

First Approach to 3D Resistive Model Interpretation in the Geothermal Area of Paipa, Colombia

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Keywords: Magnetotellurics, resistivity, 3D model, Paipa, Colombia.

ABSTRACT

The geothermal area of Paipa is located in the northwest of Colombia, in the Eastern Cordillera. On this geothermal area the distribution of the electrical resistivity was estimated from a 3D modeling of 88 magnetotelluric soundings with the WSINV3DMT algorithm. The joint inversion of the off-diagonal of the impedance tensor (zxy and zyx) and the tipper was carried out. The 3D model shows a deep resistive anomaly associated with the crystalline basement of the Floresta Massif and above it a layer of intermediate resistivity. That suggests a thicker sedimentary cover to the NW, without an obvious resistive distinction between the formations comprising it. In turn, several conductive anomalies are shown near the surface, to the NW of the models, forming apparent conduits from south to north, possibly associated with leachates from evaporite deposits. While to the SE of the models, resistive anomalies associated with the domes of Alto Los Godos and Alto Los Volcanes and probable intrusions without surface expression to the NW, were observed. Intermediate resistivity zone between the domes of the Alto Los Volcanes and Alto Los Godos, where the location of a possible geothermal reservoir is estimated.

1. INTRODUCTION

Several thermal springs with surface temperatures of up to 76°C (Alfaro, 2002) have provided evidence of the existence of a possible deep geothermal reservoir in the municipality of Paipa, Boyacá, Colombia (Alfaro et al., 2012). Several geological, geochemical and geophysical investigations have been carried out in the area (Cepeda and Pardo, 2004; Velandia, 2003; Franco, 2016; Vásquez, 2012; Llanos et al. 2015; among others) with a view to confirming the geothermal system and its probable exploitation.

Acquisition of magnetotelluric information in the area began in 2012, as part of the research project of the Research and Exploration Geothermal Resources Group of the Colombian Geological Service. Moyano and Vallejo (2015) modeled 69 MT soundings, arranged in 4 profiles perpendicular to the NE regional lineament of the geological structures (Velandia, 2003) and 4 EW profiles. Moyano and Vallejo (2015), in general, identified the resistive responses of the sedimentary cover and basement. Without identifying the possible geothermal reservoir.

The aim of this work focuses on a first approach to the interpretation of the 3D resistive model of the area of greatest geothermal interest in Paipa.

2. GEOLOGICAL SETTING

In the study area (Figure 1), there are Neogene and Quaternary sediments, and Cretaceous and Paleogene sedimentary rocks (Velandia, 2003). These sedimentary sequences are in the basement, which is composed of metamorphic rocks (Floresta Massif) and Paleozoic sedimentary rocks, as well as Paleozoic and Jurassic intrusive rocks (Ulloa et al., 1998; Velandia, 2003).

Cepeda and Pardo (2004) describe the vulcanites that are in the area (Figure 1), belonging to the Plio-Pleistocene activity of the Paipa volcano, with intercalations of sediments from fluvial, lacustrine and colluvial environments, which may be related to the heat source of the geothermal system (Velandia, 2003).

In addition, Velandia (2003), describes the presence of a hydrothermal breccia on the El Durazno sector (Figure 1). This assigns a Quaternary age subsequent to volcanic events. This presents a high degree of advanced argillic alteration (Rodríguez and Alfaro, 2015), suggesting a possible contribution of radiogenic heat to the hydrothermal system, as a product of a granitic intrusion in the zone (Alfaro et al., 2017). On the other hand, in the geothermal area of Paipa was mapped and characterized in three sectors with dome bodies. These sectors are called Alto Los Volcanes, Quebrada Honda, and Alto Los Godos (Figure 1), with ages estimated at 1.76 and 1.8 for the Alto Los Volcanes and Quebrada Honda, respectively, and 2.8, 2.7 and 2.6 Ma for the sector of Alto Los Godos (Rueda, 2017).

In structural geology, Velandia (2003) observed a series of longitudinal and transverse structures to the regional lineaments oriented to the northeast (Figure 1). He described their traces as sinuous and locally discontinuous because they are covered by Neogene and Quaternary deposits, both sedimentary and vulcano-clastic. This makes it difficult to interpret structural relationships between the Preneogene units in the Cundiboyacense Altiplano and affecting the sedimentary sequence (Velandia, 2003).

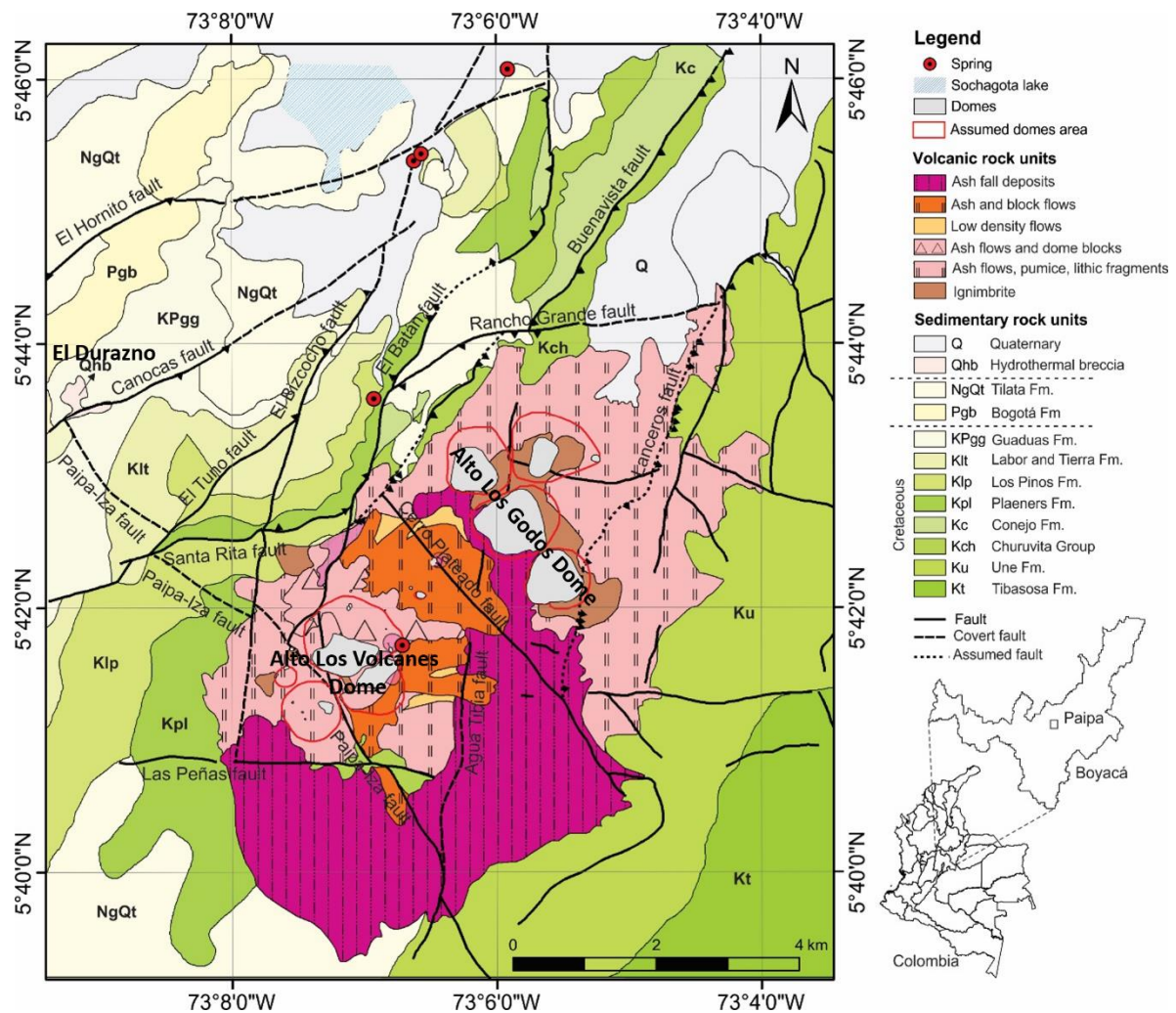


Figure 1: Location of the Paipa geothermal area based on geologic maps at a scale 1:25.000 (Velandia and Cepeda, 2004; Pardo, 2004; Rueda, 2017).

3. MAGNETOTELLURIC SURVEY

3.1 Acquisition

Moyano and Vallejo (2015) performed a 2D modeling in an area extending SE (to the municipality of Iza) and NW of the area of the greatest geothermal interest. Subsequently, complementary acquisitions were made in the polygon of greatest interest, with a total of 88 BMT soundings (Figure 2).

The soundings were acquired with Phoenix equipment, two models of V8 receivers and two models of MTU-5 receivers. Magnetic sensors capable of recording frequencies in the ranges of the magnetotelluric variants AMT (10000 - 0.1 Hz) and MT (400 Hz - 0.0001 Hz) were used. The acquisition times were 1 to 2 hours for AMT and between 12, 24 and exceptionally 48 hours for MT.

The estimation of the apparent resistivity and phase curves was performed using the SSMT2000 and MTeditor software. The SSMT2000 takes time series, magnetic sensor calibration files, and parameter files from each measurement site. In an intermediate step, it produces Fourier coefficients that are reprocessed with data from reference sites using robust processing routines. The outputs are files containing multiple cross-powers for each of the analyzed frequencies. Meanwhile, the MTeditor software takes these files as input and displays the resistivity and phase curves, as well as the individual cross-powers that are used to calculate each point in the curves. Noise-affected cross-powers were excluded from the calculations. In Figure 3 you can see examples of the estimated apparent resistivity and phase curves, where they show a good estimate of up to approximately 0.1 Hz.

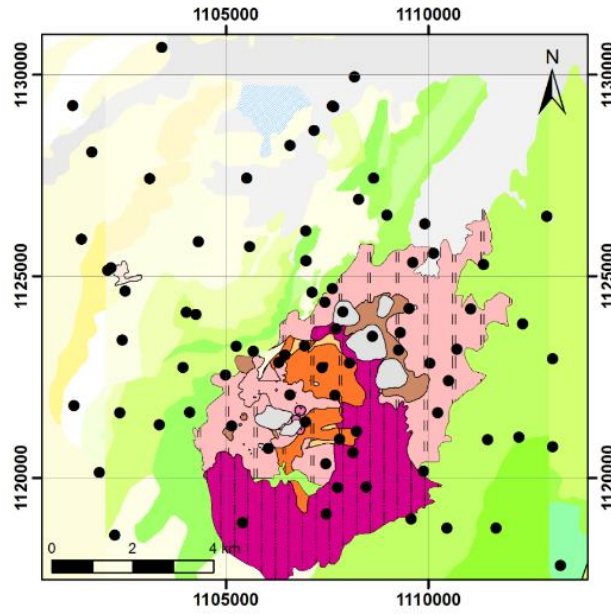


Figure 2: Magnetotellurics stations map (black circles). Scale geology map 1:100.000 (Renzoni and Rosas, 1967; Renzoni et al., 1998) and scale 1:25.000 (Velandia and Cepeda, 2004; Pardo, 2004; Rueda 2017).

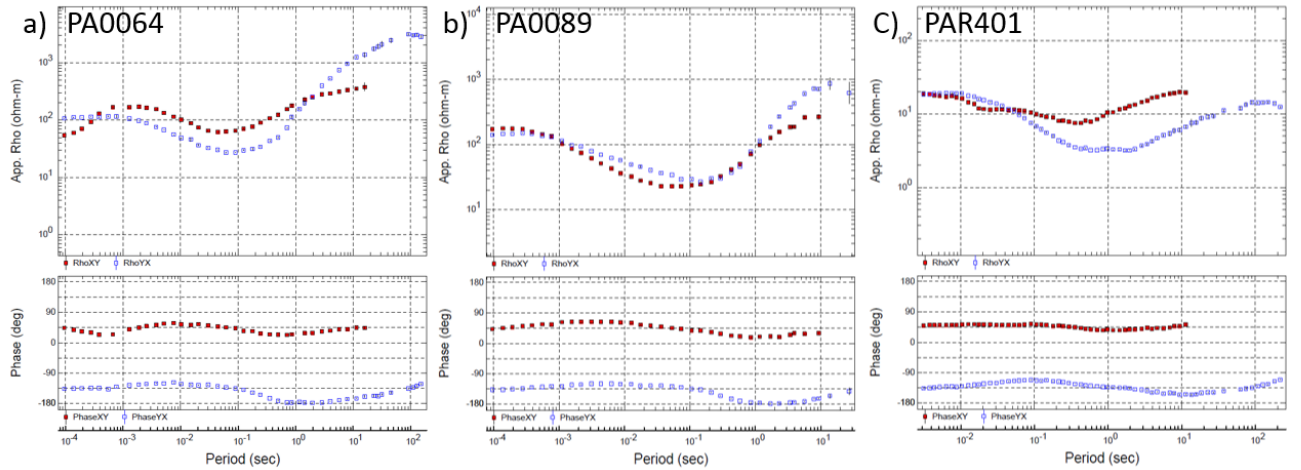


Figure 3: Apparent resistivity and phase curves examples of the study area (Gonzalez-Idárraga and Rodriguez-Rodriguez, 2017).

3.2 3D inversion

Siripunvaraporn et al. (2005) and Siripunvaraporn and Egbert (2009) developed the WSINV3DMT algorithm, which extends and implements from Occam's inversion of the two-dimensional data space.

The 3D resistive model for the Paipa geothermal area is a product of the SGC, modeled by Siripunvaraporn (2016). Figure 2 shows the polygon with 88 BMT soundings used in this modeling. To calculate the inversion, Siripunvaraporn (2016) took 16 periods of the antidiagonal of the impedance tensor (zxy and zyx) and the tipper, for each of the sampled sites, with a floor error of 5%. The inverted model was discretized using a horizontal resolution mesh of 300 m x 300 m. The topography was included and executed with an initial bottom resistivity of 100 Ω .m. Finally, a definitive resistive model was obtained with an RMS value of 3.5%.

4. RESULTS AND DISCUSSION

Figure 4 shows some E-W cuts of the 3D resistive model. An R1 resistive body is observed east of the study area with variable depth. As the cuts are observed from north to south, body R1 shows a greater extension in the southeast of the modeled zone, where it reaches an expression closer to the surface (~2000 masl). While to the northeast, its roof is shallower and appears around ~1000 masl. This body R1 is associated with the possible resistive response of the crystalline basement of the Floresta massif, which is under the sedimentary cover (Figure 5).

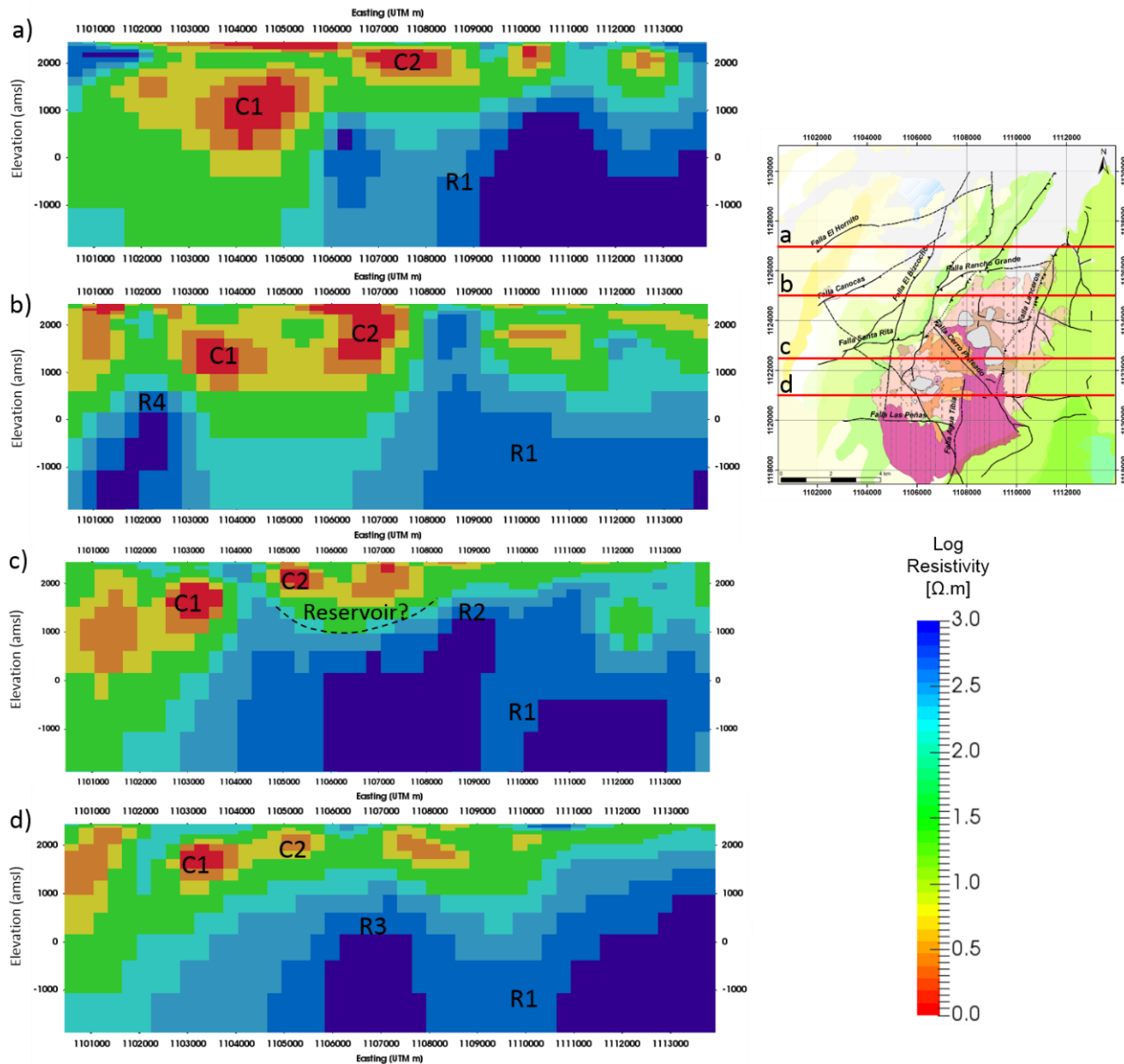


Figure 4: E-W cuts of the 3D resistive model. Bodies R1, R2, R3, and R4 correspond to the resistive responses of the crystalline basement of the Floresta massif, Altos Los Godos dome, Alto Los Volcanes dome, and El Durazno intrusion, respectively. Bodies C1 and C2 correspond to leaching of the evaporite deposits housed in the sedimentary sequence. Source: Siripunvaraporn (2016). Source: Siripunvaraporn (2016).

To the west (Figure 4), a series of conductive surface anomalies are observed in the zone of the sedimentary sequence. The occurrence of different conductive anomalies $<10 \Omega.m$ (C1 and C2) along all cuts is characteristic. These are observed near the surface, along with all cuts shown in Figure 4, with a deeper presence to the west than to the east. It is also observed that these conductive anomalies are connected, as shown in Figure 5, showing their southwestern extension to the central zone of the modeled area. This is possibly associated with the presence of faults to the west of the study area. According to the interpretation of the conceptual model (Alfaro et al., 2017), these anomalies would be related to the source of sodium sulphated salt derived from the leaching of an evaporite deposit housed in the sedimentary sequence. The circulation of this sequence generates the superficial conductive anomalies, which would probably be the saline contribution that masks the chemistry of the springs of the area (Alfaro, 2002).

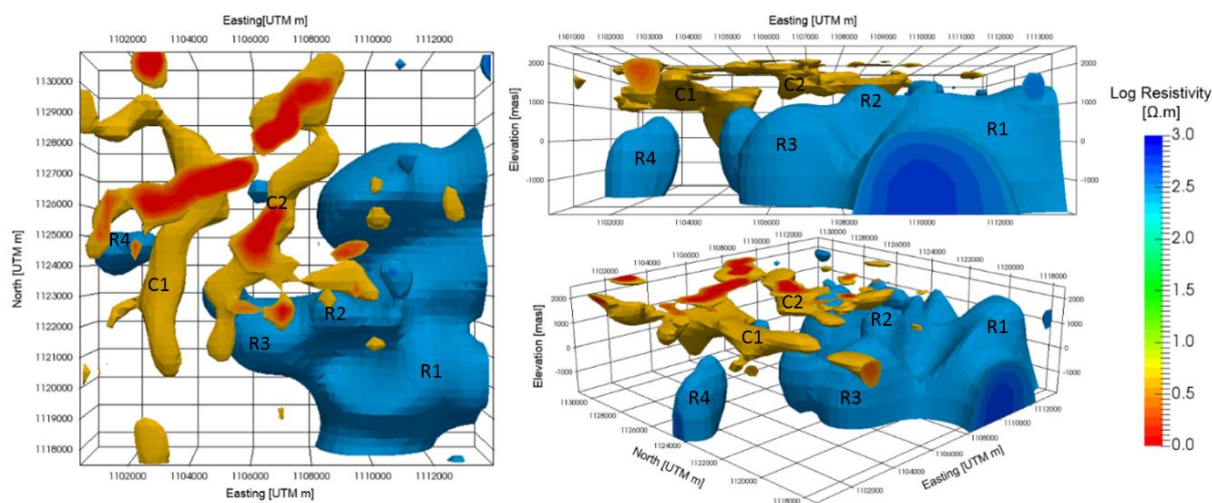


Figure 5: Resistive structures of the geothermal area of Paipa. Bodies R1, R2, R3, and R4 correspond to the resistive responses of crystalline basement of the Floresta massif, Altos Los Godos dome, Alto Los Volcanes dome, and El Durazno intrusion, respectively. Bodies C1 and C2 correspond to leaching of the evaporite deposits housed in the sedimentary sequence. Source: Siripunvaraporn (2016).

In the cuts in Figure 4, as well as in the volumes in Figure 5, the resistive anomalies R2, R3, and R4 are observed. Taking surface geology as a reference, these anomalies would be associated with the possible roots of the domes of Altos Los Godos, Alto Los Volcanes, and El Durazno intrusion, respectively. Taking into account the ages of the domic sectors of Alto Los Volcanes, Alto Los Godos, and Quebrada Honda, estimated by Rueda (2017), at 1.7 Ma, ~2.7 Ma and 1.8 Ma, respectively; they suggest that they are possibly the remaining heat sources that contribute to the geothermal system (Alfaro et al., 2012; 2017). Also, the intrusion of El Durazno would contribute radiogenic heat to the system (Rodríguez and Alfaro, 2015).

However, in the area where the geothermal reservoir is estimated (cut c in Figure 4), near Alto Los Volcanes and Alto Los Godos (Alfaro et al., 2017), it is not possible to identify whether the conductive response is characteristic of the clay cap or of one of the levels of the sedimentary sequence of the zone. Van Leeuwen (2016), establishes the challenge of being in a subsoil consisting of sedimentary geological formations, such as the geothermal area of Paipa. In this place it is known that the electrical conductivity of the formations is high, making it difficult to distinguish between different geological structures. Given the above, it is possible that the electrical response of the clay cap is attenuated and undifferentiated from the sedimentary stack by its moderate thickness. If it's as they assume (Alfaro et al., 2017), the clay cap is made up of clayite levels or altered volcanic deposits.

5. CONCLUSIONS

The resistive response of the crystalline basement of the Floresta massif was observed, with a deep expression to the northwest and close to the surface to the southeast. On the other hand, the block of sedimentary deposits showed a range of intermediate resistivity (10 - 100 $\Omega.m$), with no clear distinction between formations, suggesting a greater thickness of deposits to the northwest of the area.

Resistive responses were observed in the domes of Alto Los Godos, Alto Los Volcanes, and the intrusion of El Durazno, the latter to the west of the modeled area, and possible sources of remnant heat. On the contrary, in the northwest, conductive anomalies were observed. These anomalies were possibly associated with lixiviated from evaporite deposits, apparently forming south-north conductive corridors linked to the faults present in the west of the area.

In the zone proposed as the location of the possible geothermal reservoir, between the domes of Alto Los Godos, and Alto Los Volcanes, proposed as the remaining heat sources, a concave geoelectric structure was observed upward associated with the possible geothermal reservoir.

ACKNOWLEDGEMENTS

The author thanks Dr. Weerachai Siripunvaraporn for the 3D resistive modeling of the geothermal area of Paipa. The author also thanks Claudia Alfaro and the members of the Research and Exploration Geothermal Resources Group, of the Servicio Geológico Colombiano, for their different contributions in the interpretation of the resistive models. The Servicio Geológico Colombiano financed the present study.

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