J Geophys (1983) 54:51–59

Journal of Geophysics

Subsurface thermal conditions of Puga valley hydrothermal field, Himalaya, India

M.L. Gupta, S.R. Sharma, R.K. Drolia, and S.B. Singh
Geothermal Group, National Geophysical Research Institute, Hyderabad – 500 007, India

Abstract. Geothermal conditions in the Puga valley, located at an elevation of about 4400 m above mean sea level, have been studied by near surface thermal investigations and a combined interpretation of geochemical, geological and other geophysical results. We find that out of its total length of about 15 km a small part of about 4 km extent exhibits anomalous subsurface thermal conditions. In contrast with other parts of the valley, this small zone is characterised by positive 1 m temperature gradients, rapidly increasing near surface temperatures, and low resistivity (3–30 Ωm) subsurface layers. We infer that the anomalous near surface thermal conditions are caused by heat and mass transfer from a shallow reservoir of estimated temperature of about 165 °C. Wells drilled in this part of the valley yielded copious quantities of steam-water mixture. It is quite likely that the shallow reservoir derives its heat mainly through hot water which ascends from a main deep-seated reservoir of estimated temperature around 220 °C, and flows underneath only a part of the valley through N-S and NE-SW lateral channels. The main heat sources for the Puga geothermal anomaly is shown to be a medium sized intrusive body which could have been intruded during the Quaternary period, at a depth around 7 km, underneath an area located outside the valley not too far from it.

Key words: Geothermal resources – Geophysical exploration – Thermal anomaly – Lateral mass flow – Himalayan geothermal field

Introduction

There is a considerable interest in the geothermal potential of the Puga valley, which is located in the Ladakh district, in the NW Himalaya, and represents the most extensive hot spring activity in India. It is situated at an altitude of about 4,400 m above mean sea level with surrounding hills rising up to an altitude of about 6,000 m. The valley trends in almost E–W direction over a stretch of about 15 km with a maximum width of about 1 km, and lies to the south of the Indus-Tsangpo suture zone which has been believed to be a major crustal subduction zone, confirmed by the discovery of blue schist facies from its basic rocks by Virdi et al. (1977). The valley appears to be a downfaulted block with its northern and southern faults concealed under the valley material, which consists of recent to sub-recent deposits of glacial moraines (partly lake sediments), eolian sand, clay, and scree. Borax and sulphur, which are genetically connected with thermal fluids, occur widely in the eastern part of the valley. Over one hundred hot springs with temperatures varying from 35 to 84 °C (84 °C corresponds to the boiling point of water at Puga altitude) and discharges up to about 5 l/s occur. A line of old fumarolic activity, in a part along the base of the northern hill, has also been inferred from the presence of the sulphur deposits. A general geological map of the Puga valley and the adjoining areas is shown in Fig. 1. Various geological, geochemical, and geophysical investigations including exploratory drilling have been carried out in the valley and have shown that a definite potential for geothermal resources exist (Gupta, 1967; Gupta and Rao, 1971; Gupta et al., 1975, 1976, 1979; Shanker et al., 1976; Krishnaswamy, 1976).

The results of the near surface thermal investigations carried out in the valley are presented in this paper. These are discussed in the light of other related data so as to provide information on the subsurface thermal conditions of the valley and the heat source responsible for the observed geothermal phenomena.

Offprint requests to: M.L. Gupta

Near surface thermal investigations

Temperature studies at one-metre depth

Temperatures at a depth of one metre were measured by using probes, especially designed for the purpose, over a grid of 50 or 100 m covering a 7 km stretch of the valley.

Two representative isothermal maps based on these measurements are shown in Figs. 2 and 3.

Shallow temperature gradient studies

Temperatures at 0, 20, 40, 60 and 100 cm depths were measured in specially drilled small diameter holes on various traverse lines, mostly in a N–S direction. Measurements of temperature at 1 m depth were also carried out a few times daily during the field investigations at a base station near the camp. Appreciable diurnal and seasonal effects were not observed. Temperatures at various depths for some locations are shown in Fig. 4. The shallow temperature gradients generally vary from about 1.0 to 10 K m^{-1} with exceptions generally in the vicinity of hot springs.

Shallow temperature surveys were carried out during more or less the same months in two different years at

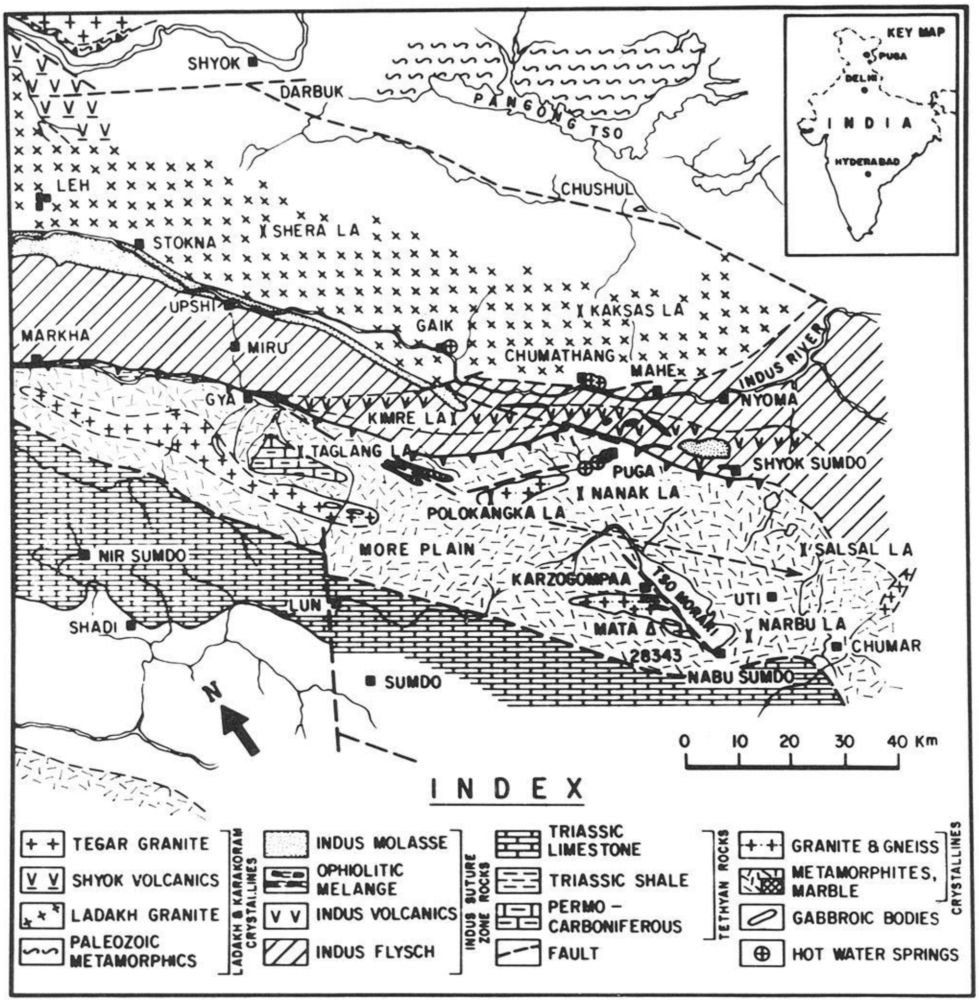

Fig. 1. Geological map of Puga-Chumatang and surrounding areas, after Sharma and Kumar (1978)

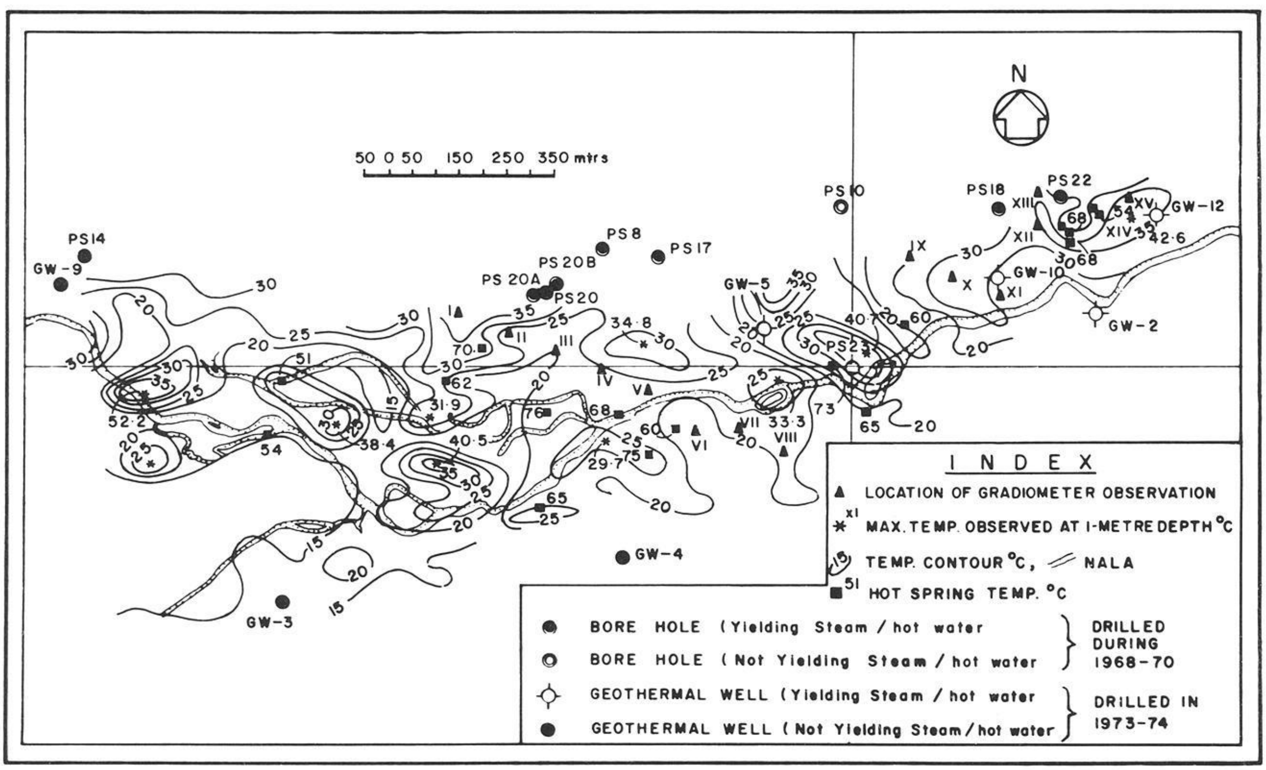

Fig. 2. Isogeotherms at 1 m depth in the Central part of the Puga valley, adopted from Gupta and Rao (1971)

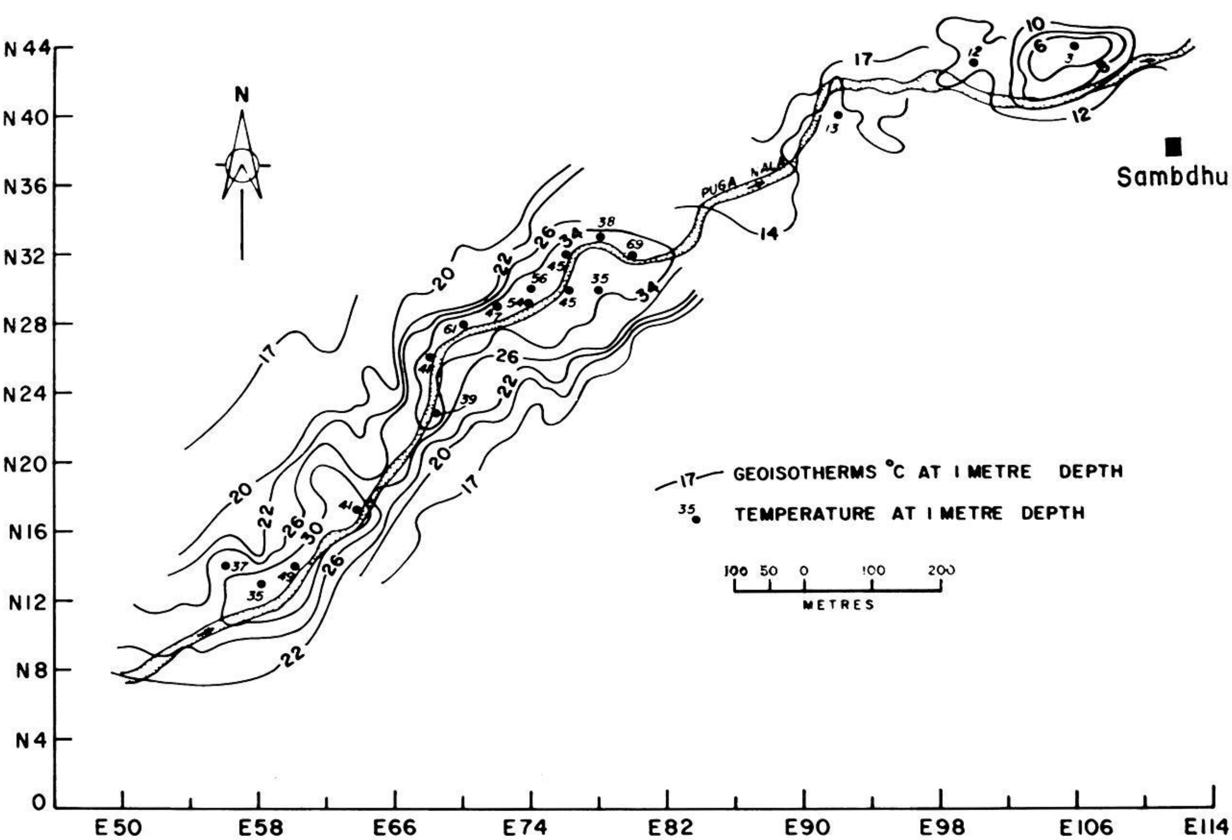

Fig. 3. Isogeotherms at 1 m depth in the Eastern part of the Puga valley

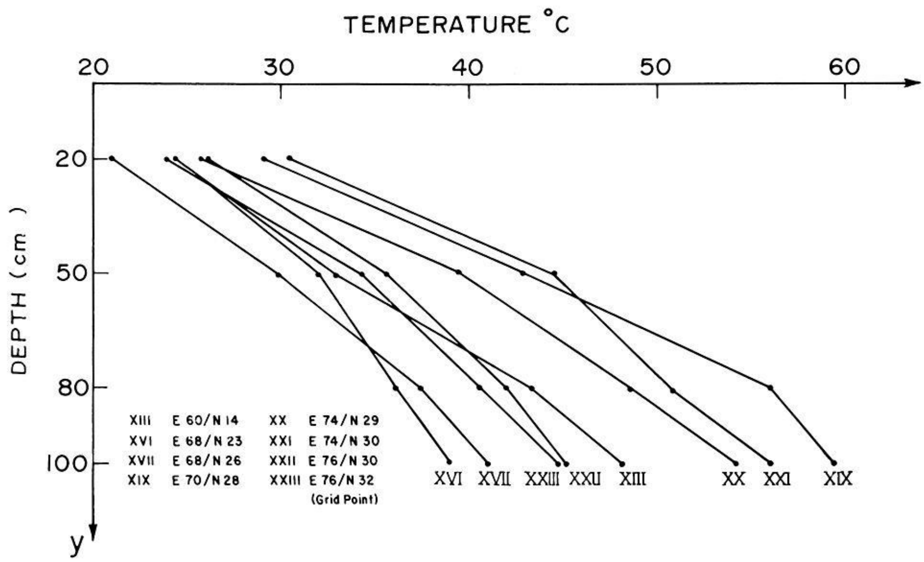

Fig. 4. Variation of ground temperature with depth at some locations

two stages. Temperature observations at base stations made in the two years showed some variation originating from the influence of annual air temperature variation. However, the variation is of a small magnitude and does not affect the overall results and inferences in the present case.

Temperature measurements in exploratory drill holes

Temperatures at up to 70 m depth, at discrete intervals in stable water column conditions, were measured in ten exploratory drill holes. Temperature gradients varying from 0.32 to 6.5 K m^{-1} were obtained.

Surface heat flow in Puga Valley

A general survey indicated that although, in some parts of the valley, the surface heat flow in the near surface layers is mainly through convective process, in most places conduction predommates. However, convection has been taken to prevail as the main mechanism of heat transfer, following

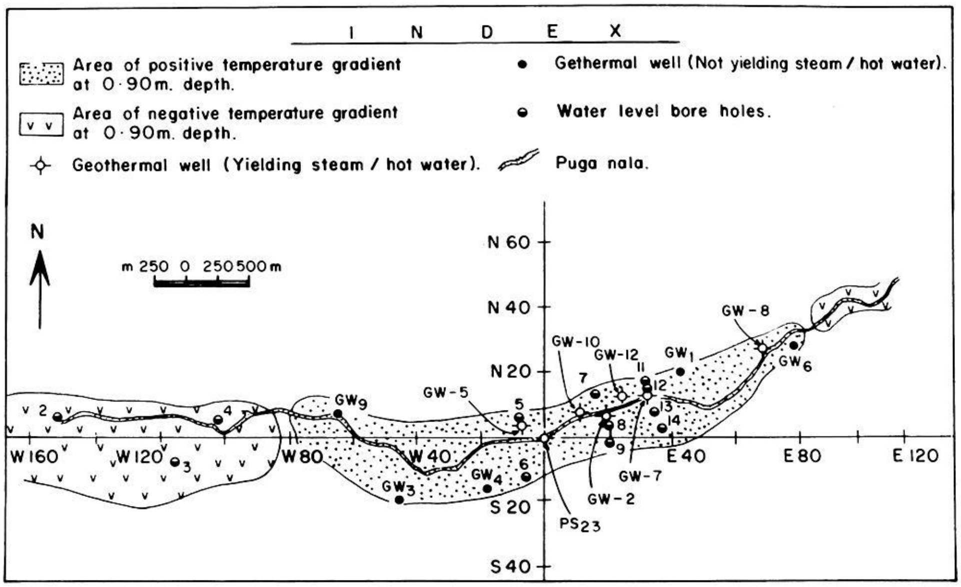

Fig. 5. Areas of positive and negative geothermal gradients (near surface) in Puga valley

a method suggested by Robertson and Dawson (1964), in areas which fell within the 30 °C isotherm at 1 m depth.

Heat flow values in areas dominated by conduction were determined by using 1 m temperature gradients and measured thermal conductivity coefficients on a large number of sediments by a so-called probe method (Gupta, 1960). The coefficient of thermal conductivity range from 1.0 to 1.7 W m^{-1} K^{-1} with a mean of 1.26 W m^{-1} K^{-1}. The heat flow values from about 1 W m^{-2} to around 12 W m^{-2} were obtained. Heat flow through the valley floor, in areas dominated by convective heat transfer, was measured by embeding sensitive heat flow transducers (Gupta, M.L., Indian Patent No. 85447), at a depth of 1 m at several locations in the valley. The heat flow transducer consisting of a large number of thermo-junctions is in the form of a thin disc. Heat flows from 12 W m^{-2} up to very high values of 100 W m^{-2} were obtained.

The coefficients of thermal conductivity of rock samples from boreholes were also determined. The heat flow calculated using the mean measured thermal conductivity of core samples and the lowest temperature gradient of 0.32 K m^{-1} observed in the non-flowing well GW3 between a depth interval 34–44 m is 0.63 W m^{-2} (15 HFU; 1 HFU = $1 \cdot 10^{-6}$ cal cm^{-1} °C^{-1} s^{-1} = 41.87 mW m^{-2}). Such a high conductive heat flow value would imply very high crustal temperatures and melting at very shallow depths. Obviously it can not be the true conductive heat flow.

Interpretation and discussion

A systematic analysis of the shallow thermal data obtained in the valley showed that the observed shallow temperature gradients are positive in a 4 km stretch of the valley, encompassing a small zone of an area of about 2.5–3 km^2 situated in its eastern portion between W80 and E82. Temperature gradients are negative outside this zone both towards the east and the west (Fig. 5).

Negative temperature gradients at shallow depths are theoretically possible and are usually observed when measurements are made during summer in an area which is not characterised by very large conductive or convective heat flows.

It can be shown that the temperature gradients at a depth Z from the surface due to solar radiation is given by (Ingersoll et al., 1954):

$$\frac{\partial T}{\partial Z} = T_o e^{-Z\mu}(-\mu)\,[\sin(\omega t - Z\mu) + \cos(\omega t - Z\mu)].$$

The temperature gradient would be negative during one half the cycle (in summer) and positive (in winter) during the other half.

The combined temperature gradient due to both solar radiation and terrestrial heat flow is given by:

$$\frac{\partial T}{\partial T} = G + T_o e^{-Z\mu}(-\mu)\,[\sin(\omega t - Z\mu) + \cos(\omega t - Z\mu)].$$

Where

G = is the temperature gradient due to heat flow from the earth's interior

T_o = is the amplitude or half range of the temperature at the surface

t = is the time with respect to the nearest maximum or minimum temperature at the surface

$\mu = \sqrt{\frac{\omega}{2\alpha}}$

α = is the thermal diffusivity of the subsurface formations

ω = is the fundamental radiation frequency, $2\pi/P$ where P is the period of the temperature wave

Climatological data for Puga valley have been collected during only a few months over many years. However data are regularly recorded by the Indian Meterological Department (IMD) for Leh (location shown in Fig. 1) and have been for several decades. Considering the IMD climatological data for Leh and applying the elevation correction for the Puga valley, the average maximum and minimum air temperatures, which occur in the months of July and January, can be taken as 19° C and −20° C respectively for

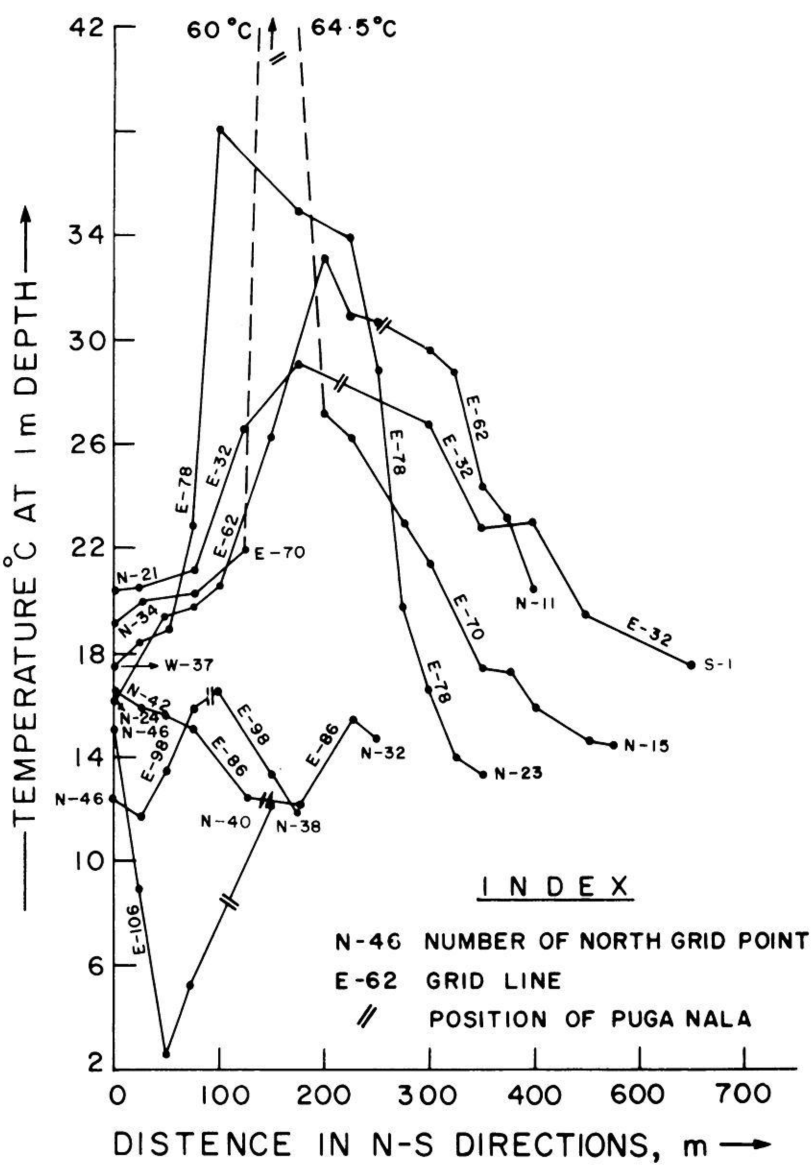

Fig. 6. Variation of ground temperature °C at 1 m depth in N-S direction

the valley. These have been used to demonstrate the occurrence of negative temperature gradients at 1 m depth in a part of the Puga valley during the period of near surface geothermal investigations.

Considering the following parameters:

$t = 60$ days $\precsim 5.2 \times 10^6$ s

after the occurence of maximum air temperature in the Puga valley.

T_0 = amplitude or half range of the temperature at the surface $\approx \pm 19.5°$ C.

$\alpha = 0.005$ and $0.01\ \mathrm{cm^2\ s^{-1}}$.

We obtain that the temperature gradients at a depth of 100 cm during the month of September, on account of the annual temperature wave due to solar radiation would be:

≈ -0.08 and $-0.06\ \mathrm{°C\ cm^{-1}}$

for $= 0.005$ and $0.01\ \mathrm{cm^2\ s^{-1}}$ respectively.

The temperature gradient due to terrestrial heat flow, even if we consider a postulated Quaternary magmatic body to occur in the vicinity of the valley, is not likely to exceed $+0.02\ \mathrm{°C\ cm^{-1}}$. Therefore, the observation of negative temperature gradients during summer months in a part of the Puga valley is in order. The positive temperature gradients in a small area of the valley (Fig. 5) have been caused by upflow of large quantities of heat through processes of conduction, convection and mass transfer.

Temperatures at 1 m depth in the anomalous zone are high along both banks of the Puga nala and decrease towards the foot hills. This pattern appears to be reversed towards east as in temperature profiles E86 and E106 (Fig. 6). Such a near surface thermal character appears to have been caused by the upflow and spread of hot water underground.

The isotherms (Fig. 2) in the central part of the valley, based on measurements made before exploratory boreholes were drilled, give a very good picture of the subsurface thermal conditions. The general appearance of the isogeotherms strongly suggests that a great deal of hot water and consequently much of the heat flow is transported through relatively isolated channels or groups of channels, which appear to be shaped more like pipes than elongated cracks or fissures. In places, there is some suggestion of alignment of these passages along what may be more extensive faults. The trend of these passages also coincides roughly with the general course of the main stream draining the valley.

The isotherms close up near the location of three boreholes (20, 20A and 20B; Fig. 2) which were drilled for exploration of sulphur and encountered thermal fluids. There is an indication that the 35 °C isotherm may continue near and parallel to the location of these boreholes. This zone seems to be a good area for encountering thermal fluids of high temperature and pressure.

Borehole PS22 (Fig. 2) which also encountered streams of hot water, is located near another 'High Temperature Zone'. The area under the 30 °C isotherm is the largest in this zone. This seems to be a very promising zone, and warrants deeper exploration (Gupta and Rao, 1971). Geothermal wells (GW-10 and GW-12), drilled later during 1973 and 1974 in this eastern high zone, encountered steam/water mixture under pressure.

Near the PS23 borehole (Fig. 2) the temperature contours show a NW-SE trend. This is most probably controlled either by the basement structure or by hot water flow in a narrow channel. This is another high temperature zone and borehole GW5, drilled later during 1975 in this zone, encountered thermal fluids under pressure, incidentally demonstrating the usefulness of the 1 m temperature studies as a rapid and quick method for determining subsurface thermal conditions.

The temperature data of the exploratory wells clearly showed that the near surface layers of the central part of the valley are characterised with high temperature gradients, which generally start decreasing after a particular depth in each drill hole. Such a behaviour suggests that a hydrothermal convective system is located at a very shallow depth. Wells drilled to deeper depths tapped buoyantly rising thermal fluids.

Puga valley hydrothermal system

The system under study is a valley filled with sediments. These are generally saturated with cold water and at places with mineralized (about 1,800 ppm of dissolved solids), uprising, deep thermal waters, which may flow either laterally into the valley at certain depths from elsewhere or from the deeper parts of the valley, through connected faults and fissures. The ascending thermal fluids, when flowing in a top of permeable layer, would gradually cool and naturally deposit dissolved constituents. This in turn, reduces their effective porosity, and renders them wholly or partially impermeable thereby forming a self sealed cap rock. Thus in the case of Puga valley some layers of the sediments of its eastern part, under which channels of thermal waters exist, have been more or less cemented and behave like a rock of low permeability. The valley fill material has become reconsolidated and compacted by silica into a hard breccia like rock by the natural thermal fluids (Shanker et al., 1976). The depth of cemented rock depends on the past history of sedimentation, thermal and tectonic activity.

High temperature gradients are registered in drill holes in top layers of reduced permeability due to the predominance of conduction. The lowering of the gradient values is due to the wells opening into formations in which temperature equilibrium takes place due to convective fluid motion. In certain parts, due to saturation of near surface layers from rapid rise of thermal waters at the surface, convection may play a significant role in heat transfer as has appeared to be the case in some parts of the valley.

The high and rapidly increasing near surface temperature points to a heat source nearby, probably a hydrothermal reservoir. As pointed out earlier, an area of about 2.5 to 3 km^2 of the valley, situated in its eastern part (Fig. 5), is characterised by abnormally high subsurface temperature and temperature gradients. The electrical resistivitiy soundings and profiling data (Gupta et al. 1976), and telluric current surveys (Rakesh Kumar et al., 1979) corroborate and substantiate the results of thermal investigations (Fig. 7). The above mentioned hot zone was found to be characterised by low resistivity (10 to 30 Ωm) subsurface formations with some isolated zones of still lower resisitivity values (3–6 Ωm). The thickness of the zone generally varies from 30 to about 170 m. Some thick layers ($\approx$250 m), of low resisitivity, were also found in the south-western portion of the valley. The analysis of tellurograms recorded with mapping techniques indicated two locations of abrupt changes of resisitivity (Fig. 7) between which there seems to a belt of very low resistivity (Rakesh Kumar et al., 1979).

According to the chloride contents of its thermal waters, the Puga hydrothermal reservoir is of hot water type. Almost equal values of temperature varying from 183 to 235 °C, from Na/K and Na-K-Ca geothermometers and a much lower temperature of 167 °C from the Silica geothermometer were reported for the Puga hydrothermal reservoir by Gupta (1974) and Gupta et al. (1975, 1979). The upper limit for the enthalpy of Puga thermal waters, according to Gupta et al. (1979), is 1,150 $\mathrm{Jg^{-1}}$. The theoretical maximum temperature of the source possessing this value turns out to be 265 °C. Generally subsurface temperatures in a hydrothermal area are lower than the boiling point of water for the corresponding depth. Under such conditions a temperature of 265 °C should occur at a depth of about 600 m.

It is obvious that the Silica geothermometer has reflected the temperature of the shallow reservoir, delineated by the geothermal and geoelectrical surveys and exploratory drillings. The majority of the shallow and medium depth drill holes in the valley tapped steam-water mixture and bottom hole temperatures up to 135 °C were recorded. The actual temperature of the thermal water in the shallow reservoir must be higher than this value, as its value should decrease both due to heat losses during ascent and flashing of thermal water into steam. A consideration of the aforesaid points separately also yield a reservoir temperature around 165 °C. High temperatures (210–240 °C), as obtained from Na/K and Na-K-Ca geothermometers, indicate the existance of a main reservoir at great depths. However geophysical surveys carried out so far in the valley have not been able to locate this.

The results of investigations so far carried out clearly indicate the existance of a sizeable shallow reservoir of hot water type with some pockets dominated by gas/vapour in the central part of the valley. The shallow exploratory geothermal wells have registered well-head pressure and fluid discharge upto 3.1 $\mathrm{kg \cdot cm^{-2}}$ and 7.5 $\mathrm{kg \cdot s^{-1}}$, respectivley, with 131 °C being the highest temperature registered

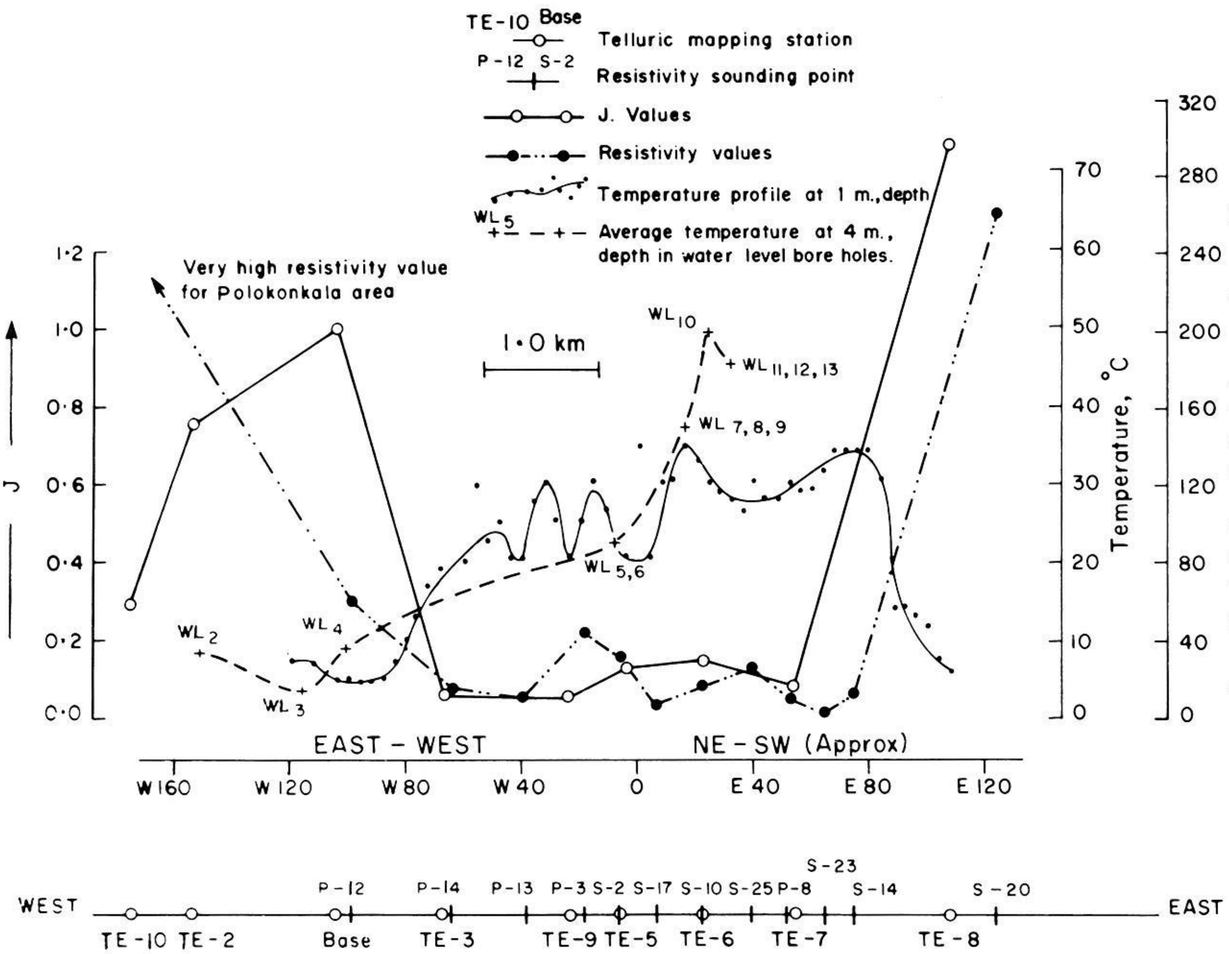

Fig. 7. Temperature at 1 m and 4 m depths. True resistivity and *J*-values (relative ellipse area) in Puga valley

at the well head with about 20% of steam in the total discharge. The thermal fluids issue out from a zone of porous breccia of varying thickness from 30 to over 100 m. The geothermal fluids have been used for experimental space heating and refinement of borax and sulphur on a suitable large scale. On the basis of inductive reasoning, locations have been selected and wells are being drilled to tap the deeper reservoir. It is believed that generation of electric power would be feasible using the fluids tapped from the lower reservoir.

Heat source

All the above reported thermal investigations yield information of the prevailing thermal conditions within the sediments, and do not provide constraints on the deep heat source. The natural heat loss from the valley has been estimated to be around 23×10^6 Js^{-1} (Gupta et al., 1974, 1979). Even if one assumes a regional high heat flow around 100 mW m^{-2} in this part of the Himalaya, a very large area is necessary to provide the estimated amount of natural heat to the flowing water. Secondly, a depth around 6 km is required to attain a temperature of 220 °C. There is also probelm in accounting for large heat losses in considering the ascent of 220 °C thermal water originating at 6 km to the shallow reservoir, and there are other associated problems. It appears unlikely that the Puga geothermal anomaly owes its origin to regional high heat flow.

Sulphur and borax deposits occur in the valley and are related to the thermal waters, which are also associated with high contents of Cs, Li, Rb etc. in general geochemical considerations indicate an association of thermal waters with magmatic components and with a late stage of magmatic activity (Gupta 1967, 1974; Shanker, 1976; Chowdhury et al. 1974). Studies of oxygen and hydrogen isotopes in Puga thermal waters (Kumar et al., 1982) show the association of waters with high temperature rocks. According to Gupta (1979) and Gupta and Sharma (1982) the tectonic environment has been conducive to the generation of crustal melting and formation of intrusive bodies in the region under investigation during most of the stages of tectogenesis and orogenesis of the Himalaya. All the available data points to an intrusive body as the most likely source of heat for the Puga valley geothermal activity. The inference of Gupta and Sharma (1982) that the present heat loss (23×10^6 Js^{-1}) from the Puga valley can be provided by a Quaternary intrusive body of about 25 km × 25 km, existing at a depth around 7 km seems to be appropriate. We estimate that the present surface heat flow, regional plus transient contribution from such an intrusive body, in the area is to be around 210 mW m^{-2}. In this case a temperature of 220 °C is likely to be encountered at a depth around 2.5 km. Impervious rocks have been assumed at lower depths. If not so, then the estimated depth would be appreciably reduced due to convective heat flow and mass flow. About 25–30 l s^{-1} of water heated to about 200 °C, after coming in contact with heated rocks at depths, is sufficient to supply the amount of heat which is continuously discharged from the valley through natural process. Considering the size and the area of surface thermal activity, it is appropriate that the body should be either outside the valley or near its fringes.

Location of heat source

Gupta and Rao (1971) stated that a great deal of hot water flow and consequently much of the heat flow, does take place through relatively isolated channels or group of channels in the Puga valley. Gupta et al. (1975) inferred lateral flow of thermal fluids approximately in N-S and NE-SW direction. N-S subsurface feature as detected by gravity and magnetic surveys in the valley have been reported by Shanker et al. (1976). The indentation and trend of isogeotherms (Figs. 2 and 3) also suggest channelised flow of thermal water. Two telluric profiles from W30 to E60 and E60 to E110, respectively, along the northern hillside also seem to support the presence, across the valley, of lateral low resistivity channels, which might act as the carriers of thermal fluids to the shallow reservoir (Rakesh Kumar et al., 1979). It appears that the N-S; NE-SW (NW-SE??) features which have been delineated by geophysical investigations are the possible passages through which thermal fluids enter the valley at certain depths and then escape to the surface through favourable paths. A cluster of epicentres of microearthquakes have been obtained at a depth of around 6–7 km towards the NE of Puga valley (H.M. Choudhary, pers. comm.). It is, therefore, likely that the heat source for the Puga valley geothermal anomaly lies towares North of the valley. MT, AMT, surveys and other investigations are recommended to confirm or reject this theory. Flow of thermal waters in the valley in NS, NE-SW (NW-SE??) channels appears to be most likely, but its direction of entry into the valley, on the basis of the present day knowledge, is unknown.

Conclusions

The above mentioned studies lead to the following main conclusions:

That only a part of the total length of the Puga valley exhibits anomalous sub-surface themal conditions.

That on the basis of the inferred subsurface thermal conditions the valley can be divided into two parts viz., into one part which is characterised by low (normal for the location of the valley) subsurface temperatures and into another part which is chracterised by abnormal surface and subsurface temperatures.

That a thin cap rock at shallow depths has been formed within the valley sediments due to cementation from the deposit of salts from the thermal waters.

That the abnormal thermal conditions are caused by heat and mass flow from an underlying shallow reservoir of hot water having a temperature around 167 °C.

That either a basement fault or a sloping basement exists in the valley towards W of SW of grid point W70.

That the shallow reservoir appears to have been regularly fed with about 25–30 l s^{-1} of thermal water at about 220 °C from N-S, NE-SW lateral channels probably from a deep seated main reservoir.

That the total natural heat loss from the valley can be caused by an intrusion of moderate size (25 × 25 km), intruded during the Quaternary period at a depth around 7 km.

Acknowledgements. We are grateful to our colleagues S/Sri G.L.N. Reddy and A. Yadagiri for assistance in field work, and to various officers of Geological Survey of India for providing help at various stages during field investigations, to Sri G. Ramacharyulu for typing the manuscript and some computational work and to the Director, NGRI for according approval of publish this paper.

References

Chowdhury, A.N., Handa, B.K., Das, A.K.: High lithium, rubidium and cesium contents of thermal spring water, spring sediments and borax deposits in Puga valley, Kashmir, India. J. Geochemistry, **8**, 61–65, 1974

Gupta, M.L.: A rapid in situ method for determining thermal conductivities. J. Sci. Indus. Res. **413**, 240–243, 1960

Gupta, M.L.: A preliminary account of geothermal investigations of hot springs of Puga valley, Ladakh. Nat. Geophys. Res. Inst. Tech. Rep. No. 67–13, 1967

Gupta, M.L.: Geothermal resources of some Himalayan hot spring areas. Himalayan Geology **4**, 492–515, 1974

Gupta, M.L.: Acidic magmatism and tectonics of Himalayas – Paper presented at IUGG Interdisciplinary symposium on "Heat production and generation of magma". IUGG XVII General Assembly symp. Digest, 441, Dec. 1979

Gupta, M.L., Rao, G.V.: Report on shallow temperature surveying in the Puga valley hot spring region. Nat. Geophys. Res. Inst. Tech. Rep. No. 71–39, 1971

Gupta, M.L., Sharma, S.R.: Possibility of Quaternary magmatic activity in Ladakh, Himalaya, India. Nat. Geophys. Res. Inst. Hyderabad, India. Annual Report 2, 1981–82

Gupta, M.L., Rao, G.V., Hari Narain: Geothermal investigations in the Puga valley hot spring region, Ladakh, India. Geophys. Res. Bull. 12 (2 & 3), 119–136, 1974

Gupta, M.L., Singh, S.B., Drolia, R.K., Sharma, S.R.: Horizontal (or lateral) flow of hot water in Puga hydrothermal field, Ladakh, India. 2nd UN Symp. on the Development and Use of Geothermal Resources, San Francisco, California, USA. Symp. Digest, III-35, 1975

Gupta, M.L., Singh, S.B., Rao, G.V.: DC Resistivity studies in Puga geothermal field, Himalayas, India. Proceedings of 2nd UN Symp. on the Development and Use of Geothermal Resources, San Francisco, California, USA, 1029–1036, 1976

Gupta, M.L., Sharma, S.R., Singh, S.B., Drolia, R.K.: Geophysical exploration and assessment of power potential of Puga geothermal field. In: Procedings of the Seminar on "The Development & Utilization of Geothermal Energy Resources. Hyderabad, India, M.S. Bhalla and M.L. Gupta, eds.: pp 23–36, 1979

Ingersoll, L.R., Zobel, O.J., Ingersoll, A.C.: Heat Conduction with engineering, geological and other applications. The University of Wisconsin Press, Madison, 49, 1954

Krishnaswamy, V.S.: A review of Indian geothermal provinces and their potential for energy utilization. Proc. 2nd UN Symp. on the Development and Use of Geothermal Resources, San Francisco, California, USA, 143–156, 1976

Kumar, B., Sahay, K.S.N., Baksi, A.K., Gupta, M.L.: Oxygen and Hydrogen isotopic composition of waters of Puga and Manikaran Geothermal Areas (Himalaya) India. In: Geothermics and geothermal energy, E. Schweizerbartsche Verlagsbuchhandlung, Stuttgart, West Germany, V. Cermak, R. Haenel, eds.: pp. 211–218, 1982

Rakesh Kumar, Singh, S.B., Sanker Narayan, P.V., Sarma, S.V.S.: On telluric current surveys in the Puga geothermal valley Ladakh district, Jammu and Kashmir State, India. Nat. Geophys. Res. Inst. Tech. Rep. No. 79–152, 1979

Robertson, E.I., Dawson, G.B.: Geothermal heat flow through the soil at Wairakei, New Zealand, J. Geol. Geophys. **7** (1), 134–143, 1964

Shanker Ravi, Padhi, R.N., Arora, C.L., Prakash Gyan. Thussu, J.L., Dua, K.J.S.: Geothermal exploration of the Puga-Chumatang geothermal fields, Ladakh, India, Proceedings of the 2nd UN Symp. on the Development and Use of Geothermal Resources, San Francisco, California, USA. 245–258, 1976

Sharma, Kewal K., Kumar Surendra: Contribution to the geology of Ladakh, North Western Himalaya. In: Himalayan Geology **8** (1), S.P. Nautiyal, ed.: pp. 252–287. Wadia Institute of Himalayan Geology, Dehradun 1978

Virdi, N.S., Thakur, V.C., Kumar, S.: Blueschist facies metamorphism from the Indus suture zone of Ladakh and its significance. In: Himalayan Geology **7**, A.K. Sinha, ed.: pp 479–482. Wadia Institute of Himalayan Geology, Dehradun 1977

Received November 9, 1981;
Revised version October 11, 1982 and July 4, 1983
Accepted July 6, 1983