Electrical characterization of the crust in the Deccan Trap region, India.

B. Prasanta K. Patro[1]
National Geophysical Research Institute, Hyderabad, India

Heinrich Brasse
Fachrichtung Geophysik, FU Berlin, Germany

S.V.S. Sarma
National Geophysical Research Institute, Hyderabad, India

T. Harinarayana
National Geophysical Research Institute, Hyderabad, India

Abstract. A wide-band magnetotelluric study was conducted in the region of the Deccan traps, where thick basaltic layers cover large areas of the Indian shield. After dimensionality analysis and decomposition, 2-D inversions were carried out. The basalts are characterized by moderately low electrical resistivities, while the crust is in general highly resistive. Several enhanced conductivity zones were delineated in the middle to lower crust, which are tentatively explained as imaging hidden, partly reactivated faults/fractures of the Precambrian basement.

1. Introduction

The Deccan Volcanic Province (DVP) of western India is one of the great igneous provinces on Earth. Vast amounts of basalts erupted some 65 Ma years ago at the Upper Cretaceous-Tertiary boundary, commonly believed to be due to the northward passage of the Indian plate over the Reunion hotspot [Duncan and Pyle, 1988]. The basaltic layers ("traps") cover an area of approx. 500,000 km^2 of the Indian peninsular shield, reaching average thicknesses of several 100 m up to 2 km. Since the entire region is blanketed with lava flows, the nature of prevolcanic geology and tectonics is until now not well understood. Three major stable continental region (SCR) earthquakes (Koyna, 1967; Latur, 1993; Jabalpur, 1997) of magnitude M > 6.0 that occurred in the Indian peninsular shield over the last decades fall in the Deccan Volcanic Province (DVP).

Several geophysical studies were carried out in the DVP including gravity [*Kailasm et al*., 1972, *Krishna Brahmam and Negi*, 1973, *Tiwari et al*., 2001], deep seismic sounding [*Kaila et al*., 1981a,b] and magnetotellurics [*Gokarn et al*., 1992]. *Krishna Brahmam and Negi* [1973] interpreted the NW-SE trending gravity 'low' passing through Kurduwadi as subtrappean rift and named as 'Kurduwadi' rift. But later studies conducted in this region [*Tiwari et al*., 2001 and *Gokarn et al*., 1992] do not indicate any rift related features like thick sediments, faults, etc. The MT study by *Gokran et al*. [1992] inferred a mid-crustal conductor at depths varying between 12 and 18 km, which they associated with the Conrad discontinuity.

Wide-band magnetotelluric soundings were carried out in the Deccan plateau region (Fig. 1) of western India along a profile cutting across significant gravity anomalies like Kurduwadi low and Sangole high. The study was aimed to understand the electrical nature of the crustal column below the trap region. A total of 43 MT sites covering a period range from

10^{-3} to 10^{3} s were set up along a profile of 330 km length with a station interval of 5-7 km during 1998 and 1999 field campaigns. Metronix GMS05 broadband systems were used for data acquisition. The time series were edited off-line to remove sections contaminated by noise and then analyzed using the Metronix PROCMT robust processing package. Unfortunately, data of the vertical magnetic field were mostly very noisy and were not considered in this study.

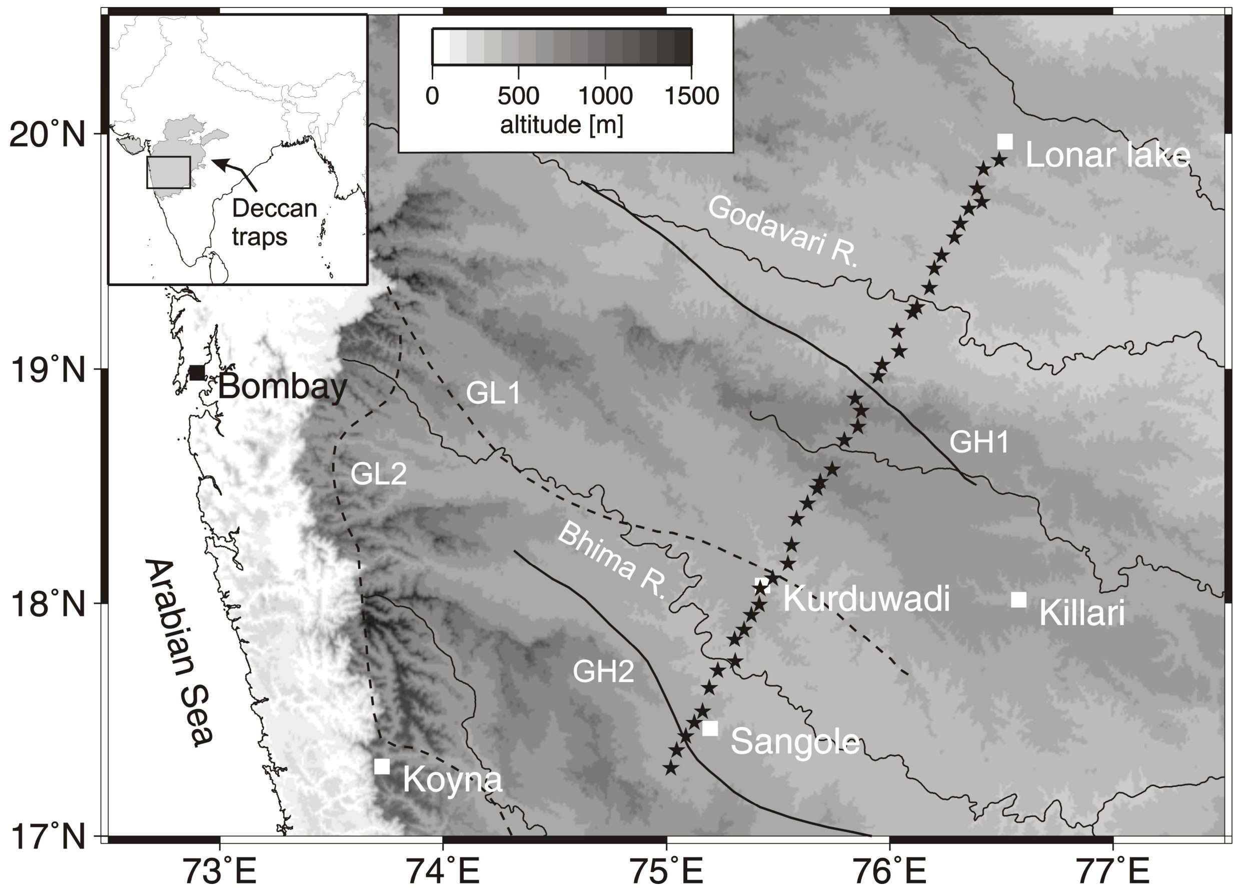

Figure 1. Location of magnetotelluric sites (stars) in the Deccan Volcanic Province (DVP). Also shown are the traces of gravity lows (GL) and highs (GH).

Typical transfer functions (site SP25) are presented in Fig. 2. They show a moderately resistive surface layer at short periods, and the steep rise of apparent resistivities to the basement for longer periods. At periods T > 1 s the curves split, indicating a deep-seated electrical anomaly. Such behavior is characteristic for nearly all sites along the profile.

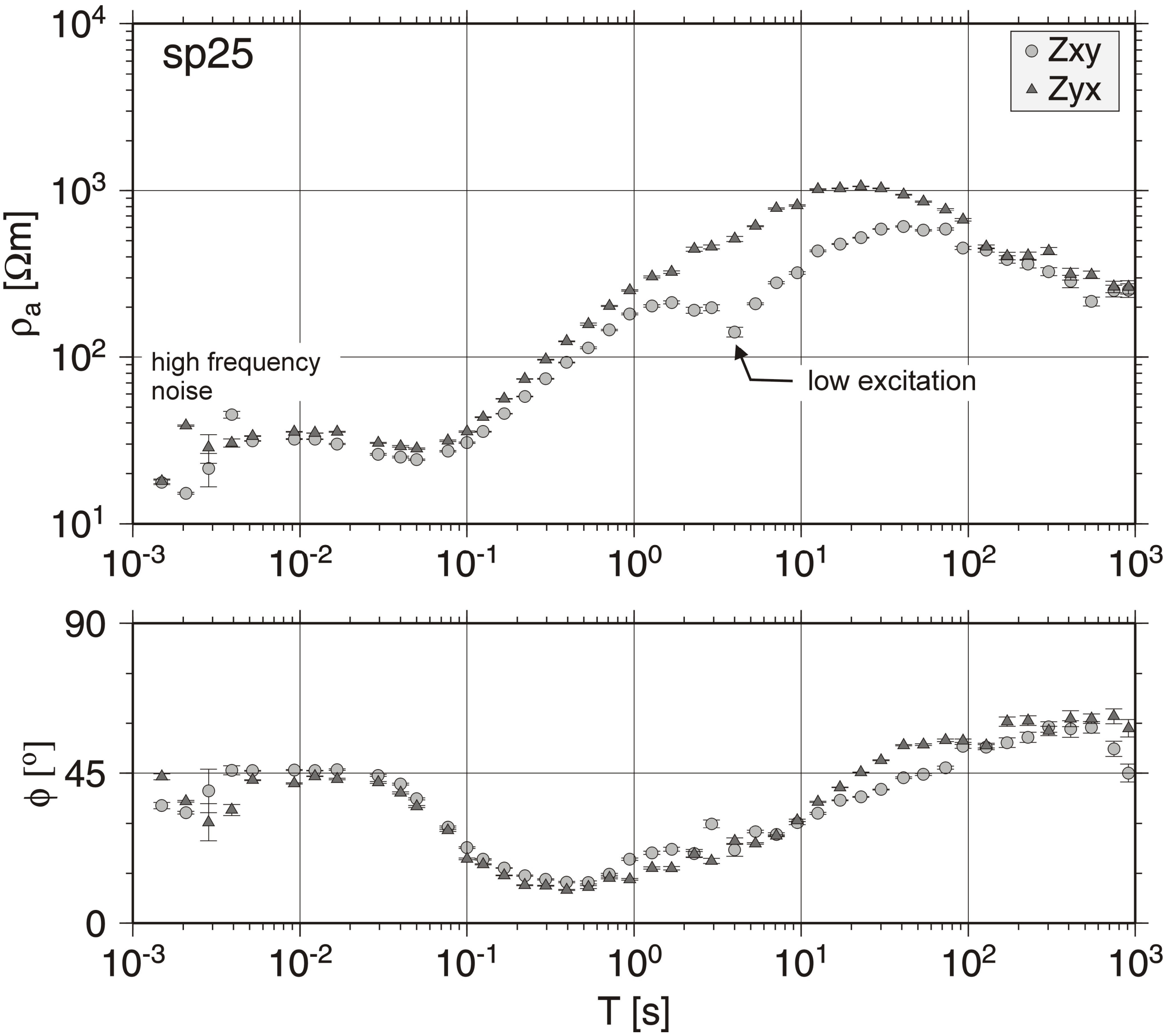

Figure 2. Example of transfer functions (apparent resistivities and phases) at site SP25 in the DVP, as measured in the original N-S, E-W coordinate frame.

2. Regional strike analysis

Fig. 3 shows the skew-period section along the profile, with the rotationally invariant skewness being a measure for deviation from 1-D or 2-D structures. Up to 1 s values are below 0.1 indicating 1-D/2-D nature of the top layer but at longer periods marginally higher values (< 0.2) are observed, with the exception of sites SP10 to SP14, where a higher value of 0.3 – 0.4 is noticed. Though there is an increase at a few locations, in general the skew parameter shows values between 0 – 0.2. Keeping this in mind the 2-D approach is applied.

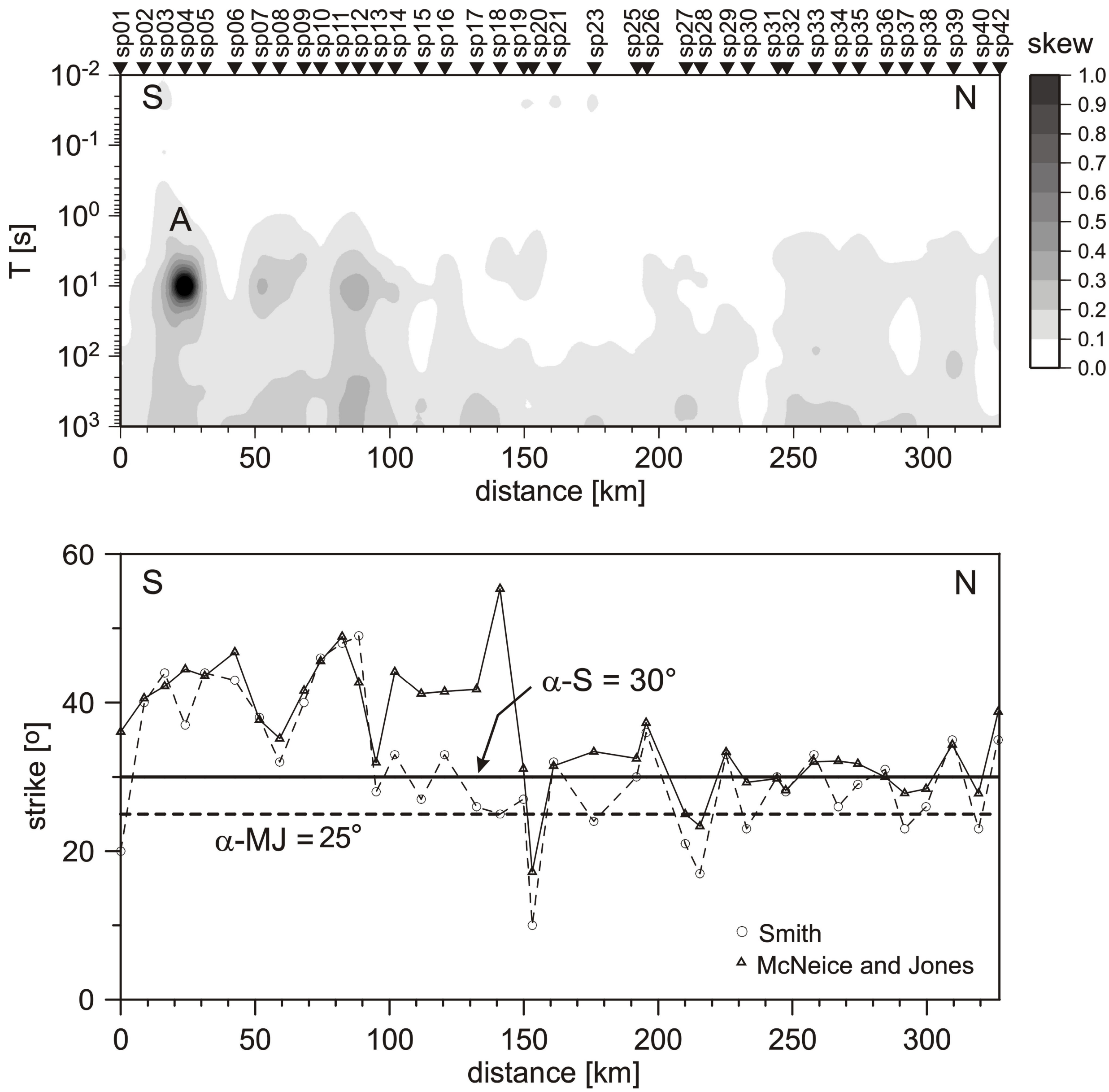

Figure 3. Skew-period section (above). High skew values (A) at site SP04 are due to bad data quality. Strike directions (below) from decomposition schemes of *Smith* [1997] and *McNeice and Jones* [2001].

Frequently the magnetotelluric impedances are distorted by the accumulation of electrical charges along near-surface inhomogeneities. This in turn poses a problem for the determination of true regional strike direction. In this particular case we have followed two different approaches by *Smith* [1997] and *McNeice and Jones* [2001]. In the case of *Smith*'s approach the impedances at each site are fitted for distortion parameters & strikes frequency by frequency, then a single best strike angle at the site is determined. And then it calculates a single best strike direction for the whole set of sites. While *McNeice and Jones* approach is an extension to the Groom-Bailey decomposition in which a global minimum is sought to determine the most suitable strike direction and the telluric distortion parameters for a range of frequencies and for the set of sites. Both approaches resulted in nearly the same strike angle for most of the sites which varies from 25° to 45°. A significant difference is observed at a few sites near Kurduwadi (Fig. 3). This corresponds to the region where the skew value is relatively high, thus the assumption of a 2-D background model is violated here.

The approaches according to *Smith* and of *McNeice and Jones* yielded similar best strike values of 25° and 30°, respectively. Taking the inherent 90°-ambiguity into consideration we have rotated the data of sites SP1 – SP18 by -50°, the rest by -65°. The derived strike direction is in general agreement with the gravity anomaly and the geology. The N-S electric field which is oriented parallel to the conductivity contrast is assigned as TE mode and the N-S magnetic field as TM mode.

3. Modeling results

3.1. Characterization of the volcanic layer

The one-dimensionality at short periods and the steep gradient of nearly 45° of the apparent resistivity curves provides a simple (crude) estimate of surface conductance S according to

$$S = \left(\frac{T(P)}{2\pi\mu_0 \rho_a (T(P))} \right)^{1/2}$$

where μ_0 is the free space permeability and P indicates a point on the 45°-rise of the ρ_a-curve, here taken from the average impedance. This yields conductancies of 5-20 Siemens along the profile (Fig. 4), in accordance with previous 1-D modeling results [*Patro*, 2002].

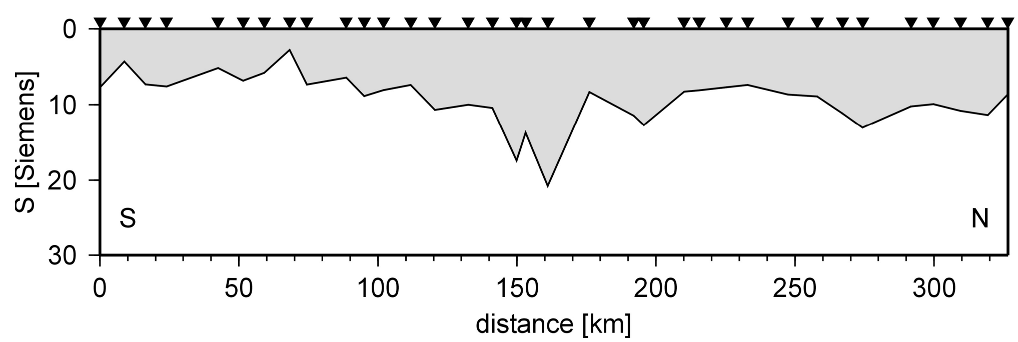

Figure 4. Conductance of basaltic layers along the profile.

The trap resistivity is at first glance surprisingly low with 35-40 Ωm along the profile. We attribute this to deep-reaching weathering of the basaltic layers, considering the time of eruption (65 Ma ago). The depth to the basement undulates around 400 m, with some exception near SP23, where it reaches up to 700 m.

3.2. Deep structure

The nonlinear conjugate gradient algorithm of *Rodi and Mackie* [2001], implemented in Geosystems' WinGLink package, was used for carrying out 2-D inversion. TE and TM mode data in a period range between 0.01 and 300 s were used as input data. In the algorithm the regularization parameter τ plays a significant role, controling the balance between data fit and model roughness. In order to find an appropriate τ, the inversion was carried out several times with different τ values. If the resulting rms errors are plotted against model norm or roughness, a typical L-shaped curve [*Hansen*, 1998] should be obtained and the preferable τ should lie in the knee of the curve. For the magnetotelluric case, however, the L-shape is often not clearly expressed (Fig. 5, see also comments in [*Schwalenberg et al*., 2002]). For the "final model" (Fig. 6a, with a comparison of data and model responses in Fig. 6b) we have chosen τ = 15. Other experiments comprised settings of error floors and horizontal/vertical weighting factors as well as evaluation of convergence behavior (for the model in Fig. 6a the number of iterations was 114, with a homogeneous half space of 100 Ωm as starting model). A minimum error floor of 15% was assigned to the apparent resistivites and 1.5° to the phase data. This helps in downweighting the apparent resistivities with respect to the phases which in turn reduces the influence of static shifts.

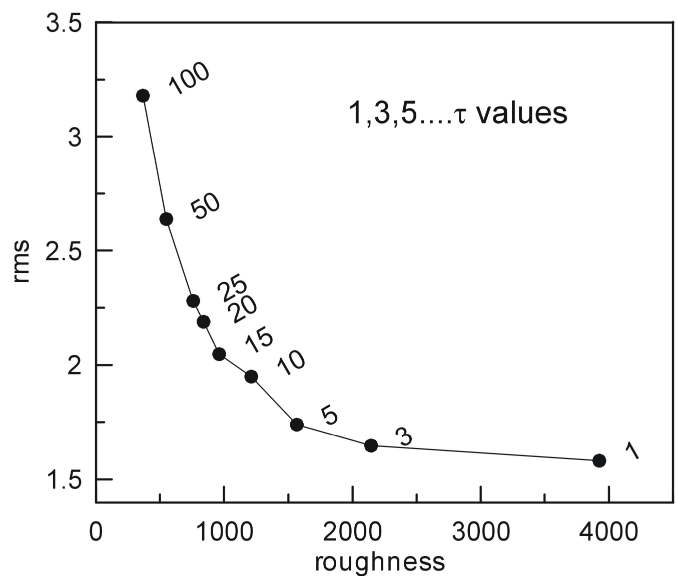

Figure 5. L-curve obtained from systematical variation of the regularization parameter.

A sensitivity analysis (not shown here) revealed that structures below a depth of ~60 km are poorly resolved, while the anomalies in Fig. 6a are resolved well. To test the significance and resolution of some of the conductive features, their resistivity values were systematically varied and the resulting responses were compared with the ones of the model in Fig. 6, following a procedure proposed by *Nolasco et al*. [1998]. In the middle to deep crust 6 low resistive features (marked as A,B,C,D,E and F in Fig. 6a) were obtained. The structures 'B' and 'C' spatially coincide with the 'Kurduwadi feature', which is characterized by a gravity low. Anomaly 'A' is lying below Sangole gravity high. The conductive feature 'F' located below sites SP40, SP42 might be associated with the Lonar crater; this structure is, however, beyond the northern end of the actual profile und thus not resolved. An exceptionally conductive broad anomaly 'E' is delineated at the northern part of the profile. The moderately resistive feature 'D' found below SP19 might be the trace of the Latur fault.

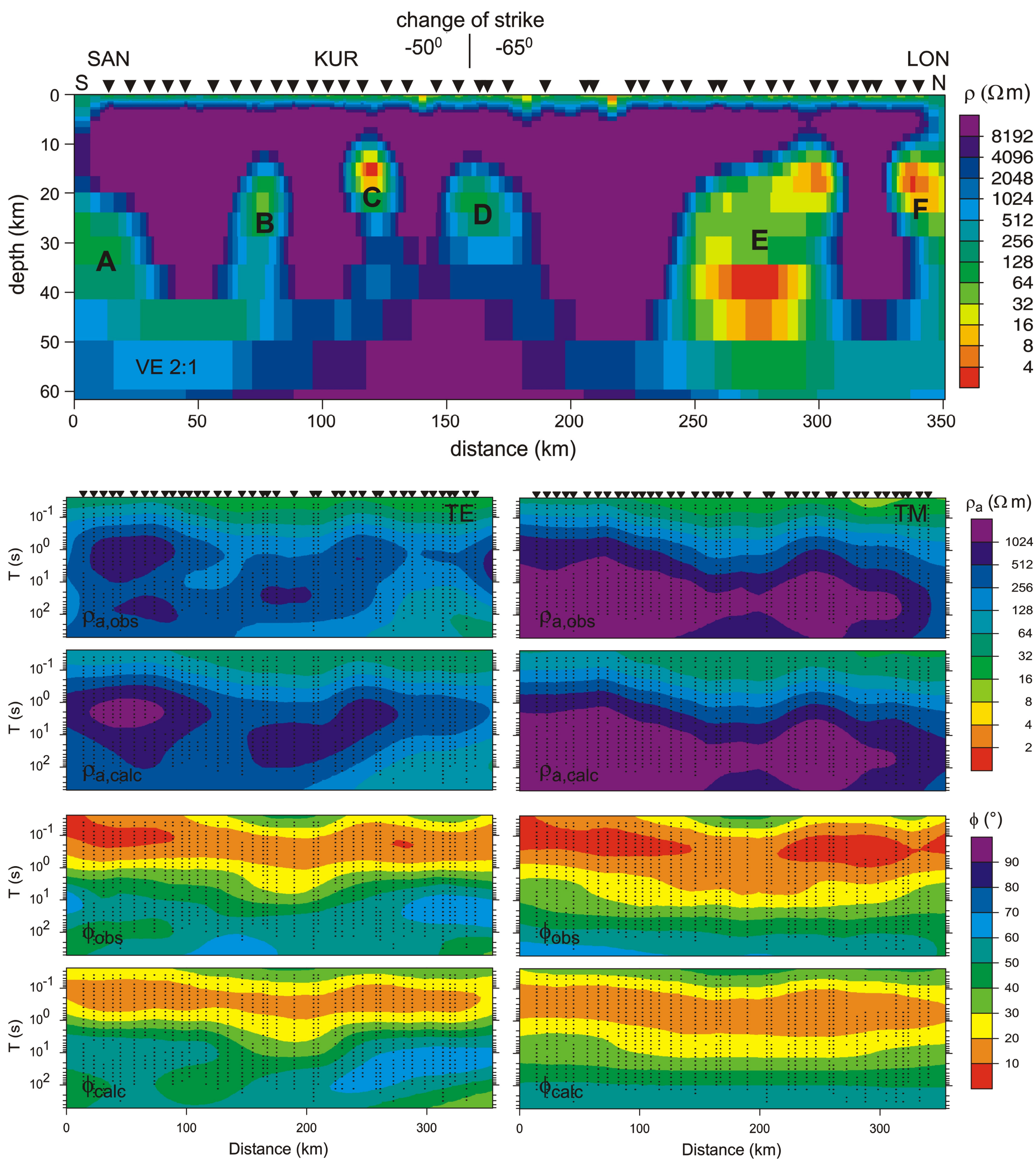

Figure 6. (a) Resistivity model derived from 2-D inversion. Mesh size is 298×45 cells. A-F: conductive structures in the lower crust (see text). Location of major towns: SAN = Sangole, KUR = Kurduwadi, LON = Lonar. (b) Comparison of data and model responses. Left TE, right TM mode.

4. Discussion and outlook

Since few other geophysical constraints exist on the electrical nature of the lower crust beneath the Deccan Volcanic Province, interpretation of the derived anomalies has to be somewhat tentative. Seismic studies [*Kaila et al.*, 1981a,b], which inferred Moho depths of ~40 km, are available only for areas to the west of the MT profile. The low heat flow values (~40 mW/m^2) observed in this part of the Indian peninsular shield [*Roy and Rao*, 2000], coupled with high resistivities for lower crustal depths, are indicative of a cold and dry lithosphere underneath a major part of the DVP. However, the deeper crust is electrically characterized by lateral heterogeneities imparting a resistive block structure separated by conductive zones. Since all enhanced conductivity zones lie at depths > 10 km, they do not image the hidden rift valleys which were proposed by *Krishna Brahmam and Negi* [1973]. They are also deeper than the estimated foci of recent major earthquakes, e.g. at Latur [*Gupta et al*., 1996].

Since partial melting can be excluded in this particular geologic environment, fluids and graphite remain as candidates to explain the enhanced conductivities. Apart from anomalies C and E (and F, which is at the margin of the profile and thus not resolved), the observed anomalous resistivities are in the order of ~50 Ωm; thus only a few percent of (interconnected) fluids are necessary to lower the crustal resistivities, and much less, if graphite is considered. For structures C and E a 1st order approximation (e.g., considering the upper Hashin-Shtrikman bound) requires up to 5% porosity to match the observed resistivities of ~5 Ωm.

We tentatively interpret the enhanced conductivity zones as images of major fault/fracture zones. These faults hidden underneath the Deccan trap cover might represent Precambrian weak zones traversing across the peninsular shield into the DVP and might play a considerable role in shaping its seismotectonic character. These hidden faults may possibly be reactivated under the influence of the ambient stress field in Indian plate due to its northward movement and its subsequent collision with the Asia plate at the Himalayas. It is necessary that these fault/fracture zones are to be carefully delineated in more detail and should be monitored for prior seismicity.

As *Heise and Pous* [2001] have shown, an anisotropic – in their case synthetic – data set may yield dyke-like structures if analyzed with an isotropic inversion scheme. This and the similarity of sounding curves and an almost constant phase split over the entire area may hint at a (macro?) anisotropic lower crust or mantle; this could no be treated in this study and is a topic for further investigation.

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B. Prasanta K. Patro, National Geophysical Research Institute, Uppal Road, Hyderabad, 500 007, India (patro@geophysik.fu-berlin.de)
Heinrich Brasse, Fachrichtung Geophysik, FU Berlin, Malteserstr. 74-100, 12249 Berlin, Germany (h.brasse@geophysik.fu-berlin.de)
S.V.S. Sarma, National Geophysical Research Institute, Uppal Road, Hyderabad, 500 007, India (sreepati@hotmail.com)
T. Harinarayana, National Geophysical Research Institute, Uppal Road, Hyderabad, 500 007, India (tharinarayana@hotmail.com)

[1]Presently at Freie Universität Berlin