

A CASE STUDY OF PUGA GEOTHERMAL SYSTEM, LADAKH, INDIA

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SUMMARY - Puga, the most promising hydrothermal system of the Indian subcontinent, is a fault-bounded system with a well-defined resistivity boundary. The deep reservoir, hosted by granitic rocks, lies underneath the southern ridge and thermal manifestations within the valley are fed by an easterly outflow within the shallow reservoir comprising reconsolidated morainic breccia and granite/gneiss. Although temperatures in excess of 250°C are expected at the deepest levels (~ 3 km) of the system, shallow reservoir, readily accessible by drilling, is expected to yield fluids with temperatures of at the most 200°C. The system is indicated to have conditions conducive for epithermal mineralisation. Moreover, it has striking similarities with the Yangbajing system of Tibet, China.

1. INTRODUCTION

A strong possibility of resumption of geothermal exploration programme at Puga in the near future and need to update major inferences drawn since the publication of a detailed account of the first two years of studies (Ravi Shanker *et al.*, 1976) have acted as a source of inspiration for presenting this case-study of the most promising active hydrothermal system of the Indian subcontinent.

Puga Valley, located at an altitude of about 4400 m above m.s.l., in the Ladakh region of Jammu and Kashmir State, is dotted with more than a hundred hot springs of temperatures varying from 28° to 84°C (local boiling point). Geothermally anomalous area stretches for over 5 km along the Puga stream and has a maximum width of about 1 km. Cumulative natural discharge from the field is of the order of 30 ls⁻¹.

Some of the characteristic surface hydrothermal features of the Puga geothermal system are eruption breccia in the eastern part, nearby advanced argillic alteration zones comprising mainly kaolinite, pockets of sulphur along the base of the ridges bounding the valley, carbonate deposits and mounds along the stream course and encrustations of borax and other sublimates spread over the entire geothermally anomalous area. There are also some suspected eruption craters, 2 to 10 m across, now occurring as hot water pools, mud ponds and alluvium - filled depressions (Fig. 1).

2. GEOLOGICAL AND TECTONIC FRAME-WORK

Puga is located just to the southwest of the NW-SE trending Indus Suture Zone (ISZ), the latter practically defining the eastern limit of the

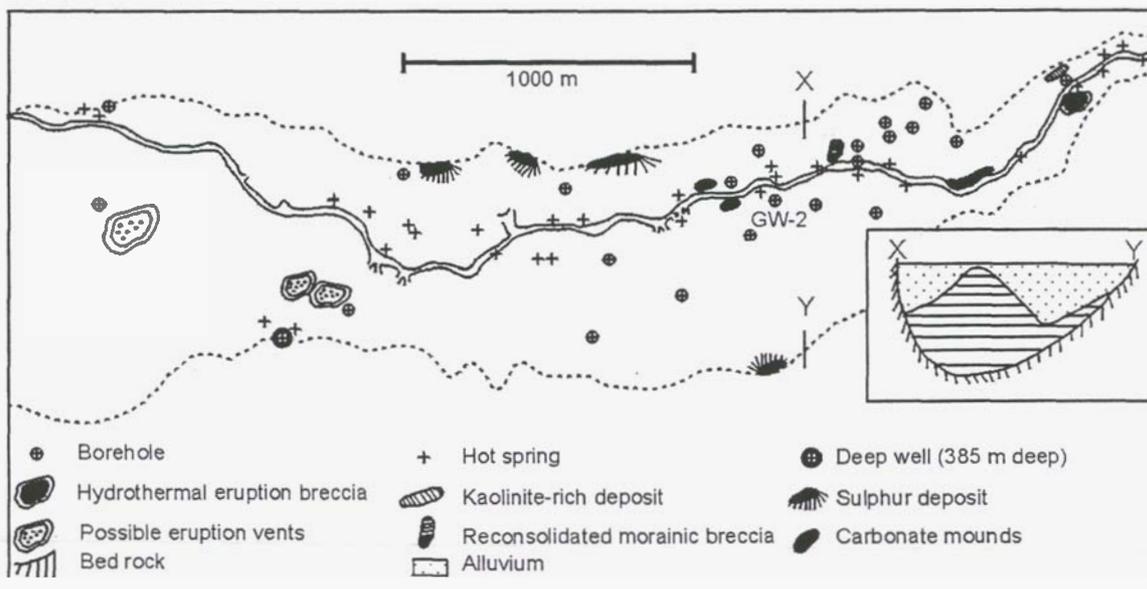


Figure 1 - Map showing surface alteration features of Puga valley geothermal system. Inset shows subsurface disposition of reconsolidated morainic breccia.

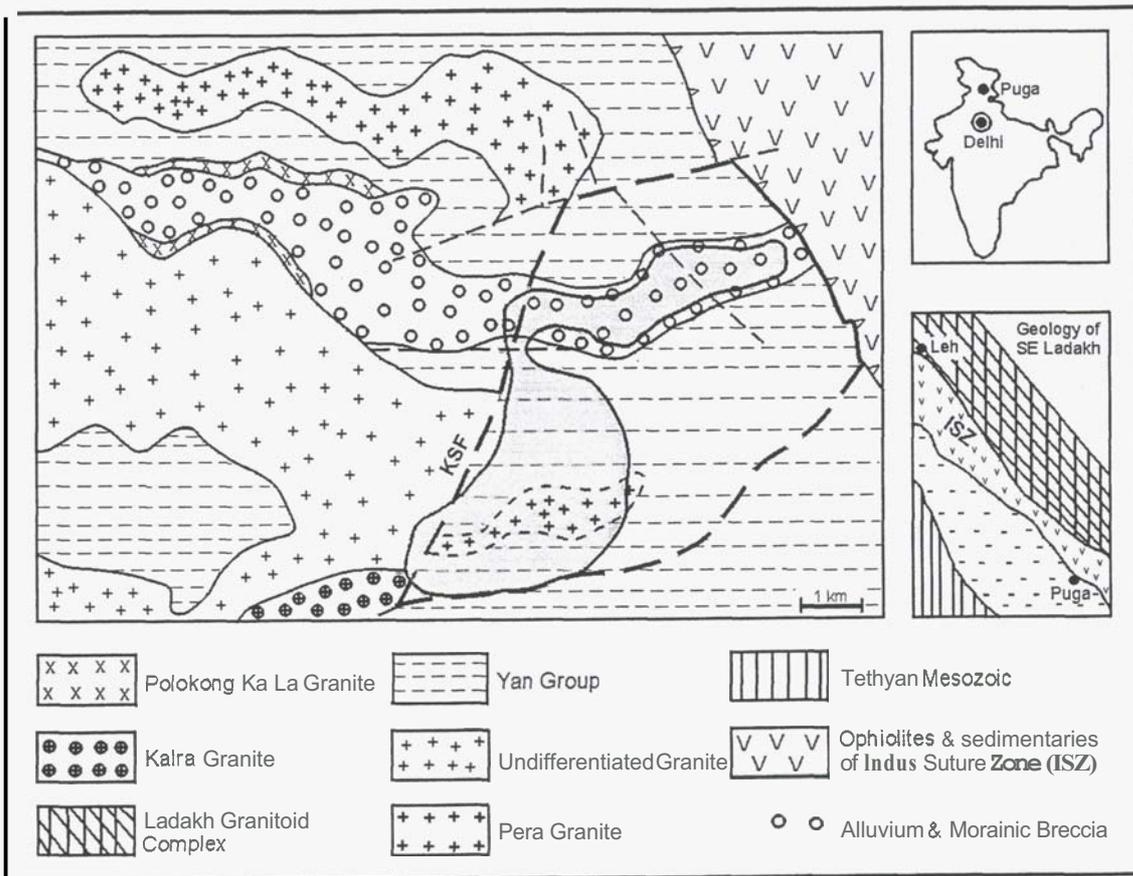


Figure 2 - Geological map of the area around Puga valley. The geothermal system is fault-bounded (faults shown in bold). Conductive zone, depicted by 30 ohm-m resistivity contour (shaded), extends underneath the southern ridge implying that the main reservoir may not be vertically below the valley.

geothermal system (Fig. 2). Rocks exposed around Puga are gneiss, garnet-mica and kyanite schist, quartzite, carbonaceous phyllite and limestone belonging to the Yan Group of Upper Palaeozoic age. These rocks unconformably overlie Lower to Middle Palaeozoic Polokong Ka La Granite and are intruded by amphibolite, eclogite and at least two distinct phases of acid intrusives, Kalra and Pera Granites, respectively (Virdi *et al.*, 1978; Absar, 1981).

A rather unique feature of the Puga geothermal system is that it is fault-bounded (Fig. 2). Field characteristics of Pera Granite and its relationship with the Kiagar Tso Fault (KSF, demarcating the western limit of the geothermal field), indicate that the youngest acidic intrusive activity in the area is of Tertiary age and that it predates the latest tectonic events. The geothermal activity in the area, therefore, might have initiated during the Quaternary period, when near present-day physiography facilitated setting-in of fluid circulation patterns between recharge areas and discharge sites to keep the system going till date.

3. GEOPHYSICAL SURVEYS

Though all conventional geophysical surveys were carried out, D.C. resistivity measurements using bipole-dipole and dipole-dipole mapping techniques and AMT surveys have, in particular, provided some very valuable information. Resistivity surveys have identified the western extremity of the conductive zone, which coincides with the Kiagar Tso Fault. Moreover, it has been clearly brought out that the geothermal system does not extend to much deeper levels vertically below the valley. The interpreted geothermal zone in the valley, extends to about 200 m in the western part and is even shallower in the eastern part (Mishra *et al.*, 1996).

AMT surveys, based on 75 soundings for frequencies of 20 Hz and above, in both N-S and E-W orientations of electric dipoles, have revealed a very well defined low-resistivity zone. This zone has a N-S trend extending underneath the southern ridge bounding the Puga valley. It, however, spreads into E-W direction in the valley. The presumed resistivity boundary of the geothermal system has been superimposed over the geological base in Figure 2. It is interesting to note that within this 30 ohm-m contour, resistivity

values of < 5 ohm-m occupy an area of about 6.5 km², more than the geothermally anomalous area marked on the basis of surface manifestations in the valley.

The lowest recorded value of 1 ohm-m is confined to a very narrow N-S trending zone in the median part of the southern ridge. It may probably indicate an upflow zone or a major conduit (Absar, 1981).

AMT and resistivity surveys thus indicate that the main reservoir, in all likelihood, occurs at a considerable depth underneath the southern ridge. Thermal manifestations in the valley, however, are fed by an outflow of hot fluids, which probably enters the western part of the valley through N-S trending conduits.

4. THE SHALLOW RESERVOIR

During the course of geothermal investigation, a total of 34 drillholes, ranging in depth from 30 to 385 m, were drilled. While some very shallow boreholes were confined to the overburden, 17 deeper boreholes struck blow-out conditions from within a grey coloured, relatively hard rock with a look of a breccia. Refraction seismic surveys indicate the depth to breccia from 20 to 50 m in the eastern part of the valley which deepens to 136 m towards the western end of the hot spring zone. This breccia is exposed near the cluster of wells northeast of GW-2 (Fig. 1). It consists of clasts of all the rock types present in the area, which are cemented together by fine sand, some clayey matter, silica and carbonate.

Clearly, the breccia forms part of the shallow reservoir at Puga. Boreholes have met with blow-out conditions 2 to 43 m below the overburden-breccia interface. There is hardly any doubt that moraines left in the valley after Pleistocene glaciation have been indurated as a result of geothermal solution action. Consolidation of moraines has been accompanied by propagation of hydraulic fracturing which facilitates ascent of fluids from deeper levels as well as their lateral flow. In the light of geophysical data, at least 100 m of gneiss and granite underlying the breccia may also be part of the shallow reservoir within the Puga valley.

5. GEOCHEMISTRY OF THERMAL DISCHARGES

Major ions chemistry of Puga valley thermal discharges is given in Table-1. Remarkable uniformity in chemical composition of borehole and spring discharges is clearly a characteristic feature of Puga geothermal system (Fig. 3). Consistent abundances of non-reactive ions, such

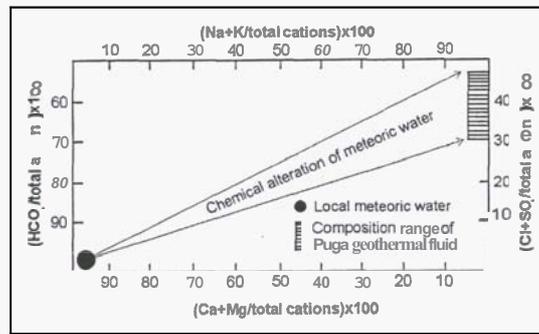


Figure 3 - Plot showing relative abundances of major cations and anions in Puga thermal discharges. Meteoric water has been chemically altered as a result of water-rock interaction to give rise to the Puga geothermal fluid. Remarkable similarity in composition of thermal discharges is a characteristic feature of the Puga-system.

as, Cl, B and F, provide unequivocal evidence for single source of thermal discharges. Moreover, groundwater mixing at shallow levels is either trivial or the fluids have been thoroughly stirred-up after dilution.

The Puga fluid is relatively dilute (TDS ~ 2400 mg/l⁻¹) HCO₃-Cl type water with abundance of alkalis and rare alkalis. It has relatively high concentrations of SO₄, B and F and has a molal Na/K of about 13. It is unique in having the highest relative concentration of Cs and being the only known geothermal fluid with Cs > Li (Ravi Shanker, *et al.*, 1999).

Gases in thermal discharges consist of CO₂, H₂S, NH₃, N₂, CH₄ and He, in the same order of abundance. Carbondioxide and He are 88 to 99 and 0.04 to 0.22 percent, respectively, of the total volume of gases collected. Empirical gas geothermometry gives temperature of 175 to

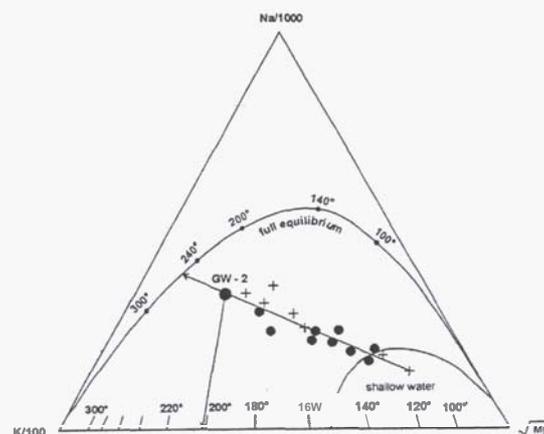


Figure 4 - Na-K-Mg plot showing thermal discharges in various stages of partial equilibrium. GW-2 discharge is the nearest representative of the Puga deep fluid, which has evidently attained Na-K equilibrium at 255°C. The shallow reservoir temperature is indicated to be around 200°C.

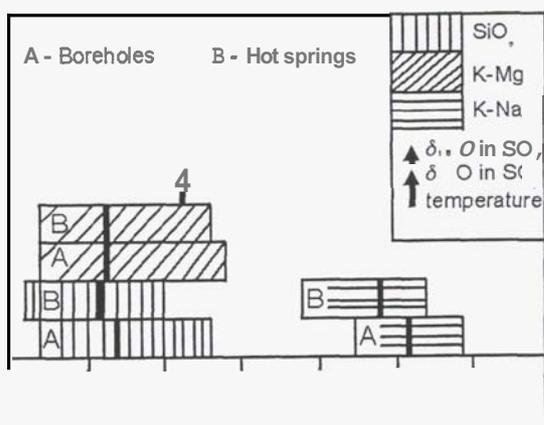


Figure 5 - Reservoir temperatures estimated using various thermometries. Similar SiO₂ and K-Mg temperatures imply that the latest re-equilibration of SiO₂ has occurred in the shallow reservoir.

205°C (Srivastava, *et al.*, 1996) for the latest equilibrium of gases.

Minor elements, such as, Ba, Sr, Pb, Zn, and Cu have been analysed in the Puga fluid, their average values being 0.2, 0.5, 1x10⁻³, 4x10⁻² and 5x10⁻³ mg l⁻¹, respectively. Gold value determined in a sample from borehole GW-2 was 2x10⁻⁵ mg l⁻¹.

As Na, K and Mg ions are temperature dependent, Na-K-Mg plot of Giggenbach (1986) has been used to get an idea about the reservoir temperatures at Puga (Fig. 4). In spite of samples being in different stages of equilibration, a trend line is observed, which joins the least equilibrated samples with that of borehole GW-2. Discharge from GW-2 may be taken as the nearest representative of the deep fully equilibrated fluid with a temperature of 255°C. Taking fast equilibrating Mg into consideration, it is seen that GW-2 discharge is derived from a shallow reservoir at a temperature of about 200°C.

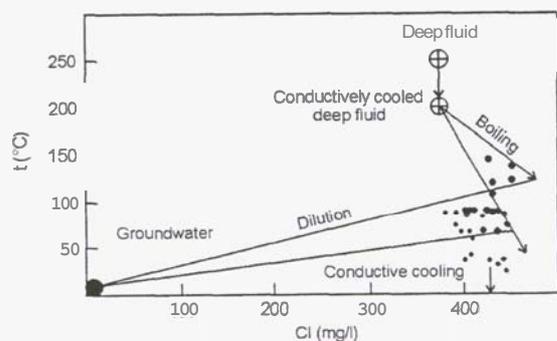


Figure 6 - Chloride-temperature relationships indicate that conductively cooled deep fluid has boiled causing a steam loss of 20%. Minor post-boiling dilution (at the most 15%) has affected most of the thermal discharges.

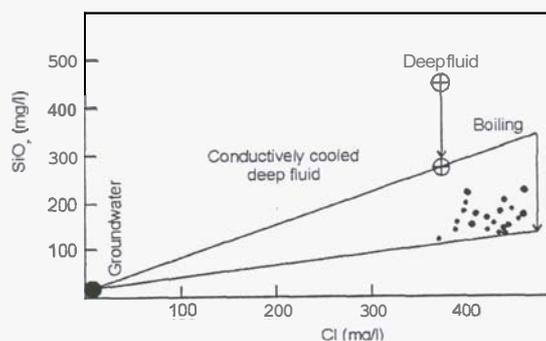


Figure 7 - SiO₂-Cl plot giving evidence for boiling and consequent SiO₂ precipitation in the shallow reservoir.

Reservoir temperatures calculated using empirical equation (Giggenbach, *et al.*, 1983; Giggenbach, 1986) are compared in Figure-5. Silica and K-Mg temperatures are almost identical implying that the latest silica re-equilibration has occurred within the shallow reservoir. A temperature of 180°C, estimated using ¹⁸O fractionation between water and its sulphate content, is also in agreement with SiO₂ and K-Mg temperatures.

Accepting a temperature of 255°C for the deep fluid before steam loss and a shallow reservoir temperature of 200°C as given by GW-2 discharge (Fig. 4), temperature-Cl and SiO₂-Cl relationships may be used to understand reservoir-related processes. For a steam fraction of 0.2, deep fluid is inferred to have a Cl content of 375 mg l⁻¹. This fluid gets conductively cooled to 200°C to match the composition of pre-steam loss GW-2 discharge. Boiling of this fluid followed by dilution by groundwater explains temperature-Cl relationship of most of the thermal discharges (Fig. 6). Mass balance indicates that fraction of groundwater present in thermal discharges probably does not exceed 15%. Relatively low temperature hot springs plotting below the dilution trend are from the western part of the valley where thickness of overburden is >100 m. Post-dilution conductive cooling, therefore, may be a distinct possibility in their case.

Silica-chloride plot (Fig. 7) shows that the deep fluid with 450 mg l⁻¹ SiO₂ conductively cools to 200°C, a temperature at which it has SiO₂ and Cl contents of 270 and 375 mg l⁻¹, respectively. Boiling of the fluid, followed by relatively minor dilution, explains SiO₂-Cl relationship of all the thermal discharges.

To assess the fluid-mineral equilibria in Puga geothermal system, deep fluid composition has been plotted on activity-temperature plots of Giggenbach *et al.* (1983). It is seen that the fluid is 'in equilibrium with Na-feldspar, K-mica, K-feldspar and calcium aluminium silicates,

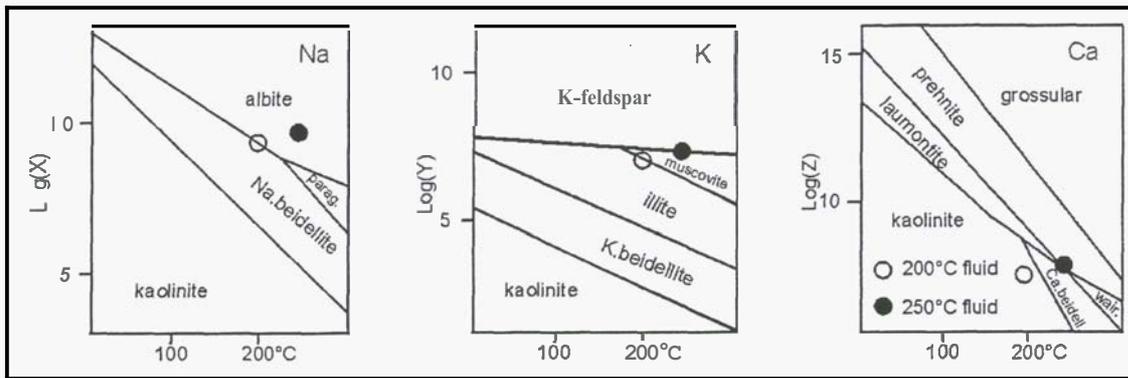


Figure 8 - Saturation of deep (250°C) and shallow (200°C) geothermal fluids at Puga with respect to common geothermal alteration minerals. pH values for these fluids are estimated as 6.6 and 6.8, respectively. The deep Puga fluid seems to be in equilibrium with Na-feldspar, K-feldspar, K-mica, wairakite and epidote (included in the prehnite stability field). $\text{Log}(X) = \text{Log}(a^2\text{Na}^+/a^2\text{H}^+)$, $\text{Log}(Y) = \text{Log}(a^2\text{K}^+/a^2\text{H}^+)$ and $\text{Log}(Z) = \text{Log}(a\text{Ca}^{++}/a^2\text{H}^+)$.

Table 1 - Chemistry of Puga Valley Thermal Discharges

Sample*	Temp (°C)	Chemical Constituents (mg l ⁻¹)									
		HCO ₃	Cl	SO ₄	F	Ca	Mg	Na	K	B	SiO ₂
GW-2	120	704	447	156	15	2	0.2	618	81	150	207
GW-3	80	1016	443	132	15	10	4	600	80	134	150
GW-5	100	909	445	133	15	14	0.5	510	80	127	175
GW-6	72	700	405	119	15	11	1.6	560	68	107	225
GW-7	135	884	464	127	15	5	0.4	580	80	134	180
GW-8	85	903	411	100	10	11	1.3	578	81	121	180
GW-10	60	939	435	155	15	24	5	650	80	135	140
GW-11	100	890	443	119	14	5	1.3	560	60	124	180
GW-14	84	710	420	119	15	4	1.5	600	80	129	158
GW-25	120	800	468	172	17	5	1.5	600	90	155	237
GW-27	83	614	405	112	13	10	2	500	60	100	150
Deep well	84	893	435	121	15	12	4	640	68	153	126
HS-1	64	860	401	138	15	14	3	620	60	124	200
HS-2	84	823	406	114	20	5	0.3	670	58	119	140
HS-3	45	934	427	140	15	26	3	660	75	132	140
HS-4	83	1160	396	128	12	9	9	600	70	132	140
HS-5	35	741	400	136	12	10	2	550	72	123	185
HS-6	80	740	425	140	10	2	2	640	76	136	155
HS-7	40	756	435	150	15	22	2	620	70	109	160
HS-8	35	657	445	160	17	4	0.2	640	73	120	200
HS-9	75	713	455	124	15	6	0.6	610	70	115	180
HS-10	40	700	440	145	17	2	0.3	600	72	118	160
HS-11	81	702	370	123	18	17	5	530	72	116	120
HS-12	38	660	405	124	15	14	2.5	580	80	123	145
HS-13	80	690	424	140	15	2	2	640	76	140	130
HS-14	63	650	395	149	12	17	3	540	68	129	150
HS-15	55	620	405	145	15	11	1	580	80	119	160

Average rare alkalis concentration : Li 7.5 mg l⁻¹ Rb 1.1mg l⁻¹, Cs 9.3 mg l⁻¹
 * geothermal well - GW, hot spring - HS

laumontite, wairakite, epidote (included in the prehnite field). The fluid in the shallow reservoir at 200°C, however, tends to be in equilibrium with clay phases of Na, K and Ca (Fig. 8).

Systematic δD and $\delta^{18}\text{O}$ studies on thermal discharges of Puga valley and cold springs/surface water bodies in the area around it, have indicated that the Puga geothermal fluid ($\delta\text{D} = -120\text{‰}$, $\delta^{18}\text{O} = -14.5\text{‰}$), in all likelihood, gets recharged from

ice bodies ($\delta D = -120\%$, $\delta^{18}O = -16\%$) covering the high altitude areas up to 6400 m above m.s.l., to the southwest of Puga. Thermal discharges, therefore, show an $\delta^{18}O$ -shift of 1.5‰ (Absar *et al.*, 1996).

6. EPITHERMAL MINERALISATION

Initial blow-out of hot fluids in most of the boreholes is accompanied by ejection of huge quantities of silica gel. This silica gel contains very fine stibnite needles constituting up to 5% of the material by volume. Similar stibnite needles occur scattered through the breccia forming the shallow reservoir and have also been reported in 284 m level core from the deep well. Sediments from hot water pools and deposits of both present-day and extinct thermal manifestation have 30 to 480 mg kg⁻¹ of Sb, which shows positive correlation with Hg. The latter, however, shows large variation in its concentration levels from < 100 µg kg⁻¹ to 45 mg kg⁻¹. Copper and Pb values have also been determined, which are 5 to 80 and 10 to 200 mg kg⁻¹, respectively.

More studies are being carried out on this aspect of the Puga geothermal system.

7. UTILISATION STUDIES

Geothermal energy at Puga has been used for experimental space-heating and refinement of locally occurring borax and sulphur. A project is presently in progress for extraction of Cs from the geothermal fluid by using ammonium 12-molybdo-phosphate (AMP) and a resin, resorcinol formaldehyde (RF).

Computer-based reservoir simulation exercises (Absar, *et al.*, 1996) indicate that even if a temperature of 170°C is encountered within the Puga valley, a modest 2 MW of electricity could be generated at a place where it is badly needed using an exhaust-to-atmosphere plant. According to another study (Ramanamurty *et al.*, 1996), the shallow geothermal reservoir feeding the existing boreholes can sustain a binary cycle power plant capable of generating 1.7 MW electricity. Inlet and outlet temperatures of the fluid are taken at 120° and 92°C, respectively, while iso-butane is envisaged to be used as the working fluid. The outlet water may be put to non-electrical uses, such as, space heating and greenhouse cultivation.

8. DISCUSSION AND CONCLUSIONS

The Puga geothermal system has its main reservoir lying underneath the southern ridge, bounding the valley, probably at depth exceeding 3000 m. That reservoir is hosted by granitoids is

indicated by very high concentrations of rare alkalis, F and B in thermal discharges. It may be assumed that granites still retain heat generating capacity as a result of which the deep fluid attains temperature of about 250°C through conduction.

The reservoir, evidently, gets recharged from ice-bodies located to the west of it at altitudes of 6400 m above m.s.l. The bulk of ^{18}O - exchange probably occurs within the reservoir, resulting in an ^{18}O -shift of about 1.5‰. The cation composition of the fluid, in all likelihood, gets fully equilibrated with the reservoir rocks. The fluid, consequently may be expected to be saturated with respect to minerals, such as, Na-feldspar, K-feldspar, K-mica, laumontite-wairakite and possibly epidote.

The single-phase deep fluid at a pressure of about 45 bars, which includes P_{CO_2} of 3.5 bars, gets cooled by conduction to a temperature of 200°C during its ascent. This fluid then enters the valley through some N-S conduits. In this regard the Kiagar Tso Fault, delimiting the geothermally anomalous area in the west, may probably have played a significant role. It is not clear whether the fluid entering the valley is two-phase or the boiling is initiated in the shallow reservoir. Within the shallow reservoir, comprising a thickness of at least 200 m of granite, gneiss and reconsolidated morainic breccia, K-Mg and SiO₂ re-equilibrations occur. That bulk of silica precipitation occurs within the shallow reservoir is indicated by large quantities of silica gel thrown out of wells. In spite of precipitation of silica, the shallow reservoir is expected to maintain sufficient permeability, probably through hydraulic fracturing, to host an easterly flow of hot fluids at the rate of 30 l s⁻¹. This shallow lateral outflow constitutes the only part of the system that has been explored till date.

There are clear indications that the nature of hydrothermal activity at Puga had been different in the past. A palaeo hot zone is identified in the deep well where epidote of pistacite variety is reported from 250 to 284 m levels. This clearly indicates that temperature of at least 200°C once occurred at such shallow levels. In addition, pockets of solfataric and advanced argillic alterations (Fig. 1) clearly indicate that a strong acidic fluid occupied parts of the valley in the past. Obviously, a low-pH condensate layer once existed, which is now characteristically absent. The boiling and steam separation, necessary for creating the condensate layer, were more vigorous in the past is also indicated by the occurrence of eruption craters and eruption breccia.

Puga geothermal system, in many respects, resembles the Yangbajing geothermal area in Tibet, China. The similarities between the two are due to identical reservoir temperatures, similar lithology and heat source and comparable fluid flow characteristics. It may be expected, though with a note of optimism, that deeper exploration at Puga may help us draw analogy between the two systems in terms of their power generation potential too.

As far as exploitation of the field is concerned, a problem may possibly be faced in selecting the sites of the production wells. The shallow reservoir within the valley, though readily accessible by drilling, may at best yield fluids with temperature approaching 200°C. For encountering higher enthalpy fluids, production wells need to be sited over the southern ridge. This would involve preparation of sites and lot of idle drilling.

9. ACKNOWLEDGEMENT

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