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Development of the Electrical Power Generation and Geothermal Exploration in Colombia: Country Update

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ABSTRACT

Since 2020 the most relevant issues for the development of geothermal in the two most essential aspects (power generation and exploration of the resources) are the definition of the geothermal potential, the energy generation from co-production from oil and gas, and the drilling of two geothermal gradient holes for resource validation in the Paipa geothermal area, among others.

Total geothermal power potential in Colombia was estimated in 1170.20 ± 31.39 MWe, with stored heat of 138.60 ± 1.84 EJ. This calculation is based on a volumetric method using hot springs in the whole Colombian territory. The greatest resources are associated with hydrothermal volcanic systems, but resources not associated with volcanic systems could be also of interest. The first geothermal power plant in the country started to operate in a pilot project of co-produced fluid from an oil and gas production in the Llanos Orientales sedimentary basin (oil producing region). It is a modular Organic Rankine Cycle (ORC) plant producing electrical power from water at temperatures below 100°C and generating 70 kWe net of baseload.

Between 20020 and 2022, the Colombian Geological Survey (Servicio Geológico Colombiano, SGC) worked on the exploration of five geothermal areas in Paipa, Santa Rosa, Azufral, Cerro Machín, San Diego and Nereidas-Botero Londoño, in the Cordillera Central. On the other hand, two geothermal gradient holes were drilled in the Paipa Geothermal Area for confirmation of the conceptual model and geological structure previously proposed by SGC. According to the direct measurements taken at the subsurface, the thermal anomaly was confirmed and the geothermal gradient was calculated at 180°C/km and 78°C/km with depths of 433 m and 454 m, respectively. Additionally, well logs (GR, SP, resistivity, among others) were taken with the aim of calculating heat flux.

Regarding the regulatory framework, the Ministry of Mines and Energy of Colombia (Ministerio de Minas y Energía, Minenergia) promted a series of working sessions with the various governmental stakeholders that directly impact the development of the geothermal industry in Colombia. These workshops were accompanied by experts of the Inter-American Development Bank (IDB) and as a result, Colombia issued Resolution 40302/2022, establishing the technical requirements for the registry of exploration and exploitation of geothermal resources for electrical energy generation.

Since 2021 and for the first time, Colombia was included in the GRÓ Geothermal Training Programme (GTP) under the auspices of UNESCO in Iceland. On the other hand, the Colombian Geothermal Association (Asociación Geótermica Colombiana, AGEOCOL), continues with the annual National Geothermal Meeting (Reunión Nacional de Geotermia, RENAG), gathering national and international experts from different topics about geothermal and its incidence in the Colombian scenario.

1. INTRODUCTION

1.1 Regulatory Legal Framework

Adding to the main laws and decrees that define the background for the existing legal frame, which are briefly described in Table 1, during the last two years was enacted the Law 2099 of 2021 with the purpose of modernize the current legislation and establish other provisions for the energy transition, and the revitalization of the energy market through the use, development, and promotion of non-conventional sources of energy for the economic reactivation of the country (Colombia, 2021). Specifically in the relation with the development of the geothermal energy, that law disposes that geothermal energy will be considered like a Non-conventional Renewable Energy Source (FNCER by its acronym in Spanish), the National Government will promote and encourage the exploration for knowing the resource potential in the whole territory, Minenergía will determine the requirements for the exploration and exploitation of the resource, the Ministry of Environment and Sustainable Development (MADS by its acronym in Spanish) will determine the environmental parameters that geothermal projects must comply with. It also establishes that Minenergía, or the entity that it designates, will create a geothermal registry where all those projects for geothermal exploration and exploitation for electricity generation will be registered, all projects being enforced to fill the geothermal registry, and in addition, Minenergía will establish the information to be provided by registrants (to increase knowledge about the country's subsoil and geothermal potential). Law 2009 also establish the official definition of geothermal resources as the heat contained in the interior of the earth, which is stored or included in the underground rocks and/or fluids of the subsoil.

In 2022, the Decree 1318 of 2022 (July 27, 2022) adjusted the Sole Regulation of the Administrative Sector of Mines and Energy in order to regulate articles 21 and 21-1 of Law 1715 of 2014 in relation to the development of activities oriented to generate electricity through geothermal resources, stablishing the general aspects and definitions on the exploration and exploitation of geothermal energy, of the knowledge of the geothermal resource, of the stages (i) Geothermal Resource Exploration, and (ii) Exploitation of the Geothermal Resource,, the Geothermal Registry, and other regulations like sanctions and the transitional regime for existing projects (Colombia, 2022). The last one was issued on August 5, 2022, and is the Resolution 40302 of 2022, from Minenergía, by which are stablished the technical requirements that will govern the Geothermal Registry and the permits for exploration and exploitation of geothermal resource for generating electricity purposes. (Colombia, 2022a).

Table 1: Previous regulations and background for the regulatory legal framework related to geothermal in Colombia.

Type of Regulation	*Number-Year*	*Description*
Decree	2811-1974	The Natural Renewable Resources and Protection of the Environment National Code: Defines the geothermal resources as the natural combination of water with an endogenous underground heat source, which result is the spontaneous production of hot water or vapors, and the endogenous underground heat sources from which it is possible to produce heat water or vapor by water injection. It also defines the geothermal resources as geothermal fluids above 80°C. According to this decree, the foreseen utilization of these resources can be for power generation, heat for heating, cooling, and industrial uses, obtaining fresh water and mineral extraction (Colombia, 1974).
Law	691-2001	Law for Rational and Efficient Use of the Energy (URE Law): Defines the geothermal energy as renewable energy source. This Law assigns to the Ministry of Mining and Energy, the responsibility to promote, organize, and ensure the development and monitoring of the programs of rational and efficient use of energy (Colombia, 2001).
Decree	4131-2011	Change the juridical nature and denomination of the former INGEOMINAS as a public entity to Servicio Geológico Colombiano (SGC), a scientific and technical institute. The SGC, institution of the national system of science and technology, is responsible of: carrying out basic and applied scientific research from subsoil resources potential, developing surveillance and monitoring of geological hazards, administering subsoil information, ensuring the safe management of nuclear and radioactive materials in the country, coordinating (and performing) nuclear research and handling and using of the nuclear reactor. Some of the functions related to geothermal are as follows: to perform the identification, inventory and characterization of the areas of greatest potential for natural subsoil resources, such as minerals, hydrocarbons, ground water and geothermal resources, in accordance with the policies defined by the Ministry of Mining and Energy or the National Government (Colombia, 2011).
Law	1665-2013	The Republic of Colombia approved the statute of the International Renewable Energy Agency (IRENA). This law includes as renewable energies, bio-energy, geothermal energy, hydraulic power, marine energy (tidal, wave power), oceanic thermal energy, solar energy, and wind power (Colombia, 2013).
Law	1715-2014	Regulates the integration of nonconventional renewable energy in the National Energy System. It declares the promotion, encouragement and incentive to the development of the activities of production and use of nonconventional sources of energy from renewable sources, mainly those of renewable character, as a public utility issue and a matter of social, public and national interest, essential to ensure the diversification of energy supply, the competitiveness of the Colombian economy, the environmental protection, the efficient use of energy and the preservation and conservation of renewable natural resources (Colombia, 2014).
Resolution	132-2014	Defined the methodology for determining the baseload feature of geothermal power plants. Issued by the Energy Regulation Commission (CREG, for its acronym in Spanish) (Colombia, 2014).
Decree	2143-2015	Defines the lineaments of the application of incentives established in the Law 1715 of 2014: Special deduction of the rent tax, exclusion of the VAT, exemption of duty taxes and accelerated depreciation regime. This decree also delegated to the Ministry of environment and sustainable development (and this in turn to the Environmental Licenses National Agency – ANLA for its acronym in Spanish-), the adequacy of procedures to get the Certification of environmental benefit and to the Mining and Energy Planning Unit (UPME for its acronym in Spanish) the definition of procedures and requirements for the registration of projects as non-conventional energy sources and the emission of the certification that endorses the papers of the project demanded for the exemption of tariff tax referred in the Law 1715 of 2014.
Decree	1543-2017	Regulates the Fund for Non-Conventional Energy and Energy Efficient Management, (FENOGE by its acronyms in Spanish) (Colombia, 2017). The resources that are going to feed the mentioned autonomous patrimony may be, among others, forty cents ($0.40) from the resources of the Financial Support Fund for the Energization of Non-Interconnected Areas (FAZNI), items that are assigned to it in the General Budget of the nation and other resources to transfer or provide the National Government, public entities, private entities, multilateral agencies and international grants and other resources to obtain or assigned to any title. The FENOGE, through the autonomous patrimony could subscribe contracts of agreements to fulfill its object. The destination of the resources of this fund is the partial or total funding of programs and projects aimed at the residential sector of strata 1, 2 and 3, both for the implementation of small-scale self-generation solutions and for efficiency improvement by promoting good practices, end-use energy equipment, adequacy of internal installations and architectural refurbishments. Also, these resources could be used for studies, energy audits, location

		adaptations, final disposal of replaced equipment and administration costs and auditing/supervision of programs and/or projects.
Law	1955-2019	National Development Plan 2018-2022 “Pact for Colombia, Pact for Equity” (Colombia, 2019). One of the pacts corresponds to the Pact for Mining-Energy Resources for Sustainable Growth and Expansion of Opportunities, whose objectives include promotion of the development and competitiveness of the mining energy industry based on clear and stable regulatory frames and consolidation of the geoscientific knowledge, role given to the SGC. Among the strategies and programs, this Plan includes the study of non-conventional energy sources and the definition of a regulatory frame for geothermal inside which the SGC will move forward studies to characterize the geothermal potential of the country and the UPME will carry out studies on comprehensive development and policy strategies around geothermal exploitation. Minenergía will establish the policies of allocation of areas, the contractual instruments to develop the activities of exploration and development of the resource and the entity entrusted to administer these resources. Likewise, working tables will be formed with the MADS, ANLA, CREG and SGC to establish the regulatory framework and environmental terms of reference that allow the proper use of this resource in the country, under strict compliance with the Law 1930 of 27 July 2018, corresponding to the conservation of paramos as strategic ecosystems of the country. The MADS already have advances on the draft of terms of references for geothermal exploration and exploitation, which were submitted to public consultation.

1.2 Power generation sector

The interest on generating electricity from geothermal is still maintained by generating companies located in the country. Since the beginning of geothermal exploration in the Nevado del Ruiz geothermal system (CHEC S.A. E.S.P., 1968), exploration studies and the drilling of a deep gradient well have been carried out (Monsalve, 1998). In 2008, ISAGEN expresses its interest in reactivating the exploration and possible exploitation of the resource for this same geothermal area. Towards the southwest of the country, for the Tufiño – Chiles – Cerro Negro binational system, a joint exploration agreement was signed by ISAGEN in Colombia and the Corporación Eléctrica del Ecuador (CELEC) in Ecuador thorough consulting services (Mejía et al., 2014).

Recently, in the case of the Valle de Nereidas geothermal project of Nevado del Ruiz, the surface geoscientific studies have been completed by CHEC Grupo EPM, and take into account the slim hole well drilled in 1997; regulatory and environmental permits are held for verification drilling, and complementary research is being carried out in the financial and technical fields to develop deep exploration. In the same way, theoretical developments for using the resource for electrical generation and direct uses are advancing involving the local academy. Regarding the environmental licenses aspects for the project, through the Resolution No. 2019-0491 from the environmental authority (CORPOCALDAS) formalized that the ISAGEN withdrew the request for environmental license for the Macizo del Ruiz geothermal project (Colombia, 2019). CHEC presented to CORPOCALDAS the request for Modification of the Environmental License in the exploratory stage (file No. 1487), and the process is awaiting a response, since the subtraction request process of forest reserve of Law 2nd from 1959. has not been solved.

Nowadays, Parex Resources Co. with the implementation of the first 100 kW geothermal plant in a sedimentary environment for the use of the resource (explained below), has begun the path of use, motivating great interest of operators in the hydrocarbon sector to generate electricity in oil fields. On the other hand, Ecopetrol, the Colombian Public Oil Company, announced the inclusion of a geothermal development pilot project for generating power from low enthalpy resources (Ecopetrol, 2013). Thus, from the development strategy disclosed by Ecopetrol for the diversification of the energy portfolio and pointing towards the energy transition (Ecopetrol, 2014), the Colombian oil company has carried out assessment studies of sedimentary basins (Gonzalez-Penagos et al. al., 2021; López-Ramos et al., 2021; López-Ramos et al., 2022).

1.3 Geothermal Education and Community

By taking advantage of the consolidation of a stronger geothermal community and involving to a greater extent the interactions between government entities such as the SGC, academia (different universities such as the Universidad de Medellín, the Universidad Nacional de Colombia in Bogotá and Medellín, the Universidad de Los Andes and others), the private companies that support and promote geothermal in the territory (such as Dewhurst Group), and the association of all these sectors in the Colombian Geothermal Association (AGEOCOL), the national government through Minenergía promoted the realization of the 7th Geothermal Congress for Latin America & the Caribbean (Newenergy, 2020), co-hosted by the Inter-American Development Bank (IDB) and the World Bank’s Energy Sector Management Assistance Program (ESMAP), that took place virtually on September 15-17, 2020 and was followed by two workshops hosted by Geothermal Development Facility for Latin America (GDF), the German government development bank (KFW) and IDB.

In turn, AGEOCOL has increased its national and international visibility in the last three years, playing a key role in establishing lines of communication between communities, government, industry, and academia. Several events included the National Geothermal Congress (RENAG) have been organized jointly with the SGC, the Government of Boyacá Department, the Minenergía, the Ministry of Environment, and universities. At the same time, collaboration with other professional associations, such as EAGE (European Association of Geoscientists and Engineers), ACH (Colombian Association of Hydrogeologists), ACGGP (Colombian Association of Petroleum Geologists and Geophysicists), the SCG (Colombian Society of Geology) and the Ecuatorian Geothermal Association, led to the organization of scientific events showing a growing interest in geothermal development in the country and highlighting the multidisciplinary feature of geothermal energy.

Within the framework of UNESCO Project 636 (Geothermal Resources for Energy Transition), Geotheroom, a free access virtual platform, has promoted the dissemination of geothermal knowledge in each of the 10 countries involved in the project. Colombia was the host during the first month (Gutierrez et al., 2022).

In turn, advances have been made in exploration research, conceptual modeling and numerical modeling (e.g., Gómez, 2020; Matiz-León, 2021; Laverde, 2022) that contribute to the generation of knowledge of the resources in the Colombian territory.

1.4 Power Matrix in Colombia

Since the latest report in 2018 from UPME on generation variables and the Colombian electricity market (UPME, 2018), the technologies participating in the power matrix are: hydraulic (69.18%), coal (9.75%), gas (9.61%), ACPM (7%), fuel oil (1.74%), mixed gas – JET-A1 (1.49 %), JET-A1 (0.25%), wind (0.1%), bagasse (0.81%), solar (photovoltaic) (0.06%), biogas (0.02%). As shown in Appendix, Table 3, the total installed capacity in operation in December 2019, is 17,658 MWe and the gross energy production 67,709 GWh/yr. The projection to installed capacity to 2020 is 18,100 MWe and gross energy production of 71,163 GWh/yr. Also, for the country for first time it is reported the geothermal pilot power plant in Llanos Orientales sedimentary basin, with 0.1 kWe in capacity.

According to UPME (2022), as part of the planning scenarios of the national electricity generation matrix, a first study and approach was developed on the impact and convenience of geothermal generation. It didn't consider possible contributions to secondary services of the electricity system that could be solved by geothermal, and the consequent additional cash flow, since they are not yet regulated or developed in the national electricity market. The study included the effects of i) the incentives of Law 1715 and the Reliability Charge (CXC) on the investor's cash flow (investor's perspective); and ii) the impact on the cost of generation to meet the electricity demand (demand side view). The two simultaneous approaches, from the point of view of the developer and the demand side, consider a financial and economic valuation of the use of geothermal energy as a new source of generation in the country's electricity matrix.

2. GEOLOGICAL BACKGROUND

2.1 Colombia's tectonic frame

Colombia is located in the northwestern corner of South America, belonging to the Pacific Ring Fire. Its tectonic framework is influenced by the Caribbean and Nazca oceanic plates and the South American continental plate, with ocean ridges, oceanic trenches, subduction zones, accretionary prisms, deformation belts, transform faults, and several other structural elements as defined by Gómez et al. (2007, 2015) and Gómez & Montes (2020) based on findings of numerous researchers (Figure 1A).

The interaction between plates results in a significant variation of the stress tensor that on its turn mark out separate seismotectonic provinces. An important consequence of this phenomenon is the movement of the North Andean block towards the north-northeast. The latter block is bounded on the East by the fault system that runs from Guayaquil, in Ecuador, to the foothills of the eastern Cordillera following the Boconó Fault in Venezuela. In the north, the movement of the North Andean block can be recognized offshore by the Caribbean Deformed Belt, a later and more outer compressional phase of the accretion prism that includes the Sinú and San Jacinto deformed belts. Said deformation involves sequences accumulated on top of the Caribbean Province's igneous basement (Figure 1), both before and after its accretion. The north Andean Block includes smaller triangular blocks bounded by all their sides by wrench faults, such as the Maracaibo Block; inside of which the Santa Marta Block is noteworthy on the northeastern corner. This complex pattern of plate and blocks interaction results in seismotectonics regimes with transpressive and transtensive deformations playing an important role (Gómez et al., 2007).

Based on the analysis of focal mechanisms and GPS measurements, Arcila & Muñoz–Martín (2020) defined the stress regime in Colombia as a seismotectonic model for the NW corner of South America, characterized by the displacement towards the SE of the Caribbean Plate, the convergence of the Andean, Coiba, and Panamá Blocks in NW Colombia, and the W–E convergence of the Nazca and South American Plates (Gómez et al.,2020). In Colombia, the highest strain rate values are located in the south, where the Eastern Cordillera detaches from the Western and Central Cordilleras. Other zones with significant strain rates are observed in the area bordering Ecuador, in northwestern and central Colombia, and south of Bogotá. In northeastern Colombia and Venezuela, lowest strain rates are observed, and the extensional–type regime dominates (Arcila & Muñoz–Martín, 2020) (Figure 1B).

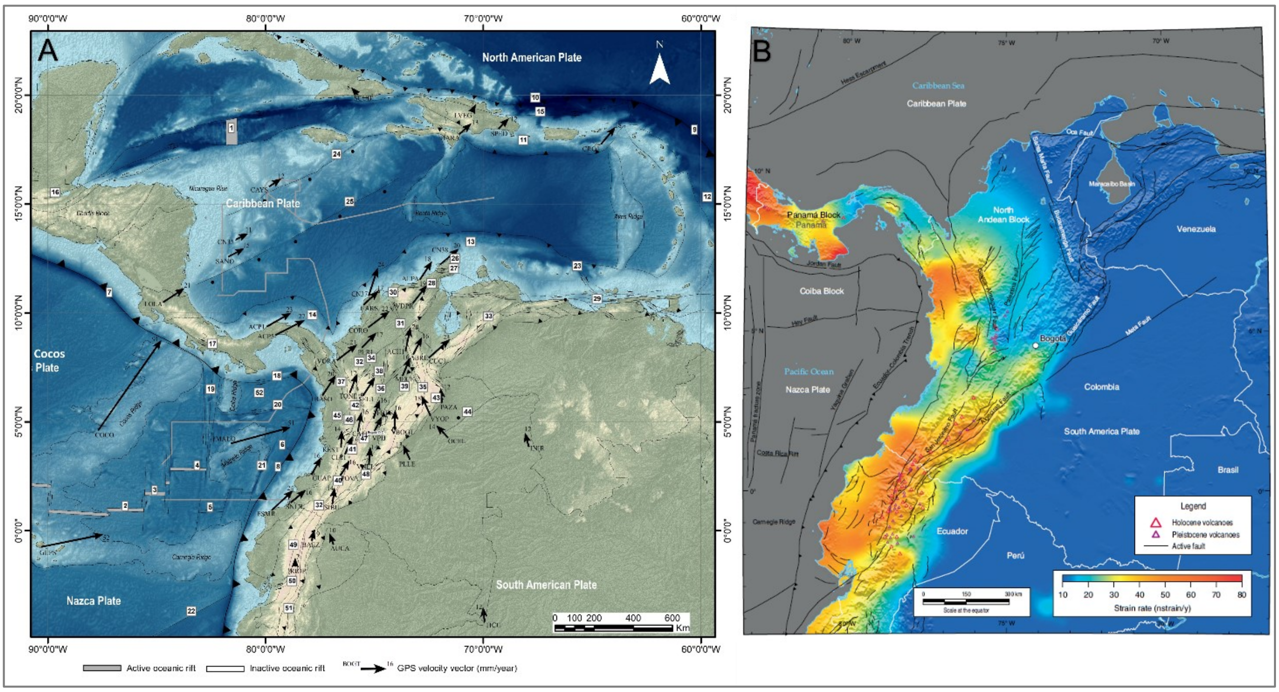


Figure 1: A) Tectonic scheme of Northern South America and the Caribbean (taken and modified from Gómez & Montes, 2020). Active Mid-ocean Ridges: (1) Cayman, (2) Galapagos, (3) Ecuador) y (4) Costa Rica. Inactive Mid-ocean Ridges: (5) Malpelo, (6) Buenaventura. Oceanic trenches, active subduction zones: (7) Middle Aerican Zone, (8) Colombo-Ecuadorian Zone, (9) Caribbean. Oceanic trenches, inactive subduction zones: (10) Puerto Rico. Accretionary prisms-deformed belts: (11) Los Muertos, (12) Lesser Antilles, (13) Caribbean (14) Panama. Transformational fault zones: (15) North-East (16) Motagua-Swan, (17) Celmira-Ballena, (18) Jordan, (19) Panama, (20) Hey, (21) Yaquina, (22) Grijalva y (23) Los Roques. Oceanic Normal Faults: (24) Pedro Bank (25) Hess. Main continental plate faults: (26) Simarúa, (27) Cuisa, (28) Oca, (29) El Pilar, (30) Santa Marta, (31) Algarrobbo, (32) Cauca-Almaguer, (33) Boconó, (34) Espíritu Santo, (35) Bucaramanga, (36) Palestina, (37) Murindó, (38) Otú, (39) La Salina, (40) Silvia-Pijao, (41) San Jerónimo, (42) Mistrató, (43) Guaicáramo (44) Meta, (45) Istmina Fault Zone, (46) Garrapatas, (47) Ibagué, (48) Algeciras, (49) Pallatanga-Pujili, (50) Peltetec, (51) Cosanga; independent lithospheric block: (52) Coiba Microplate. Vector values (mm/year) correspond to relative plate movements. B) Map of strain rates in Colombia (second invariant of the strain tensor) (Taken from Arcila & Muñoz–Martín, 2020).

2.2 Tectonostratigraphic Terranes in Colombia

The concept of terranes has been used in Colombia since 1983, particularly in two regional studies that suggested that the northwestern corner of South America consists of a mosaic of terranes, which would have been accreted into the Amazonian Craton during several geological periods (Restrepo & Toussaint, 2020). Recompilation of lithostratigraphic and tectonic data was conducted, at the beginning in 1980's by the SGC, and then by other authors, who have renamed or regrouped geological provinces (or terranes) in the last years.

The basement of the Earth crust in the Colombian territory consists of two contrasting types of rocks that are separated by the Cauca-Almaguer Fault (Figure 2A), a structure that runs in a N-S direction along the western flank of the Andean Central Cordillera: to the east of this fault, it is made of Proterozoic metamorphic rocks, mainly sialic, whereas to the west of the fault it consists on Upper Cretaceous igneous, mainly volcanic rocks of simatic composition. A similar role of separation between sialic and simatic basements is played by the Guachaca and the Simarua faults at the Sierra Nevada de Santa Marta and at the Guajira Peninsula, respectively. The separation between these different types of basements is interpreted as a result of the accretion of oceanic lithosphere fragments to the continental active margin of South America during the Eocene (Gómez et al., 2007). Twelve terranes are proposed by Restrepo & Toussaint (2020) based on U-Pb zircon dating to reassess the ages of several metamorphic units that were previously determined, which changed the characteristics of the terranes. There are also several research studies that located the terranes of Colombia within the geodynamic framework of the relationships among the Amazonian Craton, Laurentia, Pangea, proto–Caribbean, Caribbean, and other terranes in the region (Figure 2B).

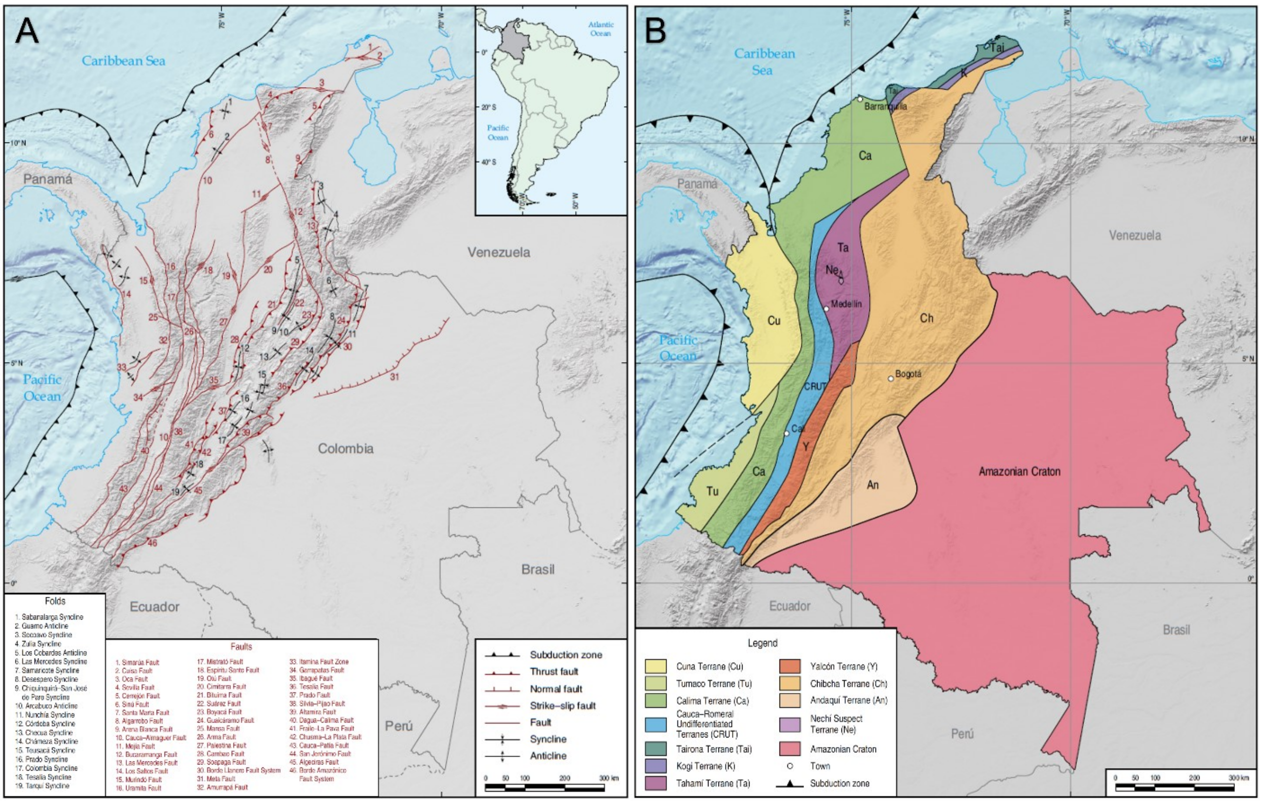


Figure 2: A) Main geological tectonic structures of Colombia (taken from Gómez et al., 2020). B) Tectonostratigraphic Terranes in Colombia (taken from Restrepo & Toussaint, 2020).

2.3 Geology of Colombia by regions

In Colombia, six natural regions are distinguished: Andean, Caribbean, Pacific, Orinoquia, Amazonian, and Insular. The geological setting of Colombia is diverse, with rocks of multiple types and ages, spanning the Paleoproterozoic to Holocene, as well as geological structures of diverse type and origin, reflecting a complex and different geological history, controlled by folds and faults (Figure 2A). The description of these natural regions is taken from Gómez et al. (2020) (Figure 3).

The Andean region corresponds to the great mountain belt of the Andes, which in Colombia is divided into the Western, Central, and Eastern Cordilleras, separated by the inter–Andean valleys of the Cauca and Magdalena Rivers that contain 23 marine and continental sedimentary basins.

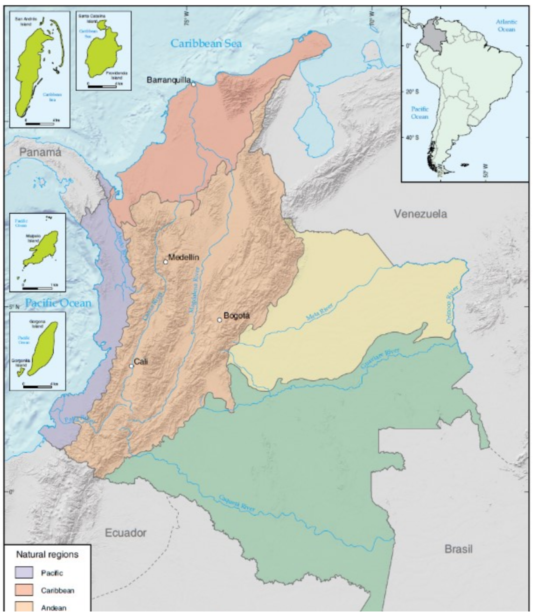


Figure 3: Map of the natural regions of Colombia (taken from Gómez et al., 2020).

The Western Cordillera is constituted by Cretaceous sedimentary, gabbroic, and basaltic rocks of the Caribbean-Colombian oceanic plateau, accreted to the western margin of Colombia during the Late Cretaceous to Paleogene; in the south sector by Paleogene plutonic and volcanoclastic rocks, and Neogene and Quaternary deposits of volcanic eruptions (some of the volcanoes are active); in the north by Miocene basalts and Pliocene volcanoclastic rocks and Neogene intrusions. The Central Cordillera has a low-grade polymetamorphic Triassic basement (last event recorded in Jurassic), is intruded by Permian, Mesozoic, and some Cenozoic plutons generated by the subduction of the Nazca Plate under South American Plate. The Mesozoic intrusions are linked to Jurassic volcanoclastic sequences in the eastern flank, while in the western flank Cretaceous volcanoclastic and low-grade metamorphic rocks are found; also Mesoproterozoic – Neoproterozoic high-grade metamorphic rocks are exposed. The Neogene – Quaternary volcanoes (some of them are active) are located in the central and northern segments towards the summit of this mountain range. The Cauca-Almaguer and Silvia-Pijao Faults exposed in the western foothills, are the tectonic limits of the Colombian continental terranes (Figure 2A).

The Eastern Cordillera is mainly composed by a basement of Mesoproterozoic - Neoproterozoic high-grade metamorphic rocks, and Ordovician low–grade metamorphic rocks, Paleozoic (Cambrian – Ordovician and Devonian) sedimentary sequences (some of them fossiliferous), and a thick succession of Cretaceous marine and Cenozoic continental sedimentary rocks that were deformed during the Andean Orogeny (Gómez et al., 2020), and volcanic activity produced pyroclastic deposits and dome complexes in the Miocene and Pleistocene (Alfaro et al., 2020a). South of the eastern flank, the Borde Amazónico Fault System and the Algeciras Fault mark the boundary with the Caguán–Putumayo Basin. To the north, the Borde Llanero Fault System serves as a boundary with the Llanos Orientales Basin (Figure 2A).

The Caribbean Region is between the Caribbean Sea and the northern foothills of the Andes, and it is characterized from flat to undulating relief and some low–elevation hills mainly, and cliffs where stands out the Sierra Nevada de Santa Marta (SNSM) with a peak over 5700 m.a.s.l. (meters above sea level) and serranías Jarara, Macuira, Carpintero, Cocinas, Abibe, Ayapel, Darién and San Jerónimo. The first three of them are composed of Triassic and Cretaceous low–grade metamorphic assemblages, Triassic and Cretaceous marine and Jurassic continental sedimentary rocks; the others are formed by Paleogene sedimentary rocks surrounded by Neogene sedimentary formations and Quaternary alluvial deposits. Jurassic plutons conform most of the SNS, and Mesoproterozoic high–grade metamorphic rocks are exposed.

The Pacific Region is made up by the coastal plains of western Colombia and some mountain ranges, such as the Serranía del Baudó. This region is a narrow fringe that extends between the Pacific Ocean and the foothills of the Western Cordillera. The central and southern parts are dominated by low alluvial and flooded coasts interrupted by short cliffs (González et al., 1998 in Gómez et al., 2020). Cretaceous basalts and Paleogene volcanoclastic sequences are found in the Serranía del Baudó, derived from an island arc accreted to the continental margin. In the other areas of the Pacific region, there are Paleogene and Neogene sedimentary units, and alluvial and coastal deposits of the Quaternary.

The plains of the northern sector of eastern Colombia form Orinoquia, while the Amazonian region constitutes the jungle region of southeastern Colombia, where the Serranía de Chiribiquete stands out. These two regions are the largest in the country, the least inhabited and the least developed. Both regions are bounded to the west by the foothills of the Eastern Cordillera, while to the east, they extend up to the border of Brazil and Venezuela. In the Orinoquia and Amazonian regions, the basement is formed by Paleoproterozoic and Mesoproterozoic medium– and low–grade metamorphic rocks, respectively, with Paleoproterozoic and Mesoproterozoic granitic intrusions and Neoproterozoic volcaniclastic rocks. This igneous–metamorphic assemblage is part of the western sector of the Guiana Shield and is covered by Neoproterozoic (Ediacaran and Cryogenian), Cambrian – Ordovician, and Ordovician marine sedimentary rocks with fossiliferous levels, exposed in mountainous areas such as Serranias de Chiribiquete and La Lindosa, as it was reported in borehole cores (Dueñas–Jiménez & Montalvo–Jónsson, 2020; Dueñas– Jiménez et al., 2020 in Gómez et al., 2020). Cretaceous marine and Cenozoic continental sedimentary rocks cover, in most of these regions, the oldest rocks.

The insular region in the Caribbean Sea comprises the archipelago of San Andrés and Providencia and several cays, while in the Pacific Ocean comprise the Gorgona, Gorgonilla, and Malpelo Islands. The archipelago consists of a platform of carbonates and reefs that cover deep volcanic cones. The atolls, islands, and coral banks to the south of the archipelago were formed around volcanoes in the early Cenozoic; that subsidence and settlement of carbonates over shallow areas and in the summits of the volcanoes during the Cenozoic and the Quaternary, facilitated their formation. To the south of Providencia, some intercalations of Miocene reef limestone between volcanic series and Quaternary marine sedimentary deposits are located (Geister & Díaz, 2007 in Gómez et al., 2020).

The Colombian insular region in the Pacific Ocean is made up of the Gorgona and Gorgonilla Islands, the Malpelo Islet, and El Viudo and El Horno rocky promontories (Díaz et al., 2001 in Gómez et al., 2020). More than 80% of the surface of the two main islands is constituted by igneous rocks, including basal peridotites and gabbros covered by basaltic lavas with komatiite flows (Díaz et al., 2001; Echeverría, 1982; Gansser et al., 1979; Parada & Tchegliakova, 1990 in Gómez et al., 2020). The remaining 15% corresponds to Upper Eocene to Upper Miocene sedimentary rocks and Quaternary sedimentary deposits that conform beaches, small deltas of surface currents, and some terraces. Reef zones surround the southern part of the main island (Díaz et al., 2001 in Gómez et al., 2020). Malpelo is a cliff formed entirely by basic volcanic rocks and in Gorgonilla, Bermúdez et al. (2016, 2019 in Gómez et al., 2020) report the boundary of the Cretaceous – Paleogene with the presence of tektites from the Chicxulub impact.

3. GEOTHERMAL EXPLORATION

Since 2020, the SGC has carried out exploration and research activities on geothermal resources associated to volcanic systems (hydrothermal systems) and sedimentary basins (conductive systems) in throughout the Colombian territory. In the case of hydrothermal systems, exploration has carried out in the geothermal areas of Paipa, Santa Rosa, Azufral and Cerro Machín, San Diego, and recently restarted in the Nereidas - Botero Londoño. In the latter, the CHEC - EPM company, has advanced in its own surface studies, and has the regulatory and environmental permits to carry out exploratory drilling. Additionally, they are advancing in the research of the geothermal area with academic support, for a possible future use for power generation or direct uses.

The SGC has begun regional reconnaissance of hidden and volcanic systems using the Play Fairway Analysis methodology (e.g., Faulds et al., 2015) for the Azufral Geothermal Area (nowadays in progress), with support from Great Basin Center for Geothermal Energy (GBCGE) at the University of Nevada, Reno. Regarding the regional exploration of heat flow, the SGC currently is giving continuity to its investigation of heat flow in sedimentary basins using information from the oil industry (Alfaro et al., 2008), and is implementing methodologies to estimate surface temperature models (Matiz-León, et al., 2020). As technical support to comply with the delivery of information required in Annexes 1 and 2 of Resolution 40302 of 2022, the SGC published the Cartographic Standard for Geothermal Information; further information can be consulted in Matiz-León et al. (2022).

3.1 Paipa Geothermal Area

As was mentioned in the past Colombia Country Update (Alfaro & Rodríguez-Rodríguez, 2020), two geothermal gradient boreholes had been planned, and actually drilled in 2020 and 2021 in Paipa Geothermal Area. With them, the gradient anomaly proposed in the descriptive conceptual model (Alfaro et al., 2020b) was confirmed. Preliminary results are presented in this paper, but for further information refer to Rueda-Gutiérrez et al. (2023) paper.

Both boreholes are located in the municipality of Paipa. The first, called AGT-01, has a depth of 433 m, and the second, AGT-02, has a depth of 454 m. Results obtained in AGT-01 are: i) the recovered lithology corresponds to claystone and siltstone (0 m to 156 m), very fine-grained sandstones and quartz siltstones with hydrocarbon impregnations (156 m to 266 m), siltstones and black mudstones (266 m to 338 m) and siliceous siltstones and silty sandstones (338 m to 433 m). ii) The thermal gradient was calculated in 180 °C/km. iii) Eleven possible aquifers were intercepted. The aquifer levels at 230 m and 340 m were characterized as chemically potable.

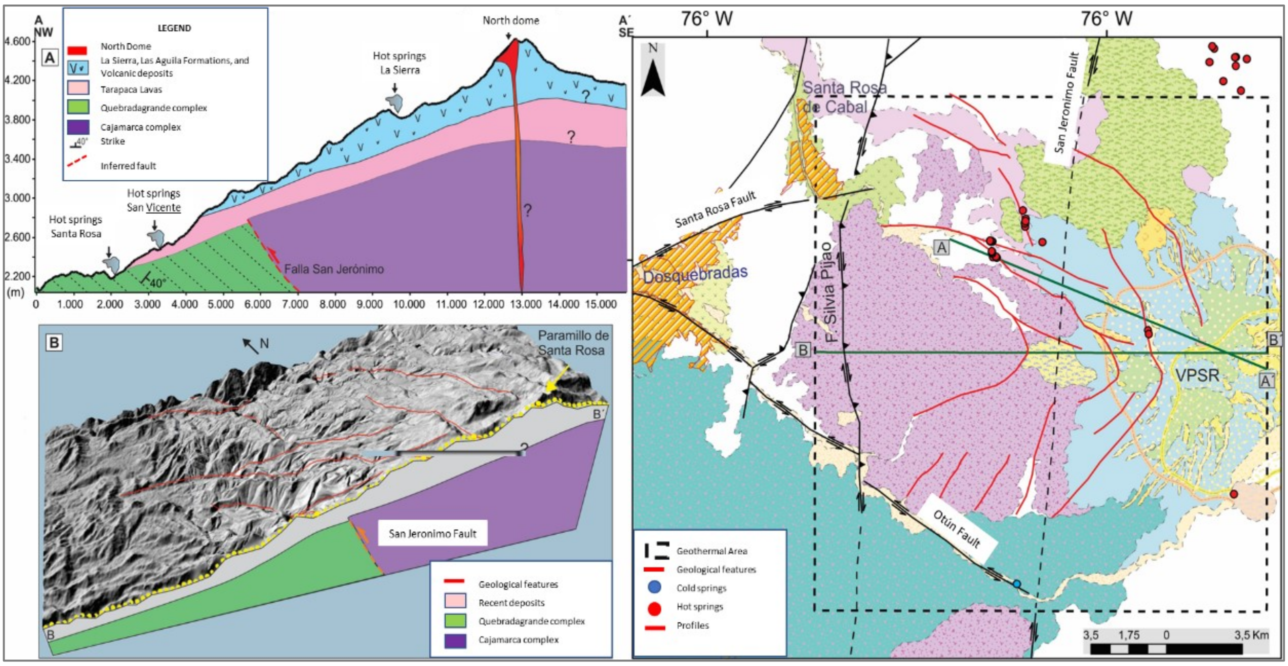
Results obtained in AGT-02 are: i) the recovered lithology corresponds to clay and sandy soil corresponding to an alluvial deposit (0 m to 25 m), sandstone and gravel in a sandy matrix (25 m to 62 m), claystone (62 m to 95 m), siliceous siltstones and claystone and limestone (95 m to 449 m) and siliceous siltstones (449 m to 454 m). ii) The thermal gradient was calculated in 78°C/km. iii) Six possible aquifers were intercepted. Iv) Nineteen coal bends were intercepted.

The preliminary results were presented to government and environmental entities, and after drilling and measurements the intervened areas were restored with the planting and growth of the vegetal cover. Thus, the project was successfully closed from the technical, social, and environmental perspective, and with the approval of the community for the results obtained.

3.2 Santa Rosa Geothermal Area

Santa Rosa Geothermal Area was presented as a new exploration area for the SGC by Alfaro & Rodriguez-Rodriguez (2020). Evidence of the geothermal potential, geological and geochemical characteristics, and the first results of the geological exploration of the Santa Rosa Geothermal Area were presented by Casallas et al. (2020). The analysis and interpretation of the structural geology and hydrothermal alterations of this geothermal area were carried out by Rodríguez & Rueda-Gutiérrez (2020). In addition, geophysics and geochemical works are currently being developed by the SGC in order to: i) make an underground model of the resistive structure from magnetotelluric soundings and magnetic anomalies, ii) update the chemical and isotopic composition of the waters of thermal and iii) characterize the chemical and isotopic composition of gases discharged by hot springs, all of the above with the main objective of creating a descriptive conceptual model in the next years.

This geothermal area is located in the western flank of Paramillo de Santa Rosa stratovolcano, in the Central Cordillera of Colombia. It is compounded by Paleozoic-Mesozoic metamorphic rocks, Cretaceous metavolcanic-metasedimentary rocks and Quaternary volcanic deposits. The integration of the morpho structural analysis with the data taken in the field shows that the area is controlled by structures in the NS-NNE, NE, NW and E-W direction. The first structure is the most regional system and is associated with the Romeral Fault System, belonging to the San Jerónimo fault, whose trace does not cross the volcanic building, and the Silvia Pijao fault, with evidence of displacements in recent deposits. The most notorious traces of structures in the NE and NW directions were associated with the Santa Rosa and Otún faults, their kinematic was proposed as dextral and sinestral type, respectively. The upwelling of the hot springs in the area has been associated by previous studies with faults in a NW direction. However, displacement was not evidenced during the field work. E-W structures are local and have kinematic compatibility with more regional structures. On the other hand, several travertine deposits are exposed in the discharge areas of the hot springs, while in the sulfur zones and some isolated sectors, an intense hydrothermal alteration is observed (advanced argillic, phyllic and propylitic).



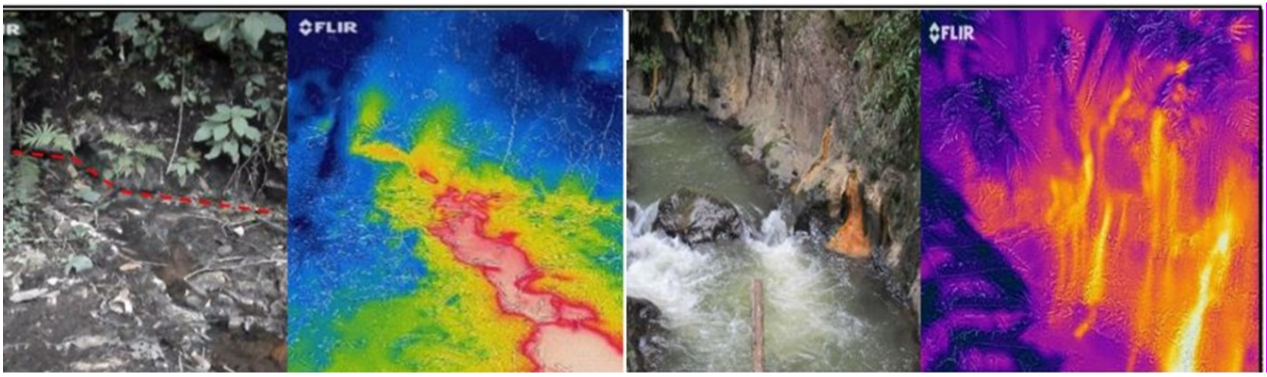


Figure 4: Geological structural model of the Santa Rosa Geothermal Area (above). Thermal photographs of hydrothermal alteration zones (bellow) (Taken and modified from Rodríguez & Rueda-Gutiérrez (2020).

3.3 Azufral Geothermal Area

Azufral Geothermal Area was recognized as a priority area given its recent and continuous volcanic activity, a complete magmatic evolution, the presence of craters of phreatic explosions inside of the caldera, existence of fumarolic activity and hydrothermal manifestations, as well as a substrate made up of Tertiary vulcanites and evidence of a high temperature aquifer. A potential reservoir of about 250°C was estimated, between the phyllic-propylitic zone and a cap rock made up of phyllic and argillic hydrothermal zones (OLADE et al., 1982 in Alfaro et al., 2022).

A preliminary conceptual model of the Azufral Geothermal Area was presented by Alfaro et al. (2013) and in past versions of the World Geothermal Congress (Alfaro et al., 2015; Alfaro & Rodríguez-Rodríguez, 2020). Currently, the SGC is proposing an update descriptive conceptual model based on new data. Parallel to the research work, the scientific divulgation of the studies has been carried out in various sectors of the community belonging to the Azufral area, e.g., indigenous reserves, government entities, and universities.

As part of the geothermal exploration that the SGC carries out throughout the national territory, the Play Fairway Analysis methodology (PFA) has been implemented in the Azufral Geothermal Area, as a pilot zone with the support of the Great Basin Center for Geothermal Energy (GBCGE) at the University of Nevada, Reno (Olvera-García et al., 2023).

3.4 Cerro Machín Geothermal Area

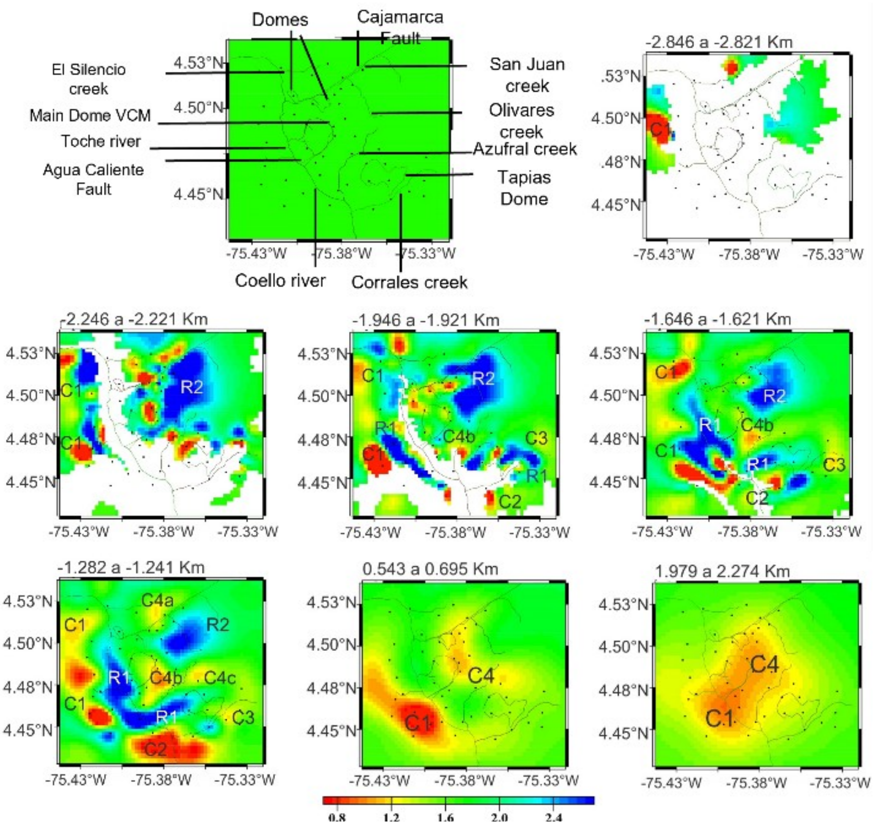


Figure 5: Plan view 3-D magnetotelluric model of Cerro Machín Geothermal Area. Letters R means resistive structures, letters C means conductive structures (taken and modified from Herrera, 2020).

As part of advancing knowledge of the Cerro Machín Geothermal Area, geochemical studies are being developed, and a 3D resistivity model of the Cerro Machín geothermal area was obtained from the inversion of 49 magnetotelluric soundings by the SGC.

Main findings about 3D resistivity model are presented in this paper, and for further information refer to Herrera (2020). Four geophysical lineaments were proposed based on the resistive contrasts of the magnetotelluric model, which seem to control the occurrence of the springs and domes. From the resistivity model several shallow conductive anomalies (depth <~ 800 m) were identified (Figure 5); these structures could represent an argillic alteration zone, rich in clays, which would serve as the caprock of the geothermal system. A conductive structure, located below ~ 2000 m deep, on the west of the Toche River, has been interpreted as a possible high-temperature magmatic body. Series of lineaments, which seem to control the occurrence on the thermal springs and would serve as paths for thermal and/or magmatic fluids circulation. Several shallow conductive structures, which could act as a caprock, were identified. The heat source of the geothermal system would be the high temperature magmatic body that fed the Machin Volcano.

3.5 San Diego Geothermal Area

San Diego is the most northern Geothermal Area located in the Central Cordillera. It was defined from the location of hot springs reported in the national inventory of hydrothermal manifestations (Alfaro et al., 2002). It is compounded by a low-relief volcanic crater (San Diego Maar), a volcano (El Escondido) and an intrusive body (Puente Linda) (Alfaro & Rodriguez-Rodríguez, 2020). From the geometries of the 2D geological data and potential field grids, a litho-constrained stochastic geophysical inversion, a 3D lithological model, a 3D density model (Figure 6), and a 3D susceptibility model, were published for the San Diego Maar Area by the SGC. Further information can be consulted in Matiz-León & Rueda-Gutiérrez (2021).

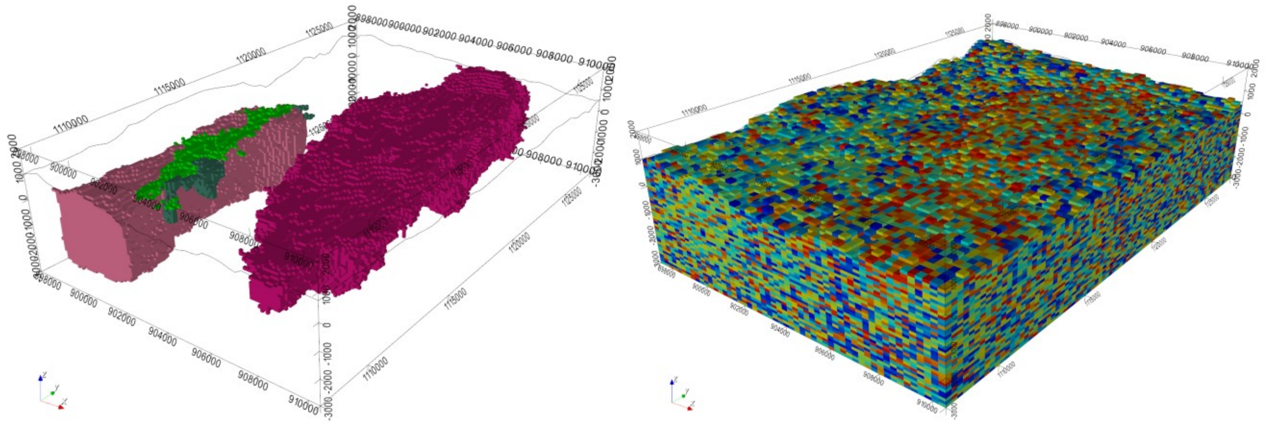


Figure 6: 3D geological model (left) and density 3D model (right) of the San Diego Geothermal Area (in the San Diego Maar area) (Matiz-León & Rueda-Gutiérrez, 2021).

3.6 Geothermal Evaluation in Sedimentary Basins

Large volumes of surface and subsurface data acquired by the hydrocarbon industry have been used for assessing the geothermal potential of deep aquifers in the Llanos Basin by López-Ramos et al. (2022). According to these authors, the integrated analysis of geothermal play elements allows them to define three regional plays as follows: Play A, characterized by naturally fractured reservoirs, in crystalline basement rocks (Paleozoic), with temperatures above 150 ºC, semi-confined aquifers. Play B, composed by Mesozoic quartz sandstone reservoirs, with primary porosity greater than 10%, temperatures between 75 ºC to 150 ºC, semi-confined aquifers, near to high hydraulic head zones with 500 m difference ranges in the regional piezometric surface. Play C, composed of Mesozoic quartz sandstones, high primary porosity, temperatures below 100 ºC, confined aquifers. Available well and Oil and Gas production data suggests that Play A is speculative, Play B is hypothetical, and Play C is known. Further information can be consulted in López-Ramos et al. (2022).

4. GEOTHERMAL POTENTIAL

The geothermal potential of Colombia (Alfaro et al., 2021), was estimated from the chemical geothermometers of the hydrothermal systems located in the volcanic complexes of the Central Cordillera of the Colombian Andes. It was used the volumetric method, by considering the dimensions assigned to the hot springs registered in the national territory, as individual or grouped hot springs (cluster), assumed as possible reservoirs (Alfaro et al., 2021). The 324 hot springs recorded in the national territory were grouped into a total of 165 clusters, distributed in 21 preliminary geothermal areas, associated with volcanic systems and 16 Departments, located outside of the preliminary delimited geothermal areas (Figure 7) (Alfaro et al., 2021).

The calculation was made for two scenarios: optimistic and pessimistic. The first one has into account an expected area of 2 km^2, thickness of 1.5 km, and a reference temperature based on the mean surface temperature calculated according to the altitude, assuming a maximum recovery factor of 0.25. For the second one (pessimistic), the area was reduced to 0.785 km^2, the thickness to 1 km, and a reference temperature of the condenser (40°C), using a maximum recovery factor of 0.2 (Alfaro et al., 2021).

In the optimistic scenario, the total electrical potential of the 21 geothermal areas distributed in 80 clusters was calculated at 1170.20 ± 31.39 MWe, with a stored heat of 138.60 ± 1.84 EJ (Table 2). The greatest resources are found in the geothermal areas of San Diego, Santa Rosa, Cerro Machín and Nereidas-Botero Londoño, with electrical potential of 141.85, 137.24, 129.94 and 100.72 MWe, respectively. These all are located in the northern block of the Central Cordillera (Alfaro et al., 2021). To the south are the areas of Caldera del Paletará and Azufral, with electrical potential of 117.96 MWe and 81.9 MWe, respectively. For the pessimistic scenario for which 94 clusters were defined, a mean electric potential of 263.6 MWe and a mean stored heat of 35.56 EJ, were calculated (Alfaro et al., 2021).

In the 16 Departments with 85 clusters of hot springs for the optimistic scenario, the total potential and heat were 24.95 ± 2.15 MWe and 49.56 ± 0.75 EJ, respectively (Table 2). The greatest potential corresponds to the Huila Department in 11 clusters, with 12.09 MWe of electrical power and 7.08 EJ of stored heat (Alfaro et al., 2021). Cundinamarca Department has the largest number of hot springs (50) grouped into 24 clusters, with the greatest amount of heat (15.75 EJ) and a power of 1.99 MWe. In the pessimistic scenario, the total calculated mean electrical power and mean stored heat were 5.73 MWe and 8.76 EJ, respectively (Alfaro et al., 2021).

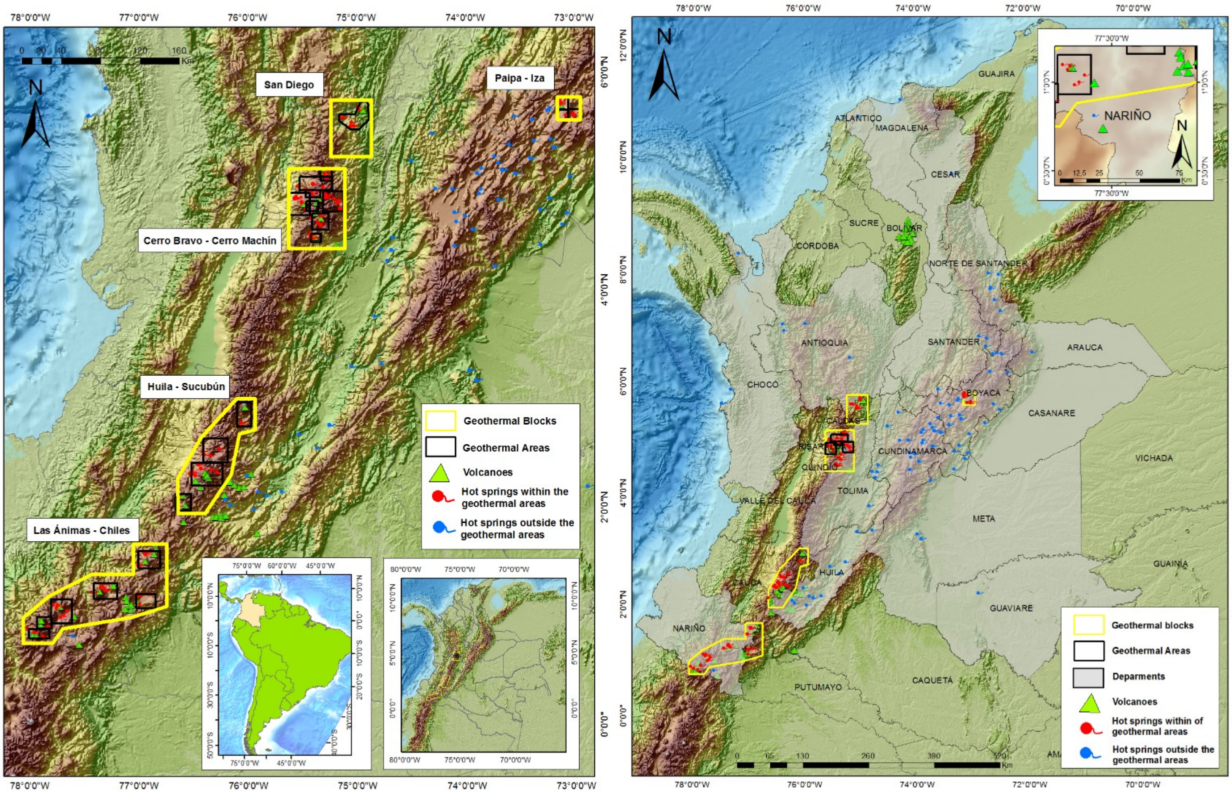


Figure 7: A) Location of preliminary geothermal areas (black polygons) and blocks (yellow polygons), and B) departments with the presence of thermal springs outside the geothermal areas (Alfaro et al., 2021).

Table 2: Geothermal potential and stored heat calculated for preliminary geothermal areas (Alfaro et al., 2021) and for departments with hot springs (Alfaro et al., 2020).

Geothermal area	Electrical power (MWe) mean	Stored heat (EJ) mean
Paipa	21.50	4.31
Iza	12.09	2.72
San Diego	141.85	12.51
Cerro Bravo Volcano	79.73	7.94
Villamaría-Termales	38.50	4.83
Nereidas-Botero Londoño	100.72	12.19
Hacienda Granates	67.24	11.57
Santa Rosa Volcano	137.24	10.66
Otún Lake	0.08	0.63
Nevado del Tolima	82.70	8.66
Cerro Machín Volcano	129.94	10.05
Huila Volcano	0.1	0.76
Gabriel López boiler	24.78	5.15
Caldera del Paletará	117.96	14.27
Volcanoes of Sotará-Sucubún	17.43	2.82
Volcanoes Doña Juana-Las Animas	37.84	5.30
Galeras-Morazurco Volcanoes	29.49	4.87
Sibundoy Volcano	9.8	3.09
Azufral Volcano	81.9	9.6
Cumbal Volcano	15.66	2.56

Department	Electrical power (MWe) mean	Stored heat (EJ) mean
Antioquia	2.27	2.04
Arauca	0.07	0.52
Atlántico	0.06	0.47
Boyacá	1.43	11.16
Casanare	0.21	1.64
Cesar	0.06	0.47
Chocó	3.27	2.30
Cundinamarca	1.99	15.75
Guaviare	0.07	0.53
Huila	12.09	7.08
Magdalena	0.06	0.50
Meta	2.54	0.32
Nariño	0.07	
Santander	0.21	1.74
Norte de Santander	0.43	3.42
Tolima	0.13	1.04
TOTAL	***24.95***	***49.56***

Chlies-Cerro Negro Volcanic Complex	23.77	4.14
TOTAL	***1170.20***	***138.60***

5. GEOTHERMAL UTILIZATION

Colombia currently has two milestones of geothermal resource utilization for power generation. Based on the exploration carried out in the country, two cases of success in the use of geothermal energy have been recorded. The first heat pump for cooling purposes was installed in an industrial park located in Tocancipá, 40 km to the north of Bogotá, D.C. (Alfaro and Rodríguez-Rodríguez, 2020). The heat pump works full time and cools down a room of 90 m^3 to -10°C. The change in the temperature of the water circulated in the subsoil, at 2500 L/h, is 6°C, from 15°C to 21°C. Two vertical wells of 70 m and one of 80 m depth support the system (Ortiz, 2017).

For the geothermal power generation, a small-scale 100 kW power plant was put in operation. The project was developed by Parex Resources Inc.,a joint project with the Universidad Nacional de Colombia-Medellin, the national government through the Ministry of Mines and Energy, and an international oil and gas exploration company. It was inaugurated at the Las Maracas field in Casanare (Eastern Llanos sedimentary basin), and the power unit can generate up to 72,000 kWh/month. The generation equipment was designed, built, and commissioned by the Spanish-based ORC manufacturer Rank (Figure 8). The utilization of the resource helps to reduce emissions from fossil fuel-sourced power generation by around 550 tons of CO_2 per year. The implementation takes advantage of high temperature gradients, permeable rocks, and fresh water which could be brought to the surface without additional cost as a co-product of oil extraction (Franco et al., 2021).

Figure 8: ORC Rank power plant at Los Ocarros block, Maracas field, San Luis de Palenque (Casanare) (Minenergía, 2021).

On the other hand, there are two more pilots in the country. Parex Resources is advancing with another low enthalpy geothermal project in Campo La Rumba, in the municipality of Aguazul in Casanare, which will have a capacity of 35 kilowatts (kW), capable of generating 672 kWh per day (Presidencia, 2021). For the second one, the Chichimene pilot is executed by Ecopetrol in the municipality of Acacías (Meta) with an installed capacity for 2 megawatts (MW), and it will be able to generate 38,400 kWh hours per day (ThinkGeoEnergy, 2021; Portafolio, 2021).

The ancestral use of the geothermal resources is based on the hot springs for bathing and swimming and used an energy utilization of 300 TJ/year installed in 39 localities (Table 4 in Appendix). The data have not changed as no new information was obtained (very rough estimation instead of statistical records of flow and inlet/outlet temperatures).

6. CONCLUSIONS

The implementation of the regulatory framework for geothermal resources will be a great accelerator and incentivize geothermal development in Colombia, particularly, for public and private agents. This will provide good signals to international markets, being not only attractive for the generation of electrical energy, but also for direct uses. It is expected that with capital investment, together with green, clean, and self-sustaining energy tax exemption programs, a new stage of geothermal exploration and development can occur, in the framework of the energy transition proposed by Minenergía. These results are largely due to the geothermal development derived from the efforts of the national government to explore and identify the resource, and the meeting of the different sectors such as academia, adjacent industries in a stronger local geothermal community.

Due to geothermal resources with possible high enthalpy located in convective systems and associated with volcanoes in the Colombian Andes, geothermal exploration has advanced significantly in the geothermal areas of Paipa, Santa Rosa, Azufral, Cerro Machín, San Diego and Nereidas-Botero Londoño. The thermal anomaly was confirmed with temperature measurements in two wells, and therefore validating the conceptual model in the Paipa geothermal area.

With the first estimate of the potential for hydrothermal geothermal resources in the Colombian territory, it is possible to firmly begin the consolidation of a real market for geothermal energy and, in turn, begin to appear in the Colombian energy matrix. The calculated potential of 1170.20 MWe could provide the country with an equivalent of 7% of the installed capacity in the entire territory. This estimate could be increased with research strategies to characterize geothermal resources associated with blind systems, hot dry rock systems and sedimentary basins, thus increasing the total geothermal potential in the country.

The Government of Colombia aims to advance in the investigation and exploration of its geothermal resources, with the implementation of different methodologies, in both convective and conductive geothermal systems associated with volcanoes and sedimentary basins.

In the conductive geothermal resources hosted in Llanos Orientales sedimentary basin, the first geothermal power plant for co-generation, with a 100kW unit, is currently in operation. was developed. This is a possible indicator that the development of geothermal resource exploitation in Colombian territory would begin in low-medium enthalpy geothermal systems, including direct-use of geothermal energy.

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APPENDIX

TABLE 3. PRESENT AND PLANNED PRODUCTION OF ELECTRICITY (1)												
	Geothermal		Fossil Fuels		Hydro		Nuclear		Other Renewables (specify)		Total	
	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr (3)	Capacity MWe	Gross Prod. GWh/yr (2)	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr
Estimated total projected use by 2020	0	0	5,375	16,479	12,425	54,421	0	0	300	263	18,100	71,163
Estimated total by 2021	0.1	0	5,375	16,479	12,425	54,421	0	0	300	263	18,100	71,163

(1) UPME. Plan de Expansión 2017-2031. Escenario 3A. Anexo XXI. http://www.siel.gov.co/Inicio/Generaci%C3%B3n/PlanesdeExpansi%C3%B3nGeneraci%C3%B3nTransmisi%C3%B3n/tabid/111/Default.aspx

(2) Based on the installed capacity and assuming 30% operation.

(3) Based on the installed capacity and assuming 50% operation

TABLE 4. UTILIZATION OF GEOTHERMAL ENERGY FOR DIRECT HEAT AS OF 31 DECEMBER 2022 (other than heat pumps)

Locality	Type	Maximum Utilization					Capacity	Annual Utilization		
		Flow Rate (kg/s)	Temperature (°C)		Enthalpy[2)] (kJ/kg)		(MWt)	Ave. Flow (kg/s)	Energy[4)] (TJ/yr)	Capacity Factor[5)]
			Inlet	Outlet	Inlet	Outlet				
Faciliities in 39 localities										
TOTAL	Bathing and swimming	159					18	79.4	300	

TABLE 5. ALLOCATION OF PROFESSIONAL PERSONNEL TO GEOTHERMAL ACTIVITIES (Restricted to personnel with university degrees)

(1) Government
(2) Public Utilities
(3) Universities
(4) Paid Foreign Consultants
(5) Contributed Through Foreign Aid Programs
(6) Private Industry

Year	Professional Person-Years of Effort [1]					
	(1)	(2)	(3)	(4)	(5)	(6)[2]
2019	12	1	4	8		5
2020	12	1	4	8		5
2021	12	1	4	8		5
2022	12	1	4	8		5
Total	48	4	12	32		20

[1] Information from Servicio Geológico Colombiano, CHEC-EPM, ISAGEN, Universidad de Medellín
[2] Dewhurst Group, LLC

TABLE 6. TOTAL INVESTMENTS IN GEOTHERMAL IN (2022) US$

Period	Research & Development Incl. Surface Explor. & Exploration Drilling	Field Development Including Production Drilling & Surface Equipment	Utilization		Funding Type	
			Direct	Electrical	Private	Public
	Million US$	Million US$	Million US$	Million US$	%	%
1995-1999	3					100
2000-2004	0.6					100
2005-2009	1.1				54	46
2010-2014	12				33	67
2015-2019	4.9					100
2020-2022*	1.5					100

*Partially