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Contribution to the Knowledge of the Paipa Geothermal System by the Application of the Magnetotelluric Method

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ABSTRACT

The Paipa geothermal system, located in the Eastern Cordillera of Colombian Andes, 150 km north of Bogotá, is an area of great interest because it may be related to volcanic bodies emplaced in a sedimentary and orogenic environment, about 400 km away from the main volcanic arc located in the Central Cordillera. Geological, geophysical and geochemical investigations, most of them developed by the Geological Survey of Colombia (formerly INGEOMINAS), have identified the presence of a caldera rim generated by the collapse of a volcanic structure, its associated deposits, the later emplacement of domes of Pleistocene age, besides other sub-volcanic bodies. At surface, the discharge zone of the geothermal system includes steam vents and, perhaps the most important feature due to the recreational use and its economic revenues, hot springs with temperatures up to 74° Celsius. These hot springs show evidence of mixing with a shallow sodium sulfate source that masks the chemical and isotope composition of the geothermal reservoir, preventing the use of geothermometers and other geochemical analytical tools. As a result of these investigations, a conceptual model of the geothermal system was formulated that included potential recharge areas, heat sources, circulation mechanisms and zones of fluid mixture with shallow sources. This investigation presents the resistivity model of the subsurface structure beneath the Paipa geothermal area interpreted from the acquisition, processing and 2D modeling of 69 sites of AMT and AMT/MT magnetotelluric soundings. Structures and other features potentially related to a geothermal system are identified, including three well differentiate resistivity zones correlated with basement, sedimentary sequence and high conductive layer, low resistivity zones product of hydrothermal alteration (cap seal), and the influence of a saline source. The deep structure Paipa-Toca Fault, with no surface expression, is possibly related to the ascending flow of fluids (magma and geothermal fluid).

1. INTRODUCTION

The Geothermal Exploration Group of the Colombian Geological Survey (SGC, for its abbreviation in Spanish) has performed several works on geology, hydrothermal fluids geochemistry and geophysics. A brief summary of them is presented in the Country Update of Colombia (Alfaro, 2015). Geophysical works applied geoelectrical (Hidrocerón, 1998; Moyano, 2010; Franco, 2012) and potential methods (Vasquez, 2012). The geoelectrical methods have shown the existence of a saline source that mixes with the geothermal fluid discharged in hot springs (Alfaro et al., 2005). The potential methods, particularly gravimetry, show important contrasts which define linear trends that were interpreted as possible fault lines with no surface expression (Alfaro et al., 2012). The current geothermal conceptual model does not include the location of the geothermal reservoir, which has been assumed inside the volcanic caldera as the most probable option.

This work, framed in the institutional geothermal project and in a Master's Degree program of the National University of Colombia (Moyano, 2014), was developed as a contribution to the knowledge of Paipa geothermal area, through the study of the resistivity structure using broad magnetotellurics (BMT) soundings.

2. GEOTHERMAL FRAMEWORK

Paipa geothermal area is located 180 km NE from Bogotá, on the axis of the plateau of the Eastern Cordillera, in a regional compressive tectonic environment. The proposed conceptual model proposes a geothermal system of high to intermediate enthalpy with a heat source related to the magma/hot rocks of Paipa Volcano. An additional heat source could be the high concentration of uranium, thorium and potassium in the shallow rocks found NW of the volcano in the quarry El Durazno. This area seems to be separated from Paipa Volcano by one structure identified in gravimetric surveys and named as Paipa - Toca Fault. A deep reservoir could be located in the basement rocks, as hydrothermal alteration of xenoliths suggest. A shallow reservoir could be located in permeable rocks of the sedimentary sequence (such as Une and Tibasosa formations with primary permeability). The conducts for the deep fluids (magma and geothermal) are normal, almost vertical, basement faults. The upflow reaches the sedimentary sequence and accumulates below the caldera depression. It flows, then, through permeable layers and low angle fault planes towards the north following the topographical slope to the discharge zones located at fault crossings. The geothermal fluid mixes with a low temperature saline source (sodium sulfate) which masks the chemical and isotopical composition. At the depth of the geoelectrical study (about 300 m), the salt source seems to be located nearby the hottest thermal spring (74°C). Cap rocks could be formed by claystones at different levels of the sedimentary sequence. The local recharge is proposed to occur through circular structures related to the caldera, highly fractured outcropping geological formations (Plaeners), and weakness areas in fault crossings. A regional recharge could also happen from a topographic high at (2900 m.a.s.l.) in the Tibasosa Anticline. (Alfaro et al., 2012).

3. METODOLOGY

3.1 Experimental Design

Based on the geology (Velandia, 2003), volcanic structure (Cepeda &Pardo, 2004) and the structural model presented in Figure 1 (Velandia, 2003), about 69 measuring stations were planned and set as shown in Figure 2.

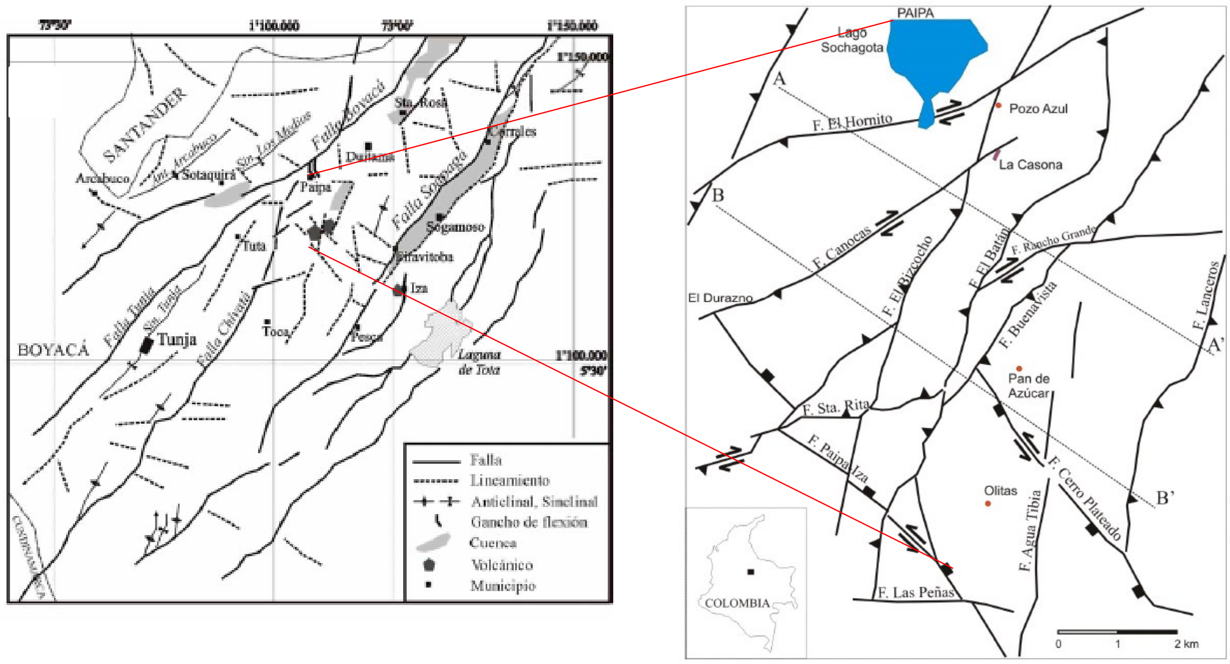

Figure 1: Structural Geology. Left: Regional frame. Right: Local faults in the geothermal area of Paipa. (Taken from Velandia, 2003)

3.2 Data Acquisition

The instruments used are two (2) MT Phoenix V8 with AMT sensors between 10.000 to 1 Hz, and MT sensors of 400 to 10000 seconds. The electromagnetic field component was measured by using non-polarizing electrodes. Pre-processing software, also from Phonexi, are SSMT2000 and MTEditor.

3.3 Data Processing

The data processing included dimensionality analysis, optimization of inversion parameters, 2D modeling and sensitivity analysis. The 2D processing software was WinGlink, Schlumberger. 3D interpolations were performed by using Voxler (Golden Software).

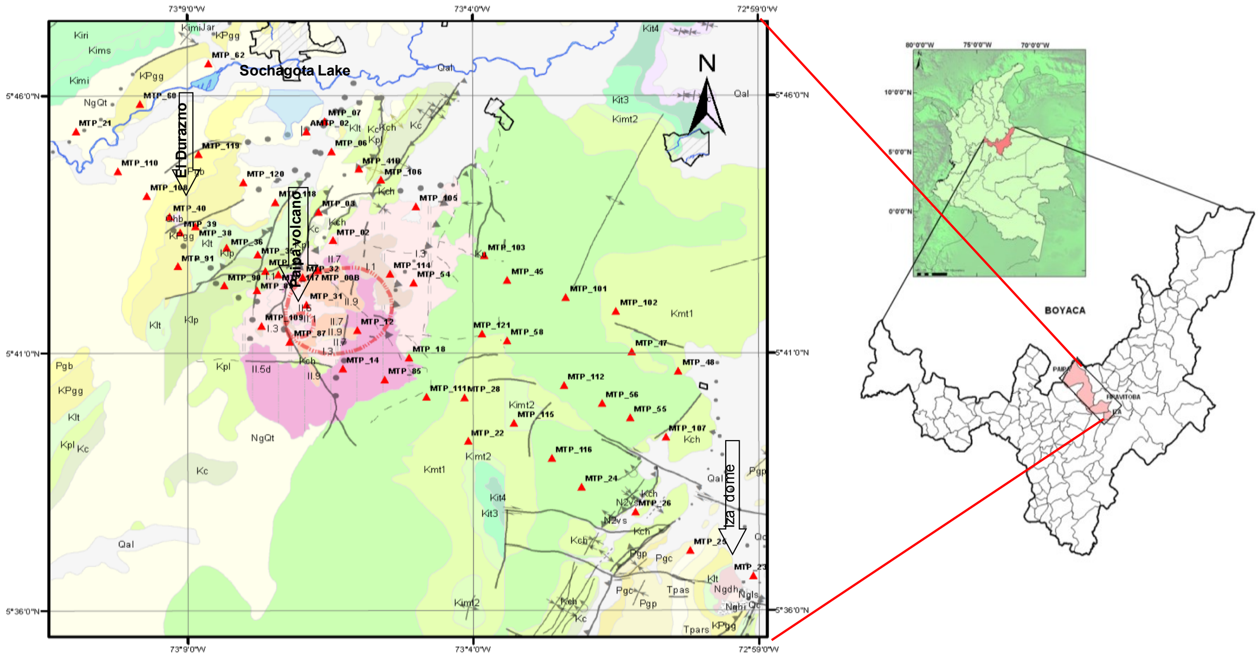

Figure 2: BMT stations. Paipa geothermal area on geological map (Velandia, 2003; Cepeda & Pardo, 2004).

4. RESULTS

After the dimensionality analysis, 4 N-W and 4 E-W profiles were defined for 2D modeling as illustrated in Figure 2. In general, the resistivity structure of the models shows a resistive basement, a sedimentary cover of lower resistivity, and a very high conductive and relatively shallow layer. From this vertical resistivity differentiation the possibility of a geothermal reservoir arises which would be located below the conductive layer.

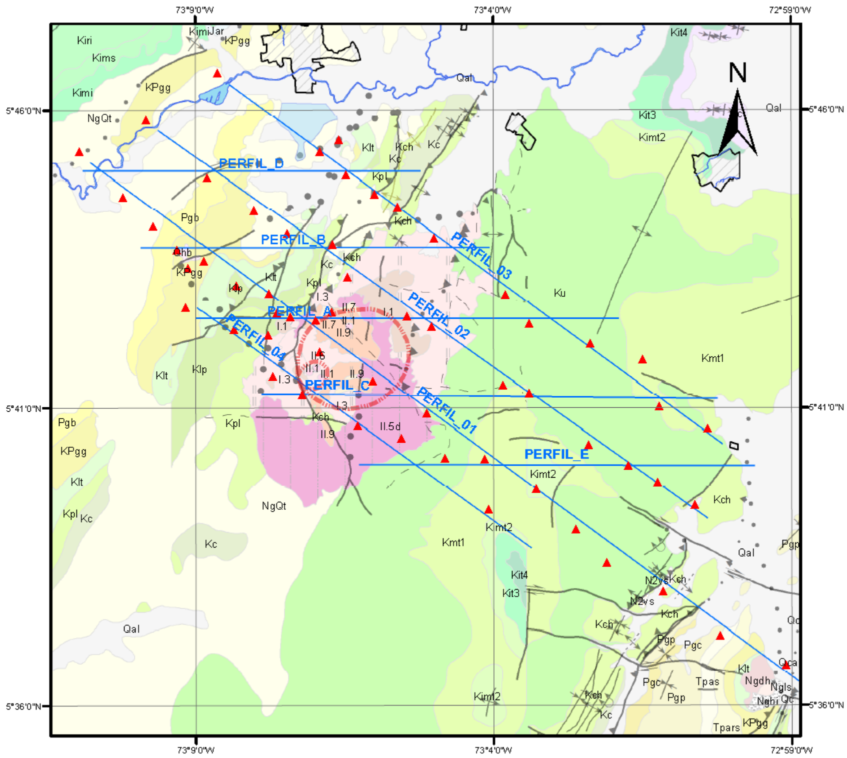

Figure 2: Profiles ("perfiles") for 2D modeling in the geothermal area of Paipa. Large red dotted circle: inferred volcanic edifice. Small red dotted circle: Domes focus. (Source: Moyano, 2014)

The profiles that best represent the resistive structure are identified as 1 and A (Figure 3) which cross northwest of the inferred volcanic edifice. The Profile 1, direction NW– SE, shows the three mentioned resistivity zones. The huge violet-blue area corresponds to the basement that coincides in shape with Tibasosa Anticline. It is cut at the left by a deep depression coincident with the Paipa-Toca Fault (Alfaro et al., 2012), previously identified from gravity surveys (Vasquez, 2012). To the left of the Paipa-Toca Fault, a conductive body of about 2 km depth corresponds to the quarry El Durazno, mapped as a hydrothermal breccia. The high sanidine contents (Mojica et al., 2009), the high uranium, thorium and potassium concentrations (Gonzalez et al., 2008), and the results of a local gravimetry – magnetometry study (Obando et al., 2012) reinforce the hypothesis of its igneous origin. Towards the east of the Paipa-Toca Fault, with lower thickness (about 500 m), there is another conductive body by the edge of the volcano. The conductive layer extends laterally for about 10 km towards the left and right of the conductive dome. It goes deeper with a lower magnitude to the left of the Chivatá Fault. The regional fault of Soápaga to the right side of the anticline separates a deeper conductive body about 6 km deep, where the sub-volcanic body of Iza dome is located.

The E-W profile A, also registers three well differentiated resistivity zones; the basement, the sedimentary cover and conductive layer close to the surface. By the NE fault of El Bizcocho there is a conductive body possibly related to the volcano. The faults Cerro Plateado and Agua Tibia, interpreted as basement faults do not show a clear correlation with electrical properties. They are located within a thicker sedimentary produced by a depression of the basement. Deep at left of the El Bizcocho Fault, the resistivity contrast marks the Paipa – Toca Fault.

The integration of the 2 profiles previously mentioned, is presented in the Figure 5. The basement, highly resistive, is deformed by the Tibasosa Anticline. In the Paipa area, west of Tibasosa Anticline, the conductive layer extends horizontally several kilometers getting the maximum thickness (about 2 km) west of the Paipa – Toca Fault.

Based on the graphical interpolation of the eight (8) profiles by using Voxler software, a 3D image was obtained (Figure 6) from which the location of the geothermal reservoir can be postulated. As in the images of individual profiles and of integration of the profiles 1 and A, the basement is clearly defined by very high resistivity (>300 to >8000 Ω.m.) The sedimentary sequence has a resistivity around ~20-300 Ω.m., and gets deeper at both sides of the anticline. The conductive layer (< 4 Ω.m.), which reaches 2 km in thickness, could correspond to a hydrothermal alteration zone (cap seal) or to a saline source. The geothermal reservoir could be hosted below the high conductivity layer. Its resistivity would be about < 4 Ω.m.

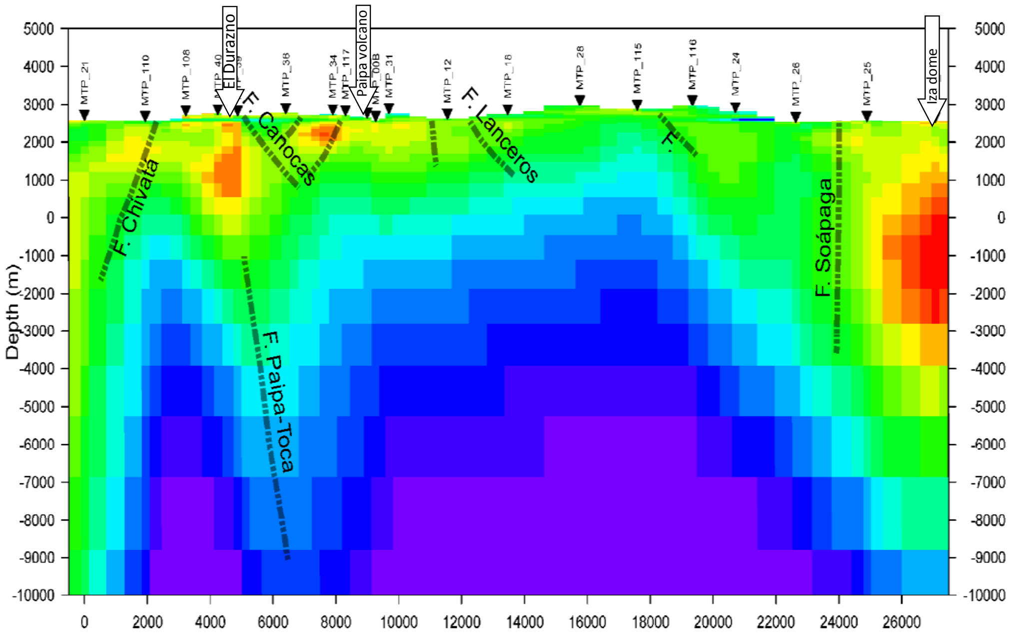

Figure 3: Profile 1 (NW-SE). The basement is cut by a deep structure previously identified as Paipa-Toca Fault. (Source: Moyano, 2014)

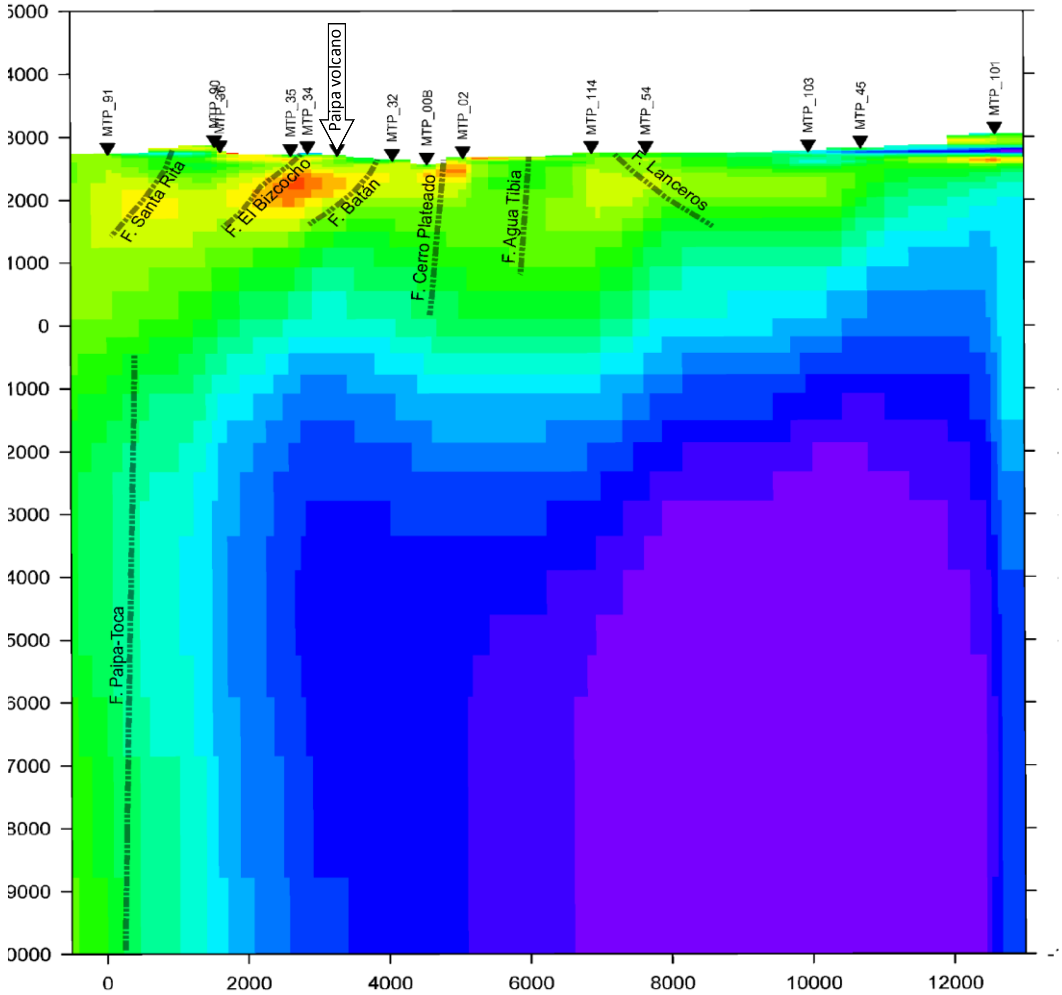

Figure 4: Profile A (E-W). A conductive body presumably related to the volcano is structurally controlled by El Bizcocho Fault. Within the caldera the deep normal faults do not show a contrast in their electrical properties. (Source: Moyano, 2014)

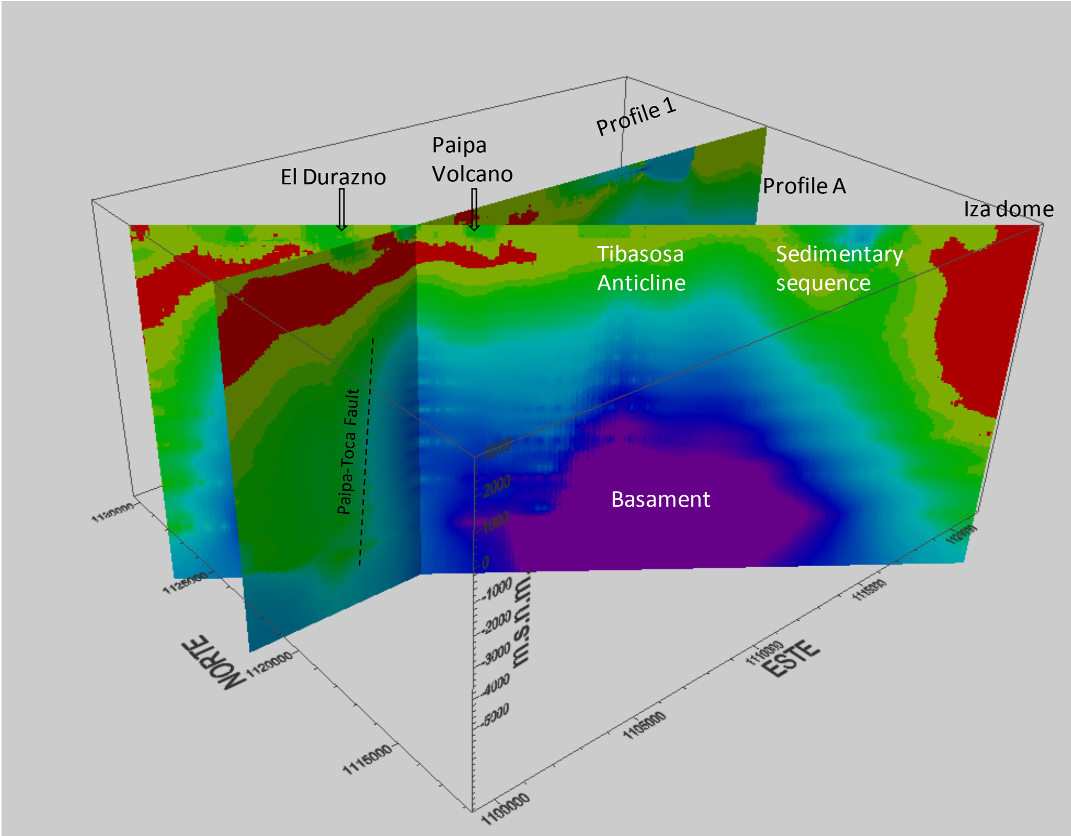

Figure 5: Profiles Integration. A conductive layer about 2 km thick extends for several kilometers west of the volcanic edifice and connects the volcano with El Durazno quarry. (Source: Moyano, 2014)

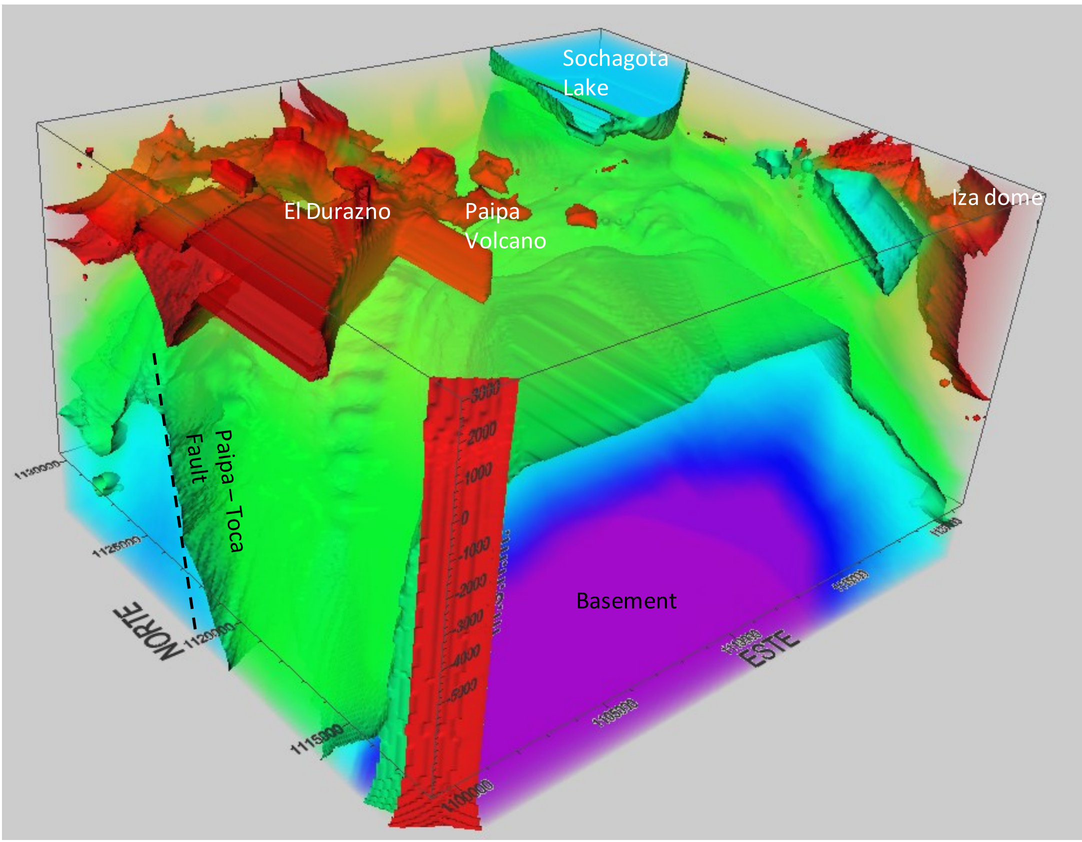

Figure 6: 3D representation of the spatial interpolation of profiles. The resistive structure of the geothermal are consist of a very low conductive basement, an intermediate sedimentary sequence and highly conductive cap towards the west of Paipa Volcano. (Source: Moyano, 2014).

5. CONCLUSIONS

The resistive structure of Paipa geothermal area is well defined by three main zones of very high (>300 to >8000 Ω.m), intermediate (100-300 Ω.m.) and very low resistivity (<4 Ω.m). They can be correlated to the basement rocks, a sedimentary sequence and a cap seal/ saline source, respectively. The reservoir resistivity is not clearly differentiated as the sedimentary sequence shaped for geological formation with high primary porosity/permeability is rich in water and the saline source could mixed with the geothermal fluid even in reservoir

At the study depth there are not geoelectrical evidences of an active magmatic source. From the resistivity structure, the most probable ascending conduct of deep fluids, including magma, could be Paipa-Iza Fault which cuts the basement very deep.

The conductive layer has a lateral high extension covering from the west of the volcano an area of 12 X 5 km.

The results of the magnetotelluric study provide elements that modify the exiting conceptual model.

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