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GEOPHYSICS

Geophysical modeling of the middle Bogotá River Basin with support from interpretation of electrical resistivity, gravity, seismic and borehole data to evaluate potential deep aquifers

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ABSTRACT

The main objective of this research was to develop a geological and geophysical modeling to infer the geometry and thickness in the sedimentary sequence of the middle basin of the Bogotá River with emphasis on the Guadalupe Group, reconstructing the stratigraphic sequence, structural setting, hydrogeological modeling, and potential geothermal uses. Various geophysical methods were applied, including vertical electrical soundings (VES), and magneto telluric soundings (MT-VES), whose results were complemented with the interpretation of seismic lines, regional and local gravity anomaly maps, and borehole data, among others, which allowed to model the subsurface from the surface to depths beyond 3000 meters, with emphasis on the interval between 500m to 1000m depth. Integrated models were developed from interpretations of electrical resistivity data, gravity and magnetic data, reflection seismic and borehole data. Based on the results, potential deep aquifers have been proposed to be confirmed by drilling. These deep aquifers can contribute to satisfy the need for water, which historically has been explored and overexploited from shallower aquifers in this sector of the basin. A recommendation was also made to consider the potential of low enthalpy thermal energy for agro-industrial purposes associated with groundwater's temperature at the depth of this research. As a result, the modeled sedimentary sequence is characterized by a thick quaternary overburden overlying an intensively folded and faulted Neogene, Paleogene, and upper Cretaceous formations, mainly composed of siltstone, sandstones, and shale sequences of fluvial and marine environment, including facies of marine regressions and transgressions near the coastline. The penetration obtained allows establishing a high hydrogeological potential in the first 2000m depth, especially associated with the Guadalupe group, where the Labor and Tierna and Arenisca Dura formations have the highest hydrogeological potential. In addition, the preliminary estimation of thermal gradients suggest that low enthalpy geothermal energy potential is feasible to be used for the agro-industrial demand of energy of the study area.

Keywords: Magnetotelluric soundings; deep aquifers; low enthalpy geothermal energy

Modelo geofísico de la cuenca media del río Bogotá con apoyo de la interpretación de datos de resistividad eléctrica, gravedad, sísmica y sondeos para evaluar potenciales acuíferos profundos

RESUMEN

El objetivo principal de este proyecto ha sido desarrollar un modelo geológico y geofísico para inferir la geometría y espesor en la secuencia sedimentaria de la cuenca media del río Bogotá con énfasis en el Grupo Guadalupe, reconstruyendo la secuencia estratigráfica, el estilo estructural, el modelo geológico conceptual y las posibles aplicaciones geotérmicas. En el estudio se aplicaron diversos métodos geofísicos, entre ellos sondeos eléctricos verticales (VES) y sondeos magnetotelúricos (MT-VES), cuyos resultados se complementaron con la interpretación de líneas sísmicas, mapas de anomalías gravimétricas regionales y locales, y datos de perforaciones, entre otros, que permitieron modelar el subsuelo desde la superficie hasta profundidades superiores a los 3000 metros, con énfasis en el intervalo entre 500m y 1000m de profundidad. Se desarrollaron modelos integrados a partir de interpretaciones de datos de resistividad eléctrica, datos de gravimetría y magnetometría, sísmica de reflexión y datos de pozos. Como resultado, se ha propuesto la presencia de posibles acuíferos profundos a ser validados mediante perforación. Estos acuíferos profundos pueden contribuir a satisfacer la necesidad de agua, que históricamente ha sido explorada y sobreexplotada a partir de acuíferos someros en este sector de la cuenca. También se recomienda considerar el potencial de la energía térmica de baja entalpía para fines agroindustriales asociados a la temperatura del agua subterránea a la profundidad del subsuelo de esta investigación. Como resultado, la secuencia sedimentaria modelada se caracteriza por una gruesa cobertura cuaternaria que se superpone a formaciones del Neógeno, Paleógeno y Cretácico superior intensamente plegadas y falladas, compuestas principalmente por secuencias de limolitas, areniscas y lutitas de ambiente fluvial y marino, incluyendo facies de regresiones y transgresiones marinas cerca de la línea de costa. La penetración obtenida permite establecer un alto potencial hidrogeológico en los primeros 2000m de profundidad, especialmente asociado al grupo Guadalupe, donde las formaciones Labor y Tierna y Arenisca Dura tienen el mayor potencial hidrogeológico. Además, la estimación preliminar de gradientes térmicos sugiere que el potencial de energía geotérmica de baja entalpía es factible de ser utilizado para la demanda agroindustrial de energía del área de estudio.

Palabras clave: Sondeos magnetotelúricos; acuíferos profundos; geotermia de baja entalpía;

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1. Introduction

The purpose of this research is to model the geometry and thickness of the middle Bogota River basin with emphasis on identifying potential deep aquifer formations, related to the Guadalupe Group, from the interpretation of electrical resistivity, gravity, seismic reflection and borehole data. An emphasis of modeling the top and base of the Guadalupe Group within the sedimentary sequence has guided this research. Additionally, estimates of thermal gradients of interest for low-enthalpy geothermal energy in agro-industrial uses are presented.

The methodology applied in this project included data collection of different entities as the Servicio Geológico Colombiano (SGC), Corporación Autónoma Regional de Cundinamarca y Boyacá (CAR) and private companies. Once the data was compiled and standardized, a complementary geophysical data acquisition was designed and implemented. The applied geophysical methods included Vertical Electrical Sounding (VES) and MT-VES (Magneto telluric VES) modeling the first 3000m depth, complemented with the interpretation of seismic lines and gravity anomalies. A network of VES and MT sounding was acquired, processed, and interpreted to generate 1D, 2D and 3D conceptual geologic models. Finally, conclusions and recommendations are presented.

Nowadays, the importance of preserving water sources has become of supreme importance for all human beings, especially in those places in the world where water is very scarce or unavailable, which means that a large part of the population does not have easy access to this resource, either for daily consumption or any other type of activities such as agriculture (United Nations, 2023). Freshwater is fundamental as this resource corresponds to approximately 3% of the total water of planet Earth (Aqua Foundation, 2024). Based on the above, the groundwater resource has increased its important value since it can be contributed to meet the water needs required by society (USGS – El Agua del Mundo, 2021). Although groundwater has been exploited since 4000 years B.C. and in Colombia for more than 100 years, water supply is still insufficient in many areas of the country, leaving more than three million people without this resource (Minambiente, 2023). In Colombia, the largest population, with more than ten million people, is in the Sabana de Bogota, including the capital of the country, in the middle Bogota River basin; Additionally, this area has the highest concentration of industrial and agriculture zones. Consequently, the water resource is insufficient to cover the demand. This research contributes to model the geological, structural, and hydrogeological aspects, of potential deep aquifers in the first 3000m depth, that at present are still poorly understood (IDEAM, 2022).

Geographic location of the study area:

The study area is located in the axial flat zone of the Cordillera Oriental of the Colombian Andes Range, more specifically in the Sabana de Bogotá, covering an area of approximately 615 km^2. This area has excellent access roads due to the proximity to the city of Bogotá, capital of the country (Figure 1). Besides, it has a thick quaternary overburden that offers good flat topographic conditions to carry out electrical, MT, seismic and gravity surveys.

Geological setting

The geologic map of the study area is presented in the sheet 227, La Mesa at 1:100.000 scale (Ingeominas, 2001; Acosta *et al.,* 2001; Montoya and Reyes, 2003; Ingeominas, 2010; Corredor and Terraza, 2015, Van Der Hammen, 2003). Cretaceous, Paleogene, Neogene and Quaternary lithological units are outcropping in the study area, with the quaternary (recent) units being the predominant overburden unit limiting the exposure of deeper formations (Figure 2). Following the nomenclature proposed by Renzoni (1962), these units are named in chronological order, from the oldest to the youngest, as follows: Chipaque Formation, Guadalupe Group, consisting of the Arenisca dura, Plaeners and Labor-Tierna formations, whose definition is found in the work of Pérez & Salazar (1971), and the youngest units, of the Paleogene and Neogene periods, which include the Guaduas, Cacho, Bogotá, Regadera, Subachoque, Tunjuelito river and Sabana formations (Table 1, Figure 3).

Structural geology

Tectonic activity was active in the Miocene, with faulting, folding, and the uplift of the Cordillera Oriental, where the basin of the present-day Sabana de Bogotá was formed (Figure 4). Subsequently, the basin was filled with the Subachoque, Tunjuelito River and Sabana Formations and at the same time glaciation events occurred that generated the deposits of the Siecha and Chisacá Formations (Velandia and Bermoudes, 2002; Ingeominas, 2005; Consorcio Magneto 2018, 2018; Consorcio Alto Suarez, 2018).

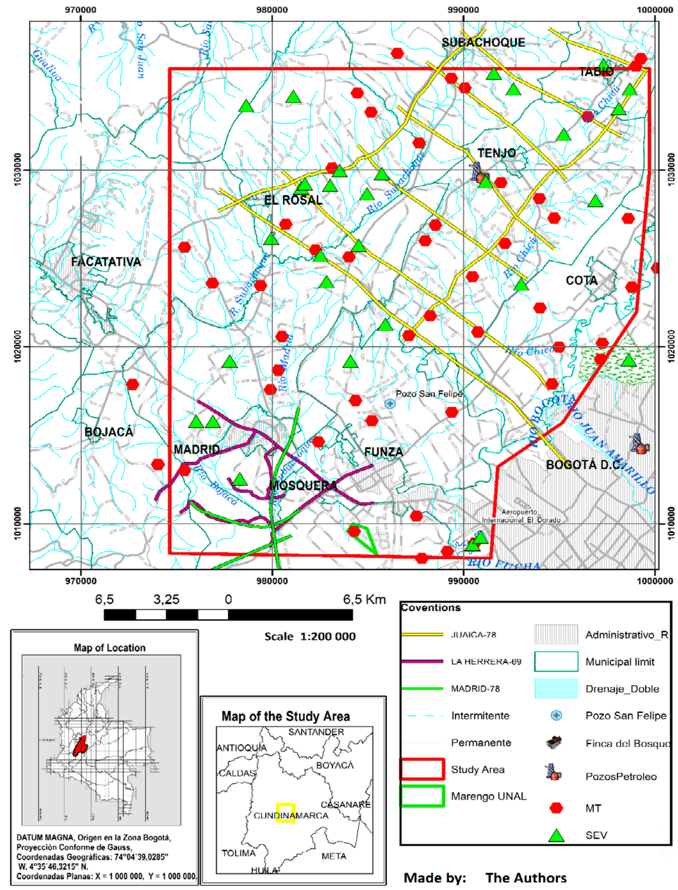

Figure 1. Location map of the study area, including the municipalities of Cota, El Rosal, Funza, Madrid, Mosquera, Subachoque, Tenjo, in the Middle Rio Bogota basin, Sabana de Bogotá, Cordillera Oriental, Colombia. The location of VES and VES-MT is also indicated.

Within the area of the Bogotá River basin, two structural styles can be established: the first, located on the eastern flank of the Cordillera Oriental, to the east of the Checua syncline, with thrust faults verging to the east, and the others of lesser importance behaving as back thrust with vergence to the west. The second structural style is presented to the west, it is characterized by thrust faults with vergences to the west as imbricated systems that arise and are controlled by northwest-direction faults that serve as lateral ramps. In addition to the regional structures, there are zones with salt diapirism located in the core of the anticlines. Diapirism is a generator of complex structures such as those observed in Zipaquirá, Nemocón and possibly between the sector of Sesquilé and La Calera, located north and east of the study area.

Hydrogeology

The Bogotá River is the most important river in the area with its main tributaries such as the Bojacá, Juan Amarillo, Subachoque rivers, which are in the province of the Cordillera Oriental, in the middle Bogotá River basin and in the Sabana de Bogotá aquifer system (Alarcón, 1998; CAR, 2006; CAR, 2016a; CAR, 2016b; Geocing SAS, 2012; Mejía and Ramírez, 2016; IDEAM, 2022; Suarez and Carreño, 1982). The climate of the area can vary with temperatures from 6°C to 20°C depending on the time of year and the different climatic conditions. In addition, these climate variations are associated with the terrain elevation which ranges from 600m to 3150 m above the sea level. With these climatic conditions as well as the rough topography of the surrounds due to the geological structures and lithological units, favorable aquifer formations have been explored and exploited, especially the unconsolidated gravel and sands quaternary deposits, sandstones of the Cacho, sandstones of La Guia and Lajosa members of the predominantly claystone Guaduas formations, and the Arenisca de labor - Tierna and Dura formations of the Guadalupe Group (Table 2). Complementary, a low-enthalpy geothermal preliminary estimate was obtained looking for changes in temperatures between 15°C to 19°C and depths from 15m to 150m (Ortiz, 2020) that may be a potential source of low enthalpy geothermal energy for the main economic activities of the area, such as agriculture (floriculture) and livestock.

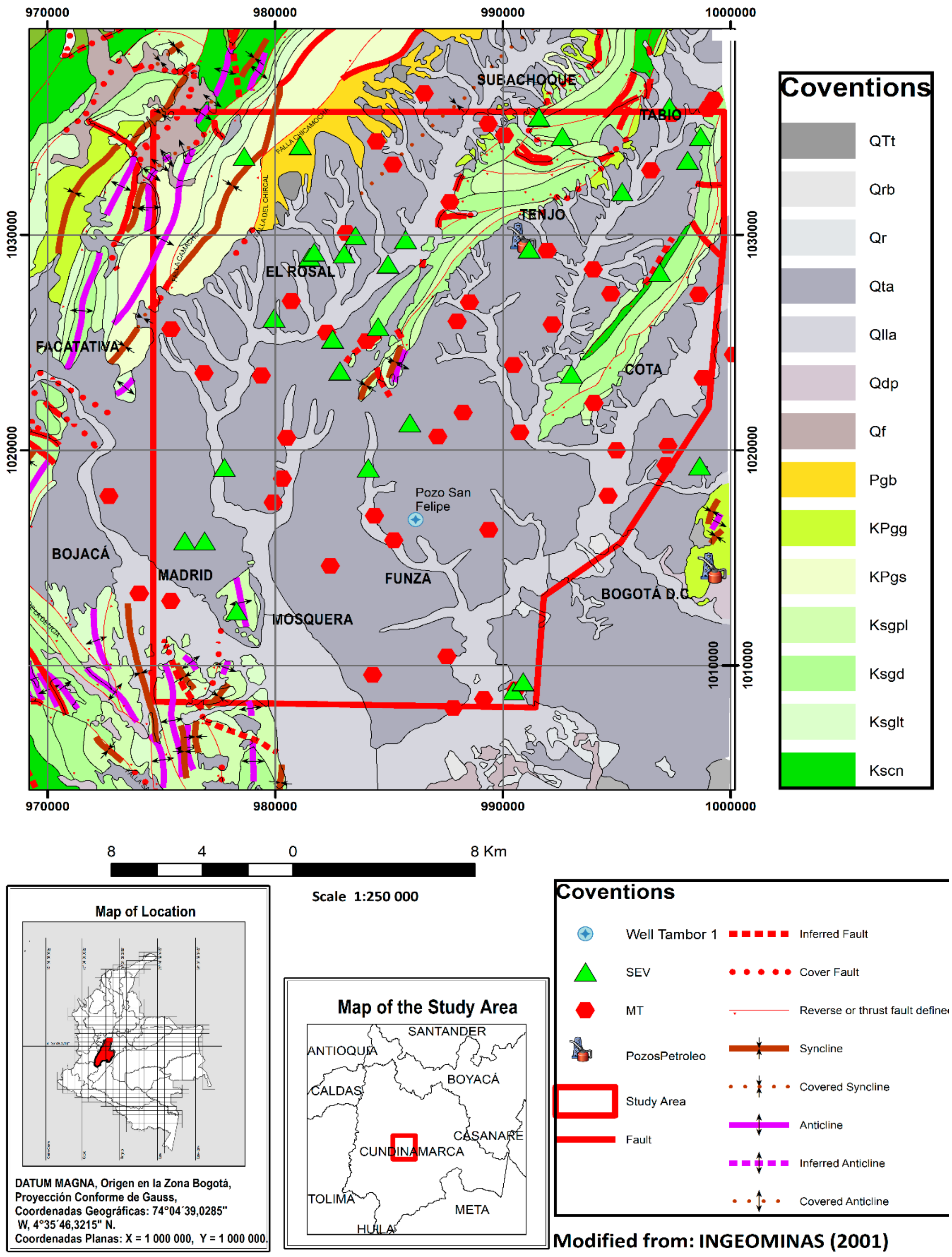

Figure 2. Geological map modified from INGEOMINAS (2001) showing the generalized stratigraphic sequence. The area is mainly covered by quaternary deposits in the flat area. Cretaceous, Paleogene and Neogene formation are outcropping in the mountainous areas.

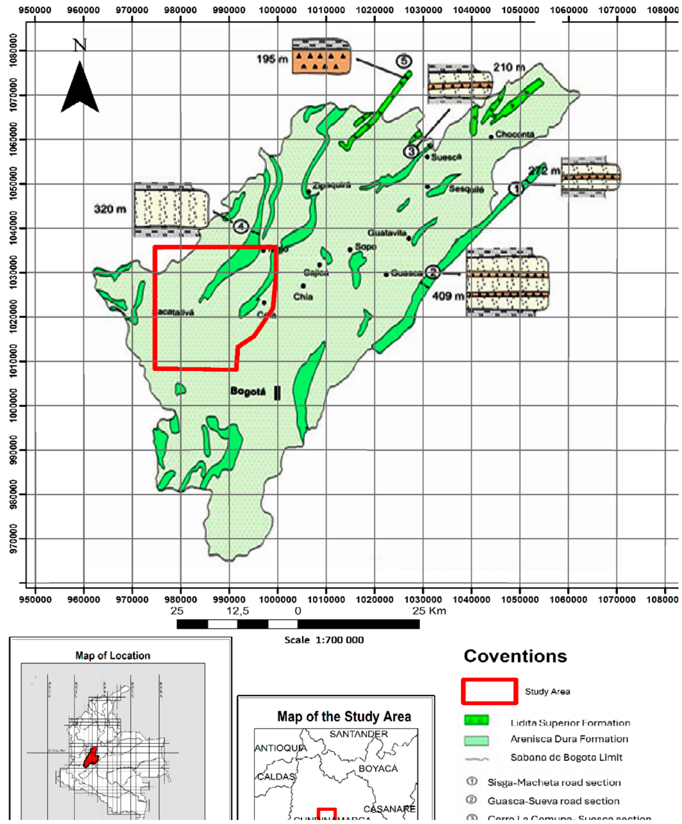

Figure 3. Distribution of outcrops and thickness of the Arenisca Dura and Lidita Superior formations, Sabana de Bogotá. By this integrated geophysical survey, these units are being modeled and projected at depth below the overlying younger stratigraphic units. The outcrops correspond to the recharging areas by infiltration of meteoric waters that flow to the potential aquifer formations at the subsurface. Modified from Montoya & Reyes, Ingeominas, 2005.

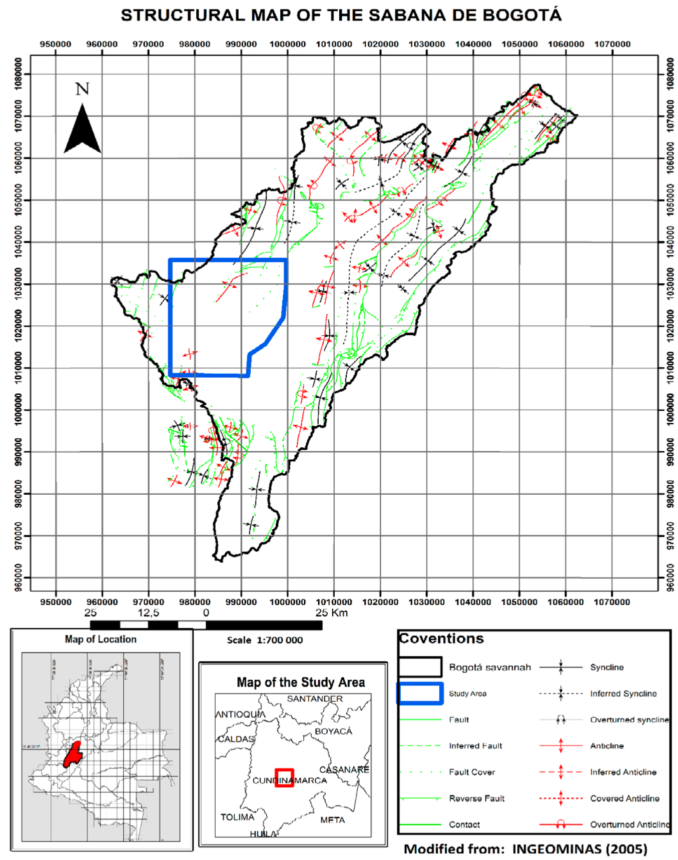

Figure 4. Structural Map of the Sabana de Bogotá, Upper and middle Bogotá River basin (modified from Montoya & Reyes, Ingeominas, 2005). This region has been intensively folded and faulted, there are several exposed and hidden anticline and syncline structures-oriented NE-SW.

Table 1. Diagram of chrono-equivalent lithostratigraphic units of the Sabana de Bogotá, Cordillera Oriental (Montoya & Reyes, INGEOMINAS 2005). The stratigraphic units proposed by Montoya & Reyes (at the right) are adopted in this study.

Chrono-equivalent lithostratigraphic units of the Sabana de Bogotá, Cordillera Oriental (Montoya & Reyes, INGEOMINAS 2005)			
AGE	FORMATION	HYDROGEOLOGY UNIT	RESISTIVITY
Pliocene	TILATA	ACUIFER	12 - 1010 ohm-m
Miocene			
Oligocene			
Eocene	Regadera	AQUITARD	70 - 110 ohm-m
	Bogotá	ACUIFER	8 - 45 ohm-m
Paleocene	Cacho	ACUIFER	52 - 401 ohm-m
	Guaduas	AQUITARD	15-20 ohm-m
Matrichiano	Labor-Tierna	ACUIFER	20-250 ohm-m
Upper campanian	Plaeners	AQUITARD	10-20 ohm-m
Lower Campanian	Dura	ACUIFER	20-250 ohm-m
Santonian	Chipaque	AQUICLUDE	15-20 ohm-m
Coniacian			
Turonian			
Cenomunian	UNE	ACUIFER	20-250 ohm-m

Table 2. Generalized hydraulic parameters of hydrostratigraphic units. (Source: Bermoudez & Quiroz, 2002). The Labor and Tierna and Arenisca Dura formations show excellent flow, transmissivity, hydraulic conductivity and specify capacity values in the Guadalupe Aquifer Complex.

	FORMATION	PREDOMINANT LITHOLOGY	WELL DEPTH (m)	FLOW (l/sec)	TRANSMISSIVITY (m2/day)	HYDRAULIC CONDUCTIVITY (m/day)	SPECIFIC CAPACITY (l/sec/m)
ARTESIAN BASIN COVERAGE	*Aquifer Complex of the Neogene - Quaternary Unconsolidated Deposits*						
	Alluvial Deposits (Qal)	Sands, silts and gravels.	< 30	0.1-2			<0.1
	High Terrace (Qta)	Clays. Silt, sands and gravels.	30-300	1-8	5-100	0.1-5	0.1-0.5
	Tilata (NgQt)	Gravels with sandy matrix, quartz sands, silts, clay and peat.	200-600	10-50	150-900	<9	0.5-3
	Relatively Impermeable Paleogene Complex						
	Usme (Pgu)	Siltstones and claystones with intercalations of sandstones of different sizes.	< 100	<1	<3		
	Regadera (Pgr)	Quartz sandstones of different sizes, with clayey matrix intercalated with claystones and siltstones.	< 100	<1	<3		
	Bogotá (Pgb)	Claystones with intercalations of sandstones in the lower part.	30-150	0.3-1.5	<3		<0.03
ARTESIAN BASIN COVERAGE	Cacho (Pgc)	Medium-grained to conglomeratic quartz sandstones with thin layers of argillites	45-160	0.2-6	9-500	0.3-2	0.1-0.6
	Guaduas (KPgg)	Claystones with sandstone strata and coal seams.	50-150	0.3-2	<5		<0.03
ARTESIAN BASIN FLOOR	*Guadalupe Aquifer Complex*						
	Labor and Tierna (Kit)	Fine- to coarse-grained sandstones interbedded with claystones and siltstones.	60-600	2-60	15-600	0.3-2	0.1-6
	Plaeners (KP)	Claystones, siltstones and lydites.	100-600	1-4	5-10	0.1-0.3	20.1
	Arenisca Dura (Kad)	Fine quartz sandstones with siliceous cementation, interbedded with siltstones and claystones.	100-600	4-30	5-350	0.5-21	0.1-2

Geophysical exploration

The Bogotá River basin has been the target of various geological and geophysical surveys at regional and local scales. The greatest lack of knowledge of the aquifer formations of the basin is related to the geometric and volumetric characteristics of the units and structures that may favor the infiltration, storage, and exploitation of groundwater. These parameters have been partially defined in isolated sectors in exploitation, without allowing an extrapolation and lateral and vertical projection of the potential aquifer formations to other sectors of the basin. In this study, the geophysical exploration makes its greatest contribution to advance in the understanding of the modeled lithologies and geological structures of hydrogeological interest. An integrated geophysical survey was conducted to determine the thickness, top and base of the geological formations in the middle Bogotá River basin. It included the compilation, design, acquisition, processing, and interpretation of several VES vertical electrical soundings, and magnetotelluric (MT-VES) soundings in order to model the top and base of aquifer geological formations, especially the sandstone formations of the Guadalupe group. The gravity method makes it possible to identify lateral variations in the specific density distribution of subsurface formations by systematically measuring the gravitational field. In the context of the middle Bogotá River basin, regional gravity studies have revealed negative gravity anomalies associated with low-density infill materials in the basin, compared to the denser materials presented in the basal and lateral formations (Consorcio Magneto 2018, 2018). Gravity data compiled from the Seismic Microzoning of Santa Fe de Bogotá (Ingeominas *et al*., 1997), consist of 370 gravity measurements were processed to obtain a complete Bouguer anomaly map and its corresponding residual anomalies that to estimates the geometric and depth of the local sedimentary basin (Figure 5).

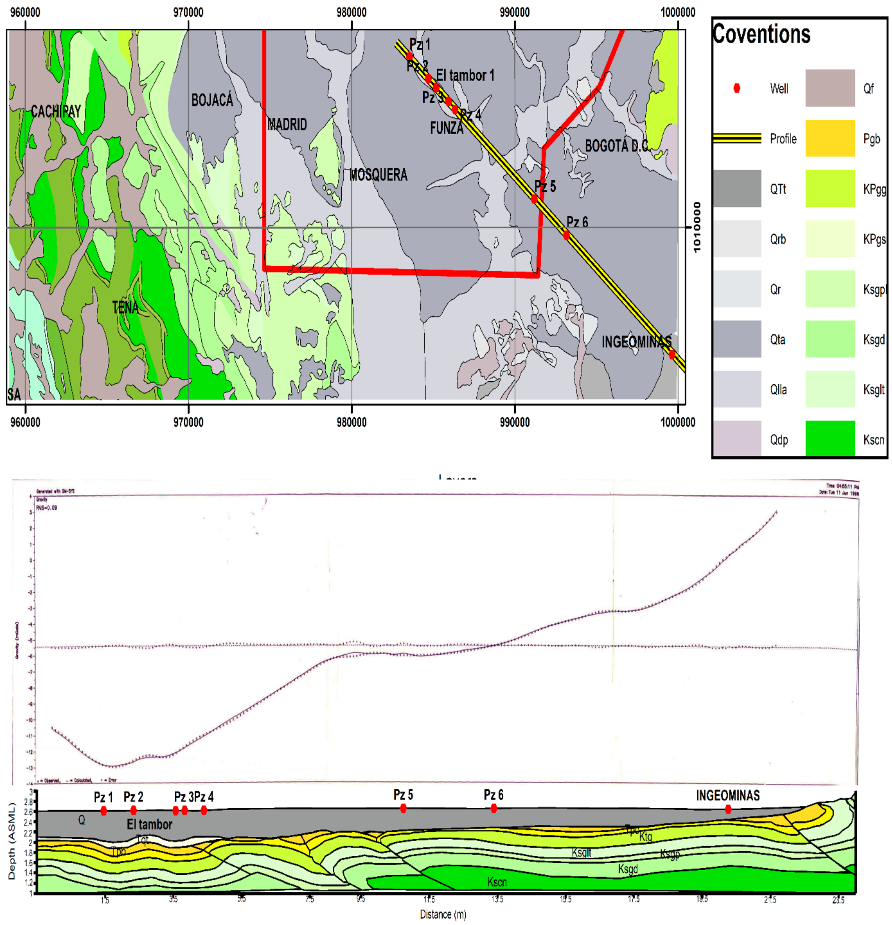

Figure 5. Geological section and its corresponding Bouguer gravity anomaly profile, where the formations of the area are presented. The profile was reconstructed from the municipality of Funza (NW) to the Ingeominas headquarters in the city of Bogotá (SE; Modified from Ingeominas *et al*., 1997). The quaternary coverage is thicker from East (right) to West (left). The Guadalupe group is outcropping in the eastern hills (right) and is deepening to the west. The stratigraphic sequence is intensively folded and faulted. The minimum Bouguer gravity anomalies are in the vicinity of Funza, showing the thicker sequence mainly of unconsolidated lagoon deposits overlying the cretaceous, Paleogene and Neogene lithological units. There is an increasing Bouguer anomaly values to the East, where the Paleogene and Neogene lithological units are outcropping.

These data were used to model the interface between unconsolidated and consolidated lithological units, which allowed estimating the infill thickness of the Sabana Formation. According to the results, this formation has a thickness of 500 meters in the hills of Cota and Suba, and 240 meters between the hills of Suba and the eastern hills of Bogotá. In addition, 520 meters of sediment were measured through exploratory drilling in Suba (Bilbao) conducted by the Secretaría de Ambiente del Distrito (CAR, 2024). Consequently, the average thicknesses modeled is close to the real estimates measured in the boreholes with an error of 5% (Consorcio Magneto 2018, 2018). Gravity data is crucial for identifying regional trends in the basin. This information is valuable in guiding the selection of sites for conducting vertical electrical soundings and magnetotelluric soundings. VES are more suitable for modelling the first 300m of the basin where the lagoon deposits are thin, while magneto telluric soundings are more appropriated for modeling the first 3000m of fluvial and marine thicker deposits (Consorcio Magneto 2018, 2018). This makes it possible to differentiate between those wells to be drilled in areas with positive gravity anomalies which may require shallower depth from those wells located in areas with negative gravity anomalies, where the aquifer formations may be deeper, below the deposits of the Sabana Formation.

Electrical resistivity data modeling

Geophysical exploration methods are applied to obtain indirect and rapid information from the subsurface, which can also be achieved through drilling at a higher cost, thus, geoelectric prospecting allows to reduce and recommend the number and location of exploratory wells and infer the thickness of subsurface lithological units of hydrogeological interest. The electrical resistivity method is based on the study of the variations in the electrical resistivity / conductivity of different types of materials of the underground to oppose the flow of electric current in the presence of an electric field. Through the contrasts of the resistivity values obtained, it is possible to differentiate permeable geoelectric layers such as gravels, sands, sandstones and conglomerates from impermeable layers such as clays, silts, claystones and siltstones (Keary and Brooks, 1991; Koefoed, 1979; Lowrie, 2007; O´Neil, 1975; Telford *et a*l., 1990). The results of the geoelectrical interpretation takes into account the Schlumberger’s algorithm, assigning the following resistivity values to the lithological units in the Middle Rio Bogotá basin (Bovachev, 2003; Gosh, 1970; Velosa, 2013; Table 3).

Table 3. Electrical resistivity values and their corresponding lithological interpretation of the Sabana de Bogota basin (modified from Velosa, 2013).

Resistivity (ohm-m)	Lithology	Observations
5 to 20	Clays	Potential seal
20 to 45	Sandy clays	Potential seal
45 to 80	Claydy sands	Potential aquifer
80 to 180	Saturated sandstones	Potential aquifer
180 to 1000	Saturated sandstones and conglomerates	Potential aquifer
Greater than 1000	Low saturated sandstones and conglomerates	Potential aquitard

A 2D cross section of Figure 6 shows the distribution of the electrical resistivity values obtained in the VES's, showing vertical and lateral variations, as follows: In the first meters the values reach resistivities of 770 ohm-m, in the central part there are variations between 5.1 and 10.5 ohm-m and in the deepest part up to 242 ohm-m. Stratigraphic correlation: The values mentioned above and others displayed in the profiles are correlated, from top to base, as follows: 770, 184 and 546 ohm-m, corresponds to dry soil, the values between 95.7 and 170 ohm-m correspond to unconsolidated deposits (Qal and Q2t) consisting mainly of sands with a varying thickness from 5m and 73m. 5.1 to 12 ohm-m, correspond to claystones, which are related to the Bogotá (E1b) and Guaduas (K2E1g) formations. Its approximate apparent thickness varies between 60 m and 326 m. 54.6 ohm-m. correspond to sandstones of the La Guia and Lajosa members of the Guaduas Formation (K2E1g). 242 ohm-m, correspond to a layer of conglomeratic sandstone of the Guadalupe Group (Ksg), with an apparent thickness of approximately 200 m. 89.5 and 145 ohm.m correspond to sandstones of the Guadalupe Group (Ksg). Structurally, the synclinal fold is a hidden structure covered by unconsolidated deposits. In addition, since there is no certainty in the contact between the Bogotá Formation (E1b) and the Guaduas Formation (K2E1g), it is not possible to have a clear visualization of the fold. From the hydrogeological point of view, in this sector that comprises a flat part in the municipality of El Rosal, the sands of the Quaternary deposits (Qal and Q2t) are classified as open aquifers with surficial recharge. The sandstones of La Guia and Lajosa members of the Guaduas Formation (K2E1g) are confined aquifer with claystones at the bottom and top of the sandstone members.

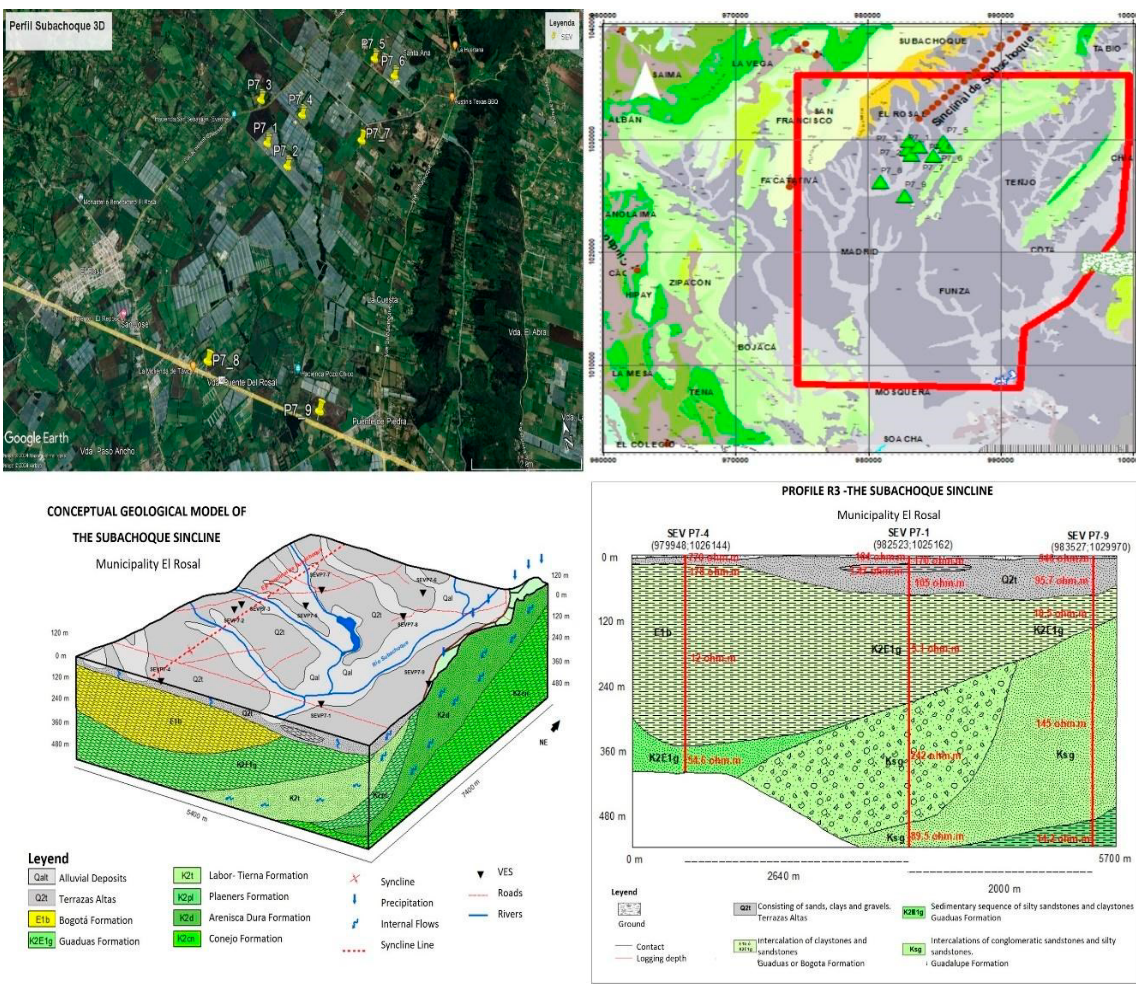

Figure 6. 2D modeling of the Subachoque Syncline, interpreted from VES electrical resistivity data. The Guadalupe group is located at the lower modeled stratigraphic sequence below the Guaduas and quaternary deposits. 3D modeling of the Subachoque Syncline, interpreted from VES electrical resistivity data Conceptual geological model of the Subachoque syncline, located in the municipality of El Rosal, with a SW-NE orientation. All vertical electrical boreholes (VESs) obtained in the area are incorporated. The diagram depicts variations in the lithological composition and path of groundwater streams. (Consorcio Magneto 2018, 2018).

The conglomerate and sandstone level of the Guadalupe Group (Ksg) behaves as a deeper confined aquifer in this synclinal structure. The conceptual geological model of the Subachoque Syncline, in the municipality of El Rosal and Puente de Piedra shows a SW to NE direction and covering an area of 5400 m wide by 7400 m long. The conceptual geological model shows the western flank of the Subachoque syncline, where the layers are dipping toward the center of the basin in a NW direction. The outcropping units present in the mountainous zone correspond to the Arenisca dura formation, of the Guadalupe Group, this sector being a porous permeable unit recharged by precipitation and infiltration in contact with meteoric waters. The Labor-Tierna Formation, of the Guadalupe Group, is recharged by infiltration, although it is not exposed at the surface, it is underlying saturated permeable Quaternary deposits. The Quaternary units behave as open (free) aquifers with surficial recharge due to the favorable porosity permeability of their lithology (sands, silty sands, and gravels). The model clearly shows the lithological and structural distribution of the Subachoque syncline, where the thickest sequence of the units is in the central (axial) area of the basin.

Magnetotelluric data modeling

The Magnetotelluric method is a natural-source electro-magnetic (EM) method that operates in the frequency domain: It is based on the measurement of the electric field in the N-S and E-W directions, the three components of the natural magnetic field are also measured, these fields flow in the subsurface at different frequencies (depths), once the measurements of both fields are obtained, the electrical resistivity of the subsurface can be determined (Keary and Brooks, 1991; Lowrie, 2007; Simpson, 2005; Telford *et a*l., 1990). The depth of these fields depends on the frequency. Lower frequencies can reach greater depths and vice versa.

The MT profile 1 has a total length of 14 km, with a general SW-NE direction. This profile includes the MT 80, MT 70, MT 81, MT 66, and MT 82 MT-VES soundings (Figure 7). The profile is in the municipality of Subachoque. Geologically, it is located on a Quaternary alluvial deposit, parallel to the hinge of a Subachoque synclinal on one of its flanks. The dominant geoelectric unit in the profile corresponds to the U2b () geoelectric unit (Consorcio Magneto 2018, 2018), interbedded and fractured saturated siltstones and sandstones with resistivity values between 4 and 30 Ohm-m, the thickness of this unit reaches 1000 m depth. The continuity of this unit is related to a tabular body of resistivities between 80 and 130 Ohm-m and extending with a thickness of 100 m between Km 4 and Km 7, as well as by a small lens of no more than 400 m and 2 km of extension near the surface between Km 12 and Km 14.

Table 4. Description of the geoelectrical units used to perform the geological interpretations with respect to the measured electrical resistivities (Consorcio Magneto 2018, 2018).

Geoelectrical Classification of MT Resistivity Values		
Geoelectric unit	**Electric resistivity (ohm.M)**	**Geological association**
U1	Variable	Intercalation of silt sands and clays forming fluvial plains and terraces
U2a	5-10	Intercalation of fractured claystones, siltstones, mudstones and mudstones with presence of saturation.
U2b	10-50	Intercalations of fractured siltstones and sandstones with presence of saturation.
U2c	50-200	Fractured sandstones
U3	1-5	Shear Zone

Given the parallelism of the profile with the Subachoque syncline axis, the apparent pitch of the units is smooth, so the resistivity contrasts are associated with lateral facies change typical of the geological environment of the site, as well as the possible presence of geological structures that move and delimit structural blocks. The presence of the Bogotá Formation is inferred, the changes in the sequence are based on the known thickness of the sequence and slight resistivity contrasts that could indicate a change in the lithological conditions.

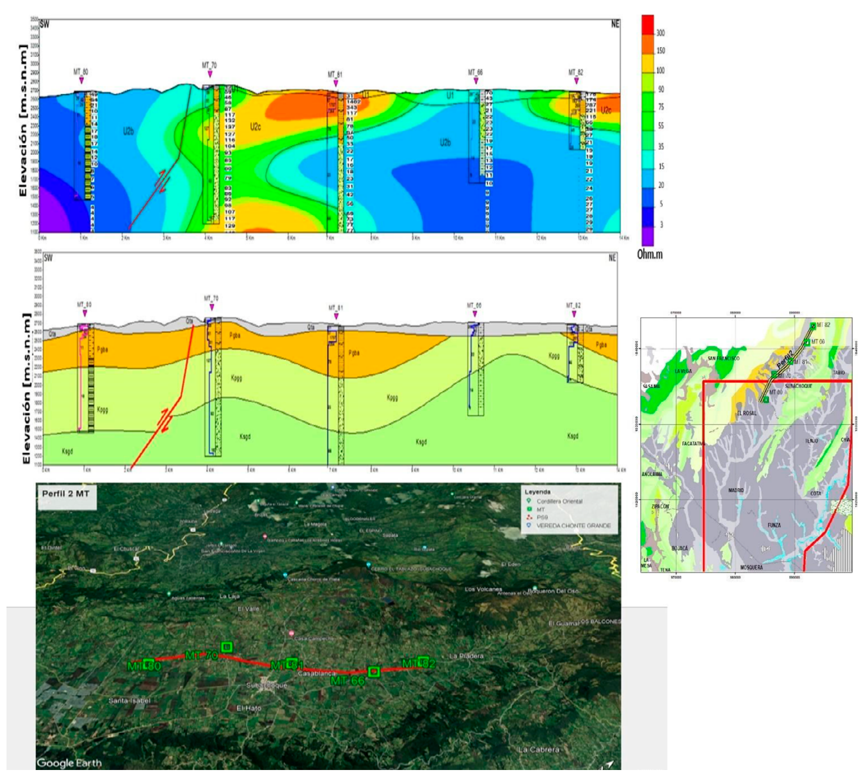

Figure 7. 2D modeling of the Subachoque Syncline, interpreted from MT electrical resistivity data. Profile 1D. The Guadalupe Group is below the Guaduas formation and quaternary deposits at 500m to 700m depth.

The MT profile 2 (Figure 8) has a total length of around 15 km, extending with a general NE-SW direction, including the MT 73, MT 111, MT 105, MT 107 and MT 58 soundings, the profile is located in the municipalities of Facatativa, Madrid and Funza. Geologically, it is located on Quaternary alluvial deposits that are perpendicular to a series of buried syncline and anticline folds. The resistivity contrasts in the profile, as well as the morphology of the contacts, reveal the presence of synclinal and anticlinal structures, apparently the core of the synclines corresponds to conductive geoelectric units (Unit U2a; Consorcio Magneto 2018, 2018), fractured saturated silty claystones and mudstones, with a thickness that can exceed 1400 m and resistivity values below 10 Ohm-m, which extend from Km 3 to Km 6, as well as between Km 10 and Km 15. The U2c geoelectric unit (Consorcio Magneto 2018, 2018) is interpreted as fractured saturated sandstones, which are related to the to an anticlinal fold, the resistivity values are between 40 Ohm-m and can exceed the barrier of 200 Ohm-m in the NE sector. According to the stratigraphic sequence, the arrangement of the geoelectric contrasts and some structural data, it was possible to partially schematize the structural sequence projected from the outcrops to north of the profile towards the subsurface. The Bogotá Formation, composed of mudstones and some claystones, make up the conductive core of the structures. The anticlines are composed of the Guaduas Formation (clay intercalations with scarce sand horizons) and the Guadalupe Group, which is characterized by a higher sandstone content, which could be associated with the increase in resistivity.

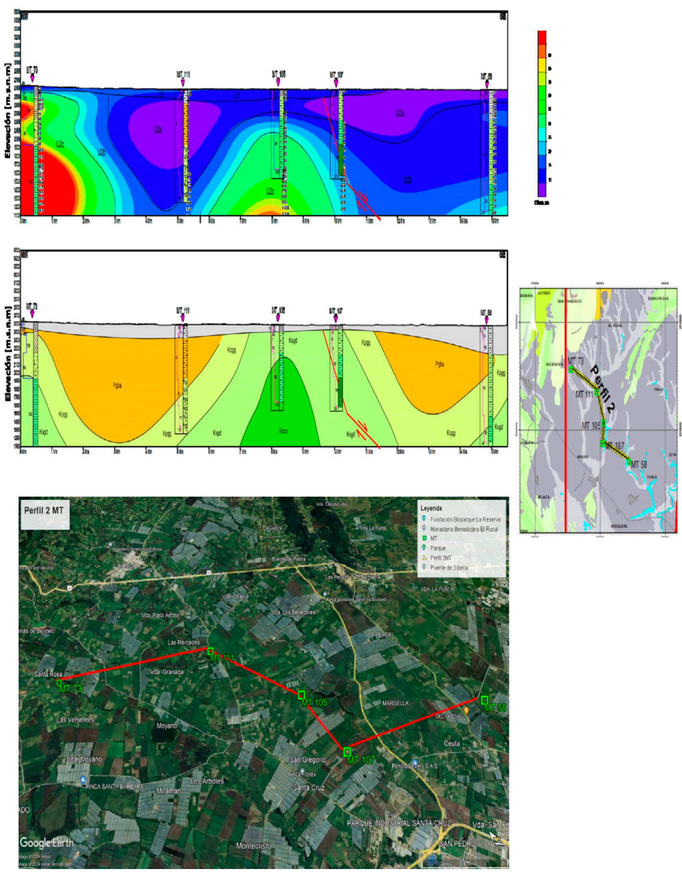

Figure 8. 2D modeling of the Subachoque Syncline, interpreted from MT electrical resistivity data. Profile 2. Two syncline and one anticline structures are modelled showing the stratigraphic sequence with varying thickness and depth.

Seismic reflection

Seismic lines are obtained through a geophysical method used to create an image of the subsurface by emitting seismic waves and recording the reflections that these waves generate in the different layers of the subsurface (Keary and Brooks, 1991; Lowrie, 2007; Simpson, F., 2005; Telford *et a*l., 1990). In the case of deep aquifers, seismic lines are used to infer the structure and geometry of the potential aquifer formation(s). The seismic method consists of the emission of seismic waves from the earth's surface through a set of geophones or sensors that are placed on the earth's surface. These seismic waves travel through the subsurface and upon encountering different layers of rocks or soils, are reflected to the surface. The sensors record these reflections and are used to create an image of the subsurface. The Juaica-78 seismic program conducted by ECOPETROL in the J78-14 line of 12km shown in (Figure 9) and which is associated with the Chitasuga 1 well (Amaya, 2020). The Tabio anticline (red line) was interpreted in the central part of the section as a hanging block structure of the vergence fault to the east of Chital. This fault has the same strike and dip expression. To the west, the Subachoque fault (red line) is interpreted as a backthrust. A stratigraphic sequence has been outlined at depth, from base to top, as follows: Jurassic (light blue) basement, and a sequence of cretaceous units, the dark green Upper Undifferentiated Cretaceous (Kind), then the blue Une formation (Kiu); these two formations are located between 2000 and 3000m depth, the Chipaque formation (Kich) of strong light green color, underlying the Guadalupe group and identifies the upper and lower (Kgs, Kgl) identified of light green color a little fainter respectively these two formations are located between 1500 and 2000m, in the upper part is delineated the Guaduas formation of Orange color (Tkg) this formation is between the surface and 1500m. The interpretation defines the Tabio anticline as a structure resulted from compressive strain and stress related to the inverse Chital fault that was initially extensional during the first stages of rifting and later inverted. This interpreted sequence has been controlled by the Chitasuga -1 well, north of the area. The seismic interpretation has also been useful to adjust the VES and MT-VES interpretations.

In line J78 11 (Figure 10) the following stratigraphic sequence was interpreted: The basement is indicated by a dark brown interfase (Bas). The Paleozoic is indicated by the brown interfase (Pz), the Jurassic units are located only on the left side of the line with the light blue interface (Ju). The Top KIU reflector (blue color) refers to the boundary of the Une Formation with a probable thickness of 100 meters, The Top (Kind) undifferenciated Cretaceous reflector (dark green). The upper Cretaceous has an approximate thickness between 650 and 800 meters. The lower unit top (Kich) reflector (strong light green) corresponds to the boundary of the Chipaque Formation with a possible thickness of 100 meters. The Middle unit top (Kg) reflector (upper and lower light green color) indicates the upper limit of the Guadalupe Group in the region, with an approximate thickness of 650 meters (Escovar Reyes, 2004). The upper unit on top (TKg1) reflector (orange color) corresponds to the upper limit of the Guaduas Formation, with an estimated thickness of 900 to 1000 meters in the area.

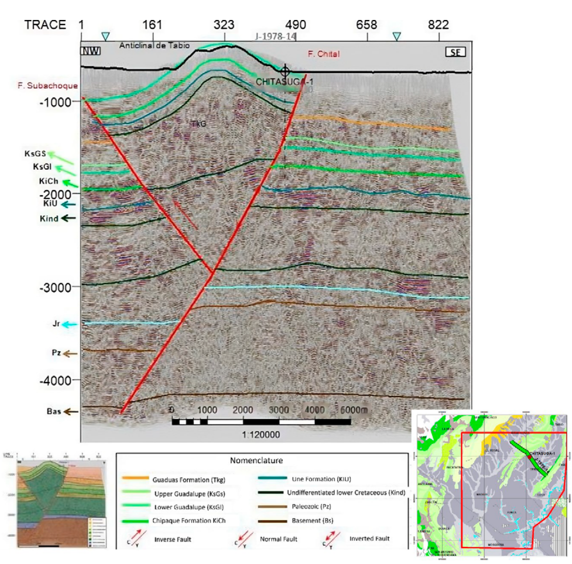

Figure 9. Seismic Line Juaica-78-14. The interfases associated with the lithological formations are related to the different colors described in the legend. On the left side is interpreted geologic section the right side is the location of the seismic and borehole (Amaya, 2020).

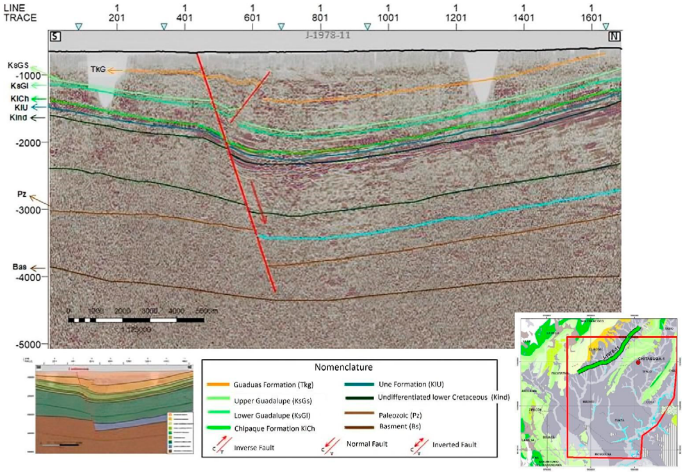

Figure 10. Seismic Line Juaica-78-11. The interfases associated with the lithological formations are related to the different colors described in the legend. On the left side is interpreted geologic section the right side is the location of the seismic and borehole (Amaya, 2020).

Low enthalpy geothermal energy

Geothermal energy is linked to the flow of heat from the Earth's interior, offering a renewable and clean source that can be used to generate electricity, satisfying the basic needs of both the population and industry in their daily activities (Lowrie, 2007; Turcotte D.L., Schubert, G, 2002). The magnitude that characterizes the work of geothermal energy is enthalpy, which is classified as high (150°C or higher), medium (between 100°C and 150°C), low enthalpy (between 50°C and 100°C), and very low enthalpy (between 3°C and 25°C), depending on the temperature (Figure 11, Table 5).

Table 5. Geothermal Energy Classification (https://amas15m.wordpress.com/2015/01/22/energia-geotermica-la-energia-renovable-del-suelo/)

Geothermal Resources		Field Temperature Range	Technology
Very Low Enthalpy		5°C < T < 25°C	Heat Pump
CONVENTIONAL	Low Enthalpy	25°C<T<50°C	May require heat pump
		50°C<T<100° C	Direct Uses
	Medium Enthalpy	100°C<T<150°C	Power Generation / Binary Cycles
	High Enthalpy	T< 150°C	Electricity
UNCONVENTIONAL	EGS-HDR	T <150°C	Power Generation / Binary Cycles
	Supercritical	T<300°C	Electricity/ Hydrogen

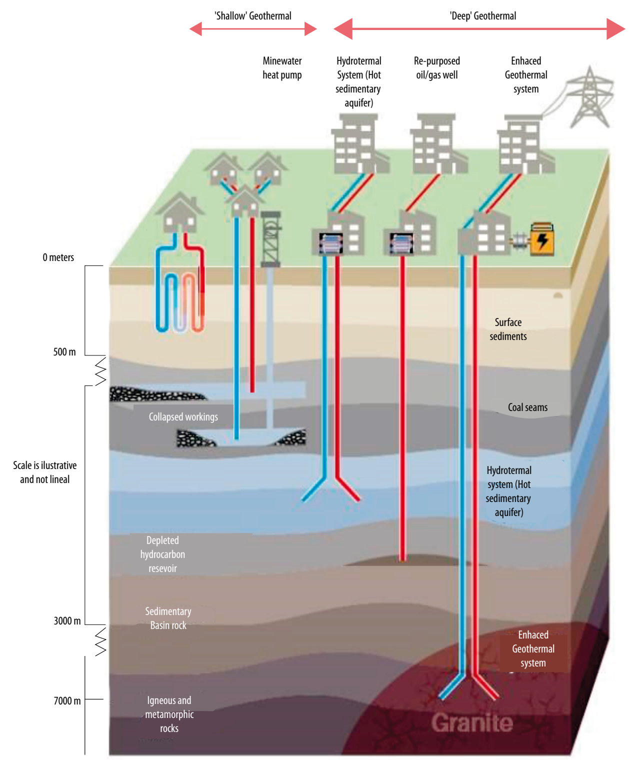

Figure 11. Geothermal system in which a heat pump converts low enthalpy geothermal energy into electricity that can power greenhouses, refrigerated rooms, and other electrical appliances. (Dr Corinna Abesser, 2022)

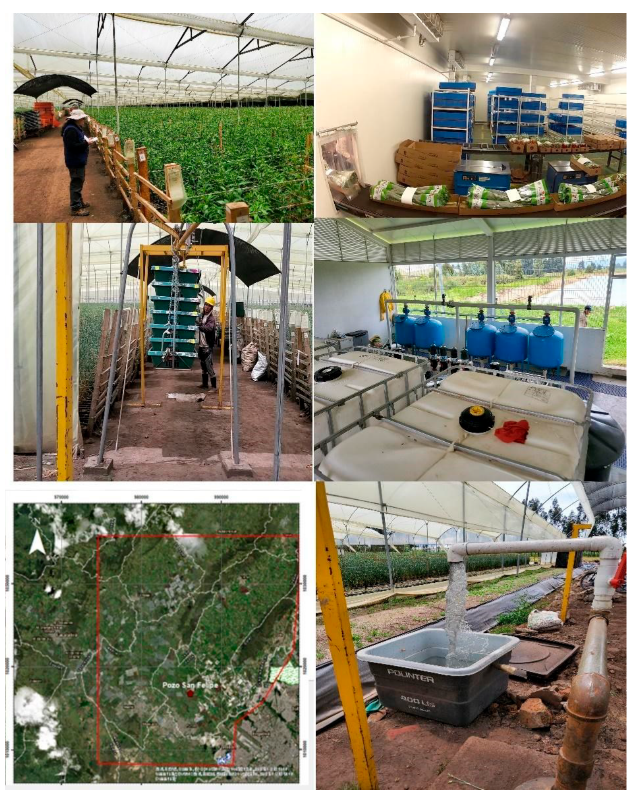

Figure 12. Flores Funza installations including the San Felipe well. On the upper right side is the San Felipe Well, on the upper left side greenhouses and a treated water pond, on the lower right side flower greenhouses and on the lower left side the location of the well.

Near the study area, there is only one known case of very low enthalpy implementation in a company in Tocancipá, upper Bogotá river basin, where a refrigerated room was activated together with an air conditioning system. With the research carried out and the implementation of innovative technologies, for example by the company Flores Funza, a clean energy project has been implemented to supply some of the energy needs (heating and cooling), using a nearby well. This objective would be conducted by means of heat pumps, which operate with extremely low temperature changes (1° to 3°C). The process involves the use of a vertical pipe fed with water from a well, the temperature of which exceeds that of the surrounding environment, thus initiating the operation of the heat pump and thus any associated electrical system. Considering the implementations and other studies already implemented by Flores Funza (Figure 12) in the San Felipe well, the feasibility of this implementation is being estimated. The objective is to take advantage of renewable energies and obtain a dual combined use of groundwater, thus contributing to sustainability and efficiency in the use of water and energy resources.

Conclusions

The interpretation of the electrical resistivity data supports the continuation of the synclinal of Subachoque to the south, underneath the quaternary overburden, limiting the base and top of sandy aquifer formations of the Cacho and sandstone La Guia and Lajosa horizons of the Guaduas formations, in the first 300m depth. The MT soundings have been used to generate 1D and 2D models of the Guadalupe formation, as a potential deeper aquifer formation in the middle Rio Bogota basin in the Sabana de Bogota, at 500m to 1200m depth, that is laterally connected to the outcrops of these units in the surrounding mountains, were the recharging of these aquifers take place by infiltration.

The magnetotelluric soundings were carried out in flat areas of Quaternary deposits that overlie Tertiary and Cretaceous formations, which are intensely folded and faulted by tectonic activity in the Miocene, composed mainly of sequences of siltstone sandstones and shales of fluvial and marine environment, where marine facies generated by regression and transgression events of the coast line produced a sequence of claystone, siltstones, sandstones, which vary vertically and laterally in the basin. The penetration obtained allowed to establish a high hydrogeological potential in the first 2000m of depth, especially from the base to top of the Guadalupe group, where the Labor and Tierna and Arenisca Dura formations are the formations with the highest hydrogeological potential.

The interpreted seismic reflection lines helped to adjust the geoelectrical and magneto telluric models and provided a complete scenery of the folded and faulted stratigraphic sequence, specially, the interfases associated with the Guadalupe Group.

The conceptual geological model defines as units of hydrogeological interest in the upper and middle basin of the Bogotá River the Quaternary deposits of sand and gravels, high terrace deposits, Sabana Formation, the sandstone members of the Bogotá Formation, the Cacho Sandstone Formation, the Guía and Lajosa sandstone horizons of the Guaduas Formation, the Arenisca Labor y Tierna formations and Arenisca Dura of the Guadalupe Group. The most favorable structural feature corresponds to the syncline of Subachoque.

The temperature of groundwater extracted from deep aquifers, with temperature of 18 °C in the San Felipe borehole, classifies it as a low enthalpy geothermal resource. For this reason, its use and exploitation should be considered.

Acknowledgements

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