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An anomalous high conductivity upper crustal body detected underneath the Surajkund hot spring area from a magnetotellric study

S. Prabhakar Eknath Rao[1*], G. Dhanunjaya Naidu [2], T. Harinarayana [3], S V S Sarma[1] and A.K. Gupta[1]

[1]CSIR-National Geophysical Research Institute, Hyderabad- 500 606, India.
[2] Central Water and Power Research Station (CWPRS), Pune, Ministry of Water Resources, India-411024.
[3] Gujarat Energy Research and Management Institute (GERMI) Research Center, Gandhinagar, Gujarat, India-382007.
[*]Corresponding author: pesatdive@gmail.com

ABSTRACT

Surajkund geothermal area in Jharkhand state is considered to be an important geothermal region after Tatapani hot spring area of Chhattisgarh state, in the Narmada-Son Lineament (NSL) zone, India. It lies within the Proterozoic metamorphites with highly fractured migmatites/gneisses associated with chert. With a view to understand the subsurface electrical structure of the hot spring area and to examine its relation to the origin of hot springs, a magnetotelluric (MT) survey covering a total of 21 stations was conducted in and around the Surajkund hot spring area. Among these stations, a subset of 12 MT soundings, which fall on NW-SE trending profile passing through the hot spring location have been selected for the present study. The 2D modeling results of the MT profile brought out an anomalous, 10 km thick horizontal crustal conductor (5-10 Ohm.m) underneath the Surajkund hot spring area in the depth range of 5-15 km. The anomalous high conductive feature in this tectonically active NSL zone is inferred to be magmatic material originated from upper mantle depths and emplaced in the upper crust. This feature is suggested to be closely related to the geothermal conditions of the area and the low resistivities are attributed to partial melts and the associated fluids. Inversion results also indicate another feature, a moderately resistive (~100 Ohm.m) narrow vertical feature at shallow crustal depths (<5 km.), close to the hot spring. This feature, which falls over a fault/shear zone indicated from surface geology is inferred to be a fault zone connected to the horizontal high conductive body and possibly provides pathways for upward transportation of fluids from deeper levels.

INTRODUCTION

Amongst the various forms of renewable energy sources, geothermal energy is emerging as an important resource. The present study is a part of a major programme undertaken by Ministry of New and Renewable Energy, Govt. of India to investigate all the important geothermal regions in the country using deep geophysical techniques to explore the geothermal energy sources.

A number of hot springs exist all along the Narmada-Son Lineament zone (NSL), in which Surajkund hot spring falls in the eastern part of the NSL zone located in Hazaribagh District, Jharkhand State. It exhibits second highest temperature (80°C) after Tatapani in Chhattisgarh State (Ravi Shankar, 1988). The heat flow values in the Surajkund hot spring area range from 125-130 mW/m^2 (Ravi Shankar, 1988). The estimated base temperature is 110°C and the area lies in the heat flow zone -II in the heat flow map of India (Fig.1). Physiographically, the northern part of the Surajkund area represents the South Bihar plain with isolated ridges, mounds and the southern part is covered by hills and highlands of the Chotanagpur plateau. The Barakar with its tributaries drains the south eastern part of the area (Guha, 1977).

Tatapani geothermal region has been explored with a number of geological, geophysical and also shallow drill holes (Ravi Shankar and Prasad, 1988). Surajkund hot spring area, which is also considered as one of the potential geothermal sources in this zone remained rather poorly explored. The present investigation has been taken up mainly to delineate the crustal geoelectric structure in and around Surajkund geothermal area. As the study area lies in a high heat flow zone, magnetotelluric technique (MT) is opted as the best suitable technique for subsurface electrical characterization. MT images the electrical resistivity of the earth and the resistivity depends on the temperature and fluid/partial melt content of the earth's crust. Besides providing the subsurface electrical structure it can thus provide constraints on the presence of fluids\partial melts and is known to be very effective in geothermal exploration (Stanley et al, 1977; Harinarayana et al, 2002; Meju et al, 2002; Azeez and Harinarayana, 2007; Ushijima et al, 2005; Knutur et al, 2000). Accordingly, a wide band magnetotelluric (MT) survey has been carried out during January-February 2005 in Surajkund geothermal region to obtain a subsurface geoelectric model for the region of the hot spring and also to evaluate its relation to the subsurface geothermal conditions. This, in turn should facilitate a broad understanding of the subsurface structure and its relation to the geothermal reservoir, when integrated with other geological, geochemical and geophysical information.

REGIONAL GEOLOGY AND STRUCTURE

Regional geology of the area is discussed in detail by Thussu (2000) and also in CRUMAN SONATA project report (GSI, 1995). The oldest lithological units exposed in the area are a group of metamorphosed argillaceous, arenaceous and calcareous sediments represented by mica schist, phyllite, quartzite and calc-silicate granulite. Quartzites occur as long linear ridges. Closely associated with these are a group of gneissic rocks consisting of granite gneiss, biotite gneiss, and hornblende gneiss of the Chotanagpur granite-gneissic complex. Out of these, granitic gneiss is the most common rock unit. Hornblende schist and amphibolites of varying dimensions occur as conformable bands within the granitic gneiss, migmatite and schist. Mica bearing pegmatite, quartz vein and dolerite traverse these rocks. From the available geochronological data, the mica bearing pegmatite has been dated as late Proterozoic [828-695 Ma]. Regional geological features of the study region are presented in Fig.1.

The rock formations show a general structural trend of NE-SW to E-W with a dip at moderate to high angles. They are generally disturbed due to folding and faulting. The gneiss occupies the valleys, while the quartzite and schist form ridges. Schist and quartzite appear to form as roof pendants in the main mass of granite gneiss. Fault zones, trending E-W/NE-SW, are traceable discontinuously from a few meters to km. of length.

DATA ACQUISITION AND ANALYSIS

MT data acquisition was carried out using ADU-06 system of Metronix, Germany. Two systems were deployed for the field measurements and at each location the magnetotelluric signals were recorded in the frequency range, 1000 Hz to 0.01 Hz, for a period of 1-2 days. Cultural noise due to the presence of high-voltage power lines and the vehicular traffic from the nearby Agra-Kolkata National highway road posed some problems at some of the sites in acquiring high quality MT data. A total of 21 locations have been occupied and the sites are distributed such that some fall close to the geothermal spring area and some located away from the springs. From these, considering the data quality as well as their disposition with respect to geothermal springs, we have finally chosen a subset of 12 MT stations, which fall on an approximately NW-SE trending traverse that cuts across the general structural trend E-W/to NE-SW of the NSL zone, in the area of study.

Single station processing mode has been adopted.

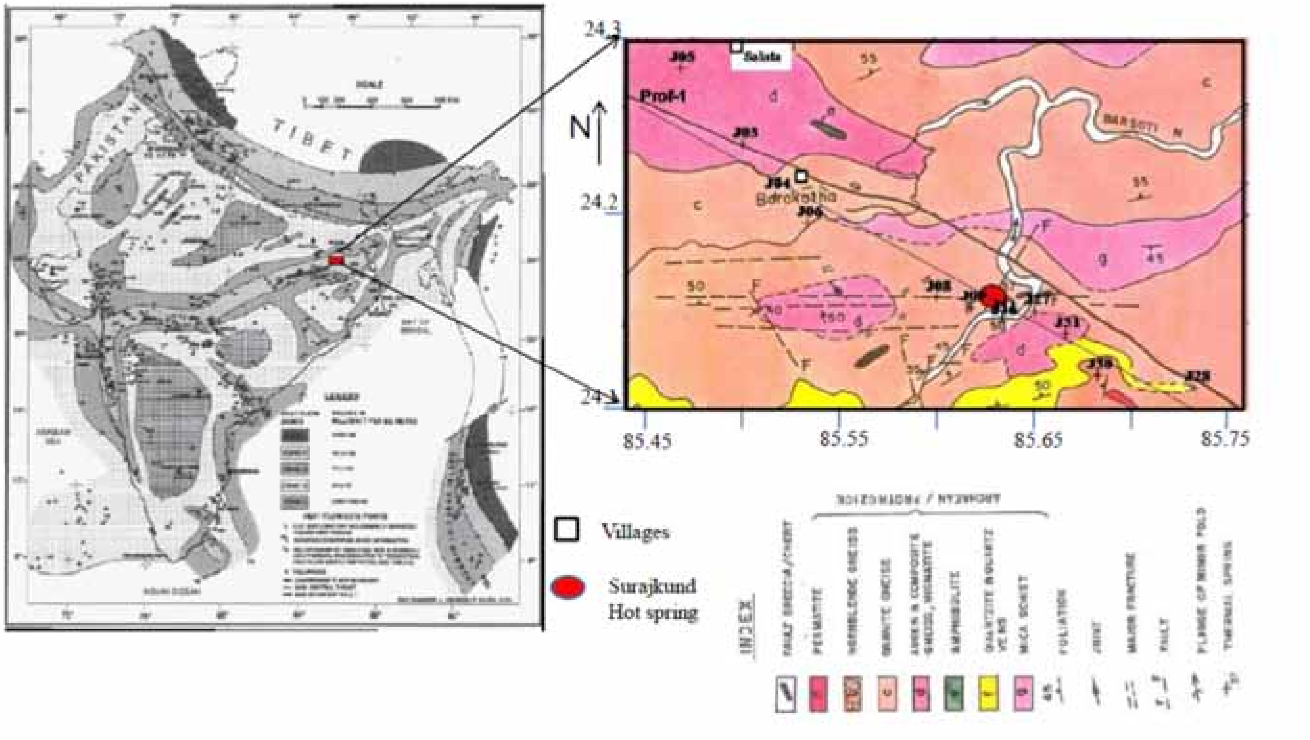

Figure 1. Location of MT sites along the profile shown on geological map of Surajkund Hot Spring region (right side), Jharkhand (modified after Thussu, 2002). Heat Flow Map of India (modified after Ravishanker, 1988). Surajkund hot spring area falls within the Heat Flow Zone (HFZ)-II (left side), marked with red rectangular box in the heat flow map.

The time domain data have been processed using robust processing code available with MAPROS software package (Friedrichs, 2005). The data processing involves different steps like trend removal – removal of the straight line trends in the data and setting the mean value (Bias) to zero, rejection of bad data segments from the measured data etc. and then processing by several methods such as selective stacking, stack all, fixing of coherency threshold etc. in order to improve the signal to noise ratio. The selective stacking method is used to minimize the outlier problem and the method, for the purpose of averaging, selects the maximum number of matrices to exclude almost all outliers from averaging. The Stack all method does the summation or stacking of power spectra from several independent data segments to improve the signal/noise ratio and such improvement is commonly observed by stacking more number of data segments. The coherency threshold method uses coherency criterion to remove outliers. The method sets a threshold coherency value for acceptance of a matrix and only those matrices whose coherency exceeds such threshold value are taken for averaging.

Typical examples of sounding curves of apparent resistivity and phase versus periods for stations J09, J11 and J30 are shown in Fig. 2a. A steep fall in the apparent resistivity for periods greater than 1 sec and also an increase in the phase may be readily seen, suggesting a conductive structure under these sites at shallow depths. The dimensionality indicator is estimated from the measured impedance tensor data. The observed skew (Bahr, 1988) values fall below 0.3 for majority of the frequencies in the range 1000–0.01 Hz, as shown in Fig. 3, thus indicating a 2-D subsurface structure in the area of study, which is considered for further analysis and estimation of the strike direction.

REGIONAL STRIKE

Before going in for 2-D modeling to obtain quantitative parameters for subsurface electrical structure, the data have been subjected to Groom-Bailey (GB) decomposition (Groom and Bailey, 1989). This would provide the regional strike direction that is necessary for carrying out 2D analysis of data and also helps to remove local distortions, if any, for e.g. galvanic distortions in the data caused by near surface inhomogeneities. The galvanic distortions are caused by accumulation of charges on conductivity gradients at the boundaries of near surface inhomogeneities that are below the level of resolution of the MT observations. They tend to dominate over the inductive response of deeper structures, causing distortion in telluric fields that often leads to erroneous interpretation, if they are not properly extracted and utilized in processing of data for determining

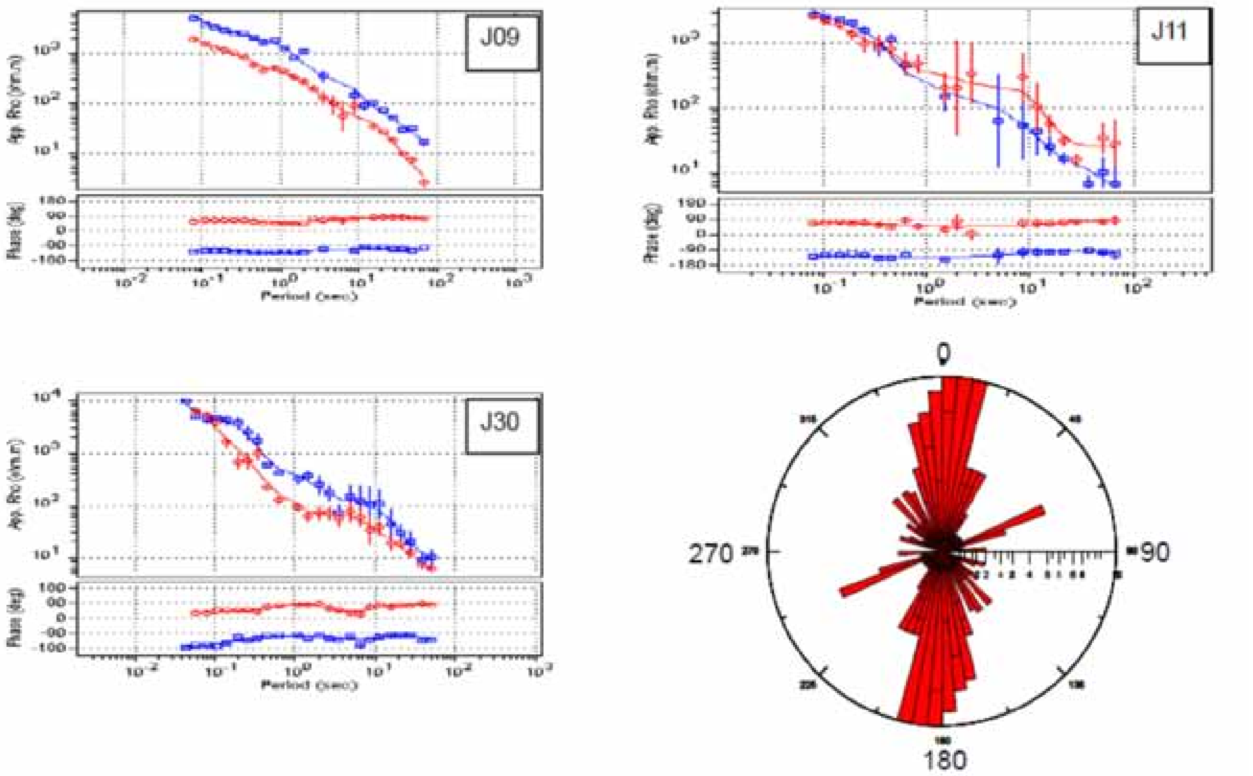

Figure 2. (a) Typical examples of apparent resistivity and phase vs. periods sounding curves for the site nos. J09, J11, J30. (b) Rose diagram shows the geo-electric strike.

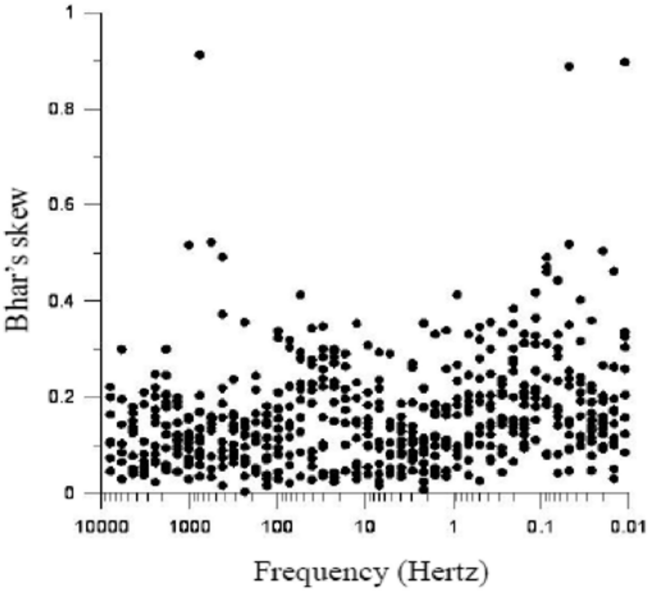

Figure 3. Dimensionality parameter-skew with < 0.3 for many frequencies indicating that the impedance data belong to 2-D rather than 3-D. Some data points > 0.3 reflects the 3-D nature due to near surface inhomogenities.

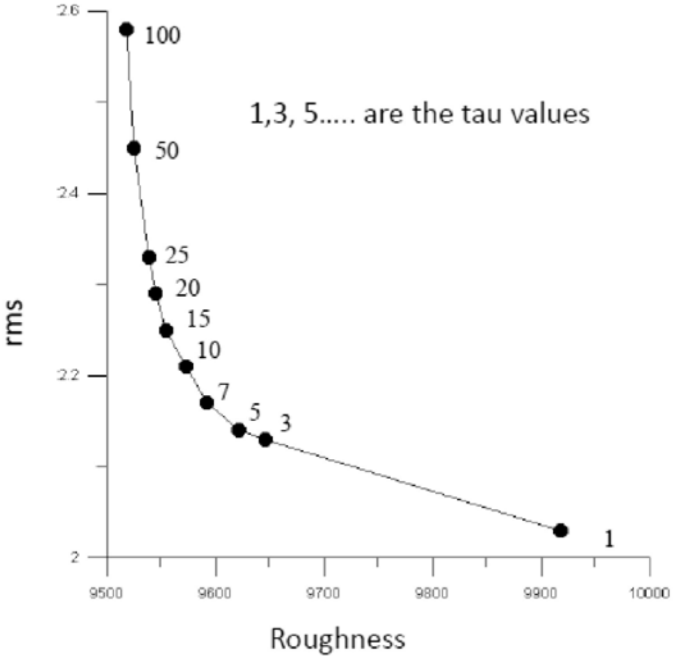

Figure 4. The trade-off parameter "τ" representing a measure of compromise between data fit and model smoothness (Hansen, 1998). The value corresponds to the corner of the curve (in our case $\tau = 5$) is considered as most appropriate for the model.

the strike direction. The distortion effects are usually represented by the two parameters, twist and shear and these two parameters, respectively reflect and represent the extent of angular distortion of the telluric current flow caused due to presence of near surface conductive/resistive bodies. The impedance tensors at each site are rotated for all frequencies (1000-0.001 Hz), at intervals of 5°, to obtain the shear and twist for each rotation. This helps retrieving the frequency invariant values of the shear and twist and also the range of the corresponding strike angles. The frequency invariant shear and twist values thus derived are kept fixed for each site and the unconstrained strike angles are obtained at each frequency for all the sites. The derived strike from GB analysis of the data for the study

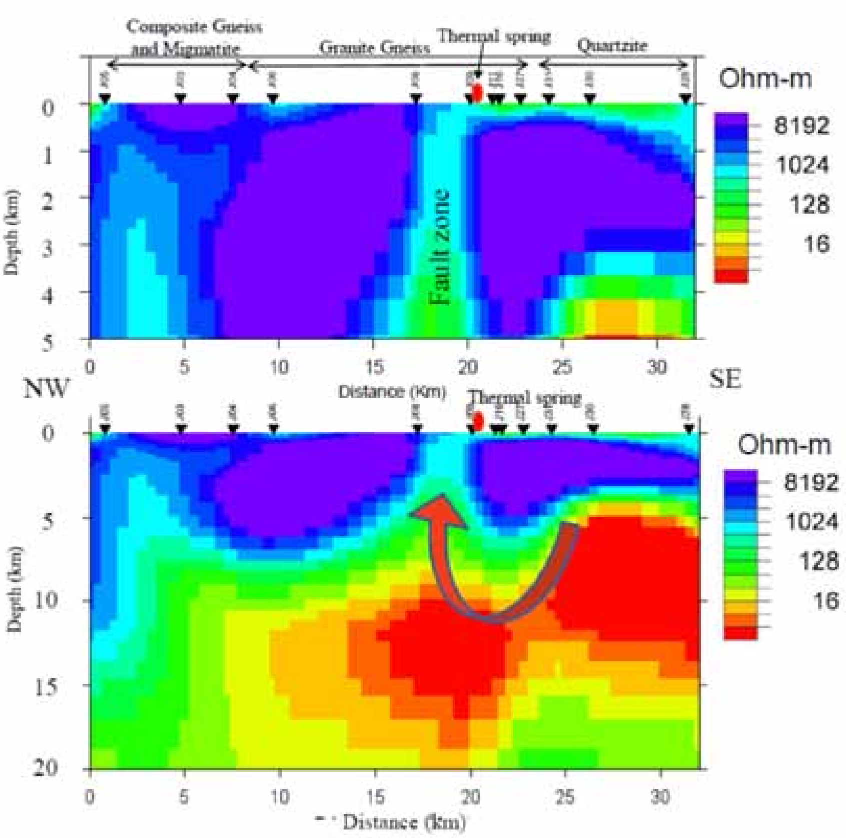

Figure 5. (a) Shallow crustal section with less resistive narrow fault zone. (b) Deep crustal section showing the distribution of resistivity up to 20 km with more details near the hot spring zone. RMS error=2.19 is obtained with tau value of 5.

area is presented in the form of a rose diagram in Fig. 2b. Most of the data points show an average geoelectric strike of N –S. Since there is an ambiguity of ± 90° in the solution from GB analysis, the estimated electrical strike direction can have two possible directions, orthogonal to each other. In the present case these are N-S and N90 ° E. One of these i.e., the direction N90°E is consistent with the known structural trend of the NSL zone viz. E-W/NE-SW. Accordingly, this direction is chosen as the general strike for the 2D modeling and all the data have been rotated to N90°E i.e., E-W direction. The rotated data, i.e. the data parallel to this direction i.e. E-W is assigned as the TE mode or TE polarization (E-Parallel to the strike,) and the data in the direction perpendicular to it i.e. N-S as TM mode (E-perpendicular to the strike).

2-D Inversion

The 2-D inversion of data (Rodi and Mackie, 2001) provides a possible model for subsurface resistivity distribution as a function of depth along the traverse. The 2-D inversion of the present data set has been performed using the Nonlinear Conjugate Gradient (NLCG) algorithm incorporated in the WinGLink package. 2-D inversion of the MT data in general involves ill-posed limitation of the electromagnetic inversion problem. In that, the measured data can be fitted to a variety of models. Hence, to find out a realistic model, Tikhonov's regularization parameter has been used, in which the range of ill-posed problems are replaced by a variety of well-posed problems. In order to reduce the effects of static shifts, if any, in the data, an error floor of 20% for apparent resistivity values and 1.5 deg. for the phase have been assigned. Further, a suitable value for the trade-off parameter "τ", which represents a measure of compromise between data fit and model smoothness is generally determined for its use in getting the final model (Hansen, 1998). Higher value of this parameter leads to smooth model but data fit may not be good, where as lower value leads to good data fit but model smoothness may not be good. To identify a reasonable value for this parameter, inversion of data is repeated with different "τ" values viz., 1, 3, 5, 7, 10, 15...... 50, 100 and the L-curve thus produced is shown in Fig. 4. The value corresponding to the corner of the curve (in our case, $\tau = 5$) is considered as the most appropriate for the modeling. With this value of τ, an RMS error of 2.1899 was obtained for the inversion of data set and the final 2D model obtained is presented in Fig. 5.

The subsurface geoelectric section in the study area is characterized by a high resistive (~10000 Ohm.m)

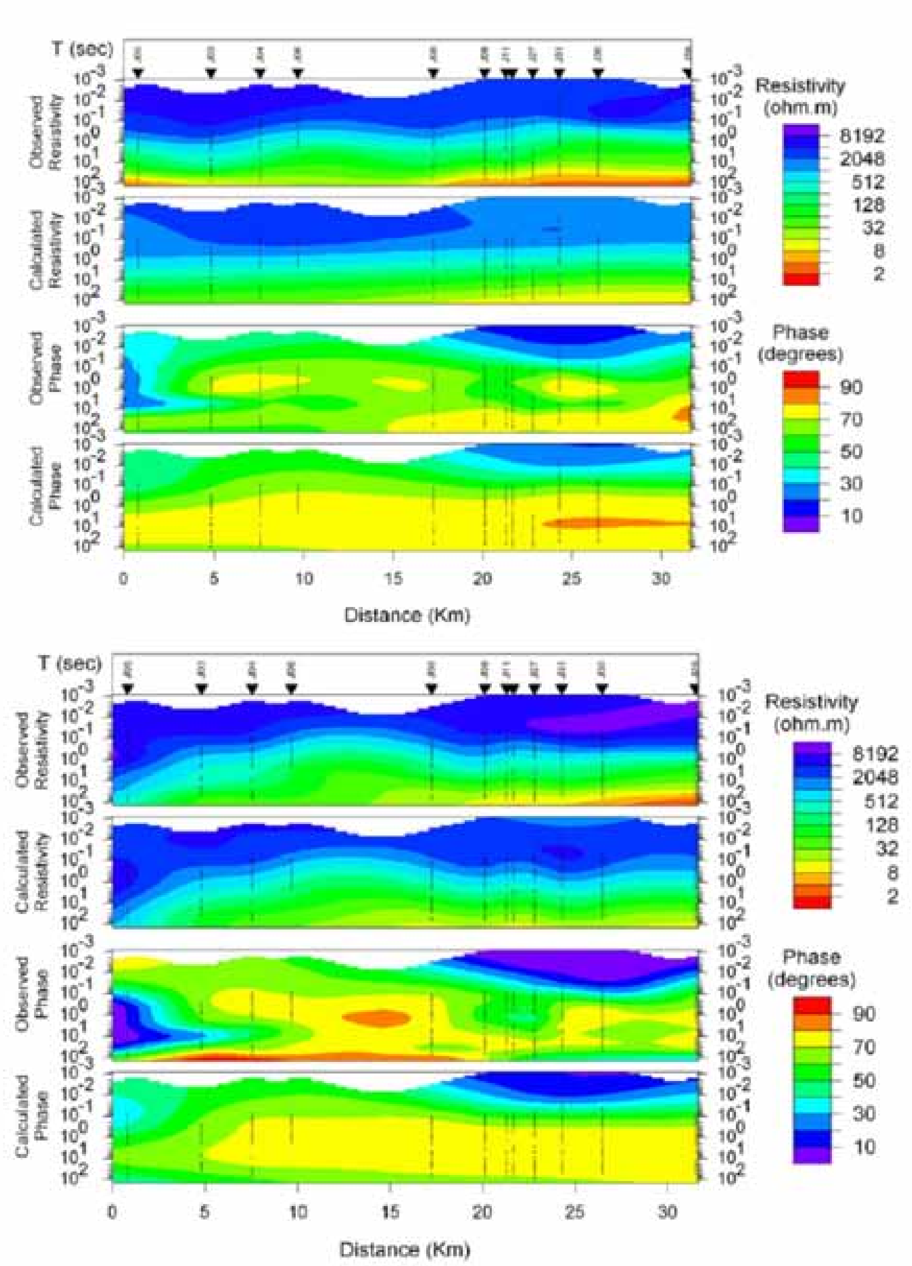

Figure 6. Pseudo sections of apparent resistivity and phase for the derived 2-D model in both TE and TM mode.

upper crustal column to a depth of about 10 km in the northwestern half, which becomes relatively thinner (5-8 km) in the southeastern half. One of the significant features brought out by the 2D model is a well defined horizontal conductor (1-10 Ohm.m) of about 10 km thickness, located underneath the Surajkund hot springs covering the southeastern half of the traverse in the depth range of 5-15 km (Fig.5b). The model also suggests the presence of a narrow vertical moderately resistive (~100 Ohm.m) feature extending from surface to nearly 5 km cutting across the high resistive crustal column near the hot spring area (Fig.5a). The MT responses for the derived model have been computed for both TE and TM modes and compared with the observed data for both apparent resistivities as well as for phase, as shown in Fig. 6a & b.

Further, in order to examine the validity of the narrow vertical moderately resistive feature suggested by the 2D model, a sensitivity analysis is carried out by replacing this vertical feature with high resistive value of 5000 ohm-m. The forward response is computed with and without the narrow vertical moderately resistive feature and the fit in the later case shows higher misfit errors at MT stations J08 and J09 located close to this feature (Fig.7). This suggests the necessity of this feature in the MT model to

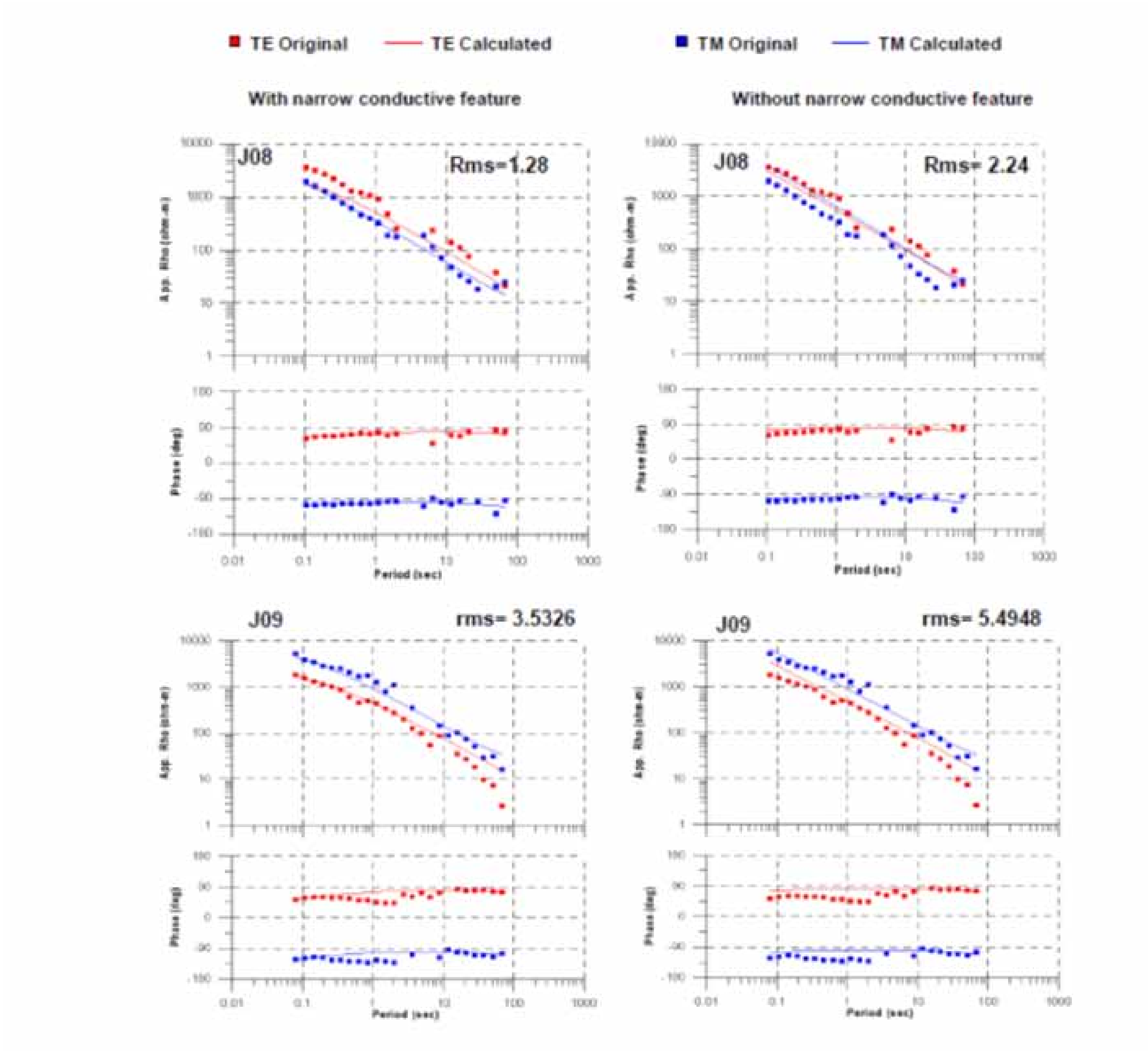

Figure 7. The forward response with and without less resistive narrow feature for the station J08 and J09.

satisfactorily explain the observed data, as may be seen from the model responses in the high frequency range up to 10 Hz corresponding to shallow depth of less than 5 km. But, for lower frequencies, lower than 10 Hz the degree of fit is rather poor and this appears to be more due to noise problems.

DISCUSSION

The Surajkund hot spring area located along the axial part of ENE-WSW trending Son-Narmada-Tapti mega lineament zone falls in the Heat flow zone-II of the heat flow map of India (Ravi Shankar and Prasad, 1988). The heat flow in the Surajkund hot spring area with values ranging from 70-100 mW/m^2 exceeds the upper limit of Zone II (GSI, 2000). Geochemical studies of the hot spring waters as also the gas leakages from the springs in the eastern half of NSL zone ,carried out earlier by Geological survey of India (Ghose and Chatterjee, 1980) revealed very low δ^{15}N values in gases emanating from the hot springs in this area viz., Agnikund (-22.8‰), Tantloi (-9.6‰) and Surajkund (-22.8‰). Though the similarity in stable isotopic composition between thermal and local non-thermal waters observed earlier is inferred to suggest that the springs are locally recharged (Majumdar, et al., 2005), the observed difference in tritium content, water chemistry and the exceptionally low δ^{15}N values of the springs, gases do not support such a possibility . As such it is inferred that the recharge of these springs in the eastern part of NSL has a deeper source.

The present magnetotelluric study in the Surajkund area has clearly brought out a 10 km thick distinct horizontal conductive feature in the depth range of 5-15 km in the upper crustal column, in the southeastern half of the MT traverse. This major conductive anomaly falls underneath the hot spring area and hence assumes importance from the point of view of its relevance to the geothermal conditions in the area. The presence of upper crustal conductors such as the one detected in this area is a common feature generally reported to be associated with many geothermal fields world over, such as Mt Amiata geothermal field in Italy (Gianni et al., 2003), Yellowstone region in United States (Stanely et al., 1977), in the Takigami Geothermal Area, Japan (Ushijima et al., 2005) and in the central Andes (Schilling et al., 1997). These are interpreted in terms of different factors related to subsurface lithology, structure, presence of fluids, partial melts etc. Earlier MT studies in the NSL zone also point out that many of the known faults\fractures like the Narmada North Fault (NNF), Narmada South Fault (NSF), Tapti lineaments are associated with linear vertical conductors (Patro et.al. 2005, Rao et.al. 2004, Naidu et al., 2011, Malleswari et al., 2012) and these were interpreted in terms of partial melts and their associated fluids. Such an interpretation is also supported by low gravity and low seismic velocity, observed in the area.

The high conductive feature in the upper crust delineated in the Surajkund area may thus be inferred to be an intruded magmatic material with associated partial melts and fluids and may be conjectured to be a source of heat to provide suitable thermal conditions for the region by increasing the temperature of the rock matrix and hence that of the waters circulating through the existing faults\ fractures in the study region.

Another feature of interest that the model suggests is the presence of a narrow vertical moderately resistive feature at shallow crustal depths. This feature cuts across the high resistive crustal column near the hot spring area. The model response in the frequency range from 100 Hz to less than 10 Hz computed for validating the presence or otherwise of this feature supports its presence. It is interesting that stations J09 and J11 between which the moderately resistive vertical feature is delineated are indeed located over a fracture\shear zone, as may be seen from the geological\structural map of the study area (Fig.1). This suggests that the vertical feature in the 2D model may be interpreted to be a fracture\shear zone that cuts across the crustal column up to depths of 5-6 km. where it tends to meet the horizontal conductor. It may be conjectured that this vertical feature serves as a zone that facilitates transmission of hot fluids from deeper levels to the surface through associated structural elements like faults.

CONCLUSIONS

1. The present magnetotelluric study has provided a geoelectrical model for the crustal geoelectric structure in the Surajkund hot spring area of the eastern part of the NSL zone. The modeling results brought out a well defined, about 10 km. thick anomalous horizontal conductive feature located underneath the hot spring area in the depth range of 5-15 km.
2. The thickness of the high resistive (5000 Ohm.m) upper crustal layer above the crustal conductor varies from about 8-10 km. in the northwestern half of the profile and becomes about 5-8 km. towards south-eastern part of the traverse.
3. The horizontal conductive feature detected underneath the Surajkund area interpreted to be a magmatic intrusive with associated partial melt and fluids is inferred to be closely related to the presence of hot springs near Surajkund area and is considered to be significant from the point of view of its role in providing suitable thermal environment.
4. The geoelectric model also suggests a moderately resistive (~100 Ohm.m) narrow vertical feature that cuts across the high resistive upper crustal column located close to the hot spring. This vertical feature tends to get connected to the horizontal crustal conductor and is inferred to be a fracture zone encompassing secondary fractures that facilitate upward transport of hot water from depths below.

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