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The San Diego Area, a New Geothermal Prospect on the Colombian Andes

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ABSTRACT

Exploration on a new area of geothermal interest on the Central Cordillera of the Colombian Andes has been initiated by the Geological Survey of Colombia (SGC). The area, located 95 km north of Nevado del Ruiz Volcanic Complex, comprises a volcanic structure with a ~2,2 km diameter crater caused by phreatomagmatic eruptions known as San Diego Maar and a newly discovered volcano dubbed here as “Escondido de Florencia”, to which are associated distinctive pyroclastic deposits, volcanic bombs and the presence of rhyolitic – dacitic domes. The diverse volcanic deposits scattered around the three hot springs locations, namely of San Diego, Florencia and El Espíritu Santo, suggest different heat sources for the hydrothermal manifestations. A mayor structure known as Palestina fault cuts on a NNE trend the northern end of Central cordillera and its trace relates the San Diego and Escondido volcanoes and the Nevado del Ruiz volcano. Location of the volcanic structures and hot springs occurrences are related to transtension structures on this fault as well as with lithological contacts of intrusive bodies.

Although the hot springs discharge temperatures are low (between 33 and 43°C) probably due to dilution, their chemical features suggests the probable existence of a medium to high temperature system. The chemical composition of hot springs at Florencia location is characterized by neutral sodium chloride water with relatively high lithium contents and oxygen-18 enrichment. A high magnesium concentration suggests a mixing process with shallow water. Based on a relatively high SiO2 contents the minimum temperature of the deep geothermal fluid is estimated in about 160°C. A well differentiated chemical composition characterizes the hot springs of the other locations: neutral sodium bicarbonate water at San Diego and neutral sodium chloride-bicarbonate mixed.

Recently acquired geological and geochemical data, bring new insights on geothermal system model aided by upcoming geophysical surveys.

1. INTRODUCTION

High enthalpy geothermal exploration in Colombia has taken place since late sixties of past century (OLADE, 1982), specifically on the Central Cordillera (CC) of Colombian Andes Range which hosts a series of active volcanoes, such as the Nevado del Ruiz volcano, remembered for the 1985´s eruption whose Lahar covered the whole town of Armero. There is although a set of volcanic foci, 90 km northeast of Ruiz volcano, that have not shown historic activity (above changes on hydrothermal regime), that is objective for high enthalpy geothermal exploration by the Geological Survey of Colombia (SGC) since year 2013.

Geothermal exploration on the northern volcanic zone of the CC was conducted by the SGC with the National Hot Spring Survey, which covered the area on the year 2011, this project helped define a new geothermal prospect around the San Diego volcano and other hot springs area. Further explorations included on-site geological reconnaissance of the area (Monsalve & Ortiz, 2013), aimed to better define the volcanic structure of San Diego and associated deposits, field work lead to identify a new highly explosive volcano located by Florencia town, 18 km SW of San Diego, which was dubbed “Escondido de Florencia”. There was also identified a circular geoform on metamorphic paleozoic basement in which interior, isolated phreatomagmatic deposits were found. (Figure 2).

Proceedings for comprehension of local geothermal system components as well as regional implications are reviewed on this document.

2. METHODOLOGY

Reconnaissance stage for the San Diego Area area follows a process as states guides for Geothermal Reconnaissance and Pre-feasibility developed by the Latin American Energy Organization (OLADE) and the Inter-American Development Bank (BID) on the year of 1982, which comprises the compelling and evaluation of available data, such as official geological cartography and documents related, aerial photography, 30 m DEM and Landsat imagery.

Taking into account the above information, field work was carried out in order to detail the geological and structural patterns of a previously mapped area on a 1:100.000 scale. The geological reconnaissance of the area took in account, rock types, joints and fault planes when available. Identification of pyroclastic deposits and volcanic sources, by stratigraphic columns correlation and laboratory analysis (XRD , petrography and geochemistry) was also taken place.

Hot springs on the San Diego Area were object to chemical and isotopes analysis following institutional procedure as well as methods by Giggenbach and Goguel (1989). The chemical analysis were performed in the “Laboratory of Aguas y Gases” and the “Laboratorio de Análisis de Isótopos Estables”, from the SGC. The used analytical techniques include volumetric analysis, ionic chromatography, UV spectrometry, Atomic Absorption and Inductively Coupled Plasma techniques. For the isotopic analysis Off-Axis ICOS (Integrated Cavity Output Spectroscopy) high resolution absorption laser spectroscopy, was applied.

Geochemical interpretation was done by graphical methods (Giggenbach & Goguel, 1989; Giggenbach, 1988). Estimation of the recharge zone was done by the functions found by Rodríguez (2004) to correlate deuterium and oxygen-18 concentration with elevation for Colombia**.**

3. GEOLOGICAL FRAME

Geologic history of the northwestern corner of South America relates to accretion of mainly allochthonous terranes (e.g. Jones et al. 1982) on western margin of Guyana Shield. These continuous processes of accretions and subductions have created a series of regional sutures, recognized as faulted areas trending NNE to NE (Figure 1), and a volcanic belt along old continental margins uplifted by convergence of tectonic plate's movements of Nazca and Caribbean Plates subducting a relatively stable South American Plate (e.g. Etayo et al., 1983; Toussaint & Restrepo, 1992; Montes et al., 2005; Acosta et al., 2007; Taboada et al., 2000; Suter et al., 2008). Plates interaction result also in three different tectonic blocks to accommodate the tectonic stress: the Panamá – Chocó Block, the Maracaibo Block and the North Andes Block, the latter where Colombian cordilleras upraise (Figure 1 left), after Acosta et al. (2007); Suter et al. (2008); Taboada et al. (2000) & Acosta et al. (2004).

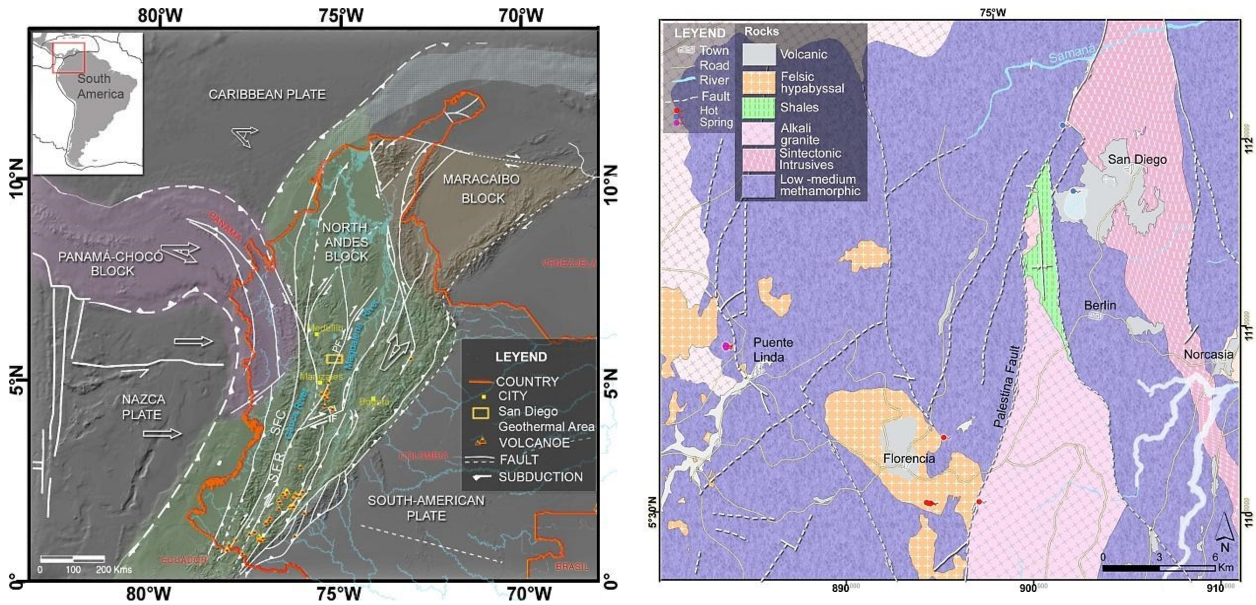

Figure 1: Left: Generalized tectonics and structures of north-western South America. Central Cordillera between Cauca and Magdalena Rivers; PF: Palestina Fault; SFR: Romeral Fault System; SFC: Cauca fault System; IF:Ibague Fault. [Sources: Acosta et al. (2007); Suter et al. (2008); Taboada et al. (2000); Acosta et al. (2004)]. Right: Detail of San Diego Geothermal Area on a geological map generalized from Barrero & Vesga (1976) and this work.

The Central Cordillera of Colombia (CC) is the tallest cordillera on the Colombian Andes (up to 5360 m.a.s.l.), it follows a mega-suture known as Romeral Fault System, that divides oceanic type rocks on the west form continental type on east. The San Diego Area is located east from this fault zone. Rocks are composed of Palaeozoic metamorphites on Greenschist to Amphibolite facies, these in turn host a series of intermediate to felsic intrusions of ages ranging from Triassic to Early Cenozoic (Gonzáles, 1989; Barrero & Vesga, 1976; Barrero et al, 1969). On the area of interest there is also a graben composed of cretaceous shales with rich on uranium (Naranjo, 1983) (Figure 1 right).

CC also hosts strato-volcanoes of mainly andesitic composition on a set of active volcanic active segments, south segment on the Western Cordillera of Colombia followed by the central and northern segment on the CC (Figure 1 left).

4. STRUCTURAL FRAMEWORK OF SAN DIEGO GEOTHERMAL AREA

San Diego Geothermal Area lies on the eastern side of the CC, a zone dominated mainly by a regional NNE trending structure known as Palestina Fault (Figure 1 left), it ranges for around 500 km and it has an influence zone from 0,5 to 30 km wide (Feinenger, 1970; Page, 1986). This fault acts a wrench fault with evidences of dextral movement of up to 27,7 km with an inverse component dipping west. Recent activity of this fault was reported by Collins et al (1970) as sinestral displacements.

Aerial photography used to find morphological lineaments and structures (Figure 2 center), showed the general tendency of N-S to NNE trending lineaments of 2-5 km long. According to Feninenger (1970) the Palestina fault deflects its trace 5°-10° toward east, on the area of the cretaceous sedimentary graben, lineaments also seem to be controlled by lithology where the relatively soft meta-sedimentary meets the Sintectonic intrusives (Figure 1 right), thus probably such lithological contacts play a notable role on the volcanic foci location on San Diego and Escondido.

The axis for the Berlin shales syncline trends NNW with a narrowing tip on the NW where the Palestina fault closes the structure (Pole diagram, Figure 2 left – bottom), this could be the result of a transpressive behavior of the fault.

The Palestina fault trace was followed on field, where evidences of inverse dextral displacements were found on the meta-sedimentary basement. Fault evidence on volcanic deposits of San Diego volcano may indicate some Neogene- Quaternary activity.

Further survey of joints and other structural evidences showed tension on a dominating SEE-NWW axis (Figure 2 right) a possible result of the dominating transcurrent behavior of Palestina fault.

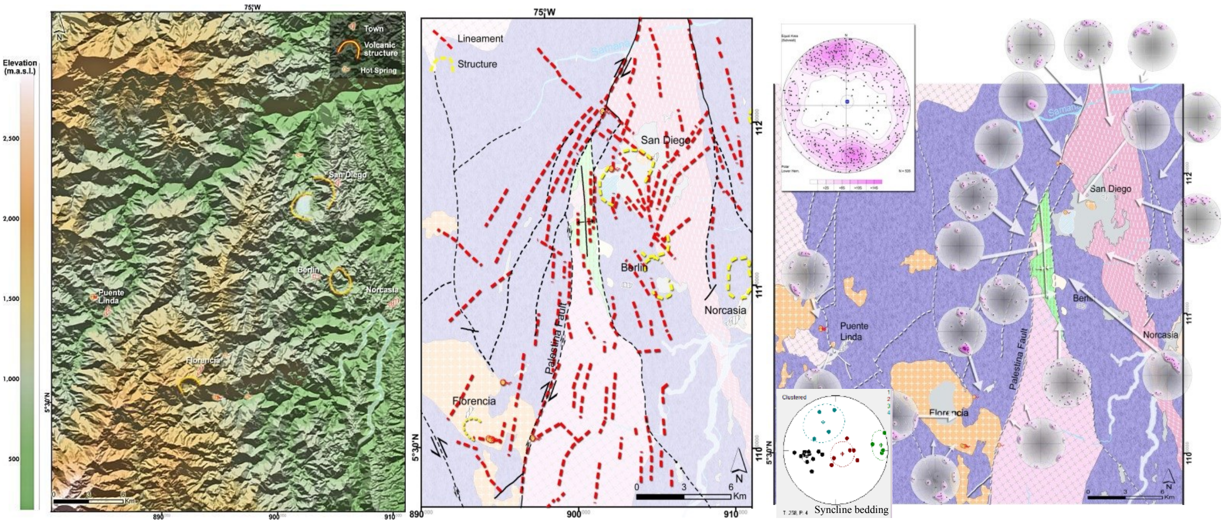

Figure 2: Left: Morphological map with location of volcanic structures. On 30 m DEM at 135° altitude and 180 azimuth Center: Aerial photography lineaments and structures. Right: map of local jointing (on Schmidth / polar net); bottom left, clusters for syncline bedding show folding axis (1-3)as a NW to NNW trend, minor (blue) tendency dipping SE probable on narrowing against Palestina fault

5. VOLCANIC STRUCTURES ON SAN DIEGO GEOTHERMAL AREA

The volcanic dome of San Diego was discovered a few decades ago, characterization of San Diego volcanism and pyroclastic in the area of Nariño, Berlin and San Diego, is based mainly in dense minerals made by Toro (1989 &1991). San Diego volcanic structure is located west of San Diego town (Figure 2 left), it contains the lake “Laguna Encantada”. Other isolated phreatomagmatic pyroclastic deposits found, by the town of Berlin, that could be associated to phreato magmatism in the area, but the foci have not been yet found.

A new volcanic structure was mapped with similar riodacitic composition to that of San Diego, a set of at least two domes and several volcanic deposits on the town of Florencia, from these discoveries a new eruption foci was inferred as explained later.

5.1. San Diego Maar Area

The 2.7 km circular volcanic structure of San Diego, displays a maar and pyroclastic ring features, recording changes in the predominant eruptive processes that formed the volcanic edifice. The crater, excavated into the basement, is occupied by a lake and at its NE sector has a “plug” or dome filling an eroded structure of tuff cone. (Figure 3)

Figure 3: Volcanic Structure of San Diego

Deposits from San Diego maar, are associated with phreatic to phreato – magmatic activity, and consist of pyroclastic breccia, flows and surges, forming the tuff ring. Powerful and very fine ash deposits with significant variation in facies and abundant accretionary lapilli associated with intense phreatic activity has been associated with the dacitic – ryolithic tuff cone.

Beside the tuff cone deposit, three main eruption phases are recognized, associated to the maar its self. The depositional sequences are defined by abrupt changes in clast size, dominant facies, block abundance and composition, and apparent water in the system. Evidence for water in the eruptive system includes, among others, abundant, accretionary lapilli, bedding, and lithics originate from country rock formations. Changes in dominant facies and facies patterns define the distinct units, which reflect changes in eruptive dynamics with time. The early eruptions are interpreted to have been dominated by efficient, phreatomagmatic blasts, which caused a progressive deepening of the eruptive center, followed by a transition to dominantly magmatic behavior in the upper sequence, tuff cone and plug dome growth occurring at the later stage of maar activity.Evidence for water in the eruptive system includes, among others, abundant, accretionary lapilli, bedding, and lithics originate from country rock formations. Changes in dominant facies and facies patterns define the distinct units, which reflect changes in eruptive dynamics with time. The early eruptions are interpreted to have been dominated by efficient, phreatomagmatic blasts, which caused a progressive deepening of the eruptive center, followed by a transition to dominantly magmatic behavior in the upper sequence, tuff cone and plug dome growth occurring at the later stage of maar activity.

5.2 Other phreatic structures in Berlin

About 8 km SE of San Diego maar, a circular morphologic feature of about 1 km. of diameter was recognized by satellite imagery. Field work showed that this structure is formed on metamorphic basement and it has at its interior an isolated accretionary lapilli rich ash sequence, originated by phreato - magmatic activity (Figure 4). At the moment non pyroclastic ring has been identified around the circular feature nor the pyroclastic deposits out of it.

Figure 4: Volcanic deposits of Berlin. Left: lamination. Right: accretionary lapilli.

5.3. Escondido de Florencia Volcano Area

A recently identified volcanic structure (1600 m.a.s.l), dubbed as “Escondido de Florencia”, or just “Escondido", is located 18 km SE of San Diego maar. Having 2 km. of diameter, this geoform opens to the southeast displaying a horseshoe shaped crater (Figure 3), and hosting a dome complex at this edge. The tuff ring or crater, stands directly above an early Cenozoic intrusion known as the Stock of Florence, a coarse-grained tonalite , granodiorite dated on 54.9 + - 1.9 m by the method of K / Ar in biotite (Barrero & Vesga, 1976).

Its morphology and associated products, such as alternating concentrated CDP deposits (pumice flow deposits, block flows and surges) as well as pumice falls, bombs and domes suggest a highly explosive activity of this volcano (Figure 5) Two 14C dates obtained, in medium level deposits have delivered results of activity between 30,000 and 36,000 years BP.

The area of the Escondido has some hot springs occurrences of chlorine thermal waters of up to 45°C. These hot springs are linked to a 2 km area south of the newly identified domes.

Figure 5: Volcanic deposits of the Escondido. On detail of a volcanic bomb (1 m. scale)

6. PRELIMINARY GEOCHEMICAL OBSERVATIONS OF HYDROTHERMAL FLUIDS.

San Diego geothermal area, defined by the location of hot springs previously identified in development of the National Inventory of Hot Springs (Ortiz & Alfaro, 2011), among other criteria, includes three main hot springs localities named Laguna de San Diego, Selva de Florencia (a National Park) and El Espíritu Santo; the latter characterized for first time more than 40 year ago (Arango et al., 1970) (Figure 6). Being located in the northernmost Andean Central Cordillera, these springs are located at relatively low elevations (500-1200 m.a.s.l.) compared with the rest of them located to the South and related to the hydrothermal systems of other volcanoes as Cerro Bravo, Nevado del Ruiz, Tolima, Huila and Puracé (between 1700 and 4520 m.a.s.l). They have low flow rate (<1L/s), low temperature discharge (<43°C) and notable gas emissions with non-detectable concentrations of H_2S (by organoleptic analysis). The highest temperature is registered in some springs from Selva de Florencia and El Espíritu Santo (Table 1), in neutral sodium chloride and neutral mixed sodium chloride – bicarbonate – sulfate water, respectively. The lowest temperatures (33°C) are found in bicarbonate springs from Laguna de San Diego.

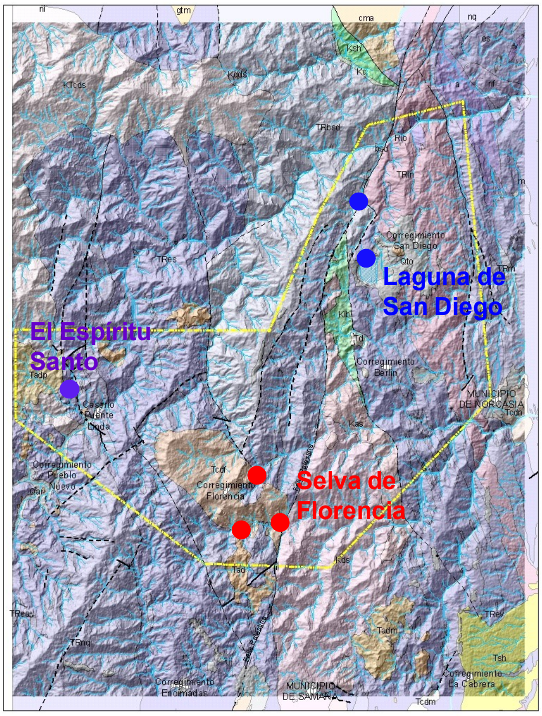

Figure 6: Location of hot springs in San Diego Geothermal area on geological map (Barrero & Vesga, 1976) . Selva de Florencia (6 chloride springs), Laguna de San Diego (3 bicarbonate springs), El Espíritu Santo (5 Mixed Chloride-Bicarbonate-Sulfate springs). Dotted yellow line highlights the preliminary defined geothermal area.

Table 1. Hot springs within San Diego Geothermal Area (data from Ortiz & Alfaro, 2011)

Hot Spring	Town	Department	Locality	Elevation (msnm)	pH	Flow (L/s)	Temperature (°C)	EC (µS/cm)	TDS (mg/L)	Chemical Classification
La Calera	Samaná	Caldas	Laguna San Diego	540	6,5	1	32,5	3530	2206	Sodium Bicarbonate
Laguna San Diego	Samaná	Caldas	Laguna San Diego	870	5,99	0,5	33	1345	1186	Calcium Bicarbonate
Geyseres I	Samaná	Caldas	Selva de Florencia	1000	6,22	0,5	33	3200	2270	Sodium Chloride
Geyseres II	Samaná	Caldas	Selva de Florencia	998	6,26	0,2	39	7770	4658	Sodium Chloride
Geyseres III	Samaná	Caldas	Selva de Florencia	983	6,1	1	40	6500	3696	Sodium Chloride
Geyseres IV	Samaná	Caldas	Selva de Florencia	967	6,3	1	42	9190	4844	Sodium Chloride
Finca Termales	Samaná	Caldas	Selva de Florencia	1200	5,99	1,5	40	3420	2026	Sodium Chloride
Termal San Antonio	Samaná	Caldas	Selva de Florencia	780	6,15	0,33	32	8740	5166	Sodium Chloride
Espiritu Santo I	Nariño	Antioquia	El Espírtu Santo	770	6,3	0,25	43,5	7410	4510	Sodium Chloride-Bicarbonate-Sulfate
Espiritu Santo II	Nariño	Antioquia	El Espírtu Santo	779	6,0	0,9	35,5	3920	2458	
Espiritu Santo III	Nariño	Antioquia	El Espírtu Santo	801	6,2	0,25	43,3	6720	4368	Sodium Chloride-Bicarbonate-Sulfate
Espiritu Santo IV	Nariño	Antioquia	El Espírtu Santo	790	6,2	<0,1	36,5	4960	3200	Sodium Chloride-Bicarbonate-Sulfate
Espiritu Santo V	Nariño	Antioquia	El Espírtu Santo	795	5,92	<0,1	33,4	3870	2540	

The relative chloride-sulfate-bicarbonate diagram (Figure 6, Left) illustrates the differences in composition of these springs. Those from Selva de Florencia of chloride water type, as it was mentioned before, have the highest probability of reservoir fluid contribution. This is consistent with their high lithium contents (5-14 ppm, SGC, 2014)). Hot springs from El Espíritu Santo show an important increase in the concentration of sulfate (20% or 320-800 mg/l, SGC, 2014). Although the origin of the sulfate could be related to mixing with steam heated waters (or sulfate water from sulphur hydrolysis), the pH do not show variation to more acidic as it would be expected.

On the other hand a linear trend in the variation of calcium and strontium versus sulfate is found, as represented in the Figure 8. It could suggest a common origin of these dissolved species in El Espiritu Santo's hot springs. The Sr is remarkable high (up to 13 mg/l) in front of the springs of this geothermal area and also compared with all the hot springs located in the Central Cordillera (lower than 2 mg/l in neutral springs and lower than 8 mg/l in acidic springs with high evidence of magmatic fluids contribution (SGC, 2014).

The observed differences in the chemical composition can be attributed to its origin in the case of bicarbonate springs from Laguna de San Diego, to peripheral waters of the geothermal system rich in CO_2. Differences between the springs from the localities of El Espíritu Santo and Selva de Florencia, could be related to mixing with other water sources of high sulfate and strontium concentration in an environment of crystalline (metamorphic and igneous) and volcanic rocks (evaporates are not expected in the zone), an intense interaction with rocks of very different composition along their assent to the surface, or to two different geothermal reservoirs.

The sodium-potassium-magnesium diagram presented in the Figure 7 (Right) highlights the high dilution of the geothermal fluid with high relative magnesium concentration. The extrapolation of the dilution trend to the equilibrium line indicate a probably reservoir equilibrium temperature above 280°C.

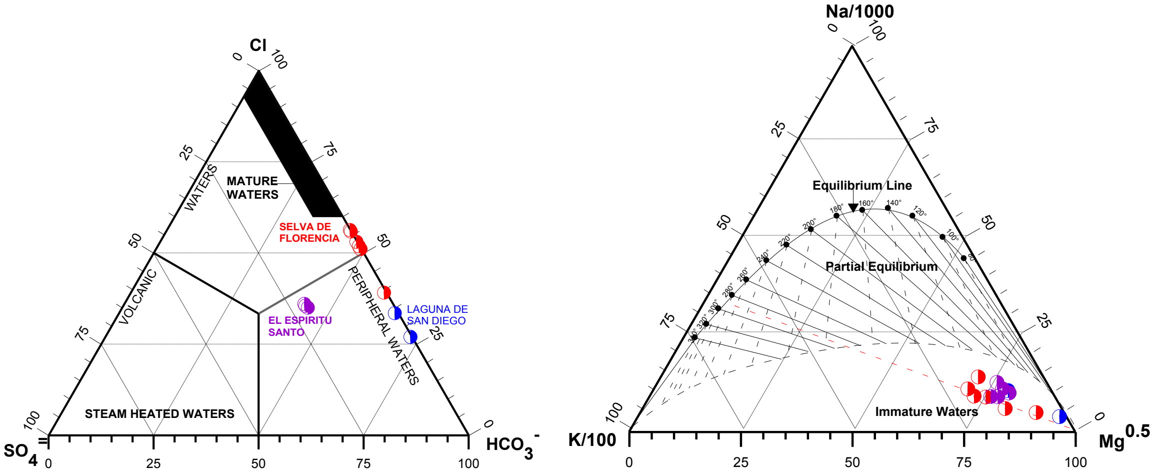

Figure 7. Relative chemical compositions of hot springs from San Diego Geothermal Area. Left: Cl-SO_4-HCO_3 (after Giggenbach & Goguel, 1989). Chloride waters are found in Selva de Florencia, assumed as those with a higher fluid reservoir contribution. Springs from El Espíritu Santo show a higher sulfate concentration which origin has not being determined. Right: Na-K-Mg (After Giggenbach, 1988). Blue: Bicarbonate springs from Laguna de San Diego. Violet: Chloride-bicarbonate-sulfate springs from Selva de Florencia. Red: Chloride Springs from Selva de Florencia. Typical high dilution with fresh water is found in hot springs of the three localities. The dilution trend points out a probable equilibrium temperature higher than 280°C for h ot springs from Selva de Florencia.

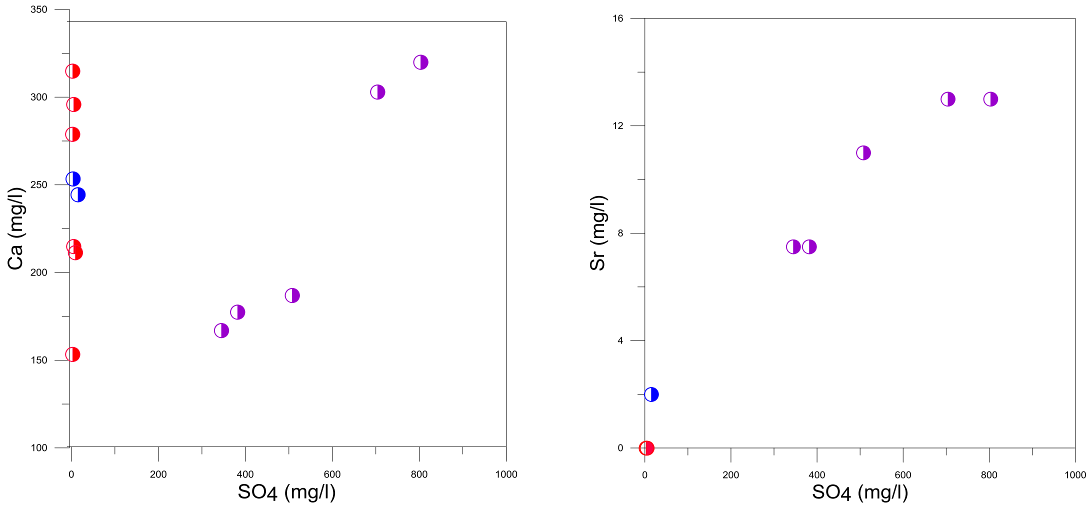

Figure 8. Calcium (left) and strontium (right) concentration Vs. Sulfate concentration. A directly proportional variation of calcium and strontium is observed in hot springs from El Espíritu Santo, which suggests the possibility of a genetic relation. The hot springs of Laguna de San Diego and Selva de Florencia do not show such a variation in the case of Ca Vs SO_4. In the case of strontium, although the available results indicate very low strontium level, just few of them were analysed. Colour conventions as in the Figure 7 .

Other aqueous geothermometers based on silica, sodium /potassium , presented in Table 2, coincide with the possibility of a high temperature geothermal reservoir in this geothermal area (even above 300°C) . The temperatures estimated by the K/Mg geothermometer is much lower due to the evident dilution process, previously cited.

The water stable isotopes indicate concentrations of deuterium between -57 and -43 ‰ and oxygen-18, between -8.2 and -5.2 ‰ (Figure 9). Coinciding with the highest discharge temperature of a chloride spring, the highest oxygen-18 enrichment is found in the hottest neutral sodium chloride water from Selva de Florencia, which is coherent with its slightly greater proximity to maturity character. The recharge zone would be located at the elevation of 1250-1500 (La Calera) and 1920 m.a.s.l. (Laguna San Diego), between 1800 to 2000 m.a.s.l. for springs from El Espíritu Santo and between 1550-1700 m.a.s.l., according to the estimation based on deuterium contents. From this, there are local effects defining the isotopic composition of the hot springs in each locality.

Table 1. Geochemical temperatures of deep fluids estimated in San Diego geothermal area

Hot Spring	Temperature (°C)	Tqtz (°C) no Steam loss (1)	Tchalcedony (°C) (2)	T Na/K (°C) (3)	T Na/K (°C) (4)	T K/Mg (°C) (5)
La Calera	32,5	123	95	237	194	101
Laguna San Diego	33	161	137	205	152	58
Geyseres I	33	168	146	323	322	108
Geyseres II	39	170	147	306	295	121
Geyseres III	40	184	164	295	277	116
Geyseres IV	42	207	191	289	267	123
Finca Termales	40	177	156	279	253	87
Termal San Antonio	32	155	130	243	202	116
Espiritu Santo I	43,5	130	103	231	186	106
Espiritu Santo II	35,5					
Espiritu Santo III	43,3	122	94	241	199	104
Espiritu Santo IV	36,5	114	85	243	201	101
Espiritu Santo V	33,4					
(1) T°C = (1309/(5,19-LOG(SIO2)))-273. Fournier, 1977. In Nicholson, 1993						
(2) T°C = (1032/(4,69-LOG(SiO2)))-273. Fournier, 1977. In Nicholson, 1993						
(3) T°C = (1390/(LOG(AH2/Al2)+1,75))-273. Giggenbach, 1988						
(4) T°C = (855,6/(LOG(AH2/Al2)+0,8573)) - 273,15. Truesdell (1976)						
(5) T°C = (4410/(14-LOG(k^2/Mg)))-273. Giggenbach, 1998						

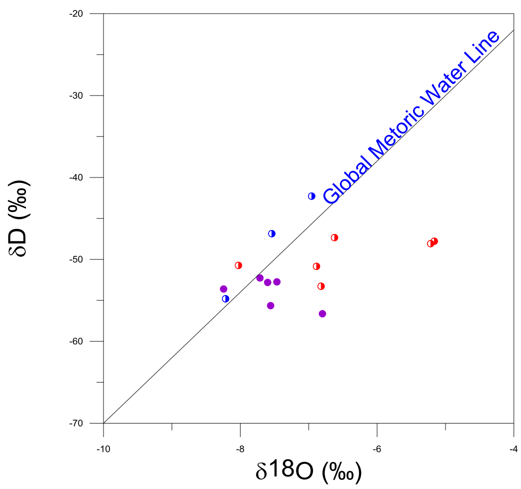

Figure 9. Stable isotopes composition of hot springs from San Diego Geothermal Area. The highest oxygen-18 enrichment is found in a sodium chloride hot spring from the location of Selva de Florencia. Color conventions as in the Figure 7.

7. CONCLUSIONS

Initial results for geothermal exploration of the San Diego Area narrowed estimates for potentiality of the system, as exploitation prospect showed favorable evidences for use of this heat source.

Studies in the area of geothermal interest in San Diego, allowed the identification of phreatic – phreatomagmatic deposits associated to San Diego maar. Other possible volcanic foci could exist in the area as several isolated outcrops of pyroclastic rocks have been mapped in regional geological work, if so the area could be considered as a volcanic province that is offset from the axis of the Cordillera Central, where the active volcanoes are located.

The predominant type of deposits (phreatic - phreatomagmatic) and its relatively recent age 33,000 years for volcanic deposits associated to the newly discovered "Escondido" volcano, indicate from the volcanological point of view, a significant geothermal potential in area to be verified with the results of studies in other disciplines.

Structural analyses showed evidences for promising geothermal reservoirs, based on the dominant transpressive regime on the area imposed mainly by the Palestina fault.

San Diego geothermal area probably hosts a high temperature geothermal system as it is inferred by aqueous geothermometers.

Chemical differences between hot springs from Selva de Florencia (neutral sodium chloride waters with low Sr concentration) and El Espíritu Santo (neutral mixed sodium chloride-bicarbonate-sulfate waters with high Sr concentration) could be related to differences in processes of rock – water interaction or mixing occurring in the two discharge areas or to their origin from different reservoirs.

Geochemical analysis of rocks as well as isotope strontium analysis for rock and waters should be done to understand the origin of these hot springs.

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