Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Geothermal Reconnaissance of the Caribbean Flank of the Rincón de la Vieja Volcano, Costa Rica

Leyner Chavarría[1] and Alejandro Rodríguez[2]

ICE, UEN PySA, CSRG, Apartado postal 10032-1000, San José, Costa Rica.

[1]lchavarriar@ice.go.cr, and [2]arodriguezba@ice.go.cr

Keywords: Costa Rica, Rincón de la Vieja, Geology, Geochemistry, Geothermal Exploration

ABSTRACT

The Caribbean flank of the Rincón de la Vieja volcano is characterized by sequences of lavas and pyroclastic rocks of andesitic composition, most of them originated in the recent Rincón de la Vieja volcanic complex.

Sedimentary rocks of marine origin, which have been reported near from the study area by other authors, could be part of a regional geological basement. Hydrothermal alteration is scarce and limited to the hot springs areas and basically consists of clays and iron oxides associated with silica, manganese oxides and calcium carbonate (travertine). Geomorphologic and field studies suggest two main local structural lineaments affecting the area with NE-SW and N-S trending, some of them could be correlated with the distribution of hot springs, CO_2 and CH_4 (methane) anomalies. By the other hand, radar image analysis shows E-W regional structural lineaments which could be also important for the permeability.

Both cold and hot springs were classified in four main geochemical facies: Cl-SO_4, SO_4, HCO_3 and mixed. Cl-SO_4 water facies corresponds to the hottest springs and also with the highest electrical conductivities in the northern sector know as *El Volcancito* (T = 57-63°C, pH = 6.0, cond. = 5660-6020 µS/cm). The springs located in southern sector (*Albergue Agroecológico*) were also classified in the same facies but present lower temperatures, conductivities and pH values (T= 21- 37°C, cond. = 319-2430 µS/cm, pH = 3.0-6.0).

Both the springs located in *El Volcancito* and *Albergue Agroecológico* are associated with a common geothermal reservoir affected by the condensation of magmatic gases. According to the Na/K/Ca geothermometer of Fournier & Truesdel (1973) the reservoir temperature was estimated in 237°C; however this value must be taken with care since the possibility of a lack of water-rock equilibrium.

1. INTRODUCTION

Rincón de la Vieja is an active volcano located in the northwestern sector of Costa Rica, in the Guanacaste Volcanic Range, 20 km NW from the Miravalles geothermal Field. This range together with the Central Volcanic Range forms the inner arc of the country, which runs parallel to the Mid American Trench (Figure 1). The Pacific flank of the Rincón de la Vieja volcano has been focus of several studies conducted by ICE (Costarican Electricity Institute) in the search of new prospects for the development of geothermal fields for electricity generation. At the present time there are two areas of interest: Las Pailas and Borinquen. In the first one, ICE has drilled 9 deep wells and the existence of a high temperature geothermal reservoir has been established, and a first 35MWe plant feasibility report was presented (Mainieri, 2005). In Borinquen there are 2 deep wells and the feasibility studies are being carried out.

To the north of Borinquen, in the Caribbean flank of the volcano, there are some hot springs and structural lineaments that make this region interesting for an evaluation of the geothermal characteristics. For this reason was decided to conduct a reconnaissance study in an area of approximately 130 km^2.

Figure 1: Location of the studied area

The aim of the study was to elaborate a geothermal model of this area and to evaluate the possibilities for future studies, also was important for us to define the relationship between the hydrothermal manifestations in this area and those present in the Pacific flank of the volcano. The study includes remote sensing analysis (aerial photographs, digital elevation models), field geology (volcanology, stratigraphy) and geochemical survey of the mineral alteration zones and hot springs. The study includes laboratory skills such as rocks thin section analysis, X-Ray diffractometry for mineral identification and chemical analysis of water and precipitates.

2. GEOLOGY

Costa Rica is located in the southeastern extreme of the Central American isthmus, between Panamá and Nicaragua. One of the most important tectonic features of the zone is the interaction between the Cocos and Caribbean plates, where the first one is subducted actively under second one. This process develops important structural and volcanic settings that contribute to the existence of geothermal resources. The known geothermal prospects of the country are linked to the inner arc, which consists mainly of

Quaternary volcanic ranges that run parallel to the Mid American Trench (NW-SE).

2.1 Structural Setting

From the structural point of view this sector of the country is characterized by E-W regional lineaments which extend from Santa Elena peninsula towards the Caribbean region of the volcanic arc, ending against a NW-SE regional system that could be related with the extension of the Nicaragua Graben (Figure 2). Other important lineaments show NE-SW trending and, some of them extend from the Pacific coast to the volcanic arc. Also is observed an N-S system that shows lineaments that cut the recent volcanic edifices.

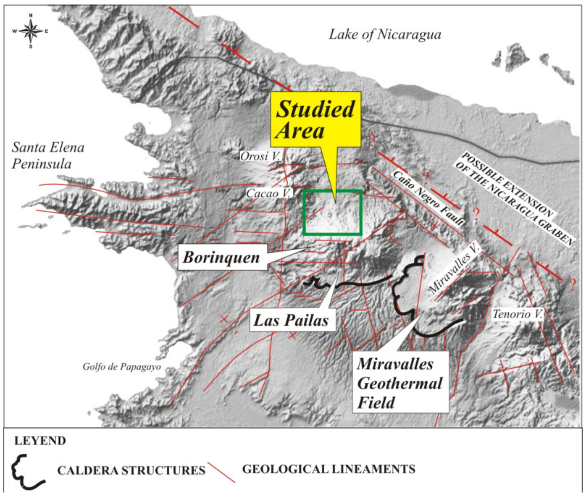

Figure 2: Regional lineaments and location of the studied area. The back ground image was taken from http://photojournal.jpl.nasa.gov/catalog /PIA03364

Field fractures are scarce; most of them were measured in fresh andesitic lavas and fewer amounts in pyroclastic fall deposits. Mainly consist of small fractures ranging from 0.5- 4 m, with openings about 2 - 15 mm. Most are vertical and show two preference patterns: N20E y N50E.

Analysis of aerial photographs and a digital elevation model help in the definition of the main lineaments. The most evident system shows a NE-SW trend and some could be related with regional structures parallel to Ahogados river. Other important families are represented by lineaments NW-SE and E-W (Figure 3).

2.1 Lithostratigraphy

In the surroundings of the study area rocks are mainly volcanic in origin, associated to the Guanacaste Volcanic Range and previous volcanic activity. Sedimentary rocks of marine origin, with ages of Eocene and Miocene have been reported near the study area by other authors (Zamora et al, 1997; Denyer & Alvarado, 2007). The presence of this kind of rock in the area is not clear, although they could be related to relics of erosion or even product of tectonic lifting.

Exactly in the studied area rock sequences are mainly of andesitic composition and related to the activity of the Rincón de la Vieja volcano; deposits include lava flows, breccias, lahars, fall and flow pyroclastic rocks. Locally, in the NW sector pyroclastic flows and lavas of rhyolitic composition were observed. These acid rocks probably correspond to a volcanic activity previous to Rincón de la Vieja.

A brief description of the main rock units is presented (Figure 3):

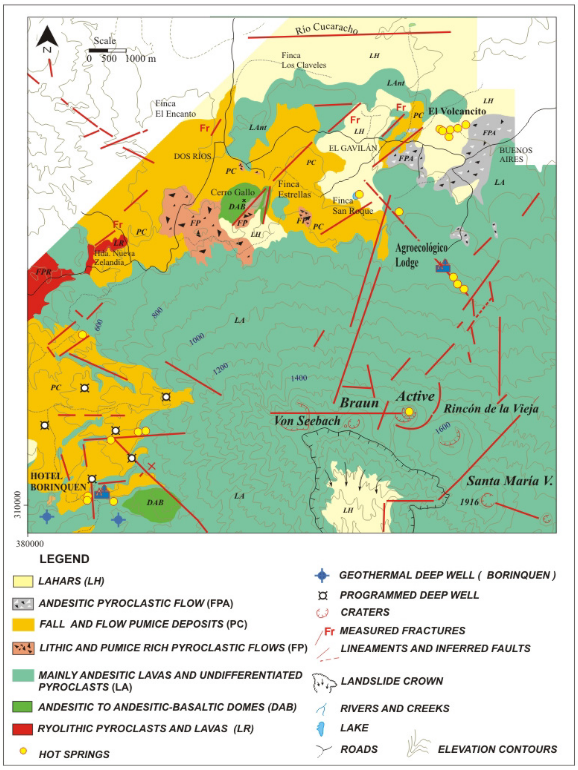

Figure 3: Geologic map showing the main rock units, lineaments and hot springs

2.1.1 Rhyolitic Lavas and Pyroclasts Unit

The unit consists of rhyolitic lavas and pyroclastic flows observed in the western sector, near *Nueva Zelandia* farm. The lavas show massive and laminar habits and are characterized by the presence of phenocryst of quartz, plagioclase and pyroxenes. The rock presents a brown glassy matrix with occasional flow structures and spherulites. In the surroundings some valleys are covered by pyroclastic flows of rhyolitic composition, apparently coming from the northern sector, toward Cacao volcano. All these rocks are partially covered by pyroclastic fall deposits of the Rincón de la Vieja volcano.

2.1.2 Andesitic and Andesitic Basaltic Lavas Associated to Domes Structures Unit

This unit is represented by a dome shape hill located to the southeast of *Dos Ríos* town (*Cerro Gallo*). This structure rise about 160 m from its base in the northern flank of the volcano. It consists of relatively fresh andesitic-basaltic lavas at the base and andesitic lavas to the top. These lavas show porphyritic and vesicular textures, occasionally with glomerocrysts and coronitic texture. The mineralogy consists of plagioclase, orthopyroxenes, clinophyroxenes, olivine and magnetite in a matrix of similar composition.

A similar dome structure was described by Molina et al. (2002) in the Borinquen sector.

2.1.3 Andesitic Lavas an Undifferentiated Pyroclasts Unit

The unit consists mainly of fresh andesitic lavas and in less proportion undifferentiated pyroclasts and breccias. These rocks are widespread around the area of study and related to the activity of the Rincón de la Vieja volcano.

Lavas exhibit a porphyritic to glomeroporphyritic or seriated texture of andesitic composition, formed of plagioclase, orthopyroxenes, clinophyroxenes and magnetite in a matrix of similar composition.

Occasionally, intercalations of breccias are observed that form permeable paths for the fresh and hot water movement.

2.1.4 Andesitic Pyroclastic Flows Unit

The unit consists of two coarse grained pyroclastic flows of andesitic composition. One of them is present in the surroundings of *El Gavilán* town and Pénjamo river; the other one is located to the town of *Dos Ríos*. The first one is characterized by high amount of pumitic blocks of white and black colors, furthermore with juvenile blocks of andesitic composition and andesitic preexisting blocks. Some juvenile fragments reach 2 meters diameter.

The flow located near *Dos Ríos* town is different because is essentially formed of a fine pumitic-lithic matrix that supports andesitic juvenile blocks (<20 cm) and preexisting andesitic blocks (less than 1 m diameter).

It is inferred that Rincón de la Vieja volcano is the source of those deposits.

2.1.5 Pyroclastic Fall and Associated Flow Deposits Unit

This unit is a sequence of several fall pumice deposits with scarce intercalations of flow events and occasionally surges. The fall deposits consist of centimetric layers of non-consolidated pumitic lapilli with a characteristic orange color caused by the oxidation of the iron rich crystals. Flow and surges are of similar composition but exhibit moderate compactation probably due to a greater temperature of deposition. These rocks are composed of pumitic fragments, andesitic and dacitic lithic fragments, and crystals of plagioclase, orthopyroxenes, clinophyroxenes and magnetite.

This unit is widespread in the studied area and could be correlated with similar deposits observed in the Borinquen sector.

2.1.6 Lahars Unit

The unit is represented by heterolithic deposits observed principally in the northern sector of the study area, in the sectors of El Gavilán and Cucaracho river. The unit consists of a soil rich matrix that supports mainly andesitic lava blocks with tuffaceous and hydrothermaly altered blocks. These materials are also associated to the activity of the Rincón de la Vieja volcano.

3. GEOCHEMISTRY

The chemical data come from water samples of hot and cold springs, rivers and creeks. Additionally, gas samples were collected at the northern and eastern parts of the study area. The sampling campaign was carried out from April to June, 2008. Also, there were other samplings during 2004. The software *AquaChem 4.0* was used for the classification of the information and for the preparation of the graphics. A description of the physical and chemical characteristics of the springs will be presented first. Then the interpretation and discussions will be exposed.

3.1 Water Classification

A water classification based on the predominance of anions and cations was useful for the definition of the geochemical facies, which are groups of samples that share the same chemical characteristics (Figures 4 and 5). A geochemical map shows the distribution of the geochemical facies by means of radial diagrams representing each sample (Figure 6).

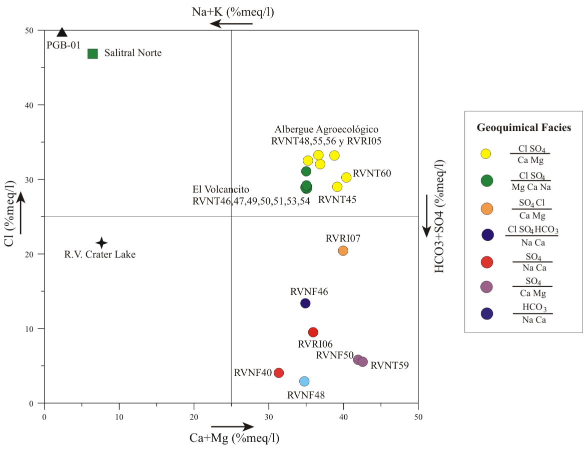

Figure 4: Ludwig-Langelier diagram

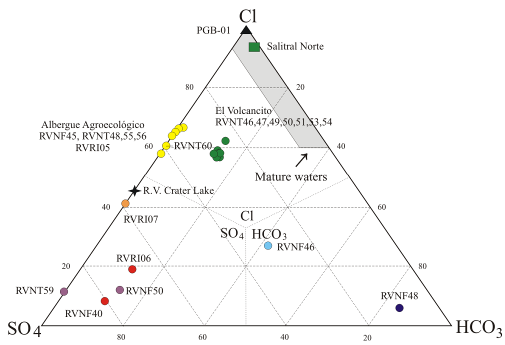

Figure 5: Cl-SO_4-HCO_3 diagram

3.1.1 Cl-SO_4 Facies

The Cl-SO_4 facies waters present a cationic composition from Ca-Mg to Ca-Na-Mg (Figure 4). The composition Cl-SO_4-Ca-Mg facies is represented by the springs located in the surroundings of *Albergue Agroecológico* (RVNT48, 55, 56 and RVNF45). There is another spring 2.5 km northeast from the lodge (RVNT60) that exhibits similar characteristics. These waters present the following parameters: T (21-37ºC), pH (3.0-6.0), Cond. (319-2430 µS/cm), Cl (41-561 ppm), SO_4 (82 - 417 ppm), HCO_3 (0 - 4 ppm), Ca (28 - 197 ppm), Mg (7 - 75 ppm), Na (11 -93 ppm) y SiO_2 (74 – 170 ppm). As can be appreciated, most of the waters are acid, with high concentrations of Cl and SO_4. Scales of intercalated black and white materials cementing organic matter like leaves and stems are very common around the springs. X-ray diffractograms revealed that meanwhile the black matter is amorphous, the white one contents the following minerals: quarz, cristoballite and gibbsite. Alternatively, chemical analysis of the black matter showed that its main composition is manganese oxides (MnO_2).

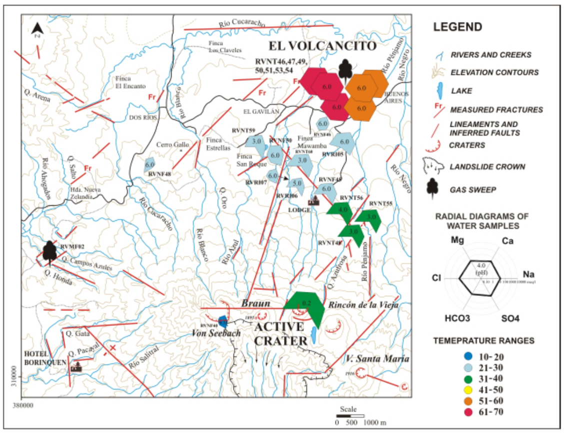

Figure 6: Geochemical map. Samples from Rincón de La Vieja Crater lake reported by Kempter & Rowe (2000)

The Mg-Ca-Na facies is located in the northern sector, at *El Gavilán*. The water comes to the surface through holes with diameters ranging from tents of centimeters to a few meters (Figure 7). The waters exhibit the following characteristics: T (57 - 63°C), pH (6.0), cond. (5660 - 6020 µS/cm), Cl (1278 - 1429 ppm), SO_4 (767 - 966 ppm), HCO_3 (523 - 576 ppm), Ca (387 - 407 ppm), Mg (280 - 299 ppm), Na (355 - 376 ppm) y SiO_2 (175 – 201 ppm). For practical purposes, these springs will be grouped as *El Volcancito* (small volcano), in reference to name of the most representative spring.

Gases come out from these springs in an intermittent manner. The main component is CO_2. The (N_2/Ar) ratio of these gases is 34, very close to 36, which is normally the ratio of ground waters saturated with air. This evidence suggests that that the thermal waters are being mixed with cold waters coming from shallow aquifers while travelling to the surface. Another relevant aspect of *El Volcancito* springs is that in conjunction with the cold gas manifestations in *Quebrada Honda* (RVMF2), they present the maximum CH_4 concentrations around Rincón de la Vieja volcano (Figure 8).

Large amounts of organic matter are cemented by calcium carbonate in form of travertine with iron oxides patinas. The average thickness of those deposits is 2 meters. However, at *El Volcancito* a maximum thickness of 5 meters is exposed. To the south the wetland, the travertine deposits are intercalated with sinter and organic matter and covered by a soil layer. This evidence suggests that probably the hydrothermal activity has been migrating to the northern part of this sector.

X-ray diffractograms of the travertine revealed the presence of magnesium calcite, gypsum, aragonite, calcite and pyrite. In the same way, the sinter diffractograms showed amorphous silica and pyrite. Other minerals identified by this technique were montmorillonite and laumontita.

3.1.2 SO_4 Facies

The SO_4 facies waters show a composition from Ca-Mg to Na-Ca (Figure 11). The springs are located to the southeast of the study area (RVNT40, 50, RVNT59 and RVRI06) (Figure 6). The following are the main chemical characteristics of these waters: T (16 - 29°C), pH (3.0 - 6.0), cond. (96 - 1120 µS/cm), Cl (2 - 45 ppm), SO_4 (28 - 505 ppm), HCO_3 (0 - 34 ppm), Ca (5 - 111 ppm), Mg (1 - 36 ppm), Na (4 - 33 ppm) and SiO_2 (33 – 90 ppm).

The chemical composition of the SO_4 facies is the result of ground waters heated by enriched H_2S vapors and a subsequent dilution with superficial waters.

3.1.3 HCO_3 Facies

RVNF48 spring is the only HCO_3 water sampled in the study area. It corresponds to a ground water with little interaction with surrounding rocks.

3.1.4. Mixed Facies

The mixed facies consist of a mixture of the described facies. For example, RVRI07 represent a combination between SO_4 and Cl-SO_4 waters. On the other hand, RVNF46 results when Cl-SO_4 waters with a similar composition of *El Volcancito* are diluted by superficial HCO_3 waters.

Figure 7: RVNT-46 spring known as *El Volcancito*.

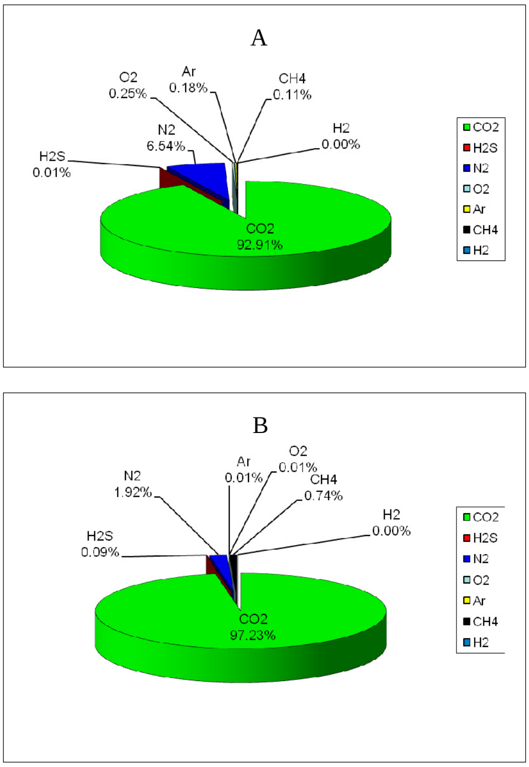

Figure 8: Gas analyses from A: RVNT-46 (*El Volcancito*) and B: RVMT02 (*Quebrada Honda*)

3.2 Discussion

The Cl waters presented at the Caribbean flank of Rincón de La Vieja volcano extremely differ from what has been called in the geothermal systems *mature waters*. Such waters are chemically representative of the reservoir because have reached the equilibrium with most of the minerals. For comparison, samples of *mature waters* obtained from *Salitral Norte* sprigs and from a deep well at *Borinquen Geothermal Area* (PGB01) (Figures 4 and 5). In the case of *Albergue Agroecológico* springs, the limiting factor is the extreme low pH. Such acid waters are far from the water-rock equilibrium because can still incorporate more cations due to rock leaching. This situation is confirmed in the Giggenbach triangle (Giggenbach, 1988) (Figure 9). A hypothesis regarding the formation mechanism of the Cl-SO_4 waters of *Albergue Agroecológico* is the condensation of magmatic vapors at depth. Such vapors are particularly rich in components like HCl, HF, H_2S, SO_2 and CO_2 which in contact with water generate considerable amounts of H^+ ions that explain the low pH of such waters.

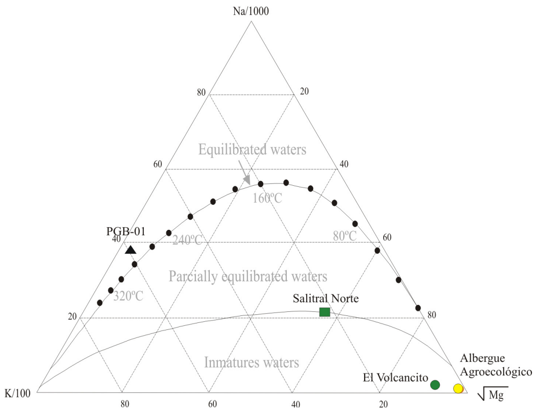

Figure 9: Giggenbach Triangle

El Volcancito springs have considerably higher pH values than the *Albergue Agroecológico* ones. Also, a very high HCO_3 concentrations and TDS (total dissolved solids). However, Cl/SO_4 ratios for both springs are basically the same (Figure 10). This evidence suggests that such waters could have a similar origin. The stable water isotopes oxygen 18 (^{18}O) and deuterium (D) for *El Volcancito* and *Albergue Agroecológico* locate this waters very close to the world meteoric water line with a very low oxygen shift. Nevertheless, mixing with meteoric waters could alter the isotopic signature of the springs (Figure 11).

Water-rock interaction would tend to neutralize acid fluids incorporating more cations at the same time and thus causing a TSD increase. However, water-rock interaction does not seem to fully explain the chemical differences between *El Volcancito* and *Albergue Agroecológico* springs, taking into account that these springs are very close to each other. In order better understand the relationships that could exist between these springs groups, a mixing model of enthalpy-chloride suggested by Nicholson (1993) and is shown in Figure 12. A reservoir temperature of 237°C was calculated from the Na/K/Ca geothermometer of Fournier and Truesdel (1973) applied to a representative sample from *El Volcancito* and corrected by magnesium as it was suggested by Fournier (1981). The enthalpy-chloride diagram explains that a parental fluid of 237°C ascends to the surface with a conductive cooling (without losing any vapor) and then mixes with steam heated ground waters and thus generates the *Albergue Agroecológico* and *Finca Mawamba* springs. In contrast, the chemical composition of *El Volcancito* springs could be explained by boiling of the parental fluid and dilution with meteoric waters. The high HCO_3 of those springs is owed to CO_2 contribution. CO_2 enters in contact with water and forms HCO_3^-. The next equation accounts for calcium carbonate formation (travertine).

$$2HCO_3^- + Ca^{2+} \Leftrightarrow CaCO_3 + H_2O + CO_2 \qquad (1)$$

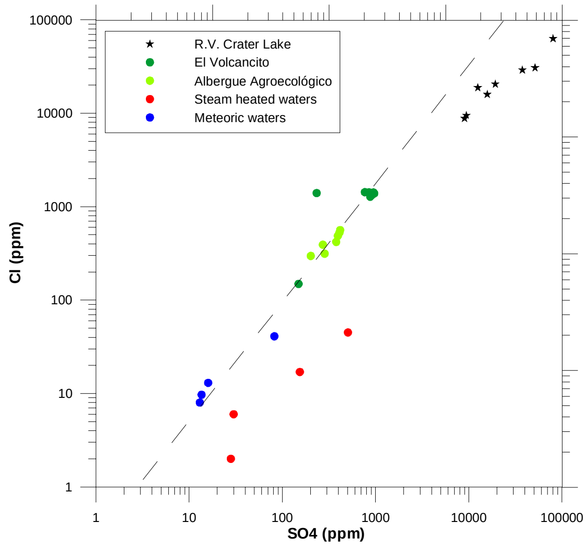

Figure 10: Cl/SO_4 ratio. Samples from Rincón de la Vieja Crater lake reported by Kempter & Rowe (2000) and Tassi et al. (2005)

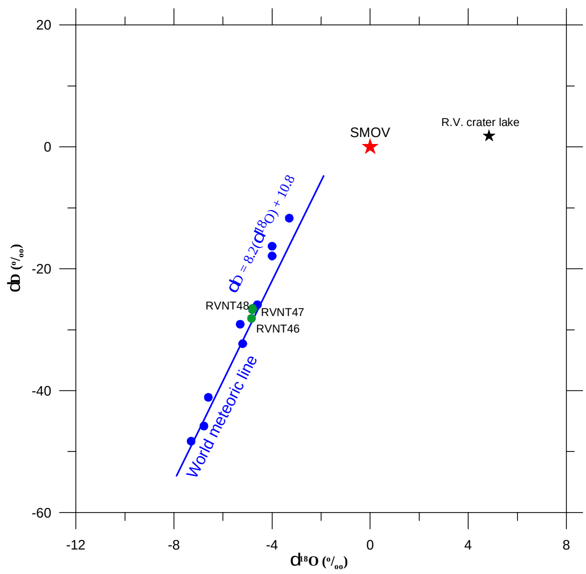

Figure 11: Water stable isotopes. Samples from Rincón de la Vieja Crater Lake reported by Kempter & Rowe (2000)

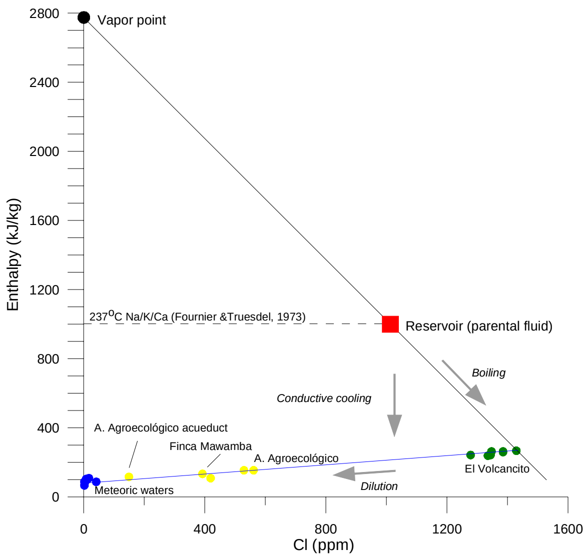

Figure 12: Cl-enthalpy diagram mixing model

The high methane (CH_4) concentration in gas samples from *El Volcancito* suggests a different gas source from volcanic activity. According to Nicholson (1993), CH_4 is the most abundant hydrocarbon present in geothermal fluids. Although it can be the result from abiotic processes, most of CH_4 is produced by alteration of sedimentary rocks at depth, particularly if organic-rich (Snyder et al., 2004).

The outcrop of hydrothermalized tubiditic sediments from Upper Paleocene to Lower Eocene has been documented by Zamora et al. (2004). In the same way, to the north of the study area Denyer & Alvarado (2007) described turbiditic sandstones, mudstones and conglomerates from Paleocene to Eocene. In such context it is not illogical to suppose that the high CH_4 concentrations could be related to a sedimentary basement. The high concentrations of Ca and Mg at *El Volcancito* springs could be also related to the presence of sedimentary rocks at depth. It would be necessary isotopic analysis of carbon 13 (^{13}C) in order to discard or accept this hypothesis.

CONCLUSIONS

Most of the outcropping rocks correspond to lavas and pyroclastic rocks of andesitic composition, related to the activity of the Rincón de la Vieja volcano. The presence of marine sedimentary rocks in the surroundings of the study area supports the hypothesis of the existence of this kind of rocks at depth (Figure 13).

Based on the morphological lineaments and field data is inferred a regional NE-SO structural system parallel to the Ahogados river. This could be related with the presence of rhyolitic lavas in the sector of *Nueva Zelandia* town and also with some high contents of CH_4 and CO_2 measured in some hot springs.

Hot springs are aligned preferentially N-S, from the active crater towards *El Gavilán* town. This suggests N-S fractures systems that allow the hot water movement. Also the alignment of acid hot springs could indicate the existence of a NO-SE fracture system from *Albergue Agroecológico* to *San Roque* farm.

The hot springs of mayor interest in the study area are those from *Albergue Agroecológico* and the ones from *El Volcancito*. In general they consist of Cl-SO_4 waters originated by condensation of magmatic steam at depth (Figure 13).

Both *Albergue Agroecológico* and *El Volcancito* hot springs seem to be part of the same reservoir, which has an estimated maximum temperature of 237ºC, however this temperature has to be taken cautiously because according to the chemical composition these fluids are not in equilibrium with the host rocks.

The mixing model suggests that *Albergue Agroecológico* hot springs experimented a conductive cooling from the reservoir and then mixed with superficial aquifers, probably steam heated waters. On the other hand, *El Volcancito* hot springs suffered a process of boiling and mixing with superficial waters. This process neutralized such fluids.

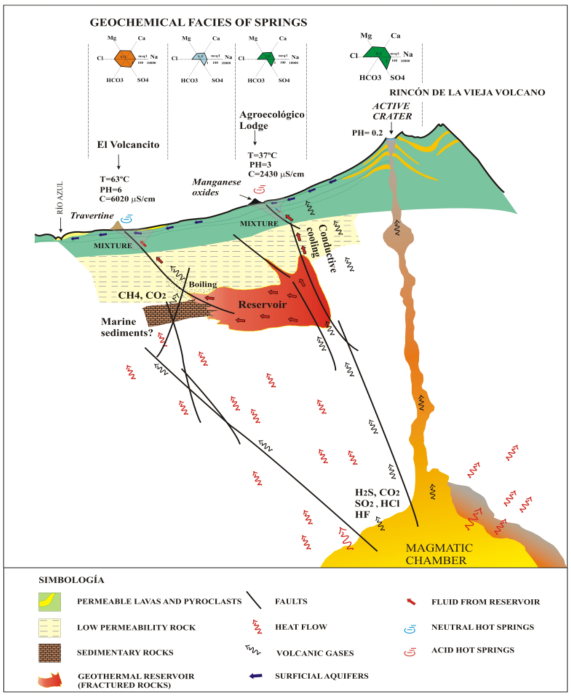

Figure 13: Geologic-geochemical model

REFERENCES

Denyer, P. & Alvarado, G., 2007: Mapa Geológico de Costa Rica. - Escala 1:400 000, Librería Francesa, San José, Costa Rica.

Fournier, R. O., 1981: Application of water geochemistry to geothermal exploration and reservoir engineering. - En: Ryback, L. & Muffler, L. J. (eds.): Geothermal Systems: Principles and Case Histories, New York, 109-143.

Fournier, R. O. & Truesdell, A., H., 1973: An empirical Na-K-Ca geothermometer for natural waters. - Geochim. Cosmochim. Acta, 37: 1255-1275.

Giggenbach, W. F., 1988: Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. - Geochim. Cosmochim. Acta, 52: 2749-2765.

Kempter, K.A., Rowe, G. L., 2000: Leakage of Active Crater lake brine through the north flank at Rincón de la Vieja volcano, northwest Costa Rica, and implications for crater collapse. - J. Volcanol. and Geotherm. Res., 97: 143-159.

Mainieri, A., 2005: Costa Rica Country Update Report. Proceedings World Geothermal Congress. Antalya, Turkey (2005).

Molina, F., Chavarría, L. & Vega, E., 2002: Geología del área geotérmica Borinquen - 52 págs. Grupo de geología, CSRG-ICE [Internal report].

Nicholson, K., 1993: Geothermal fluids: chemistry and exploration techniques. – 268 pages. Springer-Verlag, Berlin.

Snyder, G., Poreda, R., Fehn, U & Hunt, A., 2000: Los campos geotérmicos de Centroamérica: influencia del proceso de subducción sobre su composición volátil. - Rev. Geól. Amér. Central, 30: 137-148.

Tassi, F., Vaselli, O., Capaccioni, B., Giolito, C., Duarte, E., Fernández E., Minissale, A. & Magro G., 2005: The hydrothermal-volcanic system of Rincón de la Vieja volcano (Costa Rica): A combined (inorganic and organic) geochemical approach to understanding the origin of the fluid discharges and its possible application to volcanic surveillance. - J. Volcanol. and Geotherm. Res., 148: 315-333.

Zamora, N., Méndez, Joanna, Barahona, M., y Sjöbohm, L., 2004: Volcano-estratigrafía asociada al campo de domos de Cañas Dulces, Guanacaste, Costa Rica. - Rev. Geól. Amér. Central, 30: 41-58.