Audio-magnetotelluric investigation of Bakreswar Geothermal Province, Eastern India

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Bakreswar Geothermal Province (BGP) lies over the Archaean gneisses and schists formations. The heat flow and geothermal gradient of BGP are $\sim 230 \text{ mW/m}^2$ and 95°C/km , respectively. The Bakreswar hot spring (BHS) ($23^\circ 52' 30''\text{N}$; $87^\circ 22' 30''\text{E}$) is located over NNW–SSE trending fault. It lies in the eastern flank of BGP and is connected by Sone–Narmada–Tapti (SONATA) and deep-seated ONGC fault systems. Earlier studies indicated that the geothermal fluid flowed towards the same path as that of deep ONGC fault. In view of this, 24 audio-magnetotelluric soundings in the frequency range 10 kHz–10 Hz were conducted at one end of the deep ONGC fault, which is about 20 km northwest of BHS. The data analysis indicated that the data are internally consistent. Analysis of dimensionality and strike are indicative of complex conductivity structures. The 3D inversion of full impedance was performed to obtain a conductivity model of the study area and resulted in root mean square (RMS) for sites close to unity. The results have been discussed by extracting cross-section along 3 to 7 profiles (four of the profiles are perpendicular to strike, whereas three profiles were oblique to the strike direction and are perpendicular to east–west trending ONGC faults). Several low conducting zones are observed in the profiles drawn parallel and perpendicular to the strike. These common conductors show consistent model features but modified resistivity and dimension. Depth slices from 200 to 1400 m suggest that the conductors in the northern part of the study area are deeper than the conductors in the south. The study area is dominated by several shallow conductors which coincide with several fractures present in the study area. The conductors are surrounded by a resistive feature that can act as an impermeable bed and probably restricts the flow of water within the zone. The four major conductors along the oblique profiles (profiles perpendicular to deep ONGC fault) coincide with deep ONGC fault, through which probably the geothermal fluid flows.

Keywords. Bakreswar Geothermal Province; audio-magnetotelluric; ONGC fault.

1. Introduction

Geothermal energy, a natural and clean source of renewable energy, could be extracted, potentially,

at costs competitive to other forms of energy at some point in the future (Rybach 2010). Heat transfers from within the Earth to its surface can either be in the form of geothermal or hydrothermal

system (Heasler *et al.* 2009). A geothermal system is generally classified by its geological, hydrogeological and heat transfer characteristics. Bakreswar Geothermal Province (BGP) is a geologically mixed faulted area and belongs to moderate risk seismic zone III (Chaudhuri *et al.* 2011). BGP lies over the Archaean gneisses and schists formations belonging to the Chotanagpur granite gneiss complex (CGGC).

Bakreswar hot spring (BHS) (23°52'30"N; 87°22'30"E) is located over NNW–SSE trending fault (Singh *et al.* 2015) and lies in the Precambrian of the western margin of Birbhum district, West Bengal, India. BHS is a cluster of seven thermal springs with differing water temperatures (45–71°C) (Majumdar *et al.* 2005). It belongs to low enthalpy (<100°C) geothermal energy resources/systems, covering a total surface area of about 3350 m². The thermal springs are associated with a 1.2 km long shear zone linked to the Rajmahal (117 Ma) volcanic activity (Nagar *et al.* 1996). The heat flow of the area is very high ~230 mW/m² (Chaudhuri *et al.* 2010) and falls in heat flow zone I (Shanker *et al.* 1991) (figure 1a) and resembles young oceanic ridges (Chandrasekharam 2000). The geothermal gradient near the BHS is 95°C/km (Shanker 1988). Sone–Narmada–Tapti (SONATA) and ONGC faults are the two major fault systems that connect the eastern edge of BGP.

Isostatic readjustments from Precambrian to Cenozoic times due to tectonic disturbances in eastern part of peninsular India (including Bakreswar geothermal area) result in reactivation of old fractures or formation of new fractures (Desikachar 1974; Sarkar 1982).

These fractures control deep circulation of meteoric water (Mukhopadhyay and Sarolkar 2012) and subsequent thermal discharges for several groups of geothermal areas in the Chotanagpur gneissic plateau in eastern India. High water temperature, different water chemistry, negligible tritium content, very low Kr/Xe ratio, exceptionally low $\delta^{15}\text{N}$ value and high He emanation for BHS indicate that the deep circulating thermal water does not originate from local groundwater (Majumdar *et al.* 2005). The springs are chemically similar with few groups of thermal springs circulating in CGGC of eastern India and in granitic rocks of other parts of the world.

Deb and Mukherjee (1969) suggested a common origin for the springs at Bakreswar, Tantloi and Surajkund in the CGGC plateau on the basis of their geological mode of occurrences and chemical

characteristics. The springs are presumably fed by a single reservoir which is connected to each of these geothermal systems by some fracture zones associated with the major E–W trending, deep-seated fault along the northern boundary of the Gondwana basins.

Therefore, a diverging spring system is likely to characterise the central part of the Chotanagpur plateau (Majumdar *et al.* 2005). Very low tritium contents in the BHS indicate the long subsurface residence time (>50 yrs) of original water and deep circulation of recharging water possibly through a large geothermal reservoir in the Chotanagpur gneissic plateau (Majumdar *et al.* 2005). The presence of large concentration of helium (~1.4 vol.%) associated with the gas phase suggests that the waters are really deep, long circulating and related to an active hydrothermal system at great depths (Chaudhuri *et al.* 2010). Chowdhury *et al.* (1964) show that the evolution of the BHS is magmatic on the basis of the ratios of certain chemical constituents of the thermal waters. Tantloi hot springs (THS) (24°2'08"N; 87°17'15"E), having temperature range 48–70°C, are located on ENE–WSW fault. THS is about 20 km NW of Bakreswar and is controlled by a NNW–SSE trending fault (Majumdar *et al.* 2005).

Geothermal reservoirs can be characterised by gravity, magnetic, seismic, electrical and electromagnetic (EM) geophysical methods. Due to higher conductivity contrast for geothermal system EM and direct current (DC), electric methods are the most appropriate methods for mapping geothermal reservoirs (Bartel and Jacobson 1987; Pellerin *et al.* 1996). But, EM and DC resistivity surveys can only image the shallow subsurface structure.

Magnetotelluric (MT)/audio-magnetotelluric (AMT) method – a natural source EM method – can be used for greater depth exploration. It maps the lateral and vertical resistivity variations in the subsurface by measuring time variations of orthogonal components of the Earth's electric and magnetic fields. In geothermal areas, MT/AMT method is used for structural investigations, geothermal evaluation and the determination of hydrothermal circulation (Uchida 1995; Pellerin *et al.* 1996; Bhattacharya *et al.* 2002; Volpi *et al.* 2003; Wannamaker *et al.* 2004; Oskooi *et al.* 2005; Harinarayana *et al.* 2006; Sinharay *et al.* 2010; Amatyakul *et al.* 2015; Tripathi *et al.* 2015). Basically, in geothermal systems, AMT results help in defining the distribution of conductive and resistive zones associated with fluids and cap rocks in

the first few hundred metres (Sinharay *et al.* 2010; Tripathi *et al.* 2015).

Self-potential (SP), gravity, magnetic, resistivity and MT/AMT geophysical studies (Mukhopadhyay *et al.* 1986; Majumdar *et al.* 2000; Sinharay *et al.* 2010; Tripathi *et al.* 2015), geological mode of occurrence, isotopic composition, chemical composition and geochemistry (Majumdar *et al.* 2005 and others), genesis (Deb and Mukherjee 1969), radon activity measurement (Chaudhuri *et al.* 2010) and natural gases with special reference to helium discharge (Ghose *et al.* 2002) have been carried out in BGP. Location of the geothermal reservoir is deep (Sinharay 2006; Mukhopadhyay and Sarolkar 2012) and lies beyond 15 km in the northwestern side of the BHS (Sinharay *et al.* 2010).

In general, for geothermal studies, data have been acquired in grid fashion (Park and Torres-Verdin 1988; Takasugi *et al.* 1992; Park and Mackie 2000). AMT survey has been carried about 20 km northwest part of BHS (figure 1b) in a grid fashion for mapping the conduit path of geothermal fluid. 3D inversion of the acquired data has been performed using AP3DMT code of Singh *et al.* (2017) for the frequency range of 10 kHz–10 Hz. The results have been discussed over seven profiles.

2. Geology of area

BGP belongs to Precambrian Chotanagpur gneissic complex of the eastern part of the Indian peninsular shield. The basement is mainly composed of granite gneiss with minor enclaves of calc-silicate, amphibolite, gabbro, pegmatite and dolerite (dyke). Thus, the basement complex itself derives its genesis from great depths and can also act as a source of crustal heat. Furthermore, ONGC (1969) identified a nearly E–W striking, deep-seated fault running more or less parallel and close to the northern boundary of the Gondwana basins (Majumdar *et al.* 2005) (figure 1a and b). Geologically, the region manifests large-scale exposure of high-density basic volcanics (Rajmahal Trap) at a distance of about 25 km northeast of BHS. Bakreswar region has four sets of vertical to sub-vertical fractures trending NW–SE, NE–SW, N–S and ENE–WSW and are intersecting each other near the hot spring (Majumdar *et al.* 2000). The gneiss and calc-silicate are regionally folded in the form of asymmetric to symmetric anticlinal and synclinal northeast–southwest (Nagar *et al.* 1996). These faults/fractures control deep circulation of

meteoric water in geothermal system (Mukhopadhyay and Sarolkar 2012).

3. AMT data acquisition and processing

Twenty-four AMT soundings were collected (figure 1b and c) at about 20 km northwest of BHS in the frequency range of 10.4 kHz–11.2 Hz. The time series data were recorded using MTU-5A equipment of Phoenix Geophysics Ltd. Pb and PbCl₂ electrodes have been used for acquiring electric field, whereas magnetic field was measured using induction coils AMTC-30. Horizontal electric (E_x , E_y) and magnetic (H_x , H_y) field components were recorded simultaneously along the axes orthogonal to each other. Vertical component of the magnetic field (H_z) was also recorded. The length of the electrical dipole is ~100 m. The acquired time series data were processed using the extra-hybrid processing approach (Shalivahan *et al.* 2006).

Figure 2 shows apparent resistivity and phase curves of representative sites in unrotated coordinate systems (red square xy and blue circle yx). The less scatter and small error bar smaller than symbol size indicates that the data quality is good.

4. AMT data analysis

4.1 Dimensionality and directionality analysis

The dimensionality analysis has been determined by analysing Swift skew, tipper magnitude and Bahr's phase sensitive skew (PSS). Swift skew is used to determine the dimensionality of regional electrical structure with the help of impedance tensors and is mathematically expressed as

$$k = \left| \frac{Z_{xx} + Z_{yy}}{Z_{xy} - Z_{yx}} \right|, \quad (1)$$

where Z_{xx} , Z_{xy} , Z_{yx} and Z_{yy} are the elements of impedance tensor.

Swift skew is rotationally invariant. In other words, it is independent of coordinate system. For 1D/2D structures, Swift skew is less than 0.2 (Swift 1967). Higher skew values indicate the more complex structure of the site. In some cases, apparent resistivity and phase may be well behaved but skew will show high value if 3D inhomogeneity is present (Berdichevsky 1999). The diagonal terms are influenced strongly by noise.

Figure 1. Geothermal provinces of India (modified after [Chandrasekharam 2000](#); [Chaudhuri et al. 2010](#)). The blue colour ellipse shows the province within SONATA having heat flow more than 180 mW/m² (a). (b) The geological map of study area along with AMT locations (purple colour triangle) and major important network of lineaments adjacent to various major hot-springs (modified after [Majumdar et al. 2005](#)). Red circle shows the hot springs locations. BHS-Tantloi faults are marked by black-dotted lines. (c) AMT location and profile orientation perpendicular to strike orientation (AA', BB', CC' and DD'). Profiles XX', YY' and ZZ' are perpendicular profiles cut across ONGC deep fault.

Figure 2. Observed and predicted data for sites 326, 327, 328 and 329. The predicted data have been obtained from the 3D inversion of full impedance components.

PSS (Bahr 1991) is relatively insensitive to galvanic distortion effects such as static shifts and gives a better estimate of the dimensionality than the Swift skew. Mathematically, PSS is expressed as

$$\eta = \frac{\sqrt{|\text{Im}(Z_{xy}Z_{yy}^* - Z_{xx}Z_{yx}^*)|}}{|Z_{xy} - Z_{yx}|}, \quad (2)$$

where Im is the imaginary component and * indicates the complex conjugate.

The values over 0.3 can be considered as indicators of 3D-inductive effects, and the zero values indicate ideal 1D/2D electrical structures (Bahr 1991). However, in some cases, values smaller than 0.3 are assumed that the data represent the responses of a 2D structure (Garcia *et al.* 1999). The value less than 0.3 is a necessary but not sufficient indication of a regionally 2D structure (Simpson and Bahr 2005).

The tipper (T , vertical transfer function) (Vozoff 1991) relates the induced vertical magnetic field (H_z) with the source horizontal magnetic field components (H_x , H_y) as

$$H_z = H_x T_{zx} + H_y T_{zy}, \quad (3)$$

where T_{zx} and T_{zy} are the components of the magnetic field transfer function. Tipper values are zero or close to zero except in the vicinity of lateral conductivity contrast.

Tipper magnitude generally varies from 0.1 to 0.5 for 2D structure, whereas the value more

than 0.5 indicates more complex structure and probably 3D nature of the subsurface (Vozoff 1991; Berdichevsky 1999). It is particularly sensitive to 3D conductivity and can provide additional information, particularly on the lateral resistivity variations (Simpson and Bahr 2005).

Figure 3(a–c) shows the Swift skew, Bahr skew and tipper magnitude plot for the AMT data. Figure 3 suggests that the structure is either 2D or 3D. Figure 4(a) shows the impedance strike varying from N45°W to N45°E. Impedance strike shows a 90° ambiguity which can be resolved by tipper strike (Vozoff 1991). Figure 4(b) shows the tipper strike, though not well resolved, has prominent orientation at N20°W and coincides with the major regional geologic strike (which is a northwest–southeast trending anticlinal structure) and gravity axis (NNW–SSE) (Mukhopadhyay *et al.* 1986). The strike direction of N20°W was preferred for 2D modelling of the AMT data.

Directional variation of the induction vectors at different frequency may indicate complexity of underground geoelectric structures (Ghaedrahmati *et al.* 2013). Real induction vector points towards conductor (Parkinson 1959). Figure 4(c) shows the real induction vectors for all 24 sites at 10 Hz, 100 Hz, 1000 Hz and 10,000 Hz obtained from observed magnetic fields. It can be seen that the conductors are present in all the three profiles.

Figure 4(c) shows that the induction arrow for sites in the central part of the survey area indicates 2D structure, whereas the induction arrows for sites

Figure 3. Dimensionality parameters (a) Swift skew, (b) phase-sensitive skew and (c) tipper magnitude. Swift skew, Bahr's skews, tipper magnitude below 0.2, 0.3 and 0.5 (mark as red line) indicate a possible 2D features, respectively.

in the northern and southern parts of the survey area vary, both in direction and magnitude, indicating towards a complex structure.

4.2 Setting up 3D inversion parameter

The dimensionality analysis, where the value for PSS is <0.3 (figure 3) for most of the sites, is a necessary but not sufficient indication of a regionally 2D structure. Furthermore, the directionality analysis results are indicated towards a varied strike direction (figure 4), which hints towards the presence of a complex structure in the area. Unlike

2D inversion, a 3D inversion does not require projection of data. Furthermore, the 3D inversion can account for the inductive effects produced due to localised near-surface structures (Meqbel *et al.* 2014).

These prompted us to perform a 3D inversion for full impedance data of the entire data set in the frequency range of 10 kHz–10 Hz. The 3D model was obtained for all 24 AMT sites using the AP3DMT code of Singh *et al.* (2017), which is a MATLAB-based computer code, for modelling and inversion of MT data. The key feature of AP3DMT is its capability to accommodate modifications in the forward problem and their easy implementation without any modifications in other sub-program like inversion subprogram (Singh *et al.* 2017).

Error floor is a compromise between optimising data fit and the particularities of any AMT data set. A higher error floor means providing less weight to a particular data component. It may provide considerable fit in presence of severe noise conditions and thus providing minimum structure model of the considered area. An error floor of 10% of $\sqrt{|Z_{xy}Z_{yx}|}$ was used for performing the inversion. The model grid is discretised into $52 \times 44 \times 27$ cells in the X, Y and Z directions, respectively. The central part of the mesh grid has a cell size of $500 \text{ m} \times 250 \text{ m}$. The area of interest is padded with six outer cells in each direction which increases by a factor of 1.3. The thickness of the first layer is 5 m and increases with depth by a factor of 1.2 for each subsequent layer. The optimum initial half-space resistivity value for inversion was obtained by performing 3D inversion of full impedance with various half-space resistivity values of 10, 50, 100, 200 and $500 \Omega \text{ m}$, respectively. About $100 \Omega \text{ m}$ is preferred as the initial half-space resistivity because the model features do not change significantly for initial half-space resistivities below $100 \Omega \text{ m}$, and also the minimum RMS of 2.01 was obtained for $100 \Omega \text{ m}$ after 72 iterations.

5. Results and discussion

Figure 2 shows the match between the observed and calculated data sets of off-diagonal data for representative sites after the inversion of full impedance data. It can be observed that all the sites have good match. All the sites have a very low RMS value which is very close to unity. Figure 5 shows the resistivity slices at various depths namely 200, 300, 400, 500, 600, 800, 1000 and

Figure 4. Rose diagram of (a) impedance strike, (b) tipper strike and (c) magnetic induction vectors from top left to bottom right panels for four frequency ranges: 10, 100, 1000 and 10,000 Hz for all AMT sites. The red arrows show the real parts of the magnetic induction vectors. Some sites have magnitudes larger than 1.

1400 m obtained from the 3D MT inversion. The conductors, namely, C_1 , C_4 and C_6 , to the north of the study area are at relatively shallow depth of 200 m. All these conductors continue to a depth of 1400 m. Furthermore, conductor C_5 also to the north of the study appears at the same depth as C_1 , C_4 and C_6 but extends to 600 m only. Three conductors C_2 , C_3 and C_7 to the south of the study area do start appearing at the same depth as conductors to the north but with limited depth extent. Conductors C_2 and C_3 extend up to 600 m,

whereas conductor C_7 extends up to 800 m. All these conductors are surrounded by a resistive feature which can act as an impermeable bed. This probably restricts the flow of water within this zone.

Figure 6(a) shows the distribution of AMT soundings along with ONGC deep fault. Figure 6(b and c) shows the 3D vertical stack slice along with the profiles perpendicular to strike and oblique to the strike direction and are perpendicular to east–west trending ONGC faults,

Figure 5. Horizontal depth slices of 3D resistivity model computed from the full impedance tensor using the 3D inversion code by AP3DMT (2017) with a RMS misfit of 2.01. Purple triangle indicates the location of AMT stations.

Figure 6. Final 3D resistivity model: (a) location map of audio-frequency magnetotelluric (AMT) survey sites (purple triangle) used for 3D inversion, (b) 3D inversion model cross-sections perpendicular to the strike and oblique to strike, and (c) 3D inversion model cross-sections oblique to strike. All slices have a depth extension of 3 km and an approximate horizontal extension of 10 km. Purple triangle indicates the location of AMT stations.

respectively. From figure 6 we find that conductor $C_1 + C_4$ is deeper than the other conductors, similar to that shown in figure 5. Thus, we can conclude that the conductors that are linked to the conduit path are deeper in the northern part of the study area. Conductors C_1 , C_2 , C_3 and C_4 coincide with deep ONGC fault, as shown in figure 6(c).

6. Conclusion

AMT survey was carried in at about 20 km north-west of BHS for possible mapping of direction of flow of geothermal fluid. BGP lies in E–W belt along the trend of Gondwana sedimentary basin in the central part of the Precambrian Chotanagpur gneissic complex. BGP lies in the eastern extreme end of SONATA province which is characterised by anomalous high heat flow and geothermal gradient. The area comprises Chhotanagpur gneiss, intrusive dolerites amphibolite dykes and gabbros.

Several conductors have been mapped in the northern and southern parts of the study area from a shallow to deeper depths. The shallower conductors are coincide with the fractures that are present in the study area. The deeper conductors present in the northern and the southern parts coincide with the deep ONGC fault. The conductors in the northern part of the study area are deeper than the conductors at the southern part. These conductors are surrounded by resistive beds at all depths. These resistors restrict the movement of hot water within this zone, which probably is the direction along with which the geothermal fluid flows.

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