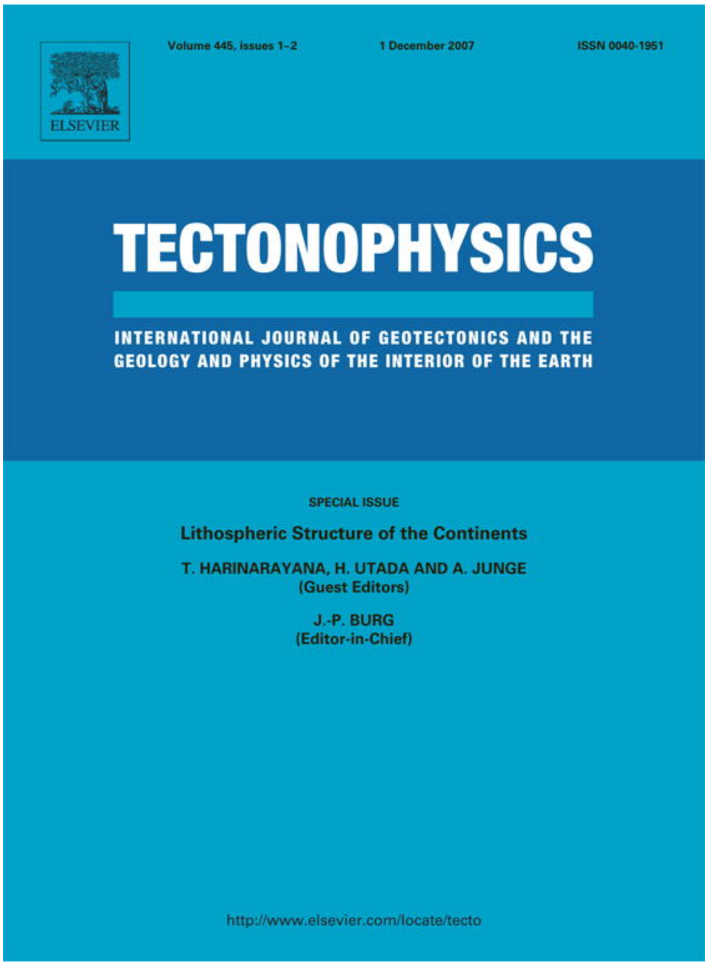

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Regional geoelectric structure beneath Deccan Volcanic Province of the Indian subcontinent using magnetotellurics

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Abstract

Understanding deep continental structure and the seismotectonics of Deccan trap covered region has attained greater importance in recent years. For imaging the deep crustal structure, magnetotelluric (MT) investigations have been carried out along three long profiles viz. Guhagarh–Sangole (GS), Sangole–Partur (SP), Edlabad–Khandwa (EK) and one short profile along Nanasi–Mokhad (NM). The results of GS, SP and NM profiles show that the traps lie directly over high resistive basement with thin inter-trappean sediments, where large thickness of sediments, of the order of 1.5–2.0 km, has been delineated along EK profile across Narmada–Son–Lineament zone. The basement is intersected by faults/fractures, which are clearly delineated as narrow steep conducting features at a few locations. The conducting features delineated along SP profile are also seen from the results of aeromagnetic anomalies. Towards the southern part of the profile, these features are spatially correlated with Kurduwadi rift proposed earlier from gravity studies. Apart from the Kurduwadi rift extending to deep crustal levels, the present study indicates additional conductive features in the basement. The variation in the resistivity along GS profile can be attributed to crustal block structure in Koyna region. Similar block structure is also seen along NM profile.

Deccan trap thickness, based on various geophysical methods, varies gradually from 1.8 km towards west to 0.3 km towards the east. While this is the general trend, a sharp variation in the thickness of trap is observed near Koyna. The resistivity of the trap is more (150–200 Ω m) towards the west as compared to the east (50–60 Ω m) indicating more compact or denser nature for the basalt towards west. The upper crust is highly resistive (5000–10,000 Ω m), and the lower crust is moderately resistive (500–1000 Ω m). In the present study, seismotectonics of the region is discussed based on the regional geoelectrical structure with lateral variation in the resistivity of the basement and presence of anomalous conductors in the crust.

Keywords: Deccan traps; Electrical conductivity; Magnetotellurics; Seismotectonics

1. Introduction

After Gondwana breakup, (~80–130 Ma), the Indian plate moved over the Reunion mantle plume (or hotspot) during its northward drift. The huge flood basaltic eruption covering an area of half a million sq. km over the central-western part of the Indian subcontinent, popularly known as Deccan Volcanic Province (DVP), is the result of interaction between the mantle plume and the overriding continental lithosphere at ~65 Ma (White and McKenzie, 1989). Krishna Brahmam and Negi (1973) postulated the existence of two major rift valleys below DVP namely Koyna and Kurduwadi rifts, filled

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with sediments corresponding to two gravity lows. Southern part of DVP and Dharwar craton has exhibited a clear NW–SE trending aeromagnetic anomalies in accordance with the Dharwarian trend (Anand and Rajaram, 2002).

In light of above, the concept that Indian peninsular shield is not stable, has once again gained credence recently after the incidence of the devastating Latur earthquake of September 30, 1993. Though the origin of seismicity in Stable Continental Region (SCR) has long been an enigma, the occurrence of the Latur earthquake in unexpected region of the Indian shield is much more intriguing. It has opened up several more challenging problems particularly in relation to the increased seismicity in DVP during the last three decades. In this context, study of deep interior of the region will have significant relevance to the understanding of possible physical processes responsible for neo-seismic activity of the SCR of peninsular India.

A major part of intraplate seismicity is believed to originate from shallow depth range in the crust (Maggi et al., 2000). Information on depth to the interface between brittle and ductile zones in the earth's crust has a close bearing on the characterization of seismicity and seismotectonic processes of a given region (Gupta et al., 1996). Amongst other geophysical methods, magnetotelluric (MT) technique provides a detailed electrical structure of the crust, which in turn could be interpreted in terms of lithology, and geological structure over a range of depths extending from very shallow levels to as deep as a few hundreds of kilometers. The subsurface information that we infer could be effectively interpreted in terms of lateral subsurface heterogeneities reflecting possible rheological changes that are known to be closely linked to the seismogenic processes (Jones, 1992). It is also believed that fluid filled zones in the crust might play a dominant role in generating seismicity in SCR (Sarma et al., 1994). Mapping of subsurface conductors might represent significant features such as fluid filled zones in the earth's crust, partial melts, feeder dykes, structural features like faults and shear zones, magma chambers, etc. They provide several basic vital clues to unravel the possible sources responsible for intraplate seismicity in the Indian stable continental region.

Magnetotelluric (MT) studies carried out after the Latur earthquake in India, have clearly established an

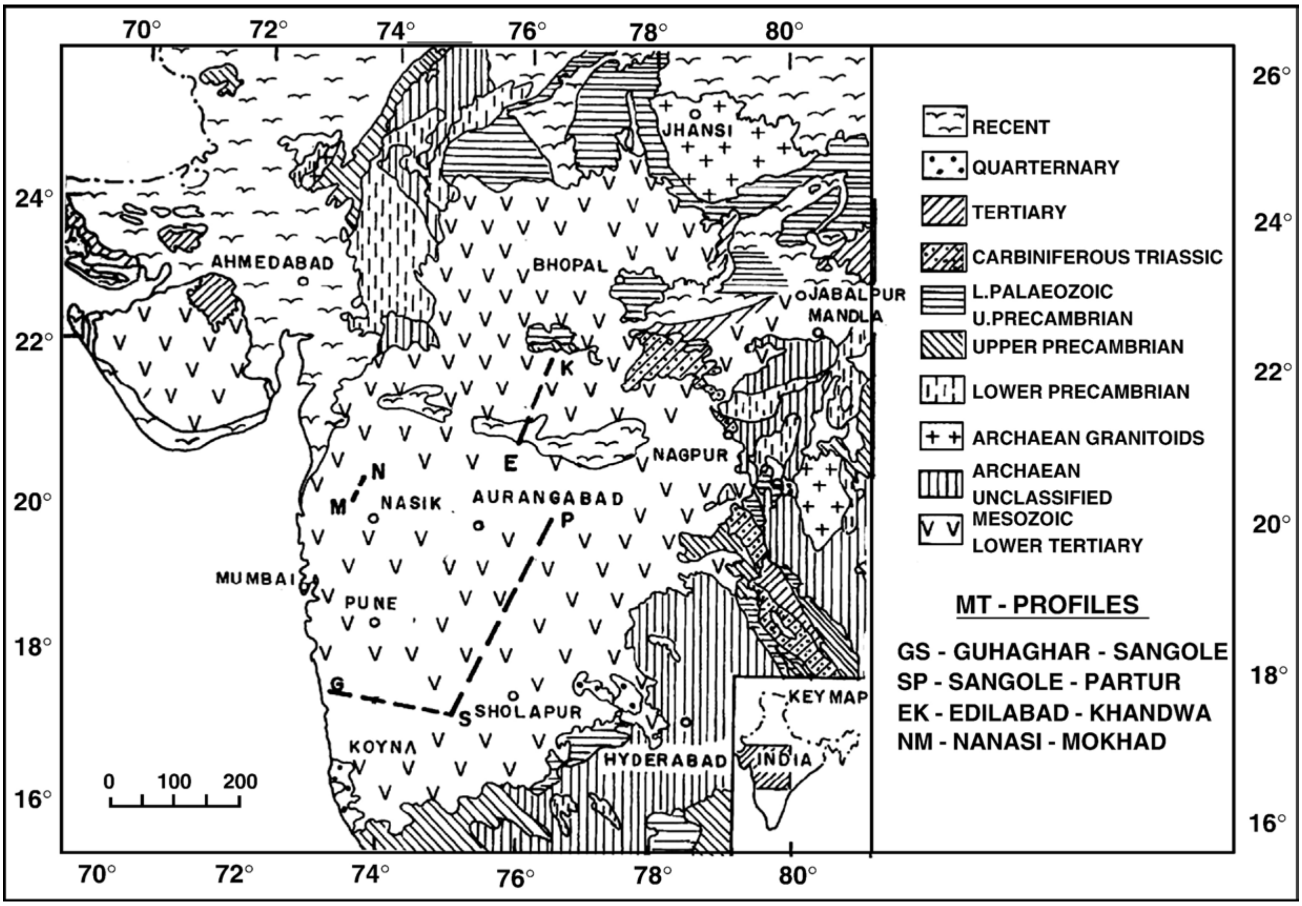


Fig. 1. Simplified geological map of the area with locations of four MT profiles (GS, SP, MN and EK) discussed in the present study.

anomalous upper crustal conductor in the hypocentral region (Sarma et al., 1994; Gupta et al., 1996). It is widely accepted that conductivity anomalies can be closely related to high temperature and presence of fluids in the crust (Jones, 1992). Detection of such crustal conductivity anomalies may have a direct bearing on the understanding of physical processes related to earthquake generation particularly under stable continental region.

A total of 49 MT sites in western India were occupied along NE–SW profile (SP) of 320 km length, one E–W profile (GS) of 200 km near Koyna region covered with 16 sites and another NNE-SSW profile (EK) of ~130 km with 21 sites across NSL zone. In addition to these profiles, another small 60 km long NS profile (NM) with 8 sites has also been occupied near Nasik (Fig. 1). Two versions (MMS04 and GMS05) of MT equipment of M/s Metronix, Germany, have been used in the present field investigations. Analysis of these MT profiles is made to determine the subsurface structure, comprehensive Deccan trap thickness and their relation to seismotectonics.

2. Earlier geophysical studies

A regional gravity survey (Kailasam et al., 1972) brought out two major regional gravity lows — one oriented N–S along Western ghats known as 'Koyna low' and the other along NW–SE in the central part known as 'Kurduwadi low'. There is a steep gradient in the Bouguer gravity anomaly near the west coast. The origin and characteristics of these large gravity lows and highs have been a matter of debate. The steep gradient in gravity anomaly from east to west coast (3–4 mgal/km) has been interpreted as due to deep-seated fault. This fault is believed to be the cause for the Western ghats scarp (Pascoe, 1964). Later on, it has been suggested that such large anomaly can not be attributed to the fault alone, and also, the down throw towards west does not favor the nature of the observed gravity anomaly. Gravity anomalies are ascribed to variations in the thickness of DT cover and also to the deep-seated crustal structures (Kailasam et al., 1972) depending on their wave-length. Regional Bouguer anomaly has been further modeled by Mishra (1989), with constrained Moho depth and Conrad discontinuities derived from Deep Seismic Sounding results (Kaila et al., 1981). Regional isostatic map depicts a low towards west coast encompassing the Western ghats and attributed to upper mantle inhomogeneities (Qureshy, 1981).

Deep Seismic Sounding (DSS) survey in the western part of DVP (Kaila et al., 1981) provides thickness of Deccan trap and crustal structure up to Moho. Broadly, the crustal section has been divided into two blocks separated by a fault coinciding with the eastern margin of Western ghats. Depth to the Moho varies from 36–40 km, deepest inferred under Western ghats. It decreases to 36 km below the Konkan plain near the west coast. Crustal velocity increases with depth, from 5.7 km/s at 2 km with velocity discontinuity at 10 km to 6.34 km/s. Further down there are velocity discontinuities at 19 and 42 km which may represent Conrad and Moho respectively. Lateral heterogeneities in electrical conductivity in Deccan trap region have been delineated by Gokarn et al. (1992, 2001) using magnetotelluric studies. Rao et al. (1995, 2004) mapped the electrical structure in rift areas like Narmada–Cambay.

It has been suggested that Western ghats are primarily an erosional feature (Auden, 1949) and may not be the result of faulting as was proposed by Pascoe (1964). Travel time and relative amplitude modeling of seismic records of these profiles (Krishna et al., 1991) revealed low velocity layers in the crust and upper mantle. Ramesh et al. (1993) observed low velocity residuals (−1.5%) from tomography experiment in the western part of DVP. This has been correlated with possible source region of the lava flows. Deep electrical soundings along a few profiles in DVP provide trap thickness varying from 220 m to 1200 m (Kailasam et al., 1976; Bhaskar Rao et al., 1995).

3. Geology and tectonics of the area

Das and Ray (1972) reported easterly dip of ~10° in the high plateau and westerly dip of ~3–4° in the Konkan plains increasing to ~15° near the coast for DVP. The change in dip is ascribed to monocline flexure, named as 'Panvel Flexure' (Auden, 1949). Several dykes are reported from Konkan coastal belt trending N–S and E–W in the Narmada–Tapti zone. Regional distribution of dykes over a part of DVP is presented by Deshmukh and Sehgal (1988). They also reported that dykes found in Konkan coastal region are younger than those found in the Narmada–Tapti region and suggested that the zone of dyke swarms is the zone of tectonic disturbance. Occurrence of dyke swarms intruding basaltic flows, may be the centers of eruptive foci of Deccan trap. There are many flows recognized in DVP (Deshmukh, 1988) with thickness varying from 10 to 160 m. The thickness of the trap cover is largest near the coast reaching to more than 2000 m while thinning eastward to a few hundred meters (Kaila, 1988).

Preliminary remote sensing studies have delineated three major lineament patterns viz., NW–SE direction parallel to Godavari trend, E–W direction parallel to Narmada–Son–Lineament and third along NNW–SSE direction parallel to the Western ghats. The intersection of these lineaments can be spatially correlated with earthquake epicenters (Arya et al., 1995).

A NW–SE trending lineament, 'Kurduwadi lineament', enters Deccan trap near Gulbarga, passing through Kurduwadi and extends to north of Mumbai. Structural disturbances at deep crustal depths are speculated (Peshwa and Kale, 1997) along this lineament from satellite imageries and its field verification. Digital image of Bouguer gravity anomalies over the Indian shield (Sreedhar Murthy and Raval, 2000) also indicate the presence of a linear feature from Mumbai on the west coast to Chennai on the east coast passing through Latur region. It coincides with the Kurduwadi lineament proposed by Peshwa and Kale (1997).

Besides the widely believed mechanisms in respect of the seismicity in the vicinity of known tectonic features like major faults, rifts and grabens, the possible causative sources for the seismicity in the apparently stable regions of the plate interiors which are well away from active tectonic features and also quite far off from the known plate boundaries are more complex. Much believed stable part of the Indian peninsular shield has witnessed several significant seismic events during the past few decades and the most unexpected events amongst these are the highly devastating 1967 Koyna and 1993 Latur earthquakes (Gupta et al., 1996).

4. Magnetotelluric survey

Among the various geophysical methods, one of the well-known and effective tools to probe the earth at deep crustal level is 'Magnetotellurics'. The method provides electrical structure, which in turn, can be interpreted in terms of lithology and structure over a range of depths extending from shallow levels to as deep as a few hundreds of kilometers. Time variations of two orthogonal components of electric (E_x, E_y) and three mutually perpendicular components of magnetic (H_x, H_y and H_z) fields are measured. Utilizing the ratio between electric and magnetic field components, the impedance tensors can be computed, which in turn provide apparent resistivity (ρ_a) and phase (ϕ) parameters. The ρ_a and ϕ responses can

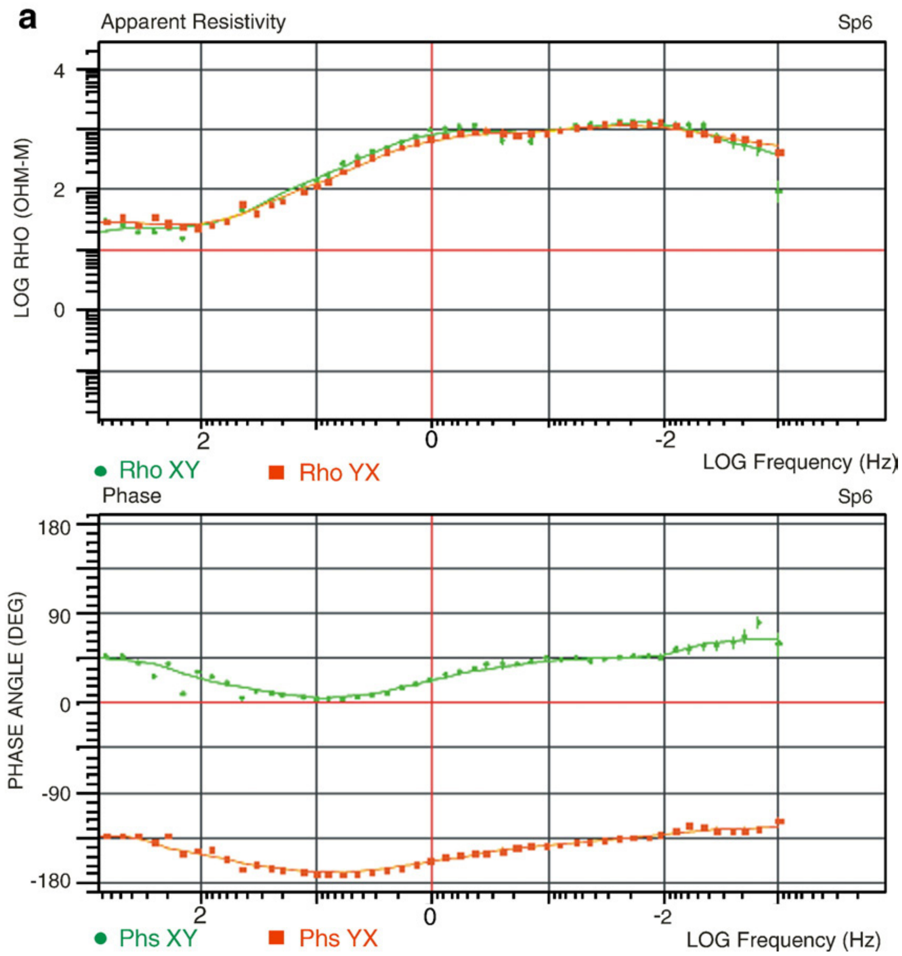


Fig. 2. a. The apparent resistivity and phase data along Sangole–Partar profile for station sp6. b. The apparent resistivity and phase data along Guwahar–Sangole profile for station gks7. c. The apparent resistivity and phase data along Edulabad–Khandwa profile for station ek8.

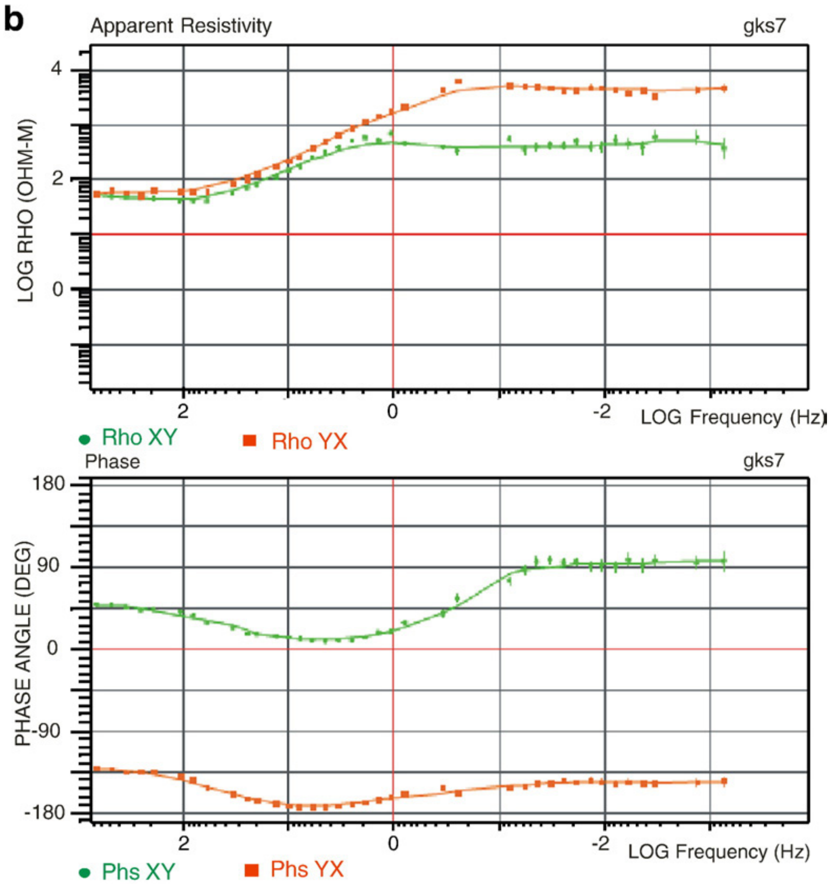


Fig. 2 (*continued*).

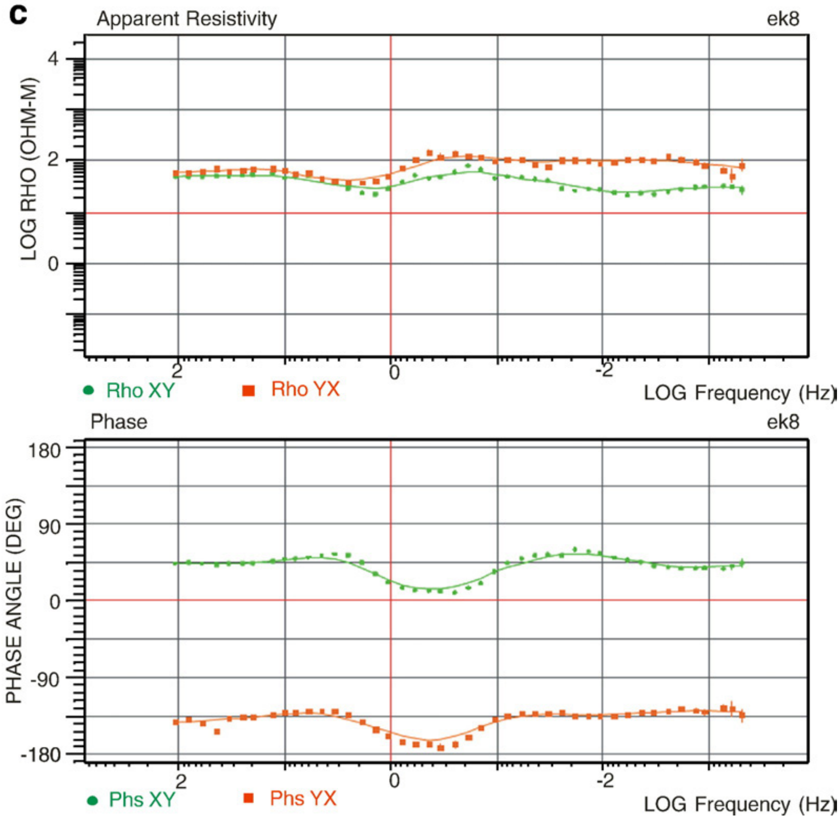
be used to make a qualitative and quantitative estimates of the subsurface distribution of electrical resistivity with depth. More details on the methodology and its application can be seen in a recent book by Simpson and Bahr (2005). Wide frequency range of signals from a few kHz to a few thousands of seconds facilitate to probe the earth from shallow level of 10–100 m to deep crust and upper mantle depths.

The data collected along four profiles have been processed using PROCMT software package (Metronix, Germany). Single site electromagnetic transfer functions are estimated using a robust technique. At many stations, good quality data is recorded due to low interference from the power lines. Examples of three sounding curves in DVP are shown in Fig. 2a, b, c corresponds to MT station SP6 of SP profile, GKS7 station of GS profile and EK8 of EK profile respectively.

Initially the time series data of each of the electric and magnetic field components have been edited manually by rejecting the bad segments (e.g. spikes) and finally the remaining data have been transformed to frequency domain using an FFT algorithm. The MT impedance tensor and two magnetic transfer functions are computed.

5. Two-dimensional modeling

The MT responses are rotated to the regional geological/geoelectrical strike direction obtained using a Groom–Bailey (G–B) decomposition technique (Groom and Bailey, 1991) after correction for local distortion by constraining shear and twist parameters. The procedure we followed, consisted in the calculation of an average strike direction, then the responses are rotated into this direction. Following this procedure, N15°E for GS profile, two strike directions are noticed for SP profile namely −50° towards SW and −65° towards NE, near E–W direction for NM profile and N80°E for EK profile are obtained as the regional geological strike direction. Basically, we allow larger variation on the apparent resistivity to account for the static shift, without obtaining the value through inversion. An error floor of 10% for apparent resistivity and 5% for phase has been assigned during the inversion. Both apparent resistivity and phase in TE, TM modes together are considered. As good quality of tipper vector could not be obtained for a few sites, this transfer function has not been considered during the



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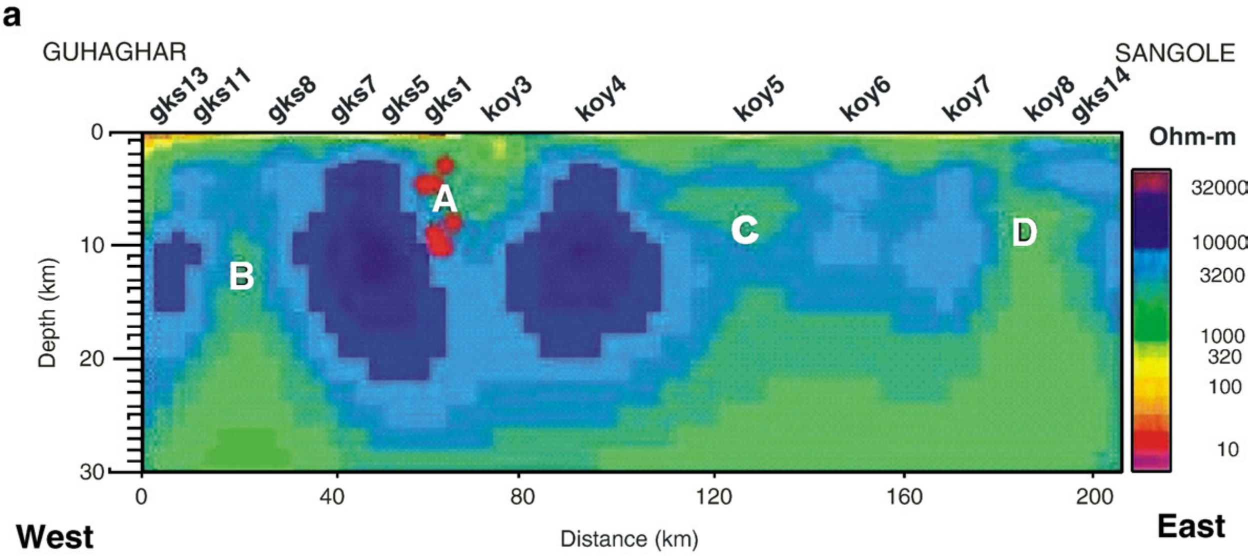
inversion. In the following, we describe details of 2-D subsurface section derived for each profile.

5.1. Subsurface section along GS profile

The subsurface electrical section along Guhagar–Sangole profile has been computed after inverting the data using RLM2D scheme (Fig. 3a). The model correlates well with seismic and also with regional gravity data (Fig. 10 in Sarma et al., 2004). The near surface layer – Deccan traps – resistivity is ranging from 40–150 Ω m and its thickness decreases towards east. The thickness of traps at the eastern part of the profile is about 500 m and increases to 1300 m near the coast towards west with sharp undulation in between. This layer is lying over a high resistive (5000–20,000 Ω m) formation. The crust beneath the trap cover is characterized by three different blocks of varying resistivities. The western block shows a high resistivity (5000–20,000 Ω m) up to 10–15 km depth while the eastern block is less resistive (5000 Ω m). At 15 km depth, two relatively low resistive (500–1000 Ω m) blocks can be observed at the stations gks11 and koy5 (Sarma et al., 2004). Another conducting feature (marked A in Fig. 3a) starts from surface and penetrates to crustal depth, coincidental with the Koyna fault zone (KFZ), a deep penetrating fault delineated from seismic studies (Kaila et al., 1981). This region also coincides with the northward extension of the tectonic boundary between western and eastern Dharwar cratons, and appears to be covered by the Deccan traps (Veeraswamy and Raval, 2005).

5.2. Geoelectric section along SP profile

The geoelectric section obtained along Sangole–Partur traverse is presented in Fig. 3b. The subsurface section shows 50 to 100 Ω m resistivity up to a depth of 500 m towards southwest and increases to about 1000 m in the central part, gradually decreasing and attaining 500 m for the rest of the profile towards northeast. This layer corresponds to the Deccan traps. In general, Deccan traps lie directly over high resistive basement (3000 to >10,000 Ω m). Further, within the high resistive basement, steep conductive features (A–F) are observed. The effect of anisotrophy has also been examined as a possibility (Patro et al., 2005a,b). The sensitivity analysis for the model can be seen in Fig. 9 of Patro et al. (2005a). It may be recalled that Kurduwadi lineament crosses the



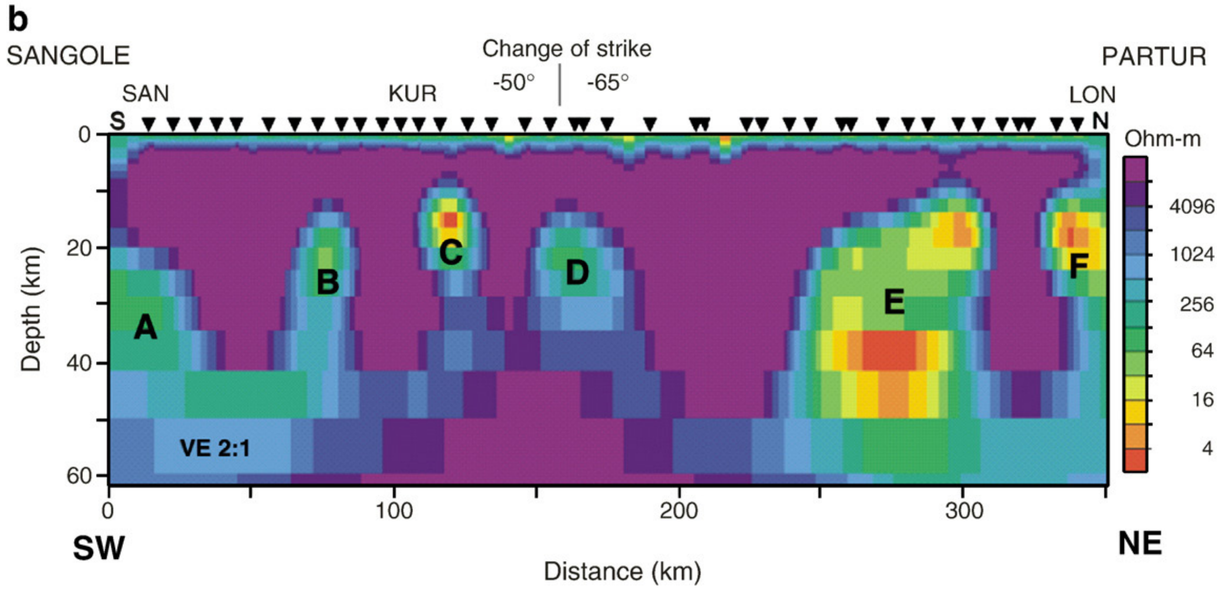


Fig. 3. a. 2-D electrical resistivity depth section along west to east oriented Guhaghar–Sangole profile. A, B, C, D indicate deep crustal conductive features. Cluster of hypocenters can be noticed near conductive anomaly ‘A’ below Koyna (gks1) region. b. 2-D electrical resistivity depth section along Sangole (SW)–Partur (NE) profile. KUR: Kurduwadi; LON: Lonar, A, B, C, D, E, F are conductive features.

profile at KUR (Fig. 3b). The presence of conductive features indicate that the basement along the profile is not uniform but is intersected by conductive features, which may have greater role in developing seismogenic processes in the region.

5.3. Geoelectric section along NM profile

The subsurface section along Nanasi to Mokhad (60 km long) exhibits a surface layer of moderate resistivities (100–200 Ω m) attributed to the presence of Deccan traps Fig. 4a). The misfit RMS error between the observed and computed data sets is 2.67%. Deccan trap layer appears to lie over a resistive basement (1000–10,000 Ω m) with a thin layer of sediments between them. The basement is highly resistive, although it shows a variation of resistivity near the center of the profile, larger than 10,000 Ω m towards south and 1000 Ω m towards north indicative of two different block structures (Harinarayana et al., 2002; Patro, 2002; Sheela, 2004). It is interesting to note that surface rupture developed at the center of the NM profile has caused panic among the local community. The extension of the rupture to a length of about 2 km near the center (between NM3 and NM4) and its correlation with the changes in basement resistivity indicate a possible remobilization of the two blocks.

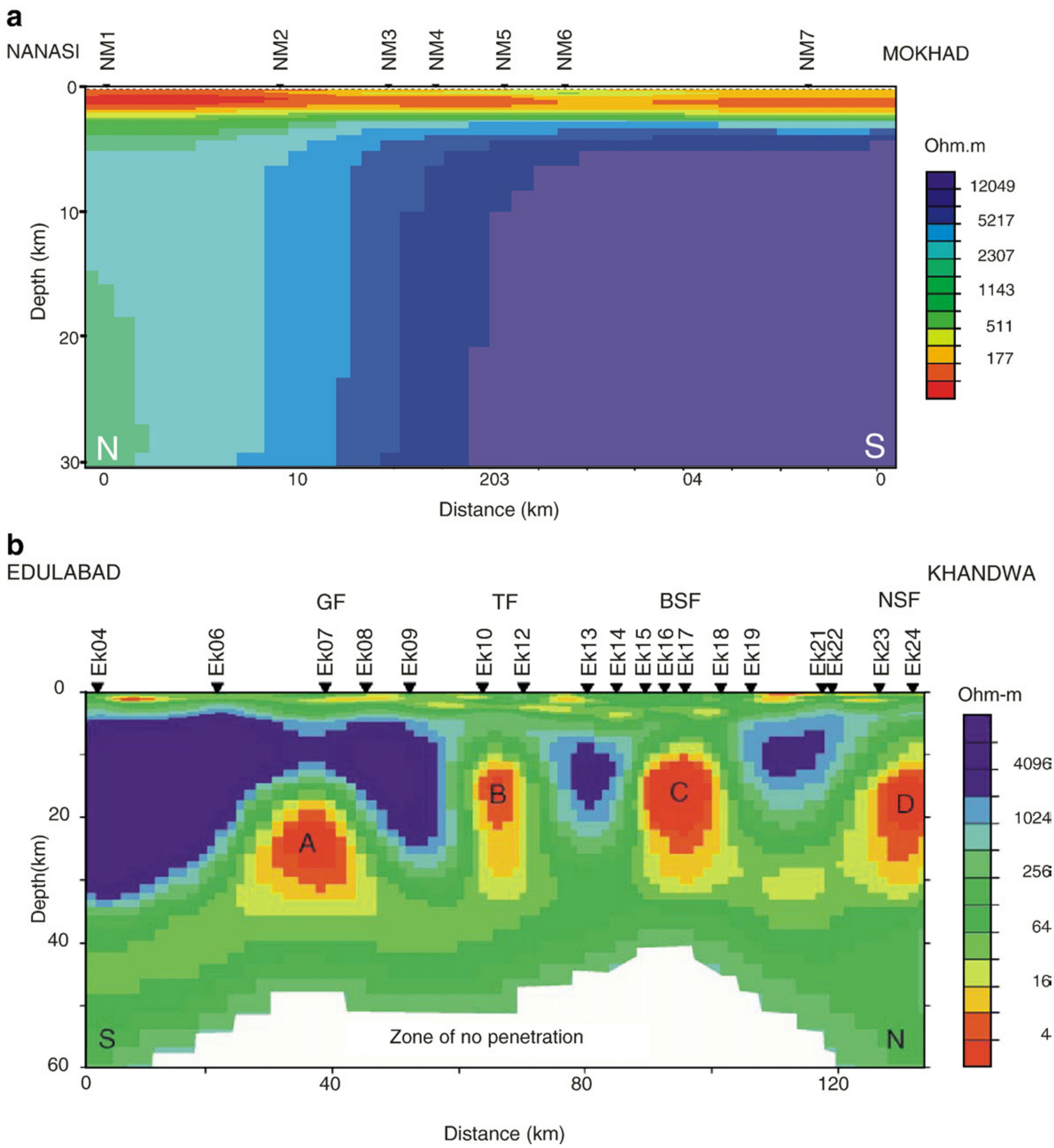


Fig. 4. a. 2-D electrical resistivity depth section along Nanasi–Mokhad north–south profile. b. 2-D electrical resistivity depth section along Edulabad–Khandwa south–north profile, GF: Gavligarh fault, TF: Tapti fault, BSF: Barawani–Sukta fault, NSF: Narmada south fault; A, B, C, D are conductive features.

5.4. Subsurface section along EK profile

The subsurface model (Fig. 4b) along Edlabad–Khandwa profile exhibits a lateral variation in resistivity that indicates complex geology of the well-known Narmada–Son–Lineament zone. The model roughness and data fit is plotted to find the trade off parameter (Fig. 8 in Patro et al., 2005b). The profile cuts across many faults, the prominent among them are Narmada south fault, Tapti fault and Gavligarh fault. The trap thickness varies from 1 to 2 km along the profile. The sediments are observed below sites EK9–EK19 with thickness ranging from 4–5 km overlying a high resistive basement. The deep resistivity structure along the profile has shown high conductive features at upper crust depths (10–25 km) near sites EK7, EK10–EK12, EK17, EK24 (Fig. 4b). These conductive features represent deep penetrating fault/lineament zones and spatially, are coincidental

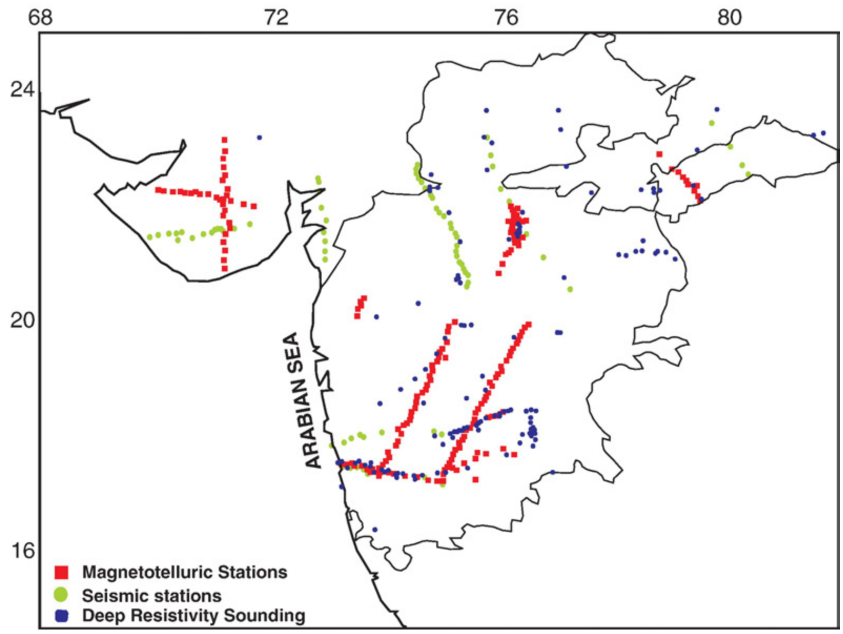


Fig. 5. Location map of magnetotelluric, deep resistivity sounding and deep seismic sounding stations in Deccan Volcanic Province (DVP) used for preparation of Deccan trap thickness map.

with known tectonic features in the region. The conductive zones 'B' and 'C' correspond to Tapti (TF) and Barwani–Sukta faults (BSF). The other features 'A' and 'D' appear to be the electrical signatures of Gavligarh fault (GF) in the southern end and Narmada south fault (NSF) in the northern end of the profile respectively. Small changes in the model parameters during modeling have drastically changed the model response, indicating that these conductive features are well resolved (Patro et al., 2005b).

6. Deccan trap thickness in the DVP

The present study with three long traverses and one short traverse covers major part of DVP. Since magnetotelluric method is effective in basalt covered areas, an attempt has been made to map Deccan trap thickness. Variation in thickness of Deccan trap may play a major role in understanding the seismotectonics of the region. This is due to the fact that Deccan trap is a denser basaltic material compared to the granitic basement. The granitic basement is always under high pressure from the top and any change in the basement structure such as presence of weak zones, fault/fracture can be the source for higher concentration of stresses. Additionally, if there is a large variation in the thickness of trap cover, then also there is a variation in the pressure on the basement and may likely to develop seismicity in the region due to greater strain. Regional variation of trap thickness in DVP helps to understand the seismicity of the region.

Although a large data base has been created from the results of the present study, we limited our analysis to construct a thickness map of the DVP. To do this, we have considered the results obtained from other geophysical studies, including a few Deep Resistivity Soundings (DRS) and Deep Seismic Sounding (DSS). Several DRS were carried out by Geological survey of India (Kailasam et al., 1976) as part of a deep geology project. A few DSS traverses have been carried out across Narmada–Son–Lineament zone by NGRI as a part of deep crustal studies and hydrocarbon exploration (Kaila et al., 1985). The information from these studies and also a few MT and DRS studies carried out in Saurashtra and central India regions for hydrocarbon exploration are included (Sarma et al., 1992; Rao et al., 1995; Sarma et al., 1998; Singh et al., 1998). The location map of these stations considered for preparation of Deccan trap thickness map is shown in Fig. 5. The data base we have created consists of 140 MT stations, 6 DSS profiles and 200 DRS stations. DSS study results are taken from Kaila (1988) and Zutshi (1992). As can be seen from Fig. 5, the stations are reasonably distributed in Deccan trap region. Since general surface elevation in the area can also play an important role on the seismicity of the region, information for every 800 m data – using 'gtopo30' from NGDC – for the region is considered and presented in Fig. 6. The data for preparation of Deccan trap thickness from different sources have been compiled, a grid has been generated and contoured with computer aided tools. The map thus prepared is presented in Fig. 7. The map showed a large

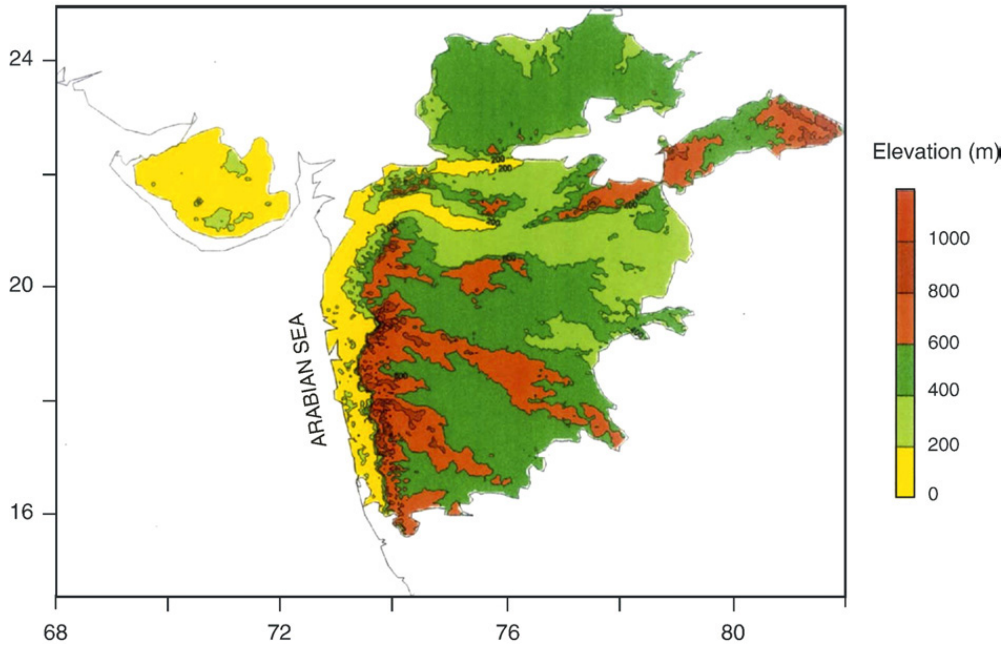


Fig. 6. Elevation map of the Deccan trap region showing sharp changes in the elevation near Western ghats.

thickness of traps towards west and gradually reduces towards the east. The thickness is larger (>2 km) towards northwestern part. It maintains uniform thickness from SW to NE direction. These observations indicate that major source for the traps lie towards the northwestern part. The changes in trap thickness and the underlying structural features may have some bearing on the seismicity of the region.

7. Seismotectonics of the region

The subsurface structure obtained along Sangole–Partur (SP) profile showed 500 m of Deccan trap thickness — with an increase in the middle (1000 m) portion of the profile (Fig. 3b). The traps lie directly over high resistive basement with thin inter-trappean sediments at places (Harinarayana et al., 2002), although no significant

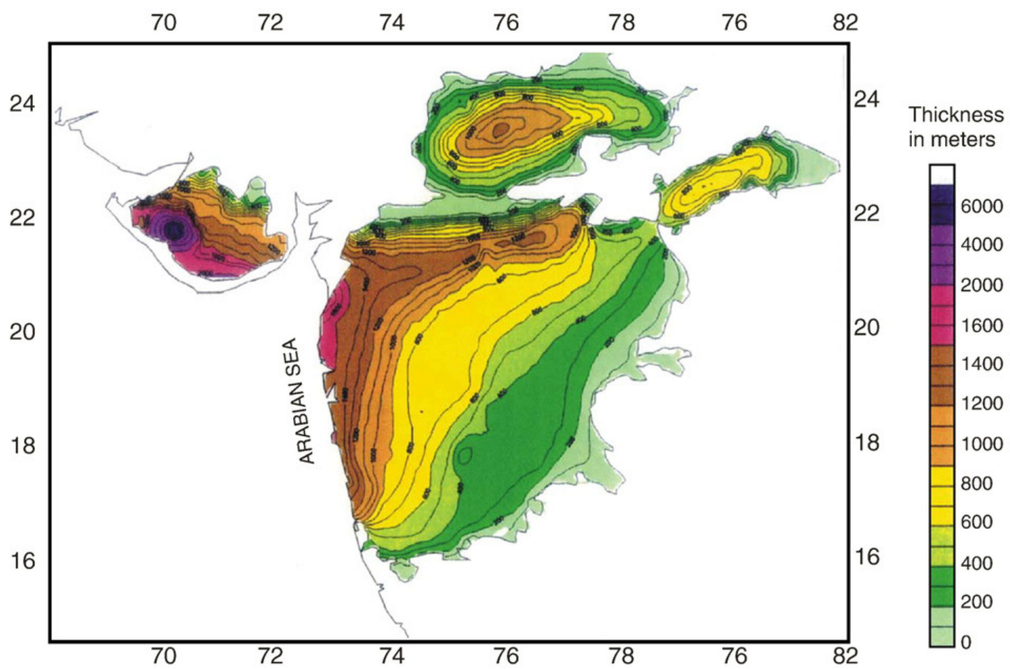


Fig. 7. Trap thickness map in Deccan Volcanic Province (DVP). Large thickness towards W–NW can be noticed as compared to E–NE.

thickness indicated for sub-trappean sediments. The basement is high resistive but not uniform and seems to be intersected by faults/fractures. This is clearly delineated from the present study as narrow steep conducting features at a few locations along the profile. These features are not localized but seem to be having wider dimensions. Six narrow conducting features (A to F in Fig. 3b) or changes in the lateral variation of resistivity are observed along SP profile. The variation of the resistivity with possible presence of anisotropic structure below the trap cover has been discussed (Patro et al., 2005a). The trend of the subsurface structure along SP profile is inline with the orientation of the aeromagnetic anomalies in Deccan traps and Dharwar craton (Anand and Rajaram, 2002). These anomalies have helped to understand the seismotectonics of the region. For example, the conductive features in the basement observed along SP profile and also along another parallel profile (Harinarayana et al., 2002) presented in a schematic diagram (Fig. 8) have shown NW–SE direction. Towards southern part of the profile, the steep conducting features (with −50° to −65° strike) also are spatially correlated with the Kurduwadi rift/lineament proposed earlier from gravity studies (Krishna Brahmam and Negi, 1973). Apart from the well-known Kurduwadi feature extending to deep crustal depths, the present study imaged additional parallel conductive features in the basement. It may be noted that regional topography and the exposed major geological formations towards south of the study region are also oriented in the same direction as that of the crustal conductive features. These features may play a greater role in the development of seismicity in the region. As is well-known, the weak zones in the deep crustal segments, shown as anomalous conductors, are the sources of concentration of stresses (Johnston and Kanter, 1990).

The MT profile across Koyna region (Sarma et al., 2004) detected a steep conductive feature (A in Fig. 3a) near the Koyna fault and another (B in Fig. 3a) related to the west coast fault. The crust is highly resistive between these two narrow conductors. The spatial variation in the resistivity can be attributed to crustal block structure in Koyna region. The variation of resistivity with depth finds an interesting correlation with crustal velocity structure obtained from seismic tomography (Rai et al., 1999). High resistive block corresponds to low velocity region while the high velocity region corresponds to low resistive region (Sarma et al., 2004). The electrical as well as velocity structures in different depth ranges indicate lateral lithological heterogeneities along the traverse with NS oriented Koyna fault acting as a boundary between different blocks even up to lower crustal depths. The gravity anomaly observed in Koyna region (Tiwari et al., 2001) also supports the block structure. Constraints on Moho depths with details of crustal block structure obtained from our study produced a model consistent with the gravity data (Sarma et al., 2004). It can also be stated that the conductive nature of upper crust in the vicinity of Koyna fault might be responsible for concentration of stresses observed in the form of increased micro-seismicity near Koyna (Gupta, 2002).

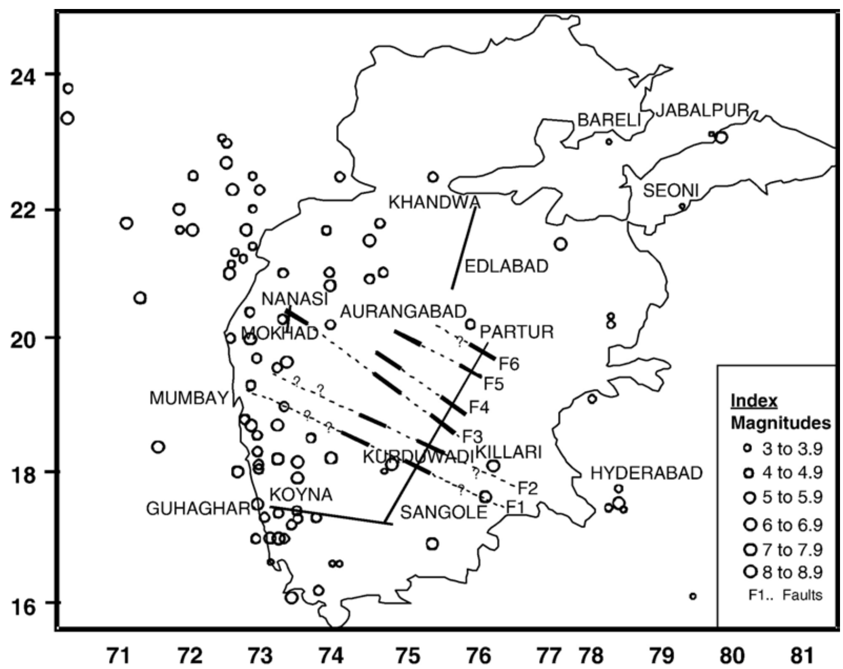


Fig. 8. Faults/fractures delineated at the sub-crustal levels in the Deccan trap covered region using MT data (modified from Patro, 2002).

According to Veeraswamy and Raval (2005), during the northward movement of the Indian plate over the Reunion mantle plume, at ~60–65 Ma, the continental lithosphere was remobilized caused bimodal tectonic and geophysical features. The signatures were (i) radial during the outburst phase of the Reunion mantle plume and (ii) linear during the trace of the plume (i.e. before and after the outburst phases). In this context, it is also necessary to note that the tectonic boundary between the western and eastern Dharwar cratons seems to extend northwards beneath Deccan trap cover and passes through conductive crustal features delineated near Koyna (Radhakrishna, 1984).

As can be seen from Fig. 7, the thickness of trap cover, in general, showed an increase from east to west. Additionally, it has relatively uniform thickness in NE–SW direction as compared to E–W direction, which can be seen from the thickness map as also along different profiles drawn for different latitudes (Fig. 9). Another interesting observation from the present study is variation of Deccan trap resistivity itself. The resistivity of Deccan traps derived from the stations located along SP profile, is relatively low (50–60 Ω m) as compared to the stations located along NM and GS profiles, where the resistivity is of the order of 150–200 Ω m. This can be attributed to the texture of the trap itself. It is known that volcanic rock may be porous and also with number of inter-trappean sediments between them (Kailasam et al., 1976). Since the present study indicated a variation in the resistivity for the trap, we infer that the trap layers towards west are less porous, devoid of inter-trappean sediments and may be more compact in nature as compared to the same rocks towards east. In this case, the rocks of the same unit towards west may be more denser as compared towards east. In such a situation one can infer that apart from the existence of basement fault, which may cause increase in seismicity as discussed before, the direction of the fault is also important. It means a fault in the basement oriented in N–S direction may be experiencing different stress regime as compared to the fault oriented in E–W direction. This is so because thickness and resistivity of trap is not uniform through out the region. To describe this more clearly, Deccan trap thickness along different latitudes are presented in Fig. 9. It can be seen from these figures that thickness of trap increases from east to west and also from SE to NW. However, in SW–NE direction it shows relatively uniform thickness (Fig. 7). Now, it is necessary to examine whether such a variation and also the existence of deep fault/fractures delineated from the study is of any significance from the seismotectonics point of view.

In this context, it is of interest to study the Koyna region much more closely. It may be observed that two prominent faults oriented nearly in N–S direction (Koyna and west coast) exist in the proximity of Koyna (Kaila et al., 1981). It may also be noted that there exists large variation in the thickness of the trap with a steep gradient in the surface topography near the well-known Western ghats (Kailasam et al., 1976). In such a situation, Koyna region might be a continuous source for the development of stresses on either side of Western ghats and release of stress in the form of seismicity.

It may be noted that the Koyna earthquake is believed to be caused due to reservoir triggered seismicity (Gupta, 2002). The present study showed that variation in the thickness of higher density rocks on the top and also the presence of basement faults oriented nearly in NS direction are the additional factors to the development of stress in the Koyna region. Apart from this, variation in the surface topography and also heavy rains reported in this region, especially during monsoon period causing extensive weathering and erosion of the exposed basalts, are some of the other factors towards development of seismicity in the region. This is so, because weathering may again bring variation in the thickness of trap cover, although small, it may become large over a period of time. From the study of variation of seismicity with season in Iceland, it was felt that melting of ice during summer has activated some of the buried faults (Johnston and Kanter, 1990).

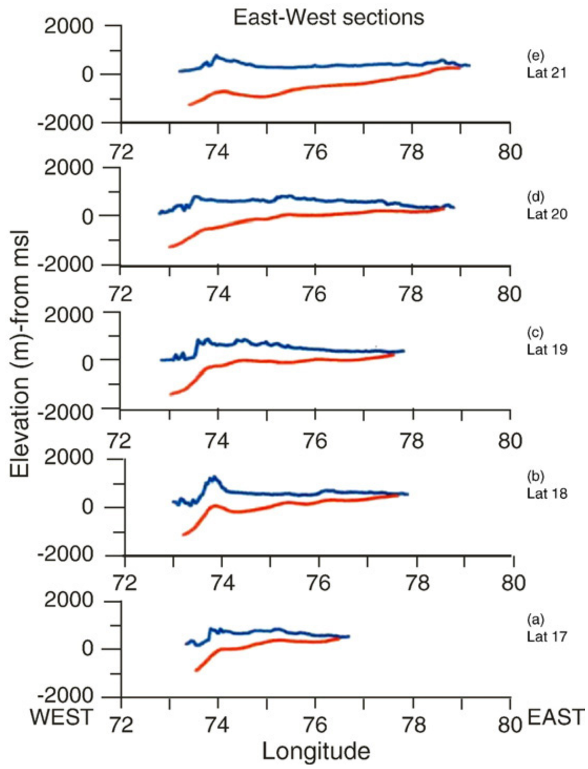


Fig. 9. Latitudinal variation of Deccan Trap thickness showing gradual decrease from west to east with sharp changes near Western ghats.

While such is the case near Koyna, one needs to explain the reasons for low seismicity in other parts of DVP. As described before, the conductive features correlate with major lineaments, which are also oriented in NW–SE direction (Fig. 8). Generation of low seismic activity may be due to lack of sharp changes in trap thickness on either side of these features. For the sake of better understanding, the seismicity of the region compiled by Rao (2000) is also shown in Fig. 8. It can be seen from the figure, major seismic activity in the form of cluster of epicenters are present all along the west coast oriented in NS direction and low seismic activity away from Western ghats. This observation is in line with the above argument.

Four anomalous conductors along EK profile in NSL region (shown as A, B, C and D in Fig. 4b) with an extension from mid to deep crustal depths and their spatial correlation with the tectonic faults such as Gavligarh fault, Tapti fault, Barwani–Sukta fault and Narmada south fault assigned prominence to understand the seismotectonics of the region. NSL is a major tectonic feature known for zone of weakness since Precambrian times (Kaila et al., 1985). The areas south and north have experienced vertical block movements (Kaila 1988). Jabalpur earthquake of 6.0 *M* during 1997 and seismic swarm activity during 1998 near Khandwa and their correlation of hypocenters with anomalous conductive medium indicate that NSL zone is a favorable location for the development of suitable conditions for the generation of seismotectonic activity.

A change in the resistivity of the basement structure along NM profile overlain by Deccan traps is indicative of two blocks of different composition. This is evident from the low resistive crust below the traps towards north as compared to south. The region may be experiencing vertical block movements as in the case of NSL. There is no evidence of a fault or fracture zone in the region. Development of a surface fissure with 15 to 30 cm width at the center of the NM profile extending to about 2 km may be due to relative movement of two different blocks observed as per the present study. However, there is no major seismic activity reported in the region before, during or after the development of the surface fissure (Rao, 2000). In view of the observation of variation in the resistivity of the basement at the center of the profile, it can be inferred that the region might get reactivated in the near future that may result in the form of more deformation leading to seismic activity in the region.

8. Summary and conclusions

The results derived from four different profiles in Deccan trap covered region have been utilized to map the regional geoelectric structure of deep crust. These results have been summarized as follows.

- Deccan trap thickness, based on various geophysical methods and from the present study, decreases gradually from west to east with about 1.8 km near Western ghats, although there exists a sharp variation in the thickness of trap observed near Koyna. The resistivity of the trap is relatively larger towards the west than to the east, indicating denser or compact nature for the basalts towards west.
- The upper crust is highly resistive, of the order of 5000–10,000 Ω m, whereas lower crust exhibits relatively low resistive (500–1000 Ω m). The results obtained recently along southern granulite terrain (Harinarayana et al., 2006) have shown lower values for lower crust (100–500 Ω m). This indicates a different lower crustal character for DVP as compared to southern granulite terrain.
- There is no significant thickness of sub-trappean sediments observed along SP, NM and GS profiles, where as large thickness of sediments, of the order of 1.5–2.0 km, is observed along EK profile.
- A conductive subsurface structure coincidental with the Kurduwadi lineament is observed in the present study. The lineament shows a relation with basement tectonics. Two basement faults with steep conducting structure on either side of the lineament are inferred from the current study. Apart from such a correlation, basement faults in the form of steep conducting features and lateral resistivity variation in the basement is observed at few locations along SP profile. Presence of macro-anisotropy is additionally considered and corresponding 2-D anisotropic modelling (Patro et al., 2005a) suggesting the existence of successions of conductive dykes in the deep crust.
- A variation in the resistivity of the basement structure is observed along NM profile, which may have relation to the development of deformation in the region in the form of surface fissures. The relative movement of the blocks in the basement is one possible explanation for such a deformation.
- Basement faults near Koyna are observed as high conductive crustal features. Resistive block structures are inferred for the region. The high resistivity of the blocks has an inverse relation to the velocity structure in the region.

From the above observation of sharp changes in trap thickness towards west and presence of deep-seated faults, their orientation, development of regional seismicity is explained. Increase in seismic activity near Koyna and also all along the west coast of India may be due to variation in trap thickness coinciding with the presence of major fault structures. Rapid erosion phenomena can also enhance the seismicity. Low seismicity in other parts of DVP may be due to the orientation of the faults and relatively uniform thickness of trap cover on either side of these faults.

The present study has demonstrated that the western part of India consists of many resistive blocks separated by conductive features. The conductive features at upper–mid crustal depths have shown spatial correlation with major tectonic fault structures. The majority of these conductive features can be considered as weak zones that have paved a way for development of stresses that may lead to concentration of seismic activity. Thus our study helps in understanding the seismotectonics of the region in a concerted way which helps to identify micro zones of the seismicity.

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