GEOTHERMAL RECONNAISSACE STUDY AT AZUFRAL VOLCANO

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Summary

Azufral volcano, one of the highest priority projects for the geothermal exploration in Colombia, is a recent (Tertiary) stratovolcano of extended and persistent volcanic activity, with evidence of hydrothermal activity and complete magmatic evolution. Its summit consists of a caldera structure which includes a lake (Laguna Verde) and a dome complex of rhyodacitic composition. The latest eruptive event created on of the domes, which presents hydrothermal alteration, fumaroles and phreatic eruption craters, suggesting the existence of an active heat source.

Fluid discharges of the hidrothermal system are found in the steam vents within the crater and in about ten hot springs. The gas composition of one of the steam vents indicates a hydrothermal origin. Some of the hot springs located between 3 and 11 km from the summit towards the West and the Southeast flanks, show deep fluid contribution. Acid sulphate waters discharge to Laguna Verde. Bicarbonate waters are also found at about 10-11 km from the summit, towards the South flank. From aqueous geothermometers, the temperature at the reservoir ranges from 200° to 250°C. A preliminary geochemical approach is consistent with the general model for stratovolcanoes with a boiling processes occurring towards the West side of the crater and an outflow to the Southeast flank, where the hot springs exhibit the highest contents in conservative aqueous components. This paper is a compilation and a review of the existing geological and geochemical information about the Azufral volcano geothermal system.

1. Introduction

The Azufral volcano (1501-09) is a stratovolcano located to the Southwest of Colombia, in Nariño District (1°08' N – 77°73' W), along the Western Cordillera. Its highest elevation is 4070 a.s.l.. The crater of about 3 km diameter presents domes, hydrothermal crater eruptions and a lake called Laguna Verde .The geothermal system associated to this volcano was selected by OLADE (The Energy Latin American Organisation) since 1982 when the National Recognizance Study, as one of the priority areas to develop feasibility studies, based on the following facts: (1) Recent age (Terciary) and extended and persistent volcanic activity, (2) hydrothermal activity (phreatic explosion craters, fumaroles and hot springs) but not historical activity, (3) long residence period of magma with the consequent differentiation, observed in the complete evolution of andesites to ryolites and (4) defined hydrothermal zonation (argilic, phylic and propilitic zones) identified in xenolites.

The Azufral volcano geothermal system, is seen by the National Government as a possible solution to the deficit in the electrical energy service for Nariño and Putumayo districts. Consequently, the government decided to start, through INGEOMINAS, geothermal exploration studies on this volcano.

The objectives of the present document are compile the available geological and geochemical information of geothermal fluids from Azufral Volcano, and propose a preliminary geochemical approach of the geothermal system.

2. Methodology

From the literature review, aspects related to the morphology, type of deposits, hidrothermal minerals and geothermal surface manifestations of the Azufral Volcano, were compiled and interpreted to produce a preliminary geochemical approach.

3. Results

3.1 Geological setting

According to Bernal, N. (1998), as a result of explosive eruptions the Azufral volcano developed a caldera structure and ring shape faults formed after this structure collapsed. Inside the caldera a green acid lake ("La Laguna Verde") about 1 km long and a dome complex, occur. Based on the surge deposits found close to the caldera, plinian, phreatic and phreatomagmatic eruptions have taken place during the last active stage, which ^{14}C ages for charcoal samples, were measured in 2800 +/- 200 years.

Breccia fragments from the shallow reservoir indicate the existence of argillic and phillitic-propilitic transition zones. The presence of epidote and adularia in surge deposits, indicates high deep temperatures (>250°) and a good permeability reservoir, when the phreatomagmatic eruption took place. Towards the Northern side of the volcano a wide altered area is found as well as veins of quartz 10 cm thick filling andesite lava fractures, besides weathered silica sinter deposits. Also, close to one of the hot springs sites (the Malaberes), old silica sinter overlies pyroclastic deposits (Bernal, 1998).

The volcanic deposits of Azufral, consist of ignimbrites, debris flows, lavas and series of pyroclasts. Lava deposits were dated by Bechon and Monsalve (1991), by using the

K/Ar ratio, obtaining an age of 0.58 +/- 0.03 Ma. The most explosive stage at Azufral volcano is recorded in a series of pyroclastic deposits which have been related to the emplacement of a dome complex by Fontaine and Stix (1993) in four different events, dated by ^{14}C, in 4050 year BP (the first one), 3600 year BP (the second and the third) and in 3470 year BP, the youngest one.

3.2. Geothermal fluid discharges.

According to the information compiled by Alfaro, C. (1998) the main surface manifestations of geothermal fluid discharges are 9 hot springs and steam vents on one of the domes inside the crater (Fig. 1).

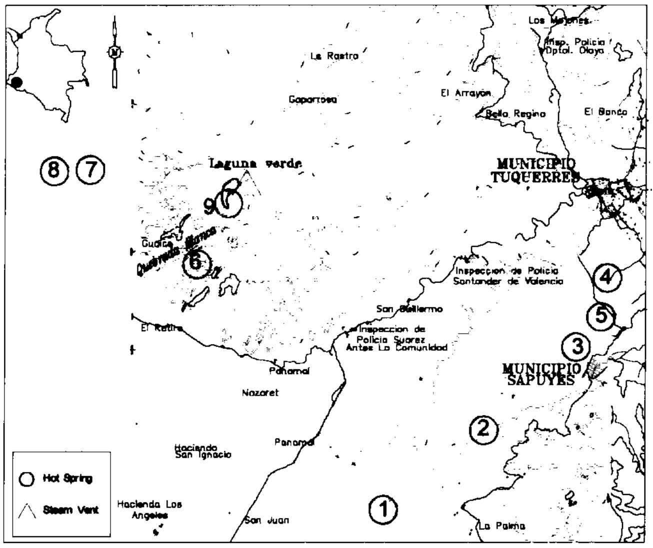

Fig. 1. Location of the thermal manifestations from the Azufral Volcano geothermal system. Laguna Verde is located within the crater.

Hot Springs. The chemical composition of hot springs, are presented in Table 1. The spring discharging to Laguna Verde registers an acidic pH. The remaining springs, located to lower elevations, register neutral pHs characteristic of deep or peripheral waters.The water classification based on the dominant anion, shown in the Fig. 2, indicates the presence of the end members common in water dominated hydrothermal systems: Neutral-chloride waters: El Salado de Malaber, sulphate-acid waters, from shallower origin (steam heated): Laguna Verde and, neutral-bicarbonate, peripheral (steam heated): La Cabaña.

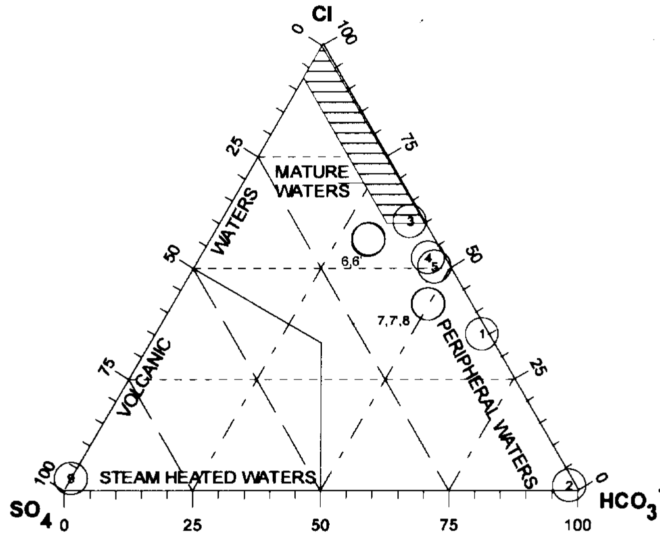

Fig. 2. Relative Cl-SO_4-HCO_3 composition. High chloride content waters are found at Malaber (3, 4, 5), Quebrada Blanca (6) and El Baño (7,8) areas. Acid sulphate steam heated waters are found at the summit of Azufral in Laguna Verde hot springs (9) and bicarbonate waters, at San Ramón (1) and La Cabaña (2).

Table 1. Chemical composition of hot springs from Azufral Volcano

No. / Ref. ( )	Hot Spring	T°	pH	Conductivity (µS/cm)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)
1 (a)	San Ramón	31	6.20	3311	462	48	64	123
2 (a)	La Cabaña	24	6.59	201	18	5	12	12
3 (a)	El Salado de Malaber	25	6.02	2933	454	46	38	94
4 (a)	Malaber 1 Sapuyes	32	6.46	10858	1906	177	190	388
5 (a)	Malaber 2 Sapuyes	32	6.55	10369	1719	165	167	360
6 (b)	Quebrada Blanca	50	6.20	2600	483	37	84	49
6' (b)	Quebrada Blanca	50	6.20	2600	483	43	84	53
7 (b)	El Baño 1	48	6.50	5200	690	86	280	300
7' (b)	El Baño 1	48	6.50	5200	667	86	280	300
8 (b)	El Baño 2	48	6.40	5200	690	86	280	300
9 (b)	Laguna Verde		2.40		58	10	34	10
No.	**Hot Spring**	**Li (mg/l)**	**B (mg/l)**	**Cl (mg/l)**	**SO_4 (mg/l)**	**HCO_3 (mg/l)**	**F (mg/l)**	**SiO_2 (mg/l)**
1	San Ramón	0.63	7.2	602	17	1089	0.33	131
2	La Cabaña	0.01	0.04	1	1	139	0.16	86
3	El Salado de Malaber	0.75	9.5	1204	49	737	0.32	113
4	Malaber 1 Sapuyes	3.29	29.7	2853	164	2435	0.38	138
5	Malaber 2 Sapuyes	2.95	27.3	2470	134	2301	<0.08	135
6	Quebrada Blanca	1.19	7.5	744	168	409		168
6'	Quebrada Blanca	1.19	7.5	744	163	409		168
7	El Baño 1	1.82	11.9	1363	264	1647		192
7'	El Baño 1	1.89	11.9	1363	269	1647		192
8	El Baño 2	2.03	11.9	1363	269	1647		198
9	Laguna Verde	0.05	0.54	16	576			120

(a) OLADE *et al*. (1982), (b) OLADE *et al.* (1987)

Those water types, by mixture form the remainding type of waters: Malaber dominated by similar proportions of chloride and bicarbonate, Quebrada Blanca, dominated by chloride and, San Ramón, dominated by bicarbonate. According to the Na-K-Mg relative composition, defined by Giggenbach (1988) as a geoindicator, Fig. 3, given its variation as a function of specific environments, the existence of mixture with shallow water is supported by à linear trend which points out a reservoir temperature around 218°C. However, the high magnesium contents locate the composition of these waters in the zone of immature waters.

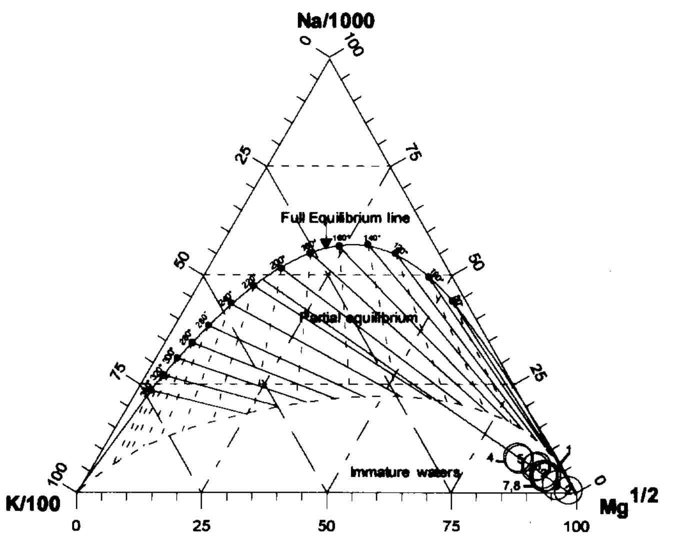

Fig. 3. Relative Na-K-Mg composition. A linear trend indicates a reservoir temperature close to 220°C. The hot springs Malaber 1 and 2 hot springs show the highest equilibrium condition.

The high aqueous conservative species contents (chloride, boron and lithium) in the thermal areas of Malaber, Quebrada El Baño y Quebrada Blanca, suggest deep fluid discharge. Their relative composition, is very close suggesting a common origin, particularly to those for San Ramón, Malaber and Los Baños waters., with predominance of the species chloride which would be explained by the absorption of low B/Cl ratio magmatic vapour or by the maturity of this hydrothermal system (Giggenbach and Goguel, 1989). As it would be expected, from the higher volatility of boron, respect to the chloride, the water of the spring located by Laguna Verde, register a higher B/Cl ratio to a lithium level similar to that registered by the remaining hot springs. The observed difference in this relative composition of La Cabaña spring in front of the others could be attributed to a different origin (heated by normal thermal gradient, for instance) or to a reduction in the precision of these analyses given their low concentrations.

Gases. The results of gas analyses of two gas samples from fumaroles (best named as steam vents due to their very low pressure) located on one of the domes of the volcanic crater, are presented in Table 2. They suggest a dominant contribution from the geothermal system rather than volcanic-magmatic contribution, that is, they are generated from a gas phase produced by boiling of the geothermal fluid. This conclusion is based on the temperature of the discharge (about the water boiling point at that elevation), on the low chloride concentration and on the relative CO_2, S_t and HCl composition, plotted in the triangular diagram from the Fig. 4, where the composition of other hydrothermal fumaroles from other Colombian volcanoes are included. Also the hot springs located within the crater (Laguna Verde), with a low temperature, a moderated acidity and a low chloride concentration, reveals an insignificant contribution of the volcanic system.

Table 2. Gas composition of fumarolic discharges from Azufral Volcano

		Molar percentage (Dry basis)					
Date	T (°C)	CO_2	SO_2	H_2S	HCl	N*	Ref.
Nov-94	86.7	97.745	0.891	1.364	0.000	0.4	1
Nov-94	86.7	97.527	1.051	1.422	0.000	0.5	1

* Número de oxidación promedio para el Azufre
1= Alfaro, C., 1995

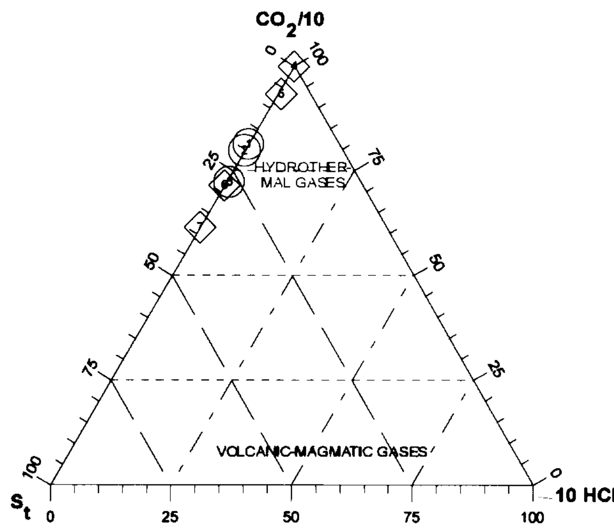

Fig. 4. Relative CO_2-St-HCl composition in steam vents discharges at Azufral. A dominant contribution of the hydrothermal system in the gas emmisions, is identified (1,2,3). The remaining points, correspond to other hydrothermal fumaroles of Colombian volcanoes: Machín (4), Cerro España (5) and Nevado del Ruiz (6 and 7).

3.4. Deep temperatures

The Table 3 presents the probable deep temperatures of the geothermal fluid, estimated from aqueous geothermometers Na/K, K/Mg, Na/K/Ca and SiO_2 (quartz) applied to neutral chloride and moderately mixed thermal springs.

Table 3. Probable reservoir temperature at Azufral Volcano geothermal system, based on aqueous geothermometers

No.	Hot Spring	Na/K (°C)	K/Mg (°C)	Na/K/Ca (°C)	Qtz, no steam loss (°C)
1	San Ramón	235	73	190	153
3	El Salado de Malaber	234	76	194	144
4	Malaber 1 Sapuyes	227	92	201	156
5	Malaber 2 Sapuyes	229	91	202	155
6	Quebrada Blanca	212	78	172	169
6'	Quebrada Blanca	223	81	180	169
7	El Baño 1	250	77	194	177
7'	El Baño 1	253	77	196	177
8	El Baño 2	250	77	194	179

Na/K = (1390/(LOG(Na/K)+1.75))-273 (Giggenbach's geothermometer)
K/Mg = (4410/(14-LOG(K^2/Mg)))-273 (Giggenbach's geothermometer)
Qtz = (1309/(5.19-LOG(SiO_2)))-273 (Fournier's geothermometer)
Na/K/Mg = (1647/((Log/Na/K)+ β(Log($Ca^{1/2}$/Na)+2.06)+2.47)))-273.
β 1/3 or 4/3 (Fournier and Truesdell's geothermometer)

The observed difference between the geothermometers Na/K (~210-250°C) and K/Mg (~80-90°C), shows an important dilution process which influence is reflected in (1) the high magnesium contents, which is responsible for the low K/Mg temperature, observed in the diagram of the Fig. 3 and (2) in the quartz temperature (between about 140 and 180°C. The Na/K/Ca geothermometer, which corrects the high concentration effect, indicates temperatures around 200°C.

4. Preliminary geochemical approach.

Besides the deep geothermal system probably exist a shallow one, as suggested before by Bernal, N. (1998). It is developed within the present caldera and presumably fed by infiltrated meteoric water. The fluid circulation is probably driven by the ring faults surrounding the caldera and the wide spread faulting of the basement observed in this region. The shallow permeability is perhaps improved by the volcanic activity before and after the dome emplacement.

According to the occurrence of the thermal manifestations, the current deep hydrothermal system at Azufral is probably located towards the South flank of the volcano with an upflow zone orientated to the Northwest of the summit. The upflow zone can be inferred on surface by the steam vents and, by acid sulphate thermal springs discharging to Laguna Verde. These thermal manifestations could be originated by vapour phase separation from the deep fluid, from the proposed shallow system or by mixing of fluids from those two systems. The higher temperatures of the hot springs located at the highest elevations, could be in part, due to the "extra" heat source related to the domes occurrence. The existence of the two systems (deep and shallow), have to be proven by gas and isotopic analyses. The deep water reaches the surface at relatively high elevations (3200 m) and short distances with respect to the upflow (~3 km), in Quebrada Blanca hot spring located Southwest of the volcano summit, although according to the total dissolved solids (2150 ppm) and the chloride concentration (740 ppm), the deep contribution, is moderated.

The main outflow direction is proposed, towards the Southeast. According to the chemical composition of the known thermal springs, the highest distance in which the deep fluid reaches the surface to the West, is about 7 km (Quebrada El Baño), while towards the Southeast flank, it is about 11 km (Malaber). As the chemical composition suggests and particularly the concentration of chloride and other conservative species such us boron and lithium, the thermal springs from El Baño receive a considerable contribution of deep fluid but it is lower than at Malaber springs. However El Baño site located to smaller distance from the upflow registers the highest deep temperature (250°C). The thermal springs from Malaber register a lower dilution and their relative Na-K-Mg composition are the closest to the equilibrium.

According to sulphate and bicarbonate concentrations, the thermal springs of El Baño are mixed with sulphate waters coming from upper elevations while those from Malaber which surface temperatures are relatively low, are mixed with cold bicarbonate water, from the periphery of the hydrothermal system.

The thermal springs of San Ramón and La Cabaña located about 10-11 km far from the crater in SSE direction, correspond to bicarbonate and low salinity waters with a poor chloride water contribution.

5. Conclusions

- The Azufral volcano hydrothermal system discharges different types of thermal water to the surface (chloride, sulphate, bicarbonate and mixed waters) which spatial distribution indicates (1) an upflow zone evident in surface towards the Northwest of the summit, (2) the occurrence of shallow processes (boiling, mixture and dilution) and (3) an outflow zone.

- The outflow of deep fluid seems to have a preferential direction towards the Southeast. This is supported by the occurrence of the hot springs from Malaber, which total dissolved solids concentration and particularly the conservative species, indicate a higher deep fluid contribution.

- The boiling zone, at the Northwest of the crater at about 3600 m, is consistent with the occurrence of a high temperature geothermal system at Azufral. That boiling zone is proposed based on the acid sulphate waters discharging to Laguna Verde as well as the existence of hydrothermal steam vents on one of the domes of the crater.

- The temperature of the deep fluid is likely between 200 and 250°C, according to the aqueous geothermometers, which allows classifying it as an intermediate to high temperature system with possibilities to generate electrical energy.

6. Acknowledgement

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