Early Exploration of San Diego Geothermal Area, Northwest Colombia

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Abstract. The geothermal area of San Diego, framed by three hot springs sites, is located in the Central Cordillera, to the north of Romeral Volcano, previously considered as the northernmost Colombian Volcano. The hot springs are located in the vicinity of a magmatic intrusion (Puente Linda porphyry) and, two volcanoes located in the area: San Diego maar and El Escondido Volcano, this last identified during the very beginning of the geothermal reconnaissance in 2013. The geology of the area is dominated by outcrops of Cajamarca metamorphic complex, the main basement rock of the Central Cordillera and igneous intrusions. The igneous rocks were characterized by lithogeochemistry and geochronology. The rocks of the most recent age are intrusions of San Diego and El Escondido volcanoes (<50,000 years). The hot springs with a highest discharge temperature of 42°C, emerge from faults, fractures and contacts between intrusions and Cajamarca metamorphic rocks. The well differentiated water types (bicarbonate, chloride and mixed bicarbonate-chloride-sulfate), their ratio between conservative species (B/Cl) and their location, allow to suggest that they can be separated systems. Although the geothermometers would not be very reliable considering the discharge temperatures, the deep fluid could reach temperatures above 250°C, in El Escondido zone.

1. Introduction

The convective geothermal systems of Colombia are located in the Andean Region: at the Western Cordillera to the south of the Country, nearby the border with Ecuador, all along the Central Cordillera and, as an isolated feature in the Department of Boyacá, on the Eastern Cordillera.

San Diego geothermal zone, was included in the reconnaissance studies of the exploration project named Macizo Volcanico del Ruiz, back in the late 1960s [4]. However it was excluded from the subsequent prefeasibility studies. In 2013 and based on the information of the inventory of hot springs...
[14], the geothermal area was defined as the new exploration objective at the Colombian Geological Survey (SGC for its acronym in Spanish). From the first geological reconnaissance, the finding of a new volcano named El Escondido, highlighted the interest of the area for the knowledge of the geothermal resources and volcanoes of the national territory [24]. To date, the advance in the prefeasibility studies include the geological map (scale 1:25,000) and the geochemical characterization of geothermal fluids, which summary is presented in this paper. Currently, studies of gravimetry, magnetometry and magnetotellurics, are in progress.

1.1. Location.

The study area is located on the eastern flank of the Central Cordillera of Colombia, in the north of South America, between latitudes 5°44’ and 5°29’ N and longitudes of 75°09’ and 74°53’ W (figure 1), it includes an area of approximately 460 km². The Central Cordillera is home of most of Colombia's active volcanoes and is mostly represented by Paleozoic metamorphic rocks with several igneous intrusions. At this point the last volcanoes are located further north of the volcanic chain of this mountain range. This volcanism is associated to the subduction of the Nazca plate under the South American plate and is located in the so-called North Andes Block [1], [20], (Taboada et al. 2000), (figure 1). In San Diego area the recent volcanism has been studied in the last 4 years evidencing the occurrence of volcanism in at least two sectors, these are: the San Diego Maar [8], [27], [28], El Escondido volcano [22], [23], [25].

![Figure 1. Location and tectonic context. The red rectangle represent the study area. Tectonic map taken of Velandia et al. [31]](image-url)
2. Results and discussion

2.1. Geological aspects

Based on Rueda & Rodríguez [19], slight changes are observed in the distribution of the principal bodies previously mapped in Feininger et al. [6]; these lithologies are (Figure 2): a metapelitic basement with metamorphism of low to medium degree (shales, graffiti, quartzites) with some lenses of amphibolites and marbles; the intrusion of a granitic body of great size in almost NS direction, with a slight orientation of the crystals known like Gneissic or Syntectonic Intrusion (Trin); two bodies of cretaceous age are presented in the center of the study area, these are the Samaná Igneous Complex (Kds) and the Samaná Leucogranite (Kas) with U/Pb ages of 133 ± 4.6 Ma and 132.8 ± 2.6 Ma, respectively [19]; finally two bodies of paleogenic age emerge in the center, Florencia Stock (Tcdf) and in the west of the studio area, the Sonsón Batholith (KTcds), with U/Pb ages of 54.6 ± 4.4 Ma and 47 ± 11 Ma, respectively. The only sedimentary unit that emerges in the area is represented by the Berlin formation, mainly represented by shales and, to a lesser extent, sandstone packages. Reports such as those by Pimiento R. [16], Ríos [17] and Caceres A. [3] study the stratigraphy, chemistry and uraniferous potential of this unit.

![Figure 2. Location and geology of the study area ([19], edited from Barrero & Vesga. 1976). San Diego and Patio Bonito Faults [15]. See location of hot springs at geothermal area (numbers from 1 to 15). Three main sites are observed; in the vicinity of San Diego Maar, El Escondido Volcano and the igneous intrusions of Puente Linda.](image)

The results of the geological mapping in Rueda & Rodríguez [19], show numerous and small intrusions with porphyritic textures, some of them first reported in this work, whose matrices present an important percentage of glass and presenting an obvious dome shapes, in some bodies (figure 3). Finally, evidence of recent volcanism is shown in at least two sectors; the San Diego maar [8], [27], [22], [23] and El Escondido volcano in Florencia town [22], [25].
Figure 3. Hypoabisal intrusions (Tad) with dome forms. Bottom right, appearance of the dacitic bodies (Td) with high alteration.

Mineralogically the big intrusions are characterized by quartz, plagioclase (albite - labradorite), biotites, amphibol (hornblenda), potassium feldspar with some alterations given by the presence of sericite and chlorite; the andesitic porphyritic bodies have a predominance of plagioclase and amphibole while the dacitic have a quartz content with some completely altered mafic crystals. These hypoabisal bodies have pervasive alteration with the presence of sericite, illite, dickite. The zones of greater alteration are limited to the western side of the study area (Puente Linda sector), where phyllic and argillic alteration predominates, although other areas show phyllic alteration and strong seritization and chloritization. El Escondido volcano are predominantly amphibole with some pyroxene crowns and plagioclase phenocrysts (albite, andesine) (figure 4a), while the dome of the San Diego Maar dome shows abundant biotite, quartz and plagioclase crystals within a microcrystalline matrix (figure 4b).
Figure 4. Recent volcanic activity (<200ka). a) Left: Domes of El Escondido volcano. Right: Photomicrograph of the domes with plagioclase (Pl) and amphibole (Amp) inside vitreous matrix (right). b) Left: Dome of San Diego (Maar San Diego Maar). Right: Photomicrograph of the dome with biotite crystals (bt) and plagioclase within a crystaline matrix.

The geochemistry of the plutonic bodies plot the samples in the field of diorites, granodiorites and granites according to the TAS classification of Cox et al., 1979 [19]. The chemical signature reflects a subduction magmatism (figure 5a) with magmas type I for most units and type II for the intrusive unit with metamorphism (figure 5b). The most recent porphyritic bodies classified as andesites and dacites present a variation in the Eu content in the REE, being positive for the former and negative for the latter related to the presence or absence of plagioclase. Recent domes show a similar pattern with a slight enrichment of LREE with respect to HREE and positive Eu anomaly, and develop a clear adakitic signature (including dacitic-andesitic porphyritic intrusives) according to the Defant & Drummond [5] diagram (figure 5d).
In addition to the granite bodies, three samples belonging to the effusive events that gave rise to the domes of El Escondido and San Diego Maar volcanoes were dated by Ar-Ar revealing an age of 153.7 ± 38.5 Ka and 89 ± 4.4 Ka respectively [19]. The first event contrasts with reported ages for deposits of El Escondido volcano in Monsalve et al. [25], which would position the intrusion of domes before the explosive events of the volcano.

![Figure 5](image)

**Figure 5.** Geochemical classifications [19]. a) Granites classification according to Chappell and White (1992), including some samples of other bodies denoted as TRin and KTcds. b) Classification of type of magmatism according to Thieblemont [26]. c) REE diagram of porphyritic bodies, including recent domes. d) Diagram by Defant and Drummond [5] for adakitic rocks.

The main structure is represented by the Palestine fault which was studied by Feininger [7] who describes it as a reverse fault with a dextral component, although new evidences redefine the kinematics of this fault as sinistral [18]; the other two faults, of shorter length, are the Patio Bonito and San Diego faults, the last one related to de San Diego volcano [15]. Measurements of fracture planes show an E-W trend (figure 6b) given by kinematic indicators such as open and filled fractures, and location of breccia bodies (figure 6a, c); these structures are superimposed on a strong foliation with N-S and NE-SW trend that predominates in the metapelitic basement with variations in the direction of the dip (figure 6d), making possible the transit of fluids, as in the fractures.
Figure 6. Structural features [19]. a) Breccia on the Samaná River. Puente Linda Site. b) Intense fracturing in the Cajamarca complex. c) Vein open and filled. d) Diagrams showing the tendency of foliation (red line) and fractures (blue line) in Puente Linda (PL), El Escondido (EE) and San Diego (SD) sectors.

2.2. Hot Spring

The geochemistry of the hot springs from San Diego geothermal area was developed in the frame of the inventory of hot springs [2], [14] and the geological mapping [19].

The location of the hot springs of San Diego geothermal area is showed in the figure 2. They are distributed in three main sites: San Diego maar, to the North; El Escondido, to the South and, Puente Linda, to the West, of the geothermal area. Their main features and composition are presented in Table 1. They are brackish water springs of neutral pH and temperature ranging between 30 and 44°C.

The hot springs emerge from structures and contacts (see figure 2), as follows. At San Diego Maar, the hot springs arise from the volcanic deposits nearby the contact between the Gneissic Intrusive body and the Cajamarca metasedimentary Complex and, the Palestina Fault zone and by the circular structure from the San Diego maar. At El Escondido site, the hot springs appear in a fractured zone of Florencia Stock, in the contact between Cajamarca Complex with the Florencia Stock and in the faulted contact between Florencia Stock and Samaná Igneous Complex. Finally, the hot springs from
the Puente Linda site, come out from the contact zone between an andesitic porphyry and rocks from Cajamarca Complex, area characterized by E-W fracturing and, along Rio Dulce Fault which crosses Cajamarca Complex.
Table 1. Chemical composition and in situ measurements, at hot springs from the San Diego geothermal area.

| Hot Spring ID | NAME            | T (°C) | pH | E.C. S/C M | Estimated Flow rate (L/s) | TDS | H₂S | HC O₂ | Na  | K  | Mg  | Ca  | Li  | Fe  | Sr  | Cl  | Br  | Si  | B   | δD (%) | δ¹⁸O (%) |
|---------------|-----------------|--------|----|------------|----------------------------|-----|-----|-------|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|--------|
| 1             | La Calera I     | 32.6   | 6.52| 5479       | 1528                       | 0.18| 2490| 610   | 61  | 30 | 254 | 3.26| <0.1| 1.4 | 835 | 2.1 | 822 | 5.1  | 0.39 | 46  | 7.5   | -56.51 | -7.59 |
| 2             | La Calera II    | 32.5   | 6.67| 5396       | 1512                       | 0.36| 2446| 610   | 66  | 30 | 249 | 3.21| <0.1| 1.4 | 822 | 3.8 | 5.8 | 0.37 | 45  | 7.2  | -50.25| -7.27 |
| 3             | Laguna San Diego| 30.1   | 6.19| 8028       | 1235                       | 0.36| 1346| 265   | 17  | 24 | 200 | 0.70| 1.31| 1.0 | 357 | 1.1 | 1.4 | 0.29 | 47  | 3.1  | -52.56| -8.12 |

San Diego Maar Hot Springs

| Hot Spring ID | NAME            | T (°C) | pH | E.C. S/C M | Estimated Flow rate (L/s) | TDS | H₂S | HC O₂ | Na  | K  | Mg  | Ca  | Li  | Fe  | Sr  | Cl  | Br  | Si  | B   | δD (%) | δ¹⁸O (%) |
|---------------|-----------------|--------|----|------------|----------------------------|-----|-----|-------|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|--------|
| 4             | El Recreo       | 31.7   | 6.24| 9829       | 1055                       | 0.36| 2120| 387   | 56  | 47 | 219 | 2.62| 4.33| 2.4 | 716 | 8.1 | 4.3 | 0.41 | 63  | 2.5  | -49.44 | -7.61 |
| 5             | San Antonio     | 30.1   | 6.19| 8028       | 2008                       | 0.36| 5128| 1.593| 150 | 61 | 290 | 7.59| 2.93| 1.8 | 2.480| 10.7| 0.23| 50  | -45.11| -5.82 |
| 6             | Geiser I        | 33.2   | 6.22| 3200       | 854                        | 0.36| 2448| 1.593| 150 | 61 | 290 | 7.59| 2.93| 1.8 | 2.480| 10.7| 0.23| 50  | -45.11| -5.82 |
| 7             | Geiser II       | 39.2   | 6.26| 7770       | 1.732                      | 0.25| 4854| 1.071| 241 | 90 | 301 | 13.80| 9.67| 1.956| 5.3 | -0.07| 80  | -47.32| -6.62 |
| 8             | Geiser III      | 41.1   | 6.60| 10600      | 1.278                      | 0.54| 4920| 1.732| 241 | 90 | 301 | 13.80| 9.67| 1.956| 5.3 | -0.07| 80  | -47.32| -6.62 |

El Encendido Hot Springs

| Hot Spring ID | NAME            | T (°C) | pH | E.C. S/C M | Estimated Flow rate (L/s) | TDS | H₂S | HC O₂ | Na  | K  | Mg  | Ca  | Li  | Fe  | Sr  | Cl  | Br  | Si  | B   | δD (%) | δ¹⁸O (%) |
|---------------|-----------------|--------|----|------------|----------------------------|-----|-----|-------|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|--------|
| 9             | Geiser IV       | 42.6   | 6.40| 8062       | 1.187                      | 0.25| 1070| 1.187| 200 | 82 | 301 | 7.85| 11.76| 3.5 | 2.226| 1.5 | 5.5 | 0.17 | 75  | -     | -     |

Puente Linda Hot Springs

| Hot Spring ID | NAME            | T (°C) | pH | E.C. S/C M | Estimated Flow rate (L/s) | TDS | H₂S | HC O₂ | Na  | K  | Mg  | Ca  | Li  | Fe  | Sr  | Cl  | Br  | Si  | B   | δD (%) | δ¹⁸O (%) |
|---------------|-----------------|--------|----|------------|----------------------------|-----|-----|-------|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|--------|
| 10            | La Mula         | 37.9   | 6.48| 12550      | 2735                       | 1.43| 6122| 5.97 | 6.9 | 620| 2941| 1.7 | <0.2| 0.36| 83  | 6.8 | -44.29| -6.39 |
| 11            | Espiritu Santo I| 43.6   | 6.46| 9612       | 1006                       | 0.9 | 4882| 9.38 | 1.06| 386| 5.47| 10.9| 1.450| 885 | 8.2 | 0.62| 43  | 5.1  | -52.22| -7.28 |
| 12            | Espiritu Santo II| 36.3  | 6.18| 5486       | 1059                       | 0.25| 2784| 8.6  | 624 | 46 | 1.71| 3.13| 0.731| 6.0 | 787 | 471 | 3.9 | 0.47 | 32  | 3.6  | -52.45| -7.52 |
| 13            | Espiritu Santo III| 44.4  | 6.25| 10130      | 9900                       | 0.1| 4672| 1.47| 1388| 86  | 346| 5.47| 1.450| 885 | 8.2 | 0.62| 43  | 5.1  | -52.45| -7.52 |
| 14            | Espiritu Santo IV| 45.1  | 6.50| 10360      | 1150                       | 0.3| 5026| 1.41| 1844| 90  | 382| 5.70| 1.069| 11.0| 1.456| 896 | 6.0 | 0.76 | 43  | 6.0  | -50.16| -7.35 |
| 15            | Espiritu Santo V| 38.4   | 6.24| 7690       | 1485                       | 0.1| 3986| 8.25| 942 | 108| 285| 4.48| 0.246| 8.7 | 1.195| 728 | 6.0 | 0.63 | 36  | 4.2  | -49.21| 8.11 |
From their relative dominant anions composition (mg/L) presented in figure 7a, San Diego maar hot springs are bicarbonate waters as the peripheral water from geothermal systems. El Escondido hot springs are mainly chloride waters, close to the typical composition of reservoir equilibrated water but with evident mixing with bicarbonate water, particularly in the hot spring 4. At Puente Linda site, the dominant water type is bicarbonate although they are actually mixed bicarbonate-chloride-sulfate waters and chloride-bicarbonate-sulfate waters (spring 11). The thermal waters from the whole geothermal area, are sodium waters.

Puente Linda springs show the highest SO\(_4\), H\(_2\)S and Sr concentrations (which reach up to 885 mg/L, 14,7 and 11 mg/L, respectively), among all the springs from this geothermal area. The high SO\(_4\) and H\(_2\)S concentrations raises the possibility of a common origin such as the input of steam heated fluid which H\(_2\)S would be oxidized to SO\(_4\) in the unsaturated zone. Although an acidic pH would be expected in the spring water, it could be neutralized by mixing with the bicarbonate – chloride source. The existence of steam heated water is compatible with the argillic hydrothermal alteration found in the igneous intrusions at Puente Linda site, previously mentioned.

The relative Ca-Sr-HCO\(_3\) and Ca-Sr-SO\(_4\) compositions, presented in figure 7a and b, allow to separate and set also three springs groups which are very similar to those shaped by their spatial distribution, except by the hot spring 10, from Puente Linda site, which shows significant similarities with El Escondido springs, not just in these relative compositions but also in its low sulfate and high chloride concentrations.

The unusual high Ca, Mg, HCO\(_3\) and Sr concentrations, up to 620 mg/L, 180 mg/L, 2700 mg/L and 11 mg/L, respectively, in hot springs, as well as the deposits of calcareous stuff, mainly in San Diego Maar site and in the spring 10 from Puente Linda site, point out the possible input from a bicarbonate source, such as the leaching of calcareous lenses as those present in the Cajamarca metamorphic Complex. On the other side, the source of Sr could be related to the leaching of igneous rocks, as suggest the coincidence in the highest strontium concentrations in hot springs and in the rocks related with them at andesitic porphyry bodies, which have the highest Sr concentration in this geothermal area (between 335-1160 mg/L).

As can be observed in Table 1, the conservative species (Cl, Li, B and Br), exhibit relatively high concentrations even in the coldest springs from San Diego Maar. A positive relation between chloride and lithium concentration is observed in which the highest concentration of these two species are found mainly in El Escondido springs and the lowest, at San Diego Maar springs. The relation between boron and chloride is also positive (although the concentration of boron is not available in all the cases) for hot springs of the same site and differentiated for site to site, as seen in figure 7d.

The relative Cl-Li-B composition is illustrated in the Figure 8a. The hot springs from the three sites show a high Cl/B ratio which, according to Giggenbach & Goguel [11], can be interpreted as the absorption of high Cl/B magmatic vapor or maturity of the hydrothermal system. The highest Cl/B ratio is found in the springs from the El Escondido.
Figure 7. Geochemistry diagrams. a) Ternary Cl-SO4-HCO3 diagram. At El Escondido site, the hot spring waters are mainly chloride. At San Diego Maar site, the dominant water type is bicarbonate. At Puente Linda site, the hot springs are mixed bicarbonate-chloride-sulfate, mainly. B and c) Ternary Ca-Sr-HCO3 and Ca-Sr-SO4 diagrams. A chemical signature is identified for each hot springs site. See the chemical affinity of the hot spring 10 from Puente Linda, with those from El Escondido. d) Boron versus Chloride in hot springs. There is a direct relation between the two variables with differences among hot springs sites. The hot spring 10 from Puente Linda site is related to those from El Escondido.

2.2.1. Geothermometry

According to the relative Na-K-Mg composition, presented in the figure 8b, all the hot springs of the geothermal area reflect immaturity or non-equilibrium conditions. By extrapolation of the defined linear trend, in which the hot springs from El Escondido site represent the water less affected by shallow water mixing, up to the equilibrium line, a highest temperature of 280-300 °C is inferred to the reservoir.

The low discharge temperatures and flow rates of the hot springs, as well as the probable input from a mineral source as it is suggested by the high concentration of TDS, HCO3, and Ca, among others, and
even the water type in some cases, would prevent the calculation of geothermometers. However, the most used aqueous geothermeters were calculated as indicative values to compare the three hot spring sites. See Table 2. As it was expected from the water type and the relation between conservative species (Li and Boron versus Chloride), the highest deep temperatures are calculated for El Escondido site hot springs. From the quartz (non-steam loss) geothermometer temperatures around 130 °C are calculated for Puente Linda and San Diego maar, while temperatures about 170 °C are calculated for El Escondido. For Na/K geothermometers, which is less affected by dilution, temperatures about 200°C were calculated for San Diego Maar, 250°C for Puente Linda and up to 300°C for hot springs from El Escondido. Nevertheless, considering the high calcium concentration, which would induce to a higher temperature [9]. In Nicholson [13] the Na-K-Ca geothermometer was also calculated. As a result, temperatures up to 188° was estimated at San Diego maar, up to 240°C at El Escondido and up to 195°C, at Puente Linda.

Table 2. Estimated deep temperatures of San Diego geothermal area, from aqueous geothermometers.

| HOT SPRING ID | NAME       | T (°C) | Chalcedony\(^a\) | Quartz (non-steam loss)\(^b\) | K/Mg\(^c\) | Na/K\(^d\) | Na/K\(^e\) | Na-K-Ca\(^f\) |
|--------------|------------|--------|------------------|------------------------------|-------------|-----------|-----------|--------------|
|              | San Diego Hot Springs |        |                  |                              |             |           |           |              |
| 1            | La Calera I | 32,6   | 110              | 137                          | 101         | 243       | 228       | 188          |
| 2            | La Calera II| 32,5   | 109              | 136                          | 99          | 238       | 223       | 185          |
| 3            | Laguna San Diego | 30,1   | 111              | 137                          | 68          | 199       | 182       |              |
|              | El Escondido Hot Springs |        |                  |                              |             |           |           |              |
| 4            | El Recreo  | 31,7   | 130              | 155                          | 89          | 263       | 250       | 194          |
| 5            | San Antonio | 30,1   | 115              | 141                          | 113         | 228       | 212       | 194          |
| 6            | Geiser I   | 33     | 145              | 168                          | 108         | 323       | 316       | 240          |
| 7            | Geiser II  | 39     | 147              | 170                          | 121         | 306       | 298       | 240          |
| 8            | Geiser III | 41,1   | 142              | 165                          | 121         | 300       | 291       | 239          |
| 9            | Geiser IV  | 42     | 143              | 166                          | 117         | 278       | 266       | 223          |
|              | Puente Linda Hot Springs |        |                  |                              |             |           |           |              |
| 10           | La Mula    | 37,9   | 149              | 172                          | 107         | 267       | 254       | 212          |
| 11           | Espiritu Santo I | 43,6 | 105              | 133                          | 105         | 259       | 246       | 206          |
| 12           | Espiritu Santo II | 36,3 | 88               | 117                          | 101         | 260       | 247       | 204          |
| 13           | Espiritu Santo III | 44,4 | 103              | 131                          | 95          | 232       | 216       | 186          |
| 14           | Espiritu Santo IV | 43,1 | 105              | 133                          | 102         | 240       | 225       | 194          |
| 15           | Espiritu Santo V  | 38,4  | 95               | 123                          | 101         | 243       | 229       | 196          |

\(^a\) \(T_{\text{chalcedony}} = 1032/(4,69-\text{LOG(SiO2)})-273,15\) (Fournier, \[30\]. In Nicholson, \[13\])
\(^b\) \(T_{\text{quarts}} = 1309/(5,19-\text{LOG(SiO2)})-273,15\) (Fournier, \[30\]. In Nicholson, \[13\])
\(^c\) \(T_{\text{K/Mg}} = 4410/(14-\text{LOG((K*/Mg))})-273,15\) (Giggenbach, \[10\])
\(^d\) \(T_{\text{Na/K}} =1390/(17,5+\text{LOG(Na/K)})-273,15\) (Giggenbach, \[10\])
\(^e\) \(T_{\text{Na/K}} =1217/(1,483-\text{LOG((AK4)/(AJ4)))})-273,15.\) (Fournier, 1979. In Nicholson, \[13\])
\(^f\) \(T_{\text{Na-K-Ca}} = 1647/(\text{LOG (Na/K)+ b LOG((Ca/Na)^0.5)+2.24})\ - 273,15\) (Fournier & Truesdell, \[9\]. In Nicholson, \[13\])
Figure 8. Geochemistry diagrams. a) Ternary Cl-Li-B diagram. The three sites show differences in their Cl/B ratio. b) Ternary Na-K-Mg diagram. Due to its high magnesium concentration, the composition of all the hot springs are classified as immature. The deep water that feeds the hot springs from El Escondido would have an equilibrium temperature of 300°C. c) Enthalpy-silica model [30]. A cooling by conduction is inferred at El Escondido hot springs. At San Diego Maar site, the thermal water is in equilibrium with amorphous silica. At Puente Linda site, the hot springs would come from the dilution of a deep fluid of about 160°C, after a boiling process. d) Relationship between d D and Cl with δ18O in hot springs from San Diego geothermal area. Some hot springs from El Escondido describe a slight evaporation trend in which the hot spring 5 represents the highest δ18O enrichment.

The Enthalpy – Silica model presented in the figure 8c, indicate conductive cooling at the hot springs from El Escondido, equilibrium with amorphous silica for San Diego Maar springs and, a dilution process at Puente Linda. From this model, the direct dilution from the deep reservoir fluid seems to be unlikely. If the dilution occurs after a boiling process; the enthalpy of the initial deep fluid would be around 680 kJ/kg which is equivalent to 160°C, about 30°C above the quartz geothermometer calculation.
2.2.2. Stable Isotopes in water.

The isotope composition of the hot springs ranges between -8.1 and -5.8 ‰ for $^{18}$O and, between -6.5 and -44.3 ‰, for deuterium. This composition is close to the global meteoric line (deviations lower than 1 ‰ in $^{18}$O). Hot springs from El Escondido site show a slight $^{18}$O and D enrichment trend which describe a possible evaporation process (slope about 2.5) in which the heaviest end-member is the hot spring 5. This process is compatible with the high TDS and Cl concentrations. See figure 8d.

CONCLUSIONS

The volcanic activity of the area has been persistent in the last 4 to 3 Ma with explosive and effusive events represented by volcanism and the variety of hypabyssal intrusions.

The San Diego geothermal area has a unique feature among the geothermal areas in Colombia, which is the outcrop of the metamorphic basement of the Central Cordillera (Cajamarca Complex). From this, deep reservoirs of secondary permeability would be expected, in the metamorphic rocks (in which some of the foliation planes also acts as permeable zones) or in the igneous rocks which cover about half of the geothermal area’s extension.

The possible heat sources would be related to the volcanic structures, but in addition, in the western sector (Puente Linda) the heat source could be related to the most recent igneous intrusions possibly without surface expression.

Differences in the conservative species ratios suggest fluids of different origin. From this, the three hot springs sites possibly are fed by geothermal fluids from different geothermal reservoirs. However, it seems that geothermal fluids from El Escondido site flow laterally up to 4 km to the North-West, to discharge in the hot spring 10, which was considered as a part of Puente Linda springs site due to its location.

Dilution and mixing processes are evident in the hot springs of the three sites. These processes cause the low discharge temperatures and the loss of representativeness of the reservoir fluid. The high concentrations of bicarbonate, calcium and magnesium, point out the possible contribution from a carbonated source as calcareous lenses of Cajamarca complex (?). At Puente Linda site an additional mixing process occurs with shallow sulfate water, presumable related to a steam heated source.

High strontium concentration in the hot springs, could be originated in the leaching of igneous rocks as it is suggested by the high Sr concentration in rocks from the andesitic porphyries and in related hot springs.

The estimation of the deep (reservoir) temperature indicates the possibility to find resources of intermediate to high temperature, in this geothermal area. The highest temperature would be found in the reservoir that feeds El Escondido springs.

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