A magnetotelluric (MT) study across the Koyna seismic zone, western India: evidence for block structure

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Abstract
Wide band magnetotelluric measurements were carried out at 16 sites along Guhaghar–Sangole traverse across the Koyna seismicity zone. The results of the study, besides providing details of Deccan trap thickness variation along the traverse, brought out several structural characteristics of the subsurface extending to deep crustal levels. The Koyna fault zone is characterized by a weak expression of a moderately conductive feature extending only up to a depth of 4–5 km. Two-dimensional modeling results bring out distinct block structure in the Koyna region and are compared with velocity and density structure of the region. The deep electrical structure is interpreted in terms of lateral lithological heterogeneities.

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1. Introduction
Since the occurrence of the devastating Koyna earthquake (M 6.3) of 10 December 1967 and the subsequent events of smaller magnitudes over the last few decades origin of the Koyna earthquakes continues to be a matter of discussion. One view is that the Koyna seismicity is associated with and to some extent controlled by the reservoir loading (e.g. Gupta and Rastogi, 1974; Gupta et al., 1972, 2002). Seismicity in Koyna region has been found to increase with the increase of water level in the Koyna reservoir and vice versa with a certain time lag (Gupta et al., 1969). Another suggestion made to explain the increase in seismicity in this region is due to release of strain accumulated in a possible zone of faults located immediately to the west of the water shed (Sahyadris) running parallel to the west coast of India, approximately between latitude 17°N and 19°30′N (Athavale and Mohan, 1976). The possibility for existence of a rift valley underneath the traps coinciding with a near N-S trending linear gravity low in the Koyna region has also been suggested. It was also pointed out that the 10 December 1967 Koyna earthquake could be related to this tectonic feature (Krishna Brahmam and Negi, 1973). Vertical crustal block movements in the Deccan trap region is another possibility for seismicity in the Deccan trap region (Kailasam et al., 1976).

For the past three decades, the seismicity of the Koyna region has been continuing and about 10,000 earthquakes have been recorded and several attempts were made to delineate the seismogenic faults of the region (Taiwani, 1997; Rai et al., 1999). In another detailed study, over 300 epicenters of Koyna...
earthquakes are relocated. The relocated epicenters are concentrated in three broad trends, a NNE trend near the Koyna reservoir, another trend 20 km west of the reservoir and a NW trend cutting through these two (Rastogi and Talwani, 1980). The events were grouped to obtain their composite fault plane solutions. The results indicate left-lateral strike slip faulting along the NNE direction and a normal faulting in the NW direction. Geological observations also point out the existence of a NNE trending strike slip fault, passing through Koyna (Harpster et al., 1979; Talwani, 1997; Gupta et al., 1999, 2002).

Whatever the nature of generation mechanism of the earthquakes, a knowledge of the deep crustal structure and its nature is essential to understand the seismicity of the Indian peninsular shield, in general, and the Deccan trap region in particular. Several attempts were made in this direction to investigate the crustal structure of the region. These include deep seismic sounding studies along two E–W traverses (Kaila et al., 1981) deep electrical sounding (Kailasam et al., 1976; Bhaskar Rao et al., 1995) seismic tomography studies (Rai et al., 1999; Srinagesh et al., 2000) and detailed gravity studies (Tiwari et al., 2001). In the present study, we make an attempt to bring out crustal electrical structure in the Koyna region, based on magnetotelluric (MT) investigations.

The magnetotelluric sounding is an effective geophysical approach for imaging electrical structure of the earth’s interior over a wide range of depths from a few tens of meters to several tens of kilometers. It is known to be one of the powerful geophysical tools for investigation of crustal electrical structure in volcanic covered areas such as the Koyna. Accordingly, we have carried out a wide band MT study along an E–W traverse, from Guhaghar to Sangole traversing across the Koyna fault zone (KFZ). The aim of the present study is to investigate the electrical structure of the crustal column along the traverse and to understand its significance, in the light of the seismotectonic information available from other geophysical studies of the region.

2. Geology and structure

The study area (Fig. 1) lies on the western flank of Peninsular India. It is covered by the Deccan Traps, a Continental Flood Basalt (CFB) province similar to the Karoo of South Africa and Parana basin of South America. The CFB provinces are believed to be intimately related to passage of continental masses over static mantle plumes (hot spots), and to the subsequent continental rifting induced by plume (e.g. Morgan, 1972; White and McKenzie, 1989; Campbell and Griffiths, 1990). It is believed that Deccan Traps were erupted during the separation of the Seychelles micro-continent from India, 50–60 Ma (end of Cretaceous—early Tertiary (Duncan and Pyle, 1988)) during a rifting event induced by the northward movement of the Indian subcontinent over the Late Cretaceous manifestation of Reunion plume.

The Archean basement exposed south of Deccan Volcanic Province exhibits a general regional strike with orientations varying from NS to NNW. A remarkable feature of Deccan volcanism is the horizontality of its flows throughout the region. The trap flows dip at very low angle, hardly recognizable by naked eye. Variation in thickness of trap flows has been attributed mainly to pre-Trap topography. The entire volcanic sequence was earlier classified into three broad stratigraphic groups viz., Upper, Middle and Lower. The oldest Traps have been identified in the western region and the younger ones seem to have spread thinning towards east and SE. Later classification based on petrological and geochemical characteristics, divides the Traps into three sub-groups—the Kalsubai, the Lonawala and the Wai, each with its own specific chemical character (Deshpande, 1998).

Several lineament features have been identified in the Deccan trap region of western India. Preliminary study of Indian Remote sensing Satellite (IRS) data delineated three major lineament patterns viz., the first is NW–SE being parallel to Godavari trend, the second, E–W being almost parallel to Narmada-Son lineament and the third along NNW–SSE being parallel to the Western Ghats. The intersection of major lineaments with minor ones in the region, may be spatially correlated with the epicenter of earthquakes (Arya et al., 1995). Peshwa and Kale (1997) suggested a NW–SE trending lineament zone named as Kurduwadi lineament which enters the Deccan trap province (DVP) near Gulbarga, passes through Kurduwadi region, south of the epicenter of the M 6.2 30 September 1993 Latur earthquake and extends further up to north of Bombay. Structural disturbances and
Fig. 1. General geology of the study area showing the MT profile near Koyna region.

Deep crustal shear zones are speculated to exist along the lineament, based on study of imageries and some field verification (Peshwa and Kale, 1997).

Geomorphologically, the study area is mainly comprised of three units, a plateau on the east and coastal (Konkan) plains on the west adjoining the Arabian sea, with the Western Ghats located between these two. The Western Ghats rise to about 900 m above the mean sea level while the adjacent plateau on the east has an average elevation of about 700 m. The Koyna fault striking approximately in a NNE direction passes very close to the Koyna reservoir. The western side of the Western Ghats is characterized by a major scarp running over their entire length.

There are many flows recognized in Deccan trap with varying thickness from 10 to 160 m. Das and Ray (1972) reported a gentle easterly dip of $\sim 1^\circ$ in the high plateau and westerly dip of $\sim 3^\circ$–$4^\circ$ in the Konkan plains increasing to $\sim 15^\circ$ near the coast. This change in the dip is ascribed to a monoclinal flexure, known as “Panvel Flexure” (Auden, 1949). Several dykes are reported from Deccan trap areas trending N–S in the Konkan coastal belt. Deshmukh and Sehgal (1988) discussing regional distribution of dykes over this part of DVP, have reported that Konkan coastal region dykes are younger than those found in the Narmada–Tapti region oriented in E–W direction and suggested that the zone of dyke swarms is the zone of maximum tectonic disturbances. Based on the occurrence of dyke swarms intruding the basaltic flows, it was presumed that these were the locales of eruptive foci of Deccan trap.
3. MT data acquisition and processing

Magnetotelluric investigations were carried out in the Koyna region during 1998–1999. MT sites were occupied along an E–W profile from Gahaghar to Sangole, which coincides with the DSS profile KOY1 (Kaila et al., 1981). The profile extending over a length of 192 km, traverses from west to east, across the Konkan plains, Western Ghats and the high plateau regions. It cuts across the Koyna gravity “low”, Karad gravity feature and Sangole gravity “high”. A total of 16 single site MT soundings were carried out with station intervals varying from 2 to 10 km. The shorter intervals were used near the Koyna (Kadoli) fault. State-of-art wide band (8192 Hz–4096 s) MT systems, GMS05 (Metronix, Germany) were used for data acquisition. Electric field components were measured in the N–S and E–W directions with either a cross or L-shaped configuration of non-polarizing CdCl₂ electrodes with a spacing of about 90 m. The magnetic field components were measured in the two orthogonal horizontal directions (N–S, E–W) and the verti-

![Fig. 2. Typical MT curves from the Koyna region.](image-url)
cal direction using induction coil magnetometers. The automatic data acquisition and real-time data processing enabled in-field data quality monitoring. Generally, the MT data are of good quality, as could be seen from Fig. 2, showing typical orthogonal apparent resistivity and phase versus frequency plots. However, at some sites the data in the longer period range show larger error bars and could be due to the electrode noise or due to high tension power lines passing through the region west of Koyna. Data from some of the sites affected by noise, for example, MT sites gks1, koy1 and koy2 could not be considered for analysis and modeling. All the time series data sets were edited by using the commercial software PROCMT (Metronix, Germany), to manually identify and remove noisy segments. Robust processing was used to get estimates of apparent resistivity and phase versus frequency data sets. Consistency of data sets for adjacent sites has been one of the factors considered for the identification of static shifts. The scattering in the apparent resistivities due to the static shift was not significant. The only exception was found at the site gks7, located on the Western Ghats—evidenced from the short period data—shift of the Rhoyx apparent resistivity curve by nearly half a decade higher than rest of the sites. As this occurred only for this site, the resistivity of Rhoyx was shifted to the same level as that of Rhoxy using Geotools’ static shift utility.

4. Strike direction

The Guhaghar–Sangole MT profile, oriented in a near EW direction, traverses almost perpendicular to the regional geological strike, which varies over a few degrees around NS direction. The dimensionality of the data has been examined using GB decomposition technique (Groom and Bailey, 1989). Fig. 3(a) shows the unconstrained GB strike for the data along the profile. The frequency band from $10^3$ to 1 Hz shows an average strike direction of N15$^\circ$E, while the strike direction for the lower frequency band (<1 Hz) lies about 18$^\circ$W of North. The Koyna fault is oriented in a NNE direction (Talwani, 1997; Gupta et al., 1999, 2002) and thus the electrical strike is close to the geological strike of the region as well as the Koyna fault. The impedance skew values for all the sites are shown in Fig. 3(b). From $10^3$ to 1 Hz the skew values are less than 0.2 and below this frequency, the skew tends to become higher indicating a possible 3D geoelectric structure at deeper levels. The small skew values and uniform strike at frequencies $10^3$ to 1 Hz, suggest that the MT data are consistent with 2D interpretation of crustal section in this high resistive
granitic/gneissic region overlain by a thin cover of basalts.

5. MT pseudosection

Pseudosections of rotated apparent resistivity as a function of frequency for both $xy$ (TE) and $yx$ (TM) directions along the profile are presented in Fig. 4. The high frequency data from a few hundred Hz down to 1 Hz at all the stations exhibit moderate apparent resistivity of 50–100 $\Omega$ m. This is followed by high apparent resistivity greater than 500 $\Omega$ m for lower frequencies. The stations located near Koyna fault region exhibit very high apparent resistivity (>3000 $\Omega$ m) at lower frequencies.
6. Modeling results

The data have been subjected first to 1D modeling using a linearized inversion scheme (Marquardt, 1963). A subsurface shallow geoelectric section along the profile from 1D modeling results is presented in Fig. 5. The trap thickness, as the model shows, is about 500 m at the gks14 site at the eastern end of the traverse and increases to about 1.4 km near the site gks13, at the western end. While this westward increase of trap thickness is the general trend, considerable thinning of traps may be seen near gks9. The details of the shallow section and also the deeper structure are discussed below in the 2D inversion results.

The data have been further analyzed using RLM 2D inversion (Rodi and Mackie, 2001). The 1D parameters obtained above have been used to construct the initial model for 2D inversion. Arabian sea, west of the profile has also been included in the initial model. In order to overcome (at least to certain degrees) from the static effects, higher error floor (20%) to apparent resistivity with respect to phase (5%) was assigned during inversion. To start with, the data have been inverted for TM (Rho TM and Phi TM) mode only. The resulting model and the computed response are shown in Figs. 6 and 7(b). The RMS misfit for this model amounts to 3.46. This model in turn is used as the starting model for inverting the data to obtain a model that fits the TE data (Rho TE and Phi TE). The model and the corresponding response for TE inversion are also shown in Figs. 6 and 7(a) and the RMS misfit is 5.46. Incorporating the features from both TM and TE inversion results in the initial model, the data have been again inverted for both TE and TM modes. The final model and the computed responses are shown in Figs. 6 and 8 which show an RMS misfit of 5.26.

The top layer of the geoelectric section (Fig. 6) characterized by resistivities ranging from 40 to 150 $\Omega$.m represents the Deccan Trap layer. Thickness of Trap, as we proceed form E to W, increases from around 500 m at the eastern most site to a value of about 1.3 km near the west coast. This layer is underlain by a high resistive medium, with resistivities amounting to several thousands of $\Omega$.m (5000–20,000). This implies that the traps lie directly on a high resistive granitic or granite-gneissic basement with little intervening sediments. The subsurface below the traps is characterized by differing resistivities in different segments along the traverse. We can recognize at least three different types of subsurface segments characterized by different resistivity ranges—a highly resistive medium (5000–20,000 $\Omega$.m) shown in dark blue color and an intermediate resistivity (3000–5000 $\Omega$.m, light blue) and low resistivity (300–600 $\Omega$.m, green). Thus in the western half of the profile, the subsurface is a very high resistivity (5000–20,000 $\Omega$.m) segment up to 10–15 km depth, while that in the eastern half it is relatively less resistive (5000 $\Omega$.m). Below 15 km depth level, the crustal column is characterized by a relatively resistive (5000 $\Omega$.m) crustal block in the middle of the traverse flanked by two relatively lower
resistive (500–1000 $\Omega$ m) blocks on either side. In addition to these, the geoelectric section brings out a few linear moderately conductive features (100–a few hundred $\Omega$ m) along the traverse. The moderately conductive (100–600 $\Omega$ m) feature “A” (Fig. 6) between sites gks3 and koy3 spatially coincides with the Koyna fault zone that cuts across the profile. Though the Koyna fault is believed to be a deep basement fault extending to lower crustal depths (Kaila et al., 1981) its electrical expression in the form of a weak conductor is limited to a depth of about 4–5 km. The significance of feature “A” was further studied by carrying out a modeling experiment with and without the feature “A”. The result shows rather small
Fig. 7. Model response obtained by inverting the (a) TE data and (b) TM data.

difference between the two responses. Hence we interpret the feature “A” is a weak image of Koyna fault.

Besides this, there are three more similar features B, C and D located below sites gks11, koy5 and koy8. The feature B spatially coincides with the well known west coast fault, which cuts across the profile at its western end. The features C and D, respectively, fall over a significant regional gravity low near Karad in the eastern half of the traverse, while the feature D coincides with the “Sangole gravity high”, at the eastern end of the traverse.
7. Discussion and conclusions

The MT study along the Guhaghar–Sangole profile provided the details of electrical structure from shallow to deeper levels bringing out the variations in the thickness of the trap cover along the profile as well as the electrical nature of the subsurface down to the crust and upper mantle regions. Although earlier studies using DC resistivity as well as seismic surveys in this region provided useful results on the thickness variation of trap (Kaila et al., 1981; Kailasam et al., 1976), the MT results provided a detailed shallow section depicting the trap thickness variations along the Guhaghar–Sangole profile. The results also brought out the nature of basement below the traps. This is shown to be highly resistive and represents the Archean granite or granite-gneissic rocks. The results point out the absence of subtrap sediments in this region. Our study also showed that the basement down to several kilometers depth for a major part of the profile is generally high resistive and rules out the possibility for the presence of any subtrap rift valley structure, believed to be associated with the Koyna Bouguer gravity low (Krishna Brahmam and Negi,
This is in agreement with inference drawn from earlier geophysical studies along the profile including Deep Seismic Sounding results (Kaila et al., 1981). The Koyna fault zone is, however, expressed weakly in the electrical section as a moderately conductive feature extending to about 4–5 km. The hypocentres of the earthquakes of magnitude 3–5 (Gupta et al., 2002; personal communication; BIS, 2002) plotted (Fig. 6) fall in this zone. The focal depth range from 4 to 10 km.

Though the first 10–15 km depth section of the crust is primarily resistive, the geoelectric section may be further subdivided into two categories. The first one—very high resistive ($10^4 \Omega m$), covering the western half of the traverse including the Koyna fault zone and the second one relatively less resistive segment ($<5000 \Omega m$), occupying the central part of the profile. Below 15 km depth the geoelectric section shows a similar structure with three individual blocks characterized by differing resistivities viz. conductive block (green) in the west, a resistive block (blue) in the central region between sites gks7 and koy6 and another conductive block (green) cover the eastern half of the profile.

The deep seismic sounding results, besides providing the moho depths along the Guhaghar–Sangole traverse, have mapped several crustal reflectors in the region above moho. Vertical displacements of an otherwise continuous chain of reflectors, including the moho reflector, have been used to identify faults (Kaila et al., 1981). The Koyna fault is identified as a deep fault extending to moho depths (Fig. 9). Upper crust in shield areas is generally considered to be transparent and less reflective as compared to the lower crust which is more reflective (Gough, 1992). A similar pattern in the reflectivity character of crustal column may be noticed along the Guhaghar–Sangole traverse. In the top 10–15 km depth range, the high resistivity regions of geoelectric sections along this traverse generally correspond to regions of less reflectivity, except in a narrow region west of the Koyna fault. On the other hand, the conductive regions correspond to regions of higher seismic reflectivity (Fig. 9). At the eastern end, the reflectivity is higher from shallow depths itself where the geoelectric section also shows conductive crust starting from shallow levels.

The available regional gravity data has been earlier interpreted in terms of possible presence of sub-trap rift valleys (Krishna Brahmam and Negi, 1973), thickness variations of Deccan Basalts (Kailasam et al., 1976), crustal block structure (Kailasam et al., 1972), variations in the depth to Conrad discontinuity and moho (Mishra, 1989). In the present study, taking into account the valuable constraints on moho depths provided by the DSS results and keeping in view of the electrical structure from the MT results, in constructing the model, the gravity data along the Guhaghar–Sangole traverse has been modeled. For the purpose of modeling, the gravity data deduced from zero-free air anomaly approach (Subba Rao, 1996) has been used. Saki software package (Webring, 1985) was used for the purpose of inversion of data and Fig. 10 shows the final model obtained. The moho becomes shallow towards the west coast. Low density
block in the region west of Koyna fault corresponds to a high resistive segment observed in the MT section which may represent highly silicic crystalline granitic/gneissic lithology with low porosity and low fluid content. Similarly the conductive lower crust is represented by a relatively high density material. The high density medium, presumably representing an altered mafic lower crustal material, appearing as a conductive material in the electrical section rises to shallow levels to account for the gravity ‘high’ near Sangole. The density variations of the blocks thus roughly correspond to resistivity variations from MT in that the higher densities corresponding to lower crustal material correspond to lower resistivities and the relatively less dense upper crustal material representing crystalline granitic/gneissic basement corresponds to higher resistivities. The constraints on moho depths from DSS results coupled with details of crustal block structure from MT, have produced a density model shown in Fig. 10 that fits well with the observed gravity.

Seismic tomography studies conducted in the Koyna region suggest an increase in the p-wave velocity in the fault zone which was interpreted to be due to high density, high velocity material in the fault zone (Rai et al., 1999; Srinagesh et al., 2000). Even if such intrusive bodies are to be present, the lower resistivity zone observed in the KFZ from the present MT study requires probable presence of some fluid content in the fault zone. Low resistivity zones have been reported by several workers (Ogawa and Honkura, 1997; Mackie et al., 1997; Unsworth et al., 1997, 1999) in the case of seismically active fault zones, indicating presence of fluids in these fault zones. Role of crustal fluids in the generation of earthquake have also gained support from various regions, for example, Latur earthquake, India (Gupta et al., 1996) Kobe earthquake (Zhao et al., 1996; Zhao and Negish, 1998). Koyna earthquakes seem to have nucleation zone only at depths greater than 3 km and have their bottom of the seismogenic zone around 8 km. It may be noted the vertical feature, representing the Koyna fault remains moderately
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