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Magnetotelluric Models for the Characterization of the Geothermal System of the Azufral Volcano

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ABSTRACT

A magnetotelluric study (MT) was carried out in the Azufral volcano (AZV) which is located on in the western Cordillera of Andes, south-west of Colombia in the department of Nariño, to 11 km west of the municipality of Túquerres. This Volcano hosts a geothermal system of high enthalpy and priority within the national context, established by reconnaissance and pre-feasibility work carried out throughout the Colombian territory, for this reason it was decided to perform 1D and 2D modeling of the resistive structure of the subsoil to characterize the geothermal system of AZV. Therefore, layers models based on the Occam inversion process were defined, elaborating interpolated horizontal views obtained after static shift correction for each of the MT stations. In the same way, robust processing was carried out by applying the cascade decimation algorithm, impedance tensor analysis to estimate the directionality and dimensionality of the subsoil and correction of the distortion tensor to eliminate the galvanic effects in the data of according to the methodologies of Groom & Bailey and McNeice & Jones. The resistive structure of the area is characterized by zones of conductive anomalies between 1-10 ohms-m, intermediate between 10-100 ohm-m and resistive zones with values more than 100 ohms-m observable in the 1D and 2D modeling. The areas of conductive anomalies extend laterally through the study area, with a thickness of 1.2 km here associated with clayey layers that would form the seal of the geothermal system. The superficial resistive anomalies were associated to unaltered pyroclastic deposits and the deep ones to the basement, which corresponds to the Diabasic group in the area. Other contributions of the models obtained to the knowledge of the subsoil structure are the intermediate resistivity contrasts generated by the Cali - Patía and Guachucal regional faults, and conductivities anomalies near the surface in the outcrop of lavas of the Azufral and Cumbal - Chiles volcanoes attributable to fracturing.

1. INTRODUCTION

The geothermal system of the Azufral volcano was considered one of the most important and high priority systems in Colombia according to the recognition made by OLADE, ICEL and Geothermal Italiana (1982), where they estimated the reservoir temperature between 160 ° C to 175 ° C from fluid geochemistry analysis. From this year until 2003, additional work was done on sampling thermal springs and analyzing gases that showed reservoir temperatures of the order of 200 ° C. However, it was not until 2003 that the complementary exploration works were taken up again from geological, geophysical and geochemical studies as part of the work of the Geothermal Resources Research and Exploration group of the Colombian Geological Service, which in turn allowed identify the need to investigate and characterize the geometry and thickness of the geothermal system of the Azufral from the generation of resistive models in depth with magnetotelluric (MT) soundings.

2. TECTONICS AND GEOLOGY OF THE AZUFRAL AREA

The geotectonic scheme for western South America and the southern part of Central America is quite complex, because it is controlled by the interaction of a series of smaller plates such as the Andean Block and the Panama plate, which in turn are located between converging plates of greater extension such as the Nazca plate, Cocos, South America and the Caribbean. This interaction allows an oceanic subduction associated with the Nazca plates that subducts the Andean Block, as do Cocos to Panama, the Caribbean to the Andean Block and, Caribbean to Panama. The Andean block and the South America plate are moving in a northwest-southeast direction with a perpendicular arrangement to the general (NE) direction of the relief. (Arcila, et al., 2000)

The western mountain range is mainly constituted by volcanic and sedimentary rocks of Cretaceous age that in turn are divided into two large groups, the Diabasic composed of massive basaltic rocks that constitute the foundation of recent volcanoes in the area and the Dagua that constitutes them sedimentites with volcanic intercalations (González, et al, 2002).

Throughout the study area there are mainly deposits, flows and pyroclastic falls with the presence of debris avalanches, as well as the identification of a complex of domes located inside the crater, associated with the ancient explosive activity of the Azufral volcano. The presence of andesitic lavas from the Pajablanca volcano and the Lajas volcanic deposits is also distinguished (Pinilla, 2007; González, et al. 2002).

The structural geology mapped on the surface allowed the identification of two main regional fault lines established for the Cali - Patía Faults (Pachón et al, 2006; Romero 2006; Ortiz, 2013) and Guachucal and a normal type fault with NW orientation called Rio Guabo. Likewise, in the area there are three guidelines defined by geological photointerpretation identified as the Azufral-Sapuyes, Quebrada El Baño and Quitasol lineaments (Rodriguez & Rueda, 2017).

3. ADQUISITION OF MT AND TDEM DATA

The acquisition of data in the field was carried out by the Geothermal Resources Research and Exploration work group between 2013 and 2017. For this, 4 MT equipment from the Geophysics Phoenix Ltda. Company was used, of which two receivers are V8 and the other two MTU-5A, with a set of magnetic sensors (AMT and MT) that manage to register frequencies from 10^4 Hz to 10^5

Hz. The measurements to correct the static shift, known as “static shift”, were performed by applying the electromagnetic transient method in the time domain (TDEM).

For the installation of the MT stations, sites were chosen where there was no electromagnetic noise such as electric fences, light poles and high-energy towers, it was also taken into account that the topographic slope did not exceed 20 ° inclination. In each place visited, the socialization process was carried out with each owner asking for the necessary permits for the installation of each equipment, whose arrangement in the field was made by locating in each quadrant a magnetic sensor to measure the magnetic temporal variations and in each cardinal point electrodes not polarizable to register the electric fields.

The data set used in this work consists of a total of 140 magnetotelluric records and 38 TDEM measurements (Figure 1). The stations cover the area of influence of the geothermal system of the Azufral volcano on its flanks SE, S and part of the W where access is limited.

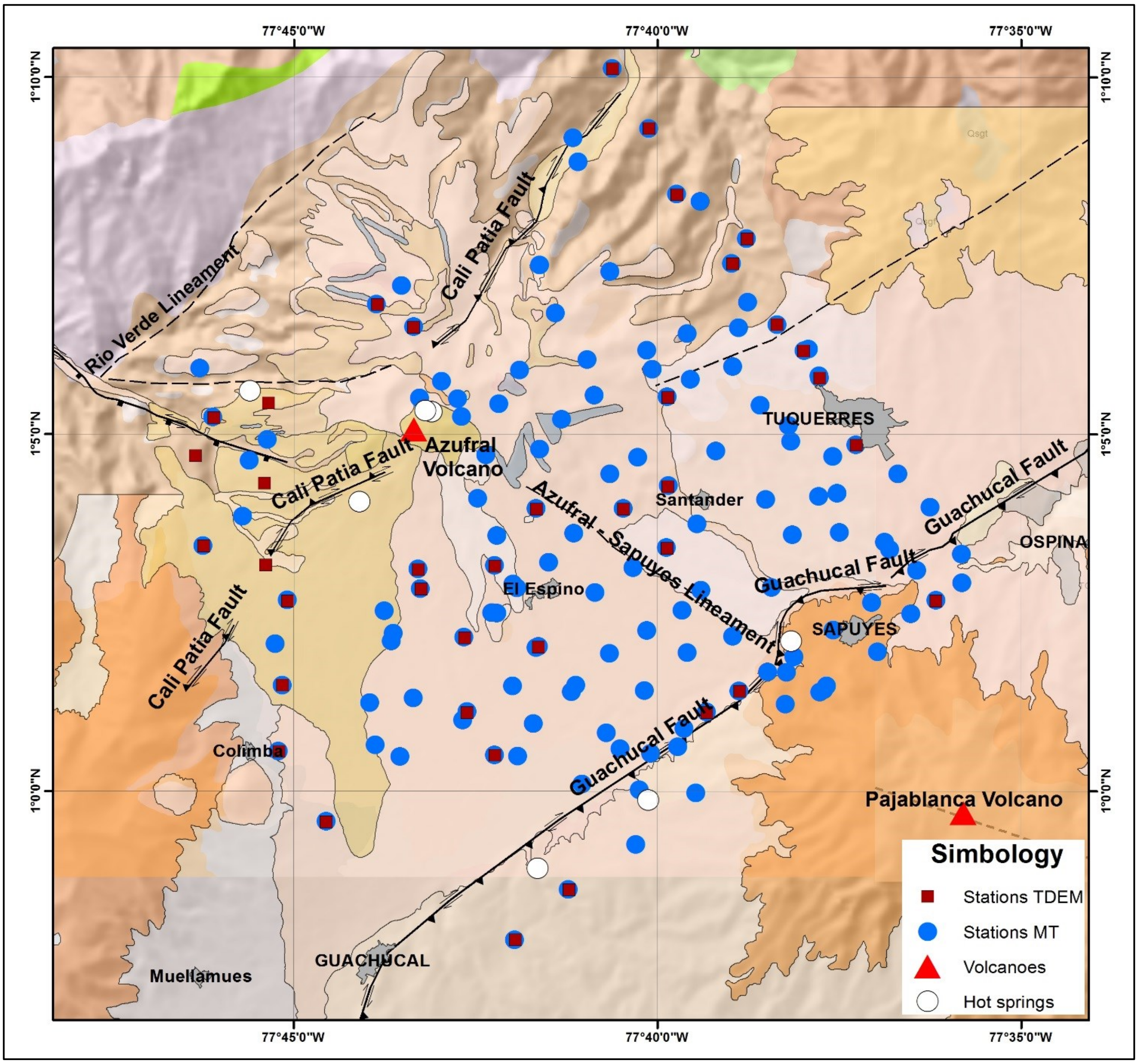

Figure 1: Location of stations acquired in the field. Geological map 1: 25.000 Pinilla et al (2007); Structural geology Rodriguez & Rueda (2017).

4. DATA ANALYSIS AND PROCESSING

From the robust cascade decimation algorithm (Jones & Jödicke, 1984) and through the fast Fourier transform the apparent resistivity and phase curves were estimated, where a station depuration was performed, eliminating atypical data from the estimates of the crossed powers, to define a clear and smoothed tendency of the resistivity curves, with which frequency values of up to 0.01 Hz of clean signal on average were reached.

For the quantitative analysis of the subsoil dimensionality for the study area, the work development was based on the application of the amplitude and phase methods described in Jones & Chave (2012). Taking into account the methods of Bahr (Bahr, 1988; 1991), WAL (Weaver et al., 2000 and Martí et al. 2005) and phase tensor (Caldwell et al., 2004, Bibby et al., 2005).

The estimation of the directionality of the geoelectric structures was based on the decomposition methodology of the impedance tensor exposed by Groom & Bailey (1989). In which, the observed impedance tensor Z_{Obs} is decomposed in terms of a distortion tensor, a 2D tensor without distortion and a regional strike. The distortion tensor can be parameterized in terms of Shear, Twist, anisotropy and gain. However, the distortion tensor has an indeterminable component formed by anisotropy and the gain of the observed site (Groom & Bailey, 1989). In a complementary way, the regional structure and distortion method for the MT proposed by McNeice & Jones (2001) was used, which is an extension to the Groom & Bailey method, since the distortion tensor parameters are resolved in each iteration building a credible model within which it finds a frequency band where the model tests show an acceptable mismatch error (Figure 2).

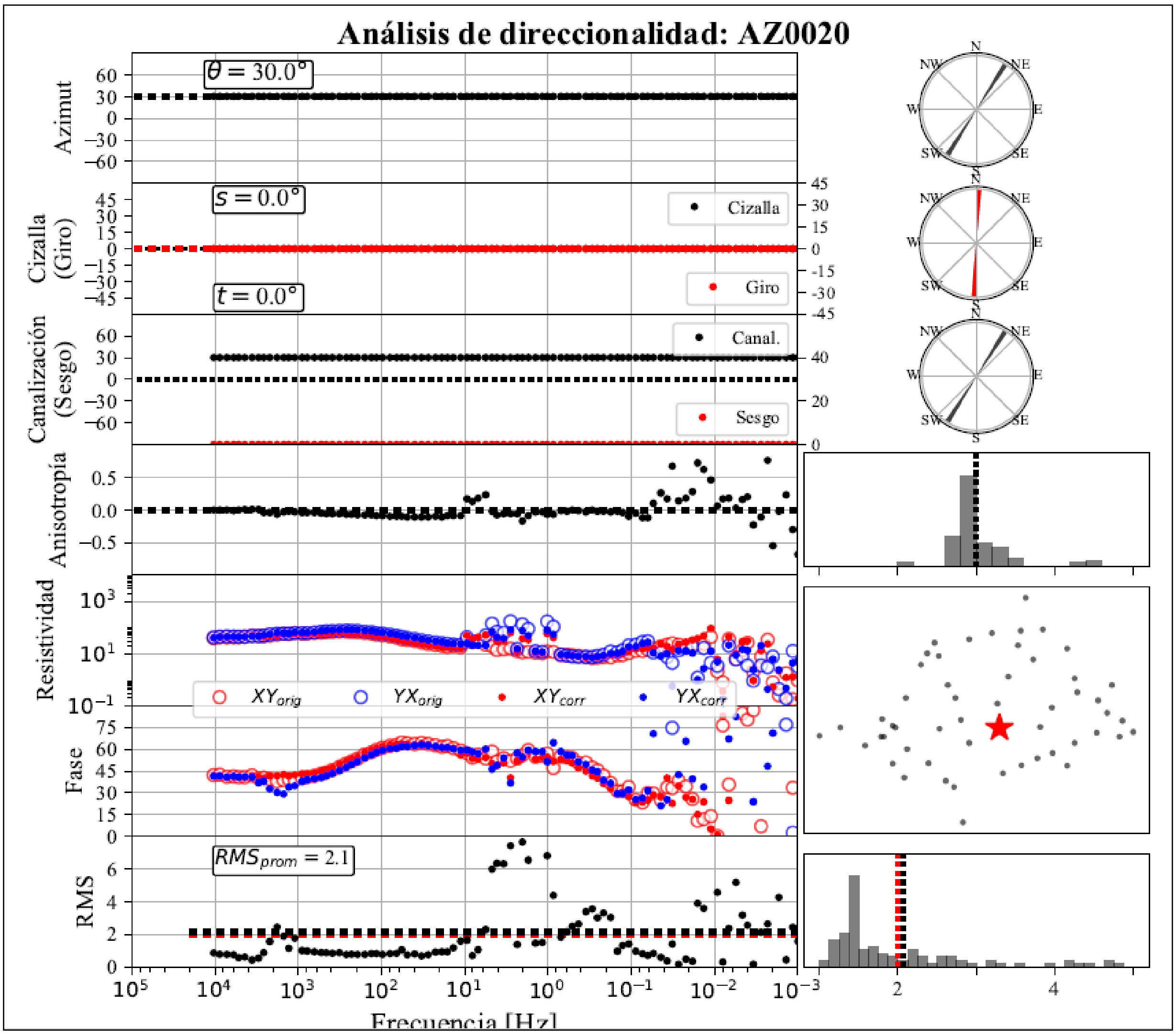

Figure 2: Result of the directionality analysis based on the Unisite - Unifrequency survey AZ0020 approach.

4.1 Static Shift Correction

The static shift is included within the indeterminable part of the distortion tensor, which is represented by the anisotropy and gain parameters. This effect corresponds visually with a small vertical displacement of some or both components of the resistivity tensor impedance curves (Chave & Jones, 2012) and is caused by areas where there are accumulations of electrical charges either by inhomogeneities near the surface , or by abrupt changes in the topography (Jiracek, 1990).

According to what Nabighian & Macnae (1991) put forward, there is the TDEM method (electromagnetic transient in the time domain) that allows estimating the values of apparent resistivity near the surface as a function of depth, and already Since these values are not affected by the static shift, they can be used to make the respective corrections to the apparent resistivity curves (Figure 3).

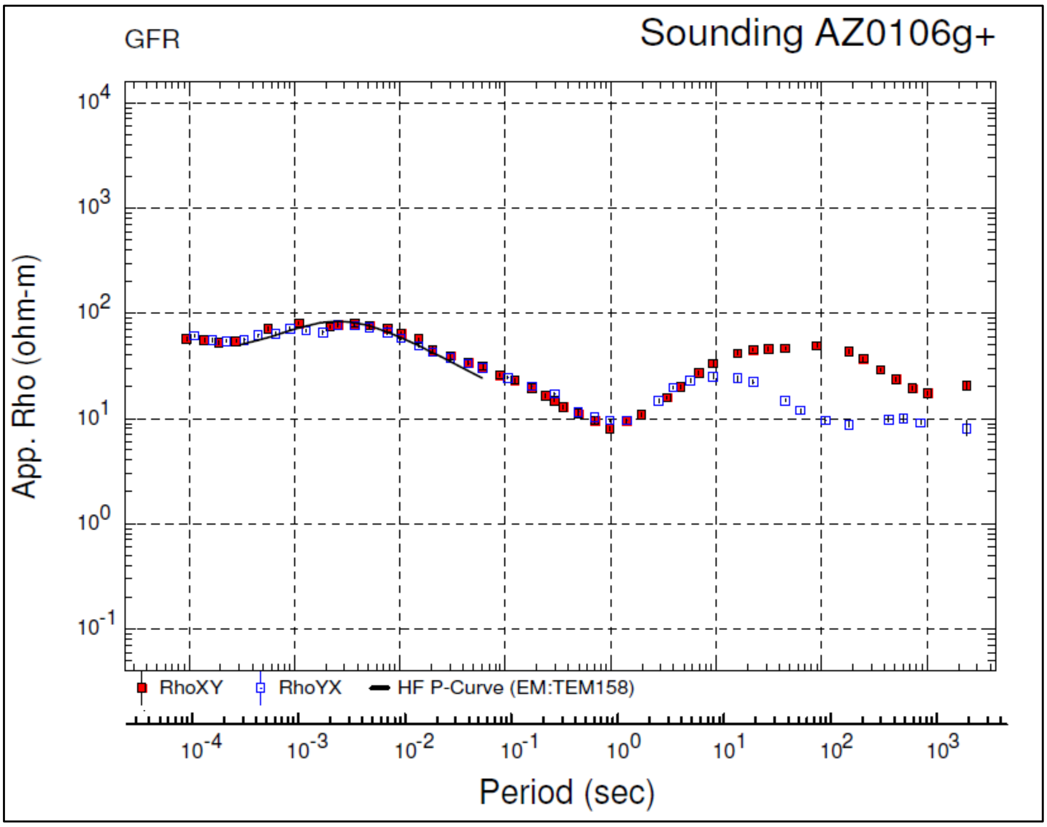

Figure 3: Correction of vertical displacement of apparent resistivity curves of MT probes

5. RESULTS AND DISCUSSION

The recording time for the AMT was 1 hour on average and 24 to 48 hours for the MT surveys, which allowed for most of the stations to define apparent resistivity curves that reached frequencies between 0.1 to 0.01 Hz. Based on the processing of these data, layer models were constructed assuming 1D dimensionality, and iterative processes were performed to adjust the apparent resistivity curves for 2D inversion.

5.1 1d Modelling

The layer models defined for each of the stations were based on the process of inversion of Occam (Constable et al., 1987), after the correction of each of the stations that were affected by the effect of the static shift using as a reference TDEM surveys. According to this, modeling was performed for the Transverse Electric (TE), Magnetic Transverse (TM) and Rotational Invariant polarization modes, based on interpolation processes for the generation of plant views at different elevations from the mean sea level , using 3 units interpolation radius, together with a logarithmic grid taken as parameters for the prediction maps, with which the risk of generating edge effects on the resulting maps could be reduced, due to areas discovered by magnetotellurics surveys. Next, the results of two horizontal cuts for the rotational invariant representative of all the one-dimensional models are presented in Figure 4.

In these results it was observed that the modes of polarization TM, TE and Rotational Invariant maintain a similar behavior in terms of the delimitation of regional anomalies, since the apparent resistivity curves maintained similar and comparable inflection points along the curves for the three methods, with which it was possible to clearly identify 3 main centers of anomalies. On the northwestern flank of the Azufral volcano, a highly resistive zone (R1) is identified with values equal to or greater than 200 Ωm that extends superficially with dimensions of 80 km^2 and with a thickness that remains up to 350 meters deep and would possibly be associated with consolidated or little altered pyroclastic flows of the Azufral volcano. As for the SE side located near the Pajablanca volcano, there is a very strong contrast of a resistive anomaly (R2) with values equal to or greater than 200 Ωm, appearing at a depth of 100 meters and with an estimated thickness of 400 meters.

There is also a highly conductive zone (C1) with values below 20 Ωm that occurs in the Azufral valley and extends laterally from the municipality of Guachucal to Túquerres, with a marked presence in the area of the Azufral volcanic cone, this anomaly appears from 400 meters deep, reaching a thickness of 1200 meters of a continuous body with these resistivities, could be associated with clay layers due to hydrothermal alteration processes.

5.2 2d Inversion

For the design of the magnetotelluric profiles, the direction of the regional electromagnetic strike estimated at N30 ° E was taken as the main base, from which the 5 profiles perpendicular to this strike with a NW (330 ° Azimuthal) direction were drawn. These profiles were proposed to intercept: geological structures such as Cali-Patía and Guachucal and anomalous areas that differed in the 3D magnetotelluric model.

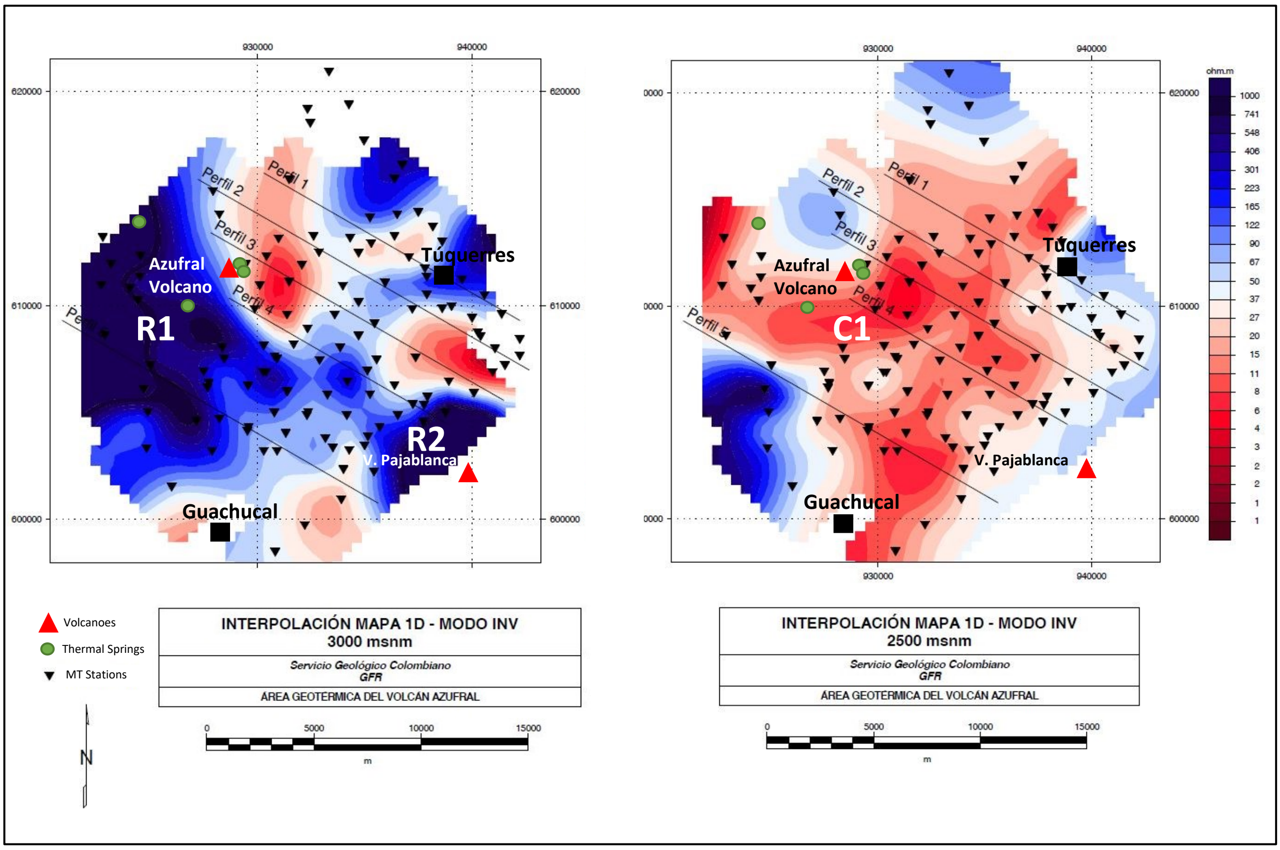

Figure 4: Plan views representative of the electrical response of the subsoil for the rotational invariant. Left cut at 3000 meters above sea level. Right cut at 2500 meters above sea level.

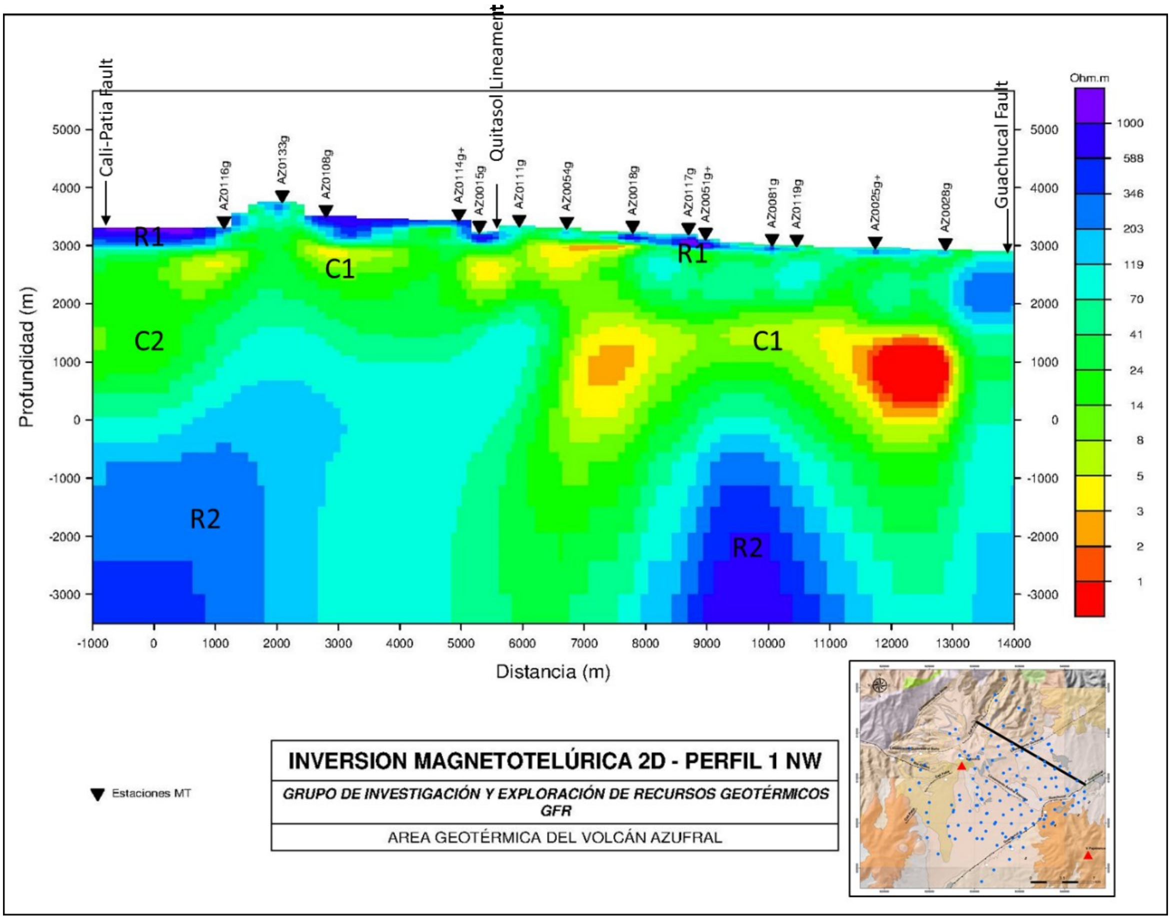

Figure 5: Magnetotelluric resistive model for profile 1 NW

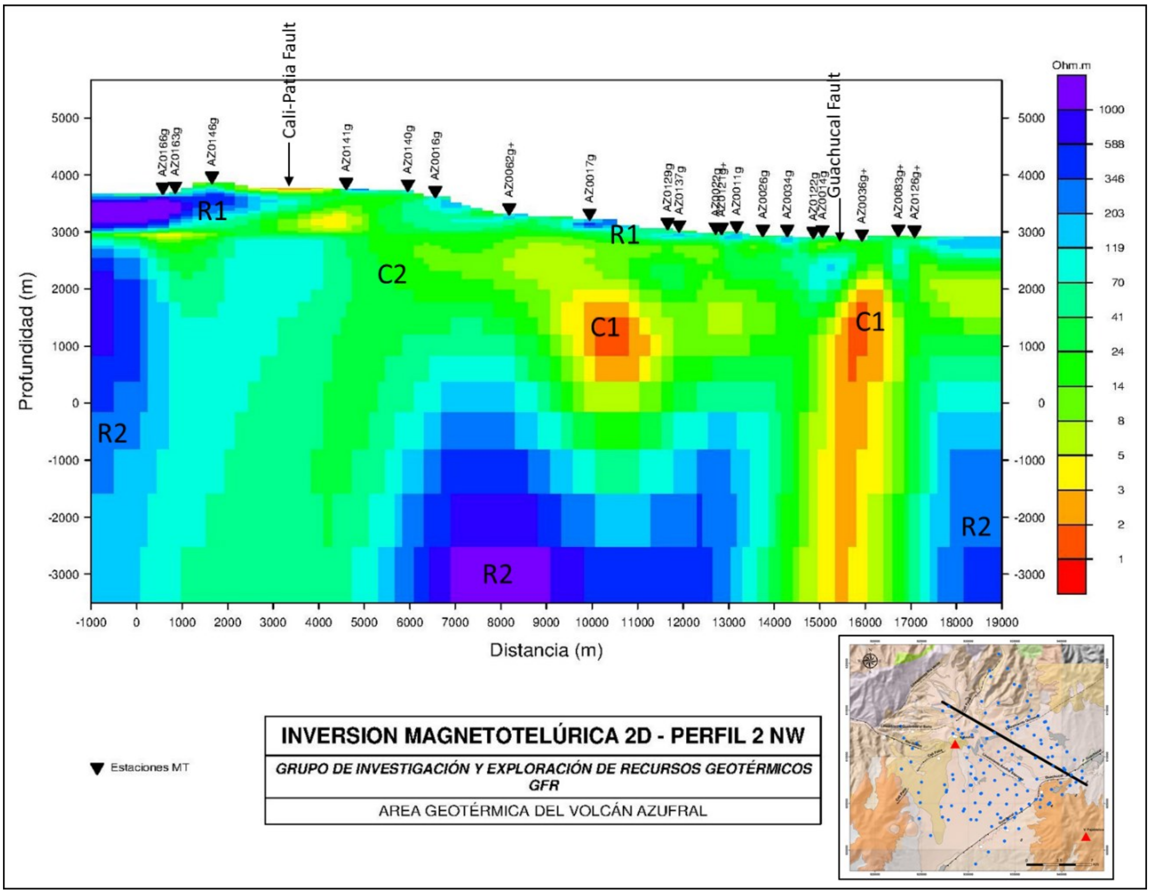

Figure 6: Magnetotelluric resistive model for profile 2 NW

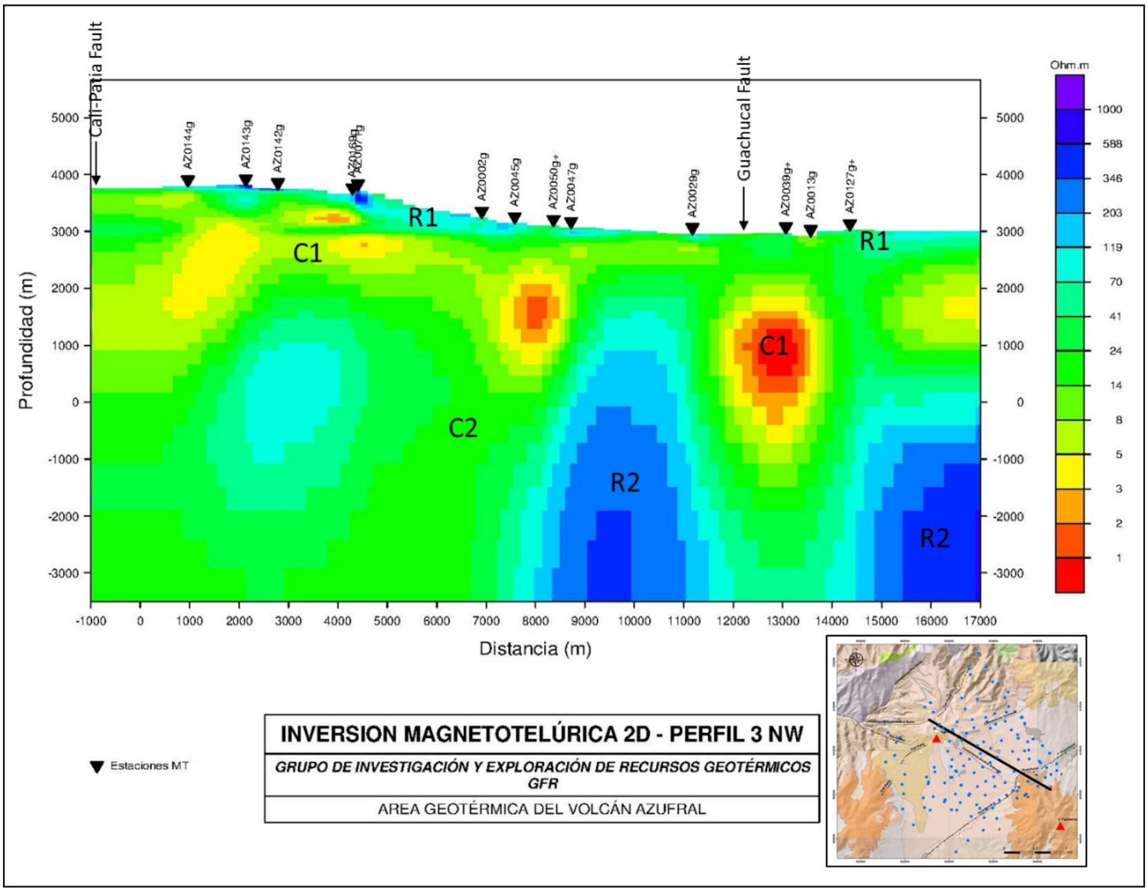

Figure 7: Magnetotelluric resistive model for profile 3 NW

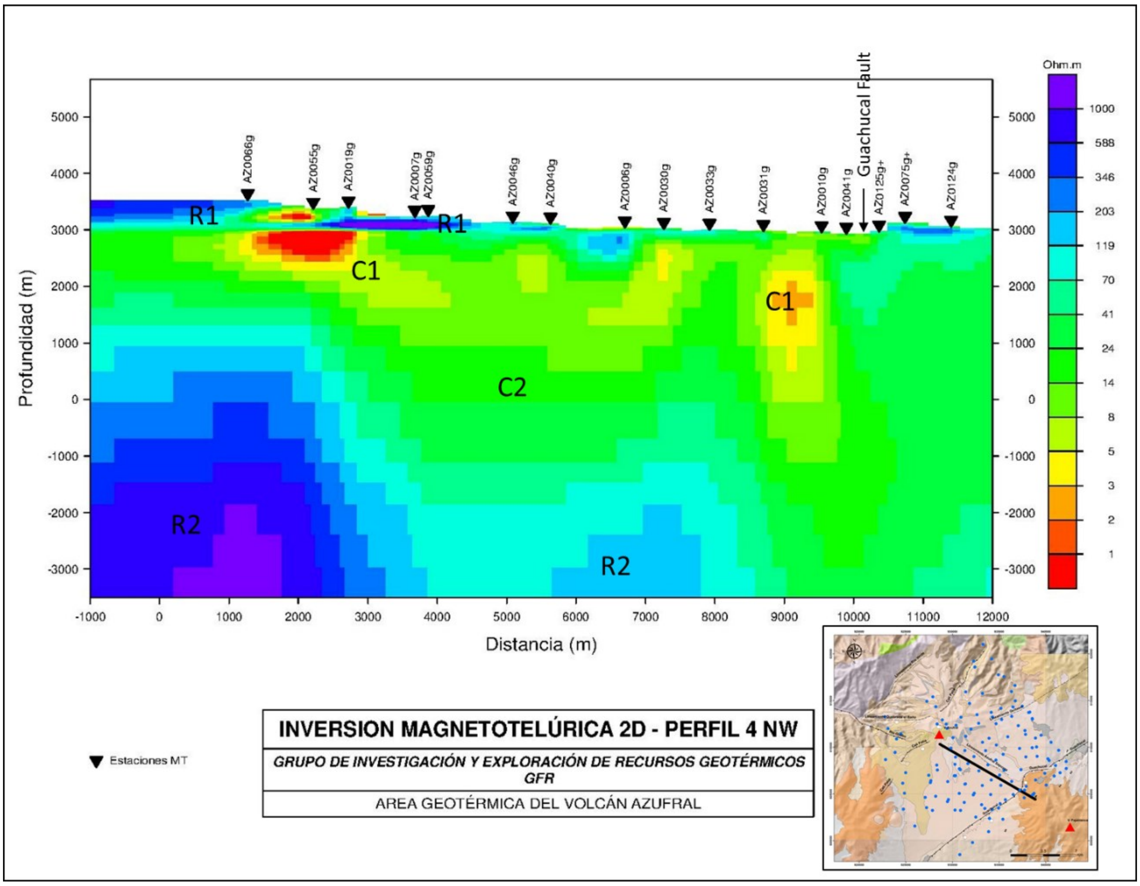

Figure 8: Magnetotelluric resistive model for profile 4 NW

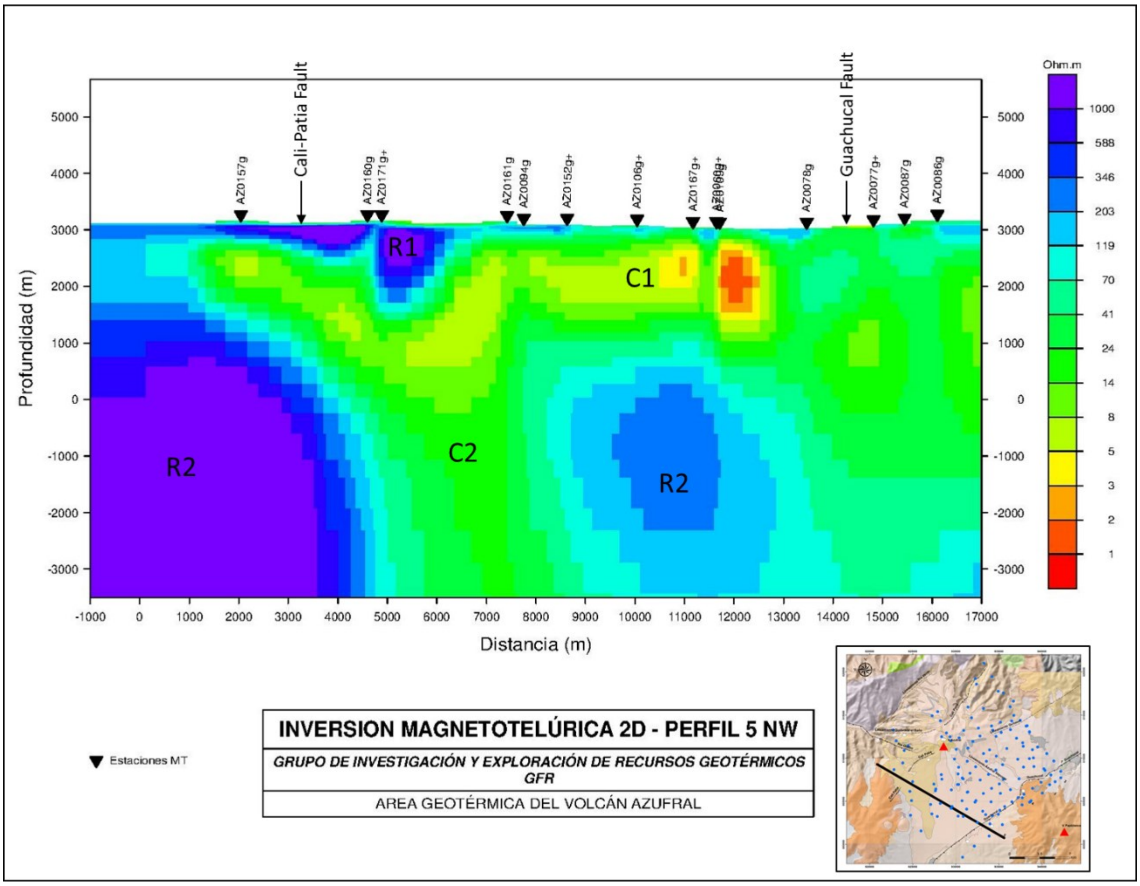

Figure 9: Magnetotelluric resistive model for profile 5 NW

Figures 5 through 9 correspond to five 2D profiles that were plotted in the NW direction in the Azufral volcano area. In these results, resistive anomalies **R1** are observed near the surface with values equal to or greater than 100 Ωm and with a thickness of 350 meters on average throughout the entire work area, they could be associated to unaltered lava flows of the Azufral and Cumbal volcano mainly. There is also a highly conductive anomaly **C1** with values less than or equal to 2 Ωm, which has an average thickness of 1.2 km and is located at estimated depths from 500 m (roof of the anomaly) to 3000 meters (maximum value found in its base). The anomaly described above is surrounded by one of greater predominance **C2** in the exploration area, with intermediate conductivity values ranging from 20 Ωm to 100 Ωm, with undefined geometries, and which can reach 7 km deep resistive models, associated perhaps fractured rocks through which hydrothermal fluids circulate. **R2** resistive anomalies were also identified with thicknesses of more than 4 km on average and locating the roof of this anomaly at 1000 meters (maximum value found east of the Azufral volcano) and its base at least 7 km deep, with values of resistivity equal to or greater than 100 Ωm, that could be associated with the consolidated basement of the Diabasic group.

To define the depth of investigation of each inverted 2D profile and the credibility of the resulting anomalies, sensitivity tests were conducted based on direct modeling of each resistive and conductive body present in the profiles. From which it was estimated that 2D models have a research range of up to 7 km deep, measured from the earth's surface.

6 CONCLUSSIONS

- The large lateral extent of the conductive anomalies that are between 10 and 15 Ωm could be associated with the seal layer of the system due to hydrothermal alteration caused by high temperature geothermal fluids.
- The resistivity contrasts do not allow to identify in depth the heat source of the geothermal system perhaps because there is heat remaining from intrusive rocks that does not allow to maintain a significant content of mineralized fluids or perhaps because the magma chamber is deeper.
- The surface resistive layers are associated with unaltered deposits of Las Lajas pyroclastic flows and the Azufral and Cumbal - Chiles volcanoes.
- Areas with intermediate conductivity anomalies may be associated with an increase in the temperature of the system, alternating rocks and creating less conductive minerals such as Illita, biotite, among others.
- The deep resistive anomalies are associated with the basement of the Diabetic group to the northwest of the work area that underline a more consolidated and fracture-free basement that would be found at a depth of 5 km.

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