Gravity and Magnetic Interpretation of Azufral Volcano Geothermal Zone

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ABSTRACT

The geothermal area of Azufral, located in the department of Nariño in the south-west part of Colombia, presents a relevant geothermal potential. During the geophysical exploration process of the zone, field trips of acquisition of gravity and magnetic data were carried out. From the acquisition of gravity and magnetic data in the geothermal area, accomplished by Quintero, Gomez and Ponce (2008), total Bouguer anomaly and total field magnetic anomaly grids are generated for the area.

The depth of source is estimated according to the total Bouguer anomaly and the total magnetic field grids and according to the fundamentals of Spector & Grant (1970). It was obtained a depth of 4 km for gravity data and 2.3 km for reduced to pole magnetic data. From these estimations the regional-residual separation is achieved, using an upward continuation filter. The calculation of analytical signal, tilt angle, Werner deconvolution and the favorability indices is implemented, from the interpretation of these new grids. The following is concluded: In the area of the Azufral Volcano body, the gravimetric source depth is 600 to 850 m and the magnetometric source depth is 1200 m to 1500 m.

The space generated by the Guachucal and Cali-Patía faults affects deep basement zones in the south-west part of the study area, generating a deposit basin. In the West part of the Azufral volcano and partially controlled by a segment of the Guabo River fault, there is possibly another intrusive body detected with favorability indices. According to Werner's deconvolution for magnetic data, the intrusive body has a depth of 750 m.

According to Werner's deconvolution applied over gravity grids, a sunken block is inferred in the southern part of the Sapuyes - Las Juntas basin, its depth is approximately 1800 m. The south-west part of the Guachucal fault has a possible deposit zone with a depth of approximately 1500 m to 2000 m. In the North West direction of the municipality of Túquerres, there is a possible intrusive body, with an approximate depth of 550 m - 650 m, linked to an opening area in the village of Santander. This zone has a great possibility to function as a deposit zone of hot fluids.

1. INTRODUCTION

Colombia, located in Northwest corner of South America, has a noteworthy geological diversity, in part due to the active subduction of Nazca Plate under South American Plate and oblique subduction of Caribbean Plate. These subductions generate many interesting geological features like volcanoes, mud volcanoes, and a strain front known as the Andean Belt. These characteristics give to the country a great energetic potential from several geothermal areas recognized since 1968 (Battocletti,1999). Nevertheless, Colombian geothermal potential remains unexplored for most areas.

Servicio Geológico Colombiano is a Science Technology and Innovation institution that belongs to the National System of Science, Technology and Innovation led by Colciencias. Since 2008 Research and Exploration in Geothermal Resources Group (REGRG) has made geophysical acquisitions (Gravity, Magnetics, Geoelectric, and Magnetotelluric surveys) over several areas with recognized geothermal potential.

Currently, REGRG is developing a conceptual model for the Azufral Volcano Geothermal Area (AVGA), and from gravity and magnetic acquisitions made by different authors over AVGA; this builds on geophysical models to estimate subsurface properties in AVGA.

The purpose of this project was to test the suitability of potential methods such as gravity and magnetic measurements to explore geothermal resources. This study demonstrated that with adequate levelling and a complete station covering over the target zones, it was possible to make a geophysical model and estimate the depth of gravity and magnetic sources. However; in order to apply the adequate filters over the main grids produced by the data analysis it was crucial to have a geological and tectonics framework previously; this in addition to some geological knowledge, interpretations made the overall process more simple and accurate.

These estimates, along with the geophysical models made from gravity and magnetic inversion, allowed to figure geometry, depth and extension of geothermal systems.

1.1 Theoretical Background

In a brief manner, we treated the gravity and magnetic data to remove all global and time-dependent variations. Those are the main mathematical expressions that we use for reducing the data and obtaining different grids, that allow us to interpret and understand the subsurface of AVGA

1.1.1 Calculation of total the Bouguer anomaly (TBA)

From observed absolute gravity, the latitude correction was calculated with further information (Moritz,1980). The Jung method was used as described by (Jacoby and Smilde, 2009) to calculate the reduction of density. The following equation illustrates the Jung method:

$$P = \rho_0 + \frac{\sum[(BA_{oi} - \overline{BA_o}) * (h_i - \overline{h_0})]}{2\pi G \sum(h_i - \overline{h_0})^2} \tag{1}$$

In eq. 1, we have ρ_0 as initial density, BA_{oi} the Bouguer anomaly with a specified reduction density at the ith station, and $\overline{BA_o}$ the mean Bouguer anomaly for all stations. h_i is the height of the ith station and $\overline{h_0}$ is the mean height of all stations (Jacoby and Smilde, 2009). After calculating the mean density, the Free Air correction was calculated, Bouguer correction and Free Air and Simple Bouguer anomalies (ABS and ABT respectively).

In eq. 2, T is a potential field; with the analytic signal, we can see the contours and zones with contrasts of density or magnetic susceptibility (Macleod et al., 1993). The derivatives can be calculated with fast Fourier transform or convolution in Oasis Montaj a Geosoft Inc. program.

1.1.2. Calculation of Total Magnetic Field Anomaly (AM)

Magnetic data was "cleansed" first, then base magnetic data (magnetograms) was analyzed in order to calculate the diurnal correction and diurnal variation, see (Udías et al., 1997) in (Ponce, 2013). The Global model IGRF-11 was used, see (Finlay et al., 2010) to calculate magnetic anomalies and to obtain the field total magnetic anomaly (AM).

1.1.3. Processing of Gravity and Magnetic Grids

The processing of gravity and magnetic grids was achieved using the main grids Complete Bouguer Anomaly (TBA) and, Total Field Magnetic Anomaly (MA) over MA applied a reduction to pole (RTP) (Kis, 1990). Also, using the amplitude correction inclination (co-inclination) factor to correct distortions in pole reduction caused by low values of geomagnetic latitude (Macleod et al., 1993) and (Geosoft Inc., 2015).

The interpretation of RP_MA allowed viewing magnetic anomalies as if they were measured at the magnetic pole. With the amplitude correction inclination, the distorted areas in N-S sense originated by the low magnetic latitude of data could be reduced (Kis, 1990). The interpretation of RTP grids allowed to find anomalies without its dipolar character, thus making the interpretation more accurate. This also reduced the noise level in the RTP grid, allowing to successfully obtain correlation with the first vertical derivative of total Bouguer Anomaly (Ponce, 2013).

The next equation defines the calculation of the main grids analytic signal (TBA and MA) and of an analytic signal:

$$AS = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \tag{2}$$

In eq. 2, T is a potential field. With the analytic signal, we can see the contours and zones with contrasts of density or magnetic susceptibility (Macleod et al., 1993). Derivatives can be calculated with fast Fourier transform or convolution in Oasis Montaj a Geosoft Inc. program.

From the analytic signal, we can deduce the angle between the horizontal component (H) and the vertical component (Z) of the potential vector T, called tilt angle (Salem, A. et al. 2007), and the equation is:

$$H = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2}$$

$$Z = \sqrt{\left(\frac{\partial T}{\partial z}\right)^2}$$

$$\theta = arctan\left(\frac{Z}{H}\right) \tag{3}$$

In order to estimate the depth of the magnetic or gravity sources, we can use the Werner deconvolution and the solutions of the analytic signal. The Werner deconvolution was a technique developed by Werner (1953) in (Telford et al., 1990), and consists in assuming the source of a magnetic anomaly in a dipping dike. The next equations describe the generalized magnetic anomaly:

$$F(x) = [M(x - x_0) + Nz][(x - x_0)^2 + z^2] \tag{4}$$

$$x^2 F(x) = a_0 + a_1(x) + b_0 F(x) + b_1 x F(x) \tag{5}$$

$$F = F(x) + c_0 + c_1(x) + \cdots + c_n x \tag{6}$$

Equation 3 is the equation that describes the magnetic anomaly from a dipping dike. In (3) x_0 is the surface point directly above the center of the top of the dike, z is the depth to the top, M and N are unknown functions of dike geometry and mineralization, respectively. Eq. 4 is a rearranging of eq. 3 in a polynomial shape. If we solve eq. 4, we find that the depth is $z = \frac{\sqrt{-4b_0 - b_1^2}}{2}$ and $x_0 = \frac{b_1}{2}$. Eq.5 is a polynomial extension of eq.4 of a dipping dike with the interference of neighboring magnetic anomalies. To solve eq. 4 we need a minimum of four stations, then, to solve eq. 5 we need a number of n + 5 stations. Such a number of stations, according to

(Telford et al., 1990), is six or seven because the polynomial equation 4 normally has a maximum order of two (see (Telford et al., 1990, p.112)).

The solution of the analytic signal is another technique to get a source depth, based on the work of (Nabighian, 1984) in (Macleod et al., 1993). From the solutions of extreme values associated with eq. 2 in the frequency domain, it is possible to estimate the depth of the edge of the magnetic body whose field is described by eq. 2.

The correlation of gravity and magnetic grids can be obtained with the calculation of the Favorability index. This technique developed by (Freese et al., 1982) in (Tan and von Freese, 1997), (Hernandez, 2006) and (Gómez Martinez et al., 2012) consists in correlating the first vertical derivative of the Total Bouguer Anomaly (TBA) with Magnetic anomaly reduced to magnetic pole (MA_PR), with basis in Poisson Theorem, see (Düzgit et al., 2006).

$$RP_{MA} = \frac{1}{G} \frac{\Delta \chi}{\Delta \rho} \left(\frac{\partial}{\partial z} TBA \right) \tag{7}$$

The previous equation said that Magnetic Field is directly proportional to the product between susceptibility $\Delta \chi$ and density contrasts relation ($\Delta \rho$). The first vertical derivative of Gravity Field, in eq. (6) G is the Universal Gravity Constant, χ is magnetic susceptibility and ρ is density.

With the assumption of eq. **(7)**, the first vertical derivative of gravity and pole reduced magnetic field are correlated, and with its normalization, we can calculate the with Favorability Indexes for these fields:

$$Z_N = \left(\frac{Z_i - \bar{Z}}{\sigma Z} \right)$$

$$SLFI = (DDZ_N + AM_N) \tag{8}$$

$$DLFI = (DDZ_N - AM_N)$$

In the set **(8)** Z_i is the potential field (Gravity or Magnetic), Z is the field average, σZ is the field standard deviation, and Z_N is the normalized potential field. For the second part of the set, **(8)** SLFI meaning is "Summed Local Favorability Index" and shows the positive correlations between gravity and magnetic (gravity peak to magnetic peak or gravity through to magnetic though). DLFI meaning is "Differenced Local Favorability Index" and shows negative correlations or correlations gravity peaks to magnetic troughs and vice versa.

In order to correctly interpret anomalies in geothermal areas, it is important to separate regional/residual components of both gravity and magnetic signals. To do that, the calculation of the power spectrum becomes essential. The power spectrum is a graphic that allows seeing the behavior of the energy logarithm of a signal vs. its frequency or wavenumber, see (Vásquez, 2012).

$$logE = log[\int [F(\kappa)]^2 dx] \tag{9}$$

From (Spector and Grant, 1970) in (Reeves, 2005), if a source of potential field exists in certain depth **h**, its power spectrum is a straight line with slope **m = −4πh**. From the analysis of different distributions of points in a power spectrum, it is possible to estimate a set of depths associated with a set of sources that have some wavenumbers.

From the maximum depth that it is possible to calculate, an upward continuation filter is used to find regional sources see (Dean, 1958)

$$F(\kappa) = F_0 e^{[-h\kappa]} \tag{10}$$

Where h is continuation height that is equal to the maximum depth of the potential source in agree with the analysis of the power spectrum and κ is the wavenumber or frequency. The residual contribution is calculated by taking the difference between the original Grid and the Regional GridUsing the grid obtained after the application of the upward continuation filter (Regional grid). The maximum depth of the residual grid obtained is calculated again and interpreted.

2. GEOGRAPHICAL, GEOLOGICAL AND TECTONIC FRAMEWORK

In this chapter, we discuss the geographical, geological, and tectonic framework of AVGA.

2.1 Geographical Location of Azufral Volcano Geothermal Area

The geothermal area of Azufral is located in the Andes Mountains in the department of Nariño at a distance of 82 km SW of San Juan de Pasto, the capital of the department, and 12 km W of the municipality of Túquerres. The area has heights from 2050 mas (Vereda Guarango and Balalaika villages in the municipality of Samaniego) to 4070 masl (top of the Azufral volcano). The temperatures in the area vary between 9°C and 24°C, but in most of the zone located in the municipalities of Túquerres and Guachucal, the average temperature is 10°C. The coordinates of the area with Western Origin, Datum MAGNA-SIRGA, can be seen in Table 1.
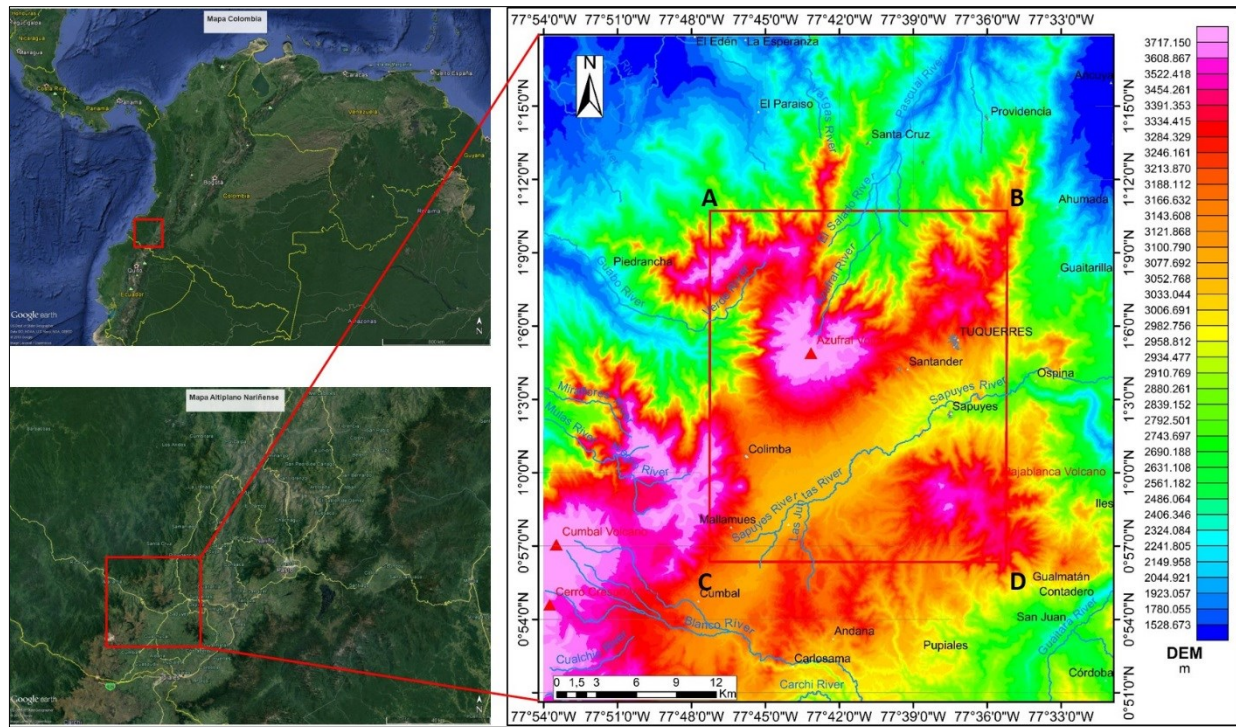
Figure 1. Location map of Azufral Volcano Geothermal Area (from own source and Google Earth Inc)

Table 1: MAGNA-SIRGAS Geographical Coordinates of the area

| Point	Latitude (degrees)	Longitude (degrees)
A	1.17855	-77.78757
B	1.17862	-77.58654
C	0.93932	-77.78776
D	0.93912	-77.58724

2.2 Geologic and Tectonic frame of AVGA

AVGA has dimensions of 20 Km x 27 Km. It consists of two main volcanoes, Azufral volcano in the north-west part of the area and Pajablanca volcano to the southeast. Several intrusive bodies can be found like Azufral domes and Colimba domes, these domes are composed of pyroclastic deposits of andesitic composition and andesitic domes. (Pinilla *et al.* 2007)

The main basin comprises Sapuyes River and Las Juntas River, and it is composed of volcanoclastic deposits from Cumbal, Azufral, and Pajablanca Volcanoes. Specifically, some units like Cumbal Antiguo Andesitic Lavas, Quitasol y Olaya Andesitic Lavas, Andesitic Lavas of Pajablanca Volcano and Pyroclastic deposits from Azufral Volcano (Pinilla, *et al.* 2006).

Basement rocks comprise the Dagua Group and Diabásico Group, the last composed of basalts and meta-siltstones of late cretaceous age (Gonzalez *et al.* 2002), and have outcrops in the north-east part of the area. Structural Geology comprises the Cali-Patía fault. This fault separates an oceanic domain to the west and a continental domain to the east (Gonzalez *et al.* 2002).

The Cali-Patía fault has a left-lateral movement with a minor normal component in latitude over 5°. To the south, this fault has an inverse sense of movement with a minor right-lateral component (Ego et al. 1995 in Rodríguez & Rueda, 2017). This fault has an intersection point with lineament El Diviso-Túquerres. This point is closely related to the uplift of Azufral Volcano (Cepeda 1985 in Rodríguez & Rueda, 2017).

Guachucal fault is an inverse fault with a dextral component and dipping to the east, with multiple variations in its strike along its trace. To the north, this structure has a major inverse component (Rodríguez & Rueda, 2017). Figure 2 illustrates the faults and most relevant geological units in AVGA
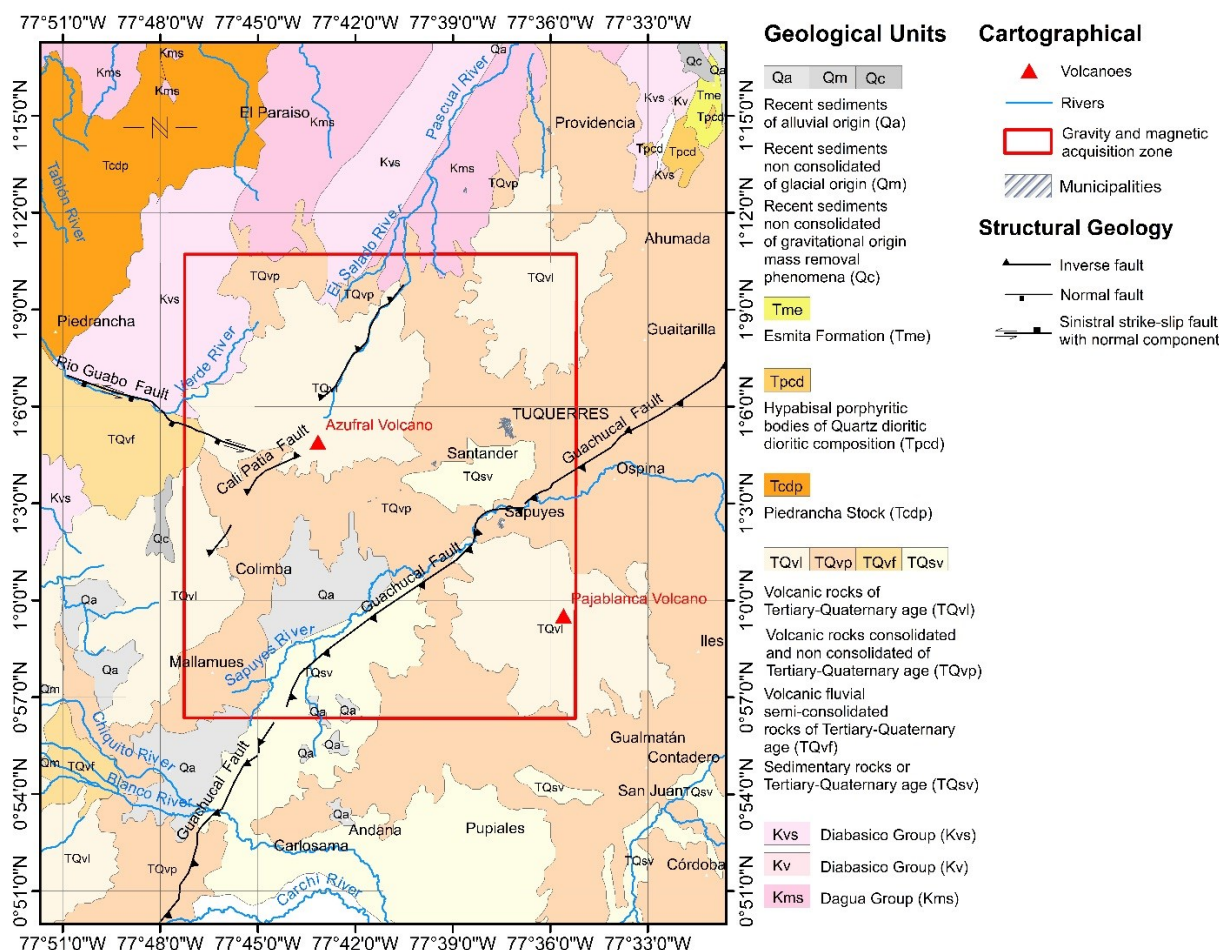
Figure 2. Regional geological map of AVGA based in Gonzalez, *et al.* **2002; Pinilla** *et al.* **2006 and Rodríguez & Rueda 2017**

Locally the geology is dominated by the pyroclastic deposits of Azufral Volcano and the strong influence of Guachucal fault in the south part of the area and the Cali-Patía Fault to the north part. Three volcanic bodies can be seen: Azufral Volcano to the north, Pajablanca volcano to the south, and Colimba domes to the west.

3. GRAVITY AND MAGNETIC SURVEYS

Gravity and magnetic data were acquired in 2008 by Wilson Quintero, Patricia Ponce, and Diego Gomez in the project of gravity and magnetic exploration of Azufral Volcano. Table 2 has a resume of the field trips and its authors:

Table 2: Resume of gravity and magnetic data acquisitions.

Authors	Begin date	End date	Device	Spacing
Diego Gómez, Wilson Quintero, Patricia Ponce, Nardy Neisa	26/05/2008	11/06/2008	Scintrex CG-5 Scintrex ENVI-MP3	600 m
Diego Gómez, Wilson Quintero, Patricia Ponce, Nardy Neisa	21/08/2008	09/09/2008	Scintrex CG-5 Scintrex ENVI-MP3	600 m
Diego Gómez, Wilson Quintero, Patricia Ponce, Nardy Neisa	22/10/2008	29/10/2008	Scintrex CG-5 Scintrex ENVI-MP3	600 m

3.1 Gravity Interpretation

From the levelling of raw gravity, data was obtained the TBA. From this primary grid was obtained the analytic signal and tilt angle, from an upward continuation filter. From the paper of (Spector & Grant, 1970), the mean depth of regional and residual grid can be estimated. The depth range is summarized in Table 3

Table 3: Range source depth from gravity data (Spector & Grant, 1970)

Spectral Values	Regional		Residual	
	From	**To**	**From**	**To**
Wave number (Km^{-1})	$1.12*10^{-1}$	$8.37*10^{-2}$	$2.23*10^{-1}$	$8.37*10^{-2}$
Power (Ln (P))	2.41	3.97	$-1.07*10^{-2}$	4.24
Wave length (m)	8960	11900	4480	11900
Depth range (m)	3510	4090	1650	3510

TBA grid, residual grid, analytic signal, and tilt angle can be seen in Figure 4. From Figure 4, we can note that in **TBA,** the maximum value of gravity is located in the zones corresponding to Dagua and Diabásico Groups and in part to the domes located in Azufral Volcano.

While in residual anomaly, it is possible to see a high anomaly in the zones where the Diabásico Group (**A, B**) has outcrops and in the andesitic lavas from Pajablanca Volcano (**C**). In Azufral Volcano, there is a lower anomaly related whit the outcrop of volcanoclastic deposits and ignimbrites (**A'**). There's another lower anomaly located in Santander town (**B'**), possibly related with local subsidence of basement rocks. The tilt angle indicates a strong structural control of Guachucal fault (**C**), which can also be noted in residual **TBA.**
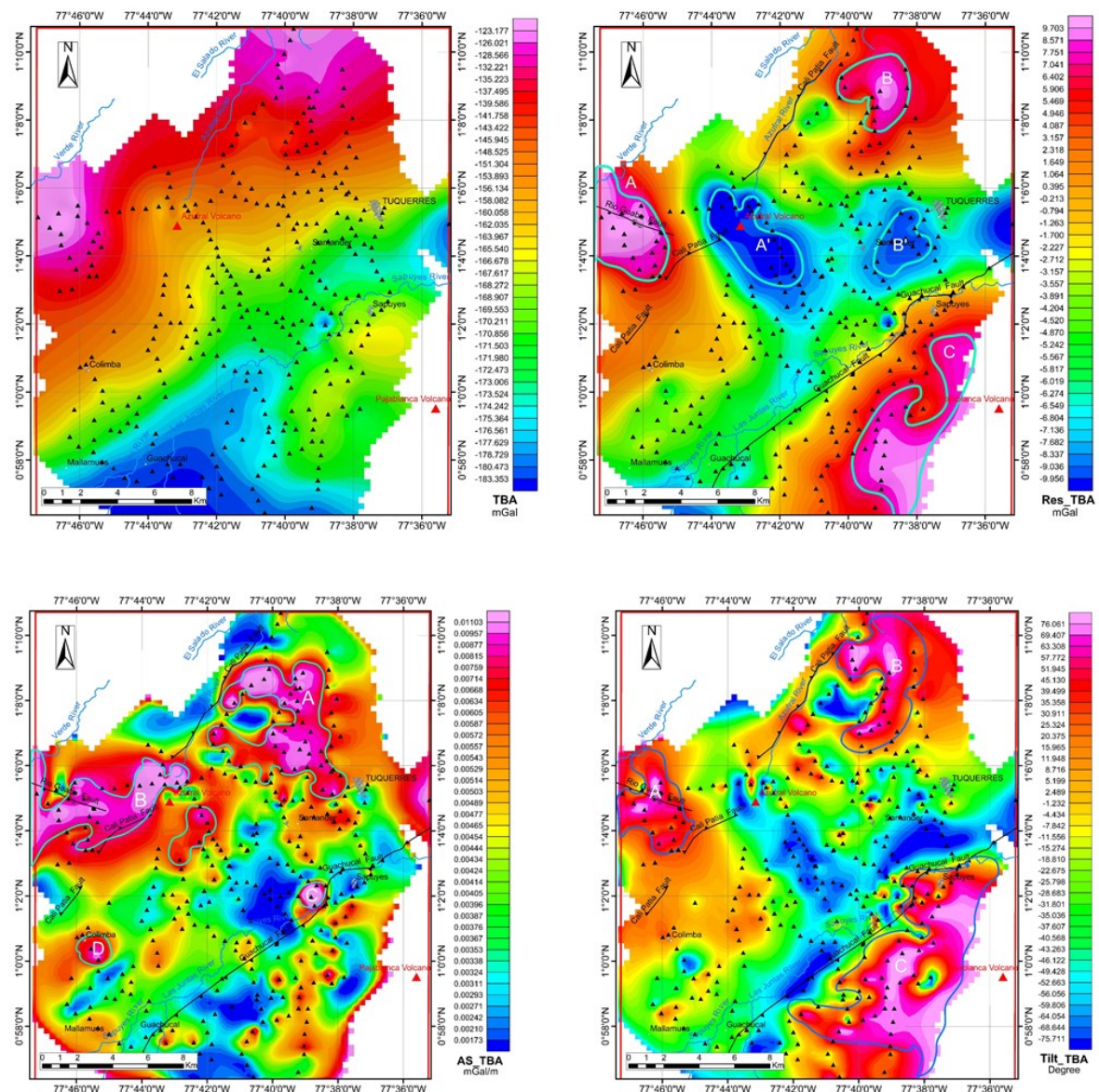

Figure 3. Total Bouguer Anomaly (TBA) to the upper left, to the upper right Residual Anomaly from TBA, in the lower-left Analytic signal of TBA and in the lower right the tilt angle of TBA (from own source)

3.2 Magnetic Interpretation

From Total Field Magnetic Anomaly (**TFMA**), we made the pole reduction **RTP**, and from it, we can calculate grids like the regional, residual, analytic signal, and tilt angle. Equal with gravity data, we use an upward continuation filter with a continuation height equal to maximum depth agree with the work of Spector & Grant (1970). From this regional grid, we subtract it from the **RTP** grid and obtain residual grid. Range depths from **RP_MA** grids can be seen in table 4.

Table 4: Range source depth from magnetic data (Spector & Grant, 1970)

Spectral Values	Regional		Residual	
	From	**To**	**From**	**To**
Wave number (Km^{-1})	$1.12*10^{-1}$	$5.58*10^{-2}$	$5.30*10^{-1}$	$1.12*10^{-1}$
Power (Ln (P))	3.58	5.38	-1.16	3.58
Wave length (m)	8960	17900	1886	8960
Depth range (m)	1610	2320	530	1610

Interpretation of grids derivate from **RP_MA**, show positive anomalies in the Azufral Volcano (**A**) in outcrops of Dagua and Diabásico Groups (**B**), an intrusive body beneath Túquerres town in (**C**) and Pajablanca volcano (**D**). In the residual grid, we can see several lower magnetic anomalies possibly related to magnetic dipoles corresponding to the remaining magnetization (**B'**, **C'**, **E'**, **F'**) related to Dagua and Diabásico Groups, Pajablanca Volcano and Colimba Domes respectively.

In the analytic signal and tilt angle, it is possible to see a slightly structural control of Guachucal fault, especially in the south part of **AVGA**.
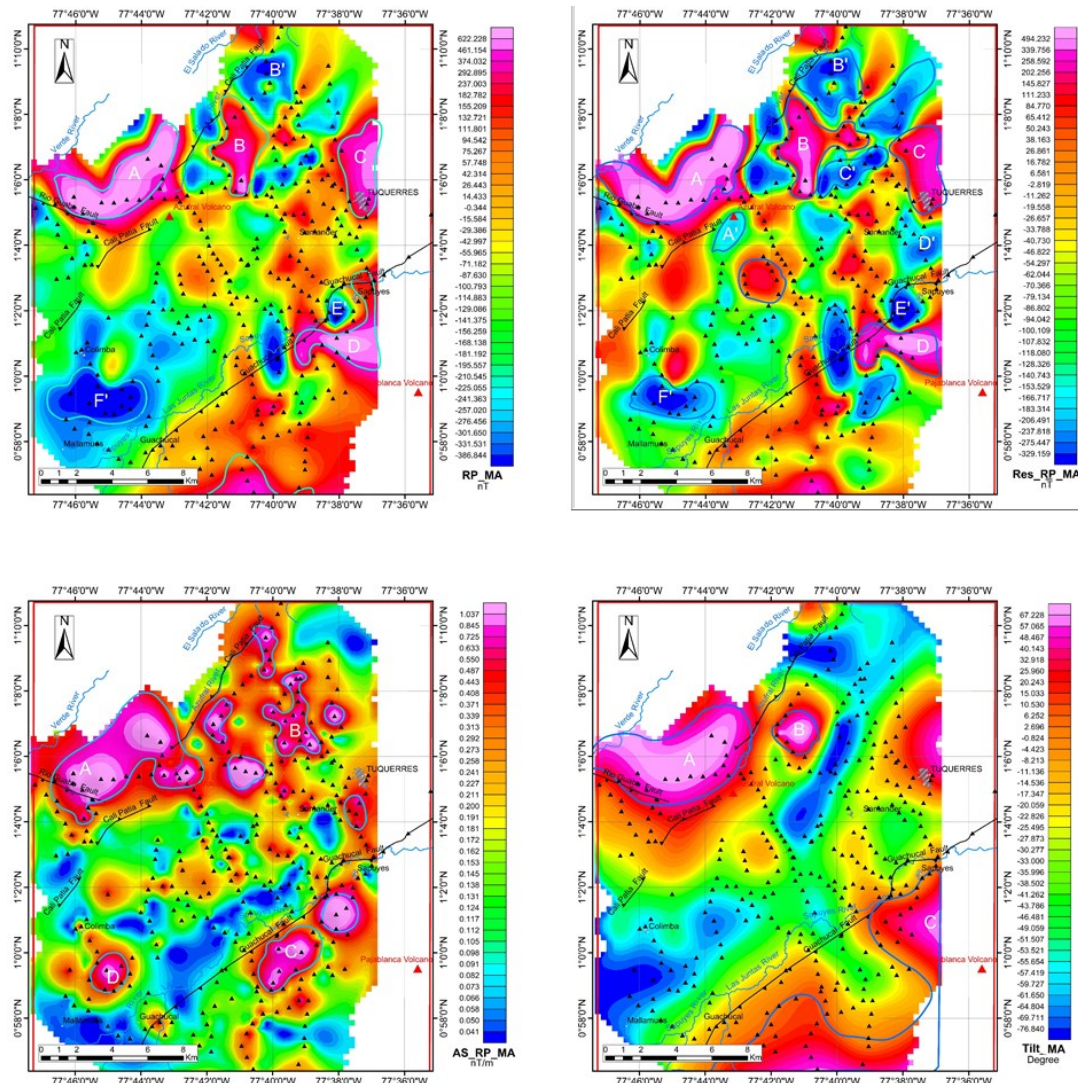

Figure 4. Reduction of magnetic pole magnetic anomaly (RP_MA) in the upper left. In the upper right Residual Anomaly from RP_MA. In the lower-left Analytic signal of RP_MA, and in the lower right the tilt angle of RP_MA (from own source)

3.3 Favorability Indexes

From using equations of set 8 over normalized **RP_MA** and **TBA** grids, direct correlation peak to peak and through to through favorability indexes can be obtained, in Figure 6, we can appreciate it.
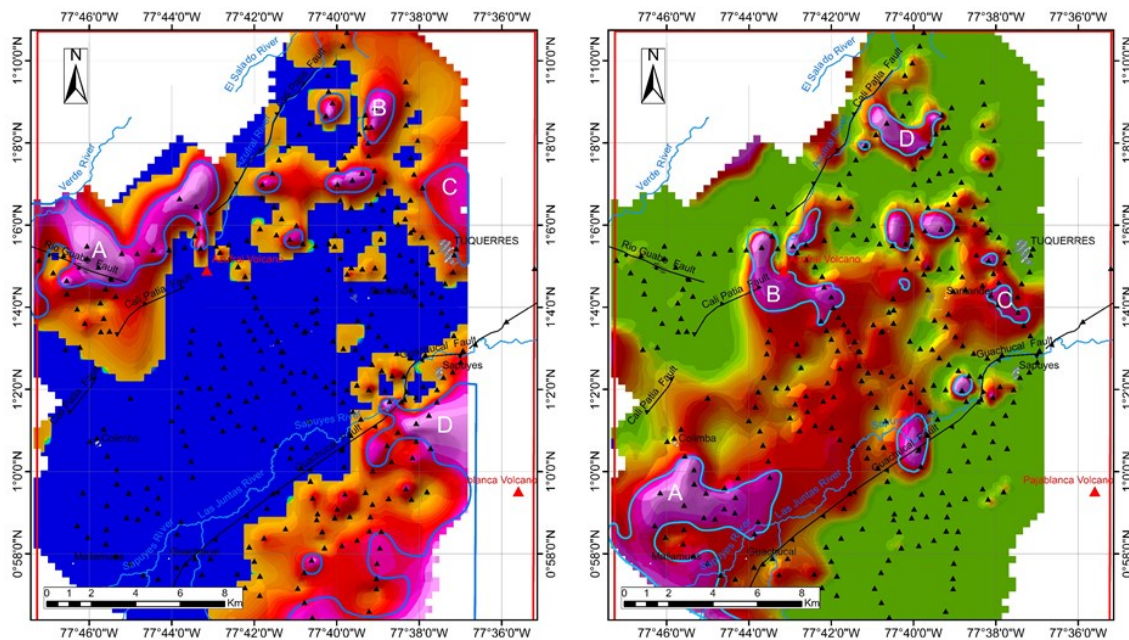
Figure 5. Summed local favorability indexes (SLFI), gravity peak to magnetic peak to the left, to the right (SLFI) gravity through to magnetic through (from own source).

In SLFI peak to peak correlation, we can see basement rocks outcrops (Dagua and Diabásico units) corresponding to zones **A** and **B**. In the south part, the andesitic lavas from Pajablanca volcano limited by Guachucal Fault. In SLFI through to through it is possible to see the Sapuyes River- Las Juntas River Basin limited by Cali-Patía and Guachucal Faults, and zones with volcanoclastic deposits related to Azufral Volcano (**B**), Cumbal Volcano (**A**) and a deep basin in Santander town (**C**)

3.4 Depth source

The calculation of Werner deconvolution using equations 4, 5, and 6 shows us a better estimation of source depth. A comparison with solutions of the analytic signal can be seen in Figure 6.

From the upper left, Werner solutions for **MA_PR** show for Azufral Volcano an intermediate depth about 1300 m to 1500 m. This implies that far from 1300 m, there are magnetized rocks beneath Azufral Volcano and probably are not hot rocks with temperatures under Curie point.

For Werner solutions, the polygons with red and purple colors indicate zones with magnetized basement near to surface. These possibly are intrusive bodies composed of cold rocks, especially beneath Tuquerres town (**A**), Colimba domes (**B**), Pajablanca Volcano (**C**), Guachucal town (**D**) all of this polygons have depths below 650 m. The deepest features from this feature indicate zones with magnetized rocks with high depths of 2200 m, especially in the traces of Cali-Patia fault and Guachucal Fault.

The Analytic signal solutions for **MA_PR** show in contrast zones with less depth from Werner solutions (<280 m). Especially in the northern part of the area where Dagua and Diabásico Groups rocks have outcrops (**A**), beneath Tuquerres and south of Santander town (**B**), Pajablanca Volcano lavas (**C**), and the rocks that surround Azufral Volcano. These are possibly related to Volcanic deposits over rocks that belong to Dagua and Diabásico Groups (**D**) or intrusive bodies and control in the west by Rio Guabo Fault

Azufral Volcano in the south part show depths of 1300 m. The deepest part of these solutions has a strong correlation with the traces of Cali-Patia and Guachucal Faults with depths of 2000 m to 3100 m.

Werner solutions for **TBA** show shallow zones beneath Tuquerres town (**A**), Azufral Volcano (**B**), Guachucal fault in its northern part (**C**) and the south-east part of Colimba domes (**D**). The depths are under 630 m to 800 m and indicate zones with intrusive bodies. The Pajablanca volcano has depths of 1250 m, the deepest zones for **TBA** reach 2600 m of depth. In the Sapuyes River basin, the depth to Gravity basement is about 1800 m.

For the Analytic signal solutions, we have similar polygons con depths about 280 m, rocks of Dagua and Diabásico Group (**A**), Tuquerres town (**B**), Pajablanca volcano (**C**) and Colimba domes (**D**) the deepest part reach 3200 m in Sapuyes – Las Juntas basin.
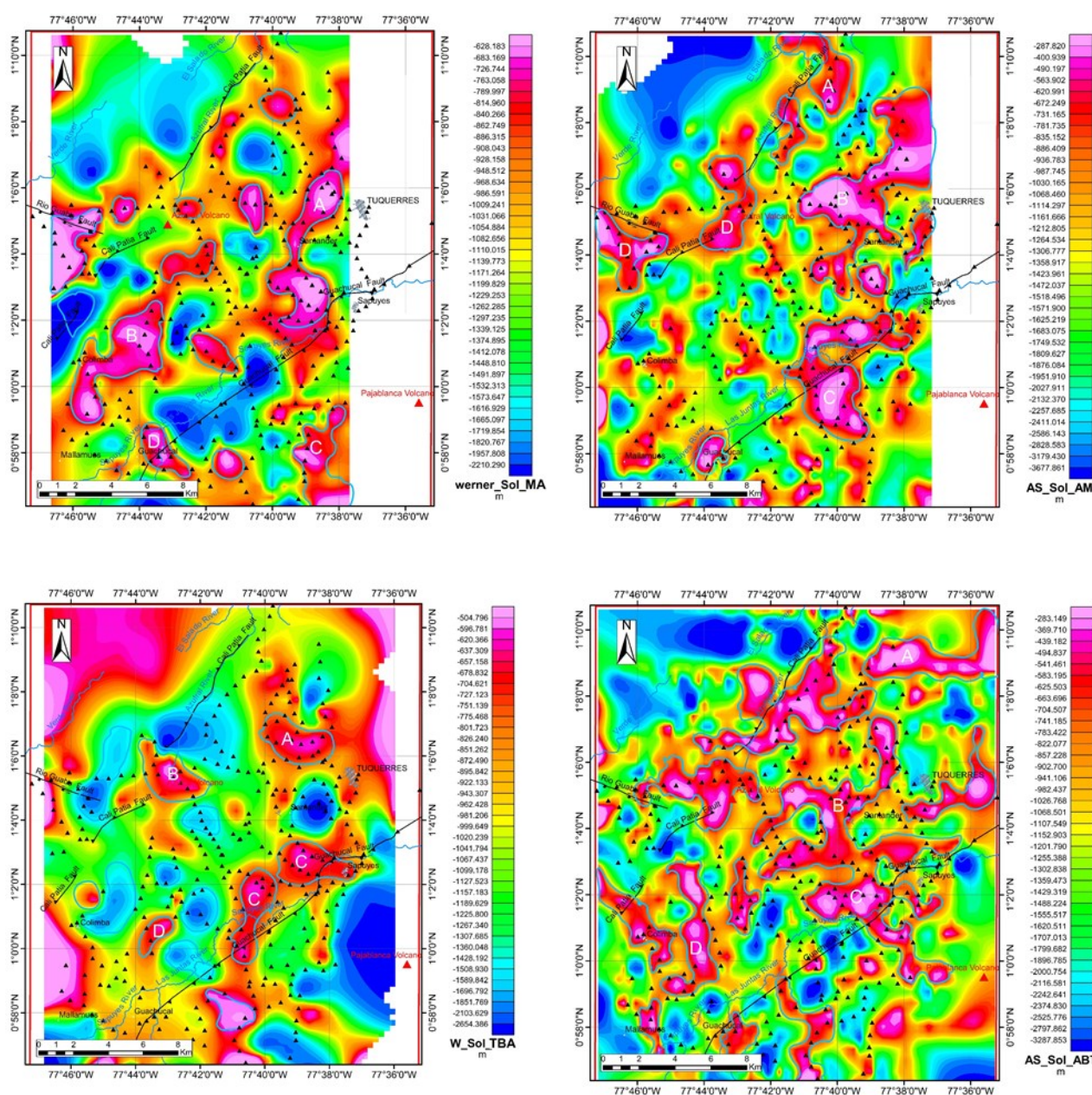
Figure 6. Werner solutions for RP_MA in the upper left. In the upper right Analytic signal solutions for RP_MA. In the lower-left Werner solutions for TBA, and in the lower-right Analytic signal solutions for TBA (from own source)

4. CONCLUSIONS

In the area of the Azufral Volcano body, the gravimetric source depth is 600 to 850 m, and the magnetometric source depth is 1200 m to 1500 m.

The space generated by the Guachucal and Cali-Patía faults affects deep basement zones in the southwest part of the study area. This generates a deposit basin, reaching depths of 2000 m to 3200 m

In the West part of the Azufral volcano and partially controlled by a segment of the Guabo River fault, there is possibly another intrusive body or basement rocks below volcanoclastic rocks. This intrusion was detected with favorability indices, and according to Werner's deconvolution for magnetic data, this zone has a basement depth of 750 m.

According to Werner's deconvolution applied over gravity grids, a sunken block is inferred in the southern part of the Sapuyes - Las Juntas basin. Its depth is approximately 1800 m.

The southwest part of the Guachucal fault has a possible deposit zone with a depth of approximately 1500 m to 2000 m. In the northwest direction of the municipality of Túquerres, there is a possible intrusive body. This intrusion has an approximate depth of 550 m - 650 m, linked to an opening area in the village of Santander with a depth of 1800 m. This zone has a great possibility to function as a deposit zone of hot fluids.

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