Geochemical Characterization of Thermal Waters in the Borateras Geothermal Zone, Peru

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ABSTRACT: The Borateras Geothermal Zone (BGZ) is located in the Western Cordillera of the Andes in southern Peru. In Borateras volcanic chains which are NW-SE aligned, volcanic rocks have been deposited over sedimentary Cretaceous basement. The geochemical interpretation of the results using Langelier and Pipper diagrams show us that thermal waters are alkaline-chloride water type. The triangular diagram shows that most of geothermal waters plot close to the chloride corner which is typical of mature geothermal deep fluids. High B concentrations lead to a relatively high B/Cl ratio as shown on a B-Cl binary diagram. This can be used to elucidate the reactions of waters with sedimentary marine rocks at deep levels. The $\delta^{18}O$ *vs* δD diagram shows a relatively high temperature or poor permeability. The results for chemical geothermometry allowed us to estimate the temperature at the depth of the geothermal resources to be as high as 200°C.

1 INTRODUCTION

Borateras is located inside the Maure basin close to the Maure river, in the Western Cordillera of the Andes in southern Peru, at an altitude of 4300 masl in the Tacna Region (Fig. 1), and has a cold and dry weather, with strong sunshine during the day and slow temperatures at nights. There is sparse vegetation, and arid and stony soils can be observed around the entire zone. The most representative species are *Polypelis* and *Azorella compacta*, commonly called Queñuales and Yareta, respectively.

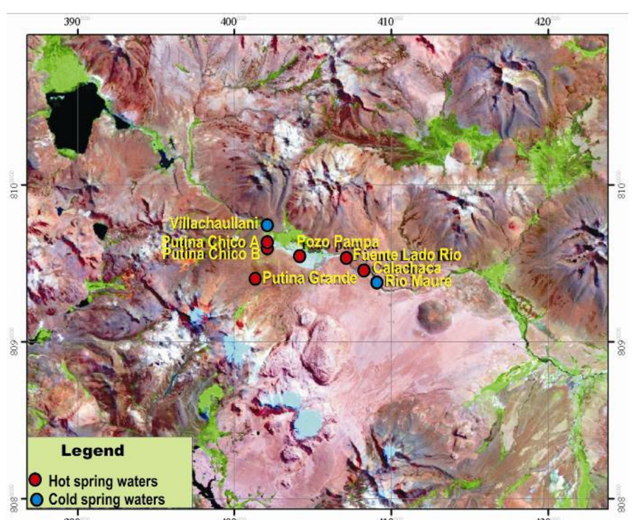

Figure 1: Localization map of the thermal waters in Borateras.

The zone is characterized by the presence of a considerable number of geothermal manifestations such as hot springs, boiling springs and mud pools. In October 2007, we carried out a study of the geothermal manifestations with geochemical methods for interpretation of their chemical and isotopic characteristics. This work was carried out for West Japan Engineering Consultants INC (WEST JEC) and INGEMMET.

2 GEOLOGICAL SETTING

Borateras is surrounded by a chain of volcanic centers, where important structural systems are found. Volcanic chains which are NW-SE aligned are found toward the south-west of the field. The following volcanic centers are recognized: Jaruma, Coverane and Purupuruni, of wich the last one is a group of dacitic domes with a diameter of approximately 850 m. These volcanic rocks were deposited over the sedimentary cretaceous basement composed mainly by interleaving sandstones, limestones and shales. To the south of the field, the mean lithology consists of andesitic lava (with crystals of plagioclases, olivines and pyroxenes) interlayered by some porphyritic lavas and sequences of pyroclastic flows. These volcanic deposits have ages from Upper Miocene to Pliocene and cover almost 90% of the entire zone.

There are some Holocenic deposit as alluvials and colluvials, mainly near the river. Some moraines cover the slopes of the Purupuruni domes.

In Borateras there are some important structures, regional faults are NW-SE aligned and local faults are NE-SW aligned, where these last ones are the main structure that controls the flows of the geothermal waters.

3 CHEMICAL COMPOSITION OF THE GEOTHERMAL FLUID

During the field work carried out in October, 2007, we collected six samples of geothermal water in the temperature range 43.5 °C to 83 °C and pH in the range 6.9 to 7.6. We have also collected two cold water samples in the lower part of the Maure River, as well as from a cold source. The isotope ratios for deuterium (δD) and oxygen-18 ($\delta^{18}O$) and the chemical composition of water samples were determined by WEST JEC in Japan.

Table 1: Chemical composition (in mg/L) of the thermal waters in Borateras

Code	Na	K	Ca	Mg	Cl	SO_4	HCO_3	B
54111-035					0.38	47.6	21.0	
54111-001	1310	91.0	68.00	0.48	2150.00	71.9	86.0	95.4
54111-009	1020	96.3	44.40	2.84	1630.00	70.3	93.0	72.7
54111-017	253	29.5	36.80	17.00	350.00	37.1	224.0	16.5
54111-015	643	77.2	40.10	9.17	981.00	73.3	128.0	43.4
54111-016	592	68.1	45.20	13.00	874.00	66.3	184.0	39.6
54113-001					0.88			
54114-001					510.00			

The 5 thermal springs (54111-001, 54111-009, 54111-017, 54111-015, 54111-016) directly associated with the BGZ, have showed concentrations of sodium and potassium between from 253 to 1310 mg/L and 29.5 to 96.3 mg/L respectively. We have also observed high concentrations of the chloride ion, ranging from 350 to 2150 mg/L and boron from 16.5 to 94.5 mg/L

Putina Grande spring (54111-035) has a low concentration, 0.38 mg/L, of chloride ion but the sulfate is the predominant anion with 47.6 mg/L.

The majority of these thermal springs are bubbling which indicates the presence of CO_2. The bicarbonate concentrations range from 21 to 224 mg/L and sulfate concentrations from 47.62 to 73.3 mg/L. The concentrations of calcium and magnesium are much lower than those of the other major anions. Chloride is the principal dominant ion in these waters, followed by the sodium. We have also observed that the waters are mainly of neutral pH and are Na - Cl waters, typical of mature deep geothermal fluids in high-temperature systems.

4 DISCUSSION

The chemical results of the thermal waters were plotted on a Langelier diagram (Fig. 2) (Fyticas et al., 1989), where we observed that all the thermal waters (54111-001, 54111-009, 54111-015, 54111-016) are located specifically in the Na-Cl sector. This indicates that the waters are sodium-chloride or alkaline water type, characteristic of geothermal waters. Likewise we notice that the Calachaca (54111-017) spring is different, this is due to the fact that the waters are mixed with meteoric waters.

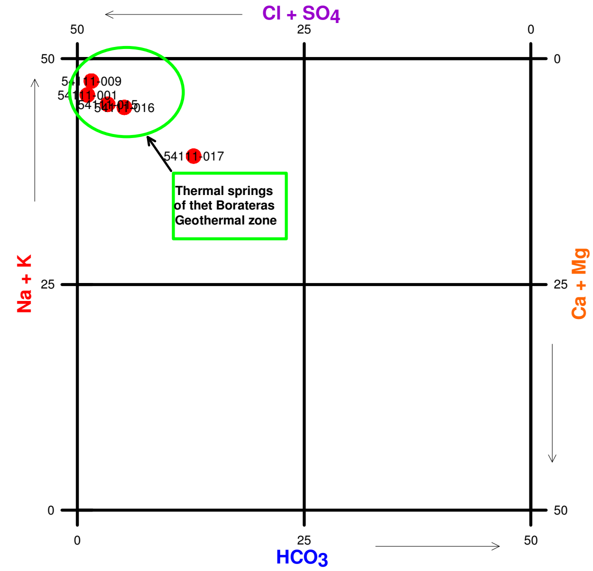

Figure 2: Langelier diagram.

According to the Cl-SO_4-HCO_3 ternary diagram (Giggenbach, 1988) (Fig. 3), the thermal springs are inside the deep chloride waters group, that is typical of mature deep geothermal fluids in high-temperature systems. Areas which contain hot, large-flow springs with the greatest Cl concentration are fed directly from the deep reservoir, and can be used to identify permeable zones within the field. This means that the waters in the BGZ come from deep level reservoirs (Nicholson, 1993).

As we observed in the Langelier diagram and the ternary diagram we corroborate that Calachaca spring water is mixed with cold shallow water. In Putina Grande the high concentration of sulfate and bicarbonate ions may indicate mixing of magmatic fluids with shallow waters.

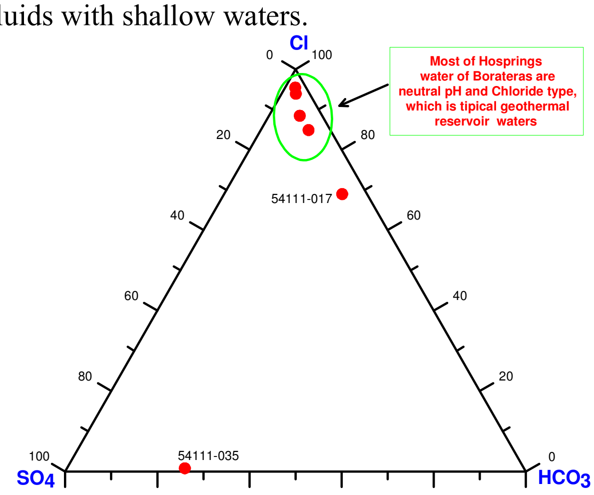

Figure 3: Cl-SO_4-HCO_3 ternary diagram (Giggenbach, 1988).

As shown by the binary B-Cl diagram (Fig. 4) there is a high boron concentration in geothermal waters in Borateras which may occur when volcanic rocks are affected by hydrothermal activity (Risacher, 1984) or it may be related to leaching by meteoric water and/or hydrothermalization of rocks rich in boron (Murray, 1996).

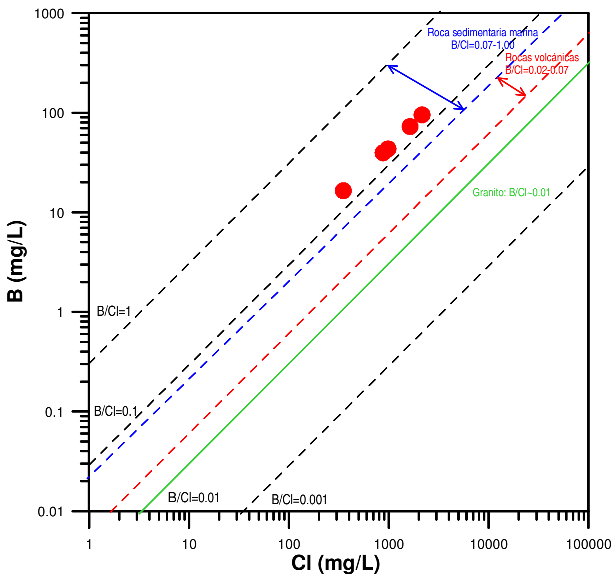

Figure 4: Borum vs Chloride diagram (Shigeno, 1993).

The Cl/B mole ratio of geothermal waters in Borateras is high, typical of neutral Na-Cl type geothermal water of low salinity reflecting the geologic structures and the volcano distributions in these areas (Shigeno and Abe 1983). The essential geothermal reservoir has in fact developed in the marine sedimentary rocks, which probably have relatively high porosity and permeability with abundant fractures (Shigeno, 1993). In case of BGZ we might indicate that B and B/Cl of the geothermal waters are high implying reaction with marine sedimentary rocks at deep level.

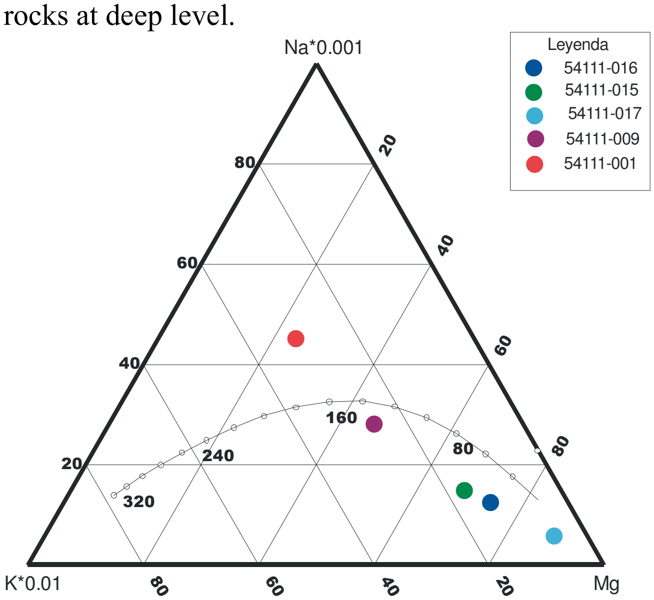

Figure 5: Na-K-Mg ternary diagram (Giggenbach et al, 1983).

The evaluation of the analytical data plotted in a Na-K-Mg ternary diagram (Giggenbach et.al., 1983) (Fig.5) shows that two samples fall on the equilibrium line characteristic of mature or geothermal waters, suggesting that their cation ratios are controlled by mineral-solution equilibria. In the case of the springs 54111-015, 54111-016 and 54111-017 these fall in the partial equilibrium field, probably due to dilution by surface waters.

5 ISOTOPE RESULTS

The isotopic ratios for $\delta^{34}S(SO_4)$, $\delta^{18}O(SO_4)$, $\delta^{18}O$ and δD were determined. The results (Table 2) show that the values of $\delta^{18}O$, for the cold waters are more negative than those for the geothermal waters, which deviate from the local meteoric water line, although not much, and indicate that the geothermal waters are associated with the mixing of magmatic fluids with meteoric waters (Fig.6) (Craig et al, 1956; Craig, 1963). Based on the entalphy-chloride model, a chloride content of 2300-2500mg/L is estimated for the main reservoir, and the mixing ratio of magmatic fluid in Borateras is estimated around 25%.

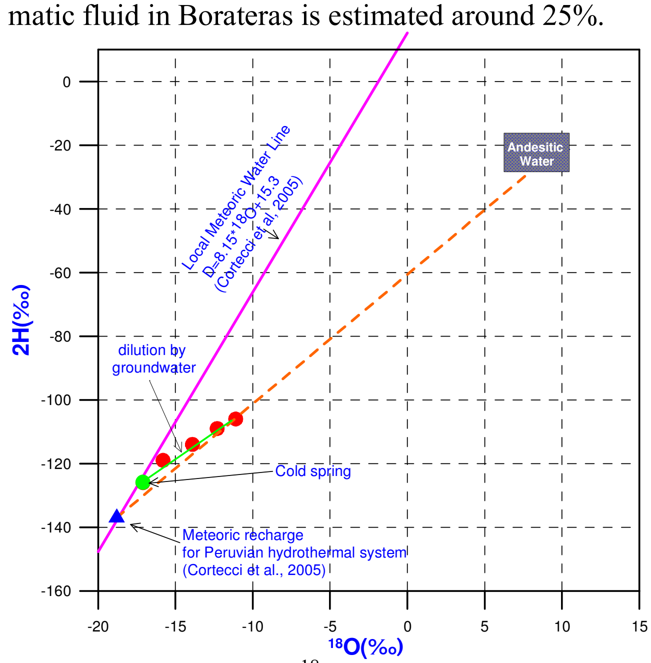

Figure 6: δD vs $\delta^{18}O$ in Borateras Zone.

Table 2: Isotope results

Code	δ D(H2O)	δ 18O(H2O)	δ 34S(SO4)	δ 18O(SO4)
54111-001	-106	-11.1	9	-5.7
54111-009	-109	-12.3		
54111-017	-119	-15.8	4.5	-1.0
54111-015	-114	-13.9		
54113-001	-126	-17.1		

6 GETHERMOMETRY RESULTS

Chemical geothermometer results calculated for the geothermal waters are presented in Table 3 suggesting the temperature in the liquid phase at depth in the geothermal resource of Borateras. Thus (Table 3 and Fig. 7) we have estimated that the temperature of the geothermal resource may be as high as 200 °C (T-Na/K, Truesdell, 1976).

Table 3: Chemical geothermometer results (in ºC)

Code	T-Quartz	T-Calcedony	T-α Cristobabalite	T-β Cristobabalite	T-Na/K	T-NaKCa	T-NaK-Ca-Mg	T-K/Mg	T-Na/Li	T –δ 18O(H_2O-SO_4)
54111-035	151	126	101	51						
54111-001	197	179	148	98	152	206	183	181	253	276
54111-009	191	171	141	91	182	222	181	149		
54111-017	154	129	103	54	205	140	140	87		116
54111-015	171	149	121	72	208	203	100	123	216	
54111-016	169	146	119	69	203	189	68	114		

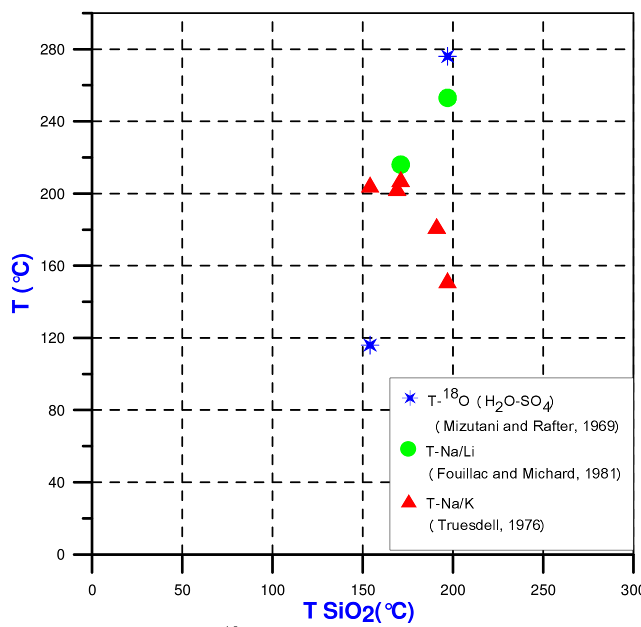

Figure 7: T-Na/Li, T-^{18}O(H_2O-SO_4, T-Na/K) *vs* T-SiO_2

7 CONCLUSION

- The geochemical characterization of the thermal springs in Borateras defines it as alkaline-chloride (Na-Cl) water type.
- The stable isotope relationship between δ^{18}O and δD suggests that the geothermal waters are a mixtue of meteoric and magmatic waters.
- The results of the chemical geothermometry for the liquid phase, suggest that the temperature at depth in the geothermal resources may be in the range 250 °C to 275°C.
- According to the extent of geothermal manifestations and estimated subsurface temperature by geochemical thermometers, the geothermal resources in this zone seem to be promising.

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