km.

A high-conductivity layer is delineated in the deep crust below the Vindhyan region. This layer has a conductance of more than 1200 S and a resistivity of less than 1 Ω m. This could be due to the presence of grain-boundary graphite. The Kimberlite pipes and diamond-producing mines in the Panna region, which is about 150 km east of Damoh on the northern part of the MT profile, supports this possibility. Serpentinization provides an alternative explanation for the observed high conductivity here.

Two crustal conductors are delineated, one below Jabalpur and the second about 25 km to the SW, below the Deccan volcanics. These conductive features are located in the gravity high region and the DSS results do not show any significant velocity changes associated with these conductors, indicating that the conductive feature may not be associated with density variations. It is thus proposed that the conductivity anomaly and high gravity may have different causative mechanisms. The high conductivity may be due to the presence of crustal fluids, whereas the gravity high seems to be predominantly due to the upwarping of the Moho.

The geoelectric cross-section shows some vertical conductivity contrasts in the depth range 30–40 km throughout the survey profile. Closer observation indicates that these may be due to the spilt over conductances below the conductive bodies (below stations 11 and 14–16). The bases of the conductive layers are not well constrained in the MT interpretations. In consideration of this fact, the resistivity variations are in a narrow range of 200–500 Ω m. Furthermore, as mentioned earlier, the low-frequency asymptote of the static shift-corrected TE apparent resistivities shows a good correspondence with the global resistivity curve (Rokityansky 1982), indicating that this region has largely retained the characteristics of a stable cratonic mass. As pointed out by one of the referees, these are rather interesting observations for this Proterozoic mobile belt, which may have been affected by the recent ($\approx$65 Ma) plume activity.

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REFERENCES

Agarwal, B.N.P., Das, L.K., Chakravorty, K. & Sivaji, Ch., 1995. Analysis of the Bouguer anomaly over Central India: a regional perspective, *Geol. Soc. India Mem.*, **31,** 37–61.

Arora, B.R., Waghmare, S.Y, & Mahashabde, M.V., 1995. Geomagnetic depth sounding along the Hirapur–Mandla–Bhandara profile, Central India, *Geol. Soc. India Mem.*, **31,** 519–535.

Balakrishnan, T.S., 1997. Major tectonic elements of the Indian subcontinent and contiguous areas: a geophysical review, *Geol. Soc. India Mem.*, **38,** 37–61.

Christensen, N.I., 1979. Compressional wave velocities in rocks at high temperatures and pressures, critical thermal gradients, and crustal low-velocity zones, *J. geophys. Res.*, **84,** 6849–6857.

Das, L.K., Agarwal, B.N.P. & Bose, R.N., 1996. Moho relief in central India from spectral analysis of gravity data, *Geol. Soc. India Mem.*, **36,** 225–234.

Fountain, D.M., Salisbury, M.H. & Percival, J., 1990. Seismic structure of the continental crust based on rock velocity measurements from the Kapuskasing uplift, *J. geophys. Res.*, **95,** 1167–1186.

Groom, R. & Bailey, R.C., 1989. Decomposition of the magnetotelluric impedance tensor in the presence of local three dimensional galvanic distortions, *J. geophys. Res.*, **94,** 1913–1925.

Jones, A.G., 1992. Electrical conductivity of the continental lower crust, in *Developments in Geotectonics*, 23, *Continental Lower Crust,* eds Fountain, D.M., Arculus, R. & Kay, R.W., Elsevier, Amsterdam.

Jones, A.G. & Craven, J.A., 1990. The North American Central Plains conductivity anomaly and its correlation with gravity, magnetic, seismic and heat flow data in Saskatchewan, Canada, *Phys. Earth. planet. Inter.*, **60,** 169–194.

Kaila, K.L., 1988. Mapping of thickness of Deccan trap flow in India from DSS studies and inferences about a hidden Mesozoic basin in Narmada–Tapti region, *Mem. Geol. Soc. India,* **10,** 91–116.

Kaila, K.L., Murty, P.R.K., Mall, D.M., Dixit, M.M. & Sarkar, D., 1987. Deep seismic sounding along Hirapur–Mandla profile, central India, *Geophys. J. R. astr. Soc.*, **89,** 399–404.

Kaila, K.L., Murty, P.R.K. & Mall, D.M., 1989. The evolution of Vindhyan basin vis-a-vis the Narmada Son lineament, India from deep seismic soundings, *Tectonophysics,* **162,** 277–289.

Kurtz, R.D., Niblet, E.R., Craven, J.A., Stevens, R.A. & Macnae, J.C., 1988. Electromagnetic studies over the Kapuskasing structural zone, in *Proc. Kapuskasing LITHOPROBE Workshop, Toronto*, pp. 169–175, ed. West, G.F.

Mall, D.M., Kaila, K.L. & Rao, V.K., 1991. Magmatic body interpreted at mid-crustal conductor level between Jabalpur and Mandla as an indicator for one of the source regions for Deccan Basalts, in *Proc. 1st Int. Symp. & Exhibition on 'Exploration Geophysics in Nineteen Nineties',* Assoc. Expl. Geophysicists, Hyderabad, India.

Pant, N.C. & Banerjee, D.M., 1990. Pattern of sedimentation in the type Bijawar basin of central India, *Geol. Surv. India Spec. Publ.*, **28,** 156–166.

Pascoe, E.H., 1959. *Manual of Geology of India and Burma,* Vol. I, pp. 285–287, Government of India Publishers, Calcutta, India.

Ramakrishna, T.S., 1995. Geophysical view of the crustal structure along the Jabalpur–Raipur transect, *Geol. Soc. India Mem.*, **31,** 37–61.

Raval, U., 1995. Geodynamics of the tectonomagnetic and geophysical signatures within mobile parts of the (Jaipur–Jabalpur–Raipur) transect, *Geol. Soc. India Mem.*, **31,** 37–61.

Ravi Shanker, 1988. Heat flow map of India and discussions on its geological and economic significance, *Indian Minerals,* **42,** 89–110.

Rodi, W. & Mackie, R.L., 1999. Nonlinear conjugate gradients algorithm for 2D magnetotelluric inversions, *Geophysics,* in press.

Rokityansky, I.I., 1982. *Geoelectromagnetic Investigation of the Earth's Crust and Mantle,* Springer Verlag, Berlin.

Stetsky, R.M. & Brace, W.F., 1973. Electrical conductivity of serpentinized rocks up to 6 Kilobars, *J. geophys. Res.*, **78,** 7614–7621.

Venkat Rao, K., Sriram, B.V. & Ramasastry, P., 1990. A Geophysical appraisal of Mahakoshal group of Upper Narmada valley, *Geol. Surv. India Spec. Publ.*, **28,** 99–117.

Verma, R.K. & Banerjee, P., 1992. Nature of continental crust along the Narmada Son lineament inferred from gravity and deep seismic sounding data, *Tectonophysics,* **202,** 375–397.

Wadia, D.N., 1983. *Geology of India and Burma,* 4th edn, Tata McGraw-Hill, New Delhi.

West, W.D., 1962. The line of Narmada-Son valley, *Current. Sci.*, **31,** 143–144.

Wight, D.E. & Bostick, F.X., 1980. Cascade decimation—a technique for real time estimation of power spectra, *Proc. IEEE Int. Conf. Accoustic, Speech and Signal Processing, Denver, CO,* pp. 626–629.

Yedekar, D.B., Jain, S.C., Nair, K.K.K. & Dutta, K.K., 1990. The Central Indian collision suture, *Geol. Surv. India Spec. Publ.* **28,** 1–43.