Magnetotelluric evidence of potential geothermal resource in Puga, Ladakh, NW Himalaya

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The Puga area in eastern Ladakh, Jammu and Kashmir, is known to be the most promising geothermal field in India, as pointed out by geo-scientific studies in the area. However, lack of deep subsurface information put constraints to the geothermal resource evaluation in Puga. The recent magnetotelluric study in Puga revealed anomalous conductive (~5 Ohm.m) structure at a depth of 2 km in the area of geothermal manifestation. Analysis of temperature logs indicated a high temperature (~260°C) associated with the anomalous conductive structure and signifies potential geothermal resource in the area. We discuss the results in the context of geothermal resource utilization for power generation in the area.

Keywords: Geothermal resource, magnetotelluric study, power generation, resistivity.

THE Hot Spring Committee, constituted by the Govt of India in 1966, has identified the Puga hot spring area in NW Himalaya as the most intense and promising geothermal field in the country. The area, located in the eastern Ladakh region of Jammu and Kashmir, evidences vigorous geothermal activity in the form of hot springs, mud pools, sulphur and borax deposits. The temperature of thermal water is as high as the boiling point of water (84°C)[1,2] at this altitude (~4400 m). Subsequent to the Hot Spring Committee report, various geo-scientific investigations consisting of geological, geochemical as well as shallow geophysical studies were carried out in Puga[1–12]. The shallow resistivity surveys[4,5] and telluric studies[6] have helped to identify a near-surface low resistive region in the area of thermal manifestation, interpreted as the shallow geothermal zone under the area. An earlier magnetotelluric (MT) experiment failed to deduce quantitative results due to poor quality of electric field measurement and qualitative inferences about the subsurface resistivity structure made from the analysis of magnetic field data[9]. These studies gave a prospect of the geothermal system; however, they could not provide any valuable information on the deep geothermal characteristics of the area. In order to assess the geothermal potential of the area, deep probing of the subsurface is imperative.

The MT technique, a natural electromagnetic method, has proved effective in mapping the characteristics of geothermal fields due to its lateral resolution and also greater depth of investigation[13]. MT survey is more appropriate for difficult topography due to its simple logistics and low cost compared to seismic survey. MT provides useful information about the lateral and vertical resistivity variations in the earth's subsurface from surface measurement of two horizontal electric field and three magnetic field variations over a typical 10^{-3}–10^{3} Hz frequency range. In this study, we report the MT results along a profile covering the Puga geothermal field and discuss the implications of the results with the geothermal manifestations present in the area to evaluate the resource potential of the area.

Geology of the area

The Puga hot spring area is located to the south of the Indus Suture Zone (ISZ) in NW Himalaya (Figure 1). The ISZ represents the collision boundary between the Indian and Asian plates in the Himalayan orogeny during the Cenozoic[14]. The area exposes Precambrian paragneisses, schists and phyllites interlayered with bands of limestone and associated amphibolite, eclogite and pegmatite. Younger granites of Tertiary age occur as intrusives. Zildat Fault separates this area from the rocks of the Ophiolite suite along the ISZ that represents the remnants of the uplifted wedge of the oceanic crust compressed between two continental masses[15].

The geothermal activity is concentrated in the 3 sq. km area of the east-west trending 15 km long Puga Valley (Figure 1). The top alluvium cover in the valley mainly comprises talus, spring deposits, borax evaporates, aeolian sand, fluvioglacial sediments and glacial moraines. Fluvioglacial sediments and glacial moraines are reconsolidated into hard breccia/conglomerate by the action of hot geothermal fluids, as seen in borehole cores. The reconsolidated rock is believed to be of Quaternary age. The Puga Formation is sparsely seen on the slopes of the mountain ranges close to the valley. At places, it is obliquely

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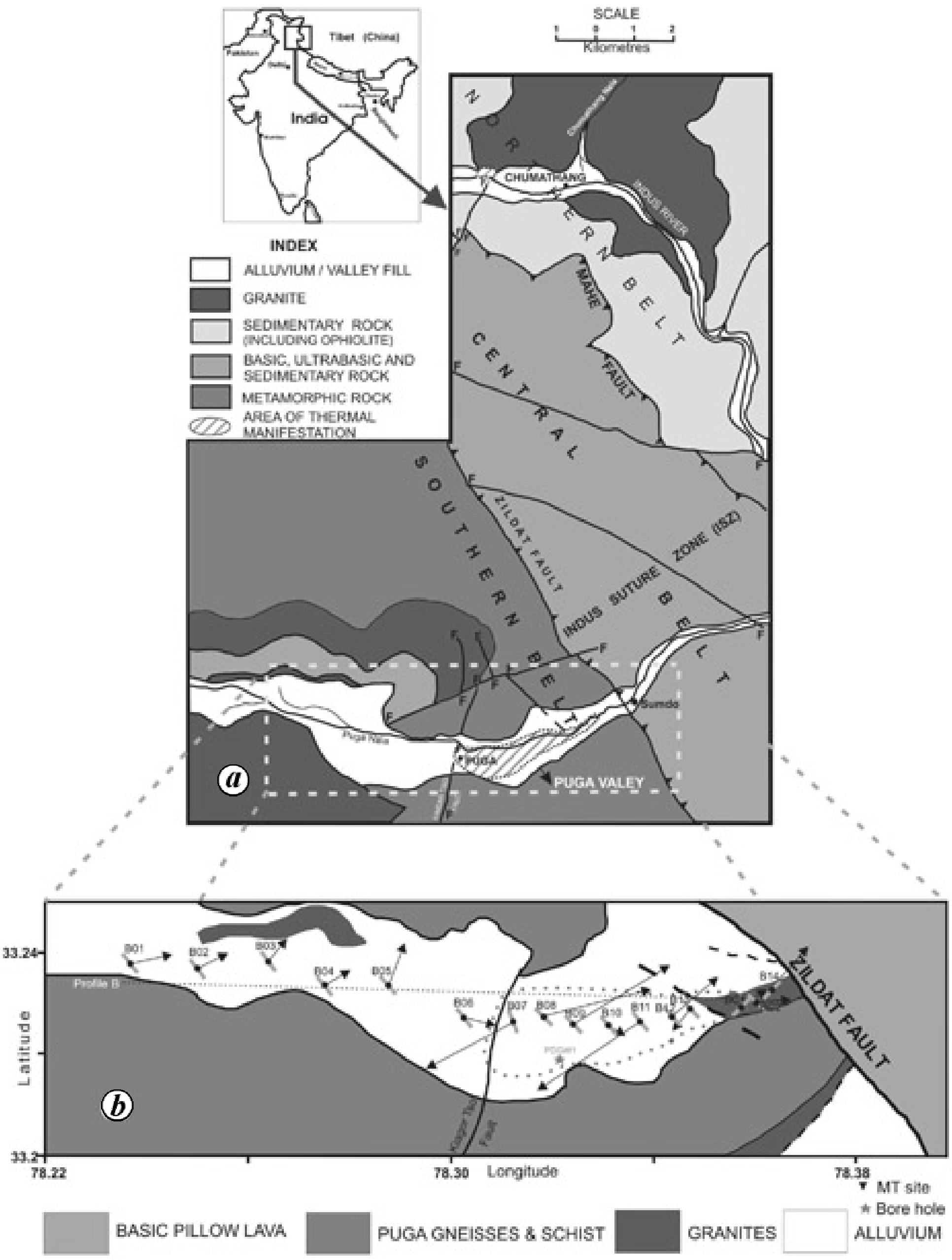

Figure 1. Map showing the geology of Puga region. ***a***, Geology and tectonic features in Puga and its adjacent region (after Ravishankar *et al.*[2]). ***b***, Geology of the Puga Valley and distribution of MT sites (solid circles) along the long profile B. The area of thermal manifestation is marked with dotted contour. Also shown are the estimated strike (grey line) and the Parkinson real induction vectors (black arrows) at every MT site for lower frequency range (1–0.001 Hz) of the measured data.

intruded by basic rocks and ambhibole–chlorite–schist in the form of dykes and sills. The intrusions are thin and are exposed on the southern slope of the valley[1]. The northern limit of the Puga Formation is marked by a major NW–SE trending Zildat Fault. Kiagor Tso Fault (KTF), a NNE–SSW trending regional fault (Figure 1) just to the west of the thermal manifestations in the area, cuts across the valley and broadly delimits the thermally anomalous area[1].

Magnetotelluric study

The five-component broad-band (1000–0.001 Hz) MT measurements were made at 35 sounding locations along three closely spaced parallel profiles (E–W trending) within the Puga Valley, with site spacing varying from 400 m (in thermally manifested areas) to about 1 km. Data were processed to give the best estimates of MT transfer functions over the frequency range 1000–0.001 Hz. Preliminary analyses of the dataset have shown qualitative distribution of conductivity variation in the study area[16]. Here, we discuss the two-dimensional modelling of MT data along the longest profile (profile B) covering the Puga Valley (Figure 1).

Prior to the 2D modelling of MT data, the characteristic geoelectric strike direction of the subsurface structures, as defined by MT data, must be derived. We applied the decomposition methods of Groom and Bailey[17], and Chave and Smith[18] that yield the correct strike from regional 2D data distorted by local 3D effects. The single-site Groom–Bailey analysis of the data showed consistent geoelectric strike direction of N40°W within about 5° at most sites, especially at the lower frequency range (Figure 1). Multi-site strike analysis of the dataset along the profile, using the Chave and Smith[18] approach, resulted a strike angle of N40°W and showed close agreement with the Groom–Bailey strike values. Considering the consistent strike directions obtained from two independent analyses, a valid regional 2D geoelectric structure can be assumed with a regional strike either along N40°W or perpendicular to it. The inherent 90° ambiguity in strike determination can be corrected using induction arrows. The real induction arrows over a 2D structure orient orthogonal to the geoelectric strike. The real induction arrows (Parkinson convention) at the lower frequency range are illustrated in Figure 1 and show NE-pointing arrows for a majority of the sites. Some sites show reversal of the induction arrow to the SW. In short, the induction arrows are aligned in the NE–SW direction and suggest NW–SE orientation of the regional geoelectric structure. The major geological and tectonic features in the region show a NW–SE alignment (Figure 1). In view of these observations, a regional strike direction of N40°W is appropriate. Accordingly, we rotated the data to the N40°W coordinate frame.

The MT transfer functions along the strike (TE-mode) and orthogonal (TM-mode) directions were inverted simultaneously using a nonlinear conjugate gradient algorithm[19], to derive the 2D subsurface resitivity distribution. The algorithm seeks a smooth model with reasonable misfit with the data. The regularization parameter that controls the roughness of the model was set to 10 to get a smooth model with least misfit error. The apparent resistivity was down-weighted during the inversion process with 20% error floor and 5% to the phase. This helps to accommodate the possible static shift effects in the data. The model stabilized after 300 iterations with an rms error value of 2.58 between the observed and model response data. The resistivity model obtained for the geothermal field is shown in Figure 2. The responses for the obtained model are presented along with the observed responses in Figure 3. There is a good agreement between the observed and modelled responses. The prominent structures in the resistivity model and its relevance to the geothermal field are discussed below.

Resistivity structure and interpretation

The derived resistivity structure showed a near-surface low resistive (10–30 Ohm.m) zone of about 300–400 m thickness (marked A in Figure 2 *a*). The low resistive region, approximately 4 km in length, correlated well with the area marked by surface expressions of geothermal activity. Earlier shallow resistivity and telluric studies in the area also demarcated a low resistive formation in this part of the valley[4–6]. The surface low resistivity (10–30 Ohm.m) zone can be explained by the varying thickness of alluvium (sands with grains of quartz and mica) in the valley, underlying fractured breccia/basement (consisting of fragments of gneiss, schists, phyllite and quartzite in an argillaceous, siliceous matrix) saturated with hot water or a mixture of deep thermal water and freshwater, as seen from the shallow drilling results. This zone is considered to be the shallow reservoir part of the geothermal field. The resistivity structure does not indicate any surface low resistive zones to the west of the KTF (Figure 2 *a*). Correlating with the above result, the area west of the fault does not show any thermal manifestations or temperature anomalies[7]. This is in accordance with the argument that the KTF delimits the area of geothermal manifestation in the area to the west[1]. To the west of the fault, the shallow subsurface section showed high resistivity representing compact metamorphic basement rocks (gneisses and quartz) along with granitic intrusives.

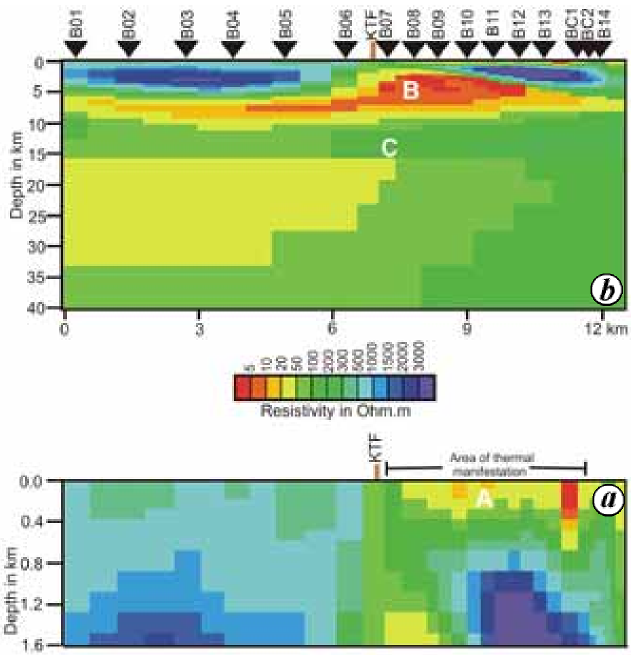

Figure 2. Two-dimensional resistivity model for the Puga geothermal field derived from inversions of MT data. ***a***, Shallow section; ***b***, Deeper section. Inverted triangles show the location of MT sites. The area of geothermal manifestation is also marked. A–C mark the major structures in the model (see text for details). KTF, Kiagor Tso Fault.

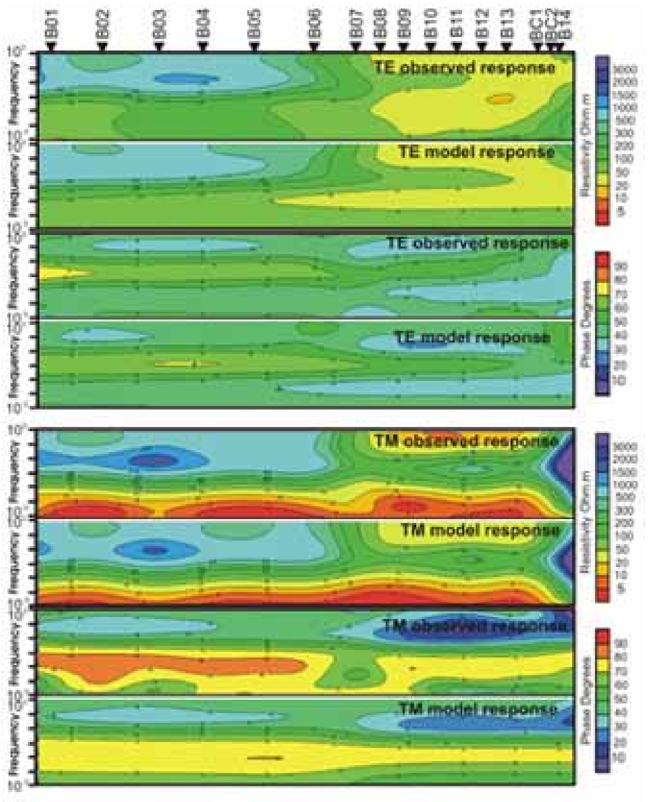

Figure 3. The observed MT data presented along with the response of the inversion model (Figure 2). Note that a good fit is obtained between the measured and model response at most sites and frequencies.

Another prominent feature, perhaps the most significant result of the study, in the resistivity model was an anomalous low resistive structure (5–10 Ohm.m) commencing approximately at 2 km depth below the geothermal manifestation (marked B in Figure 2 *b*). It occupied a large subsurface volume with vertical extension up to a depth of ~8 km. The structure seemed to continue towards the west. It appeared as a continuous low resistive crustal layer. The anomalous low resistive layer was underlain by a ~50 Ohm.m resistivity layer (marked C in Figure 2 *b*). The deeper part of the subsurface, representing the mid to lower crustal levels in the thick (~70 km) Himalayan crust, showed low resistivity (~50 Ohm.m) compared to the normal stable continental crust characterized by relatively resistive (100–300 Ohm.m) lower crust. Gokarn *et al.*[20], along a regional MT profile west of the Puga area, obtained similar low resistive deep crust beneath the Himalayan region.

The surface low resistive zone (A) and the anomalous conductive structure (B) in the model are separated by a high resistive (~1000 Ohm.m) structure (Figure 2 *b*). This is interpreted as the metamorphic basement rocks. However, a narrow, vertical low resistive feature cuts across the basement and connects the surface low resistive zone and the anomalous conductive structure. The induction arrows also suggest a low resistive region between sites B06 and B07, as illustrated by oppositely directed induction arrows (Figure 1). The position of this vertical low resistive feature spatially correlates with the trace of the KTF and can be interpreted as the MT image of the fault. It is the major structural feature that connects the deep (~2 km) anomalous conductive structure and the surface low resistive zone.

Anomalous conductivity (B) in the upper crust as well as low resistivity of the mid–lower crust (C) can be explained by analysing the various factors that cause enhanced conductivity in the crust. It is known that most silicate and carbonate minerals are resistive. To produce the high electrical conductivity observed in the upper and mid–lower crust of the study region, a conducting phase must be present in the rock matrix to allow the flow of electric current. The different candidates that can produce high conductivity in the upper and lower crust are metallic minerals, graphite, molten rock (partial melt) and aqueous (ionic) fluids[21]. The most possible cause for the observed low resistivity in the mid–lower crustal parts of the subsurface section, in an active tectonic environment such as the Himalayas, could be the presence of partial melts. Owing to the abundance and high mobility of ions, partial melt is a good electrical conductor. The observed heat flow values (>180 mW/m^2) for the Himalayan collision belt region[22] suggest conditions favourable for the presence of partial melt generation at deep crustal levels. The conductivity of the melt depends on the amount of fluid and interconnectivity of the fluid. Singh[23] observed high attenuation of seismic energy beneath the Central Himalayas at depths of 20–80 km and attributed it to the possibility of partial melting of rocks at these depths. Seismic reflection results from the neighbouring regions of southern Tibet indicated bright spots in seismic reflections, suggesting partial melts in the crust[24]. Moreover, MT results along a long profile in the NW Himalaya and from southern Tibet showed the presence of partial melt with associated aqueous fluids in the mid–lower crust of the Himalayan collision belt (Gokarn *et al.*[20] and references therein).

The anomalous low resistive (~5 Ohm.m) structure (B) in the depth range of 2–8 km under the geothermal manifestation could have two possible explanations. First, the anomalous conductive structure (B) resting over the partial melts of the mid–lower crust (C) is due to the presence of hot aqueous fluids associated with rock melts. The fluid phase associated with the rock melts might have been injected to the shallow upper crust under favourable conditions like high pore pressure. Rock melts, characterized by high temperature, could be the source of geothermal activity in the area. Collision followed by subduction of the Indian Plate with Asian Plate could result in high pressure and temperature conditions favourable for partial melting at mid–lower crustal depths. These melts with hot fluids may migrate under favourable geological conditions towards the upper crust. The rock melts with high temperature produce high heat flow values as estimated for the geothermal field[1] (540 mW/m^2). Melt production may be a continuous process in this geodynamically active region and can sustain geothermal activity for a long time.

The second explanation for the observed anomalous conductive structure could be the presence of a porous region with hot fluids located at the top of the magmatic heat source. Post-collision magmatism is a common feature in many collisional orogens around the world and has been widely reported from the Himalayan collision belt. This post-collision volcanism is still active in the active Himalayan belt region[25]. In such a case, the magmatic body might have been emplaced into the shallow crust from several kilometres below during the later stage of the post-collision volcanic activity. Such an intrusion, on its way upwards, can develop fractures in the basement and cause enhancement of electrical conductivity in the surrounding area. The slowly solidifying magma expels fluids and can be filled in the fractures to increase the conductivity of the medium. Such magma bodies at shallow depths could be connected with a deep magma source through a narrow feeder. However, such feeder channels will freeze with time and the intrusions would become independent heat sources.

Chemical analysis of thermal water reported the presence of active constituents such as silicon dioxide, sulphate, fluorine, boron, etc. along with significant amounts of cesium, lithium and rubidium[10,11,26]. Higher concentration of cesium is explained by the possible association of thermal springs with the magmatic source[10,11,26]. Similar studies by Saxena and D'Amore[12] also suggest association of thermal waters with late-stage magmatic activity. The high heat flow conditions (540 mW/m^2), abnormal shallow geothermal gradients (0.7–2.5°C/m), cinnabar encrustation and siliceous sinter deposits observed in spring areas together indicated the possibility for the occurrence of the magmatic source in the vicinity of Puga[1]. Gupta *et al.*[8,27] have inferred a Quarternary magmatic body as the heat source for the Puga geothermal field.

In the above two possible explanations, i.e. the anomalous conductivity (~5 Ohm.m) structure being either associated with partial melt or a magmatic source, it is also associated with high temperature conditions to produce the observed thermal anomalies in the area. The combination of high temperature conditions and fluid phase in the rock matrix favours potential geothermal resource in the area.

Geothermal significance of anomalous conductive layer

Subsurface temperature conditions

Geothermal investigation results from Puga area have been reported in detail[1,2,7,8] and temperature measurements are available from a number of boreholes[2] ranging in depth from ~30 to 280 m. Gupta *et al.*[7] observed higher near-surface temperature gradients ranging from 0.4 to 4°C/m, which is uncharacteristic of the region. Thermal studies have indicated high temperature conditions of about 220°C at about 2.5 km, corresponding to the main reservoir[8]. The chemical thermometry also suggests reservoir temperatures of 250°C in the area[12]. The reservoir modelling studies of Puga geothermal system suggest the possibility of temperature up to 160°C at a depth of 450 m in the valley[28].

Among the available temperature logs, the deepest (384.7 m) borehole PDGW-1 (located at the western end of the area of geothermal manifestation; Figure 1) measured the longest (280 m) temperature–depth profile[4]. The temperature profile in the borehole is the least perturbed among the available temperature profiles in the area. The lower part of the temperature–depth profile (Figure 3) between 195 and 235 m showed relatively undisturbed section. Analysis of data yielded a least squares gradient of ~12.7°C/100 m. Assuming conductive heat transfer and a mean annual surface temperature of 10°C, temperature at a depth of 2 km (corresponding to the depth to the anomalous conductive structure) was estimated to be ~260°C.

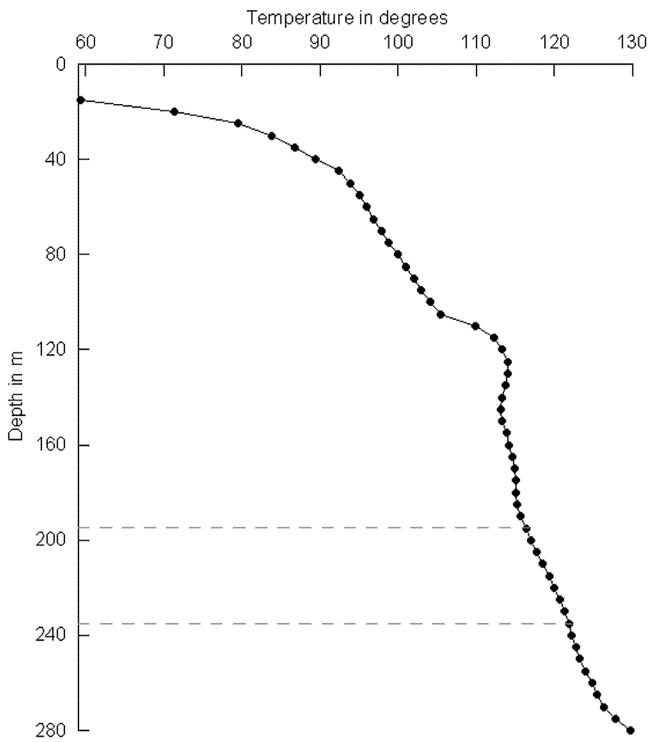

Figure 4. Temperature–depth profile obtained in borehole PDGW1 (after Ravishankar *et al.*[2]). The profile has been digitized and replotted. Symbols in the temperature-depth profile do not represent actual depth of measurement. The least perturbed part of the temperature profile considered for the analysis is also marked.

Assessment of geothermal potential of shallow crustal conductive layer

The geothermal resource potential evaluation made on the basis of earlier shallow geophysical and geological information inferred a minimum of 5 MW electricity generation for a period of 20 years from the near-surface reservoir part (first few hundred metres) of the area[29,30]. Reservoir modelling studies by Absar *et al.*[28] suggested temperatures up to 160°C at a depth of about 450 m and estimated 2 MW power generation for 30 years. However, utilization of this geothermal energy was limited to space heating of huts and greenhouse cultivation; mainly due to the lack of adequate information about deep subsurface conditions.

While such is the case with the upper few hundred metres of the geothermal field, delineation of the possible geothermal resource zone (the enhanced conductive zone at ~2 km depth with elevated temperatures) under the geothermal field, as evident from the present study, can ascertain much greater geothermal potential in the area. The results of Puga show similarities with those shown by some of the well-known geothermal fields in the world. For example, the Mt Amiata geothermal field (Italy) with temperatures reaching 350°C at 3 km depth, which is mainly exploited for electric power production, indicated deeper reservoir in the local metamorphic basement at depths greater than 2 km. MT study in this area[31] has shown the presence of electrical discontinuities in the resistive underground below 2 km. The Mt Amiata area has an installed capacity of 88 MWe. MT studies in the Yellowstone region[32] (the most dramatic thermal manifestation in the United States) demonstrated conductive zones, caused by elevated temperatures, at shallow depths in the crust, which made a great impact on geothermal exploration and geothermal resource estimation of the area.

The geothermal conditions assessed at a depth of ~2 km are highly suitable for initiating further exploitation studies in the Puga area. The depth to the expected thermal resource (i.e. ~2 km) is economically reasonable and viable to drill with the advancement in drilling technology. The hot fluids and/or higher temperature conditions at these depths can be used to propel turbines by piping hot fluids through geothermal wells to one or more separators, to produce electricity. These favourable points suggest significant potential of the thermal energy prevailing in the area for electric power generation as well for other industrial uses. However, experimental exploratory drill hole to a depth of 2 km needs to be initiated to make a realistic estimation of the reservoir conditions in the area.

Conclusion

Modelling of the MT data along the Puga Valley revealed the deep electrical structure of the geothermal field. The results confirmed that the area is characterized by a surface low resistive (10–30 Ohm.m), thin layer (~400 m), correlating with the area of thermal manifestation in the area, and an anomalous conductive (~5 Ohm.m) structure in the upper crust of the area commencing at a depth of 2 km. The surface low resistive zone and anomalous conductive structure were separated by a resistive structure. The study also imaged a major fault feature (the KTF) that cuts across the resistive structure and connects the surface low resistive zone and the anomalous conductive structure. The study showed a low resistive (~50 Ohm.m) mid–lower crust in the area.

Temperature measurements in the shallow boreholes as well as heat flow values indicated thermal anomalies in the area. The proximal cause of the anomalous conductivity structure could be either the presence of fluid zone associated with partial melting of deep crustal rocks or a hot fluid zone resting over magma emplacement into the upper crust. The estimated temperature within the anomalous conductive structure was ~260°C. The high temperature conditions at shallow depths under the geothermal field make the area highly favourable for thermal resource utilization for power production as well as for other industrial applications of geothermal energy. The large depth extension (~8 km) of the anomalous conductive structure accounted for a huge volume of the heat source substantiating its long-term sustainability. However, further detailed evaluation of these results and the geothermal characteristics of the area need to be made with an experimental deep drilling programme to a depth of at least 2 km. It appears that, if studied and developed properly, this area could produce electric power at a place which lacks conventional resources. Finally, the present findings may have an impact on geothermal exploration and estimation of geothermal resources of the Indian subcontinent.

1. Ravishankar, Padhi, R. N., Arora, C. L., Prakash, G., Thussu, J. L. and Dua, K. J. S., Geothermal exploration of the Puga and Chumathang geothermal fields, Ladakh, India. In Proceedings of the 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, USA, 1976, vol. 1, pp. 245–258.
2. Ravishankar *et al.*, Geothermal Atlas of India. *Geol. Surv. India, Spec. Publ.*, 1991, **19**, 14–17.
3. Arora, C. L., Singh, H., Das, L. K., Ghatak, T. K., Singh, R. P. and Hakim, A., Geophysical exploration of the Puga Valley geothermal field, Ladakh District, Jammu and Kashmir State. *Geol. Surv. India, Spec. Publ.*, 1983, **2**, 631–646.
4. Singh, S. B., Drolia, R. K., Sharma, S. R. and Gupta, M. L., Application of resistivity surveying to geothermal exploration in the Puga Valley, India. *Geoexploration*, 1983, **21**, 1–11.
5. Mishra, H. P., Ghatak, T. K., Rai, R. P. and Mishra, R. K., Geoelectrical studies for demarcating geothermal reservoir in Puga Valley, Ladakh District, Jammu and Kashmir. *Geol. Surv. India, Spec. Publ.*, 1996, **45**, 65–68.
6. Rakeshkumar, Singh, S. B., Sankar Narayan, P. V. and Sarma, S. V. S., On telluric current surveys in the Puga geothermal valley,

Ladakh District, Jammu and Kashmir State. Technical Report, National Geophysical Research Institute, Hyderabad, 1979, pp. 79–152.
7. Gupta, M. L., Rao, G. V. and Narain, H., Geothermal investigations in the Puga valley hot spring region, Ladakh, India. *Geophys. Res. Bull.*, 1974, **12**, 119–136.
8. Gupta, M. L., Sharma, S. R., Drolia, R. K. and Sigh, S. B., Subsurface thermal conditions of Puga valley hydrothermal field, Himalaya, India. *J. Geophys.*, 1983, **54**, 51–59.
9. Singh, R. P. and Nabetani, S., Resisitivity structure of Puga geothermal field. In Proceedings of World Geothermal Congress, Florence, Italy, 18–31 May 1995, vol. 2, pp. 887–892.
10. Chowdhury, A. N., Handa, B. K. and Das, A. K., High lithium, rubidium and cesium contents of thermal spring water, spring sediments, and borax deposits in Puga Valley, Kashmir, India. *Geochem. J.*, 1974, **8**, 61–65.
11. Chowdhury, A. N., Bose, B. B., Pal, J. C., Yudhisthir and Sengupta, N. R., Studies of some minor and rare elements in hotspring deposit from Puga, Ladakh. *Geol. Surv. India*, *Spec. Publ.*, 1984, **12**, 585–591.
12. Saxena, V. K. and D'Amore, F., Aquifer chemistry of the Puga and Chumathang high temperature geothermal systems in India. *J. Volcanol. Geotherm. Res.*, 1984, **21**, 333–346.
13. Meju, M. A. and references therein, Geoelectromagnetic exploration for natural resources. *Surv. Geophys.*, 2002, **23**, 133–205.
14. Gansser, A., *Geology of the Himalayas*, Interscience, London, 1964.
15. Ravishankar, Padhi, R. N., Prakash, G., Thussu, J. L. and Wangdus, C., Recent geological studies in Upper Indus Valley and the plate tectonics. *Geol. Surv. India*, *Misc. Publ.*, 1976, **34**, 41–56.
16. Harinarayana, T. *et al.*, Magnetotelluric field investigations in Puga geothermal region, Jammu and Kashmir, India: 1-D modelling results. *Geotherm. Resour. Counc. Trans.*, 2002, **26**, 393–397.
17. Groom, R. W. and Baily, R. C., Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion. *J. Geophys. Res.*, 1989, **94**, 1913–1925.
18. Chave, A. D. and Smith, J. T., On electric and magnetic galvanic distortion tensor deomposition. *J. Geophys. Res*., 1994, **99**, 4669–4682.
19. Rodi, W. and Mackie, R. L., Nonlinear conjugate gradient algorithm for 2-D magnetotelluric inversion. *Geophysics*, 2001, **66**, 174–187.
20. Gokarn, S. G., Gupta, G., Rao, C. K. and Selvaraj, C., Electrical structure across the Indus Tsangpo and Shyok suture zones in NW Himalaya using magnetotelluric studies. *Geophys. Res. Lett.*, 2002, **29**, 92(1–4).
21. Jones, A. G., Electrical conductivity of the continental lower crust. In *Continental Lower Crust* (eds Fountain, D. M., Arculus, R. and Key, R. W.), Elsevier, Amsterdam, 1992, pp. 81–143.
22. Ravishankar, Heat flow map of India and discussions on its geological and economic significance. *Indian Miner.*, 1988, **42**, 89–110.
23. Singh, D. D., Anelasticity of the crust and mantle beneath north and central India from inversion of the Love and Rayleigh wave attenuation data. *PAGEOPH*, 1991, **135**, 545–558.
24. Brown, L. D. *et al.*, Bright spots, structure, and magmatism in southern Tibet from INDEPTH seismic reflection profiling. *Science*, 1996, **274**, 1688–1690.
25. Turner, S. *et al*., Post-collision, Shoshonitic volcanism on the Tibetan Plateau: Implications for convective thinning of the lithosphere and the source of Ocean Island basalts. *J. Petrol.*, 1996, **37**, 45–71.
26. Ravishankar, Absar, A., Srivastava, G. C. and Pandey, S. N., Source and significance of anomalously high cesium in geothermal fluid at Puga, Ladakh, India. In Proceedings of the 21st New Zealand Geothermal Workshop, 1999, vol. 21, pp. 79–82.
27. Gupta, M. L., Singh, S. B, Sharma, S. R. and Saxena, V. K., Geothermal studies in Peninsular India and parts of Himalaya. *Geophys. Res. Bull.*, 1982, **20**, 293–308.
28. Absar, A., Kumar, V., Bajpai, I. P., Sinha, A. K. and Kapoor, A., Reservoir modelling of Puga geothermal system, Ladakh, Jammu and Kashmir. *Geol. Surv. India*, *Spec. Publ.*, 1996, **45**, 69–74.
29. Gupta, M. L., Sharma, S. R., Singh, S. B. and Drilia, R. K., Geophysical exploration and assessment of power potential of Puga geothermal field. *Geoviews*, 1979, **6**, 23–36.
30. Krishnaswamy, V. S. and Ravishankar, Scope of development, exploration and preliminary assessment of the geothermal resource potentials of India. *Geol. Surv. India*, *Rec.*, 1980, **3**, 17–40.
31. Volpi, G., Manzella, A. and Fiordelisi, A., Investigation of geothermal structures by magnetotellurics (MT): An example from the Mt. Amiata area, Italy. *Geothermics*, 2003, **32**, 131–145.
32. Stanley, W. D., Boehl, J. E., Bostick, F. X. and Smith, H. W., Geothermal significance of magnetotelluric sounding in the Easter Snake River plain – Yellowstone region. *J. Geophys. Res.*, 1977, **82**, 2501–2514.

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