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Geophysical surveys over Bakreswar geothermal region in Birbhum district, West Bengal

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ABSTRACT

Magnetotelluric (MT) and resistivity surveys were carried out in the geothermal region of Bakreswar, West Bengal to obtain a preliminary idea about the nature of conductivity structure and to prepare a meaningful conceptual model of the geothermal region.

In resistivity traverse along Bakreswar-Asanshuli, one conductive anomaly zone is mapped at n (separation parameter) =10 in between 1200-1500 m stations. Bakreswar hot spring lies adjacent to it and geologically a hidden fault could be the source of the hot spring. In the resistivity traverse along Chandrapur-Tantipara, the presence of subsurface conductive bodies (50-400 Ohm m) is inferred between stations 1000-1200 m at a pseudo depth of 400-700 m. This source could be in the form of structural breaks like shear zones/geothermal region.

1D inversion shows a high resistivity layer overlain by a conductive layer which is interpreted at a depth as shallow as 3001 m at Rajnagar but at a greater depth of 38103 m at Nakrakonda. This steep gradient in between these two stations could possibly be attributed to a fault zone. Similar type of fault is inferred in between Belsara (7484 m) and Nakrakonda (38103 m). 2D inversion shows that the entire lower crust consists of an anomalous structure of conductive layers with a relatively low-resistivity (approximately in the range 1–90 Ohm-m) imbedded in the high-resistivity background. A highly conductive feature is inferred beneath Lokpur and Idgachha region extending from shallow surface into the deep crust. This feature is interpreted as a potential reflection of the partially melted magma in the upper crust, which might correlate to mantle upwelling along the fault. It is likely that the magma is the heat source of the Bakreswar geothermal system. Thus this inference potentially provides new geophysical evidence to understand the occurrence of the partially melted magmas in the upper crust. These models suggest for a possible recovery of heat from heterogeneous, fractured geothermal reservoirs. The MT exploration of the geothermal reservoir can provide valuable constraints on the physical conditions within the delineated fault zone. It has guiding significance for the exploration of other geothermal resources along fault zones especially in granite areas.

Key words: Natural source MT, DC resistivity traverse, Geothermal Region, 1D inversion, 2D inversion.

INTRODUCTION

High electrical conductivity is one prominent feature of geothermal sources. Geothermal-water-rich rocks commonly have relatively lower resistivity than initial rocks, and the variation in the resistivity is related to the water abundance, temperature, and degree of mineralization (Spichak et al., 2007). Hot subsurface water is closely related to structural fractured zones connected to medium-deep hot sources. Water-abundant (especially hot water) and fractured zones usually have lower resistivity. The resultant low-resistivity anomalies have generally been the main target for the geophysical exploration of geothermal resources (Simpson and Bahr, 2005). This is the geophysical basis of MT soundings for geothermal resource exploration. The MT method can be used to detect the distribution of highly conductive geological bodies and faults. MT data, when combined with other geophysical anomalies and geological conditions, can be used to predict the distribution of thermal reservoirs (Spichak and Manzella, 2009). Since late 1980s, the development of remote references, robust approaches, distortion corrections, multidimensional modeling and inversion methods has made the interpretation of MT data more reasonable (Bahr and Simpson, 2005; Berdichevsky and Dmitriev, 2008). There are many successful applications all over the world of the MT method in geothermal exploration (Bai et al., 2001; Newman et al., 2008; Pellerin et al.,1996; Volpi et al., 2003; Wright et al., 1985).

Bakreswar geothermal areas are located in the Chotanagpur Gneissic Complex (CGC) predominantly comprising granitic rocks (Precambrian) with a discontinuous stretch of coal bearing Gondwana sediments (Lower Permian to Middle Jurassic). Geothermal manifestation in this area is in the form of copious discharge of hot water of about 780 l/min through several spouts. The water temperature as measured on the surface varies from 35° to 88° C (Ravi Shanker, 1991). Presently to decipher the conductivity structure of the earth MT and DC resistivity methods have been carried out in the geothermal region of Bakreswar, West Bengal (Figure 1).

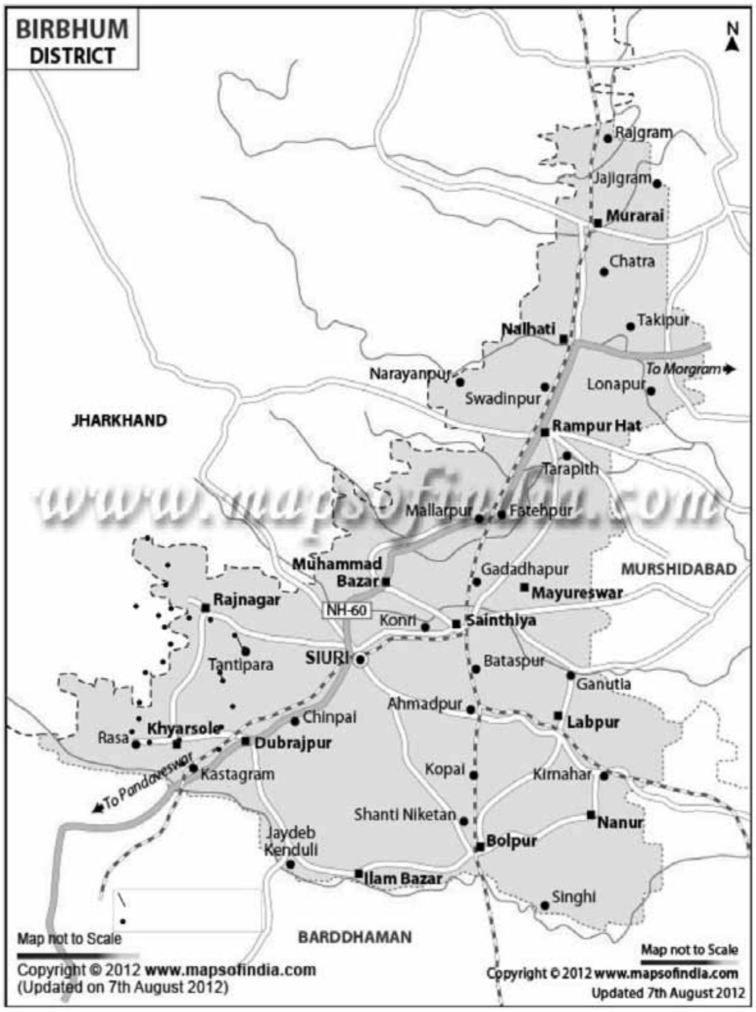

Figure 1. Location of the MT observation site and resistivity traverse in Bakreswar geothermal region.

Geological succession in Bakreswar geothermal region after Mukhopadhyay (1996):

Recent/Quaternary	Alluvium
Unconformity	
	Laterite
Unconformity	
Lower Gondwana	Dolerite dyke
	Barakar sandstone (gritty, felspathic)
	Talchir shales, sandstone and boulder bed
Unconformity	
Precambrian	Pegmatite with quartz vein, metadolerite, porphyritic granite, granite gneiss, migmatite with horneblende gneiss, amphibolite, quartzite, calc-gneisses, granulites and charnockites.

Geology of the Study Area

The thermal springs of Bakreswar occur in a topographically low lying area hosted in a gently rolling terrain which is mostly filled by alluvial or lateritic soil with sporadic exposures of basement crystallines. The basement is predominantly composed of granite gneiss with minor enclaves of calc-silicate, amphibolite, gabbro, pegmatite and dolerite (dyke)-all belonging to the Precambrian CGC (Figure 2). The gneiss and calc-silicate are regionally

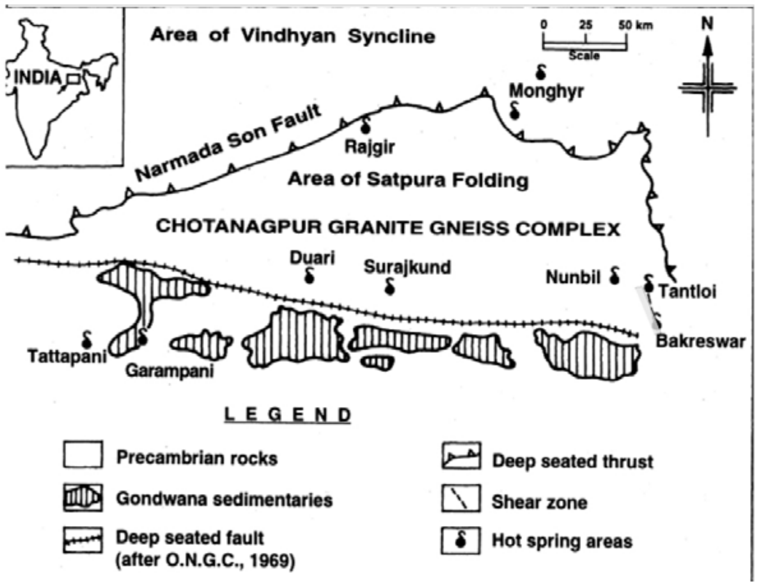

Figure 2. Regional geological setting of the geothermal areas in Eastern India.

folded to form asymmetric to symmetric anticlinal and synclinal structures trending NE-SW (Nagar et al., 1996).

Review of Previous Work:

Several workers have investigated groups of hot springs in these regions from time to time, dealing with their geological mode of occurrence and chemical composition (Mukherjee, 1967), geo-chemistry (Chowdhury et al., 1964), genesis (Deb and Mukherjee, 1969), and natural gases with special reference to helium emanation (Ghose et al., 1994), isotopic composition (Majumdar et al., 1998), and geothermal energy potential (Mukhopadhyay, 1996). Most of the previous works are restricted to surface studies and little is known about the subsurface geology related to the hot water spring activity.

Based on hydrogeology and chemical equilibria, it was suggested that a group of alkaline thermal springs, having varying temperatures (45–71°C) and identical compositions emerges through a nearly N-S trending fault in the gneissic basement (Majumdar et al., 2005). Geoelectric investigations reveal the presence of two to four prominent lithologic layers under prevailing hydrodynamic conditions (Majumdar et al., 2000). Analysis of MT data as a reconnaissance had indicated two low- resistivity zones of thicknesses 2.3 km and 3.4 km at a depth of 8 km and 12 km respectively (Sinha Ray, et al., 2001; Shalivahan, 2004).

Theory and Technique of MT Survey:

MT is a natural source electromagnetic (EM) method in which varying source magnetic field (H) induces an electric field (E) in the earth structure and they are related to each other by the equation:

$$E=ZH \text{ (Cagniard, 1953)}$$

Here Z, the impedance tensor, represents the electrical properties of the subsurface. Entire time series data set is divided into several segments depending upon the frequency of interest and spectral estimates of each segment are calculated by Fourier transform. Impedance tensors for each frequency have been estimated from the measured field vectors using the following equation:

$$Z_{ij}(\omega) = E_i(\omega)/H_j(\omega)$$

Where i and j indicate two mutually perpendicular directions in horizontal plane and 'ω' the angular frequency. Apparent resistivity (ρ_a) and phase (ϕ) are calculated from the values of Z. At a particular frequency, they can be expressed as follows:

$$\rho_{aij} = 0.2/f\,|Z_{ij}|^2$$

$$\phi_{ij} = \tan^{-1} \mathrm{Im}|Z_{ij}|/\mathrm{Re}|Z_{ij}|$$

Depending upon the orientation of measured electric field there are two modes in MT soundings, transverse electric (TE) or E-parallel and transverse magnetic (TM) or E-perpendicular.

Data Acquisition

Using the state-of-the-art digital data acquisition system ADU 06 by Metronix, Germany, 11 stations were occupied for a period of 5 days at each station. The location map of MT sites is shown in Figure 1. The equipment used is a portable system and powered with 12 V battery and incorporates latest electronics. Magnetic field sensors, measuring three orthogonal components (H_x, H_y and H_z) of earth's magnetic field variation, consist of wide band induction magnetometer coils. The electric field sensors are non-polarizing electrodes with $Pb\text{-}PbCl_2$ and are used for measuring two orthogonal components (E_x and E_y) of telluric field. During the recording,

Table 1. Layer Sequences.

Location/Sounding No.	Resistivity (Ohm-m)	Thickness (m)	Depth (m)
Belsara	103	157	157
	8736	3272	3429
	4	1790	5219
	8	2262	7481
	34274	-	-
Kenan	56	92	92
	3793	2740	2832
	6	1711	4543
	67	6383	10926
	12142	-	-
Nakrakonda	91	27	27
	2801	40	67
	78000	29018	29085
	92	9016	38101
	1584	-	-
Kharikabad	10	35	35
	23	26	61
	8677	16906	16967
	27	2894	19861
	90000	-	-
Bhaadi	20	23	23
	467	79	102
	4307	6579	6681
	30	3223	9904
	1731	-	-
Lokpur	30	14	14
	519	173	187
	6472	1878	2065
	7	2068	4133
	2644	-	-
Abadnagar	108	816	816
	1012	1500	2316
	10898	1079	3395
	1	2010	5405
	903	-	-
Shankarpur	5	2	2
	286	73	75
	994	8596	8671
	40	6894	15565
	1740	-	-
Idgachha	11	27	27
	2127	1374	1401
	738	653	2054
	24	4870	6924
	16000	-	-
Rajnagar	2	4	4
	40	1	5
	1227	1551	1556
	3	1443	2999
	1200	-	-
Rasunpur	37	25	25
	233	158	183
	3151	2600	2783
	7	2384	5167
	2953	-	-

the systems were set as synchronous by GPS antennas so that the remote reference algorithm (Gamble et al., 1979) can be used to calculate the impedance tensors.

Data Processing

MT data was processed using MAPROS software provided by Metronix (Matzander and Bernard, 2006). It includes the Fast Fourier components to transfer the data from time domain to frequency domain and is stacked at the prescribed frequencies. $E_x(\omega)$, $E_y(\omega)$, $H_x(\omega)$, $H_y(\omega)$ and $H_z(\omega)$ are stacked. MAPROS software provides mean and standard deviation of all the apparent resistivity and phase from the stacked values to get impedance tensor elements Z_{xx}, Z_{yy}, Z_{xy} and Z_{yx}. Frequency variation of apparent resistivity and phase are obtained in both TE and TM modes. For 1D modeling of MT data, the procedures described by Kunetz, 1972; Jupp & Vozoff, 1975; Marquardt, 1963; Bostick, 1977; Wight and Bostick, 1980; Fisher et al., 1981, employing linearized inversion schemes were followed. The 2D modeling of data was carried out using finite difference scheme of Rodi and Mackie, 2001; Madden and Mackie, 1989 and Jupp & Vozoff, 1977 and inversion module of WinGLink software developed by Geosystem SRL, 2006.

Discussion of Results

The location map of the study area (Figure 1) shows MT soundings (11 nos.) and resistivity traversing (2 nos.). The resistivity/conductivity of rocks is an important parameter for mapping large-scale crustal structures, which may provide a clue on the processes of crustal evolution. Subsurface resistivity distribution will be directly related to the physical characters of the lithological units. Variation in resistivity of the rocks is the main source of electrical anomaly.

1D Model of MT Sounding Data

As a first step of quantitative interpretation of MT sounding curves, 1D modeling was carried out using both Bostick and Occam of WinGLink program to obtain the resistivity and thickness parameters of different layers for each sounding. In general, four/five layer sequences are obtained for most of the MT soundings (Table 1). 1D model of few representatives MT sounding are shown in Figures 3a, 3b and 3c.

Geoelectric Section

Vertical resistivity distribution is shown in Figure 4 using Bostick and Occam 1D model. The highly resistive crystalline layer below the top-soil is estimated as having thickness varying from 1552-29059 m at a depth level varying from surface to 93 m which is the lower crust in the area. The highly conductive layer is clearly brought out below the resistive crystalline rock in all the MT soundings. It is characterized by resistivity ranging from 1-92 Ohm-m and thickness varying from 1443-9016 m as well as depth varying from 1557-29087 m. The conductive layer is interpreted as due to the geothermal activities through some fault/fracture. The high resistive layer is interpreted as due to the thickening of lower crust. This layer comes up to a shallow depth (3001 m) at station Rajnagar whereas the same occurs at a greater depth (38103 m) at Nakrakonda. This steep gradient between stations Rajnagar and Nakrakonda could possibly be attributed to a fault zone. Another fault is inferred due to steep gradient in between Belsara (7484 m) and Nakrakonda (38103 m).

2D Geoelectric Model

The above-mentioned analysis demonstrates that the subsurface electrical structure of the study area can be approximated by 2D characterization. In view of some successful cases of geothermal field exploration (Bai et al., 2001; Harinarayana et al., 2006), 2D inversions are available. 2D inversion schemes can be applied if the MT data validate a two-dimensional structure along the profile (Harinarayana et al., 2006). The MT data were inverted using the inversion method to generate 2D subsurface conductivity distribution in the area. These results are depicted in Figure 5. One prominent high resistivity zone is observed in between Belsara to Bhaadi starting from shallow surface to higher depth. Another high resistivity zone is inferred below Idgachha.

Two prominent faulted boundaries/contacts are depicted in between Bhaadi to Lokpur and Idgachha to Rajnagar respectively. The cross-section also shows a highly conductive feature beneath north of Bhaadi and Idgachha region extending from shallow subsurface (5 km) into the deeper crust. Studies over subducting plates in several parts of the world have revealed similar high conductivity layers (Jones, 1992; Adam, 1980). The high conductivity at lower levels below Lokpur to Idgachha may be attributed to several causative factors. Attempts have been made to explain these deep crustal conductors on the basis of the water percolation through the lineaments/faults/fractures or on the basis of the fluids in open pores, partial melting of the deep crustal rocks, possible serpentinisation in the remnants of the oceanic crusts and grain boundary graphite films. Geothermal studies over northern boundary of the peri-cratonic Bengal basin indicate a high heat flow of about 100 mWm^{-2} (Ravi Shanker, 1988). This high conductivity may have some links with high heat flow in the area. Because the electrical conductivity of the crust mantle silicates has strong dependence on temperature, higher the temperature of the sub–continent higher will be the conductivity. Maximum reported depth of the percolation of water from the surface is about 17 km. However, volatile phases from the mantle viz. C, H, O, N and S can come

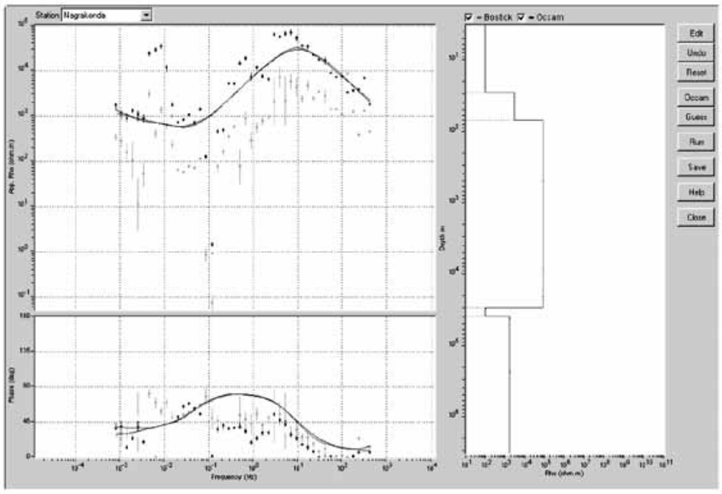

Figure 3a. 1D model of station Nakrakonda.

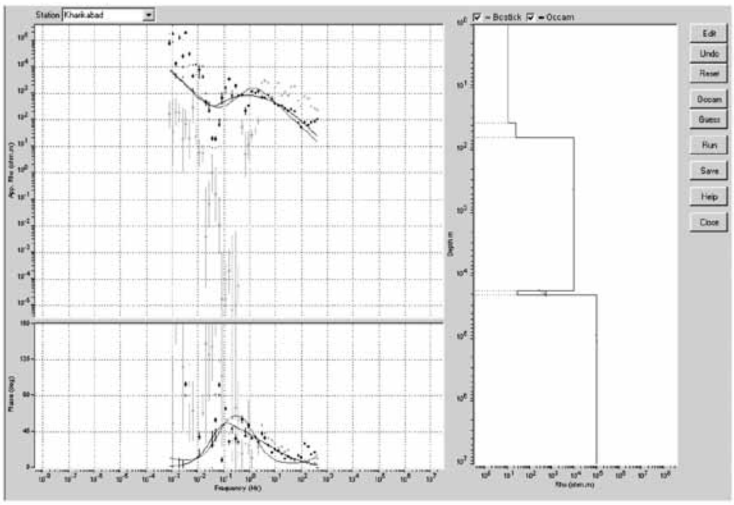

Figure 3b. 1D model of station Kharikabad.

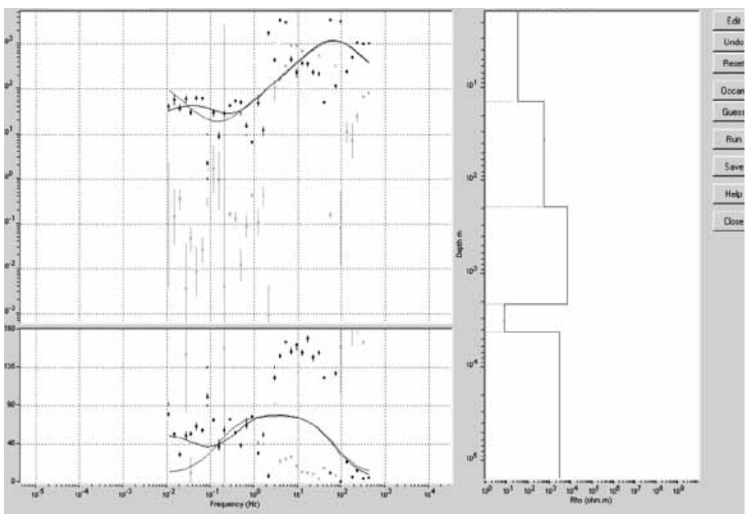

Figure 3c. 1-D inversion model of station Lokpur.

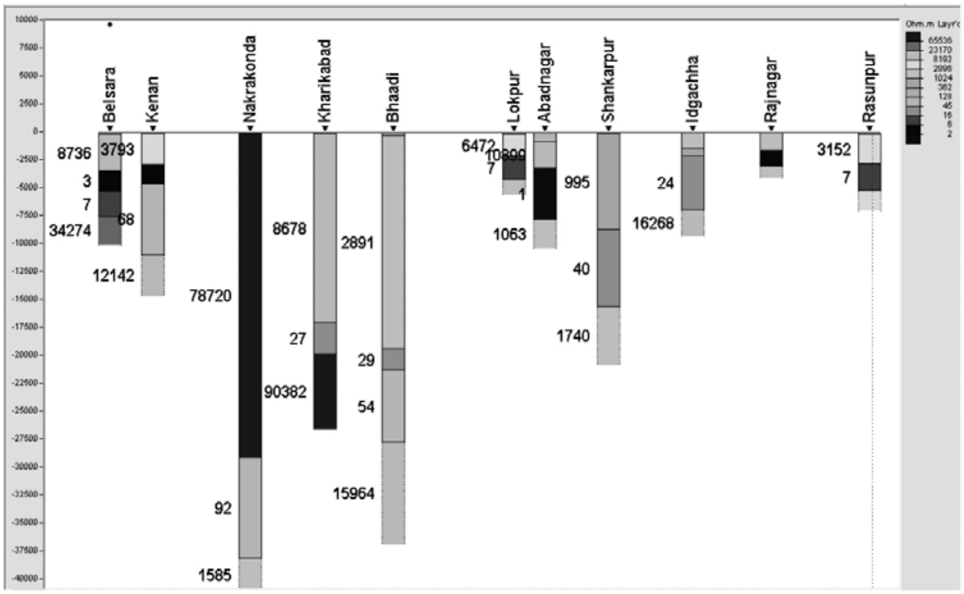

Figure 4. 1-D section along Belsara-Rajnagar-Rasunpur traverse. Vertical scale: (Depth in m; Resistivity values in Ohm-m).

to the lower crustal and upper most mantle level in the form of CO_2, CH_4 and H_2O phases. The lower crust in the entire profile is rather conductive whereas the upper crust in between Rasunpur to Belsara is resistive. It is thus possible that the entire crust may be highly conductive, intruded by high resistivity block.

Theory and Technique of Resistivity Survey

Collinear dipole-dipole array was used for observing the subsurface electrical discontinuities in the profiling mode. This method employs a constant dipole length "a". Increased depth of penetration is achieved by increasing the separation of the transmitting and receiving dipoles at intervals of "n", where n=1, 2, 3… etc. The upper limit of "n" is determined by the maximum depth of interest and signal to noise ratio. If "I" be the current injected and "V" be the potential difference measured, the apparent resistivity is

$$\rho_a = K\, V/I = \pi an(n+1)(n+2)V/I\ ;$$

K is geometric factor for this array configuration

Hallof (1957) introduced the concept of plotting the profiling data over a traverse in the form of vertical pseudo-section in resistivity survey for dipole-dipole array. The apparent resistivity values are plotted at the point of intersection of the 45° lines from the two dipole centre right below the centre of the array.

Data Acquisition

A Scintrex 3 KVA time domain resistivity unit was used for the field survey as a transmitter. The grounded or current sending electrodes were made up of steel stake rod. IPR-10A receiver of the Scintrex make was used for measuring the potential. Non polarisable electrodes (copper in saturated copper sulphate solution) were used as potential electrodes for the survey.

Results of Resistivity Profiling

Dipole-dipole profiling was conducted along two traverses each of length 2 km from Bakreswar-Asanshuli and Tantipara-Chandrapur (Figure 1).

Resistivity Profiling along Bakreswar-Asanshuli Traverse

To delineate the conductive feature in the Bakreswar geothermal region, a geoelectric traverse is laid over a length of 2 km with a=100 m and "na" separation of 1300 m. The resistivity pseudo-section is shown in Figure 6. The average order of apparent resistivity in the alluvial cover varies from 100 Ohm-m in near surface to about 1800 Ohm-m at depth around 700 m (n=13) and beyond. The first layer is characterized by an apparent resistivity of 100 Ohm-m may be representing the top soil in the area which is followed by a layer of apparent resistivity 200 Ohm-m. These are followed by a layer of resistivity 400 Ohm-m which is underlain by a high resistivity layer. Continuous increase in resistivity is observed depth wise throughout the section. One anomalously conductive zone is mapped at n=10 in between 1200-1500 m stations. The actual resistivity of the causative body is expected to be much lower than the contour value of apparent resistivity 100

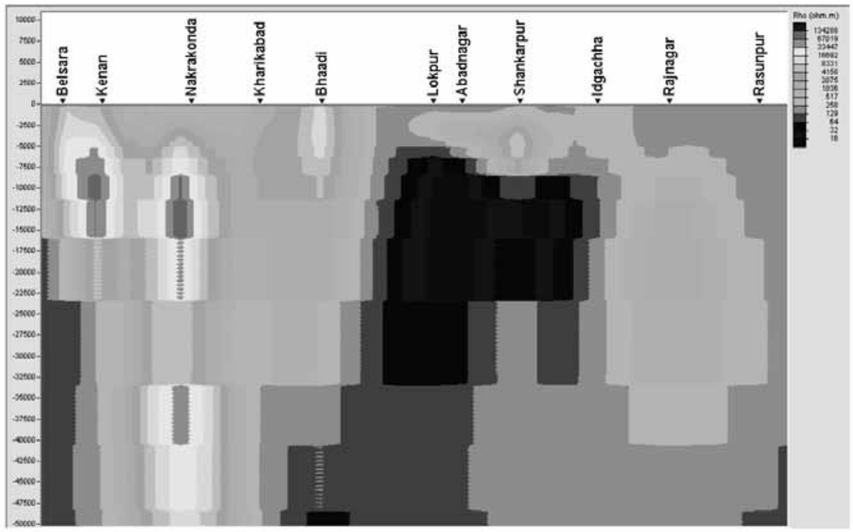

Figure 5. 2-D model along Belsara-Rajnagar-Rasunpur traverse.

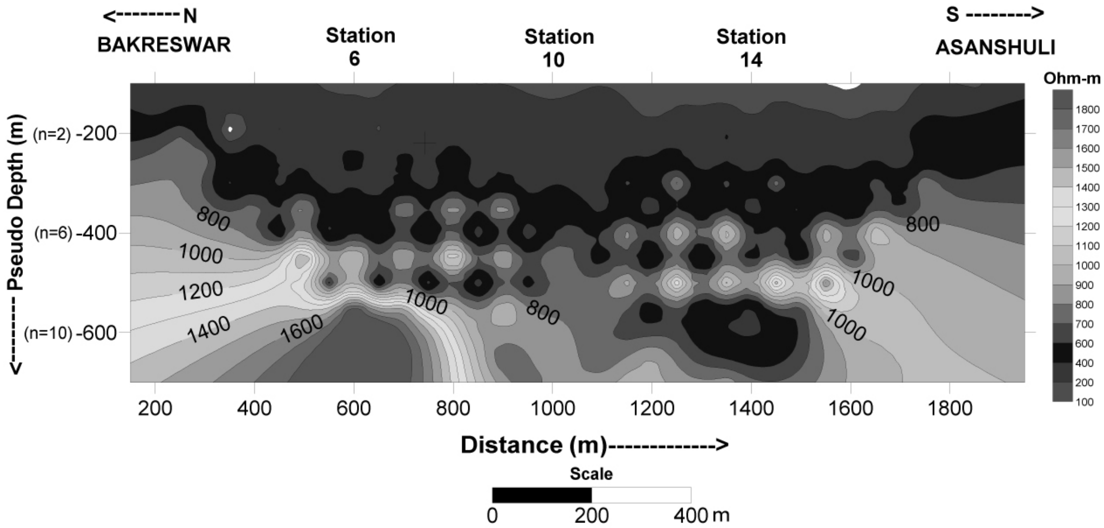

Figure 6. Collinear dipole-dipole resistivity profiling along Bakreswar-Asanshuli traverse.

Ohm-m which defines the source within a resistive host rock (1800 Ohm-m). The actual nature of the causative body is unknown. Bakreswar hot spring lies adjacent to it and geologically it may be the source of hot spring controlled by hidden fault.

Resistivity profiling along Chandrapur-Tantipara traverse

Bakreswar-Tantloi sector was chosen for deep electrical studies primarily to understand the nature of causative source responsible for geothermal activities in this area. A traverse of 2 km length was laid along Chandrapur-Tantipara section and was observed with a dipole length of 100 m with "na" separation of 1600 m. The dipole-dipole pseudo-section brought out a (Figure 7) couple of high resistivity zones, remarkably – two, in between stations 200-1000 m and 1200-2000 m at pseudo depth zones 400-800 m and 500-800 m respectively. The causative source of the first high resistivity zone (depth 400-800 m) might represent dolerite dykes/unaltered granite gneiss. Of particular importance in this traverse is the presence of subsurface conductive bodies (50-400 Ohm-m) mapped between stations 1000-1200 m at a pseudo depth of 400-700 m. This may be due to the structural breaks like shear zones/geothermal region. In view of hot spring activity near around Bakreswar, such subsurface conductors assume greater significance as a geothermal region. First 100 m might represent top soil/laterite cover followed by a conductive layer upto 300 m.

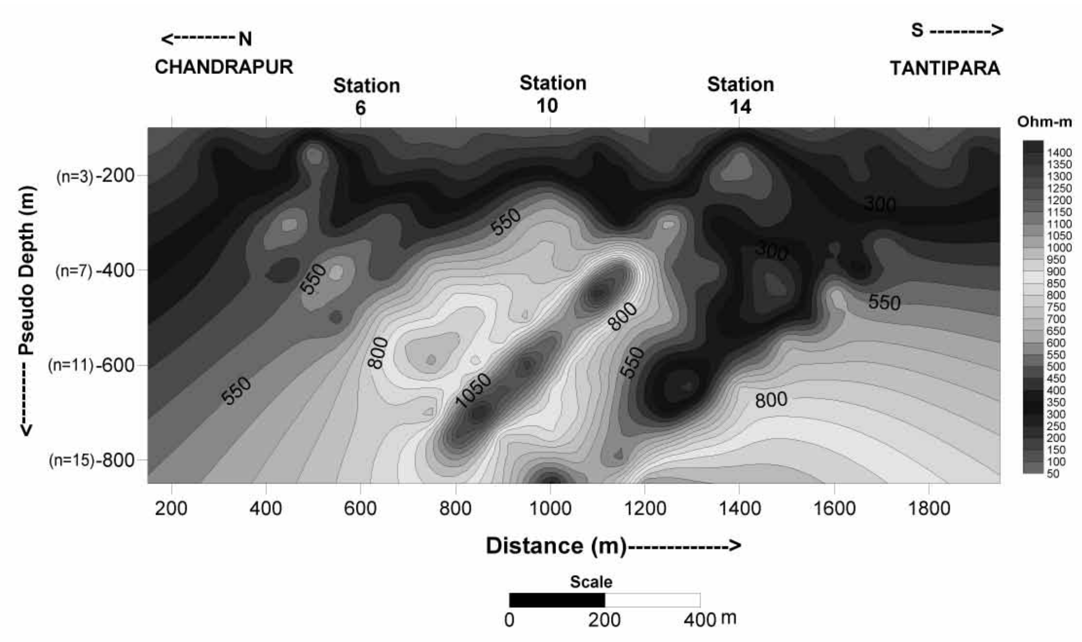

Figure 7. Collinear dipole-dipole profiling along Chandrapur-Tantipara traverse.

CONCLUSION

Geothermal resources are closely related to the conditions of deep structures. The MT method, which is one appropriate method for solving deep geologic problems, has unique advantages. The 2D images meaningfully depict the geothermal structure in the area. The fault activities and magma intrusion may result in the fractures of the lower crust/basement, which are filled with hot water and thus produce the relatively low resistivity (1-92 Ohm-m). MT method may be applied in assessing identified geothermal systems, in which the recoverable heat is estimated from the thermal energy available in a reservoir. Results of resistivity survey indicate the presence of subsurface conductive bodies due to structural breaks like shear zones/ geothermal region. In view of hot spring activities in nearby area of Bakreswar, such subsurface conductors assume greater significance as a geothermal region.

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Compliance with Ethical Standards

The author declares that he has no conflict of interest and adheres to copyright norms.

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