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Colombian Geothermal Resources

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ABSTRACT

During the last few years, new legal dispositions have favored the promotion of non-conventional energy sources in Colombia: The law 697 of 2001 declared the rational and efficient use of energy and the utilization of non-conventional energy sources, as a social and public interest matter as well as a national convenience issue. The same law, demands stimulus for developing non-conventional energy sources from the government. The edict 3683 dated December 2003, regulates the promotion of non-conventional energy sources, inside the frame of sustainable development, following the recommendations of The Johannesburg Summit, in which Colombia participated.

Since 2000 the geothermal project of INGEOMINAS which is the institution in charge of the geothermal exploration in Colombia, have worked on two topics: 1) The inventory of hot springs, in two areas: Cerro Bravo – Cerro Machín Volcanic Complex and Cundinamarca Department and 2) the first stage of exploration two areas: Azufral volcano (Nariño Department) Paipa geothermal area (Boyacá Department).

The inventory of hot springs at Cerro Bravo – Cerro Machín Volcanic Complex was based in the reinterpretation of the geochemical existing information. The Santa Rosa de Cabal group, constituted by the springs of San Vicente and Santa Rosa sectors, revealed the highest interest as an energy resource given the highest geochemical temperatures inferred in the reservoir. This is proposed as an independent system from Nevado del Ruiz.

The inventory of hot springs from Cundinamarca department indicate the existence of this surface manifestatons at 27 municipalities, from which 52 mineral and hot springs were characterized. The spatial distribution of the springs shows a trend to increase their temperature towards the East of the Department, reaching a maximum of 73.6°C at Paratebueno locality. From the geochemistry of the springs, Cundinamarca has geothermal resources of low temperature related to a normal geothermal gradient.

The first stage of exploration at Azufral volcano included the preparation of the geological cartography of the area as well as the updating of the chemical composition of hot springs. The stratigraphy of Quaternary deposits together with a geochronological study allowed defining a new geological formation. The geochemistry of the springs shows a probable contribution of a saline non geothermal source. The quartz geothermometers indicate a minimum probable temperature of 180°C.

At Paipa geothermal area the work included geological studies of cartography, tectonics and volcanological, electromagnetic surveys and geochemistry of the aqueous phase of the hot springs. From them a high temperature geothermal system is proposed with a magmatic heat source, an upflow controlled by deep faults and a shallow mixing process with a highly sodium sulfate mineralized water which “masks” the chemical composition of the deep reservoir fluid.

1. INTRODUCTION

Between 2000 and 2005, new legal dispositions have favored the promotion of non-conventional energy sources in Colombia. The law 697 of 2001 declared the rational and efficient use of energy and the utilization of non-conventional energy sources, as a social and public interest matter as well as a national convenience issue. The same law, demands encouragement for developing non-conventional energy sources from the government. The edict 3683 dated December 19, 2003, regulates the promotion of non-conventional energy sources, inside the frame of sustainable development, following the recommendations of The Johannesburg Summit.

INGEOMINAS is the governmental institution in charge of the geothermal exploration in Colombia. During the last five years this institution carried out studies of inventory of hot springs at the geothermal areas of Cerro Bravo – Cerro Machín Volcanic Complex and Cundinamarca department and the first stage of geothermal exploration at the geothermal areas of Azufral Volcano and Paipa, which are indicated in the Fig. 1.

2. GEOTHERMAL STUDIES BACKGROUND

The geothermal anomaly hosted in the Colombian territory related to the subduction zone is related in turn with several hydrothermal systems located mainly around the volcanoes of the Andean Cordillera. The main identified geothermal areas are the Cerro Bravo - Cerro Machín Volcanic Complex, the volcanoes from the south of the Country at Nariño Department (Azufral, Chiles, Cumbal, Galeras volcanoes) and the Paipa – Iza sector, in Boyacá Department. A summary of the reconnaissance and prefeasibility studies, as well as the first version of the geothermal map was presented in the frame of the WGC 2000 (Alfaro et al., 2000).

3. UTILIZATION

The geothermal resources utilization is restricted in Colombia to bathing and swimming with recreational purposes, mainly. However the local communities, where the hot springs are located, recognize their healing properties. Currently, as result of the wide access to the information, the development of the medical balneology and thermalism in many countries, particularly in Europe, is object of an increasing interest in

Figure 1. Location of the geothermal areas studied in the last five year. Two types of studies were carried out: Inventory of hot springs identified at blue areas and first stage of exploration activities at red areas.

Colombia, which is reflected in the creation of the Colombian Hydrothermal Techniques Association in 1998 with the participation of the tourism sector as well as INGEOMINAS, as the governmental institution for technical support, which after the recent reorganization keeps its mission of exploring the geothermal resources. Additionally, the agreement between the governments of Rumania and Colombia was approved through the Law 595 of 2000, for the cooperation in tourism in particular to promote the social tourism, health tourism, hydrothermal treatments, between others. The list of localities with hot springs utilization in bathing and swimming is presented in Table 1, together with the estimation of the thermal energy utilization. In the localities of Paipa and Santa Rosa de Cabal, a more systematic use of these resources has been implemented with programs for relaxation and health tourism.

3. GEOTHERMAL RESOURCES AND POTENTIAL

In Colombia the geothermal resources are still an object of preliminary exploration and there are not significant utilization developments. A description of exploration studies carried out during the last five years is presented next.

3.1 Inventory of Hot Springs

3.1.1 Cerro Bravo – Cerro Machín Volcanic Complex.

The Cerro Bravo – Cerro Machín volcanic complex is located along the Central Cordillera between Caldas, Risaralda, Quindío and Tolima departments, with an rough area of 2.000 km^2, which the Parque Natural de los Nevados and the volcanoes Cerro Bravo and Cerro Machín.

3.1.1.1 Geological Setting.

In general the stratigraphy of the area consists of a Paleozoic polymethamorphic basement (Cajamarca group) covered by massive lava flows from the early volcanic structures of the Cordillera Central of Pliocene age, which are overlayed by deposits of pyroclastic flows, lava flows and mud flows, product from the volcanic activity of the Quaternary.

The Quaternary deposits from Cerro Bravo to Cerro Machín are predominantly andesitic rocks with variations from rhyodacites to dacites (Cerro Bravo, Nevado del Ruiz, Páramo de Santa Rosa and Machín) to basaltic andesites from Nevado del Quindio and Nevado del Tolima, product of the Pleistocene and Holocene activity.

The tectonic setting of the area is defined by the systems of faults Romeral, Palestina and Mulato with NNE-SSW direction (Geocónsul, 1992). The Romeral fault, which divides the oceanic crust towards the west and, the continental crust to the east, represents and old subduction zone (Barrero et al., 1969, in Calvache & Monsalve, 1982). The compressive forces result in the uplift of the Cordillera Central and the formation of fault systems such as Mulato, Palestina, Marulanda, Salamina and Salento. Palestina fault has been an important conduct for the more ancient lava emissions for the volcanoes of the Complex (CHEC et al., 1983). Local faults related to Romeral and Palestina, represent distensive strength due to the existence of dacitic dikes related to them. The current manifestation of these faults is the volcanotectonic seismicity associated to the formation of fumarolic fields (Nereidas y La Olleta) and to the occurrence of hot springs (Calvache & Monsalve, 1982).

3.1.1.2 Hot Springs

From the spatial distribution and the probable association to specific volcanoes, the total of 100 springs, from which 74 can be considered thermal, were divided in nine (9) groups presented in Fig. 2: (1) Cerro Bravo volcano, (2) Nevado del Ruiz -eastern sector, (3) Batolito El Bosque, (4) Nevado del Ruiz – western sector, (5) Santo Domingo, (6) Santa Rosa, (7) El Bosque del Otún, (8) Nevado del Tolima and (9) Cerro Machín volcano (Alfaro et al., 2002).

A high diversity of chemical compositions is found in these springs including those compatible with a significant volcanic-magmatic fluid contribution (high temperature, high sulphate and chloride concentrations and very low pH), in the group 2. On the other hand, deep mature water contribution is inferred, mainly, in the groups 1, 4, 6 and 9.

The group 1 located at the north of the Cerro Bravo volcano is formed by 12 neutral bicarbonate springs around Cerro Bravo volcano. Their chemical composition indicates the deep water contribution. The estimated reservoir temperature, based on the silica geothermometers points out up to 156°C.

The group 4, Nevado del Ruiz-western sector, was chosen as one of the highest priority areas for the geothermal exploration (CHEC et al., 1983). It is formed by 10 springs, from which 5 are neutral chloride, exhibit high lithium and boron contents, up to 3.5 and 17.3 mg/, respectively and reaches one of the highest discharge temperatures (93°C at Botero Londoño spring). The highest geochemical temperatures indicate 255°C and 177°C for the Na/K and quartz geothermometers, respectively.

The group 6 consists of 15 springs located to the east of the municipality of Santa Rosa and distribute in two sectors: San Vicente and Santa Rosa. The highest discharge temperature

TABLE 1. UTILIZATION OF GEOTHERMAL ENERGY FOR DIRECT HEAT IN COLOMBIA AS OF 31 DECEMBER 2004 (other than heat pumps)

1) I = Industrial process heat; H = Individual space heating (other than heat pumps)
C = Air conditioning (cooling); D = District heating (other than heat pumps)
A = Agricultural drying (grain, fruit, vegetables); B = Bathing and swimming (including balneology)
F = Fish farming; G = Greenhouse and soil heating
K = Animal farming; O = Other (please specify by footnote)
S = Snow melting

2) Enthalpy information is given only if there is steam or two-phase flow

3) Capacity (MWt) = Max. flow rate (kg/s)[inlet temp. (^oC) - outlet temp. (^oC)] x 0.004184 (MW = 10^6 W)
or = Max. flow rate (kg/s)[inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.001

4) Energy use (TJ/yr) = Ave. flow rate (kg/s) x [inlet temp. (^oC) - outlet temp. (^oC)] x 0.1319 (TJ = 10^{12} J)
or = Ave. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.03154

5) Capacity factor = [Annual Energy Use (TJ/yr)/Capacity (MWt)] x 0.03171
Note: the capacity factor must be less than or equal to 1.00 and is usually less, since projects do not operate at 100% of capacity all year.

Note: please report all numbers to three significant figures.

Locality	Type[1)]	Maximum Utilization					Capacity[3)]	Annual Utilization		Capacity Factor[5)]
		Flow Rate (kg/s)	Temperature (^oC) Inlet	Temperature (^oC) Outlet	Enthalpy[2)] (kJ/kg) Inlet	Enthalpy[2)] (kJ/kg) Outlet	(MWt)	Ave. Flow (kg/s)	Energy[4)] (TJ/yr)	
Agua de Dios	B	10,2	36,2	28,0			0,35	6,47	7,00	0,63
Agua de Dios	B	10,2	36,2	28,0			0,35	6,47	7,00	0,63
Bochalema	B	3,49	57,0	33,0			0,35	2,21	7,00	0,63
Cumbal (Chiles)	B	10,5	41,0	33,0			0,35	6,63	7,00	0,63
Chinácota	B	6,43	46,0	33,0			0,35	4,08	7,00	0,63
Choachí	B	12,0	35,0	28,0			0,35	7,58	7,00	0,63
Choachí	B	4,86	50,2	33,0			0,35	3,09	7,00	0,63
Chocontá	B	6,11	46,7	33,0			0,35	3,87	7,00	0,63
Chocontá	B	3,31	58,3	33,0			0,35	2,10	7,00	0,63
Coconuco	B	3,35	58,0	33,0			0,35	2,12	7,00	0,63
Coconuco	B	2,04	74,0	33,0			0,35	1,29	7,00	0,63
Colón	B	5,98	47,0	33,0			0,35	3,79	7,00	0,63
Cuítiva (El Batán)	B	3,64	56,0	33,0			0,35	2,31	7,00	0,63
Gachetá	B	2,47	66,9	33,0			0,35	1,57	7,00	0,63
Gachetá	B	3,36	57,9	33,0			0,35	2,13	7,00	0,63
Guasca	B	11,3	35,4	28,0			0,35	7,17	7,00	0,63
Güican	B	8,37	38,0	28,0			0,35	5,31	7,00	0,63
Ibagué	B	5,58	48,0	33,0			0,35	3,54	7,00	0,63
Iza	B	5,23	49,0	33,0			0,35	3,32	7,00	0,63
Iza	B	4,40	52,0	33,0			0,35	2,79	7,00	0,63
La Calera	B	16,7	33,0	28,0			0,35	10,61	7,00	0,63
Manizales	B	4,92	50,0	33,0			0,35	3,12	7,00	0,63
Nemocón	B	14,7	33,7	28,0			0,35	9,31	7,00	0,63
Paipa	B	3,64	56,0	33,0			0,35	2,31	7,00	0,63
Paipa	B	2,26	70,0	33,0			0,35	1,43	7,00	0,63
Paratebueno	B	2,06	73,7	33,0			0,35	1,30	7,00	0,63
Puracé	B	12,0	32,0	25,0			0,35	7,58	7,00	0,63
Ricaurte	B	17,4	31,8	27,0			0,35	11,06	7,00	0,63
Rivera	B	2,79	54,0	24,0			0,35	1,77	7,00	0,63
Santa Marta	B	5,58	42,0	27,0			0,35	3,54	7,00	0,63
Santa Rosa de Cabal	B	3,64	56,0	33,0			0,35	2,31	7,00	0,63
Santa Rosa de Cabal	B	3,35	58,0	33,0			0,35	2,12	7,00	0,63
Santa Rosa de Cabal	B	1,49	89,0	33,0			0,35	0,95	7,00	0,63
Suesca	B	10,2	33,2	25,0			0,35	6,47	7,00	0,63
Tabio	B	3,16	59,5	33,0			0,35	2,00	7,00	0,63
La Cruz (Tajumbina)	B	2,79	63,0	33,0			0,35	1,77	7,00	0,63
Tibirita	B	8,12	43,3	33,0			0,35	5,15	7,00	0,63
Tibirita	B	4,70	50,8	33,0			0,35	2,98	7,00	0,63
Tocaima	B	10,7	33,8	26,0			0,35	6,80	7,00	0,63
Utica	B	16,7	31,0	26,0			0,35	10,61	7,00	0,63
Villamaría	B	2,79	63,0	33,0			0,35	1,77	7,00	0,63
TOTAL		**272**					**14,4**	**173**	**287**	

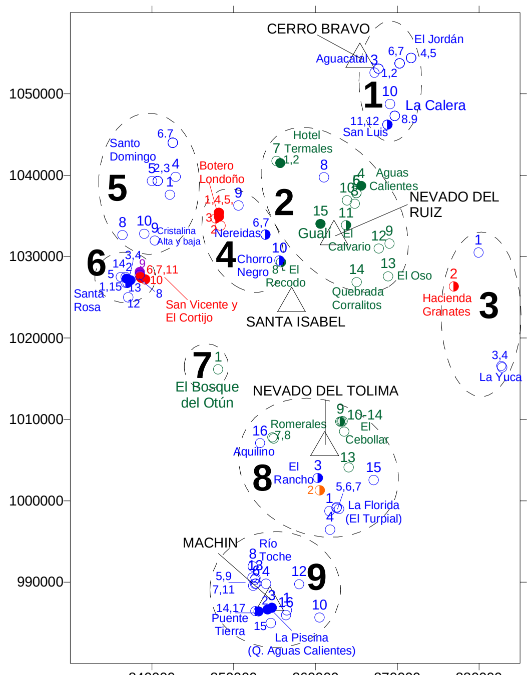

Figure 2. Location of groups of hot springs from the Cerro Bravo – Cerro Machín Volcanic Complex. Chloride springs are represented by red, bicarbonate springs by blue and sulphate by green. Discharge temperature below 40°C correspond to empty circles, between 40 to 60°C to half filled circles and higher than 60 °C to filled circles.

(91°C) is found at chloride springs from San Vicente with chloride concentration up to about 886 mg/l, lithium up to 5.6 mg/l, boron up to 22.7 mg/l with relatively low bicarbonate and sulfate (275 and 30 mg/l, respectively). The Na/K geothermometer indicates a reservoir temperature around 280°C. Bicarbonate springs from the Santa Rosa sector with discharge temperatures between 50 to 65°C, register the highest silica contents, from which temperatures around 200°C are inferred. To explain this behavior the Enthalpy-chloride model presented in Fig. 3, was applied. Two processes clearly identified are postulated to explain the differences in composition and particularly in silica contents of the springs from the two sectors: (1) direct mixing from the hot reservoir geothermal fluid with low temperature shallow water to form the springs of Santa Rosa and (2) Boiling of the geothermal fluid and thereafter, mixing with low temperature shallow water, to form the springs from San Vicente. So, at Santa Rosa springs, the mixing with shallow water decrease the chloride and silica contents and increase bicarbonate (and also magnesium and calcium) while in springs from San Vicente, the boiled fluid which gives place to the formation of the springs, has a lower temperature than the reservoir (that is lower silica contents) and higher chloride concentration, resulting from the boiling process. From the Entalphy – Chloride model, the reservoir temperature extrapolated from the dilution trend of Santa Rosa sector springs would be around 310°C.

The group 9, located at the south of the area near to the Cerro Bravo Machín volcano, is formed by 17 bicarbonate springs, located along the Toche River and bordering areas to the caldera of the volcano. Warm and hot springs from this group show a relatively high chloride, lithium and boron, which in the hottest spring (94°C) get 300 mg/l, 2.7 mg/l and 15 mg/l, respectively. Besides this, these springs exhibit high silica contents (of the order of 300 mg/l) showing a semblance with the springs from Santa Rosa sector in the group 6, which lead to a high reservoir temperature. Considering the temperature and composition of these bicarbonate waters they are not form in the periphery of the system but close to the upflow zone. The absence of chloride water on surface could be explained by the mixing of the deep hot chloride fluid with steam heated water at shallower depth. Such a mixing at short distance from Cerro Machín volcano would lead to the conclusion of a hydrothermal system of small dimensions as it was formulated before from geovolcanological and tectonic criteria (CHEC et al., 1983). The reservoir temperature was estimated in 220-240°C from the Na/K geothermometer and in 200°C from the quartz geothermometer.

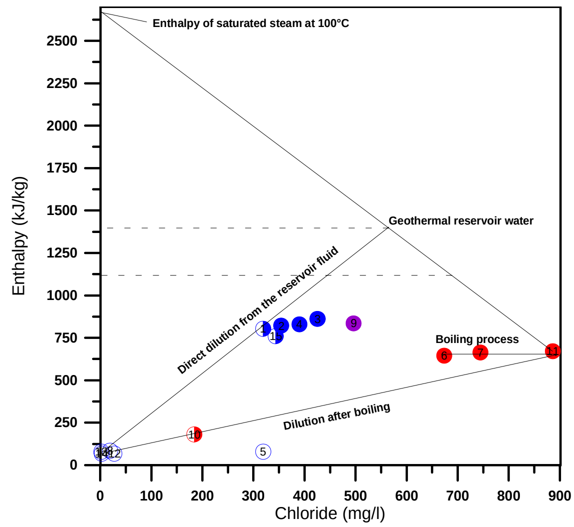

Figure 3. Enthalpy – Chloride model (Arnórsson, 2000). The composition of bicarbonate springs from Santa Rosa with a relatively low discharge temperature and the highest silica contents, are explain from this model, as the dilution directly from the reservoir water at about 310°C. Hotter springs from San Vicente seem to be the result of boiling and subsequent dilution.

As conclusion**, t**he geothermal system of Santa Rosa de Cabal could be independent from Nevado del Ruiz system as the geochemical temperatures suggest. Santa Rosa would be a higher temperature system which heat source could be associated to the magmatic bodies of Paramillo de Santa Rosa but nor necessarily related to eruption events which last occurrence was estimated as too old to be considered as a good heat source (CHEC et al., 1983). Taking into account the very high estimated reservoir temperature at Santa Rosa area, and the favorable permeability conditions inferred from geological contacts (andesitic lavas and the Quebrada Grande Formation), from several faults like San Ramón, Campoalegrito, San Eugenio, La Cristalina crossed perpendicularly by Laguna Baja, which is a normal fault (CHEC et al., 1983) and, from the occurrence of numerous hot springs.

3.1.2 Cundinamarca Department

Cundinamarca Department, located in the central region of Colombia on the Eastern Cordillera in a sedimentary geological setting and with an approximate area of 22.600 km^2 has at least 42 thermal springs well spread out from west to east. They reflect the existence of low temperature systems, in the main, likely related to the normal geothermal gradient as heat source. The highest temperature resources inferred from the springs are located towards the east at Gachetá, Tibirita and Paratebueno municipalities, where mesothermal geothermal gradients (50-60°C/km) were estimated. Their isotopic composition reveals two probable processes affecting the springs; one in springs from Útica municipality, which shows an enrichment likely due to evaporation as their high salinity suggest and, in the springs from the plateau named Sabana de Bogotá, which show a lighter stable isotopic composition with respect to the springs from both sides of the plateau. This reveals the contribution of different processes in the formation of the precipitation water. A more complete description of the results of this spring inventory is presented in a separated paper in the frame of this congress (Alfaro, 2005).

3.2 First Stage of Exploration

3.2.1 Azufral volcano

Azufral volcano is a strato-volcano located on the Cordillera Occidental, in Colombia, which priority as a geothermal prospect is well known and was registered in the frame of the previous world congress (Alfaro, et al, 2000). The geological cartography of the area in a scale 1:25.000 was studied by INGEOMINAS (Torres & Bernal, 2002). It included the compilation and interpretation of the geology of some surrounding areas to cover a total area of 1400 km^2.

3.2.1.1 Geological Setting

The outcrops of the area consist of metasedimentary rocks of Dagua Complex of Lower Cretaceous to Upper Cretaceous age and volcanic-sedimentary rocks from the Diabasic Complex, in the main. These shaped by the basement and are intruded by porfiritic rocks of andesitic to quartz-dioritic composition, which Paleogenic ages are between Eocene to Later Miocene and from which the intrusive body of Piedrancha stands out. From the Upper Miocene the sedimentary Formation of Esmita is registered, conformed by green fossilipherous limolites, narrow carbon lens in the middle of the sequence and polymictic conglomerates with intercalations of sandstones in the upper part (Torres & Bernal, 2002). The volcanic rocks from the Neogene consist of andesitic, dacites and rhyolites discordantly deposited on the previous geological strata.

The stratigraphy of the recent volcanic deposits supported by a geochronological study (^{14}C), was the basis for the definition of the geological formation of Azufral (Torres, et al., 2003) which covers an area of 420 km^2 and have a thickness is about 80 m thick. It consists of rocks and deposits resulting from the explosive volcanic activity of Azufral volcano, registered from 17.790 ± 90 to 3370 ± 70 years BP. Typical columns of Azufral Formation are located at the Sabana de Túquerres, east flank of the volcano, as well as in the basins of Azufral, Pacual, Sapuyes, Verde and Guisa rivers.

Azufral Formation is divided, from bottom to top, in six (6) members: The Túquerres Member consists of deposits of surge and pyroclastic flow, which can be found at the east and south east of the volcano and, debris avalanche deposits found at the south. La Calera Member conformed by an ash and blocks pyroclastic flow, ash and pumice and by deposits of pyroclastic surge, which highest thickness outcrops mainly at the west and south-west while towards the south, east, north and north-east it has lower thickness. The Cortadera Member has interlayered ash flow and pumice deposits with pyroclastic surge deposits and is widely distributed around the volcano. It is found in very close to the crater area as well as in distant places: Planada de Chapuesquer to the north, La Oscurana, to the west and El Tambillo at the south-west in the proximity of Cumbal volcano. El Espino Member, which consists of pyroclastic deposits (ash and pumice flows), pyroclastic surge and one debris flow (lahar) deposit, is found from the north to the south-east, reaching Sapuyes river, and to the west sector in the basin of the Guisa river. El Carrizo Member, made of ash and blocks flow deposits is located in a limited area to the south-east of the volcano following the margins of the creeks . El Carmelo and El Carrizo. Finally, Laguna Verde Member, located in the closest to the volcano areas, consists of deposits of pyroclastic surge related to the most recent activity of Azufral volcano (Torres, et al., 2003).

3.2.1.2 Hot Springs Geochemistry

The chemical composition of the hot springs, updated during 2002, did not show major variations with respect to measurements done 17 and 22 years ago (Olade, et al. 1982 and Olade, et al., 1987) which interpretation was briefly described in the proceedings of the last world geothermal Congress (Alfaro et al., 2000). The general features of the eight sampled springs include neutral pH for all of them, discharge temperatures between 18 and 49°, high salinity which source presumably is not the geothermal fluid as low temperature springs shows high salinity and a variable contribution from that saline source to the springs. From the discharge temperature (47.3 °C), total dissolved solids (2036 mg/l) and the relative Cl-SO_4-HCO_3 illustrated in the Fig. 4 and the Cl-HCO_3-B compositions the Quebrada Blanca hot spring seems to receive the major contribution of the geothermal fluid.

The aqueous geothermometers applied to the hottest, chloride springs (Quebrada Blanca) and mixed chloride-bicarbonate springs (Tercán I and II, also know as Quebrada El Baño), which besides the spring of Laguna Verde, are also the closest springs to the crater, point out high temperatures (above 215°C for Na/K geothermometer, above 178°C for the quartz geothermometer). However, the discharge water of these springs does not represent the ratio of the alkaline ionic species in the reservoir as a high sodium contribution is registered from a non geothermal source and from this, the estimated temperatures would not be reliable. On the other hand, the high dilution and possibly even a conductive cooling affects the quartz geothermometer, as the Enthalpy – Silica model from the Fig. 5 shows. That is, the reservoir temperature should be above 178°C and a more precise estimation from surface, requires the application of other geothermometers such as those based on gases composition.

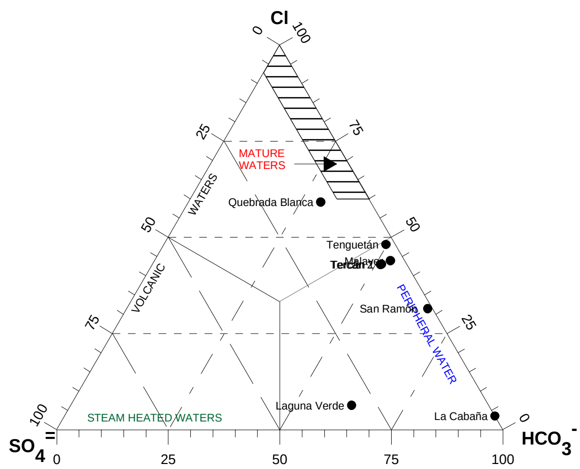

Figure 4. Relative Cl-SO_4-HCO_3 composition for springs of Azufral volcano (Base diagram from Giggenbach, 1991) Quebrada Blanca spring has the highest mature water contribution.

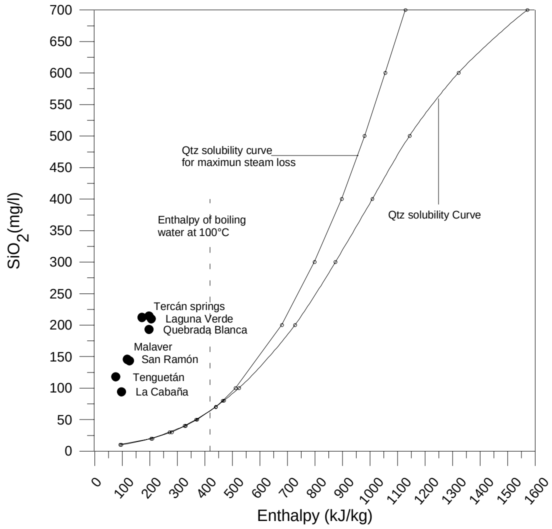

Figure 6. Stable isotope composition of springs from Azufral Volcano. A slight oxygen enrichment if found at the hottest springs (Quebrada Blanca, Tercán)

3.2.2.1 Tectonic Frame

During Late Miocene and Pliocene a fold and thrust belt was generated in the Eastern Cordillera, followed by the regional raising of the whole chain in the Pliocene-Pleistocene (Dengo and Covey, 1993). These authors suggest that the raising occur along thrust and back-thrust faults with the detachment in the cretaceous sedimentary and incompetent units, and along normal basement faults reactivated as reverse and thrust ones during the Mesozoic, as the Boyaca Fault. This tectonic inversion in the Eastern Cordillera has been documented by authors like Fabre (1983), Colletta et al (1990), Dengo & Covey (1993), Cooper et al (1995), although they no not mention the occurrence of strike slip movements during the uplift. These displacements in the Eastern Cordillera (transpression) from Pliocene, have been considered by De Freitas et al (1997), Kammer (1999), Taboada et al (2000), Sarmiento (2001) and Acosta (2002). This lateral movement affects even the inverted structures in the axial zone of the mountain chain, where the cordillera shows symmetry.

The regional interpretation of Landsat Images allows the recognition of NEE linear features related to the traces of Boyaca, Soapaga and other faults (longitudinal faults), as well as the identification of geomorphic features related to wrenching or lateral movement additional to the vertical displacement of the faults (Velandia, 2003). The identified regional faults are interpreted as an imbricate fan by overlapping fault propagation to the SE with some strike slip motion as is suggested by the oblique arrangement of fold axes regarding the main fault traces. In addition to the longitudinal faults (NEE), a transverse array is also identified in the area, which is related to the basement faults that probably controlled the cretaceous sedimentation and even the presence of the Neogene-Quaternary volcanic deposits in the Paipa area, suggesting an extensional character of these NW faults.

The obtained geological map of the Paipa geothermal area (Fig. 7) in 25:000 presents an updating and detail of the structural knowledge to better explain the geothermal system. This is also based on previous regional geological mapping (Renzoni & Rosas, 1983) and studies about geothermal and volcanic aspects (Ferreira & Hernández, 1988 and Hernández & Osorio, 1990). The area is dominated by Cretaceous marine sedimentary rocks and Late Cretaceous to Paleogene continental sedimentary rocks, as well as Neogene to Quaternary unconsolidated deposits, being important the volcanic and volcanoclastic deposits and a local hydrothermal breccia that can be related to a magmatic heat source for the geothermal system

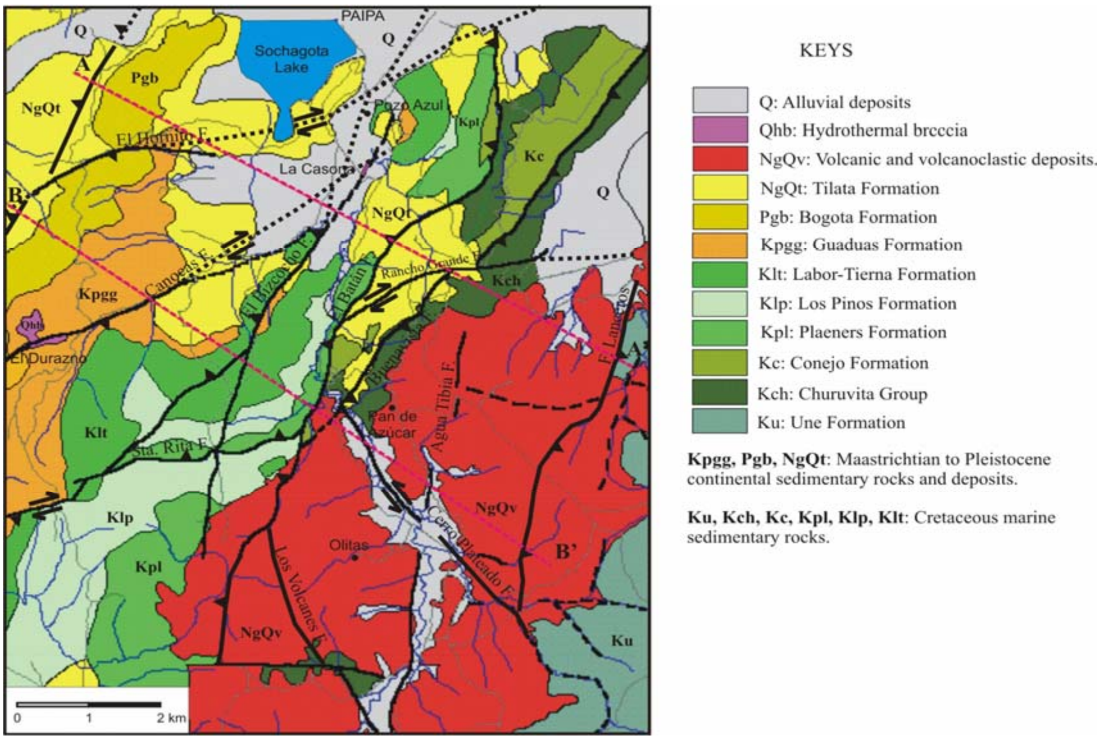

Figure 7. Geological Map of the Paipa Geothermal Area. Location of structural cross sections A-A' and B-B' presented in Figure 8 are indicated here.

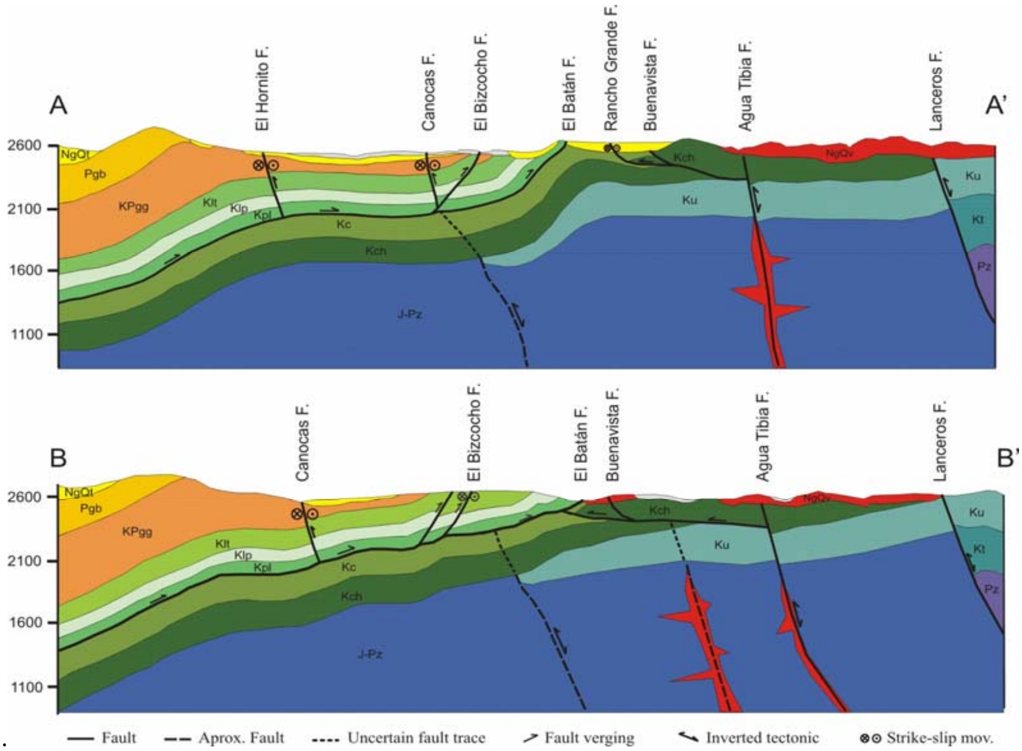

Figure 8. Structural cross sections A-A' and B-B' (located in geological map – Fig. 7), showing detachment level under Plaeners Formation and basement faults related to the volcanism and the upflow of the geothermal fluids

3.2.2.2 NEE Longitudinal Faults

Geological mapping and seismic interpretation carried out in the area, allowed to obtain a structural scheme, where NEE oriented faults are outlined with a parallel orientation to the main faults in the region, as Soapaga and Boyaca. The interpreted geological cross sections (Fig. 8) are showing two structural styles: - one that affects the basement and considered as thick skin, which also cuts the cover sequence and - other with thrust faults that are restricted to the sedimentary rocks of the cover and known as thin skin.

The thick skinned style would be related to the reverse Lanceros Fault, that has an opposite dip with regard to the Soapaga Fault, between which a block would be expelled in the shape of "pop-up". The thin skinned style is associated to the El Bizcocho and El Batan thrust faults, where the last one represents the front or more distal fault of the overlapped fan that is verging to the SE from the Boyaca Fault, with detachment along the Plaeners Formation bottom (Fig. 8).

3.2.2.3 NW Transverse Faults

These structures are observed especially to the South of the area. The Cerro Plateado Fault is observed as a shear zone in the hill, it consists of the Une Formation sandstones (Fig. 7) and with a trace along the Honda Grande creek valley to the NW that separates the volcanic bodies that usually have been known as Olitas on the south and Pan de Azucar to the north. The Los Volcanes Fault crosses the hill of the same name, where the Olitas volcanic deposit is located; regionally its trace continues to the SE up to another volcanic body and geothermal system known as Iza. These two faults are interpreted as basement structures related to a previous extensional tectonic phase, which was reactivated during Andean uplift, preserving the character of open breaks that facilitate the hydrothermal fluid flow; they are even assumed as faults of such depth that allow the ascent of magmas and the volcanism in the area

3.2.2.4 NE Transverse Faults

These faults affect the sedimentary sequence and microtectonic data were obtained in some of them, indicating right lateral displacements. El Hornito and Canocas faults concern the longitudinal structures and are interpreted as tear structures associated to thrusting. Also, these structures are considered as the most recent result of faulting in the area. The Santa Rita Fault is interpreted as a lateral ramp of El Batan thrust fault.

3.2.2.5 Structural Geology Discussion

In general, the obtained model shows structures that can be interpreted as a product of the reactivation of previous structures and the generation of new faults under the Andean Orogeny compressive regime, which shows transpressive features in the area by the effect of a NW-SE oriented maximum horizontal stress, assumed under an approximated regional tensor of 122° (from Taboada et al, 2000 and Toro, 2003).

This transpression causes thrusting, normal to the tensor orientation and lateral displacements along oblique faults to this orientation due to the local partitioning. Longitudinal and transverse faults shape blocks that can acquire an independent movement, including rotation, under this partitioning. This kinematics is shown in Fig. 9, and allows proposing an application of the structural interpretation to the exploration of geothermal resources.

From the structural model and location of current hot springs, some promissory zones are proposed for future exploration (Fig. 9). These are related to: - The fault traces, especially along the NE and NW transverse ones, since they can allow the flow of fluids, and along some NNE longitudinal faults; - The crossing of longitudinal and transverse faults, since it is assumed that the connection with the heat source happens especially along NW transverse faults and of some longitudinal faults as the Agua Tibia

Fault; - Corners opened by the rotation of blocks between the El Hornito, Canocas and Santa Rita faults, since the right lateral movement generates a distension in the surrounding of the cross of tear faults (NE) and NEE longitudinal faults, which are displeased.

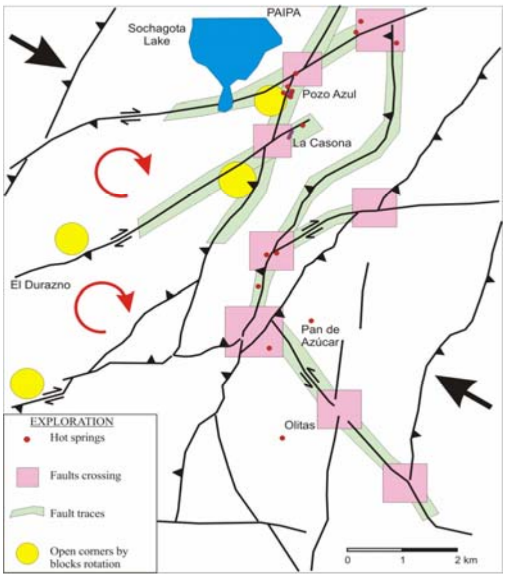

Figure 9. Structural model for the Paipa Geothermal Area showing the proposed promissory zones for future exploration. Movement direction (thick black arrows) of the shear zone causes thrusting, relative displacements and blocks rotation (red arrows), as well as open zones along parallel fault traces, where strike-slip also occurs. This kinematics is considered to point out certain sectors as geothermal promissory areas.

3.2.2.6 Vulcanology

The outcrops of volcanic rocks in the municipalities of Paipa, Tuta and Iza have been considered anomalous in the frame of the sedimentary geology of the Cordillera Oriental. The volcanic products cover an elongated area of about 31 km ^{2}, in NE direction, between the municipalities of Paipa and Tuta. Following lithological, geomorphological and structural factors the area can be divided in the sectors: El Guarruz, to the north east and, Olitas to the south west. From the lithology and the rocks distritution, the focus of the volcanic rocks is at Olitas sector. This lithology is dominated by pyroclastites interlayed with sedimentites from fluvial, colluvial and lacustrine, environments, domes and volcanic lavas. The pyroclastic flows are more abundant than the pyroclastic fall deposits. The sedimentites are dominated by the sand and slime granulometry. The tephrastratigraphy shows that the volcanic rocks overlay discordantly the sedimentary rocks from the Cretaceous and the current soil was developed on them, except in some valleys where fluvial and colluvial sediments overlay the vulcanites.

From more than 20 stratigraphic columns of the volcanic area a general stratigraphic column was obtained in order to track the eruptive activity. Two main eruptive epochs were Identified: The first one is represented by explosive eruptions that produced pyroclastic flows by the column collapse. This epoch seems to have finished with a collapse, which gave place to the formation of a 3 km diameter caldera with a rough depth of 400 m. The second epoch could be interpreted as a resurgence of the first one, inside the caldera, with eruptive foci towards the southeast rim, that is in the sector of the head board of the Olitas creek. The main feature of this epoch is the domes production which collapse generated pyroclastic flows that remained confined to the caldera depression.

The relation between the hydrothermal and the volcanic-magmatic systems can be derived from the following observations: (1) the surface manifestations (hot springs and steaming ground) discharging abundant CO_2, are located inside and toward the rim of the inferred volcanic area. (2) There is a magmatic camera likely located under the caldera structure, in the metamorphic rocks, which constitute the core of the Cordillera, that would be the heat source of the hydrotermal system. (3) There are alteration minerals at the focus of the two identified eruptive events which are indicative of existence of hydrothermal fluids.

3.2.2.7 Geochemistry of the Hot Springs

The geochemistry of the aqueous phase of springs from Paipa geothermal area, was interpreted by Alfaro & Pang (2003) as follows: The hot springs from Paipa geothermal area aligned along about 7 km **(**Fig. 10**).** Two main sectors: ITP-Lanceros, La Playa host most of the springs. Two isolated low temperature springs are registered in the sectors identified as El Hervidero, which main feature is the permanent and abundant CO_2 discharge, and Olitas. Additionally, there are two shallow wells of warm water (21°C) which feed the industrial plant of sodium sulphate (SALPA) and were including in the sampling. The temperature reaches 76°C in the spring number 1 from La Playa Sector. The highest salinity is found at the shallow wells (21 and 22).

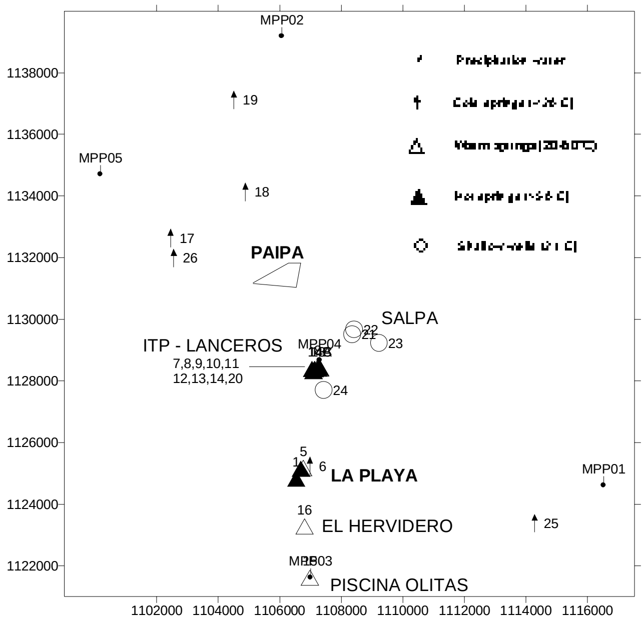

Figure 10. Location of springs and precipitation water samplers at Paipa geothermal area.

The predominant dissolved species in the high salinity warm and hot water samples from the geothermal area of Paipa, are sodium and sulfate as the Shoeller diagram (Fig. 11) indicates.

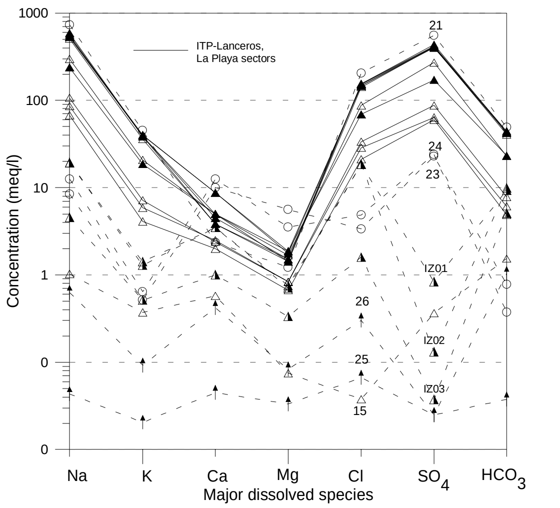

Figure 11. Schoeller diagram for Paipa and Iza springs (Base diagram from Schoeller, 1955). A predominance of sodium and sulphate is clearly observed. The highest sodium sulphate contents is found at a shallow low temperature water (point 21).

From the X-ray characterization Sodium sulphate is also the composition of the efflorescent white salt and the crusty white deposit, found on surface wide spread out in the hot springs area in the form of mirabilite ($Na_2SO_4.10H_2O$) and thenardite (Na_2SO_4). The saline source controls also the conservative species as lithium and boron. The only species which seems to follow a correlation with temperature is fluoride, which gets a highest concentration of 18-20 mg/l at La Playa, the hottest sector. Hot springs from Iza, a separated geothermal system located about 15 km south from Paipa, which occur in a similar geological setting but without the influence of such a saline source, was included as a reference. They are identified as IZ#. As it would be expected, the hot springs from Paipa as mostly sulfate while the springs from Iza are chloride and bicarbonate with evidence of high dilution.

Their relative Na-K-Mg composition dominated by sodium shows a clear mixing trend (Fig. 12) from which more concentrated end-members are the warm shallow waters from SALPA . The hot springs of are aligned along the mixing trend which cannot be extrapolated on the equilibrium line as the chemical composition is influenced by the shallow saline source and do not represent the deep fluid. On the other hand the springs from Iza highly diluted with cold ground water as their relative magnesium concentration indicates, point out a temperature between 240 to 260°C by extrapolation on the equilibrium line.

Since alkaline geothermometer cannot be reliable, silica geothermometers were applied to estimate minimum reservoir temperature which highest values indicate 120°C for quartz and 95°C for chalcedony. The highest silica concentration was found at Olitas spring (167 mg/l) which does not seem to be consistent with it low temperature (23°C). According to the Enthalpy – silica model this concentration seems to be controlled by the amorphous silica and explained by the infiltration of meteoric water through high silica rocks as the rhyolitic volcanic deposits and possibly, the subsequent slow uprising flow with conductive cooling without silica precipitation. From the same mixing model the highest temperature of 230°C is estimated assuming dilution of geothermal fluid without steam or heat loss before mixing and quartz as the mineral controlling the silica solubility

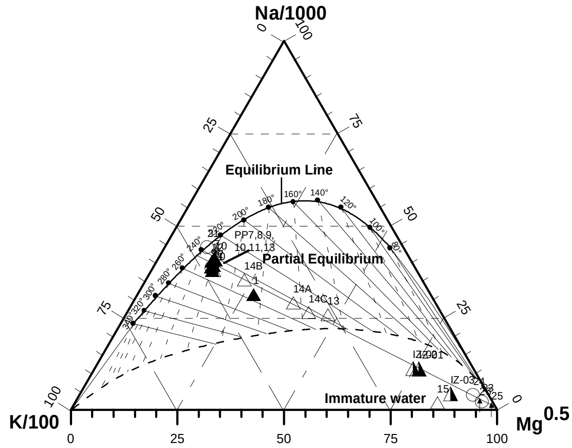

Figure 12. Relative Na-K-Mg at springs from Paipa (Base diagram from Giggenbach, 1988). A clear mixing trend includes high salinity water and hot springs.

Although the quartz geothermometer is relatively low, its presence in the reservoir was assumed from the results of the application of the code SOLVEQ. For Iza springs the highest estimate temperature by applying the enthalpy silica model is 260°C.

The stable isotopes composition presented in the Fig. 13 shows an isotope enrichment particularly of oxygen-18, which reaches its higher magnitude (around 4 ‰) at the warm water shallow wells from SALPA with the highest observed total dissolved solid contents and identified as highest sodium concentration in the mixing line observed in the Na-K-Mg relative composition diagram. The warm and hot springs follow about the same linear trend defining a line with a slope of 1.4. On the other hand, the sample PP16 (El Hervidero), shows a high δ^{8}O depletion (around 5.5 ‰) probably due to the ^{18}O exchange between CO_2 and H_2O, as it was explained before by Bertrami, et al., (1992).

The oxygen-18 enrichment could be due at least to three processes: Evaporation (suggested by Bertrami et al., 1992), high temperature water-rock interaction and, percolation through evaporitic hydrated minerals isotopically enriched from a sedimentary basin. The evaporation process would not be rare as the precipitation of the area is lower than the evaporation. However, the expected slope for dry conditions would be between 2.5 and 4 (Sofer, 1978). The possible high temperature water-rock interaction reflected in an ^{18}O enrichment could not be distinguished in the hot springs, as the end member of the mixing is a shallow high salinity low temperature water. Thus, the percolation through hydrated minerals and the oxygen-18 exchange is likely one or the process controlling the isotopes enrichment. This is common process in sedimentary basins and could happen at Paipa geothermal area which is related to the Chicamocha river basin. From this, the hydrated minerals are part of a non-marine evaporitic deposit, which are also the source of sulphate and sodium to form thenardite and mirabilite on surface.

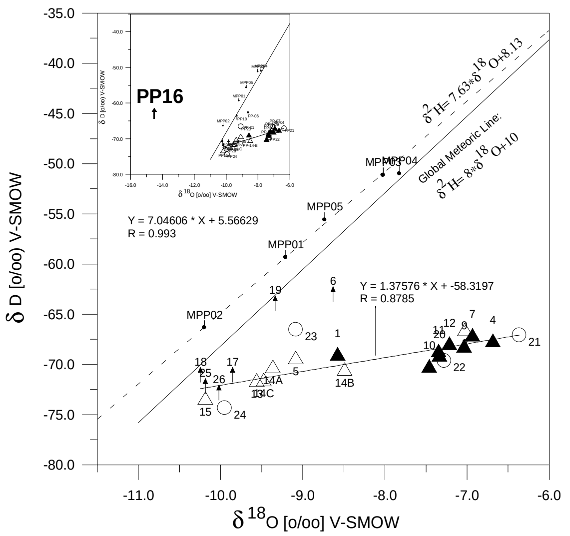

Figure 13. Stable isotopes compositions of springs from Paipa. The high enrichment observed at the shallow low temperature water of highest salinity (21) suggest its relation with evaporitic minerals. The d^{18}O depletion (around 5.5 ‰) at El Hervidero (PP16) is probably due to the ^{18}O exchange between CO_2 and H_2O.

As the hot springs do not keep the isotopic composition of the reservoir, their recharge elevation could not be determined. Hot springs from Iza are isotopically lighter and based on the correlation found with precipitation water from the area of Paipa, their recharge elevation is between 3200 and 3500 m.a.s.l.

In conclusion, the geochemistry of the springs related to the geothermal system of Paipa is complex due to a mixing process, occurring nearby the surface, of deep geothermal water with shallow sodium sulfate water, enriched in δ^{18}O and δ^{2}H. The reservoir temperature could reach up to 230°C. From this, Paipa is a high temperature geothermal system. This type of systems and the permanent and abundant carbon dioxide discharge in springs and wells are consistent with the magmatic heat source. The high discharge of carbon dioxide could be related to the found correlation between fluoride and temperature (silica contents). The fluoride would be in solution as a result of the calcium precipitation as calcite deposits. The springs from the south (El Hervidero (PP16) and Piscina Olitas (PP15)) are not affected by the high salinity ground waters and seem to belong to separated hydrological circuits.

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