Electrical and density signatures across Narmada–Son lineament zone (Central India) along the Malkapur–Mandhata profile

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Two-dimensional geoelectric section derived along the Malkapur–Mandhata magnetotelluric (MT) profile, cutting across the Narmada–Son lineament (NSL) zone, brought out a conductive (< 50 Ohm m) middle and lower crust under the NSL region. This region underlying the resistive (300–3000 Ohm m) Archaean basement shows shallow depth underneath the weak tectonic zones identified in the area. The constrained density modelling of the Bouguer gravity values suggests high density (2.8 g/cm^3) material corresponding to the conductive middle–lower crust zone. As the region has experienced widespread volcanism during the Cretaceous–Tertiary period, the crystallized mafic magmas that were poured into the crust during the volcanism and the fluids entrapped (expelled during magma cooling process) could be the possible explanation for the conductive and high-density characteristics beneath the NSL zone.

Keywords: Gravity, magnetotelluric profile, resistivity, underplating.

THE Narmada–Son lineament (NSL) is one of the most prominent tectonic features in the Indian subcontinent, which separates the Indian land mass into the northern and southern crustal blocks. The NSL appears to be a zone of weakness from the Precambrian times and has experienced many tectono-thermal events since then[1]. The areas to the north and south of NSL must have moved vertically relative to each other, as indicated by the confined Proterozoic Vindhyan rocks to the north and the Gondwana sediments to the south of the NSL[2]. Major movements such as uplift, subsidence and transcurrent motion ceased at the end of the lower Proterozoic. The Cretaceous–Tertiary Deccan volcanism appears to be the most recent of such tectono-thermal events that occurred along the NSL. The study region is covered mostly by flood basalts that erupted during the above Deccan volcanism. The region is mapped with E–W to ENE–WSW trending fault features such as the Narmada South Fault (NSF), Barwani Sukta Fault (BSF), Tapti Fault (TF), Gavilgarh Fault (GF) and Purna Fault (PF). The abnormal heat flow values along with the manifestation of anomalous subsurface thermal conditions in the form of hot springs and recent seismicity indicate dynamic tectonics under the NSL region[1,3].

The NSL zone is marked with broad, high Bouguer gravity values with occasional high local Bouguer anomalies compared to its surrounding regions[4,5]. Singh and Meissner[5] have shown that these Bouguer gravity anomalies over the NSL region with high-density layer at lower crustal depths resulted from the magmatic underplating associated with the Cretaceous–Tertiary Deccan volcanic eruption that occurred along this weak crustal zone. The high gravity anomalies were also interpreted in terms of high-density intrusive bodies in the upper crust, which could have also taken place during the major Deccan volcanic activity[4]. Kaila[6] explained this gravity high in terms of a transitional crust of very thin granitic layer underlain by a thick basaltic layer. The Deep Seismic Sounding (DSS) studies across the NSL area delineated Moho depth ranges from 35 to 45 km and identified some deep-seated faults reaching up to the Moho level[6,7]. However, the re-interpretation of the seismic data did not support the earlier contention of Moho-reaching faults[8]. Reanalysis revealed the occurrence of several high-velocity mafic intrusions in the upper crust and Moho depth ranges in accordance with the earlier studies. The previous electromagnetic (magnetotelluric; MT) studies along a few profiles across the NSL invariantly observed less-resistive lower crust in the region, possibly related to magmatic underplating and associated fluids at depths[9–12]. Rao *et al.*[9] identified two low-resistive (10–200 Ohm m) features, one below the Tapti River and another north of it, extending from shallow depths (7 km) to a deep crust (about 50 km). They explained the south conductor as due to magma intrusion into the crust, whereas the north conductor as partially molten magma emplacement from the asthenospheric depths. Patro *et al.*[10] modelled four conductive (< 10 Ohm m) features, extending from the middle to the deep crust, spatially coinciding with the major faults in the area. These conductive features in the resistive upper crust were inferred to be high-density mafic intrusions in the crust that are presumably associated with magmatic underplating. The MT studies by Naidu and Harinarayana[11], however, did not show any anomalous conductors corresponding to any of these faults. In the present study, the crust structure characteristics of the NSL zone was studied using MT data and constrained gravity modelling studies.

The present study analyses MT data at 12 sites along the ~170 km long N–S-orienting Mandhata–Malkapur profile (Figure 1). The profile cuts across the major fault structures and geologic formations within the NSL region. Five-component MT time-series (the magnetic field in two orthogonal horizontal directions and in the vertical direction, and the electric field in two horizontal direc-

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tions) data were measured simultaneously at each location and processed using robust algorithms incorporated in the MAPROS MT time-series processing software package to derive smooth impedance values. Prior to final processing, noisy segments (spikes) in the measured time-series were removed by visual inspection. The computed impedance values showed smooth, good-quality responses in the period range 0.01–100 s for all of the sites, and were considered for further analysis and modelling.

The dimensionality and directionality of the MT data were studied prior to modelling for subsurface resistivity structure. Dimensionality analysis is used to determine the appropriate modelling technique required by the data. The dimensionality of the MT data at a given frequency can be quantified from the skew values. Bahr's skew values were computed to understand the dimensionality of the present MT data[13]. The computed Bahr's skew (Figure 2), in general, showed values well below the threshold value of 0.3 (above which the data can be considered as 3D) for periods up to 100 s and supported a valid 2D assumption for the subsurface earth. Directionality analysis is required to determine the geoelectric strike that is used in 2D inversion modelling. The tensor decomposition procedure of Groom and Bailey[14] was used to estimate the geoelectric strike direction consistent with the data. The analysis showed consistent geoelectric strike values, ranging between N60°E and N80°E (or perpendicular to it), for all the sites and at different frequencies corresponding to varying subsurface depths. The geological features in the area mostly show an EW to ENE–WSW trend on the surface and agree closely with the strike direction derived from the MT data. Hence, an average N70°E strike was assumed for the subsurface geologic structures and the MT data were rotated to this geoelectric strike direction to derive the TE (parallel to strike) and TM (perpendicular to strike) responses. These 2D regional impedance responses were used in 2D inversion modelling to derive the subsurface resistivity structure.

Two-dimensional resistivity structure was obtained after jointly inverting the TE and TM responses using the nonlinear conjugate gradient algorithm of Rodi and Mackie[15]. This inversion algorithm finds a smooth 2D resistivity model with minimum structure controlled by the regularization parameter (τ), which makes a trade-off between closely fitting the data and obtaining a smooth model. Prior to the joint inversion of TE and TM responses, the data in each mode were independently inverted to find the consistency between apparent resistivity and phase data. This helped identify and remove outliers in the observed data which could not produce a satisfactory fit with the inversion model responses. A 100 Ohm m half-space model with 85 horizontal and 85 vertical grids was considered as the initial model. Many inversion models were computed for a range of control parameters (regularization parameter, the horizontal smoothness parameter (α), and apparent resistivity–phase error floors) and for different half-space values (100, 300 and 500 Ohm m) to ensure the robustness of significant resistivity features required by the MT data. All these modelling exercises showed consistent model features in

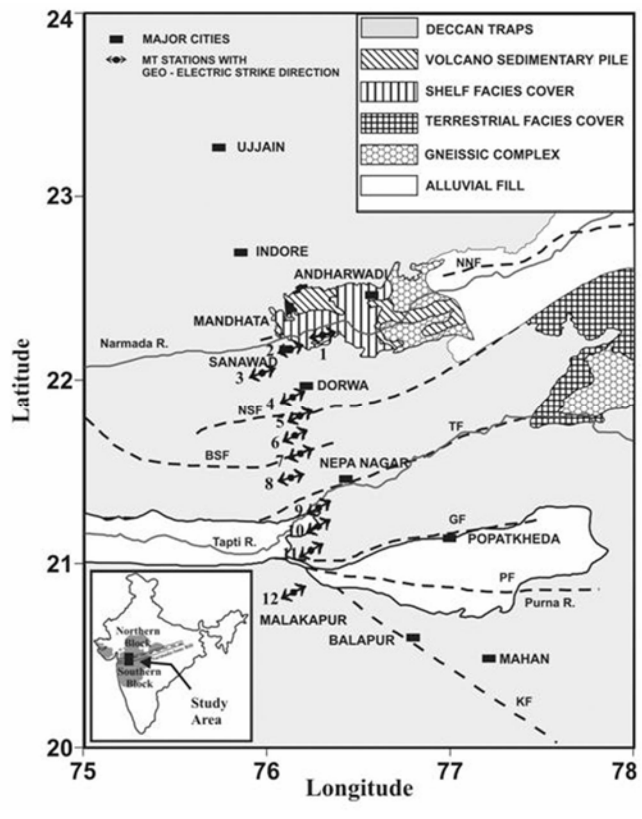

Figure 1. Location of magnetotelluric (MT) sites (black filled circles) along the Malkapur–Mandhata profile is shown over the major geological and tectonic features within the Narmada–Son lineament zone, Central India. The double-sided arrow at each MT site represents the average geo-electric strike direction obtained after Groom–Bailey analysis of the data[14]. (Inset) Location of the study area.

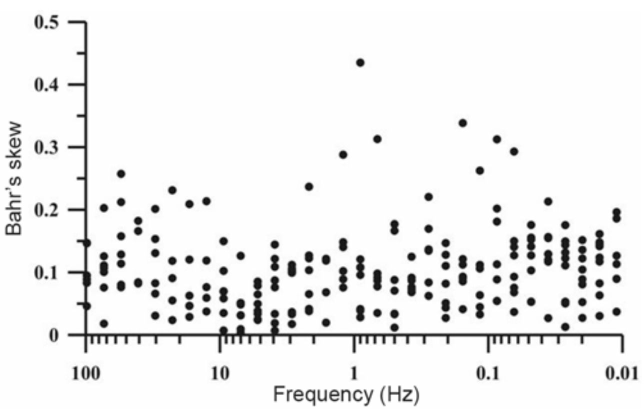

Figure 2. Bahr's skew values illustrating the dimensionality of the subsurface observed in the MT data. These are within the threshold value (0.3), above which a two-dimensional assumption for the subsurface is not valid.

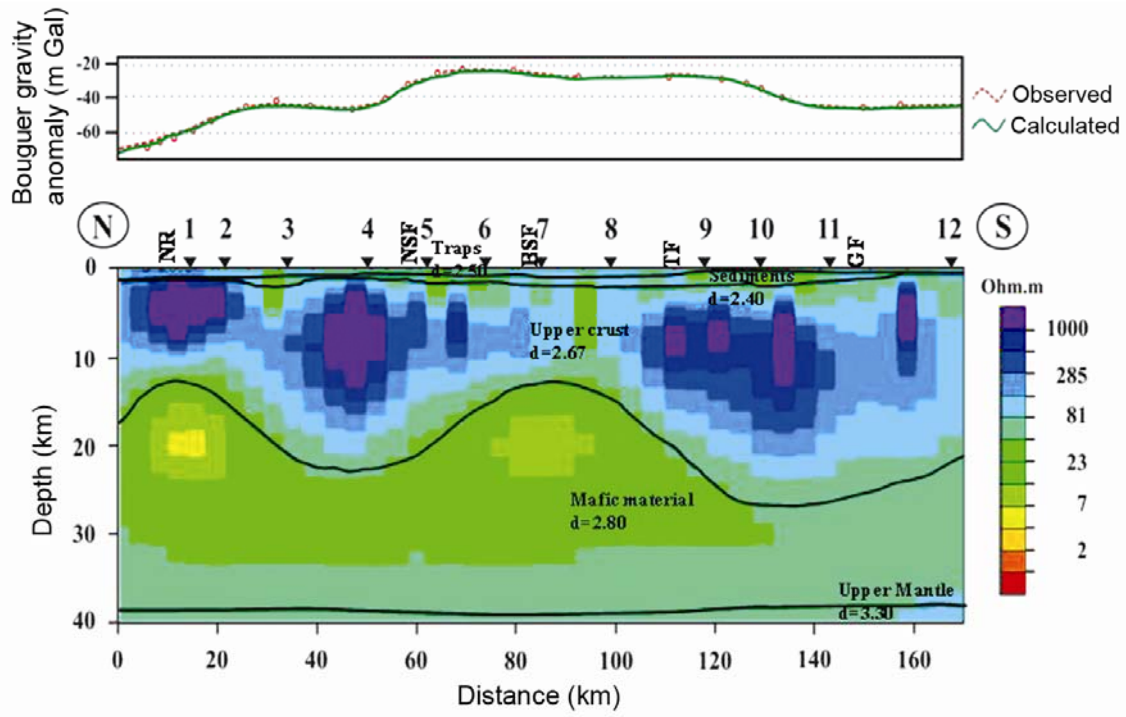

Figure 3. The 2D resistivity model obtained for the MT profile (bottom) shown along with Bouguer anomaly (top) observed along the profile. The density structures modelled to fit the observed Bouguer gravity anomaly are sketched over the MT model.

various derived models, without any significant changes in the spatial and depth extensions of the observed resistivity features. The resistivity model considered for the interpretation of the subsurface geology (Figure 3) was obtained from the joint inversion of TE and TM responses with a regularization parameter set to 3 and horizontal smoothness factor set to 1. A higher error floor in apparent resistivity (30%) was used over the phase (5%) to down-weight the possible galvanic distortion in apparent resistivity data[16]. The final root mean square misfit obtained after 200 iterations was 2.72.

The crustal geoelectric cross-section obtained from the MT data (Figure 3) shows a low resistive layer (10–80 Ohm m) overlying the resistive (> 300 Ohm m) basement formation in the area. The above low resistive layer becomes thin towards both ends (south and north) of the profile and indicates greater thickness in the central part. The study region is covered with the Deccan trap formation and the presence of sub-basalt Mesozoic formations in the region is known from geology and geophysical studies[3,7,17]. The low resistive layer observed in the model reflects the Deccan trap and underlying Mesozoic sediments. It is difficult to discern the above two formations, may be due to the overlapping range of resistivity values observed for them[18]. A conductive (< 50 Ohm m) middle to lower crust underlies the Archaean gneissic basement rocks in the area, which is imaged as a resistive (300–3000 Ohm m) feature in the resistivity model. The depth to the top of this conductive zone shows significant variation (10–20 km) along the profile. The conductive zone become shallower (~ 10 km) under the locations spatially coinciding with the known tectonic elements in the region (Narmada South Fault and Tapti Fault) and gives an impression of intrusion of these conductive zones into the resistive upper–middle crust of the region. Similar subsurface low-resistivity zones, at about 7 km depth, near Tapti and Narmada Fault zones were delineated in previous MT studies[9]. The most suitable explanation for the observed conductive zone could be the presence of fluids in the middle and lower crustal depths under the NSL zone. The presence of trapped fluids is possible under the area, as it experienced widespread Deccan volcanic activity during the Cretaceous–Tertiary boundary[9,10,12,19]. Large amount of hot mantle material (magma) might have been injected into the base of the crust and underplated during the volcanism. The pre-existing weak zones (faults) in the area may have acted as conduits for the eruption of these materials to the surface to form Deccan volcanic flows.

The observed Bouguer gravity values along the MT profile are shown in Figure 3. The Bouguer gravity values were obtained from the Bouguer gravity anomaly map of India[20], which gives 5 mGal Bouguer anomaly contours for the region. Major gravity highs and lows, with a prominent gravity high between the Narmada Fault and Tapti Fault (between MT sites 7 and 8), are noticeable across the NSL zone (Figure 3). The gravity high has a maximum value of –23 mGal close to MT site 6, with a gentle fall to –44 mGal on the southern side, but falls steeply to –67 mGal towards northern side close to MT site 4. The long wavelength anomalous high gravity between the Narmada South Fault and Tapti Fault could be an indication of the presence of deeper high-density material. For a clear understanding of the observed subsurface resistivity structures and their relation with the observed gravity anomalies over the area, constrained modelling of the Bouguer gravity values was carried out using the structural features derived from MT studies. Density values of 2.5, 2.4, 2.67, 2.8 and 3.3 g/cm^3 were assumed for the trap, Mesozoic sediments, upper crust, mafic lower crust and upper mantle respectively. The thickness of the trap and Moho depths are constrained from the active seismic studies in the area[3]. The obtained density model closely matches with the observed Bouguer gravity along the profile (Figure 3). Thus, the gravity model suggests that the conductive zone in the deep crust is also characterized by high density. Earlier gravity models also inferred such a high density medium in the middle and lower crust of the region[5]. The region is well known for the Cretaceous–Tertiary volcanic event during which the upper mantle material (magma) was poured into the deep crust of the region and may have travelled to the mid to upper crustal depths through the pre-existing weak zones in the area. The magma may have crystallized during the geologic time to form mafic rocks and may not be in molten state. However, the fluids expelled during the magma cooling process could have been entrapped in the lower crustal formation and fractured fault zones. The presence of fluids (however small it may be) and the mafic rock formations in the deep crust together explain the occurrence of low resistivity and high density under the NSL region. The existence of fluids may also provide an explanation for the persistent weakness of this region.

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