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Exploration of geothermal structure in Puga geothermal field, Ladakh Himalayas, India by magnetotelluric studies

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Abstract

To understand the crustal electric structure of the Puga geothermal field located in the Ladakh Himalayas, wide band (1000 Hz–0.001 Hz) magnetotelluric (MT) study have been carried out in the Puga area. Thirty-five MT sites were occupied with site spacing varying from 0.4 to 1 km. The measurements were carried out along three profiles oriented in east–west direction. After the preliminary analysis, the MT data were subjected to decomposition techniques. The one-dimensional inversion of the effective impedance data and the two-dimensional inversion of the TE (transverse electric) and TM (transverse magnetic) data confirm the presence of low resistive (5–25 Ω m) near surface region of 200–300 m thick in the anomalous geothermal part of the area related to the shallow geothermal reservoir. Additionally, the present study delineated an anomalous conductive zone (resistivity less than 10 Ω m) at a depth of about 2 km which is possibly related to the geothermal source in the area. A highly resistive basement layer separates the surface low resistive region and anomalous conductive part. The estimated minimum temperature at the top of conductive part is about 250 °C. The significance of the deeper conductive zone and its relation to the geothermal anomaly in the area is discussed.

Keywords: Magnetotellurics; Geothermal; Puga; Himalaya; Resistivity

1. Introduction

The Puga geothermal field, located in the northwestern part of Himalayas, is recognized as the most promising area among the various geothermal zones identified in the Indian Sub-continent. It forms a part of the Himalayan geothermal belt, located in the southeastern part of Ladakh district, Jammu and Kashmir state in India, at an altitude of about 4400 m. The Puga valley is surrounded by hills rising up to an altitude of about 6000 m, forming the Puga region as a valley. The 15 km long and about 1 km wide valley trends nearly east–west in direction between Sumdo village in the east and Polokongka La in the

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west. This area, positioned just south to the Indus Suture Zone, has hot springs with surface flow temperatures up to 84 °C (the boiling point of water at that altitude). Borax and sulfur, which are genetically connected with thermal fluids, occur widely in the eastern part of the valley. The valley appears to be a down faulted block with its northern and southern faults concealed under the valley material (Ravishanker et al., 1976). It consists of recent to sub-recent deposits of glacial moraines, eolian sand, clay and scree.

Geophysical exploration studies were initiated in early 1970s, mainly employing shallow resistivity surveys (Arora et al., 1983), to understand the geothermal characteristics and resources in the area. These experiments as well as geological and geochemical investigations could successfully establish the existence of a geothermal anomaly and the presence of shallow reservoir features. The results from the shallow resistivity studies (Gupta et al., 1975; Singh et al., 1983; Mishra et al., 1996) could throw light in to the shallow subsurface (upper 500 m) structure. The other geophysical techniques like gravity, magnetic, self-potential studies, and shallow seismic refraction also provided valuable information about the shallow geothermal zone. The earlier magnetotelluric survey carried out (Singh and Nabetani, 1995) provided qualitative information with limited narrow banded data and limited quantitative result due to noisy electric field data. Although previous studies yielded valuable information about the shallow structure of the region, deep structure of the region is poorly studied. Shallow boreholes (<200 m) were also drilled to understand the subsurface geothermal conditions in the area and the attempts to drill a deeper borehole failed due to technical problems. Thermal logging studies from these shallow boreholes and also from the available single deep borehole (384.7 m) indicated temperature gradients ranging from 0.4 °C/m to 4 °C/m (Gupta et al., 1974). In the absence of information from the deeper parts, it is difficult to estimate the possible exploitation of geothermal resources in the area for direct or indirect use. In this context, it is very important to use an efficient geophysical methodology to explore deeper parts of the geothermal field.

Since temperature and permeability are some of the parameters controlling electrical resistivity (Arps, 1953), electromagnetic and electrical methods can provide a model of the subsurface relating changes in the resistivity to changes in both lithology and temperature. Magnetotelluric (MT), a deep geophysical technique, is widely being used for the assessment of geothermal areas in many regions (Sandberg and Hohmann, 1982; Wannamaker, 1997; Bai et al., 2001). Due to its lateral resolution and also greater depth penetration, MT can give valuable information about the characteristics of geothermal structures and for further utilization of available geothermal resources. In this paper, we describe the magnetotelluric survey conducted in Puga geothermal area to image the subsurface with the main objective of locating subsurface structures related to geothermal resources in the area.

2. Geological setting of Puga

The Puga area is located to the south of Indus Suture Zone (ISZ) along which the Indian and Eurasian plate collide. It is believed to be a major crustal subduction zone with the discovery of blue schist facies from its basic rocks by Virdi et al. (1977). This zone was subjected to intense tectonic activity and this has reflected in the basic to ultrabasic, plutonic to submarine volcanism of the Cretaceous age (ophiolites) and several phases of wide spread acid igneous activity from the Upper Cretaceous to Upper Tertiary. The ophiolite suite of rocks seen along the Indus suture zone represents the remnants of the uplifted wedge of the oceanic crust.

Three distinct tectonic belts separate the area around the Puga geothermal field in the upper Indus valley (Fig. 1). Northern tectonic belt comprises of sedimentary rocks belonging to Indus group and lie unconformably over the Ladakh Granites. The central belt, described as the 'Indus SutureZone' in the literature, is characterized by a large thickness of basic, ultrabasic and sedimentary rocks belonging to Sumdo group. This belt is bounded by the Mahe fault in the north and Zildat fault in the south. The southern belt consists of thick succession of sedimentaries, metasedimentaries and metamorphics with intruded granites. The general direction of tectonic transport and intensity of metamorphism increases from north to south as a result of which rocks exposed in the southern belt

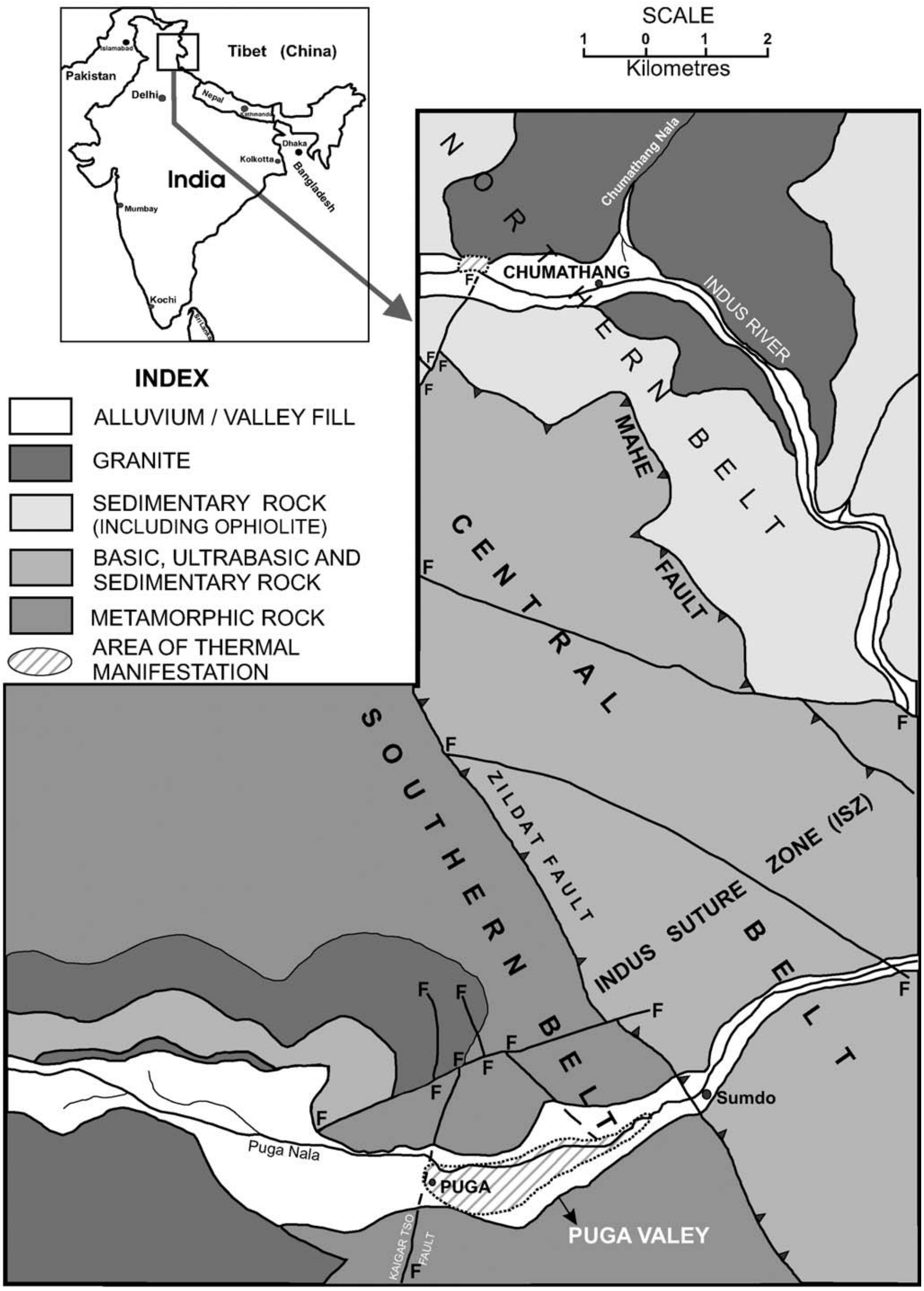

Fig. 1. Geological map of Puga and adjacent areas showing the major geologic and tectonic features.

are highly deformed and exhibit medium to high-grade metamorphism.

The Puga Valley is part of the central tectonic belt, characterized by the volcanic sedimentary assemblages of rock type belonging to the Sumdo group, bounded by prominent faults. These faults act as a conduit for transportation of the hot water from deeper levels. The Puga valley is covered by the recent and subrecent deposits such as glacial moraines, eolian sand and scree, which are encrusted with borax, sulfur and other hotspring deposits. This loose valley-fill material extends to subsurface up to 15–65 m depth. There after, the hard re-consolidated breccia lies and extends up to the depth of the basement. The basement rock consists of paragneisses and schists and known as Puga Formation probably belonging to Paleozoic age (Raina et al., 1963; Baweja, 1968). The basement is intruded by Polokongka La granite in the west. In the east, the Sumdo formations are exposed. The thermal manifestations are confined to eastern part of the 15 km valley and are broadly aligned along the faulted crest of an anticline in the Puga formation. To the west of the area of thermal manifestations, a regional fault crosses the valley. This fault (Kaigar Tso fault) broadly delimits the thermally anomalous area on the western side. Zildat fault (Fig. 1) seems to be eastern limit of the thermal manifestations. Along the base of the northern hills in the central portion of the valley, sulfur condensates are found and it probably represent an old line of fumarolic activity along a hidden fault (?) (Ravishanker et al., 1976).

3. Previous geophysical studies

Various geo-scientific investigations carried out in Puga valley since 1970. These geological, geophysical and geochemical studies were limited to the shallow part of the anomalous region. The surface heat flow studies and the borehole temperature measurements (Gupta et al., 1974) could establish the larger extend of the thermal anomaly.

The results from gravity, magnetic and self-potential studies identified the existence of a few N–S trending features disposed across the valley (Arora et al., 1983). Attempts were made using shallow seismic refraction surveys to delineate the thickness of the overburden. The estimated thickness varies from 30 m near the fringes of the valley to about 230 m towards its western end (Arora et al., 1983). The shallow electrical resistivity studies reported the presence of resistive substratum underlying a conductive layer of varying thickness in the central part of the valley, which precludes the possibility of any major geothermal resources being present at depths. The results delineated a north–south trending nature to shallow (0.4 km) low resistive zone (Arora et al., 1983; Singh et al., 1983). Another attempt was made using magnetotelluric measurements to acquire information about the deeper zones. It failed to provide satisfactory interpretation due to noisy electric field components (Singh and Nabetani, 1995).

These geophysical studies revealed the presence of conductive features at shallow depths (less than 500 m) related to shallow geothermal reservoir, but the deeper part of the geothermal anomaly remains unmapped. In order to exploit geothermal energy, it is very important to understand the deeper structure of the area that can be related to geothermal reservoir, if any. Estimation of the reservoir characteristics is important for further exploration and exploitation of sustainable geothermal energy. In this context, wide band magnetotelluric measurements were carried out to image the electrical resistivity structure of the Puga area to provide information regarding the presence of geothermal activity and resources in the area.

4. Methodology

Magnetotelluric (MT) method is a geophysical technique used to image the subsurface electrical resistivity (Cagniard, 1953; Vozoff, 1991). Using Earth's naturally occurring electromagnetic fields as source, it provides useful information about the lateral and vertical resistivity variation in the subsurface. The broad period range of electromagnetic signals makes investigation depth of MT technique to reach several tens of kilometers for longer periods, depending upon the resistivity of the rocks. Because of the well-known phenomenon of 'skin effect' (Cagniard, 1953), the penetration depth of the electromagnetic fields increases with period and resistivity. MT method determines the subsurface geoelectric model from the measurement of the horizontal electric field (E)

along north–south (x) and east–west (y) in addition to the three magnetic (H) components (two horizontal components along north–south and east–west along with one vertical component). The relationship between the electric and magnetic fields at the surface of the Earth can be written as

$$E_i = Z_{ij} H_j \quad (1)$$

where, $i,j = x$, y and Z_{ij} is the complex impedance tensor of order 2×2. When the resistivity of the earth is a function of depth (one-dimensional earth), the diagonal elements of Z are equal to zero and the off-diagonal elements are equal in amplitude and opposite in sign. For a two-dimensional (2-D) structure, in which resistivity is invariant in one horizontal direction and the diagonal terms become zero if the EM fields are defined in a coordinate system orthogonal to the strike of the structure. In this case, the impedance component for the electric field parallel to strike (transverse electric (TE) mode) will differ from the component with the electric field perpendicular to strike (transverse magnetic (TM) mode). If the impedance is measured in an arbitrary orientation, the angle required to rotate the measurements into TE and TM modes can be determined from the impedance tensor. When the earth is three-dimensional, all components of Z are usually non-zero. The apparent resistivity and phase are determined from the known value of Z using the relation;

$$\rho_a = 0.2T|Z_{ij}|^2 \Omega \text{ m where } Z_{ij} = E_i / H_j \quad (2)$$

$$\text{phase,} \ \varphi = \arctan\left(\frac{Im(Z_{ij})}{Re(Z_{ij})}\right) \quad (3)$$

for the period T in seconds, E in mV/km and H in nT.

Geothermal resources are genetically related by water and heat. Since the electrical resistivity is affected by changes in temperature and permeability, the electromagnetic and electrical methods can provide a model of the subsurface resistivity variation. Of all the electromagnetic methods, magnetotellurics seems to be the most appropriate since the investigation depth of MT can easily reach several kilometers and MT has been widely used in geothermal areas (Bai et al., 2001; Gianni et al., 2003). The ability of MT to detect conductors that are embedded in a resistive media is proportional to its dimensions and conductivity, to the resistivity contrast between the conductor and the host rocks and to specific electrostratigraphic distribution of the study area (Newman et al., 1985).

5. Data acquisition and analysis

Thirty-five MT soundings with a site spacing of 0.4–1 km were carried out along three E–W trending profile lines (Line B, Line C and Line D) within Puga valley (Fig. 2). The data were collected during June–July, 2001, using the wide band MT data acquisition units (GMS 05) of M/s Metronix. The four horizontal components of the electric and magnetic fields were measured in N–S and E–W directions in a frequency range of 8192 Hz to 4096 s. The vertical magnetic field component was also recorded at every site. The measurements were carried out for 24 to 36 h at each site in four overlapping frequency bands. As Puga valley is less populated and far away from cultural noise sources, the recorded data were of good quality. Lack of noise sources and high predicted coherency between electric and magnetic channels justifies the single station recording. All the data were processed using PROCMT (Metronix, Germany) software package. This processing facilitates robust single site estimates of electromagnetic transfer functions (PROCMT, 1998). Time series segments with obvious disturbances (spikes and spurious data points) were discarded prior to the frequency domain conversion. The MT impedance tensor and the geomagnetic transfer functions were estimated using the regression of M-estimate. The apparent resistivity and phase values computed from the impedance tensor elements are described in Harinarayana et al. (2004).

6. Qualitative and semi-quantitative results

To start with, a general qualitative assessment of geoelectric character of the subsurface along the valley is attempted through an examination of MT responses at each site. The preliminary analysis carried out by Harinarayana et al. (2004) indicated that the MT apparent resistivity curves from the sites in Puga valley could be classified into three groups indicating lateral changes in resistivity along the valley. The first group of curves from the western part of

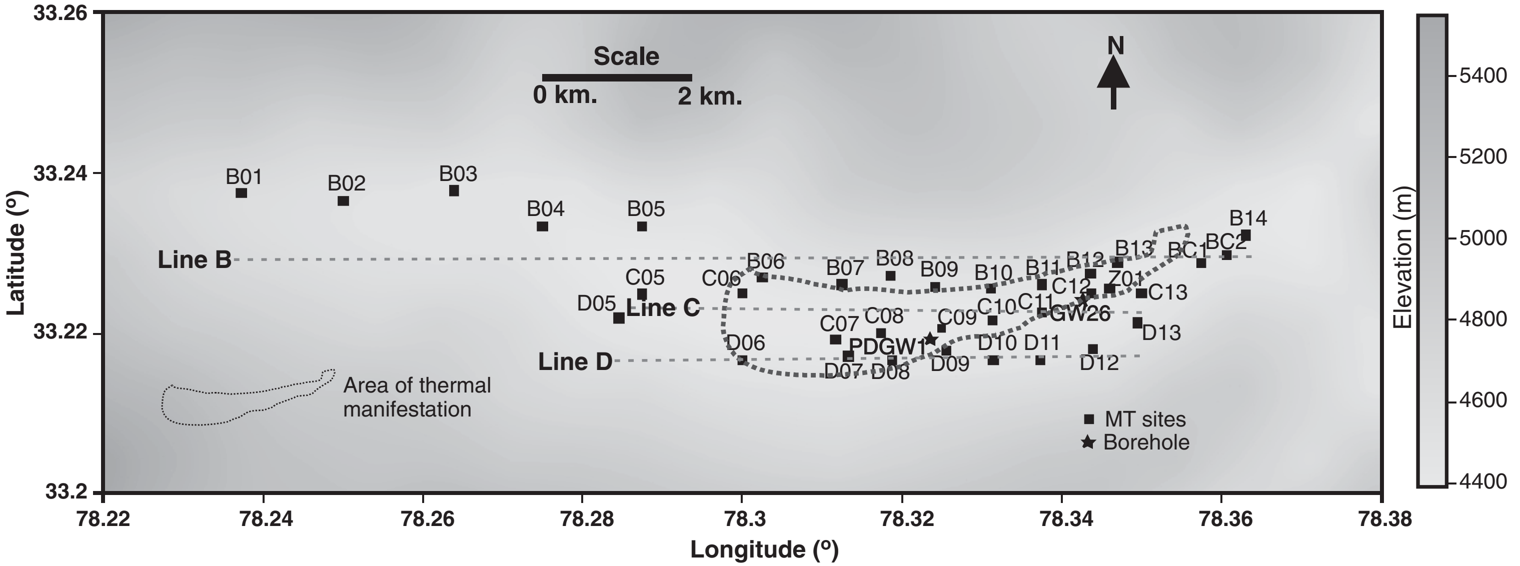

Fig. 2. Topography of Puga valley showing the locations of MT sites and the boreholes used for the comparison of MT results. The area marked for hot spring activities is also shown.

the valley showed resistive structures at higher frequencies; while the second group of curves from the anomalous (where geothermal manifestations exist) central part of the valley showed low resistive medium higher frequencies. At lower frequencies, the second group showed high conductive structures. The third group of sites from the eastern end of the valley behaved almost similar to the first group. Very low order scattering was observed in the apparent resistivity curves of each group suggesting feeble static galvanic distortion (static shift) in the data caused by very small-scale surface-scattering bodies. Prior to the two-dimensional inversion procedure, these static shift effects are considered. This distortion shifts the logarithmic apparent resistivity curves by a frequency independent factor while the phase curves remain unchanged. We used a common averaged level for the apparent resistivity curves of each group. The rotated data to the electric strike direction (N40°W; discussed later) again formed three similar groups. The scattering in the level of apparent resistivity curves within each group was less than a decade and the level of the curves were shifted accordingly. The remaining shift effects were accounted during the inversion process (see Section 8.2).

Transformation techniques (Goldberg and Rotstein, 1982), where each data point of apparent resistivity and phase value represents the resistivity as a function of depth, is useful in deriving semi-quantitative information about the subsurface. In the present analysis, the apparent resistivity and phase curves calculated from invariant average impedance ($Z_{\mathrm{aav}}=0.5\ (Z_{ij}-Z_{ji})$; Berdichevsky and Dmitriev, 1976) is used to derive resistivity depth profiles applying Bostick transformation (Bostick, 1977). The use of invariant impedances may provide a simple, relatively accurate method of magnetotelluric interpretation even in a region of three-dimensionality (Ingham, 1988). This derive a useful representation of the subsurface at each sounding point and provide the first hand information to formulate the initial models for inversion schemes. Bostick transformation of two MT sites (B02 and C10), representative of the two prominent groups (first and second), is presented (Fig. 3). The site B02 (Fig. 3) shows a resistive (200–500 Ω m) first layer followed by more resistive structure up to a depth of about 6 km. A conductive layer of 20 Ω m follows this and extends

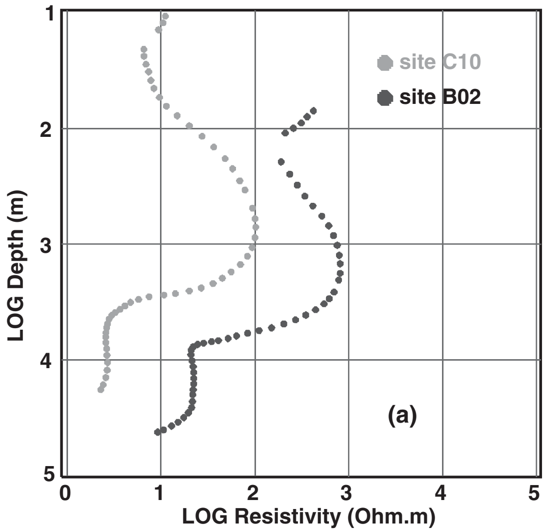

Fig. 3. Variation of resistivity as a function of depth for the MT sites B02 (symbols in black) and C10 (symbols in dark grey) using Bostick transformation.

up to about 40–50 km. The subsurface section at site C10 (Fig. 3) show significant deviation from site B02, where the resistivity at shallow depths (~200 m) has shown a value of about 10–20 Ω m representing a conductive earth. This follows a moderately resistive basement (100 Ω m) under this area. The data also indicate the presence of high conductive layer (3–4 Ω m) commencing at a depth of 2.5 km. The results from sites belonging to the third group also show a similar pattern as site B02.

7. Induction vectors

The geomagnetic transfer function between the vertical magnetic field component and the horizontal magnetic field components can be expressed as real and imaginary induction vectors. The real vector, when reversed, usually point towards region of enhanced conductivity (Jones, 1986). These vectors have been used qualitatively to map areas and find anomalies, where they pointed towards electrical current concentration at the coastlines (Parkinson, 1962). Induction vectors indicate the direction and strength of the conductor as a function of frequency. The real induction (Parkinson convention) vectors from the Puga valley exhibit the evidence for the presence of anomalous high conductive features (Harinarayana et al., 2004). Induction vectors indicate a nearly east–west trend of shallow conductive zone in the anomalous geothermal part of the region. The change in direction of induction vectors starting from B05 (Fig. 5a, Harinarayana et al., 2004) towards west could be considered as the western limit of the conductive zone related to geothermal manifestations. This shallow enhanced conductivity region marked in the geothermal anomalous part correlate with the shallow reservoir identified by various earlier geophysical and geological studies carried out in the area (Gupta et al., 1975; Arora et al., 1983; Singh et al., 1983; Mishra et al., 1996). The induction vectors at low frequencies (Fig. 5d, Harinarayana et al., 2004) indicate the presence of a 2-D conductor aligned in NW–SE direction and are consistent with the regional picture. This induction vectors directed the NW points towards the Indus Suture Zone just north of the study area. The presence of partial melts expected at depths in the Indus Suture Zone (along which Indian plate collided and subducted under Asian plate) and its surrounding region could be the possible source of high conductivity at the low frequencies.

8. Inversion studies

8.1. One-dimensional (1-D) inversion

The application of the 1-D inversion schemes to the MT data is simple and fast enough to derive the resistivity distribution of horizontal layers as a function of depth. As a preliminary step to two-dimensional inversion, the effective average impedance ($Z_{\mathrm{aav}}=0.5\ (Z_{ij}-Z_{ji})$; Berdichevsky and Dmitriev, 1976) which are rotationally invariant in the surface plane is used to generate 1-D layered models. Similarly, the average impedance data have been used to generate 1-D models to provide useful results (Ingham and Hutton, 1982; Sule and Hutton, 1986; Livelybrooks, 1986) and works well with many 2-D structures. One-dimensional inversion of the data is carried out initially with Occam linearized inversion scheme (Constable et al., 1987) and then Marquardt (Marquardt, 1963) inversion scheme. The layered model obtained from Occam inversion along with qualitative study results and geological information from the area is used to assume an initial model for Marquardt inversion. The final layered model is obtained by the inversion of the data by Marquardt inversion scheme. The resulting model for the sites B02 and C10 (belonging to first and second group of curves) are shown in figure (Fig. 4). The 1-D electric structure at site B02 (Fig. 4a), located towards the western part of the valley (first group of curves), shows a resistive top layer (400 Ω m) of 300 m thickness and underlain by more resistive (800 Ω m) layer. Below these layers, the model shows the presence of a conductive layer (15 Ω m) at a depth of 5 km followed by slight increase in resistivity character. On the other hand, the site C10 data (Fig. 4b), located towards central anomalous part of the valley, shows a conductive top layer (10–40 Ω m) of 300 m thickness sitting over a resistive layer (500 Ω m). The results show a highly conductive (less than 10 Ω m) layer at a depth of about 2 km at this site. The sites from the eastern part of the valley (third group of curves) shows resistive top layer sitting over a more resistive basement and continued by relatively low resistivity layer at larger depths. The one-dimensional modeling results of MT data are compared with the available near site borehole information. Comparison between borehole litholog and MT results shows good correlation. In Fig. 5, the layered models of sites C09 and C12 are compared with the boreholes PDGW1 and GW26 located near to the sites. The borehole litholog in general shows a top layer of alluvium with varying thickness (15–200 m) underlain by Breccia/Bedrock. The drilling results from PDGW1 borehole (384.7 m deep) show a basement depth of 130 m and other borehole GW26 (60 m deep) show basement at 36 m depth. MT models of sites C09 and C12 successfully demarcate these different lithologic units in the shallow part as seen from the illustration (Fig. 5).

8.2. Two-dimensional (2-D) inversion

Two-dimensional inversion schemes can be applied, if the MT data validate a two-dimensional structure along the profile or at least some parts of it. So, before considering a 2-D inversion, data should be subjected a dimensionality analysis. We used the tensor decomposition procedure of Groom and Bailey (1989) to remove the effects of galvanic scatterers and to derive the regional 2-D strike. The unconstrained

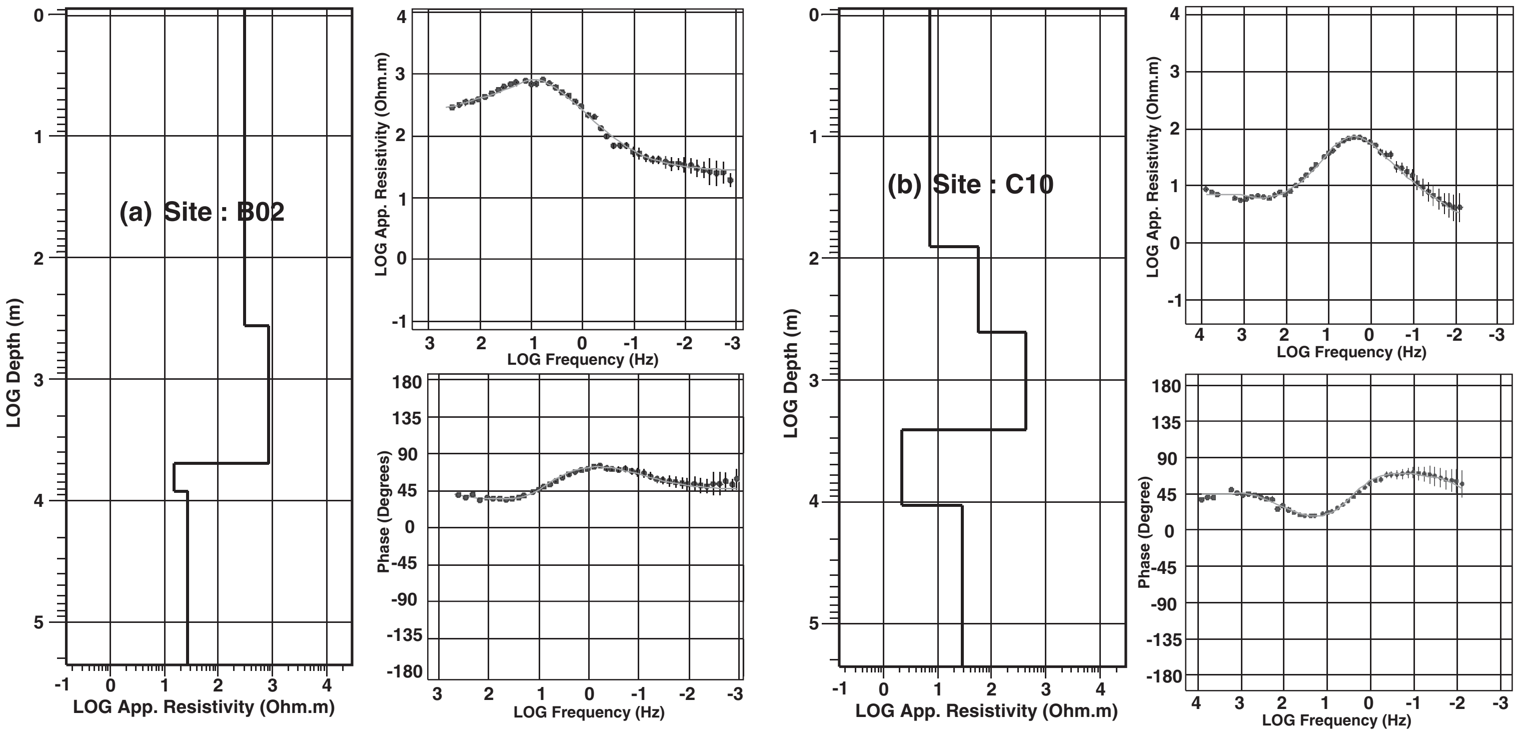

Fig. 4. 1-D Marquardt inversion of average impedance for (a) site B02 and (b) site C10. On the left is the MT model (thick line). On the right, the fitting between the measured apparent resistivity and phase (solid circle) and the model response (solid line) is displayed.

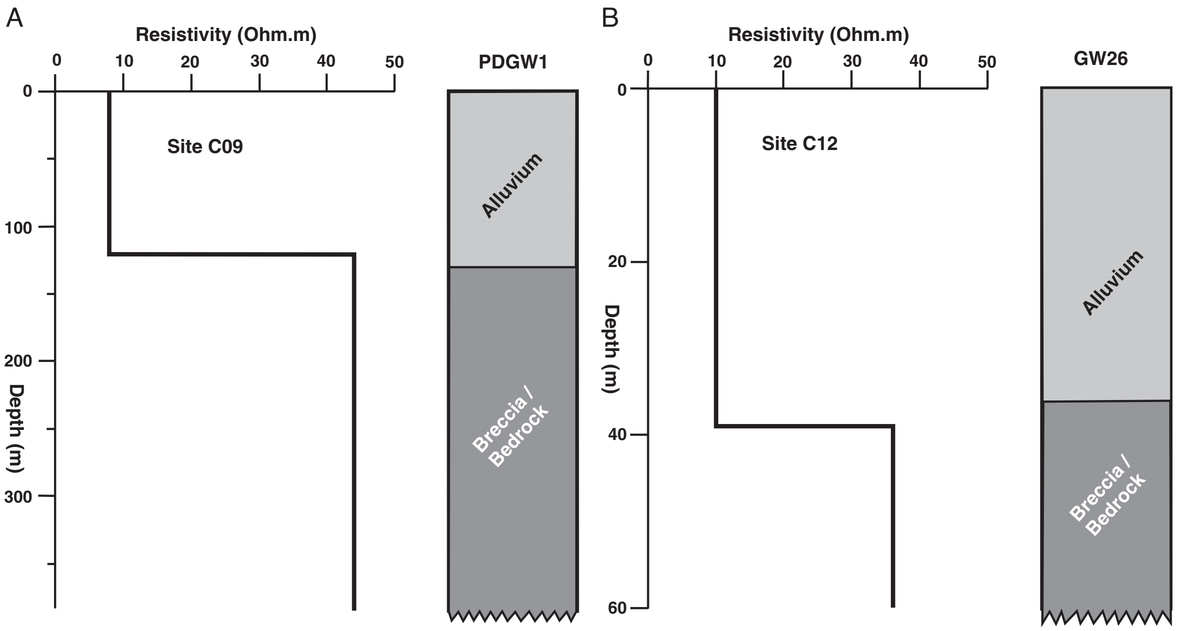

Fig. 5. Comparison of 1-D magnetotelluric inversion results with available borehole lithology near MT sites: (A) site C09 and borehole PDGW1 and (B) site C12 and GW26. On the left is the shallow part of MT model and on the right is the schematic representation of the borehole lithology.

decomposition at individual frequencies indicated that the shear had a stable value at most frequencies at most of the sites. The shear was then constrained to its mean value and the decomposition procedure repeated with unconstrained twist and strike angles. The twist was then varied in the vicinity if its median value to further decrease the frequency dependence of the observed strike angles. At low frequencies (especially in the 10 to 0.01 Hz), all the sites display a frequency independent preference of strike of N40°W within

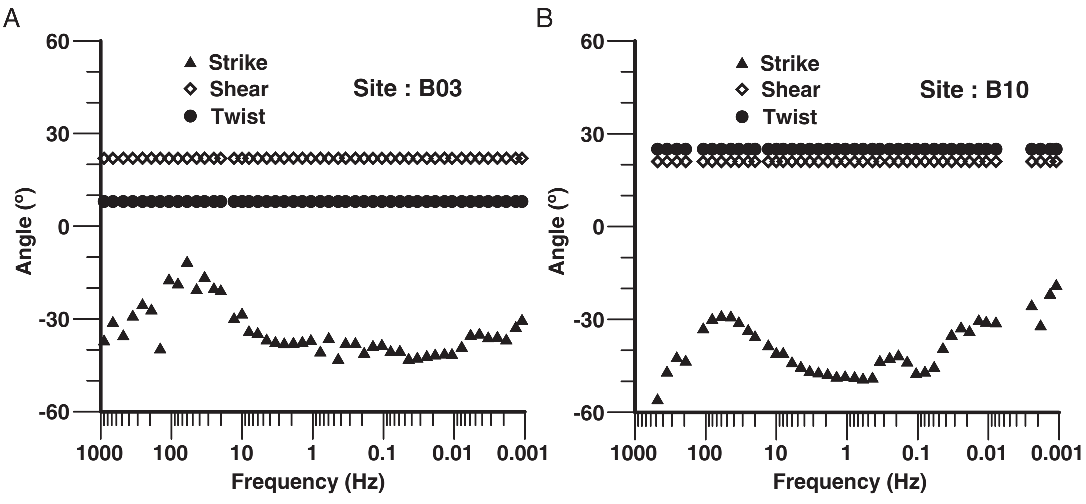

Fig. 6. Examples of estimated strikes and distortion parameters from Groom and Bailey decomposition as a function of frequency at two locations (A) site B03 and (B) site B10.

about 5°, indicating a predominantly 2-D geoelectric structure with a regional strike along an approximately northwesterly direction. At high frequencies (>10 Hz), the strike values show frequency dependence character. Fig. 6 illustrates the GB decomposition results for sites B04 and B10. The geologic and tectonic features are predominantly having a north-west–southeast orientation in the survey region (Fig. 1). The induction vectors at low frequencies (Harinarayana et al., 2004) also show a northwest–southeast strike. In view of these observations, the data at sites are rotated to N40°W and the response functions associated with the electric field parallel to this direction are regarded as the TE-mode values and those

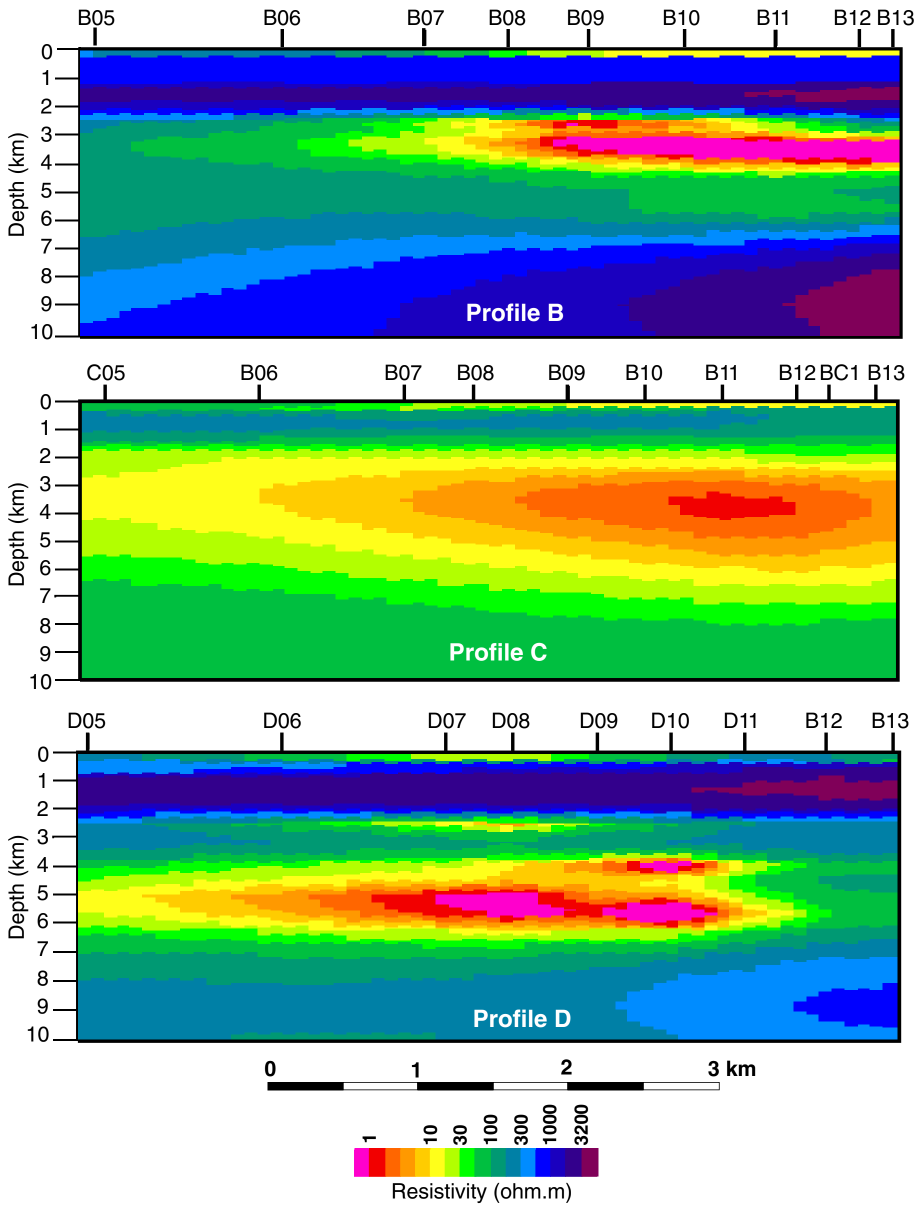

Fig. 7. Geoelectric cross-section obtained from the 2-D inversion of magnetotelluric data along the three profile lines B (top), C (middle) and D (bottom).

with the electric field measured perpendicular to it as TM-mode values.

For each profile line, the distortion corrected TE and TM apparent resistivity and phase data were simultaneously inverted using the 2D Rapid Relaxation Inversion (RRI) code of Smith and Booker (1991). The RRI inversion approach determines the resistivity model with least structure consistent with the data. A half space of 80 Ω m was assumed as the initial input model for inversion. The static shift effects are considered as described earlier (see Section 6). In order to accommodate the possibility of more static shift effects, the errors on the apparent resistivities in the entire data set were increased by a factor of 5 over those on the impedance phases before inverting the data so as to decrease their weight in the inversion process. By systematic trials, the optimal value for the weighting factor “alpha” was found to be 8. With this value of “alpha”, after 20 inversion steps, followed by 20 smoothing steps, the data misfit converged and the model roughness is found to decrease slowly. Fig. 7 shows the 2-D section for the geothermal field along the three lines. An average rms misfit of 2.45, 2.02 and 2.32 is observed for the respective final models along line B, line C and line D.

The shallow subsurface electric structures along the three lines show a conductive region (5–25 Ω m) of 200–300 m thickness. This zone of enhanced conductivity exists below the sites located in the anomalous part, and is consistent with the anomalous thermal gradient recorded with thermal manifestation. Its extension in east–west direction is about 4.5 km along line B, about 3.5 km along line C and about 1.5 km along line D. This points to the narrow down of shallow low resistive region towards the southern part of the valley. The sites falling in the non-anomalous part of the area show high resistivity at shallow depths as evident from line B.

The striking feature in the inversion results (Fig. 7) is the presence of high conductive zone of resistivity lower than 10 Ω m under this geothermal region. The top of this high conductive zone seems to be at about 2 km in line C and little more deeper in line B and D. This deep anomalous conductive part in the subsurface is invariantly seen along all the three profile lies with a width of about 4 km. This zone of low resistivity appears to be extending down to 5–6 km along lines B, C and D. The small scale deviation observed in the models that are closely placed may be due to the possible influence of structures outside the plane of the section, latitudinal direction of the lines for latitudinal object or due to the presence of 3-D features of the area. Still all the models consistently indicate the occurrence of a shallow low resistive region and high conductive part (less than 10 Ω m) at a depth of ~2 km. All these models invariantly present the major resistivity structures. So, these robust features certainly represent the major resistivity variations under the study area and give a valid electric structure for the area. The high conductive part seems to be emplaced within a comparatively resistive host medium. The surface geothermal activity in the area is confined within the two N–S trending faults, namely Kaigar Tso to the west and Zildat fault to the east and the depth extensions of these two faults may be controlling the lateral extension of the conductive zone. The projected surface position of the western flank of this conductor coincides geographically with a major fault (Kaigar Tso) on the geological map. The north heading Zildat fault may be controlling the eastern limit of the conductive feature.

9. Temperature variation at depth

In the present study, an attempt is made to correlate the resistivity and temperature observed in the area. It is known that the temperature parameter influences the resistivity of rocks and got relation ship between temperature and resistivity. During geodynamic activity such as collision of crustal blocks, the crustal materials also starts melting at high temperature and pressure conditions and thereby increasing the conductivity of the crustal materials. In such situations, high temperature values are associated with the low resistive regions and the earth behaves as a semi-conductor. Here, the resistivity variation within the valley at different subsurface depths estimated from MT study and the temperature distribution in the area at different depths (computed from available borehole temperature logs using heat diffusion relation) are considered to understand the resistivity–temperature relation existing in the area. It is known that heat diffuses from one location to the other through various rock media. The general formula relating the diffusion of heat is (Gupta et al., 1991):

$$T_Z = T_S + \left(\frac{Q_S}{k}\right) - \left(\frac{A_S \times Z^2}{2k}\right) \quad (4)$$

where T_Z=temperature at Z km in °C, T_S=surface temperature in °C, Q_S=heat flux at the surface, k=thermal conductivity of the medium, A_S=radioactive heat production and Z=depth in km.

It is interesting to study the relation between the resistivity and temperature parameters in the study area. The surface temperature values and shallow (50–200 m) borehole temperature logs are available from earlier temperature measurement studies (Gupta et al., 1974; Thussu, 2002). From this available temperature distribution in the area, temperature values at different subsurface depths can be computed using Eq. (4). Temperature distribution at 2 km depth is computed from the above relation by assuming the following values for the different parameters in the equation.

k=2.73 W $m^{-1}K^{-1}$ (for granite and granite gneisses)

A_S=2.93 W m^{-3} (for granite and granite gneisses)

Q_S=180 mW m^{-2} (Ravishanker, 1988)

For the present study, we used the average heat flow value of the region (180 mW m^{-2}) instead of the anomalously high heat flow value (540 mW m^{-2}; Ravishanker et al., 1976) recorded over the geothermal zone. This can give the minimum temperature estimates of the area at depths and will be enough to understand the geothermal significance of the area. Also, the resistivity distribution at 2 km under the study area is derived from the resistivity–depth profiles of MT sites distributed in the area.

In order to study the relation between the resistivity and temperature at 2 km depth, a north–south profile through the center of the anomalous part is considered. The resistivity and temperature values are noted at 2 km depth along this profile and plotted to analyze the relation between the two parameters (Fig. 8). The graph gave a polynomial fit for the data points. It can be seen that temperature increases as resistivity decreases and for a minimum resistivity value of 10 Ω m, the temperature becomes almost stable giving a value of about 250 °C. The result is consistent with the estimation of base temperature computed from Na–K and Na–K–Ca thermometry (Ravishanker et al., 1976).

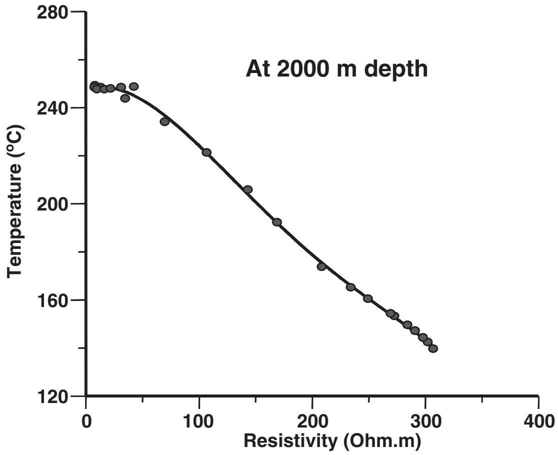

Fig. 8. Plot showing the relation between temperature and resistivity variation at 2 km depth in the Puga geothermal field.

10. Discussion and conclusion

The magnetotelluric results from Puga geothermal area allowed to characterize the electrical structure of the area. The present study shows lateral as well as vertical variation of electrical resistivity along the valley. Along the valley, the western and the eastern extreme parts characterize a high resistive top layer; while the central part and little east (the area of thermal manifestation) to it show a characteristic low resistive top layer. This low resistive layer, ranging 5 to 25 Ω m, in the central part of the area spread over an area of 3–3.5 km^2 of the region. This low resistive region coinciding with thermal manifestations present in the area extend to about 300 m in depth and found to rest over a high resistive layer, probably representing the basement rock of Puga formation. This low resistivity mapped by magnetotellurics also corroborate with the low resistive regions indicated from shallow electrical resistivity studies carried out in the area (Gupta et al., 1975; Arora et al., 1983; Singh et al., 1983; Mishra et al., 1996). The drilling data indicated that the subsurface layers consist of moraine, eolian sand and scree at the top, underlain by a fluvial glacial deposits, reconsolidated by hydrothermal action of the thermal fluids in breccia with fracture and vugular porosity (CEA, 1995). Also, the drilled boreholes in this hot spring zone yielded steam and hot water mixture. The low resistive top layer delineated by magnetotellurics can be considered to be the zone of circulation of hot water in the above-cited formations at these shallow parts and probably represents the shallow geothermal reservoir of the area. The western boundary of this low resistive region coincides with Kaigar Tso fault that broadly delimits the thermally anomalous area. The Zildat fault located in the eastern end of the valley may be controlling the eastern boundary of this thermally marked region.

The most significant result of this study is the presence of anomalous conductive zone of resistivity less than 10 Ω m at depths of about 2 km. This hitherto unknown conductivity present at this relatively shallow part of the upper crust extends to about 5–6 km down. To produce a high conductivity, as observed in the present study, a conducting phase must be present to allow electric current to flow through rock. The possible conductive materials that can be found in the Earth include metallic minerals, graphite, molten rock and aqueous (ionic) fluids (Jones, 1992). In volcanic and geothermal areas, the cause of high conductivity at depths may be due to the presence of magmatic materials. It may be noted that Puga valley is a part of upper Himalayas and located just south of Indus Suture Zone (ISZ). ISZ is the collision boundary of Indian and Asian crustal plates that were involved in the Himalayan orogeny. Presence of high conductive anomalies in the upper crust of these Himalayan belt regions are revealed from different magnetotelluric studies conducted over these regions (Bai et al., 2001; Gokarn et al., 2002; Li et al., 2003) and conductivity is attributed to the presence of wide spread partial melts. The study of Gokarn et al. (2002) show anomalous low resistivity of less than 10 Ω m (extending from shallow depth to 15 km) beneath ISZ and towards its south and they attributed this to the presence of partial melt generated from the subducted Indian crust. The Puga area has recorded intense basic to ultrabasic, plutonic to submarine volcanism of Cretaceous age and several phases of widespread acid igneous activity from Upper Cretaceous to Upper Tertiary times (Ravishanker et al., 1976). Heat flow studies indicated high heat flow values of about 180 mW m^{-2} for the Himalayan collision belt (Ravishanker, 1988) and more importantly the Puga area records high heat flow conditions (540 mW m^{-2}) in the anomalous geothermal zone (Ravishanker et al., 1976). The above knowledge with high conductivity recorded under Puga geothermal field discards the possibility of metallic minerals and graphite presence to this low resistivity. The geochemical study results showed the presence of relatively high concentration of chlorine, fluorine, boron, SiO_2, sodium, and total dissolved solids with low concentration of magnesium and high enrichment of Li, Rb,Cs in thermal spring waters and sediments (Chowdhury et al., 1974). These results along with the abundance of sulfur in the thermally manifested area strongly suggested magmatic origin for the thermal waters and associated elements. The above results prompt us to believe a magmatic source for the geothermal anomaly present in the valley. We attribute that the low conductive zone (less than 10 Ω m) identified in magnetotelluric study may thus be images of possible cooling magma chambers in accord with the existing geochemical, geophysical and geological wisdom. The temperature estimation gives a minimum expected value of 250 °C at the transition boundary from high resistive basement to the anomalous conductive zone under the area. The calculation used only the regional heat flow value (180 mW m^{-2}) and the temperature under this area may be high enough to (since the heat flow values are of the order of 540 mW m^{-2} in this anomalous zone) produce magmatic sources (partial melts) at these depths. This too supports the conclusion that the high conductive region could be related to magmatic material and it may be acting as the geothermal source in the area.

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