Systematic Review of the Geothermal Potential in Colombia: Implications as an Alternative Energy Source

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Abstract

Through literature review and information processing, the current state of geothermal energy in Colombia, its limitations, possible future uses, environmental impact and the current legal framework were described and analyzed. Approximations were made regarding the sustainability of geothermal energy in the country and its implications. Some of the projects, studies, and research that have been carried out were considered, including the Nevado del Ruiz volcano, located on the border between the departments of Caldas and Tolima; the Tufiño-Chiles-Cerro volcanic system, located on the border between Colombia and Ecuador; the Azufral volcano geothermal area, located in the department of Nariño; and the Paipa geothermal area, located in the Department of Boyacá.

For each geothermal area, geological, geochemical, geophysical, and hydrothermal alteration aspects were discussed, analyzing their characteristics and energy generation potential. The Nevado del Ruiz volcano and its surroundings have several geothermal regions whose reservoir temperatures are above 235°C and an approximate potential of 206.46 MWe, for the Azufral volcano temperatures are estimated at 250°C (with a high degree of uncertainty) and a potential of 81.9 MWe, for the Paipa geothermal area around 230°C and 21.50 MWe, and Tufiño - Chiles - Cerro Negro (Colombian area) a temperature of over 200°C and a potential of 23.77 MWe.

It is important to note that these estimates are approximate and based on data collected by the Colombian Geological Survey and studies conducted by various authors over time. Thus, they have a 90% confidence interval with a fairly considerable range and a margin of error that must be reduced. For the next few years, a considerable increase in geothermal installed capacity in the world, and consequently, in the generation and supply of electricity is predicted. Colombia estimates a preliminary capacity of 1170 MWe, framed within the national energy ideology and subject to more detailed and rigorous studies for the future to consolidate geothermal projects and reduce technological and financial uncertainty.

1 Introduction

Geothermal is a word of Greek origin, derived from "geos" meaning earth and "thermos" meaning heat: the heat of the Earth. It is used interchangeably to designate both the science that studies the internal thermal phenomena of the planet and the set of industrial processes that attempt to exploit this heat to produce electrical energy and heat useful to humans.

Several geothermal systems are being explored in order to generate electricity and there are several geothermal energy projects worldwide that produce energy on a commercial and sustainable level. Currently, the main producer of geothermal energy is the United States, with 3700 MWe of installed capacity (Lund and Toth, 2021); however, there are 10 countries worldwide that produce more than 500 MWe, among them is Mexico, with 1005 MWe (Lund and Toth, 2021).

Colombia is located in a privileged geodynamic environment being in the Pacific Ring of Fire, consequently, it has a great geothermal potential. The beginning of geothermal exploration in Colombia dates back to 1968, when an evaluation of the prospects for geothermal development for power generation in the Nevado del Ruiz volcanic complex was carried out by the Ente de Electricidad de Italia, commissioned by the Caldas Hydroelectric Power Plant (CHEC) (Bona and Coviello, 2016). These investigations were interrupted until they were resumed again in 1983, when CHEC conducted a pre-feasibility study. Starting in 1997, the Colombian Geological Service (then INGEOMINAS) began to conduct geothermal research in the country and, likewise, electric companies such as ISAGEN have begun to study, and even carry out geothermal projects in recent years in the Tufiño - Chiles - Cerro Negro volcanic complexes in conjunction with Ecuador, in the Nevado del Ruiz volcanic system, in the Azufral and Santa Isabel volcanoes, in the San Diego Maar and the Maracas Field (Mejía et al., 2014; Salazar et al., 2017). ECOPETROL is also developing initiatives to carry out low enthalpy geothermal projects.

In Colombia, energy is obtained primarily from fossil fuels and hydroelectric systems (EIA (Energy Information Administration), 2018). There are also projects using non-conventional energies such as solar and wind, however, geothermal energy is just taking its first steps in the field of production at larger scales and awaiting further systematic development based on greater investments and more detailed research. Colombia's full geothermal potential has been estimated at 17400 GWh/year and is equivalent to producing about 20% of its estimated electricity demand by 2025 (86762 GWh/year) using geothermal resources (Gawell et al., 1999; Salazar et al., 2017). By 2025, at least 1400 GWh/year is expected to be generated by geothermal energy, being 1.6% of the estimated electricity production by then (Salazar et al., 2017).

Colombia did not had a specific legislation for geothermal resources until 2022, however, this energy source had been framed and governed by the existing legislation for non-conventional energy resources, being defined as "natural combination of water with an endogenous subway heat source resulting in the spontaneous production of hot water or steam". Since Law 1715 of 2014, which regulates the integration of non-conventional energies in the National Energy System, two decrees were generated where the parameters and incentives for non-conventional energies are defined with Decree 2143 of 2015, and the Non-Conventional Energies and Efficient Energy Management Fund (FENOGE) is regulated with Decree 1543 of 2017. Likewise, there is regulation regarding environmental licenses developed by the Ministry of Environment and Sustainable Development. On the other hand, the exploration and implementation of geothermal energy is considered in the National Development Plan 2018 - 2022 and 2022-2026, and the framework to develop these activities is issued by the Colombian Geological Service (SGC) (Alfaro and Rodriguez, 2020).

Geothermal potential of Colombia can also be assessed by studying factors such as the geothermal gradient, which provides insights about potential conductive geothermal systems such as dry-rock systems. The most current geothermal gradient map for Colombia covers roughly half of the country's territory (Alfaro et al., 2009), for the rest no systematic determinations of the geothermal gradient are available. Some studies have tried to address this issue. Bachu et al. (1995) focused on the Llanos Basin, finding that geothermal gradients decrease with depth and westward. In northwestern Colombia, Quintero et al. (2019) estimated geothermal gradients using grid systems and aeromagnetic data. Matiz-León (2023) emphasized the importance of statistical methods and spatial prediction for estimating geothermal gradients in the Llanos Basin, especially in areas lacking in-situ data; and Mejía-Fragoso et al., (2024) implemented a data-driven approach to predict the geothermal gradient across the country using a Machine Learning approach.

It is important to highlight that geothermal energy is considered friendly because it has a lower environmental impact compared to conventional energy sources; it has a lower emission of greenhouse gases (gases that accumulate in the atmosphere and increase its temperature) and solids suspended in the air, and does not require the occupation of large extensions of land for its development. All this makes geothermal energy a clean energy. Unlike most renewable energies, geothermal energy does not depend on climatic variations, as do wind, solar and hydroelectric sources. Its use is local, meaning that the resource is used in the region where it is located.

2 Geothermal Energy in Colombia

The interest in renewable and sustainable energies has been increasing worldwide, due to the growing concern about the dependence on fossil fuels and their environmental impacts. Colombia, like other countries, has been no stranger to this; the country's regulatory policies have been aimed at promoting investment projects in non-conventional renewable energy sources (FNCER) through the creation of economic and tax incentives in order to diversify the energy matrix (Ruiz et al., 2021).

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From the reconnaissance study of the geothermal resources of the Republic of Colombia conducted by OLADE in 1982, it was established that the entire Colombian volcanic mountain range (Cordillera Central) hosts a pronounced regional thermal anomaly. In 2009 INGEOMINAS and the National Hydrocarbon Agency (ANH) presented a preliminary map of geothermal gradients (Figure 1a) where positive anomalies were identified mainly in areas located in sedimentary basins. In the extension of the evaluated territory (about 50%), they identified four positive anomalies in the geothermal gradient (>40°C/km), which are located in the sedimentary basins of Llanos Orientales, Cordillera Oriental, Caguan - Putumayo and Catatumbo. The maximum geothermal gradient in these basins is of the order of 60 - 65 °C/km. The maximum gradient observed in the Colombian territory (140°C/Km) corresponds to that of the geothermal well drilled in Nevado del Ruiz (SGC and ANH, 2009). Continuing with this project Alfaro and Rodriguez-Rodriguez (2020) show convective geothermal resources with superficial hydrothermal manifestations, related to volcanoes and faults (Figure 1b). Most of the geothermal systems related to volcanoes are located in the Cordillera Central and in the south of the Cordillera Occidental, regions with geothermal potential in Colombia.

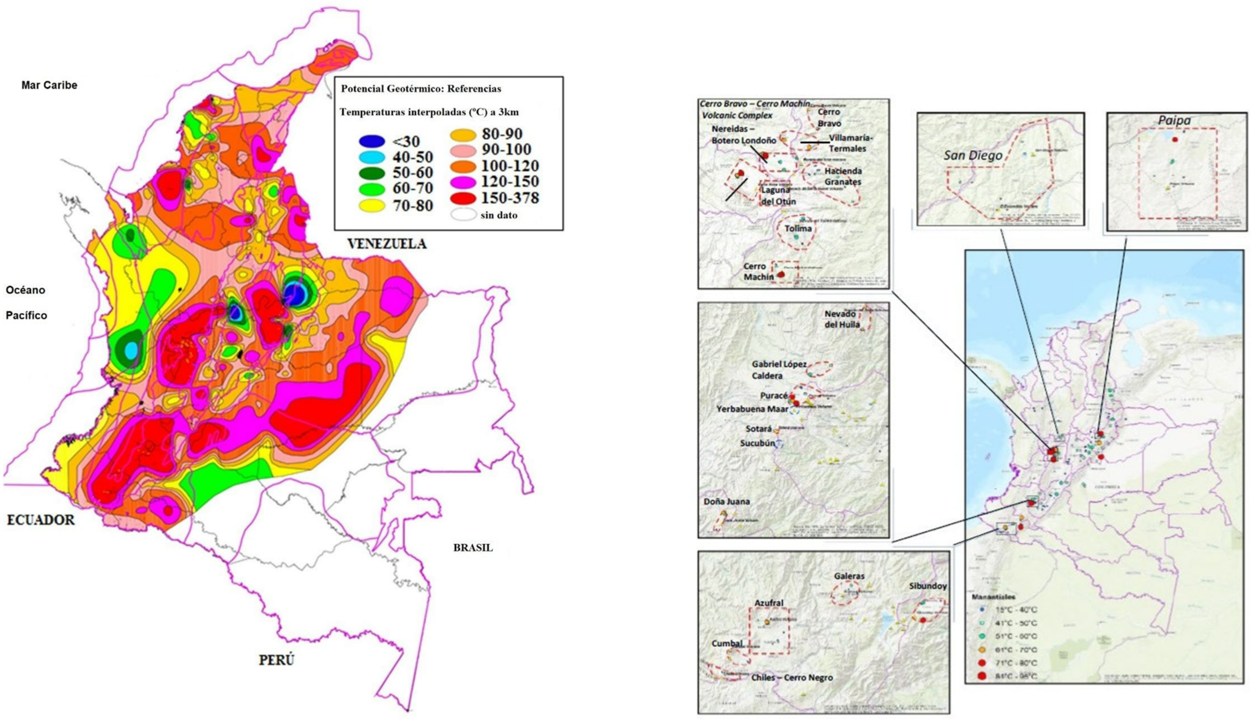
The SGC has also proposed potential geothermal areas and possible heat sources (Alfaro et al., 2020). By 2021, along with the economic reactivation of Colombia, the interest in the implementation of renewable energies increased considerably and, along with this, the creation of new projects in which geothermal is involved. The power generation potential of hydrothermal geothermal resources was first estimated for Colombia by Gawell et al. (1999) to be between 700 and 1370 MWe, with the technology available at that time. The same report estimates that there would be an increase, in generation capacity, to 1340 - 2210 MWe, with improved technology due to the development of advances in drilling and techniques to increase permeability. Based on this estimate, Colombia was considered as one of the countries where 20% of the energy demand could be covered from geothermal sources (Alfaro et al., 2020).

3 Geological Setting of Colombia

Colombia is located in the northwestern corner of the South American continent, and has a geological evolution dating back 1780 million years. This geological evolution had a great dynamism due to its location at the limit of the Nazca, South American and Caribbean plates, which has favored faulting, seismic nests and the development of the Andean orogeny (which is still in force today). Colombia has 12 tectonostratigraphic terrains with their own geological and evolutionary particularities, and a great variety of geological formations that include very old gneisses and schists (Mitú migmatitic complex), transgressive and regressive sedimentary sequences, igneous complexes and quaternary deposits (Lobo, 1987).

Colombia is located on the Pacific Ring of Fire, which encompasses a series of privileged regions for the generation of geothermal sources, which is why it has a great geothermal potential that can be explored and exploited, since it is located in a geodynamic environment of convergent plate edge that contributed to the formation of 13 active volcanoes with geothermal potential (Clavijo et al., 2008; Marzolf, 2014) as shown in Figure 2.

Most of Colombia's volcanism is evolutionarily related to the uplift of the Central Cordillera. The Upper Pliocene Andean Orogeny developed 4.5 to 3 million years ago, accompanied by extensive andesitic volcanism on the summits of the Central Cordillera, on the alignments of the Palestina fault and others, in the south of the Western Cordillera and in Panama. In addition, throughout the Sinú fold belt, from the Gulf of Urabá to Galerazamba, synsedimentary volcanism and magmatism developed with numerous volcanoes and mud diapirs (Lobo, 1987).



(a) (b)

Figure 1: (a) Geothermal potential map of Colombia, temperature in °C at depths of 3 km. Taken and modified from Vargas et al., 2009, (b) Convective systems related to volcanoes, hotr springs and faults. Temperatures of the discharging hot springs are indicated. Taken from Alfaro and Rodríguez, 2020.

There is still sedimentary volcanism on the edge of the Caribbean coast and on the platform, as periodically reminded by the mud volcanoes of Los Córdobas, Arboletes, Galerazamba and many others. Andean tectonic activity is still in force, as the earthquakes and tremors that occur frequently in the territory testify.

In this study, 4 main geothermal areas located in various regions of the country are presented in order to analyze and establish their potential. The selected areas are the Nevado del Ruiz Volcano, the Azufral Volcano, the Paipa geothermal area and the Tufiño - Chiles - Cerro system (Figure 3).

4 Nevado del Ruiz Volcano

The area of the Nevado del Ruiz Volcano (VNR) is the most studied in Colombia. It is an active stratovolcano located in Los Nevados National Park, in the department of Caldas, in the middle of the Central Cordillera. It is one of the northernmost active stratovolcanoes of the Colombian Central Cordillera (4°53'43 "N, 75°19'21" W) and rises at 5,321 masl. In this area, the only exploratory geothermal well drilled reached a depth of 1468m crossing seven lithological units and a zone with hydrothermal alteration associated with the circulation of high temperature fluids. The geothermal fluid flow pattern is structurally controlled by the Nereidas, Río Claro, Santa Rosa, Samaná Sur faults and the discontinuity of the pre-volcanic basement, favoring surface manifestations of chloride, sulfide and bicarbonate waters (Aguilera et al., 2019).

In the western sector of Nevado del Ruiz there are thermal springs with high temperature chlorinated waters, this includes the thermal areas of Las Nereidas, Botero-Londoño, El Recodo and Chorro Negro; it was identified already in the 1960s as a very promising area for geothermal exploration and to date remains the best known and studied geothermal area in Colombia (Bona and Coviello, 2016).

There is currently a project in the environmental assessment and preparation phase for the drilling of five exploratory wells in the area of the western flank of Nevado del Ruiz. These wells are planned to reach depths between 1,700 and 2,700 m to find a reservoir with a temperature of approximately 200 °C.

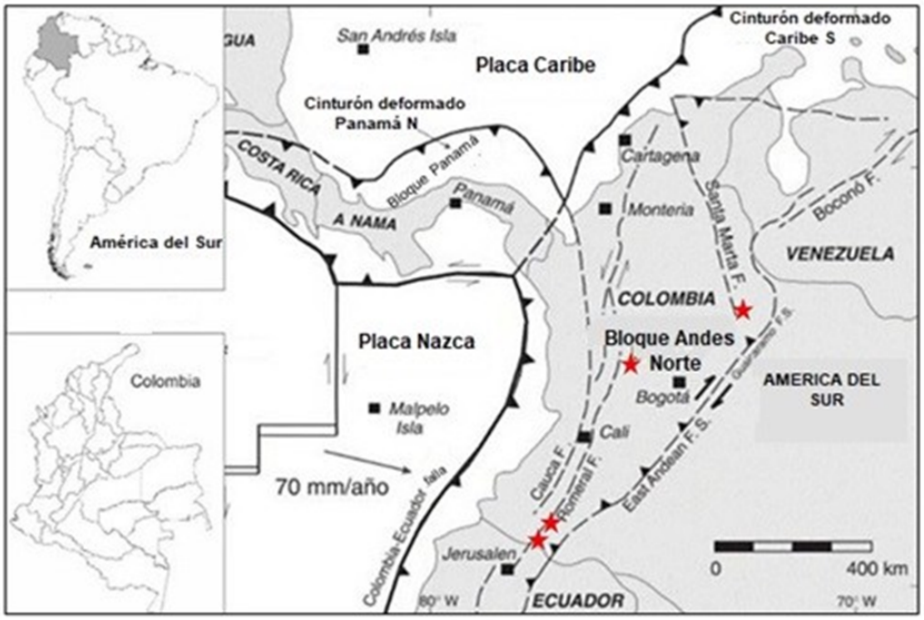


Figure 2: Structural diagram of the region to be studied for this TFI, marked with red from NE to SW: Paipa geothermal area, Nevado del Ruiz Volcano, Azufral Volcano and Tufiño - Chiles - Cerro system (Taken and modified from Aguilera et al., 2019).

(a) (b)

Figure 3: (a) Diagram of the locations of the regions studied, (b) Photos of the studied areas whose location is shown in Figure 10a. Taken and modified from Google Images.

4.1 Geological Setting

The study area is part of the northernmost active volcanic chain of the Colombian Cordillera Central, where the tectonic environment is the result of the convergence of the South American, Caribbean and Nazca plates and the Coiba and Panama microplates. This interaction is responsible for the different structural styles present in the region and the convergence between the Nazca and South American plates for the generation of volcanism along the Cordillera (Mejía et al., 2014). Subduction and its related igneous phenomena have been continuous in the northern Andes practically from the Jurassic to the present, with especially intense magmatic and volcanic events in the early and late Cretaceous, late Paleocene and mid-Miocene; this is practically continuous activity over time. This explains the formation of the currently active volcanoes in the Andes Mountains, including the VNR (Partida et al., 1997).

Lithologically, the sector is dominated by the presence of metamorphic and igneous units with different degrees of deformation, such as the Cajamarca Complex in its basement (graphitic chambered schists and green schists), which constitutes the core of the Central Cordillera, the Quebrada Grande Complex located to the west of the San Jerónimo Fault Zone, the Guacaica Granitic Milonite, the Bosque Batholith and Manizales Granodiorite Tonalite, Manizales Granodiorite or Manizales Tonalitic-Granodioritic Stock. These rocks are discordantly covered by pyroclastic deposits and lava flows produced mainly by the activity of the Cerro Bravo, Santa Isabel and Nevado del Ruíz volcanoes. The eruptive history of Nevado del Ruiz Volcano began 1.8 Ma ago and has gone through three eruptive states consisting of the ancestral, old and present Ruíz (Mejía et al., 2014). These states consist of the successive construction and destruction of the volcanic edifice, with the corresponding emplacement of andesitic and dacitic lava flows and domes, and the deposition of volcanosedimentary and volcanoclastic sequences (Rayo and Zuluaga, 2011).

During the Ruiz Ancestral some domes (i.e. Domo La Laguna, Domo Santana, Domo del Plato, Domo Tesorito) were emplaced along a NW structural trend, suggesting a tectonic control during their emplacement (Villamaría Termales Fault; Borrero et al., 2009). The volcanic products present calc-alkaline affinity typical of subduction zone volcanoes, most of them correspond to andesites and dacites with SiO2 > 64%. According to Schaefer (1995) these products can be divided into two sets: one high in K and the other low in K. The tectonic framework at regional level is dominated by a N-S faulting, known as Romeral fault system by several authors. There are also NE-SW structures that are related to the Palestina fault system. Other important structures present NW-SE and E-W strike, such as the Villamaría - Termales, Campoalegrito, Río Claro, Campoalegre, San Eugenio, Nereidas and San Ramón faults and some lineaments in the Ruíz-Tolima volcanic complex; there is also the Santa Rosa fault, with N70°E orientation (Mejía et al., 2012). In addition to the above, several volcanic edifices such as Nevado del Ruiz, Cisne and Santa Isabel are aligned NE-SW, coinciding with the southwest trend of the Palestina fault (Figure 4).

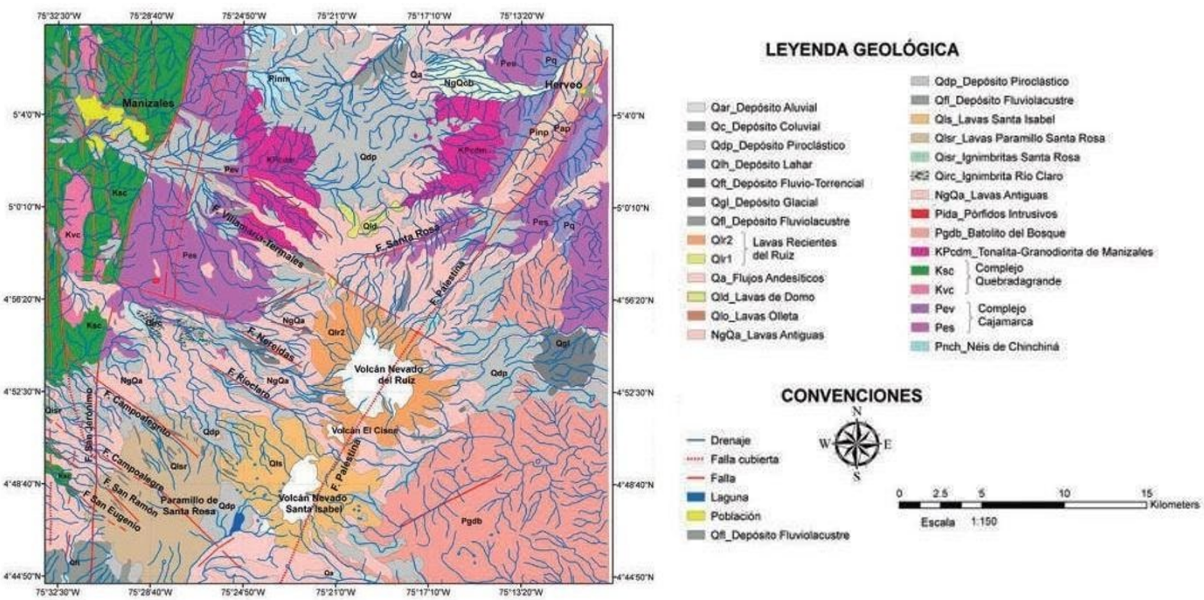


Figure 4: Regional geological map in the Nevado del Ruiz Volcano sector. Taken from Mejía et al. (2012).

The largest area of interest of the VNR corresponds to the Nereidas geothermal area (Figure 4) whose geology is characterized by a basement of Paleozoic quartz-graphitic schists intruded by Paleogene dacitic porphyries and a cover of Quaternary volcanic deposits that include andesitic lava flows (of two pyroxenes), pyroclastic flows such as ignimbrites, debris flows and mudflows. Associated with the volcanic deposits are deposits of glacial origin such as lateral moraines, bottom moraines and fluvioglacial deposits. Structurally, the region is considered a graben, formed by the intersection of the Palestina system faults with the Molinos and Río Claro faults (INGEOMINAS, 1997).

4.2 Geochemistry of Hydrothermal Fluids

Several geochemical studies have been carried out in the Nevado del Ruiz, some for research or academic purposes, others with the purpose of contributing to the geothermal initiative of the Valle de las Nereidas project, all of them providing important material on the composition and evolution of the fluids and petrography of the area. One of the most important studies was developed by Partida et al. (1997) in their work on the geochemical behavior of the geothermal manifestations in the eastern flank of the VNR (Río Claro - Las Nereidas); where the VNR is defined as the surface manifestation of an active magmatic chamber of acidic evolution, located at shallow cortical levels, capable of contributing heat to the environment.

The geochemical study showed two independent fluid circulation systems in the Nevado del Ruiz Volcano massif: one of sulfate waters to the north of the volcano and another of neutral chloride waters to the west. The thermal manifestations in the area correspond to mixtures in varying proportions of hydrothermal or geothermal fluids with surface or meteoric waters. The geothermal waters would come from a reservoir with an estimated minimum temperature of 235 °C, with 408 mg/kg of silica concentration (Partida et al., 1997).

Partida et al. (1997) analyzed three springs: Botero Londoño, La Piscina/El Billar and Nereidas. Botero Londoño and La Piscina presented distinctly geothermal characteristics with chloride-sodium composition and were defined as restricted circulation groundwater. Las Nereidas, on the other hand, had a high amount of dissolved solids, slightly acidic pH and was classified as sulfate and calcium bicarbonate (Figure 6a).

These authors also performed geothermometric analysis on the samples with geothermal characteristics, showing good agreement between Na-K- Ca, Na/K and TCCG (Cation Composition Geothermometer) geothermometers, while the magnesium correction underestimates the temperature considerably (Figure 5). The low magnesium content indicates the presence of a high temperature fluid. In the study it was considered reasonable to assume a temperature of 235 °C as mentioned above, this based on the data analysis.

Muestra	Fecha	TNaKCa (°C)	TNaKCaMg (°C)	TNa/K (°C)	TCCG (°C)
B1	Nov-1968	235	232	267	255
B1	May-1982	214	211	245	231
B1	Dic-1986	212	156	241	227
B1	Abr-1988	211	210	239	225
B2	Nov-1968	236	234	272	258
B2	May-1982	216	215	249	235
B2	Ene-1986	214	158	241	227
B2	Abr-1988	211	209	241	227
LP	Nov-1968	314	308	423	241
LP	May-1982	207	200	243	170
LP	Dic-1986	148	68	243	168
LP	Ene-1986	206	198	243	229

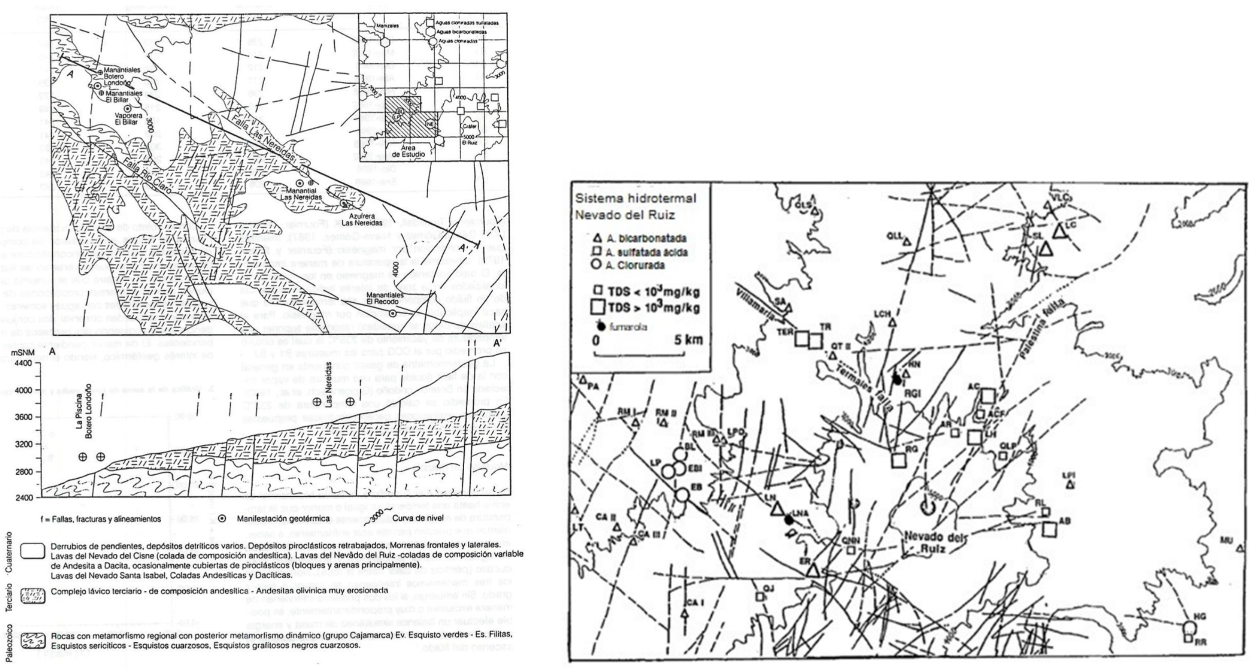
Figure 5: Geothermometric results for the studied springs. B1 and B2 = Botero Londoño, LP = La Piscina. Taken from Partida et al. (1997).

Partida et al. (1997) conclude that the geochemical evidence points to the Botero Londoño and Las Nereidas areas as sites with good potential for a geothermal project, especially considering that the geological data support the existence of a geothermal source. The Rio Claro and Las Nereidas faults, which would be responsible for the circulation of fluids, show structural controls.

On the other hand, Lopez (1992) studied in a more general way the hydrothermal system of the Nevado del Ruiz volcano, including diverse geochemical data of the fluids using the classification of Giggenbach et al. (1991), which also takes into account brackish waters (with higher TDS or Total Dissolved Solids). In this study, based on the combination of dominant anion and TDS, Lopez (1992) classified five types of waters: dilute acidic waters, dilute bicarbonate waters, acidic sulfate brackish waters, bicarbonate brackish waters and neutral chloride brackish waters. Dilute waters have a TDS of less than 1000 ppm (Figure 6b).

Neutral chloride waters are found on the western slope of the volcano (consistent with the study of Partida et al. 1992), acidic sulfate waters are generally aligned with the Villa María - Termales fault and, to a lesser degree, with the Palestina fault; bicarbonate waters are more dispersed, as can be seen in Figure 6b. The distribution of these waters suggests that the Villamaría - Termales fault is connected with the hydrothermal system and that the high permeability of these faults would allow the migration of magmatic acids to shallower depths where they mix with meteoric waters to form acidic sulfate waters (López, 1992). It is important to know that the waters of the VNR are not in equilibrium and are in an intermediate state in the process of dissolution of rock in water, evolving to mature and completely balanced waters.

Subsequently, in 2013, Correal at the National University of Colombia conducted a study of non-condensed fluids from springs and fumaroles of the VNR. The geochemical study in the area allowed recognizing a surface water circulation system of bicarbonate-alkaline waters with low salinity; associated with the interaction of meteoric waters with rocks rich in silicates (igneous, metamorphic) that outcrop in the region. These waters increase salinity without altering the other compositional characteristics when the interaction with gaseous fluids enriched in CO2 reaches the surface through zones of high vertical permeability associated with tectonic structures.



(a) (b)

Figure 6: (a) Simplified local geology showing the fumaroles and springs studied, taken from Partida et al. (1997), (b) General distribution of the waters of the VNR based on their composition. Taken from López (1992).

The study of gas geochemistry was also performed, but it was more limited. In the samples, CO2 dominant mixtures were mostly evidenced and the gaseous emanations were classified as cold or hot according to H2/CH4 ratios and with the predominance of N2. A probable temperature close to 209 °C was found (Correal, 2013). In this study it was also possible to conclude that the magmatic-hydrothermal system of the VNR presented areas with geothermal potential based on the detection of H2 that is associated with high temperature zones possibly connected to the magmatic chamber.

ISAGEN also conducted important geothermal studies in the VNR. In these pre-feasibility and feasibility studies they analyzed the geochemistry of cold springs and thermal springs, managing to estimate the origin, reservoir temperature, degree of maturity, mixing with surface or cold waters, connection with the magmatic system, steam content, water content and maturity of the reservoir; information of great value for the identification of promising areas to carry out exploratory drilling (Marzolf, 2014).

In 2017 Federico et al. studied steam discharges over Nevado del Ruiz during recent activity and analyzed the composition of the deep hydrothermal system and its effects on thermal waters. These authors measured the isotopic composition of the circulating waters and determined that they are of meteoric origin. They only found a shift in18 O in the Agua Caliente and Botero Londono thermal springs. In addition, they indicate that the data presented suggest that these springs discharge steam and gases from a hydrothermal system at a temperature of about 315 °C. This temperature is higher than that determined by the previous study. This temperature is higher than that determined by other authors.

4.3 Hydrothermal Alterations

Hydrothermal activity in the Nevado del Ruiz Volcano (VNR) generates rock alterations due to the interaction of fluids with the bedrock. In a study conducted by Forero (2012) at the National University of Colombia, the hydrothermal alterations of the NW flank of the VNR were characterized in detail using isotopes and petrographic analysis, which is an important contribution to geothermal exploration. In this study it was possible to identify the influence of gases in the generation of alterations that affect only ancient lavas. This alteration is characterized by two subsets: acid-sulfate and silicification; the acid-sulfate alteration is restricted to specific sites, associated with hot steam fluid emanations, while silicification occurs especially in fault zones.

The Advanced Argillic alteration is the most significant regional manifestation of the VNR hydrothermal system, this alteration is penetrative and presents the paragenesis quartz + kaolinite. + illite + smectite + amorphous clays + sulfates. Acid-sulfate alteration and silicification correspond to two subgroups belonging to argillization. The magmatic component had an important role in this alteration, according to the results of δ^{18}O obtained in the study (Forero, 2012).

In the Santa Rosa and Hacienda el Termal sectors, the fluids that interact with the metamorphic basement rocks are neutral and rich in CO2, precipitating mainly amorphous silica and carbonates on the surface, while the N zone of the volcano has emanations of acidic thermal waters with precipitation and exudation of sulfates. The difference in the ascending fluids in these sectors reflects the existence of different hydrothermal systems.

The Nereidas vent reflects a small hydrothermal system of heated steam alteration very close to the adventitious Olleta volcano. The alteration generated at the site is restricted to the colluvial deposit where the gases emanate and is presumed to alter only a few meters around the fracture where the fluids ascend.

The silicification formed on the Villa Maria - Termales fault trace is the result of the ascent of very acidic fluids with temperatures above 150°C in a magmatic hydrothermal environment. On the other hand, the fault has served as a transport route for fluids at lower temperatures, this is reflected in the petrography where the existence of low temperature silica polymorphs such as chalcedony, opal and tridymite was observed (Forero, 2012).

In the Palestine fault trace there are several thermal emanations, also the advanced argillic alteration is more intense, indicating that the fractures associated with this fault play an important role in the ascent of fluids. On this fault there was presence of meteoric fluids and magmatic vapors, which would allow inferring the acidification of neutral waters in the area.

According to the study, unaltered lava flows are found overlying the extensive advanced argillic alteration, indicating an ancestral alteration event resulting from the interaction of magmatic fluids with the rock for a considerable period of time. Furthermore, the low values of δ^{34}S obtained support this hypothesis.

4.4 Geophysical Analyses

The 2014 study conducted by Marzolf of ISAGEN also presented the results obtained, expected and expected from the geophysical analyses in the pre-feasibility stage for the VNR. Geophysics is used to measure a series of rock properties in order to establish, indirectly and from the surface, the structure of the subsoil up to several kilometers deep. The study is based on the measurement and contrast of magnetic, electrical and density properties that can vary with water content and rock composition. The geophysical methods of interest for geothermal exploration are: gravimetry, magnetometry, magnetotellurics, geoelectrics, seismic and thermal prospecting (Marzolf, 2014).

ISAGEN together with Colciencias, in 2012, within the framework of the geothermal exploration of the VNR, developed a series of geophysical studies of the geothermal area based on magnetotelluric soundings, modeling the resistive structure of the subsoil and improving the technological infrastructure to acquire knowledge of the subsoil through measurement instruments. Among these studies mentioned is the one carried out by Sarmiento (2014), where a methodology is applied to process and interpret magnetotelluric information over the western area of the VNR and 1D and 2D resistivity modeling of five analyzed profiles is performed.

From the resistivity sections we can conclude the presence of a very important deep conductive body located in the SE part of the area, a resistive body of great size and depth can also be observed towards the NW sector of the area, a shallow and relatively continuous high conductivity zone laterally located over the central zone of the study, over a medium resistivity zone.

Vargas and Dewhurst (2014) conducted a reconnaissance analysis of the VNR geothermal system, in which they interpreted gravimetric and magnetotelluric studies (using GIS) to understand the structural variations of the northern section of the Central Cordillera of Colombia, specifically the structures of the Las Nereidas geothermal system on the western flank of the volcanic complex. Through the interpretation of profiles we were able to identify interesting sites, with low resistivity values and potential pathways for heat transfer, which increases the potential for a viable geothermal resource (Figure 7).

This region has been considered for more than 50 years as a potential geothermal exploration site, so it is important to increase geological knowledge of the area and understand how structural (and stratigraphic) controls are essential when studying a geothermal area. Likewise, it is important to recognize that resistivity and conductivity vary significantly within the rocks of the Cajamarca complex and the Quebrada grande complex and this influences the magnetotelluric data taken in the various studies, due to the presence of conductive rocks among the metamorphic, sedimentary and volcanic sequences (García et al., 2013).

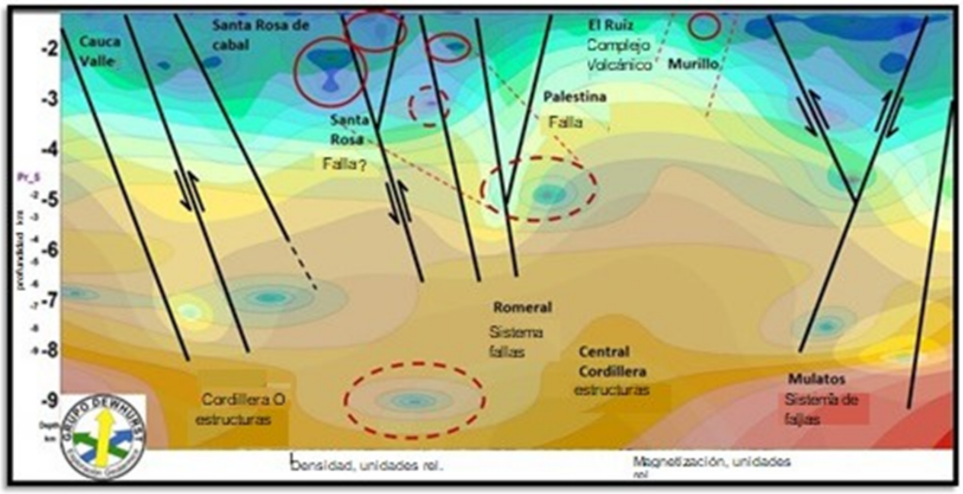
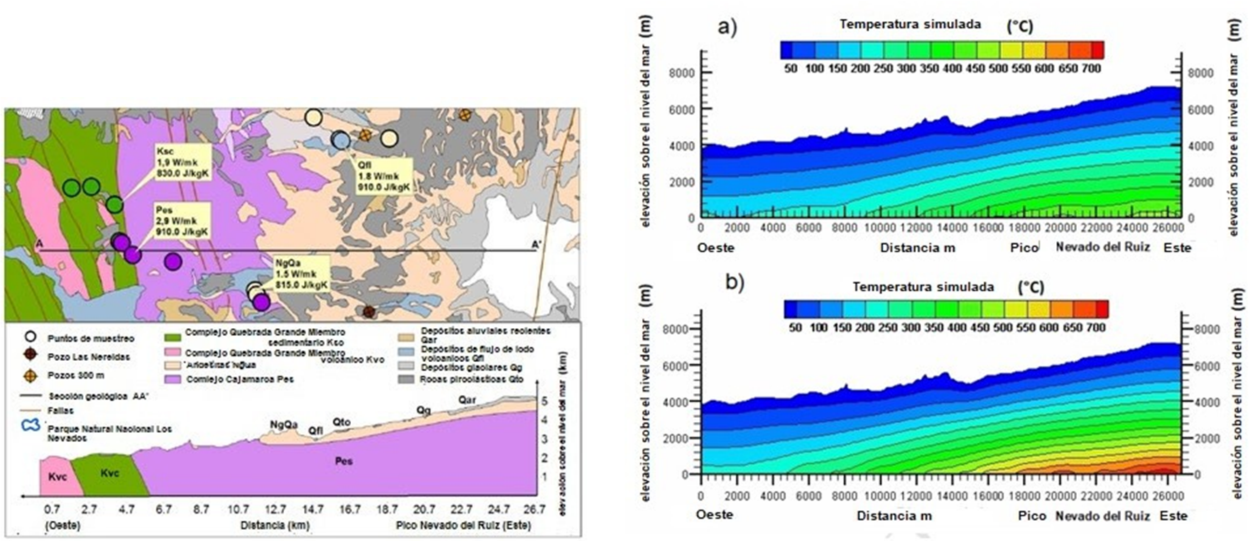


Figure 7: Gravity (density) model superimposed on the magnetotelluric model. Taken from Vargas and Dewhurst (2014).

Velez et al. (2017) estimated in more detail the geothermal potential of the VNR and with rock thermal conductivity data performed a heat transfer model. This served to reduce the geothermal development gap in Colombia and, in addition, improve the estimation of renewable resources. For the analysis they performed a cross section where they took rock samples (Figure 8a) and proposed two scenarios, one in which the thermal conductivity of the Cajamarca complex was constant (a), and another in which the thermal conductivity depends on temperature (b). For both scenarios a temperature modeling was performed and the thermal profiles for each scenario can be seen in Figure 8b. Based on these analyses, it can also be seen that in the areas of interest the temperature exceeds 200 °C.



(a)

(b)

Figure 8: (a) Geologic map showing the cross section taken for the modeling and the sampling points of the study, taken from Vélez et al., 2017. (b) Simulated temperature distribution for cases a and b. Taken from Vélez et al., 2017.

In this study by Vélez et al (2017) they estimated a capacity of 30 to 40 MWe, similar to the one indicated in Mejía et al (2014) of 50 MWe, considering both scenarios (a and b), being more realistic and optimal scenario b, where conductivity and temperature have a relationship with each other. This study also mentions that, due to the fact that the Cajamarca complex is very heterogeneous, detailed field investigations are required, and also focused on the characterization of the fault systems associated with thermal springs, in order to advance with the development of geothermal energy in Colombia.

Subsequently, following the recommendation of Velez et al. (2017), Moreno et al., 2018 performed a structural characterization and a heat transfer model of the VNR. In this study they consider three different scenarios for the influence of dip on groundwater flow and heat transfer: the one taken by convention, where the dip is 8°SE (A), another one where the dip is 45°SE (B), and a third one where the dip is 80°SW (C), this because there is still quite uncertainty regarding the dip of the faults and it is necessary to consider additional scenarios (Figure 9) (Moreno et al., 2018). In this analysis, the Samaná Sur fault was selected because it crosses through the geothermal reservoir (Cajamarca Complex). It was also found that the dip of the faults has an influence on the simulated temperatures: when the dip is in favor of the flow, the surface temperature increases and when the dip is against the flow, the surface temperature decreases.

Scenario	Fault inclination Samana South	Simulated Temperature in surface (°C)	Hydraulic gradient along the fault Samana South	Velocity along the fault Samaná Sur $(ms)^{-1}$
CASE A	80SE	60,5	0,00108	$7,70 \times 10^{-4}$
CASE B	45SE	68,1	0,00220	$1,57 \times 10^{-4}$
CASE C	80SW	54	0,00093	$6,63 \times 10^{-4}$

Figure 9: Simulated surface temperature and hydraulic gradient on the Samaná Sur fault for scenarios A, B and C. Taken from Moreno et al., 2018

The main objective of the work of Moreno et al (2018) was to understand and expose the influence of faults on the transport of hot fluids in the geothermal reservoir, which, as mentioned above, is a critical aspect in the development of these projects. Likewise, future work is required to calculate hydraulic conductivity more accurately to improve fluid and heat transfer models and reservoir temperature.

5 Azufral Volcano

The Azufral geothermal area is located in the Cordillera Occidental mountain range of southwestern Colombia, in the Department of Nariño, about 25 km north of the border with Ecuador. The town of Túquerres is located at the base of the eastern slope of Azufral and a road surrounds much of the volcanic edifice, so the sector has generally good access and logistical conditions. The area also presents a favorable location with respect to the 220 kV electrical interconnection line between Colombia and Ecuador which passes about 25 km to the east (Bona and Coviello, 2016).

In 1982 the area was classified as a high priority zone for the recognition of geothermal potential, however the actual studies and investigations began in the late nineties under the direction of INGEOMINAS under the mandate of the national government of the time. Then such project had the support of the IDB, with financing from the Japan Trust Fund, which was responsible for conducting a pre-feasibility study assigning such study in April 2001, through an international tender, to the consulting firms West Japan Engineering Consultants and Geohazards Consultants International; The study was cancelled without starting the process in 2002, due to security problems in the area and lack of support from local authorities, therefore INGEOMINAS continued the investigation in the area, completing the mapping in 2003 and carrying out the geothermal exploration in 2006 (Ovalle, 2020).

Studies of structural geology, gravimetry, magnetometry, geoelectrics, surface hydrothermal alterations, fluid geochemistry and conceptual models have been developed at Azufral Volcano, which indicate that the Azufral Volcano hydrothermal system has a temperature of around 225 °C. The surface manifestations of the hydrothermal system, such as hot springs, fumaroles and hydrothermal alteration zones, are mainly controlled by faults and their intersections (Aguilera et al., 2019). It is considered one of the most explosive volcanoes in Colombia, with a valuable geothermal potential and currently presents permanent hydrothermal and fumarolic activity (Torres et al., 2001).

5.1 Geological Setting

Azufral Volcano is located in the Western Cordillera, in the department of Nariño, 30 km SW of the city of Pasto and 30 km north of the Colombian-Ecuadorian border, on what is called the Northern Volcanic Zone of the Andes (NVZ), which extends from Ecuador to the northern part of Colombia, forming volcanic belts oriented north-south (Rangel, 2017).

The Western Cordillera is built on a Mesozoic allochthonous metamorphic basement, formed by oceanic affinity metavolcanic rocks such as phyllites, shales and shales of sedimentary protolith, and marine sedimentary rocks of very fine grain size such as shales, siltstones and mudstones; and it is mainly constituted by volcanic and sedimentary rocks of Cretaceous age that have been divided into two main groups: the Diabassic Complex, of Coniacian-Turnonian age and composed of massive basaltic rocks or in pillow lavas, with microgabbros and tuffaceous intercalations with sedimentary rocks; and the Dagua Complex, of Lower to Upper Cretaceous age and constituted by marine sedimentary rocks with volcanic intercalations affected by dynamic and local metamorphism, divided into the following groups in the Espinal and Cisneros formations of Albian to Maastrichtian age (Gonzalez et al., 2002; Rangel, 2017). Both groups have been intruded by intermediate plutonic bodies (andesites to quartzodiorites) of Paleogene-Neogene age and by andesitic to dacitic bodies related to the Piedrancha batholith (Gonzalez et al., 2002) (Figure 10). All these units are covered by ignimbritic, laharic and pyroclastic deposits of Neogene and Holocene age.

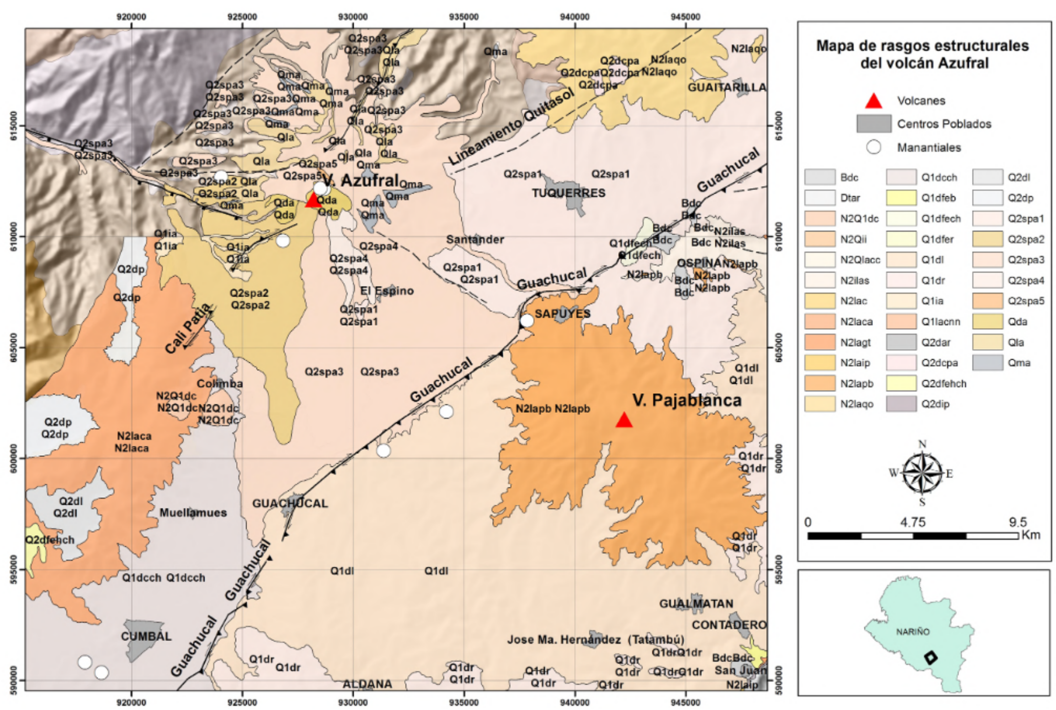


Figure 10: Geological map of the Azufral Volcano region, mostly covered by Quaternary deposits and Neogene formations, taken and modified from González et al., 2002 and Rangel, 2017.

The current volcanic edifice of Azufral is built on Cretaceous rocks, ultramafic and mafic plutonic, basic volcanic and metasedimentary, the latter belonging to the Dagua Structural Complex and all grouped in the so-called Western Cretaceous Oceanic Lithospheric Province (PLOCO), which constitute the base of the Western Cordillera and the Cauca-Patía inter-cordilleran depression. Intruding these rocks are Paleogene and Neogene igneous bodies and discordantly covering all the previous rocks, there are deposits and effusive, explosive and extrusive rocks of the Neogene and Quaternary, affected by faults of the Cali-Patía system, located towards the eastern foothills of the Western Cordillera (Torres et al., 2001).

The map of volcanic hazards and risks of Azufral Volcano prepared by INGEOMINAS in 2001 defined the geology and stratigraphy of the Neogene and Quaternary deposits and identified eight eruptions of dacitic composition represented by sequences of pyroclastic flows of ash and blocks, ash and pumice, and pyroclastic surges, the latter with a wide distribution in the area and considerable thickness. This leads to the conclusion that the recent activity of the Azufral stratovolcano has been highly explosive. The ancient sequences are made up of ignimbrite deposits and andesitic lavas, the latter dating to 0.58±0.03 Ma (Torres et al., 2001). Azufral volcano does not present glaciers and its edifice highlights the general presence of deposits associated with lava flows, large pyroclastic flows and pyroclastic fall deposits (Rangel, 2017).

The Azufral volcano responds tectonically to the subduction of the Nazca plate under the South American plate, a phenomenon that causes a complex structural style in the Western Cordillera, presenting a predominant occurrence of high-angle strike-slip faults with N-NE direction (González et al., 2002). This trend, which has been characterized by a series of active and potentially active faults parallel to the Romeral fault system, has been related to the collision of the previously mentioned plates (Nazca-South American) during the Cretaceous. This group of faults is known as the Cauca - Patía Fault System, which dips constantly to the east with angles between 50º and 70º and is located in the depression between the Eastern and Central Cordilleras towards the southeast of the country (Rangel, 2017).

To the east, the study area is bounded by the Silvia-Pijao fault, described as a north-south trending fault with a dip plane to the east. Additionally, the presence of perpendicularly oriented lineaments has also been reported, oriented to the NW, which are related to transverse faults and seem to correspond to ancient basement faults (González et al., 2002; Rangel, 2017). The faulted structures are mostly covered by volcanoclastic deposits.

To the east, the study area is bounded by the Silvia-Pijao fault, described as a north-south trending fault with a dip plane to the east. Additionally, the presence of perpendicularly oriented lineaments has also been reported, oriented to the NW, which are related to transverse faults and seem to correspond to ancient basement faults (González et al., 2002; Rangel, 2017). The faulted structures are mostly covered by volcanoclastic deposits.

Faulting, layering and shearing present NE-SW predominance, and two main fracture directions are distinguished: NE-SW and NW-SE (Gonzalez et al., 2002), which is important in terms of geothermal fluid migration (Rangel, 2017). The important aspects to consider about Azufral Volcano as a potential geothermal resource are its recent age and persistent volcanic activity, the complete magmatic evolution and differentiation (from andesites to rhyodacites), the presence of superficial thermal manifestations, and the superficial hydrothermal alteration (argillic, phyllic and propylitic), which will be discussed later.

5.2 Fluid Geochemistry

The importance of the Azufral volcano has merited the realization of several studies, among them, the preliminary geochemistry of gases within the framework of the INGEOMINAS Groundwater Exploration Program (PEXAS), which includes the geochemistry of fluids discharged by surface manifestations such as springs and steam vents. The geochemistry of thermal waters has allowed to establish, in previous works, a spatial distribution compatible with the model of geothermal systems associated to stratovolcanoes, to postulate the existence of a high-temperature geothermal system and evidence of mixing processes of the reservoir fluid with a source of salinized water by transit (Alfaro et al., 2008).

The estimated temperatures for the Azufral Volcano geothermal reservoir range from 240 to 480 °C according to the geothermometric data collected (Figure 11), which allows it to be classified as a high temperature or high enthalpy geothermal system.

Geotermómetro	t °C	t °C
H_2/Ar (1)	360	371
CO_2/Ar (2)	319	319
CO_2-H_2S-CH2-H4- (3)	407	423
CH_4/CO_2 (4)	430	417
CO_2 (5)	406	419
CO-CO_2-CH_4 (6)	283	252
CO_2/H_2 (7)	239	248
δ ^{13}C (‰) CH_4/CO_2 (8)	955	629
δ ^{13}C (‰) CH_4/CO_2 (9)	836	541
(1) Giggenbach 1991	(6) Chiodini & Cioni1989	
(2) Giggenbach 1991	(7) Koga 1987	
(3) D'amore & Panici 1980	(8) Lyon & Hulston 1984	
(4) Giggenbach 1991	(9) D'Amore & Panichi 1987	
(5) Arnorsson *et al.* 1983		

Figure 11: Estimated temperatures for the Azufral Volcano geothermal reservoir (two different intakes), from geothermometers. Taken from Alfaro et al., 2008.

Considering the estimation of reservoir temperature as the only criterion, the Azufral Volcano geothermal system has a wide potential for utilization, ranging from direct use of heat (spas, agricultural production, industrial drying, among others) to electricity generation in geothermal plants through indirect use, converting it into mechanical energy and, subsequently, into electricity. It is likely that the fluid-rock interaction in this geothermal system is in global equilibrium, even though it has not reached equilibrium in low-velocity reactions (Alfaro et al., 2008).

In a subsequent study on the geochemical characterization of the Azufral Volcano fluids (Rangel, 2017), quite detailed and complete results were obtained that allow us to better estimate the geothermal potential, from the compositional analysis of the thermal springs associated with this volcanic system, the thermal manifestations were grouped into four main chemical types and to make estimates of the temperature of the possible geothermal reservoir.

The first type is made up of high temperature moderately acidic to neutral sulfate springs, the second type has characteristics of sodium chloride waters of moderate to high temperatures, the third type has moderate temperature waters of chloride-sodium composition with significant concentrations of bicarbonate and the fourth type corresponds to low temperature magnesium bicarbonate waters, discarded as geothermal waters as they are more similar to purely meteoric waters. Of the water types mentioned above it should be noted that it is assumed that: the first group is of surface origin, the second group constitutes the geothermal waters of the system, the third group responds to mixing processes between deep and meteoric waters, and the last group is considered the final member of meteoric water for the Azufral volcanic system (Rangel, 2017).

The study of these springs made it possible to estimate the temperature of the possible high-temperature hot water reservoir, which varies from 179 to 208 °C. Relative calcium concentrations are low in the equilibrated springs and the waters have pH close to neutrality.

In this work, Na-K-Ca and K/Mg geothermometers were discarded due to their poor applicability within this context and due to some problems that reduce their validity, therefore, it is assumed that the temperature range that best reflects the thermodynamic conditions of the deep geothermal reservoir is the one provided by Na-K geothermometers (180 to 210 °C, approximately) (Rangel, Op. Cit.).

Rangel's (2017) study also manages to conclude that this geothermal system has a very broad potential for use ranging from direct uses of geothermal energy such as agricultural production, heating, balneology, among others, to electric power generation in conventional geothermal plants.

Alfaro et al. (2015) present a preliminary geothermal model of the Azufral Volcano and define four main discharge areas: Crater, Tercán (Quebrada El Baño), Chimangual (Quebrada Blanca) and Sapuyes (Malaber) and individual springs in San Ramón and La Cabaña, whose location is structurally controlled by the Carbán, Chimangual, Cali-Patía, Azufral-Sapuyes and Chimangual Faults.

Its chemical composition, represented in the Giggenbach and Goguel (1991) diagram, shows the presence of acid sulfate and neutral bicarbonate waters mixed with sulfates in the crater, neutral sodium chloride in Chimangual, neutral chloride with significant bicarbonate content in Tercán and Sapuyes, and neutral bicarbonate in the San Ramón and La Cabaña springs (Figure 12).

Aqueous geothermometers represented in the Giggenbach (1988) diagram indicate temperatures of 180°C (quartz) and 250 °C (Na/K) for the reservoir (Figure 12). On the other hand, gas geothermometers estimated from the composition of hydrothermal vents with a discharge temperature of 85°C yield temperatures between 190 and 300 °C (Alfaro et al., 2015).

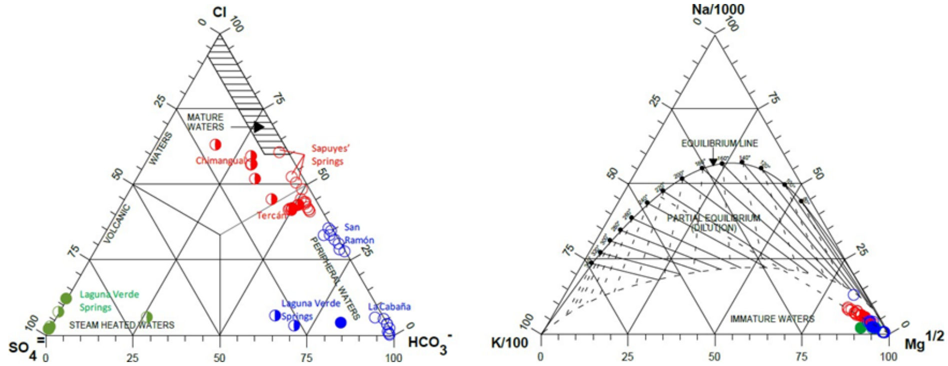


Figure 12: Relative chemical composition of Azufral volcano hot springs. The Na/K geothermometer indicates a probable reservoir temperature of at least 200 °C. Taken from Alfaro et al., 2015.

5.3 Hydrothermal Alterations

As part of the geological, seismic and geothermal research project in the Altiplano Nariñense, carried out jointly by INGEOMINAS and the National University of Colombia, within the framework of the INGEOMINAS groundwater exploration program (PEXAS), the mapping of surface hydrothermal alteration was carried out based on sampling and analysis of fresh and altered rocks. The study, based on surface alteration, allowed establishing a vertical zoning identifying advanced argillic, argillic, phyllic and propylitic zones. Quartz fillings and other forms of silica filling open fractures with NW - SE direction are also recognized. The vertical zonation has been previously established from the study of lithics collected in a pyroclastic deposit in the Espino area in the study of Recognition of the geothermal resources of the Republic of Colombia.

The preliminary conceptual model based on surface hydrothermal alteration allows inferring a mature high-temperature geothermal system with a magmatic heat source located mainly to the east of the volcano, which is consistent with the geochemical model based on the distribution and characterization of surface manifestations (hot springs and fumaroles) of Azufral Volcano. An upward flow cuts the surface towards the northeast of the crater, where a boiling process is recorded, evident in the existence of advanced argillic alteration, formed by steam-heated fluids, which develop in a surface environment characterized by the oxidation of H_2S (Figure 13) (Carvajal et al., 2008). This process is consistent with that defined in the geochemical characterization of hot springs (Alfaro et al., 2008).

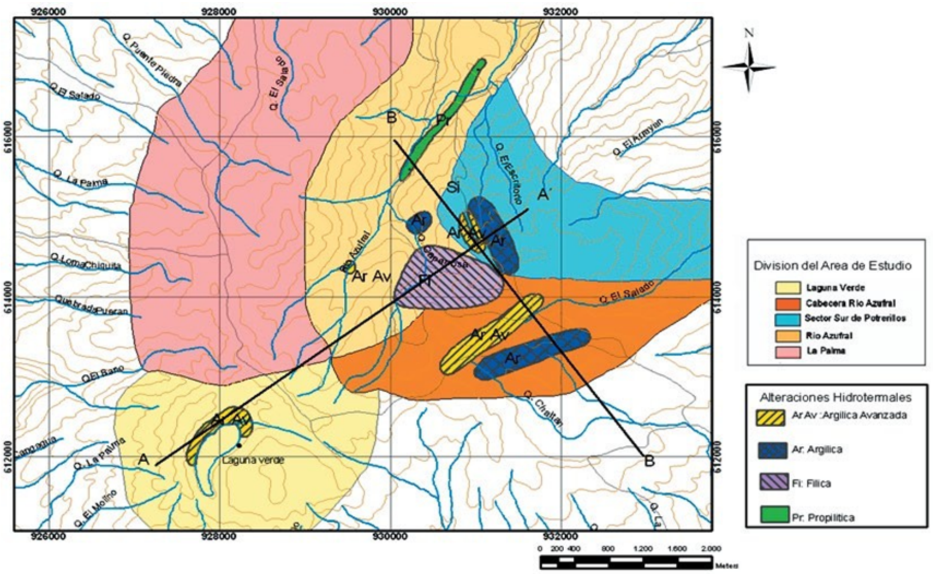


Figure 13: Spatial distribution of hydrothermal alteration recognized at Azufral Volcano. Taken from Carvajal et al., 2008.

The remaining mineral associations related to argillic, phyllic and propylitic alteration zones, located from higher to lower elevations, highlight the vertical zonation characteristic of mature geothermal systems developed in andesitic stratovolcanics (Carvajal et al., 2008). The estimate from both geothermometers and well-developed vertical zonation of hydrothermal alterations is for the reservoir temperature is between 250 and 280°C and would be located in a propylitic zone in the sequence of andesitic lavas or volcano-sedimentary rocks (argillites and siltites) (Alfaro et al., 2015).

5.4 Geophysics

Several geophysical studies have been carried out at Azufral volcano that have contributed to the study of its geothermal potential. The subsurface models based on the study of potential field anomalies carried out by Ponce (Ponce, 2013) denoted areas whose density values are low and with very low magnetic susceptibility, which could be due to the increase in temperature produced by volcanic activity. High gravimetric values with low magnetic susceptibility were also observed, which could be due to hydrothermal alteration of the rocks.

The combined interpretation of magnetometry and gravimetry was able to deduce the subsurface structure, which is mostly composed of igneous rocks of different composition and pyroclastic deposits from different volcanoes. Likewise, gradients of between 150 and 250°C/km were estimated, which would indicate a medium to high temperature reservoir at less than 2 km deep with temperature close to 242°C that coincides with a possible fault trace and the location of a thermal source, along with a zone of weakness in the basement that would be related to the ascent of magma (Ponce, 2013). Gravimetric and magnetic field measurements made by the Colombian Geological Survey in the preliminary model of the Azufral geothermal system represented, likewise, an enormous contribution to the study of resources in the area: regional and residual anomaly maps and models were made, as can be seen in Figure 14, and the geothermal gradient was estimated in a wide range from 40 to 250°C/km for a Curie depth of between 2.3 and 14.2 km. Below the volcanic edifice, the calculated Curie depth was 4 km and the geothermal gradient was 121°C/km (Alfaro et al., 2015).

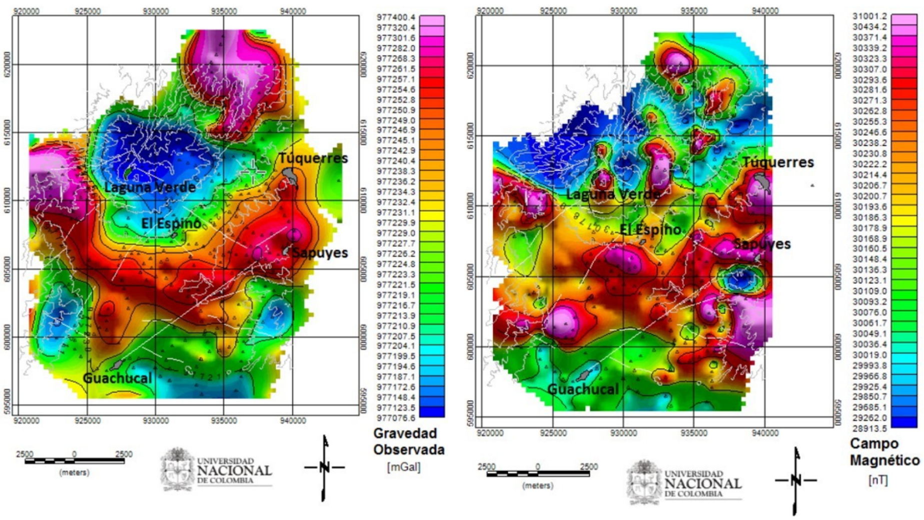


Figure 14: Gravimetric and magnetic model of the Azufral Volcano area, low gravity and magnetic anomalies were found, which defines a favorability towards the west of Tuquerres. Source: Alfaro et al. (2015), Ponce (2013).

Gravimetric and magnetic studies obtained favorable results: the thermal springs could be connected in a well-defined manner, which would be interpreted as an enrichment of hydrothermal fluids (Alfaro et al., 2015). Geo-electric and seismic studies were also carried out, which allowed identifying the type of rock and geological structures in the area, which were also favorable to host geothermal resource. The low permeability inferred based on the high density towards the west of the volcano prevents the geothermal fluid from flowing towards that zone, so it would extend westward circulating based on the NW structures related to the El Diviso - Túquerres and Azufral - Sapuyes faults. The accumulation zone can be seen in Figure 15, being bounded to the north and south by the El Diviso - Túquerres fault, to the west by the Muellamués fault and to the east by the Guachacal fault (Alfaro et al., 2015).

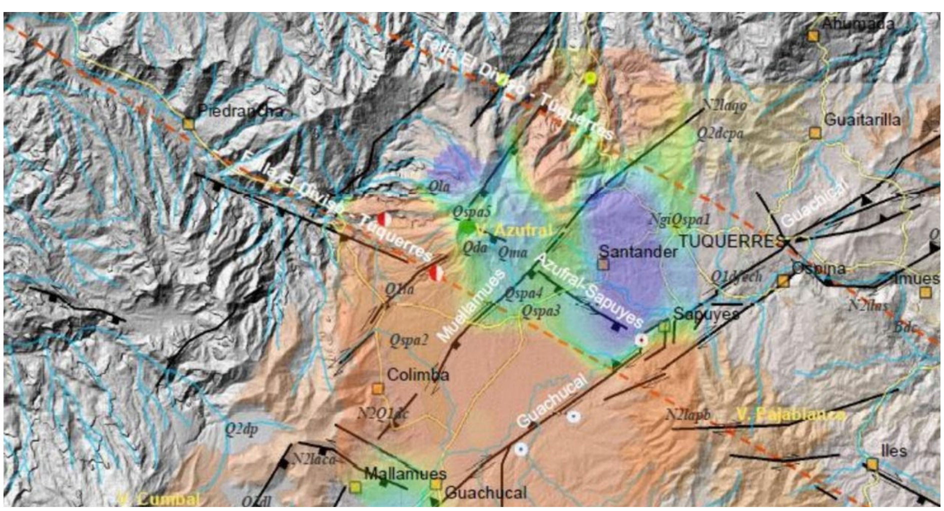


Figure 15: Favorability map of Azufral volcano, where the geothermal fluid accumulation zone can be seen (blue area). Taken from Alfaro et al., 2015.

6 Paipa Geothermal Area

The Paipa geothermal area is located in the axial zone of the eastern Andean mountain range of Colombia, 150 km northeast of Bogota, about 5 km south of the city of Paipa (Figures 8 and 10). It is a rural area that extends with gentle morphology at elevations of 2,500-2,650 m.a.s.l., easily accessible and developed, therefore, it presents good logistical conditions for the eventual development of a geothermal project (Bona and Coviello, 2016).

Thermalism in the Paipa area has been the subject of research since the first half of the 1800s, focused on the study of the chemical composition of the waters and their therapeutic principles. Since 2002 the Paipa area was included in the geothermal research programs of the national geological service (INGEOMINAS and later SGC) which, in collaboration with the National University of Colombia, has carried out a wide range of studies focused on the characterization and understanding of the hydrothermal system. The integration of geological, volcanological, hydrothermal alteration, hydrogeochemical, ground gas surveys, and geophysical studies led to the generation of a preliminary model of the Paipa geothermal system, as well as subsequent studies that served to plan a deep exploratory well (Bona and Coviello, 2016).

In the area there are several hot springs with high salinity sulfate waters that are historically recognized for their therapeutic benefits, and are used in thermal spas with a thriving associated tourism industry. These sulfate waters are identified as a low temperature saline source defined by the chemical and isotopic composition of the hot springs. This system has extensive rims composed of permeable sedimentary rocks that would represent a regional recharge zone, while the infiltration of water into the system would occur through the normal faults. The groundwater is heated by interaction with the intrusion beneath the igneous domes, thus assuming that the source of the heating is residual heat from these magmatic bodies (Aguilera et al., 2019).

6.1 Geology

The area is dominantly covered by Cretaceous, Paleogene and Neogene sedimentary rocks and Quaternary unconsolidated deposits. Approximately 31 km2 of the 130km2 mapped (Alfaro et al., 2010) are covered by Neogene volcanic products (Figure 16).

The basement area consists of sedimentary (fractured sandy levels, intercalated with claystones and siltstones) and metamorphic rocks (phyllites, schists and gneisses) from the Paleozoic, as well as Jurassic intrusives and extrusive rocks; this basement is interpreted as the continuation in depth of the Floresta massif (González-Idarraga, 2020), which outcrops to the northeast of the area.

On the basement there is a sedimentary sequence composed, from base to top, by the Tibasosa formations composed of dark gray shales, limestones and sandstones rich in fossils; Une consisting of coarse and fine grained sandstones, conglomerates and gray shales in thin layers intercalated with the sandstones; Churuvita consisting of black shales with fine-grained quartz sandstones and levels of glauconite, muscovite, fossils and limestone; Conejo (Kc) consisting of black shales interbedded with sandstones, siltstones and limestones with calcareous concretions; Plaeners consisting of shale layers with phosphorite-rich levels and a large amount of fossils; Los Pinos which consists of layers of limestones intercalated with quartz sandstones, ichnofossils, lydites, clays and siltstones; Labor - Tierna presents fine-grained layers of quartz sandstone, Guaduas is formed by layers of clays and siltstones, intercalated with quartz sandstones and iron oxides, presents coal mantles and layers of fine-grained quartz sandstone with a clayey matrix; Bogotá which consists of quartz sandstone and lithics, intercalated with layers of limestones and clays, and abundant oxides; Tilatá which is widely distributed and is made up of sandy levels intercalated with siltstones and clays, levels of iron oxides and lignite. Quaternary deposits consist of sand, silt, clay and conglomerates of alluvial and fluvio-lacustrine activity (Alfaro et al., 2010; González-Idarraga, 2020) (Figure 16).

The regional tectonic framework of the area is framed in the axial zone of the Eastern Cordillera, where it has been subjected to a tectonic inversion since the Cretaceous, and presents structures that can be interpreted as the reactivation of old structures and the appearance of new faults under a compressional regime related to the Andean orogeny (Alfaro et al., 2020), the area also shows characteristics of transtensional tectonism. There are faults that occur both parallel and transverse to the mountain range. There are two structural styles in the area: thick-skinned tectonics with faults that affect the basement (Lanceros Fault and Soapaga Fault) and thin-skinned tectonics with faults that only affect the sedimentary mantles (El Bizcocho Fault and El Batán Fault) with SE vergence from the Boyacá fault (González-Idarraga, 2020) (Figure 16).

Transverse structures are especially visible to the south: Cerro Plateado Fault and Paipa - Iza Fault, interpreted as basement structures related to a previous extensional tectonic phase (Alfaro et al., 2010), which was reactivated during uplift (Alfaro et al., 2010).

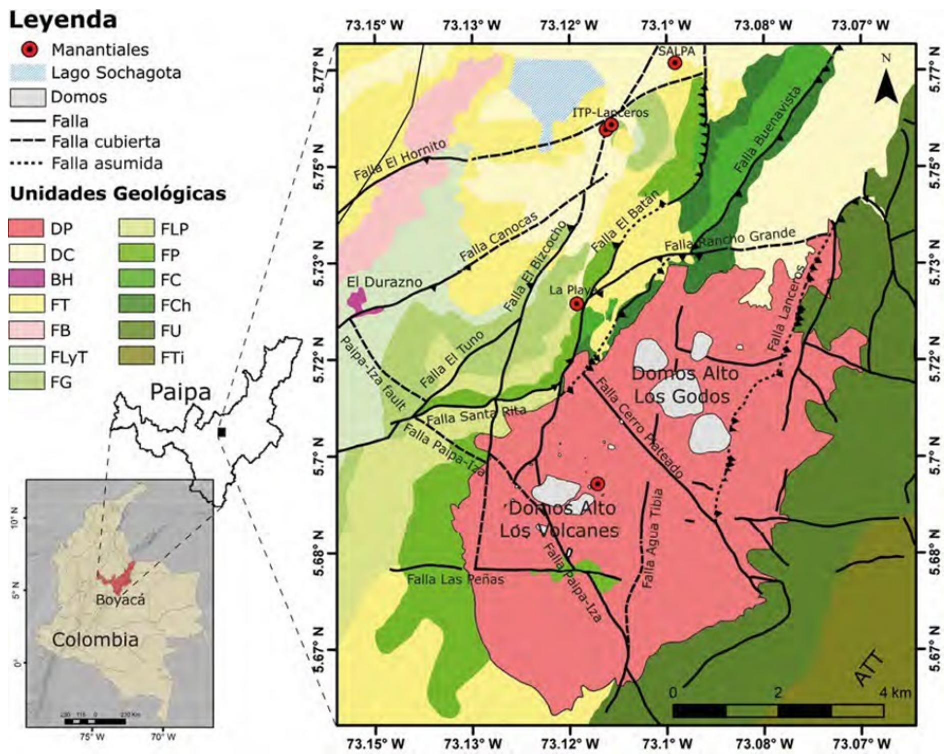


Figure 16: Geological and structural map of the Paipa geothermal area. Quaternary units: Pyroclastic deposits (DP), Quaternary deposits (DC). Neogene units: Hydrothermal breccia (BH), Tibatá Formation (FT). Paleogene units: Bogotá Formation (FB). Cretaceous units: Labor y Tierna Formation (FLyT), Guaduas Formation (FG), Los Pinos Formation (FLP), Plaeners Formation (FP), Conejo Formation (FC), Churuvita Formation (FCh), Une Formation (FU), Tibasosa Formation (FTi). ATT: Tibasosa-Toledo Anticline. Taken from González-Idarraga, 2020.

Andean, preserving fractures that facilitate the flow of hydrothermal fluid and, due to its depth, the ascent of magma and volcanism in the area. Transverse faulting affects the sedimentary sequence producing lateral displacements. The El Hornito and Canocas faults intercept the longitudinal structures and are associated with tectonic thrusts, and are also considered a product of recent tectonism in the area (Alfaro et al., 2010). These formations present, according to the resistive model made for the Paipa geothermal area (González-Idarraga, 2020), hydrogeological importance and a respective classification made by the Colombian Geological Service (SGC, 2016).

6.2 Geochemistry

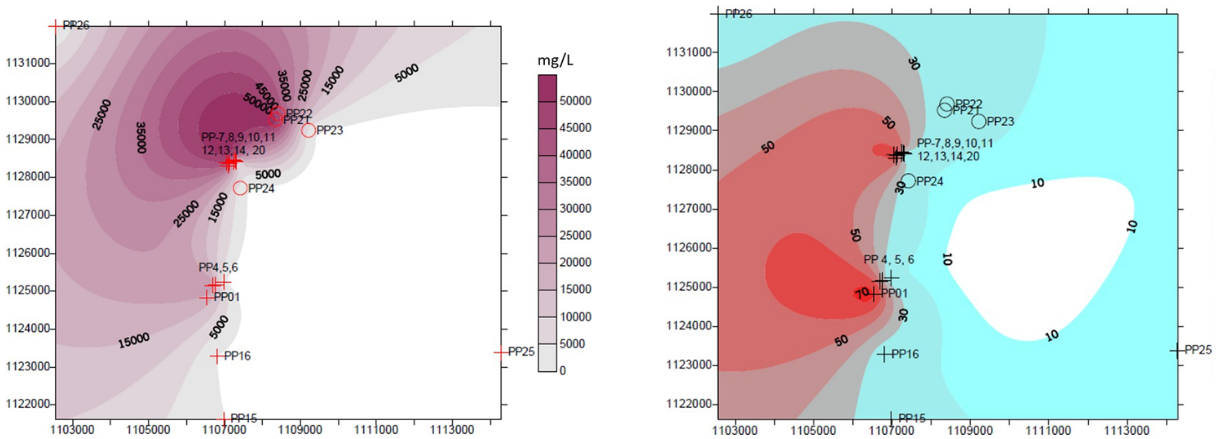
In 2002, as part of a project carried out by INGEOMINAS (Alfaro, 2002), a study was made of the springs of the Paipa geothermal area, which were analyzed for major dissolved chemical species (Na, K, Ca, Mg, Cl, SO_4, HCO_3) and minor dissolved chemical species (Li, Sr, B, F, and SiO_2). The salinity of these springs was determined to be very high, with a maximum total dissolved solids of 55800 mg/L, attributed to the enrichment of water in salts by dissolution of a salt bank located near the surface or mixing with a shallow saline aquifer.

As a result, the composition of the geothermal water is "masked", generating waters that are mostly classified as sulfate. The contour maps generated indicate that most of the measured ionic species have their source (maximum concentration) in the saline focus, located towards the northeast of the system. Important exceptions are found in the concentrations of SiO_2 and F. SiO_2 records its maximum concentration (98 mg/L) in a freshwater thermal spring (Piscina Olitas), located to the south of the system, indicating the highest concentration in that area.

temperature in the subsoil, even though its surface temperature is low (23 °C). The fluoride content does not seem to be dominated by the saline focus either, and so it registers its maximum concentrations in the springs of the La Playa and ITP sectors, where the hottest springs of this geothermal system are concentrated. The springs in the La Playa sector apparently receive the greatest contribution from the geothermal source.

The springs of the Iza system, which are hot and of low salinity, are probably fed by geothermal reservoir water, diluted with shallow cold water. Apparently the geochemistry of this system is of lower complexity than that of Paipa. Both systems appear to be high temperature and it is very likely that their heat source is magmatic (Alfaro, 2002).

The high salinity of the Paipa hot springs made the application of conventional geochemical criteria for their interpretation such as chemical tracers and geoindicators and geothermometers very difficult (Figures 17). However, its surface temperature (up to 77 °C) suggests an anomalous heat source, consistent with a probable minimum temperature of about 100-120 °C in the reservoir, estimated from the silica geothermometer.



(a) (b)

Figure 17: (a) Total dissolved solids (mg/L), in Paipa springs. Taken from Alfaro, 2020. (b) Contour map showing surface temperatures of the springs of the Paipa Geothermal System, taken from Alfaro, 2020.

Temperatures calculated from other aqueous geothermometers (Na/K, K/Mg, Na/K/Ca), register values on the order of 250 °C, values that are not reliable since the composition of the waters does not reflect the equilibrium conditions of the minerals with the reservoir water, but which are mentioned because they were calculated in previous studies (Alfaro, 2002). Figure 8b illustrates the spatial distribution of surface spring temperatures (Alfaro, 2002).

Ferreira and Hernández (1988), carried out geological observations and chemical characterization of the thermal waters, resulting in the formulation of the geothermal system, formed by a heat source generated by a magmatic intrusion. A reservoir with a geochemical temperature of more than 200°C, of primary permeability, probably hosted in the Une formation, the seal layer formed by clayey layers of the Churuvita Group. The recharge zone related to outcrops of the Une formation and a deep discharge zone driven by NE-SW normal faults (Gómez, 2019).

The thermal waters of the Paipa geothermal area can be classified as Hyperthermal waters, with strong mineralization and alkaline, however, 2 points are observed where the pH is lower classifying as Hyperthermal waters, with strong mineralization and acidic (Gómez, 2019).

Preliminary gas geochemistry presented in the work of Alfaro et al. (2010), based on data from 6 springs, indicate that they are not representative of a system in equilibrium. The estimated temperatures show a high dispersion, showing temperatures of 240 and 290°C ($CO–CO_2–CH_4$), 285 and 335°C (CO_2/Ar) and 220–230°C (^{13}C exchange in CH_4/CO_2). The authors suggest the existence of hydrocarbons in some subsoil strata, therefore,

the geothermal fluids of the Paipa geothermal system undergo mixing with a non-geothermal saline source and with gases of organic origin. The stable isotope composition of the water isotopes shows important effects of evaporation and vapor separation, the isotope geothermometer indicates a temperature between 220 and 230°C (Bertrami et al., 1992), agreeing with the results of the aforementioned geothermometers.

6.3 Hydrothermal Alterations

Surface hydrothermal alteration in the Paipa geothermal area (AGP) is related in principle to the interaction between aqueous fluids and rocks or deposits, involving low temperature acidic waters. Studies indicate the existence of igneous phases of sanidine and quartz and hydrothermal minerals of kaolinite and alunite. The acid hydrothermal alteration extends to depths between 50 and 100 meters (Alfaro et al., 2020).

Previous works of characterization of volcanic lithologies and hydrothermal alterations in the Alto de los Godos, CEMEX quarry and ALFAGRES areas mention argillic type alteration processes, in pyroclastic deposits, inferred by the presence of kaolinite, in addition to higher temperature alteration inferred from minerals such as epidote, adularia, chlorite and illite, found in xenoliths (Figures 18) (Garcia Lara, 2021).

The pyroclastic deposits of the CEMEX sector are hydrothermally altered, specifically they present argillic alteration based on the presence of minerals such as smectite, illite, kaolinite and quartz, reaching formation temperatures for the smectite-illite group in the range of 100-200 °C. On the contrary, for the ALFAGRES sector, the presence of 7Å halloisite and 10Å halloisite may be related to formation conditions of neutral pH and lower temperatures, on the order of 70-100 °C, as well as the lithologies in the SE dome sector of the Alto de los Godos (Figure 18b) (García Lara, 2021) (García Lara, 2021). X-ray diffraction by Alfaro et al. (2020) of volcanic deposits characterizes oxidation and weathering overprinting hydrothermal alteration. These comprise kaolinite veneer covering the surface of the pyroclastic deposits and hematite-limonite forming yellow and reddish stains.

Xenoliths in the upper Los Volcanes sector show low-intensity, high-temperature alteration. Some xenoliths comprise sedimentary and rhyolitic clasts in which plagioclase is replaced by epidote and transverse veins are filled with chlorite and albite, indicating temperatures above 220 °C. Metamorphic xenoliths containing veins filled with biotite, adularia and quartz suggest hotter alteration temperatures up to 320 °C (Alfaro et al., 2020).

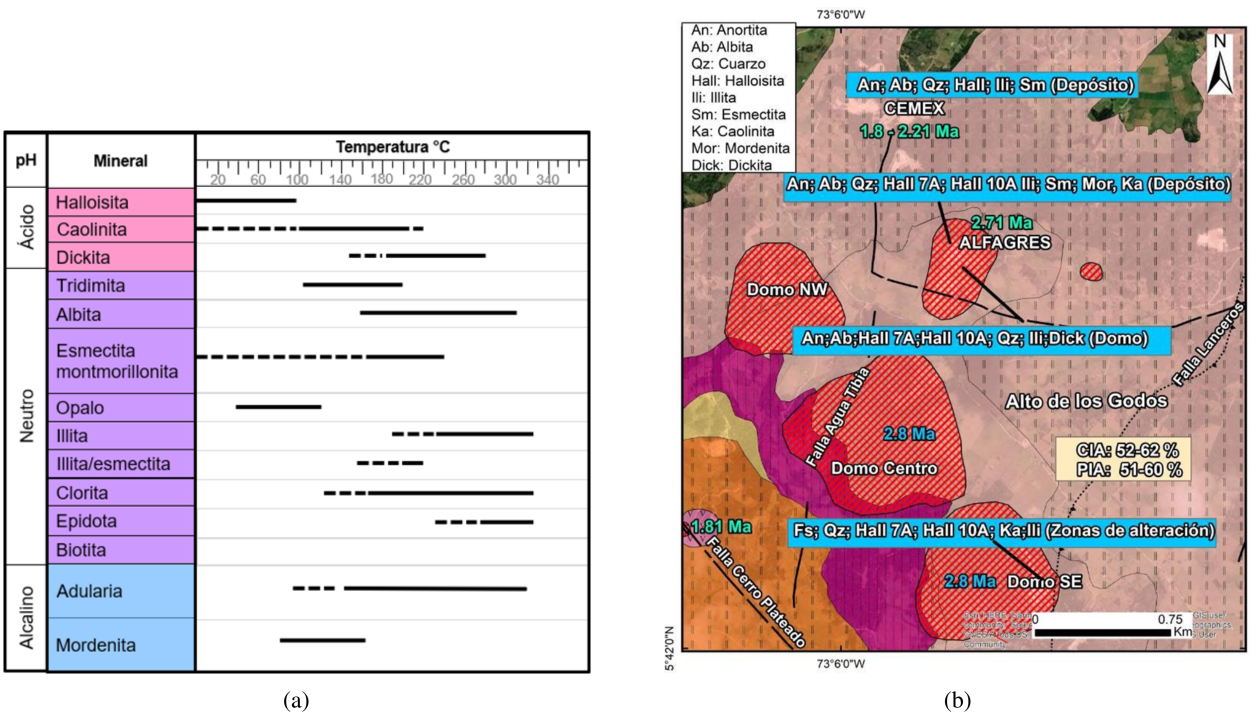


Figure 18: (a) Hydrothermal alteration minerals in the Paipa Geothermal Area. Source: García Lara, 2021, Alfaro et al., 2020. (b) Distribution map of alteration minerals in domes and deposits of the Alto de los Godos sector of the Paipa Geothermal Area. Taken from García Lara, 2021.

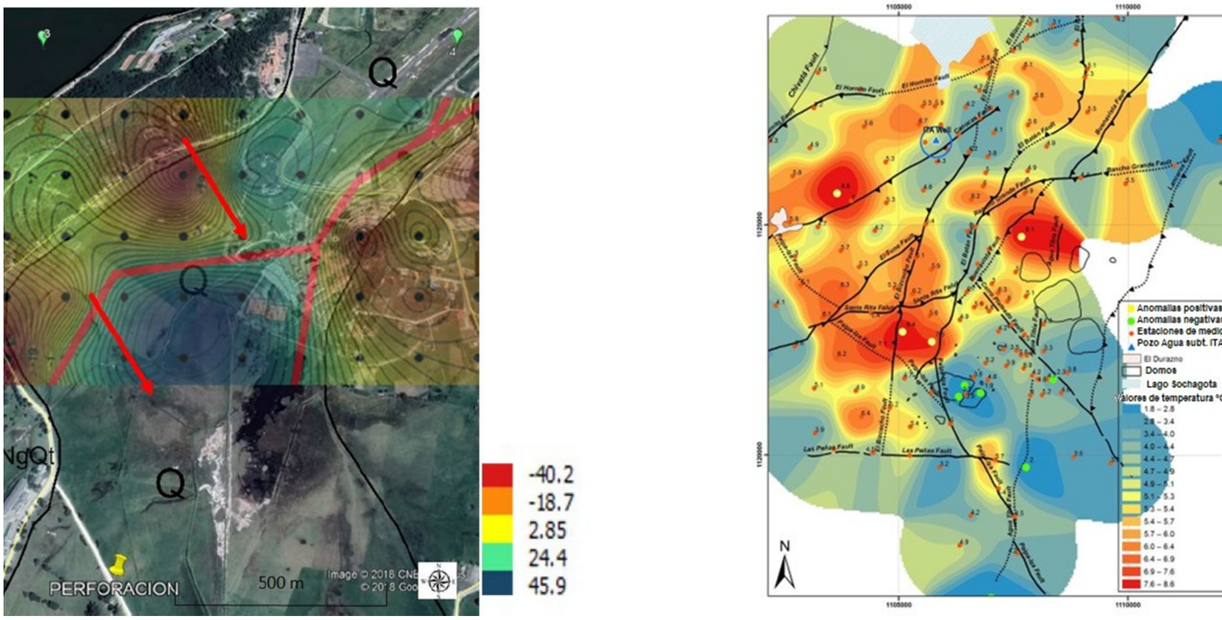
6.4 Geophysical Analyses

The Paipa geothermal area has also been material for geophysical analysis and methods to determine surface temperature, geological and physical properties of the layers, geological structures at depth, among others.

According to Gómez (2019), in his geothermal model of Paipa, resistivities and layer thicknesses were identified by vertical electrical sounding, to a depth of approximately 160m. The resistivities vary in the Quaternary deposit depending on the natural humidity. The magnetic survey allowed us to know the spatial variation of the magnetic anomaly, and to infer the possible location of the geological faults at depth (Figure 19a).

The discharge of the geothermal system takes place to the east of the junction between the El Bizcocho - El Hornito faults. These structures and especially their junctions are of special importance in the hydrothermal flow, as the faults interpreted by means of magnetometry.

Evaluated the structural geology found in the study area and the high temperatures measured in the thermal water outcrops, favorable conditions for the use of geothermal energy in the sector are evident (Gómez, 2019). In the study by Alfaro et al. (2017), soil temperature measurements were taken, performed at 141 stations partially covering the study area, at 1.5 m depth and distance from the emergence points of the thermal springs. Two areas of positive anomalies are observed in the zone dominated by thin-scaled faults, around the intersection between El Bizcocho, Santa Rita, El Tuno and Paipa - Iza faults, and near the El Durazno intrusion, which extends in the corridor defined by the Canocas and El Hornito faults. Additionally, an isolated anomalous measurement is recorded north of Alto Los Godos (Figure 19b).



(a)

(b)

Figure 19: (a) Map of magnetic anomalies and possible location of deep faults (red line). Taken from Gómez, 2019. (b) Map of surface temperature (1.5 m). The recorded values correspond to the difference between the measured temperatures and the mean temperature estimated for each point. Taken from Alfaro et al., 2017.

In the sector where there are normal basement faults (Paipa-Iza, Cerro Plateado and Las Peñas), presence of domes and in which consequently a greater possibility of occurrence of the geothermal system is presumed, negative temperature anomalies are recorded, behavior that could be associated with greater thermal insulation originated in the clayey or weathered layers of the pyroclastic deposits.

The thermal anomaly between the Canochas and El Bizcocho faults, would be confirmed by the temperature of the sodium bicarbonate water discharged by the water supply well (34.8°C), located at the Instituto Técnico Agropecuario - ITA about 3 km NE of the El Durazno intrusion, north of the Canocas Fault, i.e. in the possible direction of water circulation to the NE up to the junction with the El Bizcocho Fault. From this observation, there is the possibility of a low temperature (35°C) thermal water flow, compared to that of thermal spring discharge (70-75°C), circulating in a different water circuit than that of the higher temperature geothermal system (Alfaro et al., 2017).

The gravimetry results obtained in Alfaro et al. (2017) define three features of much interest for model formulation: (1) positive anomaly of great extension probably related to the metamorphic basement rocks of the core of the Tibasosa-Toledo anticline with discontinuity in the middle zone of the area that would be related to the Firabitova fault, (2) igneous intrusions mainly in the central zone of the working area, (2) igneous intrusions, mainly in the central zone of the work area, thus interpreted, thanks to the relation between their areas of occurrence and the surface expression of some of them, mainly in the dome zone of Alto los Volcanes, and (3) well defined structures based on contrasts between anomalies, such as the Cerro Plateado fault (Figure 20).

Magnetometry results also indicate positive anomalies related to igneous intrusions in the dome occurrence zone. Intrusions without surface expression at the northwestern and eastern end of the polygon defined as the Paipa geothermal

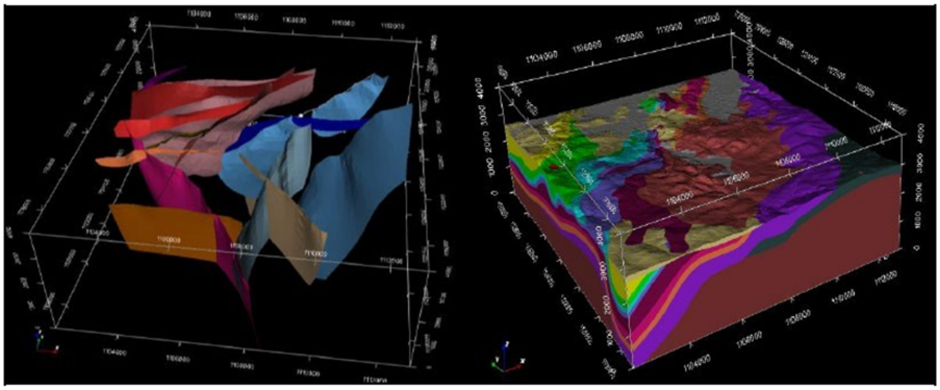


Figure 20: Direct geological model of the Paipa geothermal area. Left: network of faults. Right: geological formations. Taken from Alfaro et al., 2017.

area from the magnetic anomalies of greater magnitude, and also structures at depth associated with geothermal flow. The geoelectric characterization allows relating the highest conductivity anomaly (1Ωm) with the zone where the maximum concentration of sodium sulfate is inferred (topographic low of the Chicamocha River), to the east of Lake Sochagota. The other zones of high conductivity (5-10 Ωm) could be related to circulating salt water of lower concentration in total dissolved solids, with hydrothermal fluids or with clay levels, frequent in the sedimentary sequence of the area (Alfaro et al., 2017).

The Paipa geothermal system has very particular characteristics, as a result of the conditions of the area where it occurs: sedimentary environment (Eastern Cordillera Basin), evidence of magmatic and volcanic activity, igneous rocks with positive anomalies of radioactive elements, an evaporitic system that gives rise to highly mineralized sodium sulfate waters and the presence of hydrocarbons. The thermal springs of the system discharge fluids whose composition is not representative of the geothermal fluid, due to the mixing processes it undergoes.

The heat source of the geothermal system is magmatic and could be associated with remnant heat from intrusions or radiogenic heat. The age of the most recent magmatic activity expressed at the surface corresponds to the domes of the Olitas Sector and is of the order of 1 million years. However, it is possible that more recent magmatic activity without surface expression has been recorded (Alfaro et al., 2017). The final conceptual model can be seen in Figure 21.

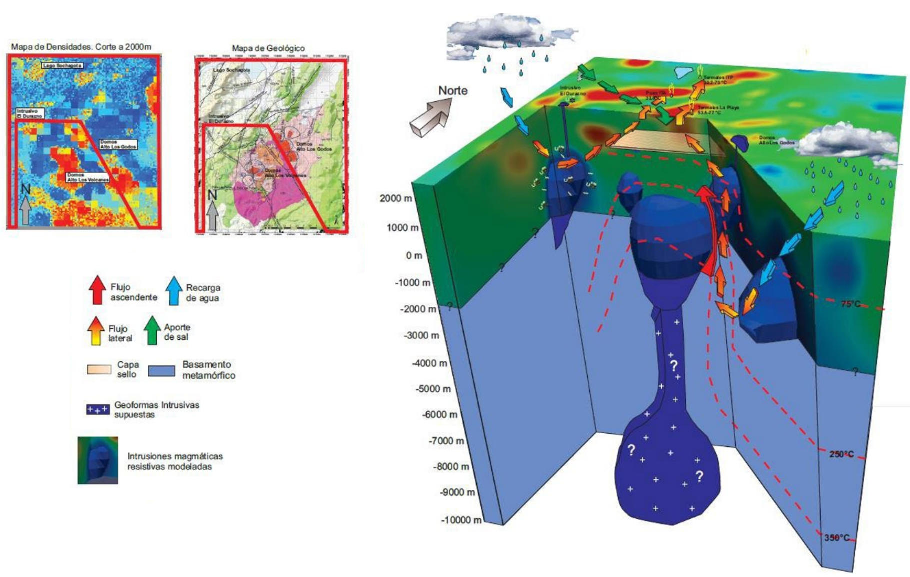


Figure 21: Conceptual model of the Paipa geothermal area. The arrows indicate the possible path of water from the recharge areas to the area of interest. Source: Alfaro et al., 2017; Gómez, 2019.

7 Tufiño-Chiles-Cerro Negro Volcanic Complex

The Tufiño - Chiles - Cerro Negro geothermal area is located in the Cordillera Occidental, in the department of Nariño, Colombia and the province of Carchi, Ecuador (on the border of both countries) (Figures 8 and 10). The area of geothermal interest is located around the Chiles (4,730 m) and Cerro Negro (4,470 m) volcanoes. The Preliminary Geothermal Model is based on the general geothermal model consisting of a magma intrusion at a relatively shallow depth (Heat Source); a formation of permeable rocks that hosts a hot confined aquifer (Reservoir) and a layer of impermeable rocks that form the hydraulic seal and act as a thermal insulator to prevent irradiation of heat accumulated in the reservoir. Gas geothermometers suggest reservoir temperatures of up to 230 °C (Aguilera et al., 2019).

The Chiles - Cerro Negro project is currently in the pre-feasibility stage, and due to its possible temperature, a limit of economic interest was estimated between 15 and 30 MW (Herrera, 2019), although according to Mejía et al., (2014), the complete system would imply a potential in excess of 130 MW.

7.1 Geological Setting

The geological evolution of the area begins in the late Cretaceous, specifically in the Campanian, with the formation of an oceanic floor, represented by the Diabassic and Dagua Groups. Subsequently, a change in the movement of the Caribbean Plate generated oblique accretion with respect to the northern margin of South America, causing the uplift and subsequent erosion of the Central Cordillera. Several authors propose a reorientation in the movement of the South American, Caribbean and Farallón plates, where the splitting of the latter generated the Cocos and Nazca microplates, initiating the Andean orogeny event (Bocanegra and Sánchez, 2017).

Bayona et al. (2012) propose that subduction events and magmatic activity occurred since the Late Cretaceous, quiescence in the early Paleogene and subsequent reactivation of magmatism in the Miocene due to the subduction of the Nazca plate. Again, in the Lower Pleistocene, magmatic activity decreased until its reactivation in the Upper Pleistocene with the formation of the Caguil, Cerro Crespo-Nasate and Cerro Colorado volcanic edifices. This activity lasted approximately 200,000 years, during which time new edifices were formed, such as those of the Chiles and Cerro Negro volcanoes, with stages of volcanic eruptions and effusions, continuing this activity until about 200,000 years ago.

15,000 years ago, when Chiles volcano was in the last stages of its effusive activity, while Cerro Negro exhibited eruptive activity approximately 6,200 years ago (Bocanegra and Sanchez, 2017). The area presents a complex structural style with strong chevron-type folding with a vergence towards the W, mainly in the Cretaceous units, while regarding faults the regional trend shows a preferential N20E direction (Bocanegra and Sanchez, 2017). The main features of the faults documented in the area of interest are the following:

- **Guachucal Fault:** It has a transcurrent character, with dextro-lateral displacement. The directions of the associated fault planes vary between N55E/35NW, N20E/45SE, and N55W/80SW.
- **Chiles-Cumbal Fault:** Topographic lineament through the Chiles volcano area and the E side of the Nasate volcano crater, extending towards the equator. There is evidence of hot springs in the Rio Blanco Creek, adjacent to this lineament. It is considered a continuation of the Cauca-Patía Fault.
- **Nasate Fault:** It has a NW-SE direction and affects the Nasate volcano.
- **Chiles-North Fault:** Its trace runs along the N sector of the area of interest of the PGB, it is a transverse fault that follows the Mayasquer River channel towards the W.
- **Chiles-Cerro Negro Fault:** Transverse fault that passes through the craters of the two volcanoes in the study area. It probably follows the course of the Chilma River to the W and to the E is associated with the thermal springs of the "Aguas Hediondas" sector in Ecuador.
- **Cerro Negro-Nasate Fault:** It has a NE direction, crossing the Cerro Negro and Nasate volcanoes. The identification of this fault was based on topographic lineaments and the existence of a highly fractured zone on the southern edge of the crater of Cerro Negro volcano.
- **Tufiño Fault:** It extends from Ecuador and marginally crosses the area of interest of the PGB with a N30E direction. The identification of this fault was based on the existence of volcanoes aligned in the same direction on the equator, as well as abrupt topographic changes.

The volcanoes of the geothermal system have each exhibited two similar stages of activity, separated by minor glacial unconformities. The predominantly effusive activity of the Chiles Volcano has been characterized as a sequence of six episodes, from the oldest to the most recent: 1) andesitic lava levels with low-medium degree of alteration, 2) strands of dacitic lavas, 3) elongated lava stripe in S78°E direction of dacitic composition, 4) chordate lavas with S72°E direction of dacitic composition, 5) andesitic lavas with columnar appearance elongated in N50°E direction, and 6) short flows of dacitic and and andesitic lavas (Garcia and Sanchez, 2019).

On the other hand, the volcanic edifice of Cerro Negro Volcano is a sequence of lava flows and pyroclastic flows emplaced in 5 episodes (Cortés and Calvache, 1996), which from the oldest to the most recent are: 1) lavas of andesitic composition, 2) lava flow in blocks of dacitic composition, 3) pyroclastic flow deposits, with clasts of dacitic composition, 4) dacitic lava flow in blocks, 5) chordate lavas of dacitic composition. Some fall deposits are observable in the surroundings of both volcanoes, but the source would correspond to Azufral volcano or an Ecuadorian volcano (Garcia and Sanchez, 2019) (Figure 22).

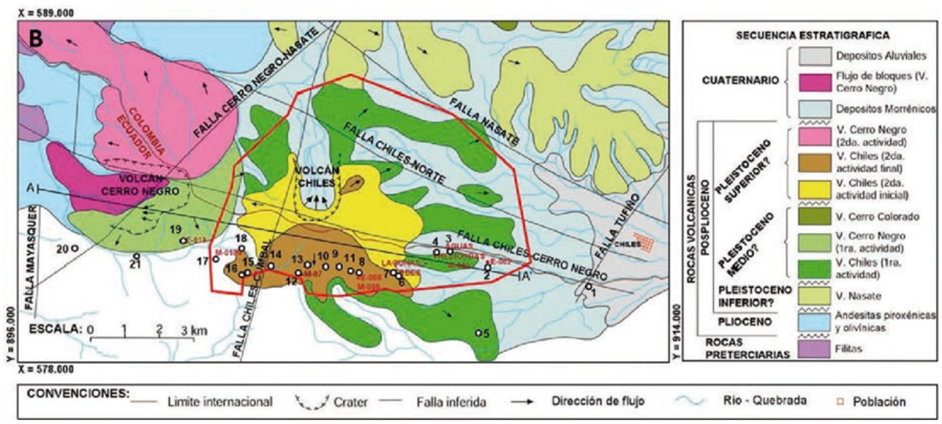


Figure 22: Simplified geologic map of the Chiles - Cerro Negro volcanic complex with thermal springs marked in red. Taken from García and Sánchez, 2019.

7.2 Hydrothermal Alteration

In the project area, hydrothermal alteration is very intense on the surface around the Chiles and Cerro Negro volcanoes; inside the craters of both volcanoes and defines the structural form almost destroyed by the glacial activity of the Nasate volcano crater. It also stands out in the domain of the Cumbal volcano towards the northwestern limit of the study area (Instituto Colombiano de Energía Eléctrica - ICEL, 1983). Additionally, it appears at the fault crossing sites around the Chiles and Cerro Negro volcanic edifices, contributing to define the surface limits of the geothermal field. Surface alteration in the project area is practically the result of fumarolic activity and amorphous silica deposition in zones of structural weakness. The hydrothermal alteration zones are mainly manifested in the crossing of faults near the Chiles and Cerro Negro volcanic edifices, towards their summits and delimiting the structural contour of ancient craters and collapse forms of ancient volcanoes (ICEL, Op. Cit.).

Sulfate acid alteration is very common towards the higher parts of the mountain range in both Colombian and Ecuadorian territory and is particularly prominent at road cut-off sites, both in the Ecuadorian zone that goes to Maldonado and in the Colombian zone that passes through the northern flank of the Chiles volcano. The deposit of amorphous silica is very common, as it occurs in the thermal springs of Aguas Hediondas and Aguas Negras in Ecuadorian territory.

Fumarolic alteration and that associated with acid sulfate vapors have resulted in the formation of clay minerals such as montmorillonite and those of the kaolin group, opal deposit and eventually alunite. All these minerals have contributed to plug the pre-existing conduits that allowed the circulation of fluids, in such a way that in places where a clear permeability of the rock was evident, it has been replaced by the opposite phenomenon, giving rise to the phenomenon of self-sealing with its impermeability. The associated minerals and their significance in the geothermal field imply that this kind of alteration is found in an argillic zone (ICEL, Op. Cit.).

OLADE (1987) in his study indicates the presence of a thick conductive stratum, located under the Aguas Hediondas zone and the central-northern portion of the Tufiño depression, which can be considered an indication that the circulation of hot fluids has originated an intense hydrothermal alteration of the host rocks.

7.3 Geophysics

The pre-feasibility studies carried out by Aquater (OLADE, 1987), allow us to outline the following geothermal model, which is based on surface data and geophysical exploration using gravimetric, magnetometric, geoelectric and magnetotelluric methods (Coviello, 2000).

The Tufiño-Chiles-Cerro Negro area is located within a region affected by an intense and persistent volcanic activity, reason for which the existence of a regional heat flow anomaly is very plausible, to which local anomalies directly related to the feeding system of the recent volcanism would be superimposed. The regional heat source is inferred due to the compositional variations of the products emitted by the volcanoes (Upper Pleistocene), which suggest a magmatic evolution in time that allow us to suppose the presence of a shallow magmatic chamber large enough to produce a thermal anomaly (ICEL, 1983; Coviello, 2000).

At a depth between 3 km and 7 km, isolated conductive bodies with an extension of a few km2 and a thickness varying between hundreds of meters and a few kilometers have been detected as horizons with a resistivity of a few Ohm-m and can be interpreted as zones of high permeability saturated by hot saline fluids or, possibly, residues of magma intruded along fractures. In addition to the above, it is estimated that the minimum temperature, at a depth of 15-20 km, would be around 700-750 °C, with an average geothermal gradient of 36-50°C per km, which represents a value of 1.2 to 1.7 times the normal gradient.

The presence of a geothermal reservoir in the Tufiño-Chiles area can be supported on the basis of the following evidence derived from experimental data: the manifestations of the geothermal reservoir in the Tufiño-Chiles area, and the presence of a geothermal reservoir in the Tufiño-Chiles area.

The thermal springs of Tufiño and Aguas Hediondas emerge with temperatures between 26 and 53 °C, significantly higher than the average annual temperature of the entire area (9 °C). Equilibrium temperatures calculated with geothermometers exceed 100 °C and tend to increase near the Chiles volcano, where they reach 220 °C (op. cit.).

Geophysical surveys reveal a 3-layer stratigraphy with the following characteristics: A superficial layer (A) with a medium-high resistivity (of the order of hundreds of Ohm); density between 2.4 and 2.6 g/cm3 and high magnetic susceptibility. Electrical soundings reveal, within this layer, the presence of the following 3 electro-stratigraphic levels:

- A shallow resistive layer with an average thickness of a few tens of meters.
- An intermediate conductive layer of variable thickness and resistivity of a few tens of Ohm-m.
- A basal resistivity layer with resistivity values in the order of hundreds of Ohm-m.

The thickness of the entire superficial stratum (A) varies from a few hundred meters to approximately 1 km. This stratum hosts two aquifers, one of them superficial. An intermediate stratum (B), strongly conductive, with a variable resistivity between a few and a few tens of Ohm-m; a low density, between 2.2-2.4 g/cm3, and a negligible magnetic susceptibility (Table 8). The thickness of the intermediate stratum (B) varies between 1,000 and 2,000 m and decreases significantly towards the western edge of the Tufiño depression, where it reaches only a few hundred meters. This stratum would constitute the seal layer, formed by deeply hydrothermalized volcanic products along which small amounts of the deep fluids ascend. A basement (C), highly resistive, with resistivity values between several hundred and a thousand Ohm-m; high density (2.7 g/cm3) and very high magnetic susceptibility (Figure 23).

	ESPESOR	RESISTIVIDAD
ESTRATO A	Fijo: 800 m	100 Ohm-m
ESTRATO B	Variable	5 Ohm-m
ESTRATO C1	Variable	100 Ohm-m
ESTRATO C2	Infinito	1.000 Ohm-m

Figure 23: Four-electro-strata model of the Tufiño-Chiles-Cerro Negro geothermal system. Taken from Coviello, 2000.

The 4-layer model proposed by OLADE (1987) assumes a resistive, magnetic and high-density basement, which would be formed by a package of fractured lavas and permeable, in which hot and saline fluids circulate and, therefore, with a lower resistivity than that of the basement.

7.4 Geochemistry and Hydrogeology

Based on the hydrogeochemical studies carried out by ICEL (1983) and OLADE (1987), two possible geothermal fluid producing horizons were defined: A.) A deep reservoir, located near 2,000 m depth, with temperatures above 200°C; B.) A shallow reservoir, at a depth of 500 to 1,000 m, with temperatures around 150°C.) The deep and higher temperature reservoir is the main target for exploration and development of the geothermal resource.) A shallow reservoir, at a depth of 500 to 1,000 m, with temperatures around 150°C.) The deep and higher temperature reservoir is the main target for exploration and development of the geothermal resource (ICEL, Op. Cit.).

From the above mentioned strata, which were defined by OLADE (1987), it was identified that stratum A hosts two aquifers: a superficial one characterized by calcic bicarbonate waters with a very low salinity and another deeper aquifer with a temperature of at least 100°C. The relatively high geothermal temperatures calculated for this stratum could not be explained only by conductive phenomena, but by a heating due to a mixing with deeper and much warmer fluids. The relatively high geothermometric temperatures calculated for this stratum could not be explained by conductive phenomena alone, but by heating due to mixing with deeper and much warmer fluids.

Layer (B) constitutes the impermeable cover (seal layer) formed essentially by volcanic products with deep hydrothermal alteration up to the clayey facies and affected by some fractures, along which small quantities of deep fluids ascend.

Geochemical data and thermal balances indicate that there is probably an additional aquifer in addition to those located in stratum A and would be located under the impermeable layer B, at depths greater than 1,300 m, which is the one with temperatures of industrial interest (OLADE, Op. Cit).

The recharge of these aquifers occurs because water infiltrates through the peaks of the mountain range, forming two flow directions directed towards its flanks (east and west). Most of the fluids tend to flow through the interior of the lava series that forms the immediate substrate of the volcanoes, contributing to the recharge of the reservoir within the sequence of Pliocene volcanites (ICEL, 1983).

In the pre-feasibility phase I (ICEL, 1983), 28 thermal and cold samples were collected in an area of 900 km2 whose parameters were analyzed both in the field and in the laboratory (pH, ambient temperature, water temperature, among others), and he following chemical species were determined in ppm: Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Cl^-, SiO_2, Li^+, Fe^{3+}, Sr^{2+}. The waters were regrouped into different chemical types relating them to the geochemical processes that originate them at depth, which allowed estimating the temperature and its spatial distribution. The results of these studies are summarized in Figure 24.

TIPO QUIMICO	Sub-grupo	SALINIDAD (meq /L)	TEMPERATURA (°C)	SITUACION HIDROGEOLOGICA	SIMBOLO GRAFICO	No. DE MUESTRAS
BICARBONATO ALCALINO TERREAS	Baja Salinidad	1.4 - 6	14	Circuitos Someros	⊙	7
	Media Salinidad	12 - 26	20 - 40	Circuitos más profundos que interactuan con gases calientes ricos en CO_2 o áreas con alto flujo de calor.	+	8
	Alta Salinidad	41 - 137	14.2 - 32.4		✲	6
SULFATADAS ALCALINO TERREAS	———	21 - 28	16.8 - 22.7	Circuitos someros que Interactuan con gases volcánicos ricos en H_2S. Lixiviación de rocas Hidrotermalizadas.	/	4
SULFATADAS ALCALINAS	———	20 - 37	31 - 51.5	Circuitos someros de aguas bicarbonatadas con adición de H_2SO_4 (Oxidación del H_2S)	x	3

Figure 24: . Chemical types of waters in the Tufiño-Chiles-Cerro Negro geothermal system, taken from ICEL, 1983.

Six samples were also taken for geothermometric measurements in the study area in order to find the estimated temperature at depth based on the Silica, Sodium-Potassium and Sodium-Potassium-Calcium geothermometers (Figure 25). Based on these data, ICEL (1983) concludes the following:

- The alkaline-earth bicarbonate waters 11, 12, 13, 21, 18, 19, 20, 25, 26, and 27 are in rock-water disequilibrium, without ruling out that samples 11, 12, and 13 are clearly associated with groundwater in greater quantities and are present on the surface in very diluted form.
- The alkaline-earth bicarbonate waters of groups (2, 3, 4, 5, 6) and (14, 15, 16, 17) show temperature differences between the geothermometers very similar to each other, which could be associated or interpreted as a tendency to equilibrium with feldspathic rocks at depth.
- Samples 7, 8, 9, 10 associated as alkaline-earth sulfate waters present the greatest differences between the geothermometric evaluations related to the situation of disequilibrium at depth.

- The temperatures estimated at depth with the Sodium-Potassium-Calcium Geothermometer seem to be the most reliable given the agreement between their temperatures; their average temperature estimated at depth is 224°C.

Muestra No.	SILICE Ec. 1	SILICE Ec. 2	SODIO - POTASIO	SODIO-POTASIO CALCIO
MFAH - 1	104	102	398	238.5
MFAN - 2	122	123	343	233.1
MFAL - 3	89	85	320	191.0
MChC1 - 4	113	112	386	233.8
MChC2 - 5	89	85	375	226.1
MChBI - 6	120	121	355	219.2

Figure 25: Temperature estimates in °C at depth for each sample, according to each geothermometer. Taken from ICEL, 1983.

8 Economic Aspects and Market Development

Colombia's energy vulnerability, together with the governmental policy of progressive promotion of sustainable development in the different national territories, has continuously generated favorable conditions for the development of geothermal resources. However, considerable work has had to be done in order to solve the technical, legal, institutional and infrastructural limitations that hinder the optimal development of these projects (Moreno-Rendón et al., 2020).

In Colombia, energy is obtained primarily from fossil fuels and hydroelectric systems (Energy Information Administration, 2018) as seen in Figure 35. If, in an ideal case, Colombia's geothermal resources were fully exploited, the full geothermal potential could be estimated at 17400 GWh/yr; and would be equivalent to producing about 20% of its estimated electricity demand by 2025 (86762 GWh/yr) using geothermal resources (Gawell et al., 1999; Salazar et al., 2017). By 2025, at least 1400 GWh per year is expected to be generated by geothermal energy, being 1.6% of the estimated electricity production by then (Salazar et al., 2017).

Currently, Parex Resources (Canadian oil company), the Ministry of Mines and Energy and the Universidad Nacional, Medellín headquarters, have started operating the first project for the generation of energy from geothermal energy in the Maracas Field, in Casanare. This geothermal plant was built because during oil production high temperature, permeable rocks and fresh water were found that could be brought to the surface at no additional cost as a co-product of oil extraction.

In terms of power generation, it is a basic source of energy and can provide a lower cost of electricity generation compared to diesel or gas in remote locations. This plant has an installed electricity generation capacity of 100 kW, capable of generating up to 72,000 kWh/month, which will help reduce emissions from fossil fuel power generation by about 550 tons of CO2 per year (Jorquera, 2021).

In addition to the above mentioned, Parex has another pilot in Campo La Rumba (low enthalpy), in the municipality of Aguazul in Casanare, with a capacity: 35 kW and generation of 672 kWh/day, equivalent to the consumption of 117 homes. Ecopetrol is developing another pilot in Chichimene (also low enthalpy), in Acacías, Meta, with a capacity of 2 MW and generation of 38,400 kWh/day, equivalent to the consumption of 6,659 homes (Jorquera, 2021).

The Colombian Geological Service, in order to investigate and promote geothermal production, conducted a preliminary study at national level where 21 geothermal areas associated with active and inactive volcanic systems were considered, which are grouped into five blocks located in the Eastern Cordillera (Paipa - Iza); north (San Diego and Cerro Bravo - Cerro Machín) and south (Huila - Sucubún and Las Ánimas - Chiles) of the Central Cordillera, with some areas on the eastern flank of the Western Cordillera (Azufral, Cumbal and Chiles - Cerro Negro). According to the study, Colombia's preliminary geothermal potential is 1170 MWe (Alfaro et al., 2020). However, there is still not much interest from the private sector, as there is a lack of promotion from the public sector. Figure 26 presents an infographic on Colombia's geothermal potential and the main pilot projects.

Figure 26: Infographic on Colombia's geothermal potential and main pilot projects. Retrieved from https://www.piensageotermia.com/inaugurada-primera-planta-de-energia-geotermica-en-colombia/.

8.1 Expectations at the National Level

As mentioned in previous sections, Colombia's geothermal potential was estimated at 1170 MWe according to the preliminary study conducted by the SGC in 2020 (Figure 27) and is framed as a development opportunity for the country, not only for electricity generation, but for various uses of thermal energy such as balneology, heating, greenhouses, aquaculture, agriculture, various industrial processes, among others.

Área Geotérmica	Termales	Clústeres	Calor** (EJ)	Intervalo confianza 90%	Calor recuperable (EJ)	Potencia** (MWe)	Intervalo confianza 90%
Paipa	14	4	4,31	3,41 a 5,22	0,5	21,50	10,96 a 32,04
Paipa*	14	--	2,87	--	--	20,89	--
Iza	4	3	2,72	2,27 a 3,14	0,3	12,09	6,45 a 178,73
San Diego	15	6	12,51	11,45 a 13,6	1,15	141,85	118 a 165
Volcán Cerro Bravo	8	4	7,94	6,96 a 8,92	0,88	79,73	63,49 a 95,98
Villamaría-Termales	9	3	4,83	4,03 a 5,62	0,51	38,50	27,39 a 49,71
Nereidas-Botero Londoño	14	5	12,19	10,55 a 13,83	1,31	100,72	71,60 a 129,85
Hacienda Granates	19	9	11,57	10,39 a 12,76	1,36	67,24	52,04 a 82,43
Volcán de Santa Rosa	20	3	10,66	9,27 a 12,05	1,07	137,24	105,6 a 168,9
Laguna Otún	1	1	0,63	0,3 a 0,95	0,08	0,08	0,03 a 0,13
Nevado del Tolima	18	4	8,66	7,50 a 9,82	1,17	82,70	60,70 a 104,71
Volcán Cerro Machín	14	2	10,05	8,29 a 11,81	1,14	129,94	93,65 a 166,23
Volcán del Huila	4	1	0,76	0,37 a 1,14	0,09	0,1	0,03 a 0,16
Caldera Gabriel López	8	4	5,15	4,55 a 5,75	0,57	24,78	19,69 a 29,83
Caldera del Paletará	21	8	14,27	12,86 a 15,67	1,48	117,96	96,13 a 139,78
Volcanes de Sotará - Sucubún	2	2	2,82	2,37 a 3,27	0,3	17,43	12,06 a 22,62
Volcanes Doña Juana-Las Animas	6	3	5,30	4,62 a 5,99	0,55	37,84	29,82 a 45,86
Volcanes Galeras-Morasurco	8	4	4,87	4,22 a 5,51	0,68	29,49	20,68 a 38,29
Volcán de Sibundoy	4	3	3,09	2,66 a 3,52	0,33	9,8	5,52 a 12,83
Volcán Azufral	8	6	9,6	8,69 a 10,52	0,91	81,9	67,41 a 96,36
Volcán Cumbal	1	2	2,56	1,59 a 3,51	0,25	15,66	5,41 a 25,90
Complejo Volcánico Chiles - Cerro Negro	5	3	4,14	3,5 a 4,8	0,48	23,77	16,98 a 30,55
TOTAL	203	80	138,60	136,76 a 140,43	15,11	1170,20	1138,81 a 1201,58

Figure 27: Stored heat and electrical power in the areas studied by the Colombian Geological Survey. Source: Alfaro et al., 2020.

It is important to take into account that the quantification of geothermal resources implies a level of detailed knowledge of geothermal systems, which is preceded by the development of exploration programs through which, among other variables, dimensions and physical and physicochemical characteristics of geothermal reservoirs and fluids are defined. This level of knowledge is not yet available for geothermal systems in the Colombian territory (ISAGEN, 2012).

However, Colombia's energy sector demands approximate information on the magnitude of these resources in order to make possible a projection of their possible contribution to the diversification of the energy matrix, and to define an action plan for the development of these resources (Alfaro et al., 2020).

On the other hand, based on the National Energy Plan (PEN) with projection to 2050 made by the UPME, attached to the Ministry of Mines and Energy, the addition of 1398 MW of capacity from non-conventional sources is expected in the short term. It is expected that by 2028, alternative energies will have a 15% share in the country's energy matrix, with a forecast of 275 MWe of installed capacity in geothermal plants. In an optimistic vision, by 2030, 375 MWe of geothermal capacity will have been added if optimal compliance with the initiatives and objectives of the PEN: Access, Diversification, Low Emissions and Innovation (UPME, 2015, 2020) is achieved.

It is important to keep in mind that the implementation of geothermal energy in Colombia is something relatively new, so there is still a high range of technological uncertainty, added to the country's little experience in the development of this type of energy. This is contemplated in Law 1715 of 2014, which postulates the guidelines for energy transformation and specific technologies for its development.

There is also a considerable degree of financial uncertainty due to the above, however, according to UPME, the Cost of Capital for geothermal energy is 2251 COP/kW, being more expensive than solar energy or biomass, but considerably less expensive than hydroelectric power, which is the conventional source at present (UPME, 2020).

The geothermal potential and expectations for the areas considered in this work, according to studies conducted by the SGC and by various authors, will be presented in the following sub-subsections.

8.1.1 Nevado del Ruiz Volcano (VNR)

For the Nevado del Ruiz Volcano and its surroundings (Parque Nacional de los Nevados) three promising geothermal areas were identified, the first and most important is Nereidas- Botero Londoño, west of the VNR, whose energy potential was based on the sum calculated for five different groups of springs whose total area is 16.8 km^2 (Figure 28) (Alfaro et al., 2020).

The heat stored totaled 12.19 EJ and the power 100.72 MWe, the main springs are Botero Londoño, Quebrada Nereidas, Hacienda El Plan, La Quinta, La Piscina, Hacienda Termales Cascada, Laguna Alta 1, 2 and 3 (72.27 MWe). The second area is Villamaría-Termales to the southeast of the VNR, the stored heat totaled 4.83 EJ and the power 38.50 MWe for three groups of springs, the main Termales springs are Ruíz I, II and II, La Gruta, Termales del Otoño and Minal del Hierro I and II (20.05 MWe).

The third is Hacienda Granates, east of the Nevado del Ruiz, El Cisne and Santa Isabel volcanoes. For nine groups of springs a heat of 11.57 EJ and a power of 67.24 MWe was estimated. The highest electrical power is estimated for two groups formed by three and two springs, respectively; these are: El Coquito, Aguablanca, La Cabaña, El Balcón and Botalón (22.56 and 18.89 MWe) (Alfaro et al., 2020).

8.1.2 Azufral Volcano

This geothermal area is located in the southwest of Colombia, in the department of Nariño, and covers part of the Chiles - Cumbal páramo that is also part of this work (Tufiño-Chiles-Cerro). The estimation of the energy potential was based on the resulting sum of six (6) groups of springs with a total extension of 12.8 km^2. The stored heat added up to 9.65 EJ and the power of 81.91 MWe (Figure 29) (Alfaro et al., 2020). The highest electrical power is estimated the three springs of Laguna Verde (20.07 MWe) (Alfaro et al, 2020).

8.1.3 Paipa Geothermal Area

The Paipa geothermal area is located south of the municipality of the same name, in the department of Boyacá. The estimation of the energy potential of the Paipa geothermal area was based on the sum of the values calculated for three of the four spring clusters, whose total cumulative extension is close to 9.26 km^2.

The accumulated stored heat is 4.31 EJ and the power is 21.50 MWe, however, based on the estimated volume for the reservoir from the geothermometry inferred in the SGC study (Alfaro et al., 2020) and assuming the same reference and reservoir temperatures, the stored heat would be 2.87 EJ and the electrical power would be 20.89 MWe (Table 15).

Área Geotérmica	ID	Número de Clusters	Calor almacenado (EJ)		Potencia eléctrica (MWe)	
Nereidas-Botero Londoño	NB	5	Media	12,19	Media	100,72
			Intervalo de confianza del 90%	10,55 a 13,83	Intervalo de confianza del 90%	71,60 a 129,85
			Desviación estándar	1	Desviación estándar	17,71
			Mediana	12,2	Mediana	100,74
			Incertidumbre	0,032	Incertidumbre	0,56
Área Geotérmica	ID	Número de Clusters	Calor almacenado (EJ)		Potencia eléctrica (MWe)	
Villamaría-Termales	VT	3	Media	4,83	Media	38,50
			Intervalo de confianza del 90%	4,03 a5,62	Intervalo de confianza del 90%	27,39 a 49,71
			Desviación estándar	0,48	Desviación estándar	6,79
			Mediana	4,81	Mediana	38,48
			Incertidumbre	0,015	Incertidumbre	0,21
Área Geotérmica	ID	Número de Clusters	Calor almacenado (EJ)		Potencia eléctrica (MWe)	
Hacienda Granates	HG	9	Media	11,57	Media	67,24
			Intervalo de confianza del 90%	10,39 a 12,76	Intervalo de confianza del 90%	52,04 a 82,43
			Desviación estándar	0,72	Desviación estándar	9,24
			Mediana	11,54	Mediana	67,1
			Incertidumbre	0,023	Incertidumbre	0,290

Figure 28: Accumulated Geothermal Potential and its statistical variables for the main areas of the Nevado del Ruiz Volcano. Source: Alfaro et al., 2020.

Área Geotérmica	ID	Número de Cluster	Calor almacenado (EJ)		Potencia eléctrica (MWe)	
Volcán Azufral	AZ	6	Media	9,6	Media	81,9
			Intervalo de confianza del 90%	8,69 a 10,52	Intervalo de confianza del 90%	67,41 a 96,36
			Desviación estándar	0,55	Desviación estándar	8,80
			Mediana	9,60	Mediana	81,71
			Incertidumbre	0,01	Incertidumbre	0,26

Figure 29: Accumulated Geothermal Potential and its statistical variables for the Azufral Volcano. Source: Alfaro et al., 2020.

8.1.4 Tufiño-Chiles-Cerro Negro Volcanic Complex

This geothermal area is located in southwestern Colombia on the border with Ecuador. The Chiles Cerro Negro volcano is part of the province of Carchi (Ecuador) and Nariño (Colombia). The SGC study area covers part of Páramo Chiles Cumbal (Alfaro et al., 2020).

The estimation of the energy potential was based on the resultant for three groups of springs with a total extension of 6.9 km^2 . The stored heat added up to 4.14 EJ and the power of 23.77 MWe. The highest electrical power is estimated for the group formed by the Rio Blanco thermal springs (11.21 MWe) (Table 16).

It is important to clarify that the estimate of geothermal potential made by the Colombian Geological Service corresponds only to the area of Colombia, however, based on Almeida (1990) and Beate and Urquizo (2015), a potential of 138 MWe is estimated for the Ecuadorian area based on surface data and volumetric methods.

8.2 Geoscience Strategic Plan 2022

Within the framework of the Geoscientific Strategic Plan for 2022 of the Colombian Geological Survey, a geothermal research program was proposed due to the aforementioned growing interest in the Colombian subsoil and its energy content in the form of heat, its existence in diverse geological environments, its relationship with magmatic and tectonic activity, with hydrocarbon systems, with deep and shallow reservoirs of hot and mineralized fluids, with characteristic chemical and isotopic composition, and with hydrothermal alteration zones, among others; as shown in Figure 32 (SGC, 2022).

Área Geotérmica	ID	Número de Cluster	Calor almacenado (EJ)		Potencia eléctrica (MWe)	
Paipa	PP	3	Media	**4,31**	Media	**21,50**
			Intervalo de confianza del 90%	3,41-5,22	Intervalo de confianza del 90%	10,96 -32,04
			Desviación estándar	0,55	Desviación estándar	6,41
			Mediana	4,31	Mediana	21,49
			Incertidumbre	0,02	Incertidumbre	0,20

Figure 30: Accumulated Geothermal Potential and its statistical variables for the Paipa Geothermal Area. Source: Alfaro et al., 2020.

Área Geotérmica	ID	Número de Cluster	Calor almacenado (EJ)		Potencia eléctrica (MWe)	
Chile Cerro Negro	CCN	3	Media	**4,14**	Media	**23,77**
			Intervalo de confianza del 90%	3,5 a 4,8	Intervalo de confianza del 90%	16,98 aa 30,55
			Desviación estándar	0,39	Desviación estándar	4,12
			Mediana	4,16	Mediana	23,78
			Incertidumbre	0,01	Incertidumbre	0,13

Figure 31: Accumulated Geothermal Potential and its statistical variables for the Tufiño-Chiles-Cerro Negro Volcanic Complex. Source: Alfaro et al., 2020.

The methodology proposed by the SGC contemplates 4 lines of research that include: that include: Geothermal investigation of hydrothermal systems, Geothermal favorability zones based on Play Fairway Analysis (PFA) methodology, Terrestrial heat flow and Shallow geothermal resources.

The strategies proposed for the execution of the Colombian Geothermal Research program include the performance of research by the SGC with the current work team and an additional complementary team, formed for this program, with the aim of addressing the lines of research by applying the methodologies already implemented to geological, geophysical, geochemical, and 3D geological modeling investigations.

Likewise, the research infrastructure will be improved through the replacement and acquisition of new measuring instruments (magnetotelluric equipment, accumulation chambers for measuring carbon dioxide in soil air, instrument for measuring $\delta 13$ C in CO_2, among others) and the implementation of new methodologies (slip/dilation for structural geology studies and estimation of multicomponent geothermometers and geochemical modeling for fluid geochemistry studies).

Funding opportunities will also be sought with international entities, such as the Inter-American Development Bank, World Bank, IRENA, cooperation agencies and national entities, such as MinCiencias, the Energy Directorate of the Ministry of Mines and Energy, National Hydrocarbon Agency, Ecopetrol, and the governments of the departments where the work areas Nariño, Risaralda, Caldas and Tolima are located (SGC, 2022).

9 Regulatory Framework

It is important to clarify that Colombia did not have a specific regulatory framework on geothermal energy until 2022, until then, it was not clear if regulations provide legal certainty to investors during the development of projects of this type (Martínez, 2021). Geothermal energy was framed and governed by the existing legislation for non-conventional energy resources, being defined as "natural combination of water with an endogenous subway heat source resulting in the spontaneous production of hot water or steam", until the Law 1318 of 2022, that determined the general aspects and definitions on the exploration and exploitation of geothermal energy to generate electric power.

From Law 1715 of 2014, which regulates the integration of non-conventional energies in the National Energy System, two decrees were generated where the parameters and incentives for non-conventional energies are defined with Decree 2143 of 2015 and the Non-Conventional Energies and Efficient Energy Management Fund (FENOGE) is regulated with Decree 1543 of 2017. Likewise, there is regulation regarding environmental licenses developed by the Ministry of Environment and Sustainable Development.

On the other hand, the exploration and implementation of geothermal energy is considered in the National Development Plan 2018-2022 and the framework for developing these activities by the Colombian Geological Survey (SGC) is issued (Alfaro and Rodríguez-Rodríguez, 2020).

Plazo de ejecución	Meta
2024	Informes técnicos, mapas y memorias, bases de datos, perforaciones, modelos conceptuales, artículos y jornadas de apropiación del conocimiento de las áreas geotérmicas de Paipa, Nereidas-Botero Londoño, San Diego, Cerro Machín y volcán Azufral. Investigaciones geofísicas en el área geotérmica de Santa Rosa de Cabal.
2026	Informes técnicos, mapas y memorias, bases de datos, perforaciones, modelos conceptuales, artículos y jornadas de apropiación del conocimiento de las áreas geotérmicas de Paipa, Nereidas-Botero Londoño, San Diego, Santa Rosa de Cabal, Cerro Machín, Cerro Bravo y volcán Azufral.
2028	Informes técnicos, mapas y memorias, bases de datos, perforaciones, modelos conceptuales, artículos y jornadas de apropiación del conocimiento de las áreas geotérmicas de Santa Rosa de Cabal, Cerro Machín, Cerro Bravo y volcán Azufral. Investigaciones geocientíficas en las áreas geotérmicas de Cerro machín y San Diego.
2030	Informes técnicos, mapas y memorias, bases de datos, perforaciones, modelos conceptuales, artículos y jornadas de apropiación del conocimiento de las áreas geotérmicas de interés, Santa Rosa de Cabal, Cerro Machín, Cerro Bravo y volcán Azufral. Investigaciones geocientíficas en el área geotérmica de Santa Rosa de Cabal.
2032	Informes técnicos, mapas y memorias, bases de datos, perforaciones, modelos conceptuales, artículos y jornadas de apropiación del conocimiento de las áreas geotérmicas de interés. Investigaciones geocientíficas en el área geotérmica de Cerro Bravo.

Figure 32: Geothermal Research Line of Hydrothermal Systems. Taken from SGC, 2022.

Article 51 of the Natural Resources Code stipulates that the use of natural resources can and must be granted, by operation of law, by means of permit, concession and association if this represents an exception to Art. 86, Decree-Law 2811 of 1974, which states that all inhabitants of the national territory have the right to use free of charge, without exclusivity and without the need for a permit, the natural resources of the public domain, to satisfy their elementary needs, those of their families and their domestic animals, to the extent that such use does not require the construction of infrastructure or violate the law.

The National Code of Natural Resources, in 1978, defines geothermal resources as water naturally occurring or injected into an endogenous heat source underground, resulting in the spontaneous production, natural or induced, of heat and steam, at a temperature greater than 80 °C. This same code discusses the use of geothermal systems (heating, electricity generation and mineral extraction), as well as permits for exploration and exploitation.

Law 99 of 1993 establishes the creation of the SINA and, therefore, the creation of the regional autonomous corporations, responsible for managing, monitoring and controlling the use of natural resources within their jurisdiction. This law also defines environmental licenses and their implications. In 2001, Law 697 was enacted, which defines the rational and efficient use of energy, including geothermal energy. Law 1715 of 2014 integrates non-conventional energy resources within the national energy system, and establishes tax incentives to encourage research and development of these resources. These incentives allow the deduction of 50% of the investments made during 5 years from the annual income; exemption from value added tax (VAT, known as IVA in Colombia) on equipment, articles, machinery, etc.

According to this law, the evaluation of geothermal potential is the responsibility of the National Government, which will implement instruments to promote and encourage exploration and research work in the subsoil for the knowledge of the geothermal resource, which will be considered, in accordance with Law 2099 of 2021, for the generation of electricity and its direct uses, for which permits or requirements may be required for the development of projects that promote the use of high, medium and low temperature resources (Art. 13, Law 2099 of 2021).

Resolution 1283 of 2016 establishes the requirements to obtain the benefits stipulated in Law 1715 of 2014. Resolution 2000 of 2017 establishes the form and requirements to submit to the ANLA the accreditation requests to obtain the sales tax exclusion.

It is important to highlight that Law 2099 of 2021, which establishes provisions for the energy transition, the dynamization of the energy market, the economic reactivation of the country and other provisions; explicitly mentions the concession of both surface and groundwater, which implies that both categories of water can be used for geothermal energy generation projects.

10 Social and Environmental Implications

The energy transition in Colombia, including the implementation of geothermal energy, presents several social factors involved, ranging from the common citizen to the business sector. Corporate social responsibility (CSR) plays an important role, appearing in the face of the need for regulation and control in the business environment, in order to protect the individual and collective interests of society. This materialized in the United States through the Sherman Antitrust Act (Garcia, 2021). The principles of CSR in the Colombian state are observed through its legal system focused on human and fundamental rights, which translates into social and environmental diligence in compliance with the constitution.

On the other hand, the industrial component plays an important role in the implementation of geothermal projects and in the energy transition, especially the mining industry; first, because of the requirement of materials for this to be carried out, generating new jobs and in turn new impacts on the environment and the population, and second, because of the role that would involve a technification and implementation of the circular economy in order to reduce waste and pollution. The technology and telecommunications sector will be involved; technological advances aim to generate an increase in the efficiency of devices in order to maintain - or even reduce - energy demand, but raw materials are required for this. Likewise, the transportation sector will be important in these projects, which indirectly implies a greater demand for materials and labor.

In conclusion, many materials that previously had no or only a limited participation in the economy (lithium, gallium, arsenic, phosphorus, silicon, iron, among others), will have an almost abrupt increase. In this sense, it is a challenge and an opportunity to develop a responsible exploitation, aligned with the environmental principles that gave rise to the need for energy transition.

It is important to take into account that due to the increase in the demand for materials and competition, there may be a strong uncertainty in prices, with the risk of discouraging internal growth and favoring foreign investment, generating an internal crisis due to the impact this would have on the communities and the labor sector from an economic, social and even environmental point of view (García, 2021). The Colombian post-conflict also plays a great role, due to the fact that the armed conflict has always affected in one way or another the energy sector and the exploration of the soil and subsoil in certain regions of the country. It is important to introduce commitments and proposals with a social approach to all the actors and roles of the armed conflict within the CSR policy, and, additionally, the liberation of regions that, at the time, were inaccessible.

Finally, the lack of standardization in the presentation of information to the communities involved and the relevance of disinformation and fake news in decisions on projects involving the use of subsoil resources should be highlighted. It is necessary to improve the mechanisms for citizen participation and provide tools that allow the community to have better contact with the industry and the project, as well as to participate constructively in decision-making.

Geothermal deposits, as well as groundwater, must be found for their subsequent exploitation, due to this, in the initial phase of geothermal energy generation projects a great effort is made to advance the stages of recognition, prefeasibility and feasibility that seek to determine which are the most suitable areas to exploit the resource, therefore a complex study must be carried out to have detailed information regarding its existence and exploitation capacity. In accordance with the above, it is convenient to have some type of environmental authorization that regulates the exploration of geothermal resources, similar to the groundwater exploration and prospecting permit, which also takes into account the technical and financial challenges that are inherent to a geothermal energy generation project (Martínez-Ruiz et al., 2021).

While on the one hand the Ministry of Mines and Energy is in charge of determining the quality requirements that geothermal projects must comply with to generate electricity, follow up and control all the requirements; the Ministry of Environment and Sustainable Development will determine the environmental parameters that these projects must comply with, as well as the mitigation of possible environmental impacts that may arise. In addition, Law 2099 of 2021 makes the caveat that in no case shall geothermal power generation projects be developed in areas of the National System of Protected Areas SINAP (Art. 21, Law 1715 of 2014; Art. 13 Law 2099 of 2021).

It is important to note that the extent and type of environmental impact of geothermal projects are determined by the nature and characteristics of the resource. In the exploitation of high temperature geothermal fields the environmental implications are mainly in the construction phase of the plants themselves. Once completed and in operation the impacts may consist of: gaseous emissions (CO2 and H2S), which constitute a tiny fraction compared to those produced by the use of fossil fuels, noise from the operation of the plant and visual disturbance to the previous landscape. This can be avoided through legislation and appropriate technology. In relation to direct use, at least two negative effects on the environment can be considered as having the greatest impact in the case of discharge of fluids into surface ecosystems.

Firstly, chemical pollution, which can become particularly important when large volumes of wastewater with high saline content are involved, and secondly, the so-called thermal pollution, a consequence of the discharge of wastewater at temperatures higher than those of the pre-existing ecosystems. Both effects can be avoided by means of currently available technology (dilution, cooling, reinjection wells, reverse osmosis, etc.).

The impact on the environment must be carefully considered, and solutions to possible situations must be found in the early stages of the projects. The functionality of the measures to be adopted varies according to the existing conditions at each site. It is important to mention that, although geothermal energy generation has advantages over other types of energy, such as low energy costs, it is not always possible to generate energy from geothermal energy.

emissions of greenhouse gases and small land occupation, geothermal fluids may contain dissolved minerals such as boron, mercury and arsenic, which are harmful to health, flora, fauna and could contaminate water (Martínez, 2021). For this reason, the law has established the requirement to have an environmental license, an authorization that requires compliance with measures for prevention, mitigation, correction, compensation and management of environmental effects (Law 99 of 1993).

The National Environmental Licensing Authority (ANLA) will have exclusive authority to grant or deny the respective environmental license. Although geothermal energy is not explicitly included in the list of activities that require an environmental license, this license is imperative and applicable when surface and subway water is involved, and when there is evidence of environmental impact due to the chemical components involved in a geothermal system.

Discussion

This study highlights the significant geothermal potential of Colombia, especially in volcanic areas and geothermally active regions such as the Nevado del Ruiz and the Paipa geothermal areas. These findings align with Colombia's geological features, characterized by the active Andean volcanic belt and the presence of numerous fault systems which facilitate the migration of hydrothermal fluids.

Globally, countries like the United States and Mexico have successfully harnessed their geothermal resources to meet a substantial portion of their energy demands. The United States, for example, has an installed capacity of 3700 MWe, significantly higher than what is currently projected for Colombia. This disparity underscores the untapped potential within Colombia, given its favorable geodynamic setting along the Pacific Ring of Fire—a region known for its extensive geothermal activity.

Our findings suggest that with an estimated potential of 1170 MWe, geothermal energy could contribute up to 7% of the national energy matrix. This would not only diversify the country's energy sources but also enhance sustainability, given the lower environmental impact of geothermal energy compared to fossil fuels. Such a shift could significantly advance Colombia's commitments to reducing greenhouse gas emissions and adhering to global climate change mitigation strategies.

Despite the promising potential, there are substantial hurdles to overcome. Technological and economic uncertainties are prevalent, primarily due to the nascent stage of geothermal exploration and exploitation in the region. Moreover, our estimates, while based on comprehensive data from the Colombian Geological Survey and various studies, carry a significant degree of uncertainty. This necessitates further detailed geophysical studies and exploratory drilling to reduce these uncertainties and accurately map the geothermal reservoirs.

The need for enhanced geological and geophysical data is evident from the variability in the temperature estimates and the geothermal gradients reported in our study. For instance, the discrepancies in temperature readings across different geothermal areas highlight the complexity of subterranean heat flow dynamics and the influence of local geological structures.

To capitalize on its geothermal resources, Colombia requires targeted policy interventions. These should include incentives for geothermal exploration and development, streamlined regulatory frameworks, and support for technological innovation in deep drilling and reservoir management. Furthermore, integrating geothermal energy into the national grid demands adjustments in infrastructure and regulatory practices to accommodate the variable output and location-specific nature of geothermal plants.

Conclusion

This study underscores the significant geothermal potential of Colombia, driven by its unique geological and tectonic characteristics. Key points from our analysis include:

1. **Geothermal Richness:** Colombia's Central Cordillera, home to volcanic landmarks such as Nevado del Ruiz and Azufral, harbors the majority of the country's geothermal resources. These volcanic systems are complemented by non-volcanic areas like the Paipa Geothermal Area, which together highlight diverse opportunities for both power and heat generation.
2. **Underutilized Capacity:** Our preliminary assessments suggest a potential of 1170 MWe, constituting about 7% of the national energy capacity. This reveals a significant but largely untapped resource that could substantially bolster Colombia's energy infrastructure.
3. **Need for Further Exploration:** Despite promising indicators, the geothermal potential is currently under-explored. Existing data, while extensive, is still marked by uncertainty requiring further refined geophysical studies and exploratory drilling. These efforts are crucial for uncovering 'hidden' geothermal systems and evaluating the feasibility of utilizing hot dry rock and sedimentary systems.
4. **Geological Complexity:** The geothermal reservoirs are likely situated within complex geological formations, including volcanosedimentary and pyroclastic rocks with primary permeability, as well as volcanic, metamorphic, and igneous rocks with secondary permeability. This complexity underscores the need for sophisticated mapping techniques to fully understand the geothermal framework.
5. **Policy and Economic Considerations:** To fully leverage this renewable resource, targeted policy support is essential. This includes financial incentives for exploration and development, streamlined regulatory frameworks, and investments in technology. Such measures will mitigate existing technological and economic uncertainties and align with governmental goals to enhance non-conventional renewable energy capacity by up to 1500 MWe in the near term.

In conclusion, while Colombia's geothermal energy sector holds promising potential for contributing to a sustainable and secure energy future, realizing this potential will require concerted efforts in exploration, technology development, and policy-making. By addressing these challenges, Colombia can enhance its energy security and sustainability, setting a precedent for renewable energy development in Latin America.

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