Geoelectric investigations in Bakreswar geothermal area, West Bengal, India

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Abstract

A cluster of hot springs in Bakreswar geothermal area, which belongs to the Chotanagpur Gneissic Complex in the eastern part of Peninsular India, is characterised by varying temperature and similar chemical composition.

Vertical electrical sounding (VES) investigations in and around Bakreswar reveal the presence of two to four prominent lithologic layers under prevailing hydrodynamic conditions. The intermediate weathered zone and the fractured rocks constitute a single aquifer system of varied hydraulic conductivity under water table condition. Lithology and groundwater conditions, as inferred from the VES, as well as hydrological studies, are in agreement with the nearby bore hole lithologs. Water table contours accompanied by VES findings of the region indicate that the occurrence and movement of groundwater take place mostly within the weathered and fractured rocks under unconfined condition. 1D interpretation of VES results reveals few promising groundwater potential zones in the eastern part of the region. Wenner resistivity profiling, coupled with VES and geological studies, indicates the presence of a nearly N–S striking buried fault providing passage for hot water to emerge in the form of springs. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Hot spring; VES; Resistivity profile; Aquifer; Fault

1. Introduction

Bakreswar geothermal area (23°52′48″ N: 87°22′40″ E) is one of the few groups of geothermal areas in the Chotanagpur Granite Gneiss Plateau of the eastern part of the Indian Peninsular Shield (Fig. 1). The geothermal areas in the terrain are characterised by surfacial manifestation of a cluster of springs with varied temperatures (35–88°C) and similar chemical compositions (Deb and Mukherjee, 1969). The springs mostly issue out of fractures in a reactivated composite mass comprising predominantly granitic rocks (Precambrian) with an E–W belt of sparsely occurring sedimentary outliers of Gondwana formation (Lower Permian to Middle Jurassic).

Several workers have investigated Bakreswar group of hot springs from time to time, dealing with their geological mode of occurrence and chemical composition (Ghosh, 1948; Mukherjee, 1967), geochemistry (Chowdhiury et al., 1964), genesis (Chaterji and Guha, 1968; Deb and Mukherjee, 1969), natural gases with special reference to helium emanation (Chatterjee, 1972; Ghose and Chatterjee, 1980; Ghose et al., 1989, 1994), isotopic composition (Ghose and
Fig. 1. Schematic setting of hot springs in Eastern India (after Gupta et al., 1976; ONGC, 1969).

Chatterjee, 1978; Majumdar et al., 1998) and geothermal energy potential (Mukherjee, 1982; Majumdar et al., 1992; Mukhopadhyay, 1996).

Most of the previous works are restricted to surficial studies and little is known about the subsurface geology related to the hot spring activity. On the basis of geophysical magnetic and electrical studies done by the Atomic Minerals Division (Calcutta) in the Bakreswar geothermal area, Nagar et al. (1996) have suggested the presence of a N–S trending fault extending for about 2 km in this area. Details of their investigations are not, however, published.

The weathered and fractured rocks present a good resistivity contrast with compact basement crystallines, and the structures, such as joint, fault, dyke, etc., in a geological terrain impose marked anomalies on the resistivity profiles. Hence, electrical resistivity investigations involving Schlumberger sounding and Wenner profiling are carried out in and around the Bakreswar geothermal area in conjunction with geological studies to (1) identify various lithologic layers for examining the nature of aquifer systems, (2) probe into the hydrology of the springs, and (3) detect the possible major fault zone or buried fractures leading to the hot water emergence in the form of springs.

2. Tectonic set-up and general geology

The eastern part of the Peninsular India including the study area has been subjected to different cycles of plate movements with intervening periods of isostatic readjustments during Precambrian (Sarkar, 1982) to Cenozoic times (Dunn, 1939, 1941; Ghosh, 1948; Desikachar, 1974; Ravi Shanker, 1991). The occurrence of several groups of hot springs in the Chotanagpur plateau can be ascribed to deep circulation of meteoric water along the major fractures that have been newly created or reactivated in the basement crystallines in response to tectonic disturbances in the terrain (Deb and Mukherjee, 1969).

The Bakreswar group of hot springs (44.5–71°C) are located in a topographic low in a slightly undulated terrain, which is mostly mantled by alluvial or lateritic soil with sporadic exposures of basement...
crystallines (Fig. 2). The basement is predominantly constituted of granite gneiss with minor enclaves of amphibolite and pegmatite, and dykes of dolerite or metadolerite cropping out at places. The rocks belong to Chotanagpur Granite Gneiss Complex (Precambrian).

The granite gneiss is regionally folded to form a major anticlinal structure trending NE–SW. The dolerite dykes appear to be emplaced mostly along the tensile fractures developed parallel to the axial plane of the fold. The basement rocks are intersected by four sets of vertical to subvertical joint trending NW–SE (most prominent and open type), NE–SW, N–S and ENE–WSW. The most striking structural feature of the area is a N–S trending weak zone marked by repeated silicification and brecciation. It is traceable over 1.4 km from Gohaliara to Tantipara and further north. The zone disappears about 1.5 km north.

Fig. 2. Geological context of Bakreswar geothermal area modified after Nagar et al., 1996.
north of Bakreswar and is no longer exposed at or near the spring site, not even to its south. From a consideration of the trends of silicified zone, fold axis, joint planes and alignment of seven springs in the geothermal area, it is suspected that the emergence of hot water and gases is controlled by intersecting fractures trending N–S and NW–SE, as well as NE–SW.

3. Geoelectric resistivity investigations

As a part of ground reconnaissance survey, geoelectric resistivity studies have wide applications in hydrogeological and geothermal field investigations (Arora, 1986; Ilkisik et al., 1997; Monteiro Santos et al., 1997a,b; Raju and Reddy, 1998; Yadav and Abolfazli, 1998).

A Schlumberger vertical electrical sounding (VES) study in and around Bakreswar geothermal area is aimed at ascertaining the vertical distribution of water-bearing zones, constituting the aquifer bodies in the region. Alongside, Wenner resistivity profiling investigation is carried out to delineate major subsurface fractures and fault, and reconcile them with the distribution of the Bakreswar springs.

3.1. VES methodology

The VES study is conducted at 20 locations in and around Bakreswar, with a maximum electrode spacing of 440 m (Fig. 3). The field data, so obtained, are interpreted by 1D inversion technique. For this purpose, a computer software viz. GEOELINV.EXE (Christensen et al., 1993) is used. Preliminary values of the model parameters, as obtained by manually matching the VES field curves with the theoretical master curves and auxiliary point charts, are subsequently used as input (starting model) in GEOELINV.EXE for further refinement of results by 1D inversion algorithm. The degree of uncertainty of the computed model parameters and the goodness of fit in the curve fitting algorithm are expressed in terms of standard deviation and residual error, respectively. The resistivity of different layers and the corresponding thickness are reproduced by a number of iterations until the model parameters of all the VES curves are totally resolved with minimum standard deviation and residual error. Analysis of the model parameters is exemplified with two VES results in Table 1, which justifies the acceptability of the final results. The nature of field data for seven VES points, viz. R3, R5, R6, R8, R9, R17 and R18, indicates the influence of 2D or 3D effects due to near-surface inhomogeneities/lateral contacts, such as joint/fracture zone, dyke, vein, fault or shear zone. This is also obvious from the structural condition of the region (Fig. 2), as well as from the Wenner profiles (Fig. 9). Such lateral inhomogeneities often give rise to very thin and low resistive false layers in VES curves, which are likely to be misinterpreted as water-bearing zones at depth (Ballukraya, 1996). Monteiro Santos et al. (1997a) have argued that under such complex situations, 1D interpretation is not always able to properly present a realistic resistivity model because of the high degree of misfit between field data and model response. Therefore, 1D interpretation for these data is done by omitting the artificial layers, i.e. by truncating the data up to the acceptable limit. The behaviour of four VES curves, viz. R3, R5, R6 and R18, is, however, documented in Fig. 4a,b by showing the full data and the truncated data.

1D inversion reserves its importance and utility, as the interpreted model parameters can serve as starting models for 2D and 3D approaches for better approximation of the subsurface geology of an area. In such cases, 1D interpretation is usually found to be fairly consistent with those observed in 2D and 3D inversions (Monteiro Santos et al., 1997a,b; Olayinka and Weller, 1997).

The results of VES and electrical profilings are interpreted in terms of subsurface geology and aquifer characteristics under prevailing hydrodynamic conditions.

3.1.1. Observations

Inversion results for all the 20 VES points are interpreted and subsequently correlated to resolve the lithological conditions in Bakreswar and its adjoining areas.

The nature and distribution of different lithologic layers as represented by depth-wise variation of resistivity values are illustrated in a fence diagram to
Fig. 3. Locations of geoelectric resistivity investigations and bore holes: VES (Schlumberger) and profiles (Wenner).

show the existing hydrogeological environment in the region (Fig. 5). It reveals the presence of two to four prominent layers. The first layer is always constituted of soil. The second layer may be the compact basement or the water-saturated weathered or fracture zone. The third layer, as found in 12 VES results, is the crystalline basement. In some cases (three VES points), the water-saturated fractured rocks form the third layer (i.e., fracture zone) beneath the weathered zone; below it lies the compact resis-

Table 1
Analysis of the model parameters for VES R3 and R16 as done using the computer program GEOELINV.EXE of Christensen et al. (1993)

<table>
<thead>
<tr>
<th>VES</th>
<th>Layer no.</th>
<th>Resistivity</th>
<th>Dev.</th>
<th>Thickness</th>
<th>Dev.</th>
<th>Depth</th>
<th>Dev.</th>
<th>Total residual</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Data</td>
<td>Parameters</td>
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<tr>
<td>R3</td>
<td>1</td>
<td>76.7</td>
<td>0.24</td>
<td>1.6</td>
<td>0.76</td>
<td>1.6</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>55.0</td>
<td>0.06</td>
<td>18.2</td>
<td>0.18</td>
<td>19.8</td>
<td>0.12</td>
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<tr>
<td></td>
<td>3</td>
<td>3612.8</td>
<td>2.04</td>
<td>0.1919</td>
<td>0.0000</td>
<td>0.1919</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R16</td>
<td>1</td>
<td>102.5</td>
<td>0.04</td>
<td>5.2</td>
<td>0.35</td>
<td>5.2</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>217.9</td>
<td>0.34</td>
<td>16.0</td>
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<td>0.23</td>
<td></td>
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<td>3</td>
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<td>0.58</td>
<td>0.4513</td>
<td>0.0000</td>
<td>0.4513</td>
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<td></td>
</tr>
</tbody>
</table>

*Dev.* is the relative uncertainty of the model parameters.
Fig. 4. Documentation of behaviour of VES data and model curves with lithological interpretation: (a) for locations R3, R5 and R6, and (b) for R14, R16 and R18. AB/2 = half current electrode spacing. Error bars are for the apparent resistivity values given as input in GEOELINV.EXE for a series of specified values of AB/2.
Fig. 5. Fence diagram constructed from VES interpretation shows lithological characteristics in Bakreswar and its surrounding areas.

The lithological conditions as conceived from the fence diagram (Fig. 5) are summarised in three concise models (Fig. 6).

In all the cases, the top-most layer is composed of alluvial or lateritic soil with low to moderate thickness. The first model (Fig. 6a) shows a two-layer case, where the compact basement lies immediately below the soil cover at depths ranging from 4.6 to 7.4 m. In two cases, i.e. R6 and R19, the weathered or the fracture zone occurs at depths of 7.5 and 8.5 m, respectively, and is suspected to extend to a deeper level. Here, the hard basement is not found from the VES results, as these sounding points lie on the downthrown side, as well as close to the disturbed zone of the fault. The second model exhibits a three-layer case (Fig. 6b), where the weathered or the fracture zone (2nd layer) forms an unconfined aquifer overlying the compact basement. These water-bearing zones show a wide variation in thickness and depth of occurrence. The fracture zone is notably thicker than the weathered profile. Basement crystallines are encountered in the depth range of 7.4–44.1 m. In the third model, i.e. four-layer case (Fig. 6c), the weathered zone, in combination with the fractured basement (i.e. fracture zone) lying immediately below, chiefly constitutes the unconfined aquifer system with moderate to appreciably high thickness. Here, depth of compact basement ranges from 24.7 to 69.9 m.

Therefore, the three simple models are useful for prediction of the hydrogeological environment of Bakreswar and its surrounding areas in terms of lithological characteristics.
Fig. 6. Proposed models of subsurface lithological divisions in and around Bakreswar geothermal area (summarised from Fig. 5 and VES results).
Fig. 7. Resistivity contours drawn from VES results for four different depth levels: (a) 2, (b) 5, (c) 10 and (d) 40 m. Contour values are in ohm-meter.
3.1.2. Resistivity contour

Resistivity contours for 2, 5, 10 and 40 m depth levels are drawn to examine the variation in resistivity at the respective depths due to subsurface anisotropy. Contours are drawn by ‘inverse distance’ gridding method that uses a weighted averaging technique to interpolate grid nodes from the XYZ data; X and Y are the cartesian coordinates of a location in a map, and Z is the parameter studied (i.e. resistivity). The method can be used for irregularly spaced data as in the present case. Resistivity contours for various depths fairly represent the subsurface lithological variation under the existing hydrological condition (Fig. 7). Contours for 2-m depth level shows mostly low resistivity values (< 25 Ω m) of the topsoil composed of alluvial sediments, laterite, silty clay and clay (Fig. 7a). At a depth of 5 m, the contours are mostly in the range of 25–100 Ω m (Fig. 7b). It is interesting to note that low resistivity contours (25–50 Ω m) pass through the silicified zone, the hot spring area and the adjacent Bakreswar stream (in Fig. 3), indicating availability of groundwater at this depth. Contour pattern for 10-m depth level (Fig. 7c) shows gradual rise in the resistivity values, thereby indicating the increasing effect of basement rocks. However, some low resistivity contours (25–100 Ω m) are found in the northeastern and southeastern parts of the area around the VES points R2, R3, R6, R7, R13, R14 and R20. Fig. 7d shows a sudden rise in resistivity values at 40-m depth, implying the effect of resistive basement at this depth level. Low resistivity contours (100–200 Ω m) still persist near the VES points R2 and R14. Such low values account for the groundwater potentiality of weathered and fractured rocks in some restricted zones even at 10- and 40-m depths.

3.2. Bore hole lithology

Lithologs of four bore holes, viz. BH-1, BH-2, BH-3 and BH-4, sunk by PHED (1990, 1993) in and around the Bakreswar geothermal area are shown in Fig. 8 and their locations are also marked in Fig. 3. In all the bore holes, the fractured basement is encountered at depths ranging from 4 to 7.3 m. Litholog of BH-1 drilled down to a depth of 40.5 m at Gohaliara shows the succession of a 4.26-m-thick layer of sticky clay at the top, followed by weathered zone of thickness 3 m, granite gneiss (27 m) and dolerite downwards (Fig. 8a). Test yields at 15.5- and 35-m depths are 0.227 and 0.454 m³/h, respectively, thereby indicating the presence of water-bearing fractures in the basement gneiss. Interpretation of VES result of the nearby location R2 in Fig. 3 also qualitatively accords with the original subsurface field condition. The bore hole BH-2, drilled down to 37.5 m slightly off the silicified zone

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<table>
<thead>
<tr>
<th>DEPTH (m)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>Soil/ Sticky clay</td>
</tr>
<tr>
<td>5-10</td>
<td>Weathered zone</td>
</tr>
<tr>
<td>10-15</td>
<td>Granite gneiss</td>
</tr>
<tr>
<td>15-20</td>
<td>Dolerite</td>
</tr>
<tr>
<td>20-30</td>
<td>Water-bearing rock fractures</td>
</tr>
</tbody>
</table>

Fig. 8. Lithologs of four bore holes: BH-1, BH-2, BH-3 and BH-4 (see Fig. 3 for bore hole sites).
adjacent to Gohaliara, exposes a sequence of soil cover (8.5 m) succeeded by weathered zone (2.13 m) and granite gneiss having yield prospects of 0.908 and 1.362 m³/h at depths of 12.12 and 30 m, respectively (Fig. 8b). Higher yield from greater depth indicates considerable fracture permeability in the gneissic basement. VES result of R1 near the silicified zone (see Fig. 3) approximates the bore hole data and indicates the presence of water-bearing fractures in the crystalline basement. At Bakreswar, litholog of the 40-m-deep bore hole BH-3 exhibits a downward succession of soil (1.2 m), weathered zone (2.8 m) and dolerite capable of yielding 1.362 and 1.816 m³/h of groundwater from 14 and 27 m.

Fig. 9. Wenner apparent resistivity responses along five profiles for 20- and 30-m array spacings (see Fig. 3 for locations).
depths, respectively (Fig. 8c). The lithological conditions revealed by the bore hole corroborate the result of nearby VES investigation at R13 (Fig. 3). Litholog of BH-4 at Haridaspur lying southwest of Bakreswar, as shown in Fig. 3, exhibits a succession of soil (2.12 m), weathered zone (2.12 m) and dolerite downwards (Fig. 8d). Here, basement fractures are encountered at very shallow depth (4.24 m) with a low yield potential (0.227 m³/h at 14.5-m depth). The litholog of this bore hole testifies to the result of nearby VES point R16 (in Fig. 3), which shows comparatively high resistivity of the fractured basement, as well as poor groundwater condition in the subsurface layer. Wenner curve of the profile P-5 near this bore hole also shows high resistivity values, indicating the presence of basement rocks at shallow depth (Fig. 9).

The bore hole lithologs reveal that groundwater occurs mostly in the fracture zones, and to some extent, within the overlying weathered rocks occurring at shallow depth and, thus, they significantly substantiate the VES findings as regards lithology, occurrence and distribution of weathered, as well as fractured rocks, and their groundwater potentiality.

3.3. Resistivity profiling

Five Wenner resistivity profiles, viz. P-1, P-2, P-3, P-4 and P-5, are taken along E–W direction for array spacings of 20 and 30 m at intervals of 20 and 30 m, respectively (Fig. 3). Resistivity responses along the different profiles are shown in Fig. 9. Profile P-1 is taken for 30-m array spacing across the N–S trending exposed silicified zone between Gohaliara and Tantipara lying north of Bakreswar. The noteworthy feature of the Wenner curve is that the resistivity value drops just over the exposures of the silicified rocks, indicating the conductive nature of the otherwise highly resistive silicified zone. It is possibly due to water content in the fractures of the sheared and jointed silicified zone. Good water yields in the dug wells and tube wells constructed at few places along this tract lend support to this observation.

In profiles P-2 and P-3, high and low values of resistivity response are observed. In profile P-2, a resistivity high is noticed over VES point R4 for both the spacing of 20 and 30 m. This ‘high’ may be associated with any structural feature, such as dyke.

In profile P-4, the western part of the Wenner curve for 30 m spacing shows a characteristically low resistivity value (near R10 in Fig. 9), which can be attributed to the incursion of water from the adjacent Bakreswar stream into the fractures of gneissic basement. What is interesting in the eastern part of the curve is that the resistivity response falls abruptly to 1.8 Ω m (repeatedly checked) from the preceding value of 125 Ω m at a point about 230 m east of the southerly flowing streamlet that merges into the Bakreswar stream to the northeast of spring site. Such feature is, however, lacking in the curve of 20-m spacing. It follows that the very low value in resistivity response is probably due to 3D effects.
In profile P-5, taken about 200 m south of the spring site, overall resistivity value for 30-m spacing is higher than that of 20-m spacing. Resistivity response is clearly higher in its western part than that of the eastern part, presumably due to the existence of highly resistive dolerite intrusive under the soil cover. Results of VES at R16 and litholog of nearby BH-4 altogether confirm the occurrence of dolerite at shallow depth. The resistivity responses in most of the profiles for 20-m array spacing show a number of peaks with varying magnitude, indicating a high degree of lithological inhomogeneity even at shallow depth.

3.3.1. Apparent resistivity contour

Taking the apparent resistivity values of the five profiles for 30-m array spacing, a contour diagram is drawn for better comprehension of the lateral subsoil...
face discontinuity in the basement (Fig. 10). The contours are mostly extended along N–S direction and the resistivity decreases towards the eastern part of the area.

Near the central part of the area, a N–S trending linear tract encompassing the sheared silicified zone and the spring site (lying further south) can be discerned from the contour pattern ($\sim 125–150 \ \Omega \text{m}$). The area lying on the east of this tract shows low resistivity values, as compared to the area to the west, thereby indicating variation in overburden thickness on the two sides of the tract. Moreover, geological traverse along several profiles in an E–W direction across this linear zone reveals the thickening of the overlying sediments towards the east. It is evident from the VES results and the nature of the profile curves that the basement rocks occur at greater depth in the eastern part of the area than in the western part. Relying on the presence of a brecciated silicified zone and variation in the depth of basement, as revealed from geoelectric and geological investigations, a nearly N–S trending buried fault with the downthrown block in the east is strongly suspected.

4. Hydrology of the geothermal area

For a better understanding of the hydrology of Bakreswar geothermal area, geological and geophysical investigations, coupled with bore hole inventory, are carried out. It is revealed that the occurrence and movement of shallow non-thermal groundwater take place mostly in the weathered and fractured rocks, constituting a single aquifer system in the area. Groundwater occurs in water table condition unconfined state. Water table condition in Bakreswar and the surrounding villages is studied from the inventory of several dugwells in March 1997. For the purpose, dumpy level survey is done in this region. Water table contour pattern generated from those dugwell data indicates varying hydraulic conductivity of the heterogeneous aquifer system (Fig. 11). Hydraulic gradients are mostly towards the spring site from the relatively high topographic areas in the north, northeast and southwest, suggesting thereby, mixing of non-thermal groundwater with deep-seated hot water.

A comparative study of thermal and chemical behaviours of the hot springs and the non-thermal groundwater of the adjoining localities by Mukherjee and Majumdar (1999) and isotopic signatures, viz. $\delta^{18}\text{O}$, $\delta^2\text{H}$ and tritium contents of surface water, non-thermal groundwater, as well as hot spring water (Majumdar et al., 1998), however, indicate insignificant mixing of spring water with non-thermal groundwater at the spring site. Orifices of spring discharge are restricted in nature, being controlled by fractures within the shallow basement crystallines. From geological and geoelectric investigations, it can be inferred that a nearly N–S trending buried fault zone provides the major outlets for the emergence of hot water. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ contents of spring water bear resemblance with those of local meteoric water, even though its tritium content is remarkably lower than in local meteoric water. From such observations, it can be reasonably inferred that circulation of meteoric water along deep-seated active fractures augments its temperature, which, under suitable hydrogeological conditions, emerges as hot springs.

5. Conclusions

The geoelectric investigations, coupled with geological and hydrogeological studies, reveal the following characteristics of the Bakreswar geothermal area and the adjoining areas in relation to geological setting, aquifer condition and groundwater movement.

(1) The area of investigations consists of two to four prominent lithologic layers; the bottom-most layer is the compact basement crystallines (predominantly granite gneiss) having mostly high resistivity. Groundwater is mainly confined in the intermediate weathered and fracture zones (fractured basement), forming an unconfined aquifer system. The groundwater conditions of the region, as discerned from the VES study, significantly correspond with the bore hole data.

(2) VES findings unearth few promising groundwater-bearing zones of appreciably high thickness at northeastern (R2) and southeastern part (R14) of the region. These zones can be tapped for sufficient water to combat acute water scarcity in the area.
(3) Resistivity profiling and sounding results indicate the presence of a nearly N–S trending buried fault with downthrown block in the east. Surface manifestation of the fault is represented by a zone of repeated brecciation and silicification about 1.5 km north of the Bakreswar geothermal area.

(4) Springs are fracture-controlled and located in the disturbed zone of the fault.

(5) Water table contour configuration in and around Bakreswar shows a wide variation in hydraulic conductivity of the aquifer due to varied lithological conditions. Convergence of hydraulic gradients towards the spring site is suggestive of mixing of shallow non-thermal groundwater with deep-seated hot water. But temperature behaviour and contrasting tritium contents of the groundwater and the spring water indicate insignificant participation of the former in the spring site.

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