Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Status of the Geothermal Resources of Colombia: Country Update

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Keywords: Colombia, Update, Colombian exploration, Paipa, Azufral Volcano, San Diego Maar, El Escondido de Florencia, Paramillo de Santa Rosa, Cerro Machín.

ABSTRACT

In the last 5 years the most relevant events for the geothermal development in Colombia are the evolution in the regulatory frame, the advances in the geothermal exploration, the consolidation of a very active geothermal community, the installation of the first utilization project for direct use, with the exception of bathing and swimming uses, and changes in power generation sector.

Regarding the regulatory frame, from the Law 1715 of 2014 which regulates the integration of nonconventional renewable energy in the National Energy System (Colombia, 2014), two new decrees from the Ministry of Mines and Energy (MME) 2143 of 2015 and 1543 of 2017, have reinforced the legal frame for promoting the non-conventional energy sources. The first of them defines the guidelines for the application of the incentives established in the Law 1715 of 2014 and, second one, regulates a non-conventional energies and efficient energy management fund, FENOGE (for its abbreviation in Spanish). Also worth mentioning the terms of reference project for the environmental license for exploration and exploitation developed by the Ministry of Environment and Sustainable Development. On the other hand, the National Development Plan for four-year-period (2018-2022) foresees the expedition of the regulatory framework for geothermal exploration and exploitation and, the continuity of the Servicio Geológico Colombiano (the Colombian Geological Survey, SGC for its Spanish abbreviation) in geothermal research and exploration.

The geothermal exploration advanced in Paipa, Azufral Volcano and San Diego geothermal areas and started in two new areas located in the middle area of the Central Cordillera: Paramillo de Santa Rosa and Cerro Machín included as objectives of exploration in 2018. The following achievements are some of the most relevant achievements in exploration. Updating of the model of Paipa geothermal system. Completion of the exploration studies of Azufral volcano system. Construction of 3D magnetotelluric models for Paipa and Azufral areas and the local implementation of this capability. The completion of the geological map in scale 1:25.000 and the geochemistry of geothermal fluids and, the beginning of the geophysical studies (potential fields and magnetotellurics) in San Diego area.

It is noteworthy that the SGC formulated and started to work on a geothermal gradients drilling project in Paipa geothermal area. However, it had to be postpone in consideration of the adverse answer of the local community shaped by peasants of the rural area (without indigenous population involved) who following their environmental leaders relate any drilling activity with mining projects and fracking. This fact obliged to the reinforcement of the strategy of socialization for constructing confidence and credibility in the community.

The consolidation of the geothermal community started from the interest of the students and professionals of different universities, particularly from the geology departments, formed geothermal seedbeds for the research and promotion of geothermal resources. They summoned to all the interested parties, power generation companies, the SGC and private project developers. From those seedbeds, the Asociación Geotérmica Colombiana (AGEOCOL, for its Spanish abbreviation), a national geothermal association, was created. This association organized several shorts courses in different subjects, with guest experts, and signed cooperation agreements and established the Reunión Nacional de Geotermia (RENAG), an annual geothermal meeting, which has had three (3) editions (2016 to 2018), with invited experts from El Salvador, Chile, Iceland, among others. A significant contribution to the motivation of the local geothermal community was the creation of the Geothermal Resources Council representative office in Latin America (GRC-LATAM).

The success in the application of the new legal frame and particularly the incentives for investment, research and development of environmental clean technologies to produce energy and improve the energy efficiency, harvest its first result in a pilot project for energy saving by using a heat pump for cooling. The project obtained the VAT tax exemption for the purchase of the heat pump. This is the first geothermal installation in Colombia, located in an industrial park in Tocancipá, a municipality located 40 km north from Bogotá.

The changes in the power generation sector with impact on the geothermal development expectations consist of the privatization of ISAGEN S.A. E.S.P, the third power generation company, since Colombian Government sold its actions to the fund of investments Canadian Brookfield Asset Management Inc. (BAM). It is not clear the future of geothermal projects in development by ISAGEN MW. For its part, CHEC-EPM, which keeps an environmental license since the drilling of Nereidas-1 well in 1997, is intending to start the drilling stage to confirm the geothermal resource.

The document presents a brief updating of exploration, legal frame, and utilization of geothermal resources of Colombia.

1. INTRODUCTION

1.1 Legal aspects.

The main laws and decrees that define the existing legal frame of the geothermal resources in Colombia are briefly described next:

The Natural Renewable Resources and Protection of the Environment National Code: Decree 2811. This decree defined the geothermal resources as the natural combination of water with an endogenous heat subterranean source, which result is the spontaneous production of hot water or vapors and, the endogenous heat subterranean 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 is in power generation, heat for heating, cooling and industrial uses, obtaining fresh water and mineral extraction (Colombia, 1974).

The Law 691, known as URE Law for the acronym of Law for Rational and Efficient Use of the Energy (Colombia, 2001)), 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.

The Decree 4131 (Colombia, 2011) changed the juridical nature and denomination of the INGEOMINAS as a public entity to Servicio Geológico Colombiano (SGC), a scientific and technical institute. The SGC, institution of the science and technology national system, is responsible of carrying out basic and applied scientific research from subsoil resources potential, to develop surveillance and monitoring of geological hazards, to administer the subsoil information, to ensure the safe management of nuclear and radioactive materials in the country, coordinate (and perform) nuclear research and handling and use of the nuclear reactor. Some of the functions of the SGC include generate and integrate knowledge, compile, validate, store and provide information of geology, subsoil resources and geological hazards, in accordance with the policies of the National Government. Other roles of the SGC include 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, among others, and to develop programs for the reconnaissance, prospecting and exploration of the national territory, in accordance with the policies defined by the Ministry of Mining and Energy or the National Government.

The Law 1665 of July, 2013 (Colombia, 2013), of 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.

The Law 1715 of 2014 regulates the integration of nonconventional renewable energy in the National Energy System (Colombia, 2014). It declares the promotion, encouragement and incentive to the development of the activities of production and use of non-conventional 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, competitiveness of the Colombian economy, environmental protection, the efficient use of energy and the preservation and conservation of renewable natural resources.

The Resolution 132 of 2014 issued by the Energy Regulation Commission (CREG, for its acronym in Spanish) (Colombia, 2014), defined the methodology for determining the firm energy of geothermal plants

The Decree 2143 de 2015 (Colombia, 2015), defines the lineaments of the application of incentives established in the Law 1715 de 2014: Special deduction of the rent tax, exclusion of the VAT tax, 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 Licences 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 abbreviation in Spanish) the definition of procedures and requirements for the registration of projects as non-convencional energy sources and the emission of the certification that endorses the papers of the project demanded for the exemption of tariff tax refered in the Law 1715 of 2014.

The Decree 1543 de 2017 regulates the Fund for Non-Convencional Energy and Energy Efficient Management, FENOGE (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.

The Law 1955 of 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 which 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. The MME 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 this resources. Likewise, working tables will be formed with the Ministry of Environment and Sustainable Development (MADS), ANLA, CREG and SGC in order to establish the regulatory framework and environmental terms of reference that allow the appropriate 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 Modernization of the energy sector in Colombia

The Colombian National Government, through the Ministry of Mines and Energy (MME) is undertaking an energy transformation for diversifying the energy basket by the integration of the non-conventional renewable energy sources (FNCER). This objective takes part of the National Development Plan from the current government (2018-2022) through the named Pact for Mining-Energy Resources for Sustainable Growth and Expansion of Opportunities.

The objective for the next four (4) years is to increase the installed capacity of alternative energy sources from 50 MWe to 1500 MWe. A renewable energy auction was called by the MME through the Resolutions 41307 y 41314 of 2018. The auction done in February 2019, based on the offer of 10-year power purchase agreement. At least 15 companies showed interest in taking part of the process to develop 22 projects: 17 from solar energy, 4 from wind energy and 1 from biomass (Portafolio, February 2019). However, it was not adjudicated as the projects did not get the competitiveness standards. A second auction is being programmed for the second semester of 2019 (La República, 1999). On the other hand, the National Government decided to define a roadmap for the modernization of the energy sector and for this purpose the formation of 20 national and international experts commission was announced. This commission is going to work in aspects considered strategic: competitiveness, participation and structure of the market, the role of natural gas in the energy transformation, decentralization, industry digitization and efficient demand management (Portafolio, May 2019).

The National Government is strongly interested in the promotion of the geothermal resources as it is inferred from the National Development Plan: Law 1955 of 2019 (Colombia, 2019). With the support of the Inter-American Development Bank (IDB) a Working Table of Geothermics was formally open in August 2019 focused in the following subjects: preparation of the legal, regulatory and institutional framework for geothermal exploration and exploitation for direct and indirect uses, evaluation of the financial and economic viability of geothermal and its potential for participation in the national electricity market, planning for adequate social and environmental management of geothermal projects, strengthening the knowledge and information available on geothermal potential and, development of technical capacities to regulate, monitor and carry out geothermal projects.

The Government's interest in the geothermal energy was revealed in the region during the 6th GEOLAC Congress where the capital city, Bogotá, was announced by the Vice-Minister of Energy as the venue of the next version of this conference in 2020.

1.3 Geothermal Community.

During the last few years a very active geothermal community has come out. It consists of professional working in geosciences, mainly, coming from seedbeds, some of them registered as GRC student chaperts, who have been born in the Universities from the interest of students and professors and, from the Servicio Geológico Colombiano. The seedbeds belong to the Universidad Nacional de Colombia in Bogotá and Medellín, the Universidad de Los Andes and, the Universidad of Medellín. They all are united in an association, the Asociación Geotérmica Colombiana (ASOGEOCOL) with about 150 members. This Association was derived from the Asociación de Estudiantes de Geociencias in 2017. It has three regional chapters: Central in Bogotá, Santander (NE) in Bucaramanga, Valle del Cauca (SW) and Antioquia (NW). At least four (4) new chapters are being projected for the near future in the Caribbean region, Nariño (border with Ecuator), the “Coffee axis” which group the department of Caldas, Risaraldo, Quindio and Tolima, and the Eastern Llanos.

The ASOGEOCOL with the support of Universities, companies from the energy sector such as CHEC-EPM, ISAGEN, LaGeo, from El Salvador, and public entities such as ANLA, COLCIENCIAS (the equivalent to the national administrative department of sciences and technology) and SGC, and private companies as Dewhurst Group, have organized and hosted 3 national geothermal meetings since 2016. In the frame or these events, besides the technical session, courses on different subjects of exploration and utilization, mainly, have been carried out, which have been dictated by experts from LaGeo, CEGA from Chile, CeMIEgeo from México and IGA.

Moreover, the Universidad de Los Andes, is developing a cooperation agreement with Reykjavik University. In this frame and from the Internationalization Direction of the university, they held a workshop on geothermal regulation with the support of the Agencia Presidencial de Cooperación Internacional de Colombia (APG, for its acronym in Spanish) to which representatives from governmental institutions were invited (Universidad de Los Andes, 2019)

In 2018, the Geothermal Resources Council (GRC) created a representative office in Latin America (GRC-LATAM) which is host in Bogotá by Dewhurst Group, LLC (DG) member of the GRC. “The focus of the GRC-LATAM will be geothermal development and support for Latin America, bringing geothermal education and outreach to the region. The main goals for this office will be to expand GRC membership, provide services in Spanish, and support meetings and forums within the region. The GRC-LATAM will provide a bridge to help developers and prospective investors with Latin American geothermal development. Activities within the GRC-LATAM” (GRC, 2018). As a result, the first GRC Annual Meeting with a session in Spanish was hosted in 2018 in which Colombian institutions, including Universidad de Medellín and SGC, among others.

1.4 Interest of the power generation sector.

The geothermal exploration started in Colombia since the interest of CHEC S.A. E.S.P. (1968) in the geothermal system of Nevado del Ruiz Volcano. This company, currently part of the group EPN, carried out exploration studies which concluded with the drilling of the first (and still single) deep exploration well drilled in Colombia (Monsalve, 1997). A new interest came out in 2008 when ISAGEN another company from the power generation sector and CHEC, started separately to reactive the exploration in Nevado del Ruiz. In addition, ISAGEN on behalf of the Colombian side and the Corporación Eléctrica del Ecuador (CELEC), on behalf Ecuadorian site, signed an agreement for the joint exploration of the binational systema Tufiño – Chiles – Cerro Negro thorough consulting services (Mejía et al., 2014). On the other hand, ECOPETROL, the Colombian Oil Company, today a public corporation announced the inclusion of a geothermal development pilot project for generating power from low enthalpy resources (Ecopetrol, 2013).

Currently, the interest of CHEC –EPM and Ecopetrol on the geothermal resources as power generation source, persists. CHEC-EPM after getting a new geothermal model based on recent exploration studies carried out between 2012 and 2016, keeps the application for the extension of the environmental license to the west of Nevado del Ruiz; its project is known as Valle de Nereidas Geothermal Project, located between the rivers Molinos, Nereidas and Claro. This company has projected five (5) wells 2500 m deep and the corresponding Environmental Management Plan (López, 2018). Ecopetrol announced the definition of the strategy for the development of this resource as a part of its program of energy diversification (Ecopetrol, 2014) and included 5 MWe from geothermal in its portafolio 2023 (Ecopetrol, 2019). On the other hand, the company ISAGEN was privatized by the sale of the majority of the actions to Canadian Brookfield Asset Management Inc. (BAM) in 2016. From then, the signs of interest of this company in its previous geothermal projects are not clear: the geothermal projects were not mentioned in the 2017 Management Report (ISAGEN, 2017) and the Resolution No. 2019-0491 from the environmental authority (CORPOCALDAS) formalized that the company withdrew the request of environmental license for the Macizo del Ruiz geothermal project (Colombia, 2019).

1.5 Power generation in Colombia.

Based on the latest report from UPME (2018), the technologies taken part 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 Appenix, Table 1, 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.

2. GEOLOGY BACKGROUND

Regional geological considerations, based on a tectonic frame and a brief description of the Colombian geological provinces, taken from Alfaro (2015) are presented next.

2.1 Colombia's tectonic frame

The present-day configuration of the Colombian territory, in particular the Andean zone is due to the interaction of the Cocos, Nazca, Caribbean and South American plates and also to the Coiba microplate. On a regional basis, this interaction results in a great variation of the stress tensors that on its turn mark out separate seismotectonic provinces. An important consequence of this phenomenon is the movement towards the North-northeast of the North Andean block. The latter is bounded on the East by the fault system that runs from Guayaquil, in Ecuador, to the foothills of the Eastern Cordillera fallowing the Boconó Fault in Venezuela. On 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. This deformation involves the sequences accumulated on top of the Caribbean Province's igneous basement (Figure 1), both before as after its accretion. The north Andean Block includes smaller triangular blocks bounded, on all their sides by wrench faults, such as the Maracaibo Block inside of which is noteworthy the Santa Marta Block on the northeastern corner. This complex pattern of plate and blocks interaction results in seismotectonics regimes on which transpressive and transtensive deformations play an important role (INGEOMINAS, 2007a). The intensity of the active tectonic processes as the subduction, formation of mountain ranges, basins and volcanic chains, cortical structures reactivation and neoformación, and an intense seismic production, are due to the current condition of the kinematics and geometrically heterogeneous convergence especially between Nazca and South America plates, and its evolution through the time (INGEOMINAS, 2007b).

2.2 Geological Crustal Provinces of Colombia

The basement of the Earth crust's in the Colombian territory consists of two contrasting types of rocks that are separated by the Cauca-Almaguer Fault a structure that runs in 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 basement is interpreted as a result of the accretion of oceanic lithosphere fragments to the continental active margin of South America during the Eocene (INGEOMINAS, 2007a).

The Colombian territory has been divided in five (5) geological provinces presented in Figure 2.

The description of these geological provinces, from some excerpts taken from INGEOMINAS (2007a) is as follows:

Within the eastern Proterozoic metamorphic basement there have been recognized three geological provinces believed to be related to the Paleozoic history of collision between the Gondwana and Laurentia continents. From East to West these provinces are: 1. Rio Negro-Juruena Province-RNJP (from Tassinari 1999, In INGEOMINAS, 2007b), 2. Grenvillian Colombian Province-GCP, 3. Arquía Province-AP.

The Rio Negro-Juruena Province-RNJP is a part of the Guayana Shield, the Gondwanic autochthonous craton around of which, nucleation by amalgamation to its west, of Laurentian Continent's fragments, occurred during the northwestern drift of the latter, relative to Gondwana. The RNJP extends towards the West, under the Cenozoic Andean molasses, up to a structure –that according to the structural location of the Serrania de la Macarena whose basement is akin to the adjacent crustal province GCP- probably runs buried paralleling the Guaicaramo Fault that marks the limit of the Andean uplift. It is believed that this underground structure represents a former continental suture buried by the Andean molasses.

To the West of this structure the crystalline basement consists of Grenvillian Colombia Province GCP made of amphibolites and granulites that crop out as insulated faulted blocks at the Serranías de La Macarena y San Lucas, at the Garzón and Santander Massifs and at the Sierra Nevada de Santa Marta and Guajira Peninsula as well as roof pendants brought out by Mesozoic plutons. The GCP is bounded to the West by the San Jerónimo Fault.

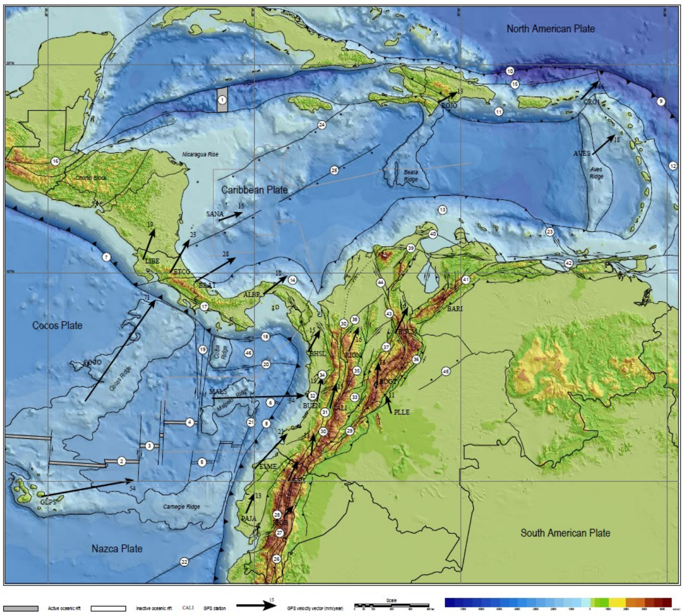

Figure 1: Tectonic scheme of Northern South America and the Caribbean (Taken from INGEOMINAS, 2007a). Active Mid-ocean Ridges: (1) Cayman, (2) Galapagos, (3) Ecuador) y (4) Costa Rica. Inactive Mid-ocean Ridges: (5) Malpelo, (6) Buenaventura. Oceanic trenches, active subduction zones: (7) Middle Aerican 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) Consaga, (27) Peltetec, (28) Pallatanga – Pujili, (29) Algeciras, (30) Cauca – Almaguer, (31) Cali – Patía, (32) Garrapatas, (33) Ibagué, (34) Itsmina Fault zone, (35) Palestina, (36) Guaicaramo, (37) La Salina, (38) Espiritu Santo, (39) Oca, (40) Cuisa, (41) Boconó, (42) El Pilar, (43) Bucaramanga (44) Algarrobo, (45) Meta. Independent lithospheric blocks: (46) Coiba Microplate. Vector values (mm/year) correspond to relative plate movements.

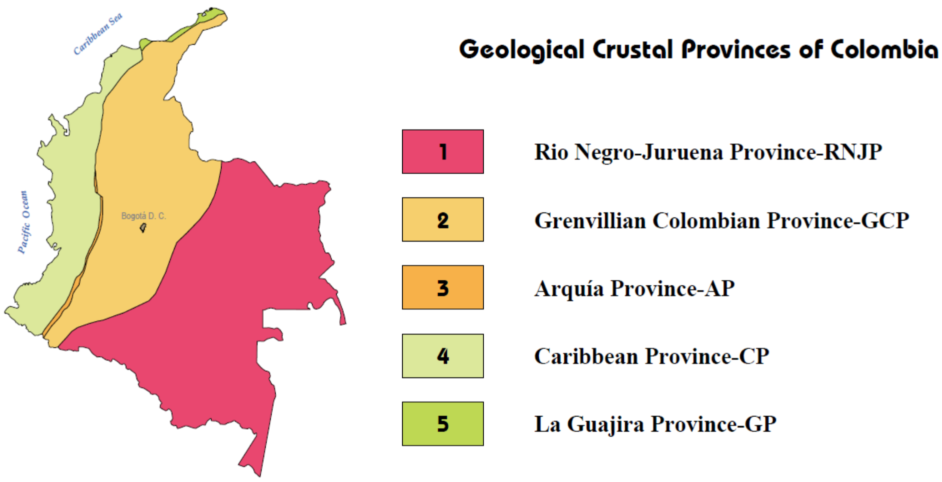

Figure 2: Geological Provinces of Colombia. Taken from INGEOMINAS, 2007a.

The westernmost metamorphic basement corresponds to the Arquia Province- AP of oceanic affinity that outcrops as a long and narrow belt bounded to the East by the Silvia-Pijao Fault and to the West by the Cauca-Amaguer Fault that is make of quartz-sericitic and amphibolic schists, amphibolites that at some localities are granatiferous. Then, the latter structure marks the western boundary of the Proterozoic crystalline basement. Lower grade metamorphic rocks and younger igneous intrusions suggest that the GCP was affected by orogenic events during the Ordovician- Silurian, and, Devonian and Permian. Associated to the crystalline basement (RNJP, GCP and AP) there exist some Paleozoic sedimentary rock intervals that might have accumulated on its top; however, due to the poor preservation of the original sequences and also to the fact that the studies of their fossils, that are mainly Ordovician, have not, so far, been aimed to prove if the faunas display provinciality, the age of suture of these provinces remains unknown. Some facts, like the presence of Devonian syntectonic and Triassic postectonic plutons intruding both the GCP and the AP might postdate the suture event between these two provinces. In between the San Jeronimo Fault, GCP's western boundary and the Silvia-Pijao Fault, AP's eastern boundary outcrops the Quebradagrande Complex, a discontinuous belt of blocks of mainly oceanic rocks, made of tectonic slices of deformed ultramafic rocks, gabbros, basic volcanic and sedimentary rocks.

To the West of the AP, from which it is separated by the Cauca-Almaguer Fault there is the Caribben Province-CP made of crustal fragments of oceanic affinity. The rocks of this province outcrops on the western foothills of the Central Cordillera, the Western Cordillera and the Serranía del Baudó. There, they consist on strongly faulted and deformed slivers of ultramafic rocks associated gabbros and tonalites and also associations of basalts and felsites , there also outcrop picrites and komatiites of which those of Gorgona Island are the unique example of Phanerozoic komatites around the world. Lithologic characteristics of this province like the presence of picrites and komatiites accompanied by the bimodal basaltic-rhyolitic composition of the volcanic rocks as well as their trace element composition suggest that these rocks were formed in an oceanic plateau. In response to its high relief and higher buoyancy relative to the normal oceanic crust this oceanic feature was accreted to the South American active margin during the Eocene by accretion/subduction processes. The latter process involved the rocks of the plateau into an accretionary complex, the deformation of which, conspicuous in the sedimentary rocks, has migrated in a westward direction.

Oceanic Cretaceous rocks of La Guajira and the Sierra Nevada de Santa Marta, make up La Guajira Province- GP. Given the low level of understanding has not been possible to establish the type of oceanic crust and the time of accretion of the same (INGEOMINAS, 2007b).

2.3 Geothermal resources of Colombia.

The Colombian territory hosts convective geothermal resources with hydrothermal surface manifestations, related to volcanoes and faults and possibly, conductive systems in sedimentary basins (Figure 3). Most of the geothermal systems related to volcanoes are located in the Central Cordillera and in the south of the Western Cordillera. However, an isolated geothermal area is found in the Eastern Cordillera: Paipa, related to an ancient volcano and Iza, to a cryptodome. Up to now, the geothermal exploration has been focused on these systems (Figure 1A).

The systems presumably related to faults are found in the Andes but also in the Caribbean, Pacific and Eastern Llanos sedimentary basin. Assuming the preliminary geothermal gradients anomalies in sedimentary basins (Figure 1B) as indicative of possible low to intermediate (?) enthalpy conductive systems, where temperatures above 150°C (more than 5 km deep) have been registered, the most promising areas for this type of resource are the following sedimentary basins: Eastern Llanos, Cagüan – Putumayo, Catatumbo, Central Cordillera and Middle Magdalena Valley (INGEOMINAS-ANH, 2008).

3. ADVANCES IN EXPLORATION

During the last five years, the Servicio Geológico Colombiano (SGC) carried out exploration activities in the geothermal areas of Paipa, Azufral Volcano, San Diego, and new geothermal areas in the Cerro Bravo – Cerro Machín volcanic complex. A summary of these activities are briefly described next.

3.1 Paipa’s geothermal area

In the period of interest, the surface exploration of Paipa geothermal area was concluded. This is an isolated geothermal area located in the Eastern Cordillera in a sedimentary basin (Figure. 3). The studies of the last five year include domes mapping and dating (Rueda, 2017), description and chemical analysis of core samples from shallow wells (50 and 100 m) of an altered igneous intrusion (El Durazno) (Rodríguez & Alfaro, 2015) , a 3D geological modelling constrained by gravity and magnetic data (Llanos et al., 2015), 2 and 3D magnetotelluric modelling (González-Idárraga & Rodríguez-Rodríguez, 2017; Siripunvaraporn, 2016), updating of the geoelectrical study (VES) (Franco, 2016), the updating of a conceptual geothermal model (Alfaro, et al., 2017) and the study of the local meteoric line (Malo & Alfaro, 2017). In this conference the following subjects are presented as separated papers: the updated conceptual model (Alfaro et al., 2020), characterization of altered igneous intrusions, 3D magnetotelluric resistive model and local isotopic meteoric line (Malo & Alfaro, 2020). In addition, a gas phase characterization is currently underway. This have been possible through a cooperation agreement with the Istituto Nazionale di Geofisica e Vulcanologia, Palermo, Italy (INGV), which have experienced researchers on fluid geochemistry and the capability for making the chemical and analytical work.

Two geothermal gradient boreholes have been planned to be drilled in Paipa´s geothermal area (SGC, 2017). Their projected characteristics are: slim holes, 500 m deep, core recovery and cased – cemented from top to bottom. Although the project was expected to start in 2017, it has to be postponed due to the doubts and distrust of the local community, as they relate drilling activities with mineral mining projects and fracking. As a consequence, a new stage of the socialization was started in which activities such as meetings with presentations, geothermal days, banners and mock-up show, as well as the distribution of educational booklets and flyers made by the technical group, were carried out. The Figure 4 presents the cover of the three (3) booklets as well as the character created as the story teller, whose name is Chitu, word that means hot water in Muisca language. The terms of reference for the drilling and supervision contracts are going to be published in the first days of August 2019 and according to the 2019 project planning, the drilling will start in the fourth quarter of 2019.

3.2 Azufral volcano geothermal area.

The Azufal volcano, located on the Western Cordillera to the south of the national territory, is one of the most promising areas as geothermal resource, classified as a high temperature geothermal system. In order to complete the surface studies at Azufral Volcano geothermal area, which preliminary conceptual model was presented in the past version of the WGC (Alfaro et al., 2015), some complementary studies as the resistive structure based on magnetotelluric data and radon preliminary, were carried out. Currently a gas characterization is also being performed.

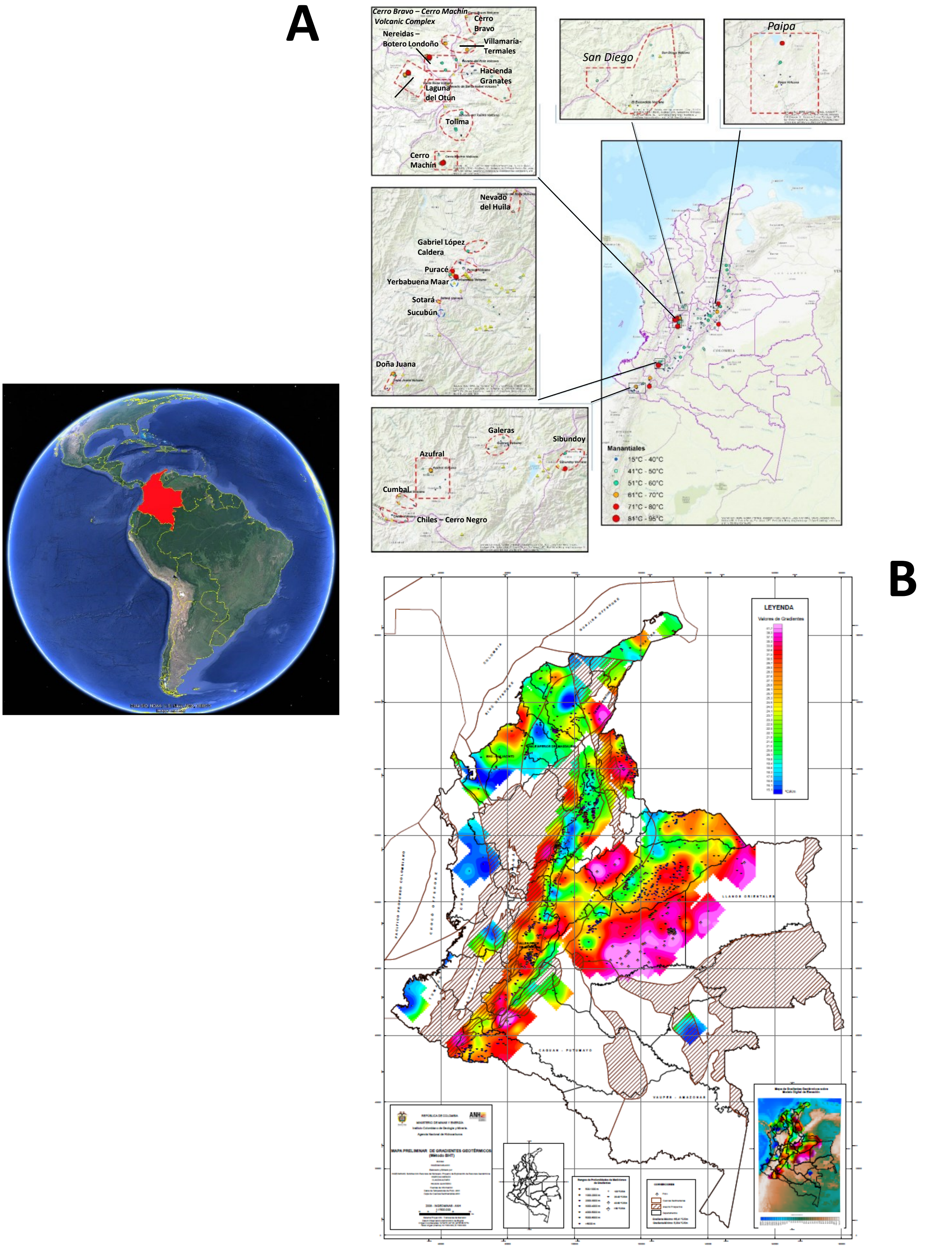

Figure 3: Geothermal resources of Colombia. A. Convective systems related to volcanoes (in zoom windows) and faults, on the hot springs map <hidrotermales.sgc.gov.co>. Discharge hot spring temperatures are indicated. B. Geothermal gradients as possible indicator of low-intermediate (?) enthalpy conductive geothermal systems (INGEOMINAS – ANH, 2008)

Figure 4: Booklets prepared by the technical group for educational and divulgation purposes. Below to the right, Chitu "the story teller".

From the magnetotelluric data collected by using Phoenix instruments, 2D (Rodríguez-Rodríguez, 2018) and 3D (Meqbel, 2017) resistive models has been built. The results of the 2D modelling is going to be presented in a separated paper in this event (Rodríguez-Rodríguez, 2020). According to the joint interpretation of the technical group, the 3D model which gets a depth around 7 km, the resistive structure of the area consists of a highly conductive thick layer (up to about 1500 m), with resistivity below 5 Ω·m, which top is between 1000 to 1500 m deep and extends laterally from the volcano to the east. This could be related to the possible cap rock (Figure 5). High resistivity rocks near the surface are assumed to belong to lava flows or unaltered pyroclastic deposits. Deep high resistivity rocks (above 100 Ω·m) located to the west of Cali-Patía, a regional fault, would be related to the basement rocks made of volcanic-sedimentary rocks of marine affinity and Upper Cretaceous age, named Diabásico Group. Intermediate resistivity zones (betweem 5 to 100 Ω·m), could correspond to pyroclastic deposits with water circulation at shallow levels and to the geothermal reservoir, just below the cap rock. The intermediate resistivity has a great thickness from the highly conductive layer (cap rock) to the base of the model at depth. It is interpreted as a lateral change of the basement produced by Cali-Patía fault which seems to be the eastern limit of Diabásico Group. To the east of this fault, less consolidated rocks from continental affinity would be the basement with intermediate resistivity. Other deep high resistivity zone located towards the east of the area, would be related to more consolidated rocks as magmatic intrusions in Pajablanca volcano area. Between the two high resistivity deep bodies observed (Figure 5) there is a topographical and geophysical depression which behaves like a small basin of NE-SW direction.

Preliminary radon surveys in soil air, based on measurements of alpha emissions with the instrument Rad7 in more than 180 stations, indicate concentrations ranging between 0 and 74664 Bq/m^3 to ^{222}Rn and between 28 and 55840 Bq/m^3 for ^{220}Rn) (Malo&Alfaro, 2018) . Most of the measurements (above 80%) reported emissions below 17000 Bq/m3 of ^{222}Rn and 12500 Bq/m3 of ^{220}Rn. The higher emissions of both radon isotopes do not seem to be controlled by faults neither related to the vicinity of the volcano. However, they are spread out in a large area from Quitasol lineament, a NE structure, about 7 km towards the east of the volcano, mainly above the Azufral – Sapuyes lineament (Figure 6). These emissions could be caused by a higher permeability zone.

3.3 San Diego geothermal area.

The San Diego geothermal area is the most northern in the Central Cordillera. It was defined from the location of hot springs reported in the national inventory of hydrothermal manifestations and includes the San Diego Maar, El Escondido de Florencia volcano (discovered during the reconnaissance mission before starting the geological work of the area (Monsalve, 2013) and Puente Linda intrusion. The activities carried out during the last years involve the geological mapping in scale 1:25.000, the geochemistry of fluids and advances in gravity, magnetometry and magnetotelluric studies.

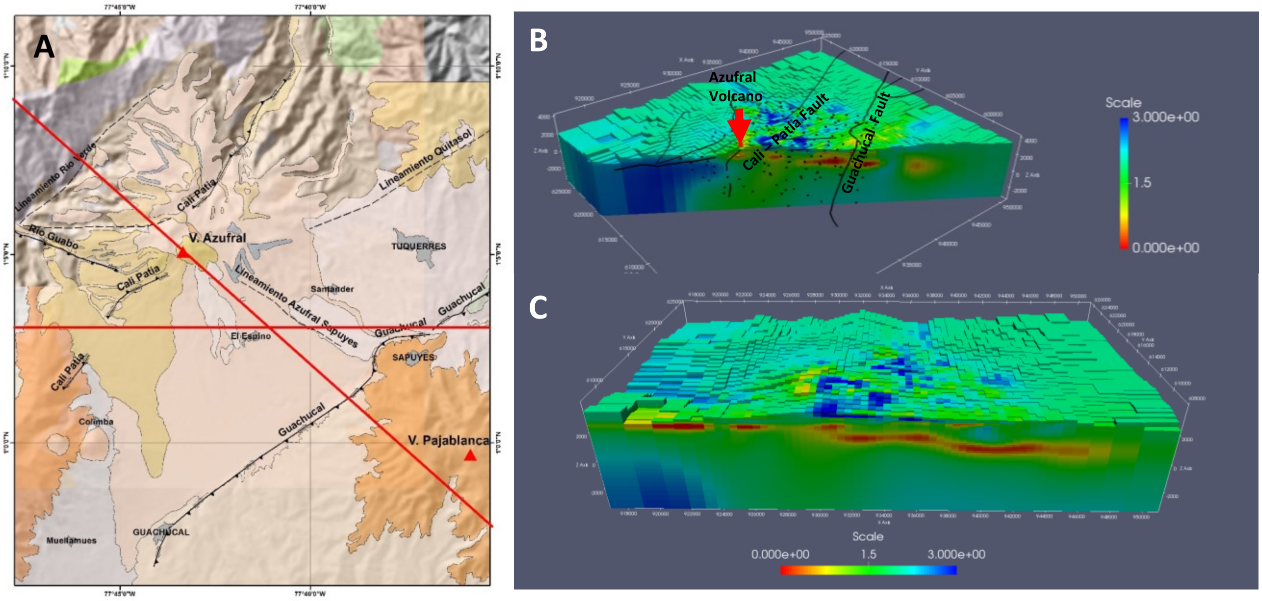

Figure 5: 3D Resistive structure of Azufral volcano geothermal area (Meqbel, 2017). A. Geological (Pinilla, et al., 2007) with structural geology (Rodríguez & Rueda, 2017) presenting the location of the two shown profiles. B NW profile across the top of Azufral volcano. Measuring stations and main faults are indicated. C. EW profile. See the highly conductive thick layer which extends laterally and is interpreted as the cap rock of the geothermal system. A high resistivity basement gets the surface (and outcrops) at the west Cali-Patía fault.

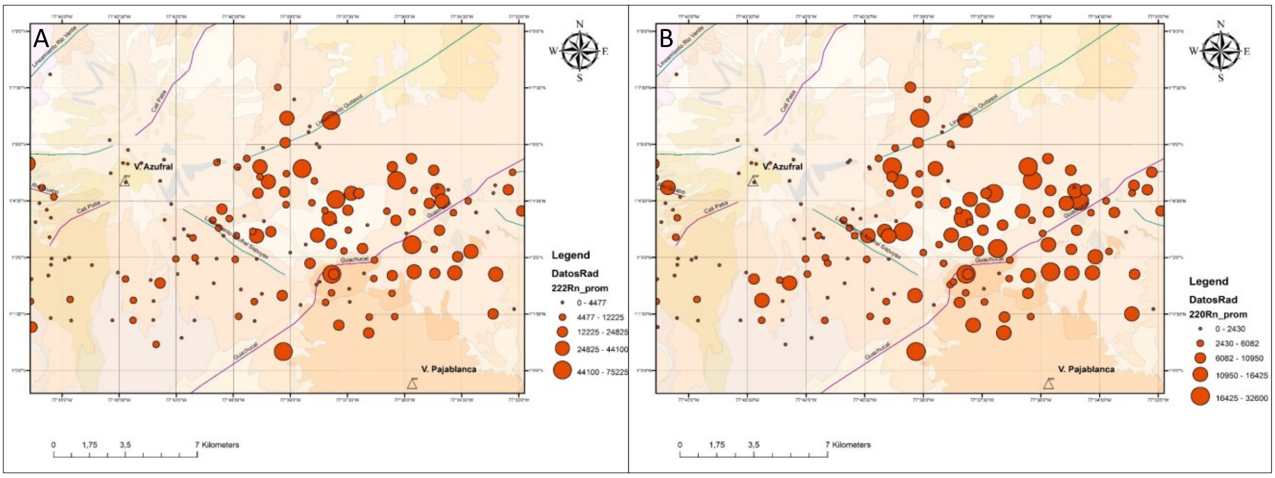

Figure 6: Preliminary radon concentration (Bq/m^3) in soil air at Azufral geothermal area (Malo & Alfaro, 2018). A. ^{222}Rn. B. ^{220}Rn. It seems that high emissions are no related to the vicinity of the volcanic edifice but to the east of Quitasol lineament.

The 1:25.000 geological map presented in the Figure 7 (Rueda & Rodríguez, 2016) describes: a metapelitic basement with metamorphism of low to medium degree (shales, graffiti, quartzites) with some lenses of amphobolites and marbles (Cajamarca formation); the intrusion of a granitic body of great size in almost NS direction, with a slight orientation of the crystals known like Gneissic or Syntectonic Intrusion (Trin); two bodies of Cretaceous age in the center of the study area: Samaná Igneous Complex (Kds) and the Samaná Leucogranite (Kas) with U/Pb ages of 133 ± 4.6 Ma and 132.8 ± 2.6 Ma, respectively; two bodies of Paleogene age emerge in the center and west of the study area Florencia Stock (Tcdf) and Sonsón Batholith (KTcds) with U/Pb ages of 54.6 ±4.4 Ma and 47 ±11 Ma, respectively. The only sedimentary unit in the area is Berlin formation, shaped by shales and, to a lesser extent, sandstone packages. Recent volcanism (<200 ka) is represented by San Diego Maar and El Escondido de Florencia volcanoes. In addition, numerous and small intrusions are present with porphyritic textures and matrixes with high glass content. According to Rueda & Rodríguez (2016), the main structures are Palestine, Patio Bonito and San Diego faults which have a N-S direction. Measurements of fracture planes show an E-W trend given by kinematic indicators such as open and filled fractures, and location of breccia bodies; these structures are superimposed on a strong foliation with N-S and NE-SW trend that predominates in the metapelitic basement with variations in the direction of the dip, making possible the transit of fluids, as in the fractures.

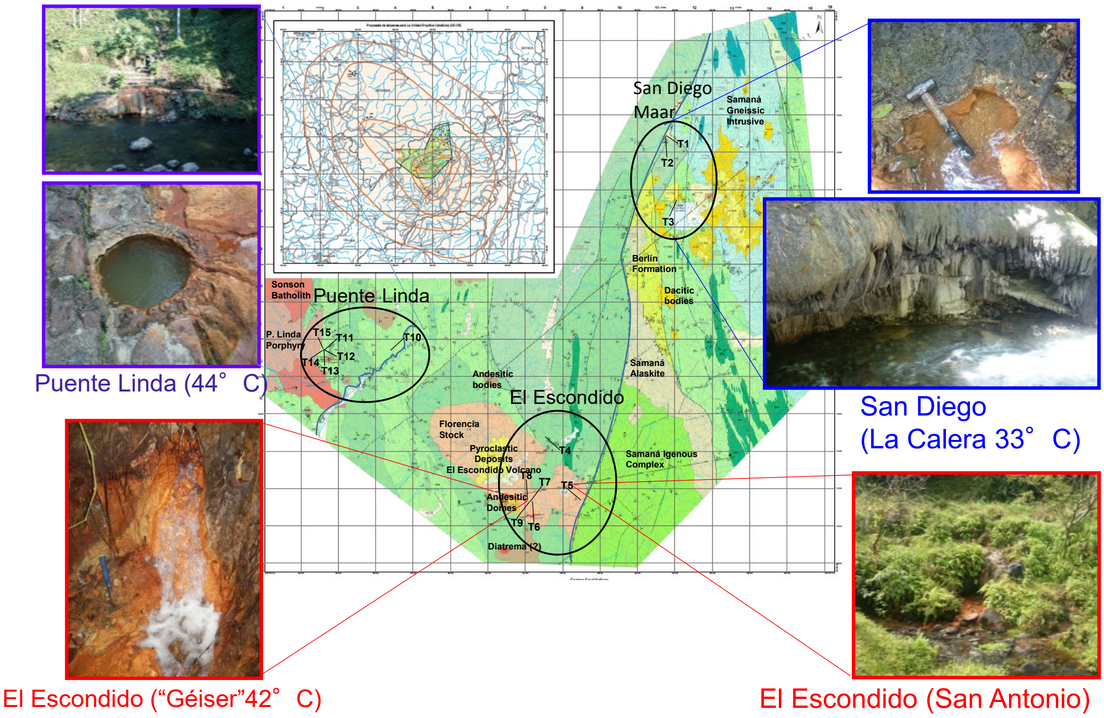

Figure 7: San Diego geothermal area. Geological map (scale 1:25.000) (Rueda & Rodríguez). Metamorphic and igneous rocks dominate the area. The hot springs distribution and their chemical composition suggest three different geothermal fluid origins. The chemical type water are differentiated: sodium bicarbonate in San Diego; sodium chloride in El Escondido; sodium bicarbonate – chloride in Puente Linda.

The hot springs are distributed in three main sites: San Diego maar, to the North; El Escondido, to the South and, Puente Linda, to the West, of the geothermal area. They are brackish water springs of neutral pH and temperature ranging between 30 and 44°C. The dominant water type of the hot springs is sodium bicarbonate in San Diego Maar, sodium chloride in El Escondido and sodium bicarbonate-chloride with high sulfate concentration in Puente Linda (Figure 7). High concentrations of Ca, Mg, HCO_3 and Sr, mainly in the hot springs from San Diego Maar, up to 620 mg/L, 180 mg/L, 2700 mg/L and 11 mg/L, respectively, reveal the contribution of a non-geothermal source such as the dissolution of calcareous lenses present in the Cajamarca metamorphic Complex (?). On the other side, the high Sr concentration could be also related to the leaching of igneous rocks, particularly near andesitic porphyry bodies which according to the chemical analysis, have high concentrations (between 335-1160 mg/L). Based on the geothermometers, the area could host high temperature systems up to 170°C for Qtz non-steam loss and 300°C for Na/K in El Escondido area. However, there is high uncertainty in this estimation as the discharge temperatures are low and possibly, there is a contribution of alkaline elements from a non-geothermal source (Alfaro & Malo. In Rueda & Rodríguez, 2016).

3.4 New exploration areas in the Cerro Bravo – Cerro Machin Volcanic Complex

In 2018 two new exploration areas were included in the called Macizo Volcánico del Ruiz (CHEC, 1983), which actually correspond to separated volcanoes from the Cerro Bravo – Cerro Machín volcanic Complex along the Central Cordillera. See their location in the Figure 3.

The geothermal system of Paramillo de Santa Rosa volcano (SR), was selected in consideration of the high discharge temperatures of hot springs (up to 91°C), type of water (sodium chloride) and high geothermometers calculated (>225°C), which are even higher than those calculated for the Nereidas – Botero Londoño system located to the west of Nevado del Ruiz Volcano (>225°C) (Alfaro et al., 2002) and, from the availability of the 1:25.000 scale geological map made by Group of Geology of Volcanoes of the SGC (Pulgarín et al., 2017).

The Cerro Machín volcano (CM), was also chosen from similar criteria related to the hot springs; their discharge temperatures are even higher than those from SR (up to 96°C), measured recently by the SGC (SGC, 2019), high geothermeters (200 to 220°C) (Inguaggiato et al., 2017) but they are sodium bicarbonates waters type with lower chloride, boron and lithium concentrations than those from SR (and Nevado del Ruiz). This particularity poses an interesting case of study for a hydrothermal system in a subduction zone. Would be the hot spring composition the result of a non-geothermal source contribution such as high CO_2 magmatic neutralized gases or dissolution of limestone or any other calcareous source (?). This area counts with vulcanites map (Cepeda et al., 1995; Méndez, 2001).

The exploration studies in the new mentioned areas started with a work on structural geology and hydrothermal alteration. The advances are summarized in a separated paper presented to this conference (Casallas et al., 2019). Currently, other exploration studies are being carried out in Cerro Machin area: adquisition of gravity, magnetic and magnetotelluric data, as well as geothermal fluid sampling for updating the water analysis and gas phase characterization through the mentioned cooperation agreement.

In Nevado del Ruiz geothermal area, the most studied geothermal area in Colombia since 1968 (CHEC, 1968) where the first well, Nereidas-1, was drilled (Monsalve et al., 1998) which remains the only deep geothermal well drilled in Colombia, has been of interest for stakeholders of the power generation sector as CHEC-EPM and ISAGEN. Between 2008 and 2016 those organizations carried out separately new exploration studies. Public institutions as the SGC (between 2008 and 2012) and the Universidad Nacional de Colombia (between 2010 and 2016) were involved through cooperation agreements with the exploration promoted by ISAGEN. (INGEOMINAS – ISAGEN. 2008; ISAGEN-SGC-Universidad Nacional de Colombia, COLCIENCIAS, 2012a; ISAGEN-SGC-CIF-COLCIENCIAS, 2012b). The results of those studies are confidential.

Some additional work has been done by the SGC and Universities. The SGC carried out a preliminary 3D geological model of Nereidas – Botero Londoño area (Matiz, 2017), based on the 1:25.000 geological map (Martínez, et al., 2014) constrained by gravity and magnetic data (Beltrán, 2017) (Figure 8). The Universidad de Medellín where the geothermal research line is being developed supported the modelling of the geological structure from data shared the SGC (Cervantes, 2019) and carried out a study on geothermal potential of Nevado del Ruiz based on evaluation of heat transfer rock properties (Velez et al., 2018). From this study the geothermal power of the geothermal system of Nevado del Ruiz was estimated in 1.54×10^{-2} MW m−1 ($\sigma = 2.91 \times 10^{-3}$ MW m−1) and 1.88×10^{-2} MW/m ($\sigma = 2.91 \times 10^{-3}$ MW m−1) for the two modeling scenario considered, pessimist and optimist, respectively.

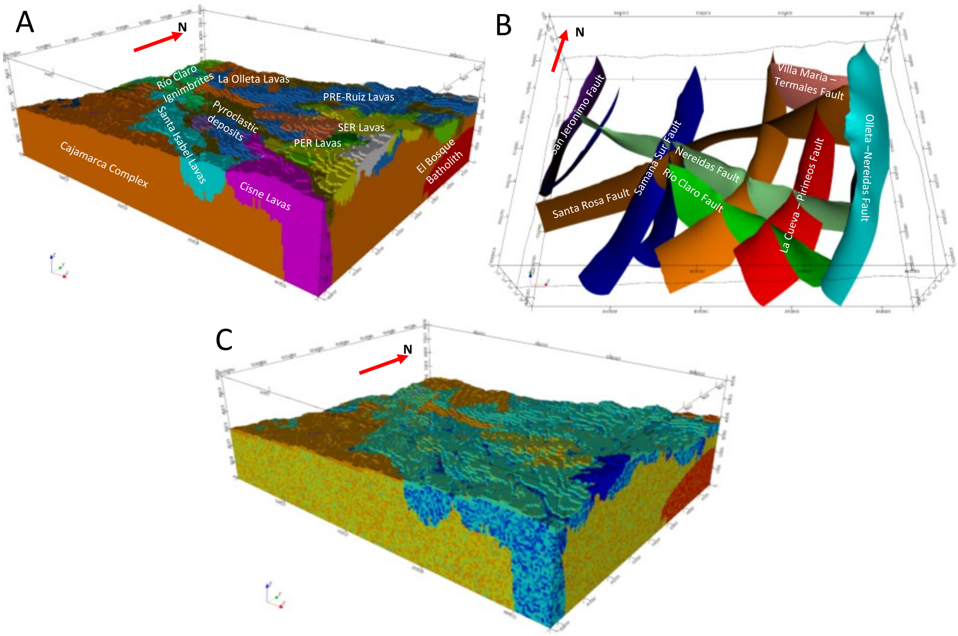

Figure 8: Preliminary 3D geological model constrained by gravity and magnetic data with the software GeoModeller. A. Geological inversion model. B. 3D modelled faults. C. Density model. (Matiz, 2016).

5. GEOTHERMAL UTILIZATION

The utilization of the geothermal resource in Colombia started to register a change with the successful installation of the first heat pump.

The ancestral use of the geothermal resources is based on the hot springs for bathing and swimming. The reported energy utilization of 300 TJ/year installed in 39 localities (Table 2 in Appendix), was previously reported (Alfaro, 2015). The figures have not change as no new information was obtained. As stated in that reference, those figures are based on a very rough estimation instead of statistical records of flow and inlet/outlet temperatures.

The first heat pump for cooling purposes, was installed in an industrial park located in Tocancipá 40 km to the north of Bogotá, the capital city. The heat pump works full time and cools down to -10°C, a room of 90 m^3. 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. Three vertical wells support the heat pump; two of 70 and one of 80 m deep (Ortiz, 2017). This was the first geothermal project to get incentives from the Law 1715, which was formalized by a resolution from ANLA (Colombia, 2018).

Although the geothermal utilization is still limited to the mentioned direct uses and there is uncertainty on the geothermal development previously foreseen by the company ISAGEN in power generation, there are remarkable efforts of the government, power generation sector, universities and the geothermal local community, as never before, orientated to overcome the main barriers that prevent a proper geothermal development of Colombia. As a consequence, as stated before, concrete plans to establish a regulatory frame, definition of risk mitigation strategies, plans to streamline the geothermal exploration and the environmental knowledge of the potential geothermal areas, are being implemented.

6. FUTURE DEVELOPMENT AND INSTALLATIONS

Currently, two (2) geothermal power developments are projected. One corresponds to the project Valle de Nereidas, Nevado del Ruiz, which foresees a 65 MWe installed capacity power plant (CHEC-EPM, 2017). The other one is the installation of 5 MWe from low-temperature geothermal water (Ecopetrol, 2019).

7. CONCLUSIONS

The geothermal resources in Colombia are abundant and wide spread. Convective systems, possible of high enthalpy, located in the Colombian Andes. Conductive geothermal resources are hosted in sedimentary basins. Up to now, the exploration studies have been focused on convective systems.

The geothermal exploration studies have been extended to new areas. Currently the government, through the SGC, has completed surface exploration studies in the geothermal systems of Paipa, Azufral Volcano. Significant advances have been reported in the geothermal areas of San Diego, Cerro Machín and Paramillo de Santa Rosa, besides those realized in joined work through cooperation projects in the Nevado del Ruiz. A new stage of wider coverage of exploration is foreseen, based on the actions derived from the energy transformation and modernization undertaken by the government through the Ministry of Mines and Energy.

Positive new signals to the geothermal development in Colombia come from the national government, the academy and a flourishing local geothermal community.

The expectations on the geothermal development in Colombia is reflected in the investment and the numbers of professional involved in exploration and specific academic work, even without large-scale projects in development.

The utilization of the geothermal resources of Colombia started to change. Besides the traditional utilization in bathing and swimming, a successful heat pump for cooling was installed recently.

ACKNOWLEDGEMENTS

The authors are grateful to the persons who shared information to write this paper: Engineer Julián López from CHEC; Engineers Juan Carlos Aponte y Henry Josué Zapata from UPME, Doctor Daniela Blessent from the Universidad de Medellín, Engineer Julián López de CHEC-EPM, Geologist Alberto Ortiz from the company SAGG S.A.S., the Engineer Hermes Meneses from ECOPETROL and the Geologist Valeria Garcia from AGEOCOL. Also thanks to the Geociencias Básicas Technical Direction, Geologist Mario Cuellar and Alberto Ochoa, from the Servicio Geológico Colombiano (SGC), for its support and trusting and to members of the Geothermal Exploration Group of the SGC for their friendship, permanent support, commitment with the geothermal research and share the dreams of knowing and applying the geothermal resources of Colombia.

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APPENDIX

TABLE 1. 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
In operation in December 2019	0	0	5.298	13.923	12.260	53.698	0	0	100	88	17.658	67.709
Under construction in December 2019	0	0	0	0	60	262	0	0	0	0	60	262
Funds committed, but not yet under construction in December 2019	0	0	77	236	87	381	0	0	200	175	364	792
Estimated total projected use by 2020	0	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 capacitiy and assuming 50% operation

TABLE 2. UTILIZATION OF GEOTHERMAL ENERGY FOR DIRECT HEAT AS OF 31 DECEMBER 2019 (other than heat pumps)

Locality	Type	Maximum Utilization					Capacity	Annual Utilization		
		Flow Rate	Temperature (°C)		Enthalpy[2)] (kJ/kg)			Ave. Flow	Energy[4)]	Capacity
		(kg/s)	Inlet	Outlet	Inlet	Outlet	(MWt)	(kg/s)	(TJ/yr)	Factor[5)]
Faciliities in 39 localities										
TOTAL	Bathing and swimming	159					18	79,4	300	

TABLE 3. 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 Prograr
(6) Private Industry

Year	Professional Person-Years of Effort [1]					
	(1)	(2)	(3)	(4)	(5)	(6)[2]
2015	9		2	1		8
2016	10		2	10		6
2017	10	2	2	15		6
2018	12	2	4	6		5
2019	12	1	4	8		5
Total	53	5	14	40		30

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

TABLE 4. TOTAL INVESTMENTS IN GEOTHERMAL IN (2019) US$

Period	Research & Development Incl. Surface Explor. &	Field Development Including Production	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