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Magnetotelluric evidence on the southward extension of the Eastern Ghats mobile belt from Ongole, India

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ABSTRACT

There has been a longstanding and scientifically contentious issue, concerning whether or not the Eastern Ghats mobile belt (EGMB) extends southward beyond Ongole in the state of Andhra Pradesh, in south India. Various geological and geophysical investigations carried out in different campaigns could not conclusively address this important issue. Some argued that the EGMB that originates near Mahanadi in the northeast of India and extends along the eastern continental boundary, is abruptly cut near Ongole in the south, swerves eastward towards the Bay of Bengal and joins the erstwhile east Antarctica boundary. Others opined differently and debated about its southward extension beyond Ongole. In the present study, we provide a conclusive evidence for the first time on this perplexing issue, by determining the deep earth electrical resistivity structure of the EGMB region through broad-band magnetotelluric (MT) investigations carried out along two different profiles laid out one near the Ongole region (profile AA′ of 35 km length) and the other near the Nellore region (profile BB′ of 52 km length). The latter is located at a distance of about 125 km south of the former. The lengths of both these profiles are sufficiently far from the influences of the electrical nature of the subsurface of the adjoining geological terrains namely, the east Dharwar craton, the Cuddappah basin and the southern granulite terrain. This enables to determine the electrical nature of the EGMB alone and examine whether or not it extends south of Ongole. Two-dimensional inversion of MT data of both the profiles revealed a very thin top conductive layer of about 1–10 Ω-m with an average thickness of about 500 m, representing the alluvium. This layer is underlain by very high resistive subsurface with resistivity of about 10^7 Ω-m extending up to about 30 km and probably further beyond (not shown in the present study). Since the major rock types in the study area, namely, Khondalites, Calc-granulites, Charnockites and Granitic gneisses of Archaean age, have large overlapping resistivities, MT data could not explicitly discern the nature of the multilayered crust beneath the EGMB. As a result, the subsurface beneath both the regions shows up as a very thick single layer of very high resistivity. The high grade rocks of the Ongole domain and supracrustals of Nellore Schist Belt (NSB), which lies south of Ongole domain, have undergone synchronous tectonic activity at ca.1.6 By. This is evident by the Kanigiri and Kandra ophiolites within NSB that signify the Proterozoic subduction of the EGMB. This geological evidence together with the similar nature of the high electrical resistivity of the subsurface observed at Ongole and Nellore regions confirm the southward extension of the EGMB beyond Ongole.

1. Introduction

Two major issues concerning the Eastern Ghats mobile belt (EGMB) region that are widely debatable are: (i) its southward extension beyond Ongole and (ii) its subsurface structure. Discussing the tectonic evolution of Archean high grade terrains of south India, Ramakrishnan (1988) first considered the EGMB was cut-off near Ongole in Andhra Pradesh and extended towards Antarctica. However, he later believed that the EGMB extends southward beyond Ongole through Madras (currently named as Chennai) up to Palghat-Cauvery shear system and that it may be linked to the highland group of Sri Lanka (Ramakrishnan, 1993). Yoshida et al. (1992) believed that the western boundary of the EGMB, adjoining the peninsular cratons, swerves eastward at Ongole and is linked to the Rayner-Napier boundary of Antarctica, suggesting that the EGMB does not extend southwards beyond Ongole (see inset of Fig. 1). However, based on age of granulite facies metamorphism, Dasgupta (1995) explained that the part of the EGMB south of Godavari rift does not have a counterpart in Antarctica. Meanwhile, it is also observed that the age along the western boundary of the EGMB to be about 500 my (Pan-African age) (Dobmeier et al., 2006), which

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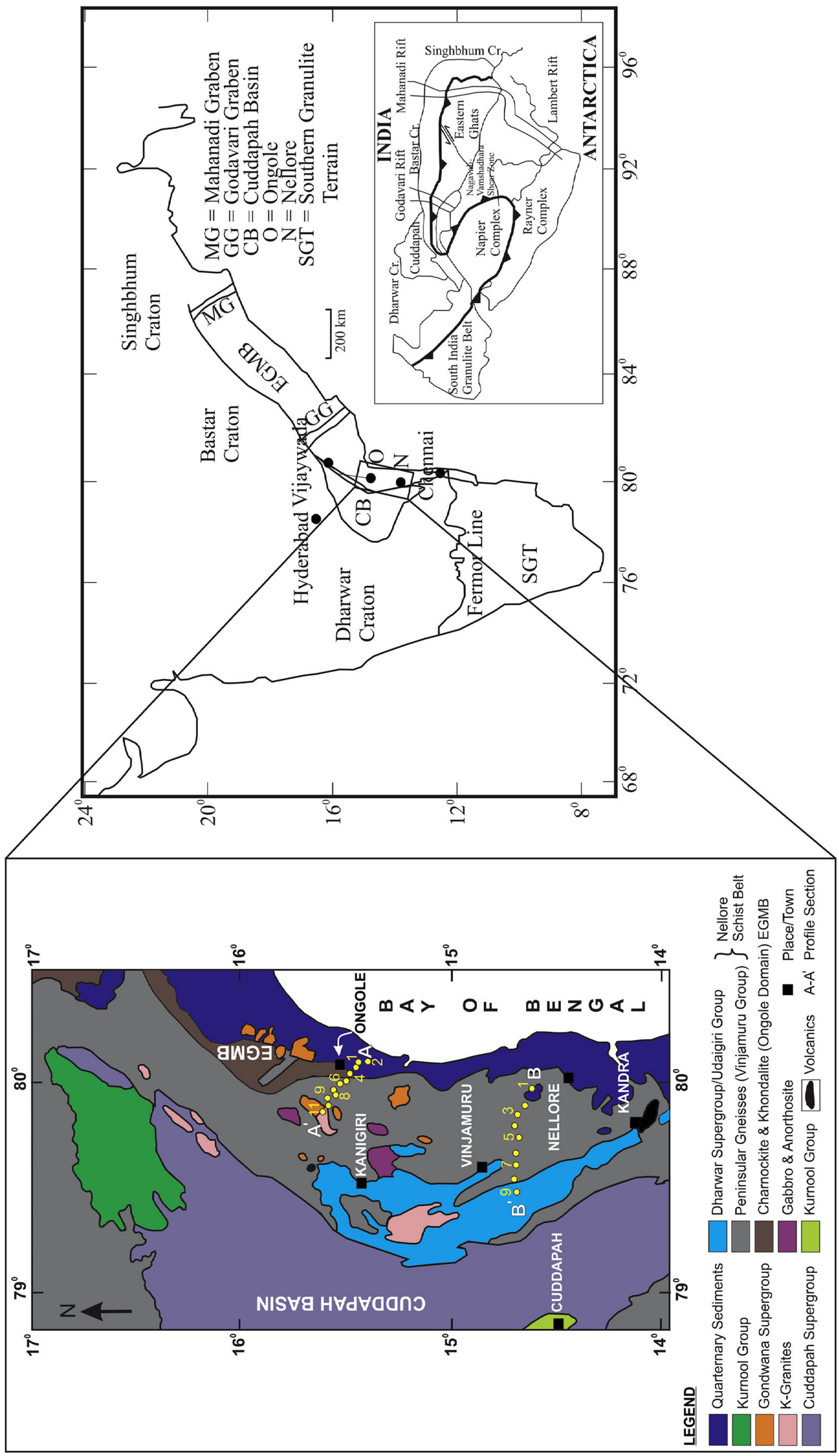

Fig. 1. Map showing the EGMB and its adjoining tectonic setting. The area of MT study is indicated in a box, whose zoomed version depicts the Ongle (AA′) and Nellore (BB′) profiles. Geographical locations of both the profiles are superposed on the geological map of the study area. Inset shows the East Gondwana assembly.

correlates well with that of the southwestern part of Rayner complex, but not with that of its northeastern part. This led to believe that most likely the EGMB continued to extend southwards beyond Ongole.

Based on gravity data, while Subrahmanyam (1983) reported the continuous stretch of the EGMB extending southwards up to Cape Comorin, without a break, and then swerving westward towards the west-coast of India, Hari Hari Narain and Subrahmanyam (1986) indicating a break between the Eastern Ghats and the Southern Granulite Terrain, explained the importance of E-W trending Madras-Bangalore gravity high. Reddi et al. (1988) using aeromagnetic data contradicted these observations and suggested an eastward extension of the EGMB from Tamil Nadu coast towards Bay of Bengal.

Subrahmanyam and Verma (1986) analyzing their gravity data of four profiles, observed an intervening gravity low over the boundary of the Bastar craton and the EGMB, in an otherwise continually increasing gravity eastward, indicating a thicker and denser crust beneath the EGMB compared to that beneath its adjoining Bastar and Dharwar cratons. Focusing on the gravity high, observed on either side of the Bastar craton-EGMB boundary, Murthy et al. (2005) attributed the gravity high to a faulted crust beneath the EGMB. Assuming a vertically uniform (but laterally varying) density up to Moho, Subrahmanyam and Verma (1986) estimated the Moho depth beneath the EGMB to be about 38 km, while that beneath its adjoining cratons is 34 km. Kaila et al. (1979), through their deep seismic sounding (DSS) studies, observed some differences in seismic wave velocities, implying notable density variations beneath the EGMB. A further comparative analysis of DSS investigations carried out in the (i) Mahanadi valley, (ii) Godavari valley and (iii) near Ongole, has revealed no significant contrasts in the seismic velocities between the granulites and basement along the EGMB (Kaila et al., 1987, 1990). However, they have noted a small discontinuity of about 0.5 km/s in the seismic velocity in the depth range from 6 to 8 km. By studying the seismicity around Ongole, Reddy and Chandrakala (2004) attributed the frequent seismicity in and around Ongole to the neotectonic activity coupled with the effects of India-Antarctica breakup and the reactivation of faults. To understand the evolution process of the deep crust during Archean age, Gokarn et al. (2004) and Naganjaneyulu and Harinarayana (2004) have made magnetotelluric (MT) investigations in the Dharwar craton (west of Ongole). Harinarayana (2007) also had made a comparative study of electrical structure of the Dharwar craton with the southern granulite terrain of south India.

Based on all the above geological and geophysical investigations, no comprehensive and conclusive ideas could be drawn about the southward extension of the EGMB beyond Ongole. This leaves the problem still wide open, requiring further investigations, which can provide unambiguous evidence on the nature of the deep subsurface near Ongole and further south of it. In an attempt to address this intriguing issue and to unravel the complexity in correct understanding of the southward extension of the EGMB, we, in the present study, discuss the electrical nature of the deep subsurface beneath Ongole and Nellore regions based on our MT investigations carried out along two different profiles: one near Ongole (AA′ profile) and the other near Nellore (BB′ profile) (see Fig. 1). The BB′ profile lies at a distance of about 125 km south of AA′ profile. The organization of the paper is as follows. Section 2 discusses the geology of the study area. Section 3 provides a brief description of MT survey details, data acquisition in the study region and MT data processing and strike angle estimation. Section 4 discusses the MT data inversion results and modelling. Section 5 describes the results and discussion and Section 6, the conclusions of the present work.

2. Geology of the EGMB

The EGMB is a Precambrian Orogenic belt, stretching along the east coast of India over a length of about 1200 km starting from Mahanadi in Orissa (see Fig. 1). It is surrounded on its three sides by the Singhbum craton (in the North), the Bastar craton (in the West) and the Dharwar craton (in the Southwest). It is crossed by two Mesozoic rift valleys, namely the Mahanadi rift in the North and the Godavari rift in the South (Fig. 1). The EGMB contains several granulite facies rocks that have been mapped into five litho-tectonic zones from west to east: the Transition Zone (TZ), the Western Charnockite Zone (WCZ, with charnockites, enderbites, mafic granulites and the banded iron formations), the Western and Eastern Khondalite Zones (WKZ and EKZ, Khondalites intercalated with quartzites and calc granulites) and the Central Migmatite Zone (CMZ, migmatite gneisses with intrusion of granites and anorthosites) (see Fig. 1 of Biswal et al., 2000). The TZ represents a mixture of lithounits belonging to the cratons and the EGMB. Dasgupta et al. (1992) showed that the EGMB exhibits an early phase of UHT granulite facies metamorphism followed by retrogression marked by anticlockwise as well as clockwise PT paths. Several ductile and brittle-ductile shear zones dissect the mobile belt in diverse orientations (Chetty and Murthy, 1994). The most significant amongst them is the Terrane Boundary Shear Zone (TBSZ) that defines the tectonic margin of the EGMB with the surrounding cratons (see Fig. 1 of Biswal et al., 2000). The TBSZ shows a curvilinear geometry with a WNW–ESE strike and strike-slip character in the north and NNE–SSW strike with a thrust character in the west. It assumes listric geometry at depth, forming décollement for the fold-thrust belt, developed on the northwestern front of the EGMB around Khariar (see Biswal and Sinha, 2003). Alkaline plutons are emplaced close to the terrane margin, namely at Rairakhol, Khariar, Koraput, Kunavaram and Elchuru (Madhavan and Mohammed, 1989; Leelanandam, 1993; Biswal et al., 2004). The Eastern Ghats have been divided into several isotopic domains cutting across the lithotectonic zones (Rickers et al., 2001).

A predominant Grenvillian-age granulite facies metamorphism and charnockite emplacement characterizes the EGMB, which forms the basis for correlation with the Rayner Complex of Antarctica (Fig. 1) (Grew and Manton, 1986; Aftalion et al., 1988; Paul et al., 1990; Mezger and Cosca, 1999). A Pan-African thermal event, represented by amphibolite facies metamorphism and pseudotachylite formation is reported in the vicinity of the shear zones (Kovach et al., 1997; Mezger and Cosca, 1999; Lisker and Fachmann, 2001; Dobmeier et al., 2006). The final juxtaposition of the EGMB with Indian cratons has been argued to be during Pan-African period (Biswal et al., 2007). As a matter of fact, the Pan-African metamorphism is not reported from the part of the Rayner Complex facing India (Kelly et al., 2002), although it is present on the opposite side (Prydz Belt or Prydz-Denman-Darling Belt, Fitzsimons, 2000a, 2000b). This raises a question about the location of exact piercing points between India and Antarctica.

The southern portion of the EGMB, where the present study is focused, is contentious, concerning the continuity of the EGMB further south of Ongole. To the south of the EGMB, there lies the Nellore Schist Belt (NSB). The NSB is considered to be a part of the eastern Dharwar craton as it is dominated by volcano-sedimentary rocks with granitic gneisses. Cuddappah Supergroup breaks the continuity between the eastern Dharwar craton and the NSB. The western margin of the NSB with Cuddappah Supergroup is thrusted. Some recent studies have provided significant geochronological data, which suggest that the NSB is of the same age as the southern part of the EGMB, except for the change in grade of metamorphism (Dobmeir and Raith, 2003; Dobmeier et al., 2006; Ravikant, 2010; Henderson et al., 2014). The southern part of the EGMB, marked by Ongole domain, shows isolated outcrops of charnockite, khondalites, anorthosites and alkaline rocks (Ramakrishnan et al., 1998). It shows an age of ca. 1.6 By, which is older than the other parts of EGMB and thus thought to be an exotic terrane. It was part of Antarctica and has been attached to India during 1.6 By orogeny. The NSB is called as Krishna Province. It is divided into western Udaigiri Group and eastern Vinjamuru Group. The Udaigiri Group is dominated by phyllites while the Vinjamuru Group has gneisses and metavolcanics showing amphibolite facies. These are intruded by Kanigiri and Kandra ophiolites. The protolith age of NSB is

2.6 By, which has been reset by deformation and metamorphism to 1.6 By (Henderson et al., 2014). Hence there is an age similarity between the EGMB and the Krishna Province. We have carried out MT investigations along two different traverses, one in the Ongole domain of the EGMB and the other in the NSB. The depth variation of electrical resistivity beneath these two profiles helps to bring out either the differences or similarities between the two geological units and their continuity. Therefore, the present study forms an important exercise to understand whether the EGMB continued southward beyond Ongole towards Nellore, or swerved eastward from Ongole and connected with the Antarctica through Bay of Bengal.

3. MT data acquisition and processing

Wide-band five-channel MT data were recorded using the ADU07 instrument of Metronix GmbH at a total of 19 sites along two different profiles, namely the Ongole profile (AA′), having 10 sites and the Nellore profile (BB′), having 9 sites. The length of AA′ profile is 35 km and that of the BB′ is 52 km. The average inter-station spacing in AA′ profile is about 3 km, while it is about 5 km in BB′ profile. The location of BB′ profile is chosen to be sufficiently far away (125 km) from AA′ profile, so as to not have any possible interference in the subsurface resistivity structures of both the profiles. Also, we have chosen the profile lengths in such way, so that they do not cross the adjacent geological terrains, namely, the Cuddappah basin and the east Dharwar craton. This is to ensure that the MT data do not contain any signatures of the subsurface structures other than EGMB. Fig. 1 depicts a map showing the EGMB and its adjoining tectonic setting along with the East-Gondwana assembly in the inset. Geographical locations of both the profiles, superposed on the geological map of the study area are also shown in Fig. 1. The magnetic field measurements were made using MFS06 coils and the electric field measurements were made using Pb-$PbCl_2$ electrodes. At almost all the sites in both profiles, the E-W and N-S electrode separation was maintained at about 70–80 m. Data were recorded at each site for about one day, in the period range 0.001–1000 s. At sites along the BB′ profile, the data appear to have been affected due to cultural noise, mostly in the form of agricultural chemicals in the soils and due to seawater intrusion at shallow depths at a few sites located closer to the coast. Junge (1996) explained that the noise sources in measurement of EM fields also arise due to the electrochemical processes in plants. Such noises basically arise from use of agricultural chemicals in soils for farming. Szarka (1988) and Junge (1996) provided extensive details of different types of noises that affect MT data and their corrections. Chandrasekhar et al. (2014) discussed the effect of seawater intrusion on the observed electrical resistivity in and around Nellore region. The MT dead-band noise (that arises usually due to the cross-over frequencies between ionospheric induced energy and lightening induced energy) has also contaminated the data at a few sites in both the profiles. Data were processed with MAPROS and PROCMT softwares, supplied by Metronix GmbH. Both these softwares use the spectral stacking algorithm of Junge (1996) to determine the apparent resistivity and phase estimates.

3.1. Strike angle estimation

Following the procedure outlined by Groom et al. (1993), we have decomposed the MT impedance tensor elements to constrain the galvanic distortion parameters: shear, twist and strike (Groom and Bailey, 1989). This was done using the '*strike*' program of McNeice and Jones (2001). We have considered the entire recorded period range (0.001–1000 s) of the data for estimation of distortion parameters and the strike angle corresponding to both the profiles. The procedure that we have adopted to determine the twist, shear and strike angles is detailed in Chandrasekhar et al. (2009, 2012). The distribution of finally constrained shear and twist angles of all the sites along the profiles AA′ and BB′ are shown in Fig. 2. While the average of twist angles at all the sites in each profile is about 10°, the average of shear angles of all the sites in AA′ profile is 15° and that for BB′ profile is 25°. Notable distortions of twist and shear are seen at site 1 in AA′ profile and at sites 3 and 7 in BB′ profile (Fig. 2). The existence of not so negligible twist and shear angles in the data particularly at short periods suggests the presence of near-surface inhomogeneities or galvanic distortions, which severely affect the impedance tensor elements. Fig. 3 shows the rose diagrams depicting the individual strike angles obtained for the AA′ profile (Fig. 3a) and BB′ profile (Fig. 3b). The definitive strike angles considered for subsequent impedance tensor rotation is +40° for AA′ profile and +22° for BB′ profile to calculate apparent resistivity and phase at each site of both these profiles. The static shift effects observed at a few sites in both profiles were corrected by comparing the apparent resistivity values of adjacent stations (Christopherson et al., 2002). The final calculated apparent resistivity and phase values obtained after impedance tensor rotation and static shift correction were found to be noisy at very short periods (less than 0.01 s), particularly at some sites of BB′ profile. This is believed to be due to the high cultural noise in the data. Therefore, the data corresponding to the period range of 0.01–10 s only was considered for implementing the two-dimensional inversion scheme. The same period range is considered for inversion of the data of AA′ profile also.

4. Two dimensional inversion

Two-dimensional inversion of MT data of both profiles in the period range 0.01 s −10 s was carried out using the non-linear conjugate gradient algorithm of Rodi and Mackie (2001). We have jointly inverted the TE and TM mode apparent resistivity and phase data with error floors of 10% (15%) on apparent resistivity and 5% (7%) on phase for AA′ (BB′) profile. For both profiles, a starting uniform half-space model of resistivity 100 Ω-m was used. The smoothing factor (τ) for the inverting the data was set at 3 and 10 respectively for AA′ and BB′ profiles. τ indicates the trade-off between the data misfits and the model smoothness. Larger values of τ result in smoother models, but at the expense of a poorer fit between the data and the model. Rodi and Mackie (2001) suggest that τ can be set in the range of 3–300. However, it should be so optimally chosen, that the RMS error between the data and model be about 1.0–1.5. Since we wanted to have as much best fit as possible between the data and model, such low values of τ were chosen. Fig. 4 shows the fit between data and model response for a few selected sites of Ongole profile (Fig. 4a) and Nellore profile (Fig. 4b) together with their respective RMS errors. Fig. 5 shows the pseudosections depicting the agreement between the observed and calculated apparent resistivity and phases of TE mode (Fig. 5a) and TM mode (Fig. 5b), corresponding to the sites of AA′ profile. Fig. 5c shows the resulting geoelectrical model corresponding to AA′ profile with an RMS error of 1.94. Beneath the entire profile length of 35 km, the top high conductive layer of about 500 m thick represents alluvium. Between the sites 06–08, the subsurface up to a depth of about 7 km is highly conductive. The entire subsurface up to the depth of 30 km along the AA′ profile is highly resistive, with resistivities at some depths being greater than 10^7 Ω-m.

Fig. 6 shows the pseudosections depicting the agreement between the observed and calculated apparent resistivity and phases of TE mode (Fig. 6a) and TM mode (Fig. 6b), corresponding to the sites of BB′ profile. A notable mismatch of the observed and calculated phases at short periods in TE mode (Fig. 6a) at sites 06, 07 and 08 suggests the strong effect of the galvanic distortions on the data (cf. Section 4). However, this has not affected the TM mode data (Fig. 6b). (The percentage difference maps corresponding to the observed and modelled apparent resistivity and phase data of TE mode and TM mode pseudosections of AA′ profile (Fig. S1) and BB′ profile (Fig. S2) are provided in supplementary material). It may be observed that although maximum scale ranges are shown in Figs. S1 and S2, the percentage difference between the observed and modelled pseudosections of TE and

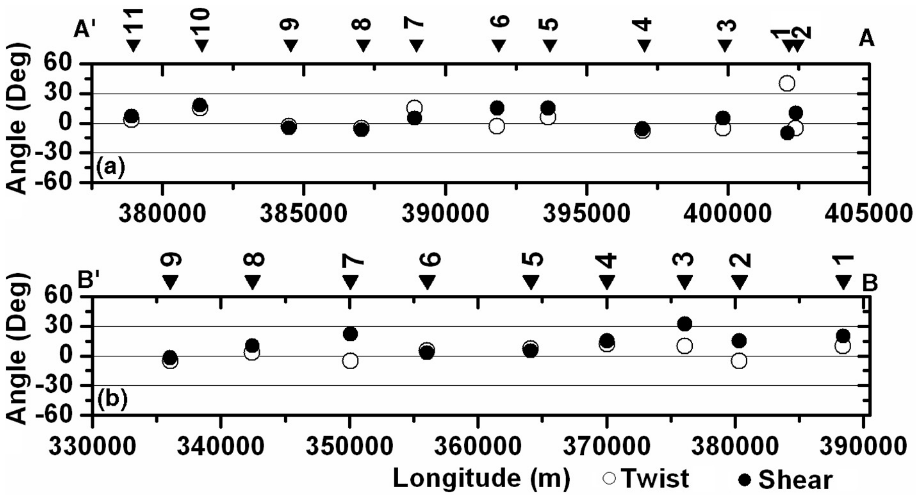

Fig. 2. Spatial distribution of distortion parameters, twist and shear corresponding to each site in (a) AA′ (Ongole) profile and (b) BB′ (Nellore) profile (see text for more details).

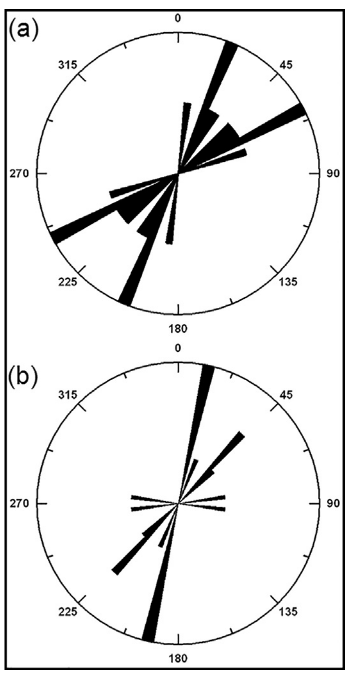

Fig. 3. Rose diagrams depicting the strike angles corresponding to the sites of (a) AA′ profile and (b) BB′ profile. The definitive strike angles considered for subsequent impedance tensor ration is $+40^{\circ}$ for AA′ profile and $+22^{\circ}$ for BB′ profile.

TM modes within the modelled period range (0.01–10 s) is dominantly ± 15–20%. Given the considerable influence of high levels of cultural noise in the MT data at short periods, the obtained percentage differences in the respective pseudosection plots are in the acceptable range. Fig. 6c shows the resulting geoelectrical model corresponding to BB′ profile with an RMS error of 1.82. Due to relatively higher error floors considered in the inversion of the apparent resistivity and phase data of BB′ profile, the RMS error for this model is lower compared to that of AA′ profile. Fig. 6c also shows the alluvium covered high conductive thin top layer. The entire subsurface from beneath the alluvium layer up to the depth of 30 km along the BB′ profile is also highly resistive ($> 10^7$ Ω-m), showing a striking similarity with the subsurface structure of AA′ profile.

5. Results and discussion

In Fig. 5c, the high conductive and very thin top layer (of about 500 m thick) beneath the entire AA′ profile represents alluvium. The entire subsurface below this thin layer is highly resistive, with resistivities of the order of 10^7 Ω-m, comprising mainly of rock units of the khondalite (garnet silimanite cordirite gneiss associated with minor quartzite), calc granulites and charnockite (hypersthene gneiss/pyroxene granulites/quartz magnetites) groups of the Eastern Ghats Supergroup and granite gneisses of Archaean age (Swamy et al., 2008). The subsurface resistivities in Ongole region have been observed to increase with depth, from 10^3 Ω-m at the top to $> 10^7$ Ω-m at 25 km and beyond. The gradual increase in resistivity implies the gradual waning away of rock weathering in this tropical region, thereby making the entire subsurface extremely highly resistive. Analyzing the gravity data of northern regions of EGMB, Sarkar et al. (1988) identified the average densities of Khondalities, Charnockites, Granites and Gneisses as 2.75, 2.78, 2.78 and 2.65 g/cc respectively, suggesting that there has been a significant overlap of these rock types. Thus the configuration of the crust beneath EGMB is believed to be multilayered (Nayak et al., 1998). However, through the deep seismic sounding (DSS) studies, Kaila et al. (1987) suggested that the in situ measurement of velocities near Ongole indicated a disturbed crust and that it has not been possible to distinguish the above rock types from the basement rocks based on velocity data alone. In the present study, because the major rock types in the study region also have large overlapping resistivities, MT data also could not explicitly discern the nature of multilayered crust of EGMB near Ongole region. As a result, the subsurface near Ongole region shows up as a single large resistivity structure (Fig. 5c) right from the top to 30 km depth. In Fig. 5c, the interesting feature that is of concern is the high conductive zone seen beneath the sites 06–08, in an otherwise very high resistive subsurface. Inset of Fig. 5c depicts the geology and major tectonic features surrounding the AA′ profile. As seen in this inset, a portion of the AA′ profile lies in the lateritic zone, while the rest lies in the alluvium and charnockite zones. The high conductive zone seen beneath the sites 06–08 in Fig. 5c represents the Cenozoic laterites (Swamy et al., 2008). As well known, laterites consist mainly of quartz, zircon, and oxides of titanium, iron, tin and aluminium, which remain during the course of weathering. In the study region, they are formed due to the leaching of the parent metamorphic rocks, which leaves predominantly the insoluble forms of iron and aluminium making the zone highly conductive.

In the EGMB region, there have been a number of NE-SW trending faults developed within the continental rocks, which are consequent to

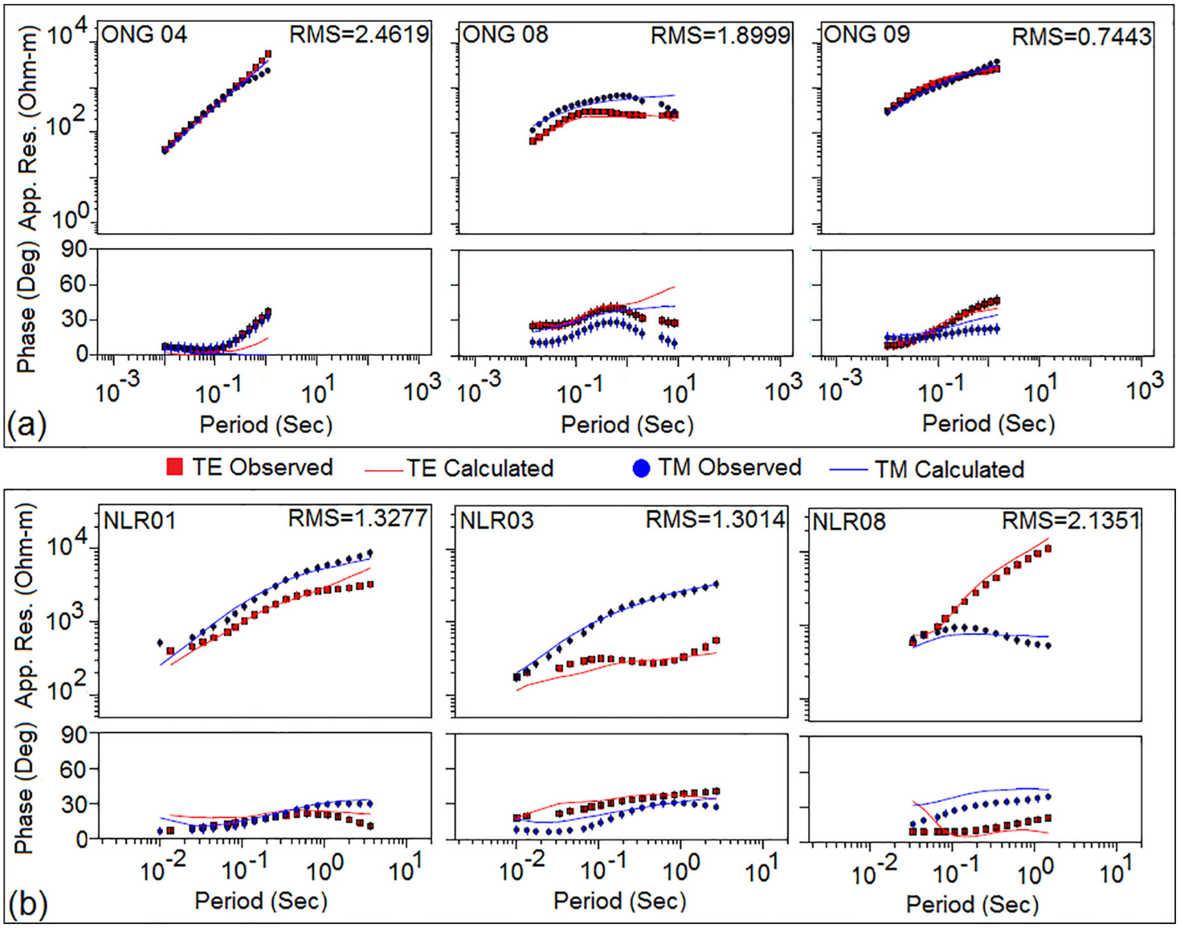

Fig. 4. Comparison between the observed data and their corresponding modelled responses of TE and TM modes at some of the selected stations of (a) AA′ profile and (b) BB′ profile shown in Fig. 1.

the extension of the continent in NW-SE direction. They are believed to be related to the Gondwanaland break up, when Bay of Bengal/Indian Ocean formed (Subrahmanyam and Chand, 2006). In fact, the entire east-coast of India was developed due to such faulting. Similar faults are also observed within the Bay of Bengal. The faults within the continents have made a way for groundwater and surface water to seep through them and weather the rock into laterite. As the laterite has high porosity, the zone is more conductive in nature. Further, as the AA′ profile lies in agricultural farm lands in coastal area, the deeper accumulation of clay sediments together with the agricultural chemicals and rock-leaching, which generally occurs due to percolation of rain water, along one such NE-SW trending possible fault zone delineated beneath Ongole profile between the sites 06–08, could be one of the prime factors responsible for high conductivity at shallow depth. The correctness of the electrical nature of the subsurface beneath AA′ profile could be validated against the very good match between the observed and calculated apparent resistivity and phase data of TE (Fig. 5a) and TM modes (Fig. 5b). The estimated RMS error, depicting the fit between the data and model is 1.94.

Interestingly, the geoelectric model of BB′ profile also is found to be highly resistive (Fig. 6c) and bears quite a good similarity to that of AA′ profile (Fig. 5c). The average thickness of the top alluvium layer in Nellore region (Fig. 6c) is slightly higher than that seen in Ongole region (Fig. 5c). The entire subsurface beneath the alluvium layer is highly resistive, with resistivities varying in the range of 10^3 Ω-m at shallow depths to > 10^7 Ω-m at deeper regions. The major rock types occurring in Nellore district are granite gneiss, migmatite quartzites, hornblende schist, and granitic gneiss of Archaean age (see Chandrasekhar et al., 2014). Discussing the evolution process of the deep crust during Archean age, Gokarn et al. (2004), through their geoelectrical model obtained by MT studies, showed that the high resistive crust of the western Dharwar craton subducts beneath the east Dharwar block along the Archean suture identified along the Chitradurga–Gadag schist belt (see Fig. 12 of Gokarn et al., 2004). Gokarn et al. (2004) also advocate that the geological setting near their MT profile is similar to that near the DSS profile of Kaila et al. (1979) and thus their geoelectrical model could be compared with the results of Kaila et al. (1979). The subsurface resistivity determined by Gokarn et al. (2004) in the east Dharwar region is about 10^4 Ω-m. It may be recalled here that Naganjaneyulu and Harinarayana (2004) carried out the MT survey along the same DSS profile of Kaila et al. (1979) and determined a very low resistivity structure beneath the entire Kavali-Udupi profile. Since most MT sites in the large profiles of Gokarn et al. (2004) and Naganjaneyulu and Harinarayana (2004) cut across different geological terrains other than the EGMB, their delineated low-resistive subsurface dominantly corresponds to those geological terrains and not entirely of EGMB. If we also had observed the subsurface features as low resistive in our study region, then we would have prudently argued about the discontinuation of EGMB at Ongole. There also is a distinct difference between the subsurface resistivities of the EGMB and eastern Dharwar craton and Cuddapah basin, with the resistivity of the EGMB rocks being much higher than that of the Dharwar and Cuddapah blocks. Since the resisitivities seen beneath Ongole and Nellore regions are as high as 10^7 Ω-m and more, it can be easily understood that our present study clearly distinguishes the high resistivities of rocks of EGMB and Dharwar blocks, suggesting that the observed high resistive subsurface structure in Nellore region could in fact be construed as a southward extension or rather continuity of the EGMB beyond Ongole

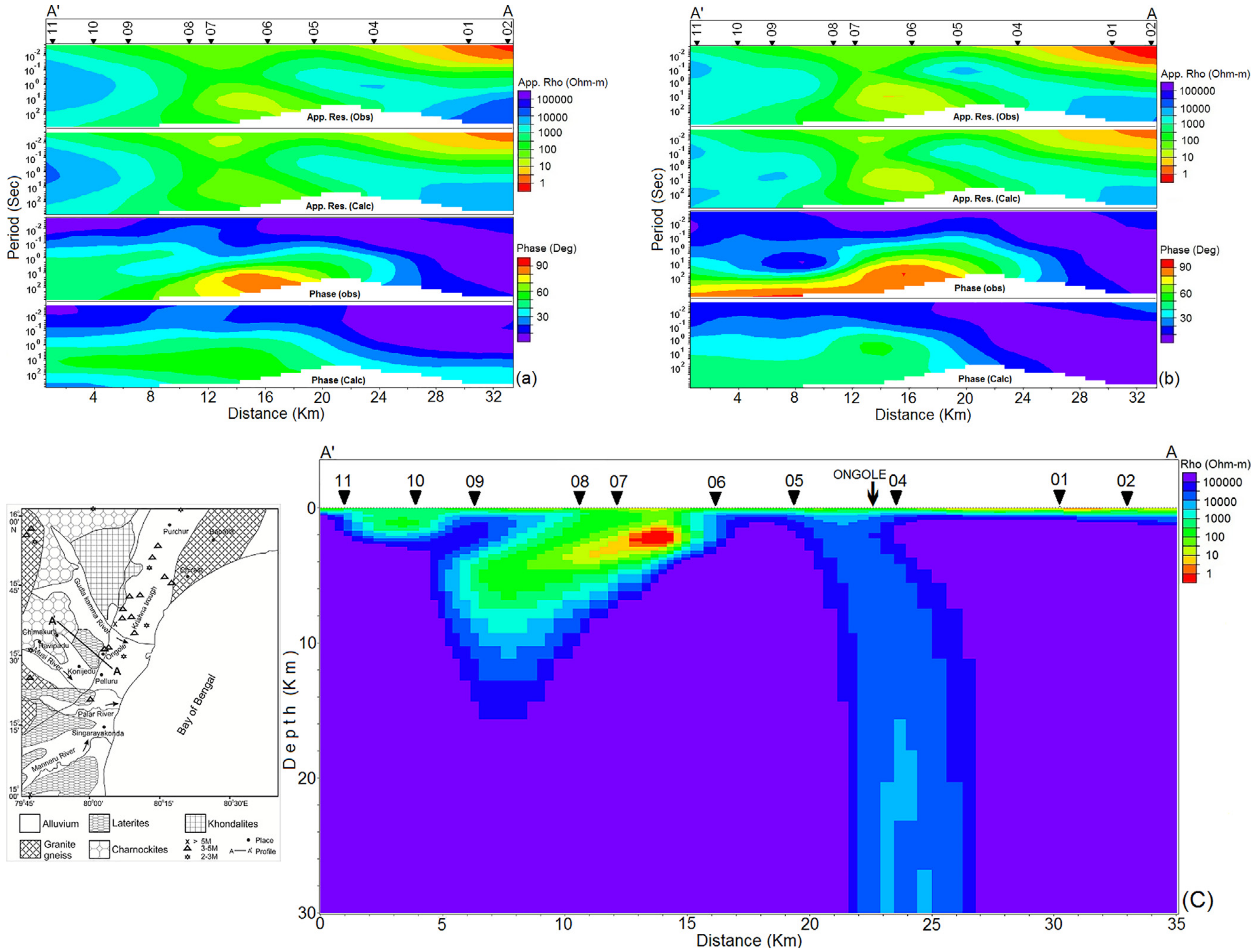

Fig. 5. Pseudosections depicting the observed and calculated apparent resistivity and phase data corresponding to (a) TE mode and (b) TM mode of sites of AA′ profile. (c) Two-dimensional geoelectric model of MT data of Ongole (AA′) profile. The model is obtained after jointly inverting the TE and TM mode data with error floor of 10% considered for apparent resistivity and 5% for phase. The RMS error for this model is 1.94.

and towards Nellore. This is also consistent with the geological observation that the Ongole domain of the EGMB and the supracrustals of the NSB have undergone synchronous tectonic activity at ca.1.6 By (Henderson et al., 2014). Evidently the Kanigiri and Kandra ophiolites within the NSB also signify the Proterozoic subduction of the EGMB.

Therefore, we strongly believe that the delineated high resistive subsurface beneath Nellore region (Fig. 6c), which confirms with the local geology and bears a striking similarity with that observed at Ongole region (Fig. 5c), provides an unequivocal evidence that the EGMB does not get cut abruptly near Ongole, but extends further south of Ongole towards Nellore. As mentioned earlier, particularly in Nellore region, the data have been largely affected by cultural noises in the form of aqua culture and farming activities. This could be due to the presence of high conductive sediments at the top (Fig. 6c), which are thicker than that observed near Ongole region (Fig. 5c). This has particularly affected the MT phase data at some sites, resulting in not so good fit between the observed and calculated phases of both TE (Fig. 6a) and TM mode (Fig. 6b), even when the set error floors for apparent resistivity and phase for BB′ profile data are relatively higher than those set for AA′ profile data.

In an attempt to have a deeper understanding of the high conductivity nature of the delineated top layer in this zone, we have carried out a 2D electrical resistivity imaging survey at the same sites, where MT data were recorded along the BB′ profile (see Fig. 1 of Chandrasekhar et al., 2014). We also have studied the geochemical analysis results of groundwater samples collected during pre- and post-monsoon periods at some places close to the MT and electrical resistivity imaging sites, where boreholes were drilled by the groundwater board of the state government of Andhra Pradesh, India. Joint interpretation of geochemical analysis results and electrical resistivity images revealed different reasons at different sites for high conductivity at shallow depths along the BB′ profile. While the high conductivity at sites 01–03 has been mainly due to sea-water intrusions (probably due to aqua culture activities near coastal sites), the high conductivity at sites 04–07 has been due to the high concentrations of fertilizers and water-rock interactions, leading to high TDS and Ca/Mg ratios. At sites 08 and 09 (which are almost about 55 km from coast) the conductivity has mainly been due to the presence of paleochannels (see Reddy and Chandrakala, 2004) acting as excellent conduits for transportation of seawater, well inland. Fig. 7 shows the plates of resistivity imaging results of each site of BB′ profile. For more details of this joint interpretation of resistivity imaging data and geochemical data, the reader is referred to Chandrasekhar et al. (2014).

6. Conclusions

MT investigations carried out along two profiles, namely, the Ongole profile and the Nellore profile clearly show striking similarities

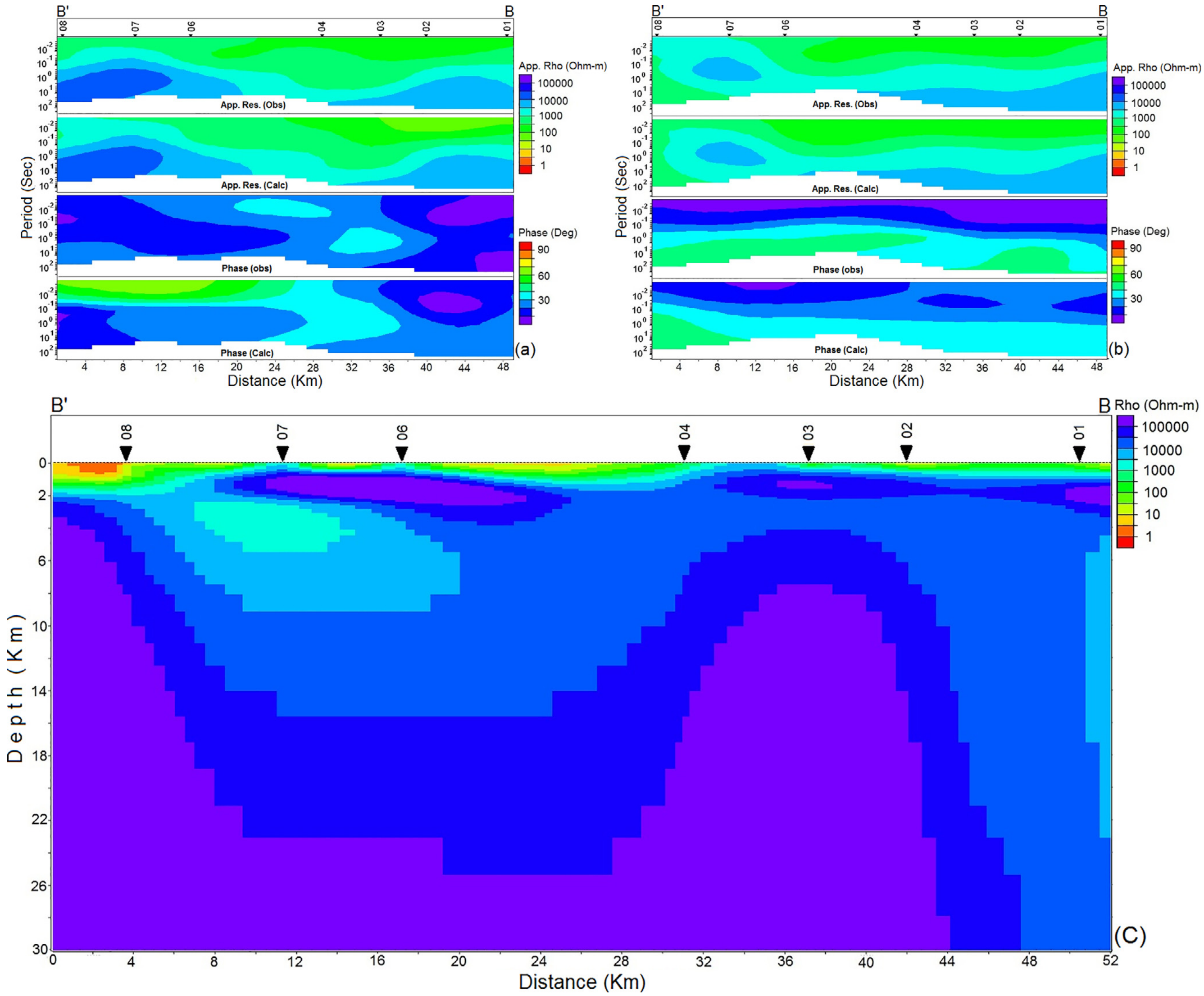

Fig. 6. Pseudosections depicting the observed and calculated apparent resistivity and phase data corresponding (a) TE mode and (b) TM mode of sites of BB′ profile. (c) Two-dimensional geoelectric model of MT data of Nellore (BB′) profile. The model is obtained after jointly inverting the TE and TM mode data with error floor of 15% considered for apparent resistivity and 7% for phase. The RMS error for this model is 1.82.

about the high resistive nature of the subsurface and provide an unequivocal evidence, suggesting the extension of the EGMB from Ongole towards Nellore. The distinct differences in the subsurface electrical resistivities seen at the adjoining Dharwar craton, which is about 10^3 Ω-m (Gokarn et al., 2004; Naganjaneyulu and Harinarayana, 2004) and at the Ongole and Nellore regions, which is as high as 10^7 Ω-m and more (present study) clearly explains that the high resistive subsurface structure in Nellore region could in fact be construed as a southward extension or rather continuity of the EGMB beyond Ongole and towards Nellore. The similarities in isotopic age, signatures of the Proterozoic tectonics and thrust dynamics with craton emphasize the continuity of the EGMB to further south of Ongole through NSB. Finally, the present results also suggest that the surface rock types seen at these two regions are not limited to only near surface regions, but also extend deep up to crustal depths and perhaps further beyond. The geophysical evidence provided through this study also bears high significance because, for the first time, the electrical nature of the deep subsurface of the EGMB is discussed solely on the lines of its southward extension from Ongole towards Nellore.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jseaes.2018.06.009.

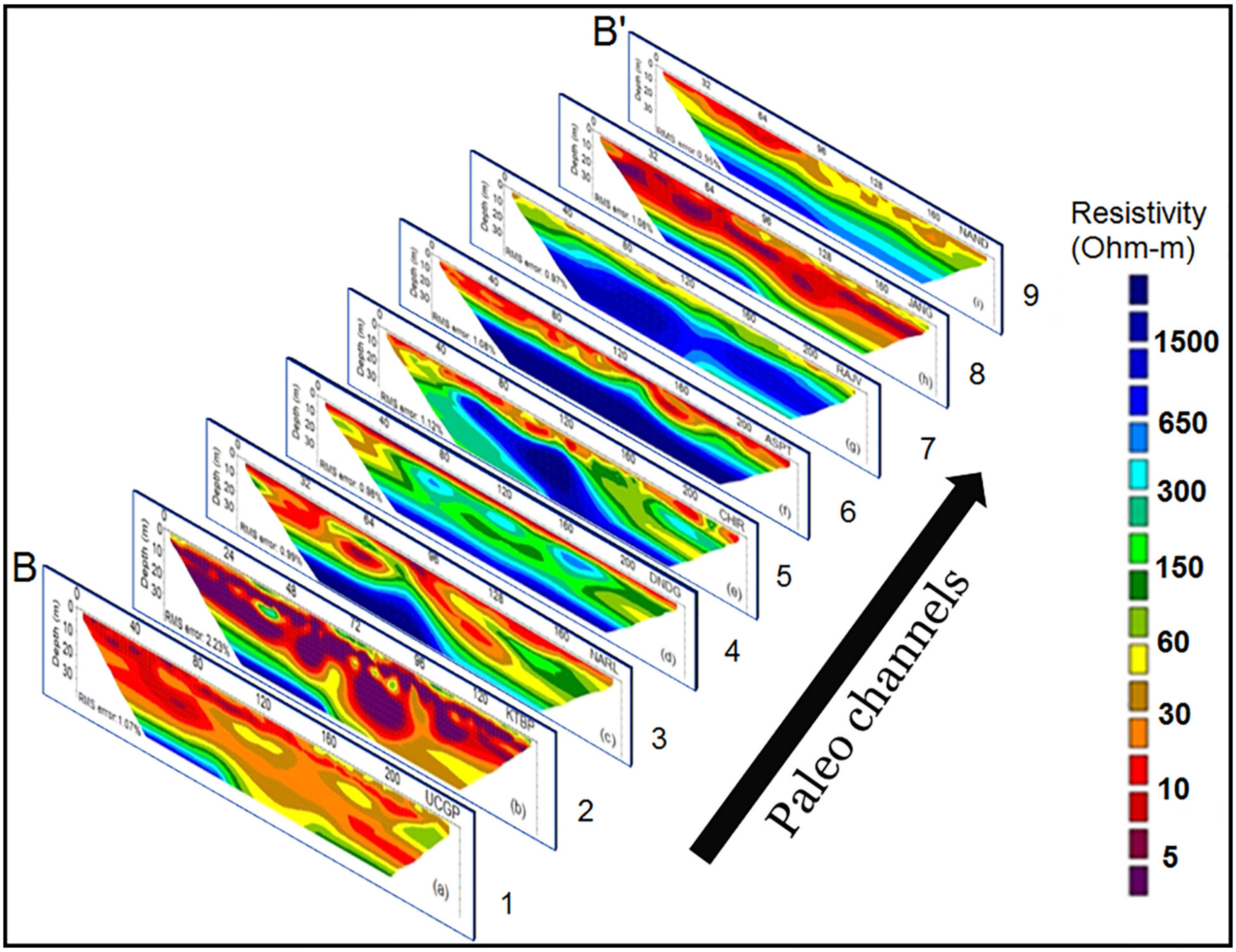

Fig. 7. Two-dimensional models of multi-electrode resistivity imaging data corresponding to the sites of BB′ (Nellore) profile. Respective site numbers are shown alongside each plate. The four-lettered code of each site is also shown on respective plate. See Chandrasekhar et al. (2014) for more details on the interpretation of the shallow resistivity structure in this region. RMS error of each model corresponding to each site is also shown in the respective plate.

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