PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2019
SGP-TR-214

Low Enthalpy Geothermal System at Dabeiba, Colombia; an Assessment Through the Hydrogeochemistry of Thermal Waters

Esteban Gómez Díaz

Iceland School of Energy, Reykjavik University, Menntavegur 1, 101 Reykjavík, Iceland.

esteban18@ru.is

Keywords: Colombia, Hydrogeochemistry, Thermal waters, Solute geothermometers, Low enthalpy system.

ABSTRACT

Dabeiba is a small locality situated at the northern part of the Western Cordillera of Colombia which has the presence of thermal springs with interesting geology and hydrochemistry data. Through stable isotopes a faint mixture between the geothermal waters with superficial waters was identified. The springs are sodium-chloride type slightly diluted, with high concentration of boron. Using the conservative elements allowed identifying all springs from the same reservoir and they are in partial equilibrium according to Na-K-Mg diagram. The reservoir temperature was measured with solute geothermometers selected by the suitable conditions, identifying a low enthalpy system with values of ~150°C. The geothermal system is associated with deeply circulating waters in a fracture zone, where the waters possibly come of releasing from meta-sedimentary rocks and apparently with a bit of magmatic input, explaining the high concentrations salt components and boron.

1. INTRODUCTION

Colombia is a country with a high volcanic activity, produced by the interaction of the Nazca and South American plate, being part of the Pacific Ring of Fire. Given that, the country predominates volcanic geothermal systems where the main studies have been carried out in Nevado del Ruiz and Cerro Negro-Chiles-Tufiño areas, resumed by Salazar et al (2017). On the other hand, the Geological Survey of Colombia (SGC by its acronym in Spanish) has done studied the pre-feasibility in geothermal areas such as Azufral, Paipa and San Diego volcanoes resumed by Alfaro (2015), among others in studies the recent years (e.i Gomez-Diaz and Marin, 2018; Rayo, 2012; Rojas, 2012). As stated above, all these studies are related to high temperature system, however, there are areas associated to the not-volcanic system, as in the case of the Dabeiba area located to the northwest of Medellín, on the northern part of the Western Cordillera of Colombia. The purpose of this study is to provide information on the understanding of the geothermal system in Dabeiba zone since it is an area absent of geothermal studies, through hydrogeochemical analysis of thermal sources and the known geology, allowing to contribute information about the interaction of a geothermal system in other non-typical areas of the country and, thus, to have a better compression of the different plays of Colombia and greater support in the geological hypothesis about underground studies.

1.1 Geological settings

The study area is located above Guineales Formation which it is composed of coarse polymictic conglomerates with interbedded sandstones and it is on the convergence zone between Chocó-Panama Block and the Cañas Gordas Block (Figure 1). The Chocó-Panama Block constituted by the Batolito de Mandé (Álvarez, 1971) and the Santa Cecilia-La Equis Complex (Calle and Salinas, 1986) and Cañas Gordas Block constituted by a basement of oceanic affinity basaltic composition T-MORB, represented by the Diabasas de San José de Urama (Rodríguez and Arango, 2013; Mejía and Salazar, 1989) and a set of Cretaceous sedimentary units , known as Penderisco Formation (Álvarez and González, 1978). Structurally, the study zone is located near the triple junction of the Nazca, Caribbean and South American plates, this sector being largely a deformation and tectonics that results in a mosaic of tectonic blocks limited by faults, oriented in a N-S regional direction (Rodríguez et al, 2010), where the Guineales Formation is strongly influenced by the Dabeiba-Pueblo Rico Fault to western limited by Cañas Gordas and by La Cerrazon Fault to the east. Rodríguez et al, (2010) describe the Dabeiba-Pueblo Rico Fault constitute the system present normal, inverse movements, occasional thrusts and displacements of sinextral path and La Cerrazon Fault as a thrust fault with vergence to the east, which corresponds to the eastern contact of the Guineales Formation with the Santa Cecilia-La Equis Complex, setting out to ride volcanic and pyroclastic rocks from the Santa Cecilia-La Equis Complex on sediments of the Guineales Formation.

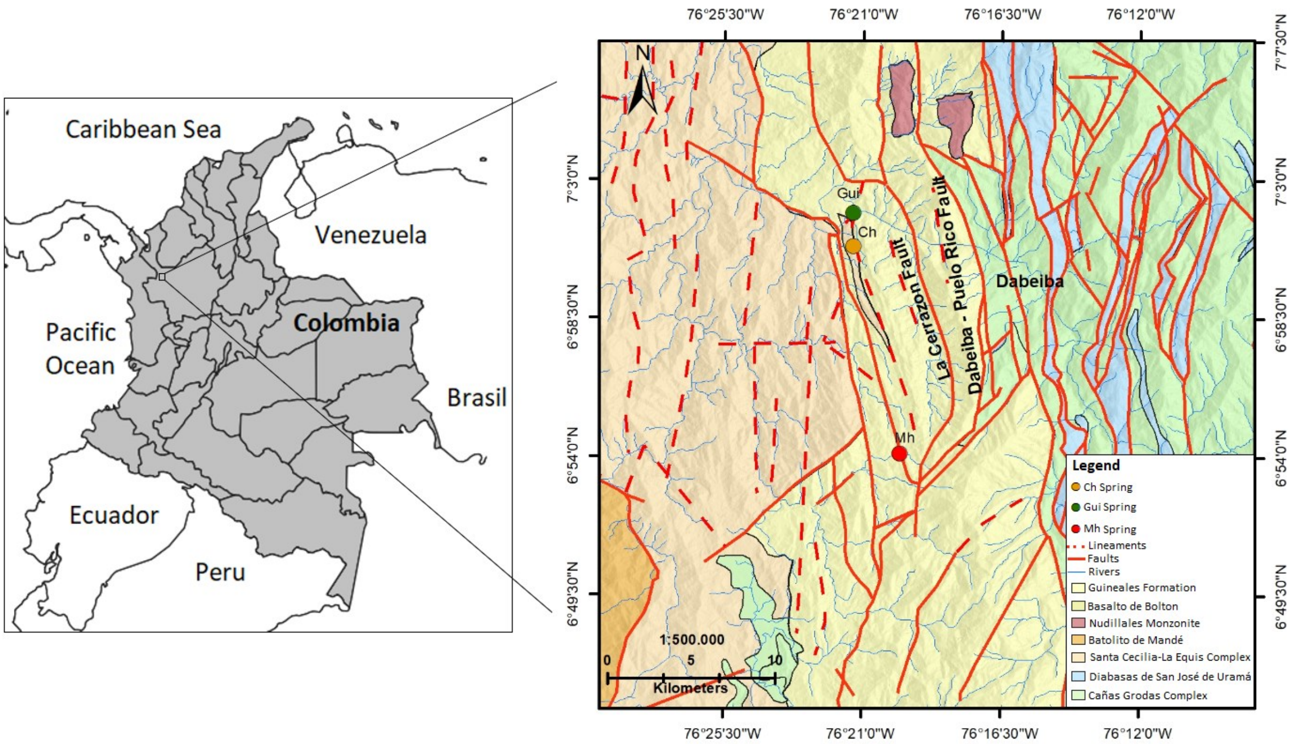

Figure 1. Localization of the study zone and geological map. Dabeiba Springs; Mohan (Mh), Guineales (Gui) and Chobar (Ch).

2. METHODOLOGY

2.1 Hydrochemistry dataset

The chemical data of the Dabeiba thermal waters were obtained from the National Inventory of Hot Springs (2012) by the SGC and the compiled dataset is showed on Table 1. The remaining major chemical constituents were analyzed in the Water and Gas laboratory and the Stable Isotope Laboratory from SGC. The analytical techniques used were standard methods such as volumetric analysis, ion chromatography, UV spectrometry, atomic absorption and inductively coupled plasma techniques and Off-Axis ICOS (Integrated Cavity Output Spectroscopy) high resolution absorption laser spectroscopy for isotopes.

Table 1. Major chemical constituents of thermal waters from Dabeiba. The species of solution in Mg/L.

		Mg/L												
Sample	**pH**	**Li**	**Na**	**K**	**Ca**	**Mg**	**SiO2**	**B**	**Cl**	**Sr**	**SO_4**	**HCO_3**	**δ18O**	**δD**
Mohan (Mh)	7,39	7,52	4029,25	118,52	23,63	22,73	122,89	84,20	3446,23	3,77	2469,00	1439,80	-1,84	-37,62
Chobar (Ch)	7,84	2,07	3122,00	41,30	30,70	23,50	84,49	71,07	4405,00	5,76	725,90	1751,00	-1,2	-28,53
Guineales (Gui)	7,97	1,36	3332,00	40,00	24,00	18,44	27,04	75,03	5072,47	6,43	636,00	1415,20	-0,45	-28,01

The Charge Balance Error (CBE) (Equation 1) was first calculated in all the spring in order to verify the reliability of the chemical dataset got by the SGC and thus, avoid the sample with ionic imbalances where the results of the Charge Balance Error (CBE) exceeds +/- 10%, the sample is not suitable for plot and geothermometers (Nicholson, 1993).

$$CBE\% = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} \times 100 \ldots Ecuation\ 1.$$

Where the Cations used were Na^+, $K^{+,}$ $Ca^{+}2$, Mg^{2+}, Li^+ and Sr^{2+} and the Anions used were HCO_3^-, F^-, SO_4^{2-} and Cl^-.

2.2 Analysis of the thermal waters

With the CBE calculated, it proceeded to an analysis of stable isotope with the intentional to identify mixing process, thus have a better understanding in the moment of characterizing the type of water and how this affect the samples. Stable isotopes were used for this study ($\delta^{18}O$ and $\delta^{2}H$) plotting on the graph of stable isotopes based on Giggenbach (1992), allowing identify the origin of the waters and mixing process.

The Cl-SO4-HCO3 diagram was used to characterize the type of water allowing classify geothermal fluids and associate them with the geology, subsurface process and if they are suitable for geothermometers. Through "conservative" elements was performed the diagram of CL-Li-B and Cl-Sr-B. It should be noted, the lithium in this case is regarded a "conservative" element, despite being reactive because in high temperature it is highly mobile, and the B is also regarded as a conservative because in a geothermal system it only forms in soluble mineral and their sources of supply to the geothermal fluid are too limited to saturate with any mineral (Arnórsson, 2000). Followed this, the Na-K-Mg diagram proposed by Giggenbach (1988) was applied to establish the physic-chemical balance between the fluid and the host rock, given a first sight of the temperature of the reservoir and identify if they are suitable for the solute geothermometers. The diagrams and the calculation of solute geothermometers were performed based on the spreadsheet by Powell and Cumming (2010). Finally, an interpretation of the geothermal system was performed, understanding the association of the species in solution of the springs and the interaction with the geology together with the results of all the above mentioned.

3. RESULTS AND DISCUSSION

3.1 Water origin and mixing processes

Since the study zone is a region with high rainfall and multiple fault systems, it is expected that it could be mixed with meteoric waters or ground waters. Considering this factor, it was decided to make an evaluation of mixtures despite the waters show a certain balance. It is important to highlight that due to the mixing process, the water to emerge on the surface may have been cooled down when the fluid ascended from the reservoir produced by cold groundwaters and this process could disturb the chemical equilibrium.in the Figure 2 illustrates the thermal waters of Dabeiba plotting to the right of the GWML (Global Meteoric Water Line) and CML (Colombia Meteoric Line) with a slight slope. It may indicate the thermal waters has been influenced for slightly mixing, probably for ground waters with magmatic waters or fossil waters trapped in marine sediments. Although, process as water-rock interaction might generate an exchange of oxygen between geothermal waters and rock if the temperature is ≥ 220°C, where the percentage of oxygen-depleted from the rock is equal to the enrichment of oxygen in the geothermal water (Chandrasekharam & Bundschuh, 2008).

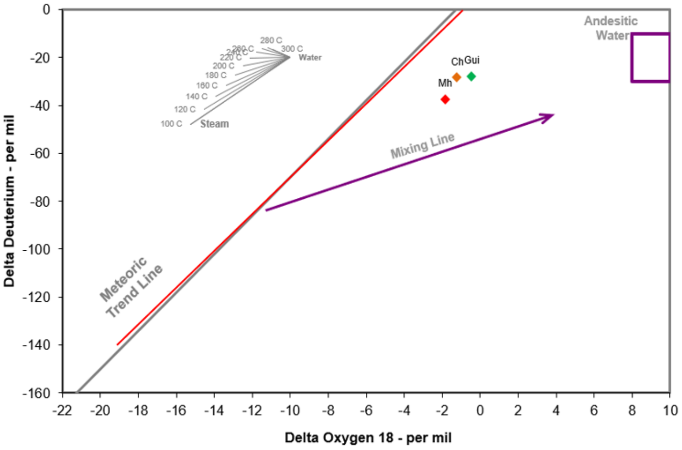

Figure 2. Cross-plot of the stable isotopes of water (δ18O – δD). The red line is the segment of the Colombian Meteoric Line (CML) and the gray line is Global Meteoric Water line GWML, the range of andesitic water as proposed by Giggenbach (1992). Dabeiba springs dots reflect a slight rise and to right. Mohan spring is represented by a red dot, Guineales by a green dot and Chobar by an orange dot.

3.2 Water classification and geothermometers

The Dabeiba springs are sodium-chloride slightly diluted waters close to mature water, except Mohan which is close to sulphate waters despite being from the same apex (Figure 3). Generally, the waters sodium-chloride are related of a geothermal system where it ascends through the reservoir as a single-phase fluid until it reaches a depth at which it boils and the CO_2 and H_2S gases dissolved within it partition to the vapor phase and continue to ascend with the fluid (Browne & Rodgers, 2006). According that, these springs could be related with a direct link to the deep reservoir with minimal mixing effects as it is supported by previously but is not clear if also is cooled by conductive cooling. The high chloride concentrations may also be related with upflow zones in high temperature systems, but it is not clear yet.

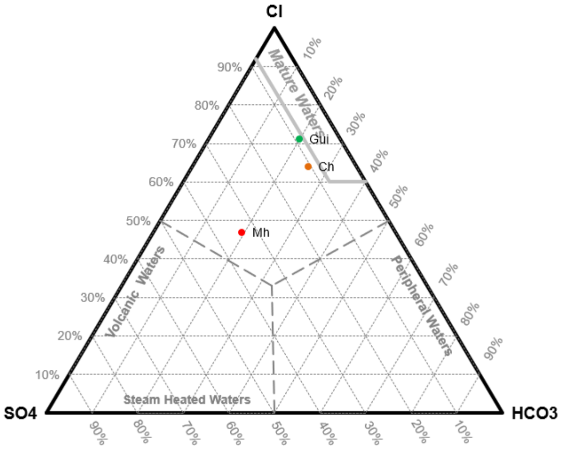

Figure 3. CL-SO4-HCO3 Plot. Mohan spring is represented by a red dot, Guineales by a green dot and Chobar by an orange dot. The plots were made on using the spreadsheet of Liquid Analysis v3 (Powell and Cumming, 2010).

The "Conservative" elements (Cl, Li, Sr and B) were used to determine if the springs come from the same system, they were projected in a ternary plot (Figure 4). The first one is the ternary plot of Cl, Li, and B, also proposed by Giggenbach (1991), and the second one is Cl, Sr and B where the Li is replacing for Sr which is another conservative element present in these waters. Both ternary plots show a strong relationship between of Guineales and Chobar waters, however, Mohan spring does not distance much from them showing potential relationships among the waters. Otherwise, the high amount the B may suggest that the fluids traveling rapidly to the surface where usually because they do not have time to become incorporated into low-rank alteration such as clays and zeolites (O´Brien, 2010).

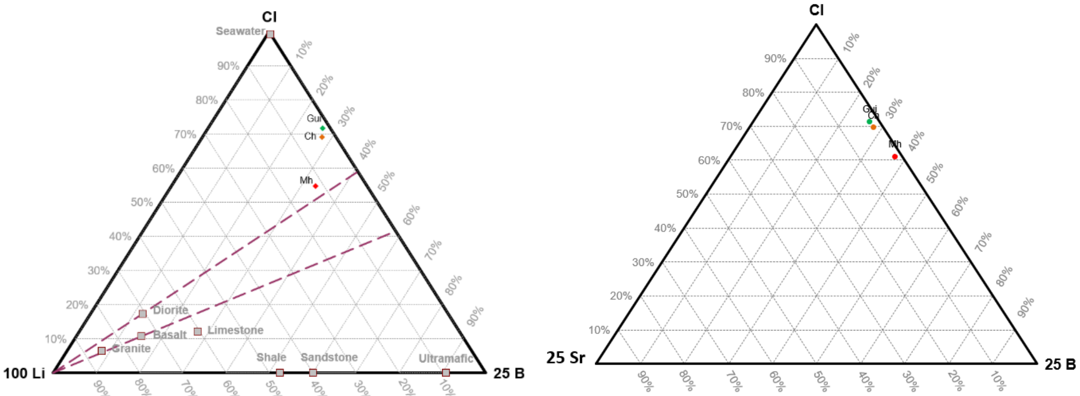

Figure 4. Left; Cl-Li-B Plot and Right; Cl-Sr-B Plot; Mohan spring is represented by a red dot, Guineales by a green dot and Chobar by an orange dot. The plots were made on using the spreadsheet of Liquid Analysis v3 (Powell and Cumming, 2010).

Once the type of water and the relationship between them are identified, the Na-K-Mg diagram is performed (Figure 5) shows all the springs fall into the range of partial equilibrium where Guineales and Chobar is around 110°C, whereas Mohan approximately to 150°C. Despite the diluted waters with a moderate concentration of HCO_3, influenced apparently for the mixing process. They are still regarding to be used for certain solute geothermometry since they are falling in partial equilibrium, even if geothermometry is not possible the spatial distribution of the springs is an important tool to help with understanding the system (Nicholson 1993).

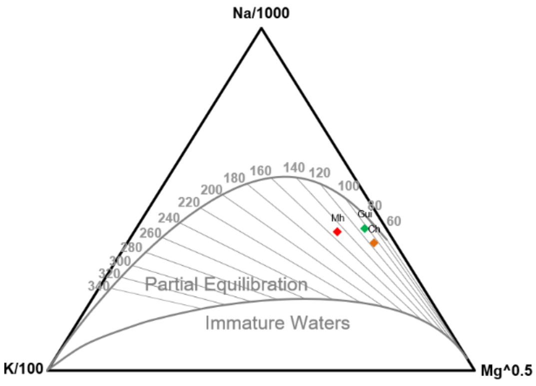

Figure 5. Na-K-Mg plot. Mohan spring is represented by a red dot, Guineales by a green dot and Chobar by an orange dot. The plots were made on using the spreadsheet of Liquid Analysis v3 (Powell and Cumming, 2010).

The silica geothermometer chosen was the chalcedony by Fournier & Potter (1982) due to the quartz conductive and adiabatic are regards for temperature >150°C while, the cation geothermometers regarding were Na-K-Ca of Fournier & Truesdell (1973), Na/K of Giggenbach (1988) and K/Mg Giggenbach (1988). By means of the chalcedony, geothermometer was observed that the maximum temperature is for the Mohan spring with a range of 120°C, while the lowest was Guineales with 44°C. This difference may be since this spring is more affected by boiling or mixing processes, besides the silica concentrations in geothermal fluids are controlled by the solubility of different silica minerals depending on the temperature, then in a low geothermal system this geothermometer is less reliable. Na-K-Ca geothermometer indicates a reservoir temperature around 125-170°C. However, this geothermometer in low temperature environments (<100-120°C), and/or with fluids relatively rich in CO_2 or Mg may throw misleading temperature (Nicholson, 1993). The Na/K geothermometer corresponds to a reservoir temperature of 106-150°C and K/Mg shows values below 122°C, being Mohan spring the highest values in all geothermometers. The values geothermometers are illustrated in Table 2.

Table 2. Reservoir temperatures (°C) estimated by solute geothermometers in Dabeiba thermal springs

Samples	Chalcedony Fournier & Potter, 1982	Na-K-Ca Fournier and Truesdell (1973)	Na/K Giggenbach 1988	K/Mg Giggenbach 1988
Mohan	124	170	150	122
Chobar	100	127	110	92
Guineales	44	125	106	94

3.3 Hydrogeochemical features

As it was mentioned above, the thermal waters contain high Cl concentration >3000Mg/L which usually in the geothermal systems the high concentration suggests a direct link to the deep reservoir with minimal mixing effects or conductive cooling (Nicholson, 1993). The relatively high concentration of HCO_3 can be originated by absorption of CO_2-bearing gases or condensation of CO_2-rich geothermal steam in O_2-free environments along with a slight mixture of ground cold waters, it is also reflected by Mg concentrations (~20Mg/L). The SO_4 presents in a relatively high amount between ~600 to ~700Mg/l for Guineales and Chobar waters, while Mohan spring contains ~2200Mg/l. The increase of SO_4 is strongly related to the oxidation of hydrogen sulphide. However, this process would expect a change into the pH of the water turning more acidic, hence meaning that the SO_4 is possibly controlled by the dissolution of gypsum and/or anhydrite and pyrite oxidation.

With the purpose of support the identification of upflow zone and mixing, the Na/K, Na/Ca and Ca/Sr ratios were calculated. Low value the Na/K and high Na/Ca ratio is related with upflow zones, indicating a more direct feed from the reservoir (Nicholson,1993), while low Ca/Sr ratio is linked with weakly mixing with shallow groundwaters (Yanxin et al, 2000). The Mohan spring showed the lowest Na/K ratio (34) and highest Na/Ca ratio (170), supporting that it is most directly linked with the upflow zone. Otherwise, all the thermal waters presented a low Ca/Sr ratio supporting that these waters are slightly mixed as previously identified.

The boron is another element that stands out in this system, containing concentrations ~80 Mg/l which can be related for releasing of unstable boron-bearing mineral phases in the altered meta-sedimentary rocks, or a magmatic input. This element is mainly expressed as boric acid, $B(OH)_3$ and the borate anion $B(OH)_4$, whose relative abundances are sensitive to pH, while at low pH $B(OH)_3$ predominates, at high pH (>8–9) $B(OH)_4$ is a primary anion (Barth, 2000), although BF_3 may also be present in gases evolved from acidic in high fluoride fluids (EPRI, 1986). In the geothermal systems, the boron is readily dissolved by steam condensate or near-surface steam-heated waters, in which it can attain elevated concentrations notably when steam inflow is approximately equaled by evaporation (Glover, 1988; Tonani, 1970) therefore lost from the vapor phase with increased migration and shows highest concentrations in upflow zones (D'Amore and Truesdell, 1984). In the Dabeiba thermal waters the boron present Ph ~ 7, indicating the boron is related mainly in the form of $B(OH)_3$, probably associated for degassing flux from a deep source, the BF3 is discarded by the absence of fluoride in the fluids.

On the other hand, the boron is not only used as an indicator to obtain information about the origin of thermal waters as was mentioned earlier, but this is also used to understand the lateral flow (e.i Duchi et al,1987). Mohan spring presents Cl/B and B/Li ratio lower than Guineales and Chobar waters indicating Mohan spring is less affected by a progressive rock dissolution by a greater lateral flow and that B and Cl are released from rock during water-rock interaction or adsorption of boron, it being removed from solution by absorption onto clays and incorporation into secondary minerals, especially in clays. Otherwise, the HCO_3/SO_4 ratio of Chobar and Guineales spring is higher than Mohan probably because of loss of H_2S by rock-water reactions with the increased lateral flow.

3.4 Understanding the system

Apparently, the reservoir of the system is related to deep fracture zones in the meta-sedimentary rocks and cataclasites(?) from Guineales Formation, being the seal rock impermeable Neogene sedimentary units from the same sedimentary formation and/or for an impermeable altered zone and a plutonic-metamorphic as the basement, which is not totally clear. The heat source is possibly associated to the felsic intrusion riches in radioactive elements such as may be the intrusion describe by Zapata and Rodríguez (2012), that are monzodioritic – monzonitic intrusion, with shoshonitic affinity from late Miocene (9 to 12 Ma). The system is probably related by extensional event Miocene (Guineales formation), followed by emplacement event characterized by high angle normal faults where the fluid flow along faults is controlled by the state of stress in the reservoir rock. The fault structures perform a relevant role in the vertical and lateral permeability of the geothermal system, allowing that the thermal waters flow through them.

The Chobar and Guineales springs are in the margin of the system where they are more affected by the lateral flow, while Mohan spring is apparently more linked with the upflow. The concentration of CL, SO_4, and B inferred that the system is influenced by a deep resource with a minimal diluted process and inferring that the system is interacting with degassing of magma of an intrusive, contributed by sedimentary layers or a process of water release from metamorphism of marine sediments, however, more isotope studies such as 3He/4He and/or $\delta^{11}B$ are required to confirm it. Otherwise, the high content of salinity and boron could be a risk from the ground waters affecting some vegetation, due to larger concentrations it becomes toxic (Todd, 1980), even for the human being, making it clear that if these waters interact with more surface underground reservoirs, they could become contaminated. The temperature of the geothermometers were below 150°C, being unattractive at first sight unlike other systems in the country. However, with new geothermal plant technologies, these faults controlled geothermal systems of medium temperature (150 ±30°C) could be developed to small-scale geothermal programs providing energy for small communities even in remote areas (Moeck, 2014).

4. CONCLUSION

The geothermal system in Dabeiba is characterized for mixing water in low portion where geochemical characterizations of the thermal springs are slightly dilute chloride waters. The "conservative" elements allowed identifying that the springs come from the same reservoir, being Mohan spring most reliable for solute geothermometers estimating a temperature around 150°C indicating a low enthalpy system. The high amount of boron is related mainly by contribution by sedimentary layers or a process of water release from metamorphism of marine sediments and probably a degasified intrusive input. Although Dabeiba is not an energetic interest as other areas of the country due to its low temperature, its data help to understand the different systems that are generated in Colombia and how they can differ from one another. It also provides relevant information on the geology of the area explaining sub-surface processes.

ACKNOWLEDGEMENTS

The author thanks to the Geothermal Exploration Group of SGC for the great job of sharing the data through the National Inventory of Thermal Springs and encouraging the geothermal exploration in Colombia and Reykjavik University for supporting in the participation in this event.

REFERENCES

Alfaro, C. 2015. "Improvement of Perception of the Geothermal Energy as a Potential Source of Electrical Energy in Colombia," in World Geothermal Congress, Melbourne, Australia.

Álvarez, J. 1971. Informe preliminar sobre geoquímica de la Cordillera Occidental. INGEOMINAS. Internal report. Medellín.

Álvarez, E., and González, H. 1978. Geología y geoquímica del Cuadrángulo I–7 (Urrao). Scale 1:100.000. INGEOMINAS. Report 1761. 347p. Medellín.

Arnórsson, S. 2000. Mixing process in upflow zones and mixing models Chapter 11 (pp. 200-211) in S. Arnórsson (2000) Isotopic and chemical techniques in geothermal exploration, development, and use. Sampling methods, data handling, interpretation, 152-199. International Atomic Energy Agency, Vienna.

Barth, S.R. 2000. Utilization of boron as a critical parameter in water quality evaluation: implications for thermal and mineral water resources in SW Germany and N Switzerland. Environ Geol 40(1–2):73–89.

Browne P.R.L and Rodgers K.A. 2006. Occurrence and significance of anomalous chloride waters at the Orakei Korako geothermal field, Taupo Volcanic Zone, New Zealand. Geothermics 35(3): 211-220.

Calle, B. and Salinas, R. 1986. Geología y geoquímica de la Plancha 165, Carmen de Atrato. INGEOMINAS. Report. Medellín. 140p.

Chandrasekharam D and Bundschuh J 2008. Low-enthalpy geothermal resources for power generation. Leiden, The Netherlands, CRC Press/Balkema.

D'Amore, F., and Truesdell, AH., 1985. Calculation of geothermal reservoir temperatures and steam fractions from gas compositions. Trans. Geoth. Res. Council, val. 9-1, 305-310.

Duchi, V., Minissale, AA, Martino, S. and Roman, L., 1987. Geothermal prospecting by geochemical methods on natural gas and water discharges in the Vulsini Mts volcanic district (Central Italy). Geothermics, 16, 147-157.

EPRI, 1986. A theory on boron in geothermal fluids. Research Project 1525-6, final report AP-4670. Electric Power Research Institute, California, USA.

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

Fournier, R.O. and Potter, R.W., 1982. A revised and expanded silica (quartz) geothermometer. Geoth. Res. Council Bull., November, 3-12.

Giggenbach, W.F. 1988, “Geothermal solute equilibria,” Geochem Cosmochem Acta, 52, 2749-2765.

Giggenbach, W.F. 1992. Isotopic shifts in waters from geothermal and volcanic systems along convergent plate boundaries and their origin, EPSL 113, 495-510.

Glover, R.B., 1988. Boron distribution between liquid and vapour in geothermal fluids. Proc. 10th New Zealand Geothermal Workshop, Auckland University, 223-227.

Gómez-Díaz, E. and Marin-Cerón, M. 2018. "Preliminary Geochemical study of Thermal Waters at the Puracé Volcano System (South Western Colombia): an Approximation for Geothermal Exploration.," Boletín de Geología, vol. 40 (1), pp. 43-61, 2018.

Junko Kamei, Akiko Kawabata, Hisao Kato and Akira Ueda. 2000. Strontium concentrations and isotopic ratios in the Sumikawa and Ohnuma geothermal field, Japan. Proc. World Geothermal Congress 2000, Kyushu - Tohoku, Japan.

Mejía, M., and Salazar, G. 1989. (Publicado 2007). Mapa geológico de la plancha 114 Dabeiba, escala 1:100.000. INGEOMINAS. Medellín.

Moeck, I. 2014. Catalog of geothermal play types based on geologic controls. Under Review at Renewable & Sustainable Energy Reviews.

O'Brien, J. 2010. Hydrogeochemical characterization of the Ngatamariki geothermal field and a comparison with the Orakeikorako thermal area, Taupo volcanic zone, New Zealand (Master Thesis). University of Canterbury, New Zealand.

Powell, T. and Cumming, W. 2010. Spreadsheets for Geothermal Water and Gas Geochemistry. Proceedings, Thirty-Fifth Workshop on Geothermal Reservoir Engineering. Stanford University, California, pp. 4-6.

Rayo, L.2012. Evolución Geoquímica y Térmica del Volcán Nevado del Ruiz, Colombia. (Master Thesis) Universidad Nacional, Colombia.

Rodríguez, G., y Arango, M.I. 2013. Formación Barroso: arco volcanico toleitico y diabasas de San José de Urama: un prisma acrecionario T-Morb en el segmento norte de la Cordillera Occidental de Colombia. Boletín Ciencias de la Tierra, 33: 17-38.

Rodríguez, G., Arango, M.I., Zapata, G., Bermúdez, J.G. 2016. Estratigrafía, petrografía y análisis multi-método de procedencia de la Formación Guineales, norte de la Cordillera Occidental de Colombia. Boletín de Geología, 38 (1): 101-124.

Rodríguez, G., Zapata, G., and Gómez, J.F. 2010. Geología de la Plancha 114 Dabeiba. Colombian Geological Service, Medellín, 205p.

Rojas, D. 2012. Contribución al Modelo Geotérmico Asociado al Sistema Volcánico Nevado del Ruiz Colombia, por Medio del Análisis de la Relación entre la Susceptibilidad Magnética, Conductividad Eléctrica y Térmica del Sistema. (Master Thesis) Universidad Nacional, Colombia.

Salazar, S., Muñoz, Y. and Ospino, A. 2017 "Analysis of Geothermal Energy as an Alternative Source for electricity in Colombia," Geothermal Energy, vol. 5, p. 27.

Todd, D.K. 1980. Groundwater Hydrology, Second Edition, Wiley, New York.

Tonani, F., 1970. Geochemical methods of exploration for geothermal energy. Geothermics, Special Issue 2, 1,492-515.

Zapata, G. and Rodríguez, G. 2012. Basalto de El Botón, arco volcánico mioceno de afinidad shoshonítica al norte de la Cordillera Occidental de Colombia. Boletín de Ciencias de la Tierra, 30:77-91.