

Boletín Geológico, 46, 5–22, 2020  
[https://doi.org/10.32685/0120-1425/  
boletingeo.46.2020.514](https://doi.org/10.32685/0120-1425/boletingeo.46.2020.514)



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Received: December 10, 2019

Accepted: March 6, 2020

Published online: June 30, 2020

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# Interpretation of geophysical anomalies for mineral resource potential evaluation in Colombia: Examples from the northern Andes and Amazonian regions

Interpretación de anomalías geofísicas para la evaluación del potencial de recursos minerales en Colombia: ejemplos del norte de los Andes y Amazonía

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## ABSTRACT

This paper focuses on presentation of the methodology used by geophysicists at the Servicio Geológico Colombiano (SGC) for the processing, anomaly selection and interpretation of airborne magnetometry and gamma spectrometry data. Three (3) selected magnetic anomalies from different geological settings (Andes Cordillera, San Lucas Range and Amazon region) are presented as examples. 3D magnetic vector inversion (MVI) modeling of each of the selected magnetic anomalies shows magnetic sources less than 100 m deep or exposed with sizes from 2.5 to 6 km. The magnetic data interpretation also allows the identification of linear features that could represent structural control for fluid migration and/or ore emplacement. Additionally, the integration of the geophysical data with other geoscientific information (geologic, metallogenic and geochemical data) leads to the proposition of an exploration model for each anomaly: intrusion-related/VMS deposits for the Andes, porphyry/intrusion-related/epithermal deposits for San Lucas and carbonatite/kimberlite for Amazonas. The methodology used and examples presented illustrate the potential of SGC airborne geophysical data for mineral resource evaluation and as input for the design of fieldwork for geological, geophysical, geochemical and metallogenic characterization of an area of interest.

**Key words:** Geophysical data processing, 3D modeling, magnetic anomalies, mineral resources.

**RESUMEN**

Este documento se centra en la presentación de la metodología usada por los geofísicos del Servicio Geológico Colombiano (SGC) para el procesamiento, selección de anomalías e interpretación de datos de aeromagnetometría y gamma-espectrometría. Se presentan como ejemplo tres anomalías localizadas en diferentes ambientes geológicos (cordillera de los Andes, serranía de San Lucas y Amazonia). La modelación 3D a partir de la inversión del vector magnético (MVI) de cada una de las anomalías seleccionadas muestra fuentes magnéticas a menos de 100 m de profundidad, o aflorantes, y con tamaños de 2.5 a 6 km. La interpretación de los datos magnetométricos también permitió identificar rasgos lineales que pueden representar controles estructurales para el ascenso o emplazamiento de mineralizaciones. Adicionalmente, la integración de los datos geofísicos con otra información geocientífica (geología, metalogenia y datos geoquímicos) permitió proponer posibles modelos de exploración de cada anomalía: depósitos asociados a intrusivos/sulfuros masivos vulcanogénicos (VMS), en el caso de la anomalía de los Andes, pórfido/asociado a intrusivo/epitermal para la de San Lucas, y carbonatita/kimberlita para la del Amazonas. La metodología empleada y los ejemplos presentados ilustran el potencial de los datos geofísicos del SGC para evaluar el potencial de recursos minerales y como un insumo para la definición del trabajo de campo enfocado en la caracterización geológica, geofísica, geoquímica y metalogénica de un área de interés.

**Palabras clave:** Procesamiento de datos geofísicos, modelado 3D, anomalías magnéticas, recursos minerales.

**1. INTRODUCTION**

Airborne geophysics is the easiest and most economical way to improve geological knowledge of large areas and to detect direct anomalies for further interpretation and subsequent drilling. The presence of an isolated magnetic anomaly attracts the attention of a mineral explorer. Once found, the next step is to estimate the physical and geometric parameters of the magnetic rock that produces the anomaly. Magnetic interpretation techniques such as detailed processing, 2D filters and 3D modeling can be applied to better understand the anomaly and suggest new exploration methods or target drilling. Magnetic anomalies can be the expression of several types of mineral deposits, such as iron oxide-gold-copper (IOCG) deposits, porphyries (Au and Cu), kimberlites (diamonds), alkaline complexes (phosphate and niobium), nickel deposits (both sulfide and laterite), volcanogenic massive sulfide deposits (VMS), and banded iron formations (BIFs). In this context, the absence of a radiometric anomaly coincident with the magnetic anomaly is a strong clue that we will not find any evidence of the rock at the surface.

The geophysical data used for the present work correspond to surveys carried by the Servicio Geológico

Colombiano (SGC), separated in blocks that cover broad areas of the Andean and eastern parts of Colombia, including more than 900,000 linear km of high-resolution airborne magnetometric and gamma spectrometric data (Moyano et al., 2018). Each block is surveyed with a line separation of 500 or 1,000 m and data sampling of 10 Hz (magnetometry) and 1 Hz (gamma spectrometry), which yield spatial resolutions of 7-9 m and 70-90 m, respectively. These sampling rates and flight line separations allow the interpolation of grids with spatial resolutions of 125 x 125 m and 250 x 250 m, providing details not previously available in Colombia, considering the broad coverage of the surveys.

This document presents the interpretation of three magnetic anomalies located in three different geologic environments in Colombia: one in the Andes Cordillera, with some surface expression and a gold geochemical anomaly; one in the San Lucas Range area without any surface expression; and one in the Amazonian craton without surface expression or rock outcrops. Each area has different levels of previous geologic and mineral potential knowledge, from a lack of data other than the magnetic anomaly in the Amazon region to good geological control, geochemistry and metallogenic characterization for the Andes anomaly. These three anomalies illustrate the

potential of the geophysical data acquired by the SGC for the assessment of mineral resource potential in Colombia.

## 2. GEOLOGICAL SETTING

Colombia is located northwestern South America, an area with specific tectonic features and a physiographic landscape modeled by the complex interactions among the Nazca, South American and Caribbean plates (Figure 1). The Colombian Andes are considered a mixture of many fragments of parautochthonous and allochthonous crustal fragments and tectonic wedges of continental, peri-cratonic and oceanic affinities. These fragments were accreted by strike-slip faults and subduction zones along the NW margin of the Guyana shield during many periods, with some of the major periods occurring in the Permo-Triassic, Jurassic and Late Cretaceous (Bustamante et al., 2017). This highly fertile metallotectonic envi-

ronment is supported by the significant production of gold, silver, emeralds, platinum group elements (PGE), ferronickel and other commodities such as copper, lead and zinc as principal or secondary products at a modest scale. All of these elements are found in a wide variety of geological environments, combined with hundreds of manifestations, occurrences of active or abandoned mines and showings (Au, Ag, Pb, Zn, Cd, Cu, Mo, Sb, Hg, Cr, Ni, Pt, Pd, Ti, Mn and Fe); the majority of them have no historical exploration, and minimal academic studies are available (Shaw et al., 2019).

The convergent margin regime that was present throughout the Phanerozoic and the multiple occurrences of mineral deposits related to this tectonic regime led to the identification of at least three “copper belts” (Sillitoe et al., 1982), delimited in the metallogenic map of Colombia (López et al., 2018) as different “metallogenic belts” with Jurassic, Miocene and Eocene ages (Figure 1).

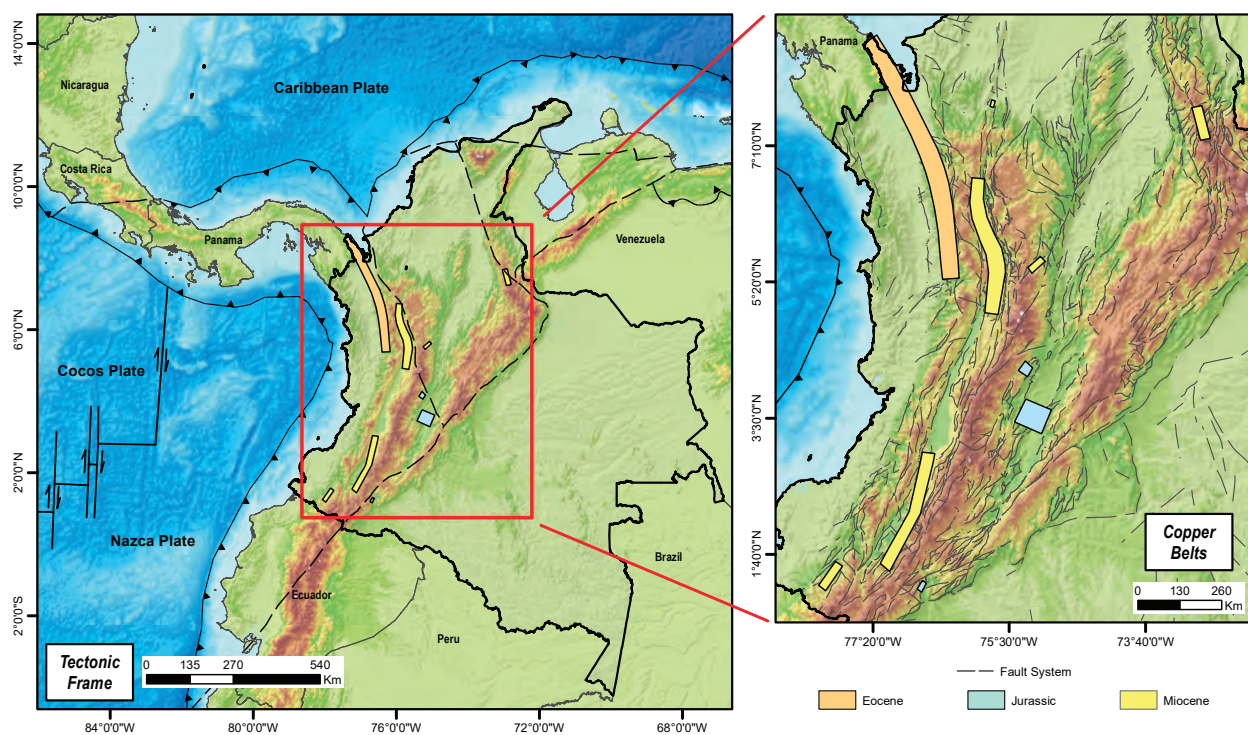


Figure 1. Tectonic setting of NW South America; the inset shows the copper belts and the main geological faults (dashed black lines) Modified from López et al. (2018)

Additionally, recent data have defined at least seven magmatic/mineralization events with a NNE trend and distributed all across the country (Leal, 2011), which occurred between the early Paleozoic and the Pleistocene and were related to magmatic belts, island arcs of variable composition and intracratonic environments.

### 3. GEOPHYSICAL METHODS USED

Airborne geophysics is a very useful method to increase geological knowledge of large and remote areas such as the Amazonian region of Colombia, not only for geological mapping but also for potential assessment of mineral resources. For this purpose, the SGC began an extensive airborne geophysical survey that, by the end of 2019, had accumulated a coverage of nearly 550,000 km<sup>2</sup> in the Andean, Caribbean and Amazonian regions, collecting

more than one million linear kilometers of high-quality magnetometry and gamma spectrometry within specified polygons, herein referred to as blocks (Figure 2).

Data acquisition was performed with instruments mounted on “fixed wing” aircraft, with line spacings of 500 m (Andes and Bolivar regions) and 1,000 m (Amazon) and a flight height of 100 m above terrain over flat areas. In the mountainous areas, a “drape” survey design was used with heights between 100 and 300 m or more, securing aircraft safety and good data quality. The on-board geophysical equipment included high-sensitivity magnetometers that recorded the variations in the Earth’s magnetic field, 512- to 1,024-channel gamma spectrometers with 2,056 in<sup>3</sup> of downward-detection crystals and high-definition GPS and radar altimeters to ensure the quality of the raw data. The sampling rates were 10 Hz for magnetometry and 1 Hz for gamma spectrometry, measu-

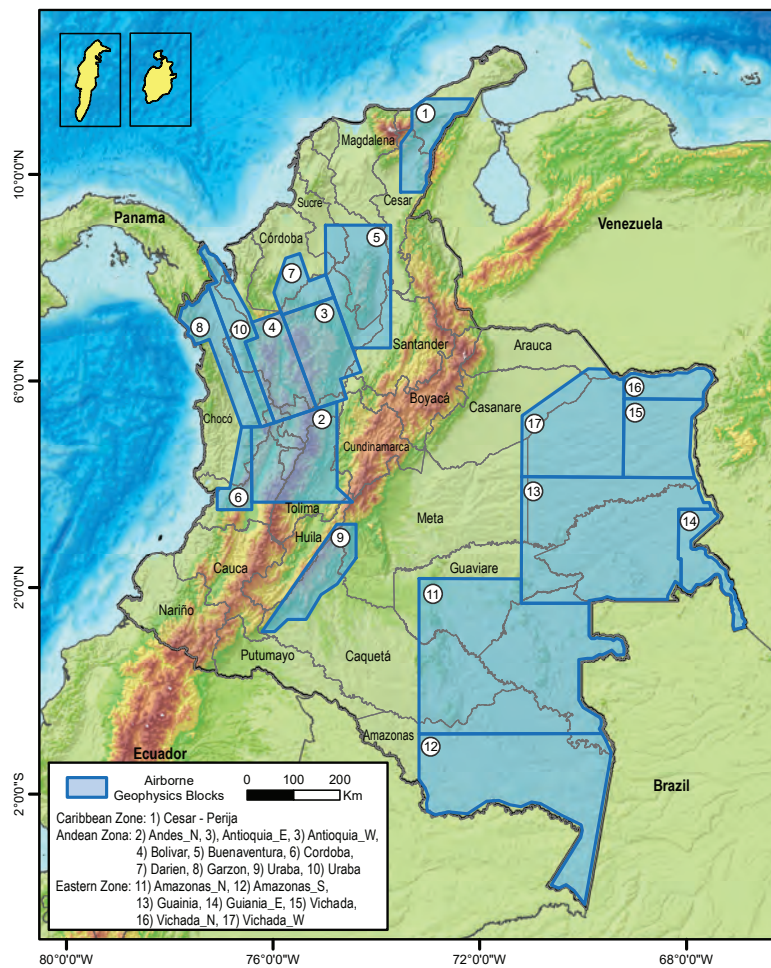


Figure 2. Blocks selected for airborne geophysics surveys



ring geophysical data every 7 to 9 m and 70 to 90 m, respectively. The 500 m flight line blocks were processed into 125 x 125 m grids, and the 1,000 m blocks were processed into 250 x 250 m grids. The processed grids included total magnetic field anomaly (TFA) and concentrations of potassium (K, %), uranium (U, ppm) and thorium (Th, ppm). All postprocessing and interpretation were performed by geophysicists and external advisors of the SGC.

The magnetometry method, used as an exploration tool, evaluates the lateral variations in the Earth's magnetic field that are assumed to be a response to the variations in the amounts of magnetic minerals contained in the rocks. These changes in magnetic mineral content could mark variations in the rock type or internal changes due to other geological processes, such as hydrothermal alteration or metamorphism. Therefore, magnetometry data are useful to identify magnetic bodies covered by nonmagnetic lithologies, to delineate geological structures and to target exploration on the increase/decrease in magnetic mineral content related to the most common geological mechanisms for ore formation: magma intrusion, faulting and hydrothermal alteration processes.

Gamma spectrometry data reflect the relative concentrations of the common radioactive elements uranium (U), thorium (Th) and potassium (K) that are naturally concentrated through magmatic differentiation. This process generates the highest concentrations of these elements in acidic rocks as well as in its metamorphic and sedimentary-related lithologies. Because of the relation between natural radioactivity and the mineralogy of lithological units, gamma spectrometry helps in the "lithogeophysical" characterization of surface materials and allows the determination of secondary alteration processes; such processes change the geochemical composition of the rocks because of the emplacement of magma bodies, which triggers processes that result in ore deposits.

#### 4. DATA PROCESSING AND ANOMALY SELECTION METHODOLOGY

The analysis of the magnetometry information aims to detect and describe data attributes such as geometry, intensity and orientation that may represent anomalies reasonably related to geological features. For this purpose, it is useful to reduce the natural complexity of the magnetic anomalies by reduction to pole transformation (RTP; Baranov 1957) or by computation of the analytical signal (AS, Nabighian

1972). Additionally, other transformations, such as the tilt derivative (Miller and Singh, 1994) and composite ternary images of different order vertical derivatives (1, 1.25, and 1.5 order), are used to locate anomalies and magnetic domains from a consistent interpretation of the data and to relate these anomalies to a geological framework, such as intrusions, dikes, shear zones, kimberlites, carbonatites, etc., that may host mineral resources.

Gamma spectrometry data are useful to identify and correlate outcropping lithologies and anomalies in radioactive element distributions that may be related to secondary geological processes of mineral enrichment or depletion, such as hydrothermal alteration zones and weathering zones. The use of gamma spectrometry images (potassium, uranium or thorium) and ternary red, green, blue (RGB) images (red = K, green = Th, blue = U) with lithological information and magnetic anomalies enhances the geological interpretation and the possible types of related mineralization.

For the data processing, interpretation and target selection from geophysical airborne data, a procedure to generate standardized information for the entire area covered is established. The suggested steps are as follows:

- » Calculate the RTP and/or the analytical signal of the TFA
- » Calculate the tilt angle derivative.
- » Calculate vertical derivatives of the RTP and display them on a ternary RGB image (R = lowest order, G = middle order and B = highest order)
- » Make a ternary image (RGB) of the relative distributions of the concentrations of radioactive elements potassium (R), thorium (G) and uranium (B).
- » Select magnetic anomalies and create a regular window (polygon) around each anomaly.
- » Run inverse 3D modeling of each selected anomaly. For this case, the algorithms used are those included in Oasis Montaj "magnetization vector inversion (MVI, Ellis et al., 2012)" included with the VOXI extension using iterative reweighting inversion (IRI) focusing with 2 passes to sharpen positives.

Considering this information, every 3D model is described (geometry of the magnetic source, depth to top, etc.); then, radiometric data and topography are checked to identify whether the source crops out or whether a

feature related to the source is modeled. In addition, the available geology is checked to see if the calculated source has already been mapped, and other mining (deposits, occurrences) and geochemical (soil, sediment, rock) data are integrated to refine the interpretation.

### 5. EXAMPLES OF ANOMALIES TARGETING AND INTERPRETATION

The procedure presented above was applied to three anomalies located in different tectonic and geological settings (Figure 3): the first one in the Central Andes Cordillera, the second one in the western foothills of the San Lucas Range and the last one in the Guyana shield. These anomalies were used not only to demonstrate the potential of airborne magnetometry and gamma spectrometry for increasing the geoscientific knowledge of wide areas but

also to generate multiple exploration targets to aid in the development of the mineral potential of Colombia.

### 5.1 Andes anomaly

The Andes anomaly is located on the eastern flank of the Central Cordillera of Colombia, where the Triassic core of the Andes Cordillera and the Cretaceous Antioquia Batholith form a block limited by the nearly N-S trending Palestina Fault System to the east and the Romeral Fault System to the west (Gómez et al., 2015).

#### 5.1.1 Geology

Locally, the southern part of the area corresponds to the northernmost outcrop of the Antioquia Batholith (Kgd, Figure 4), with some mafic bodies to the north (Kg), cataclastic granites (Kgn), altered lava flows (Krv) and the

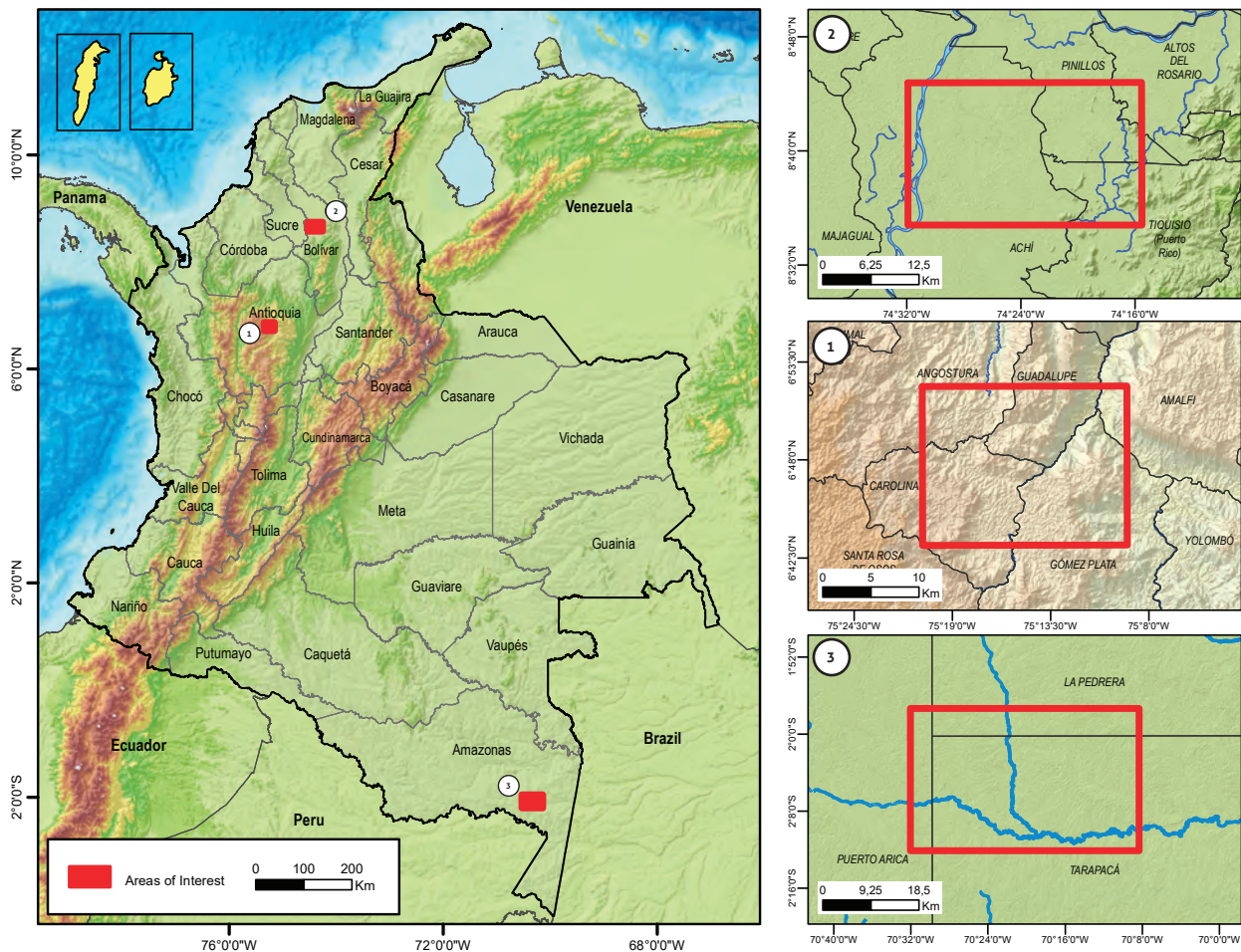


Figure 3. Locations of the selected anomalies: Andes (1), San Lucas (2) and Guyana shield (3)



nonmagnetic San Pablo Formation (Kap), a Cretaceous sedimentary unit frequently intruded by the batholith. Specifically, the anomaly is related to a quartz-rich dacitic porphyry (Kda), strongly linked to the edge facies of the batholith (Hall et al., 1972).

### 5.1.2 Anomaly description and 3D modeling

The Andes anomaly is detected as a strong (326 nT peak-to-peak amplitude in the TFA) and large (6 km diameter) magnetic anomaly located in an area containing several mineral deposits (López et al., 2018). The gold anomaly occurrence (yellow dot, Figures 5a and 5b) in the center of the anomaly is important to prioritize its study. Furthermore, on the tilt derivative image (Figure 5c), dominant nearly NE-SW lineaments are identified, which may represent a structural control on possible fluid migration and/or emplacement.

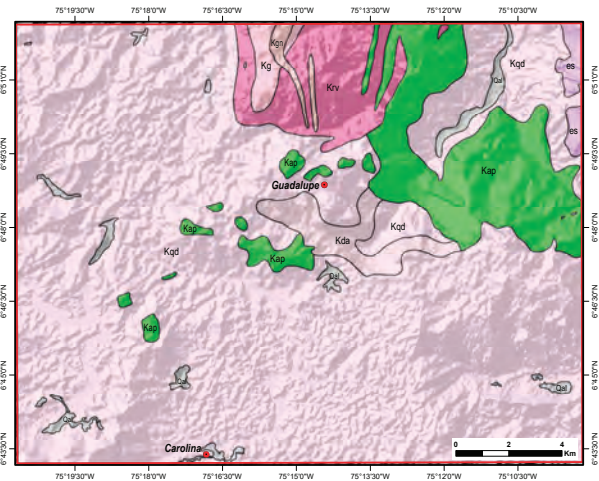


Figure 4. Geology of the area containing the Andes anomaly: Antioquia Batholith (Kgd), mafic bodies (Kg), cataclastic granites (Kgn), altered lava flows (Krv) and the nonmagnetic San Pablo Formation (Kap) and quartz-rich dacitic porphyry (Kda) Modified from Hall et al. (1972)

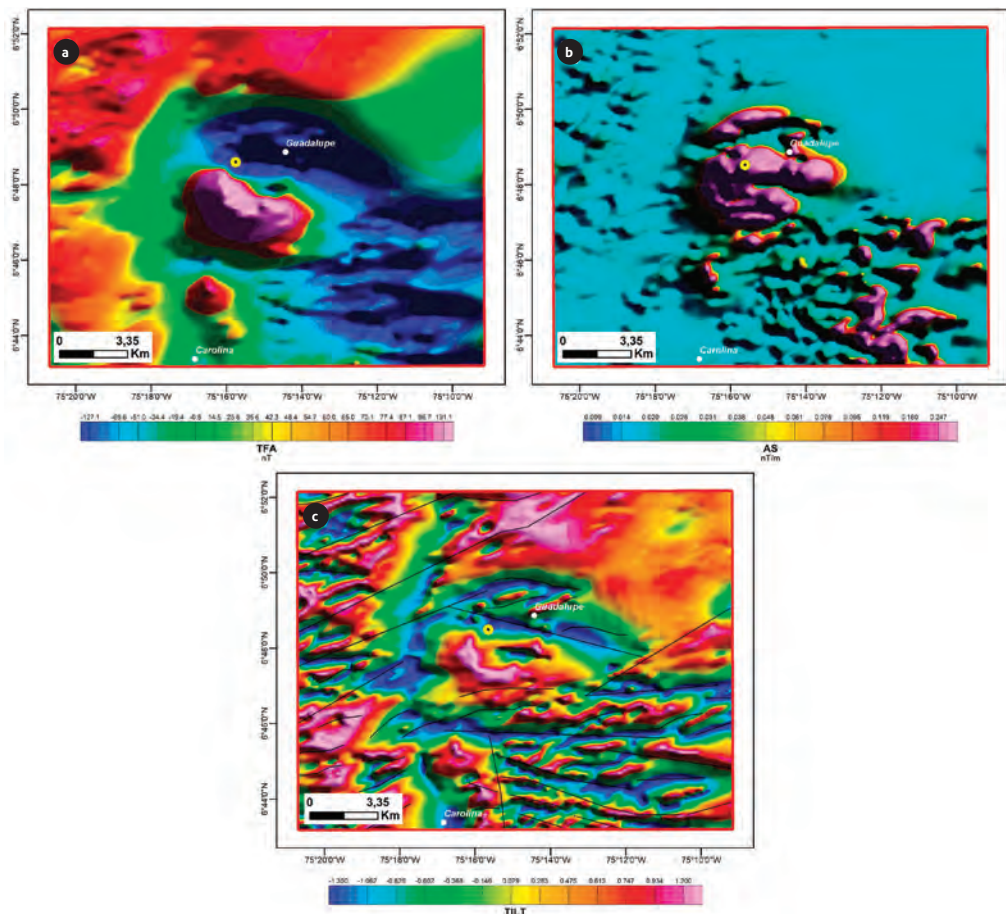


Figure 5. Magnetometry images of the Andes anomaly: a) Total field anomaly (TFA), b) analytical signal (AS) of the TFA, c) tilt derivative image with magnetic lineaments. The yellow circle represents the location of the sample with a high gold content

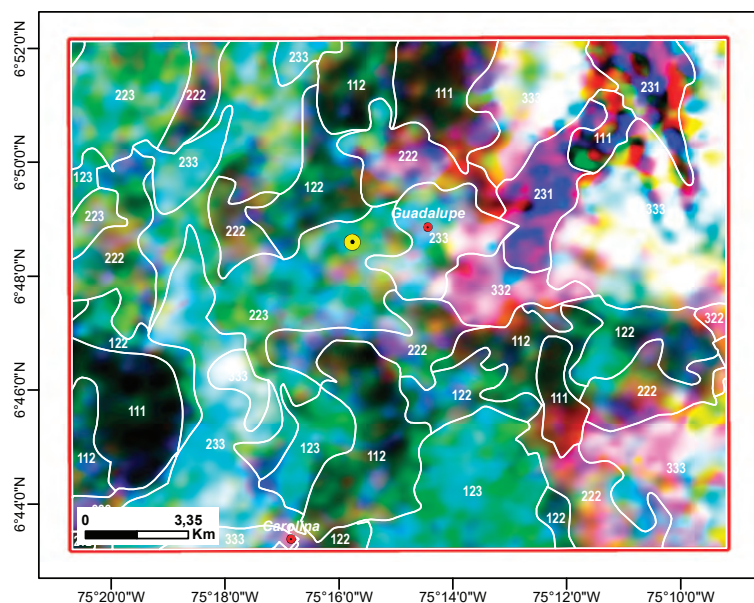
The ternary radiometric image (Figure 6) shows that the magnetic anomaly is coincident with a rock outcrop that presents high grades of Th, U and K, generating a white color in the image.

The 0.03 SI cutoff isosurface from the 3D magnetic susceptibility MVI model depicts a large (7 x 3.5 km) E-W elongated magnetic body (Figure 7). The model shows some portions close to the surface or cropping out, but clearly, a large part of the body is below the surface.

The follow-up procedure for this anomaly could include fieldwork for rock sampling and a regular sampling grid for geochemical analysis. The data obtained can guide the next steps in the evaluation of the anomaly.

### 5.1.3 Mineral resource potential

The Andes anomaly is located within the Guadalupe Au-(Ag) metallogenic district and east of the Amalfi-Anorí metallogenic district (López et al., 2018). The Guadalupe district is characterized by the presence of intrusive-related deposits and includes a copper volcanogenic massive sulfide (VMS) deposit known as the Guadalupe project (Figure 8). For this area, geochemical data report 144,000 ppb of gold from a vein inside the most magnetic portion of the anomaly and 58.2 ppm of silver within a neighboring dike. Due to the metallogenic context and known deposits/occurrences in the area of the Andes anomaly, the exploration target could be an intrusion-related/VMS and/or epithermal deposit.



K	U	Th	Combination	Code
Low	Low	Low	Kl-Ul-Thl	111
Low	Low	Medium	Kl-Ul-Thm	112
Low	Medium	Medium	Kl-Um-Thm	122
Low	Medium	High	Kl-Um-Thh	123
Medium	Low	Medium	Km-Ul-Thm	212
Medium	Medium	Medium	Km-Um-Thm	222
Medium	Medium	High	Km-Um-Thh	223
Medium	High	Low	Km-Uh-Thl	231
Medium	High	High	Km-Uh-Thh	233
High	Low	Medium	Kh-Ul-Thm	312
High	Medium	Medium	Kh-Um-Thm	322
High	High	Medium	Kh-Uh-Thm	332
High	High	High	Kh-Uh-Thh	333

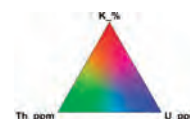


Figure 6. Ternary radiometric image of the Andes anomaly with contoured radiometric domains. The yellow circle represents the location of the 144,000 ppb Au sample



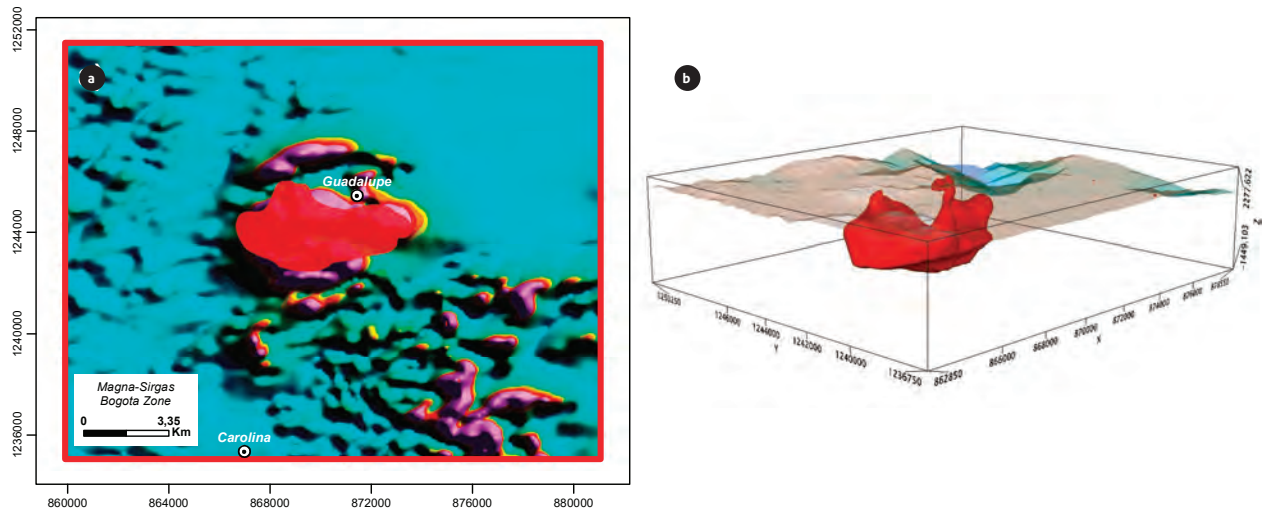


Figure 7. 3D model of the Andes anomaly: a) Analytical signal from the TFA with 0.3 SI MVI model, b) 0.3 SI isosurface of the 3D magnetic susceptibility model from MVI inversion

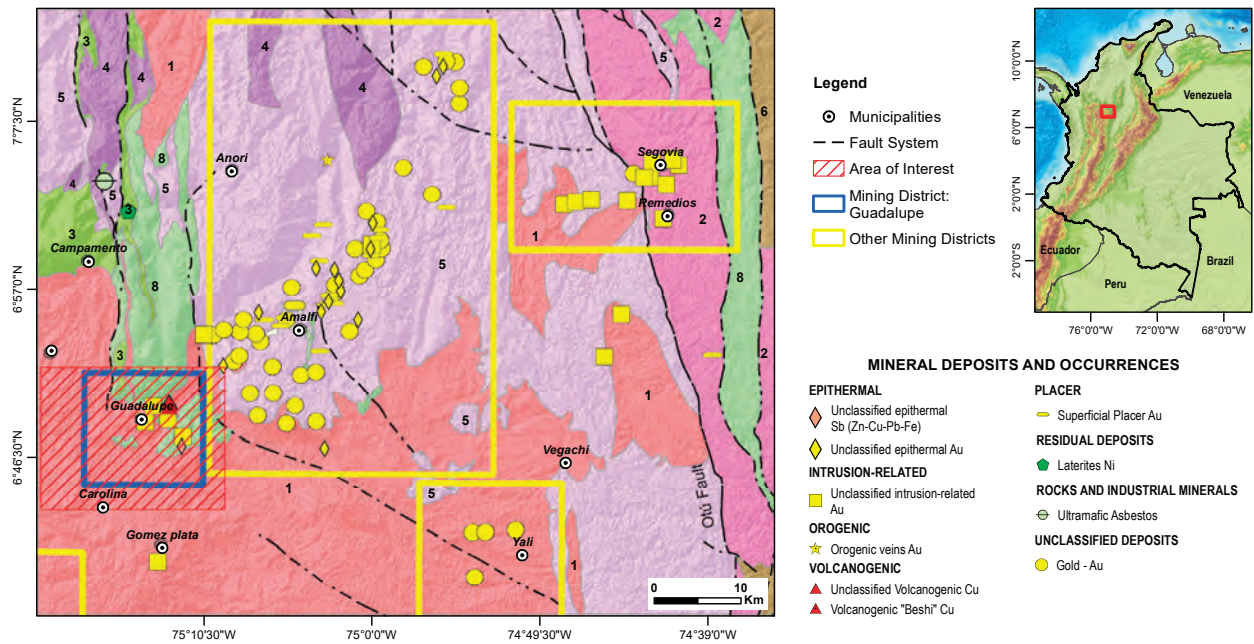


Figure 8. Mineral deposits and metallogenic districts near the Andes anomaly (yellow boxes); the numbers represent the local geology: 1) Felsic igneous rocks (Cretaceous), 2) felsic igneous rocks (Jurassic), 3) mafic and ultramafic igneous rocks (Cretaceous), 4) gneiss and intrusive rocks (Permian-Triassic), 5) low-grade metamorphic rocks (Triassic), 6) high-grade metamorphic rocks (Proterozoic), 7) sedimentary rocks (Cenozoic), 8) volcanic and volcanic-sedimentary mafic rocks (Cretaceous)  
 Modified from López et al. (2018)

## 5.2 San Lucas Range Anomaly

This anomaly is located in the northernmost part of the Central Cordillera in the western foothills of the San Lucas Range at the confluence of the Magdalena and Cauca rivers.

### 5.2.1 Geology

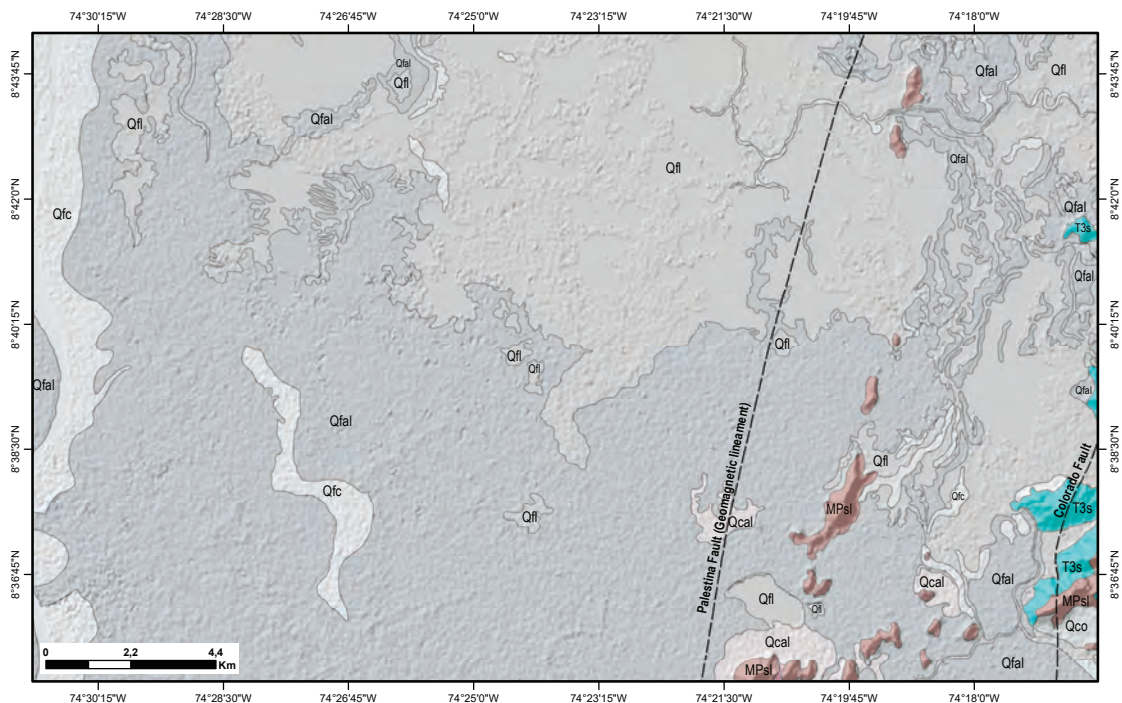
Nonmagnetic floodplain and lacustrine deposits bounded to the south by the last outcrops of the Central Cordillera and some Cenozoic deposits cover the San Lucas Range anomaly. To the east of the Palestina Fault is mapped the gneiss of the San Lucas Formation (MPsl), a gneiss often intruded by igneous bodies and covered by Quaternary deposits and the Sudan Formation (T3s), which consists of very thick beds of conglomerates intercalated with intervals of clay limestone and beds of tuffaceous sandstones (Figure 9).

### 5.2.2 Anomaly description and 3D modeling

The magnetic anomaly corresponds to an isolated dipole with a 1,000 nT peak-to-peak amplitude (TFA) within an

area of low magnetic contrast related to the sedimentary cover; the anomaly is limited to the east by a strong gradient area related to the Palestina fault-controlled transition to the San Lucas Range crystalline rocks (Figures 10a and 10b). The tilt derivative image (Figure 10c) shows predominantly NNE-SSW-oriented lineaments, one of which delineates the Palestina Fault located east of the anomaly and other of which is located west of the anomaly. This structural trend interpreted from the geophysical data suggests that the magnetic source “emplacement” was probably controlled between these structures.

There is no relation between the gamma spectrometry data and the magnetic anomaly, which suggests that there could not be a surface expression of the causative magnetic body (Figure 11). However, gamma spectrometry data themselves reflect changes in the surface materials that are useful for lithogeophysical mapping, such as changes in the radioactive element contents of the sedimentary deposits, delineation of crystalline rocks cropping out to the east of the Palestina Fault and even fault delineation itself.



**Figure 9.** Geology of the San Lucas anomaly: Floodplain (Qfal) and fluvio-lacustrine (Qfl) deposits, fluvial channel (Qfc) deposits, fan and terraces (Qcal) deposits, San Lucas gneiss (MPsl), Sudán Formation (T3s) Modified from Ingeominas (2006)



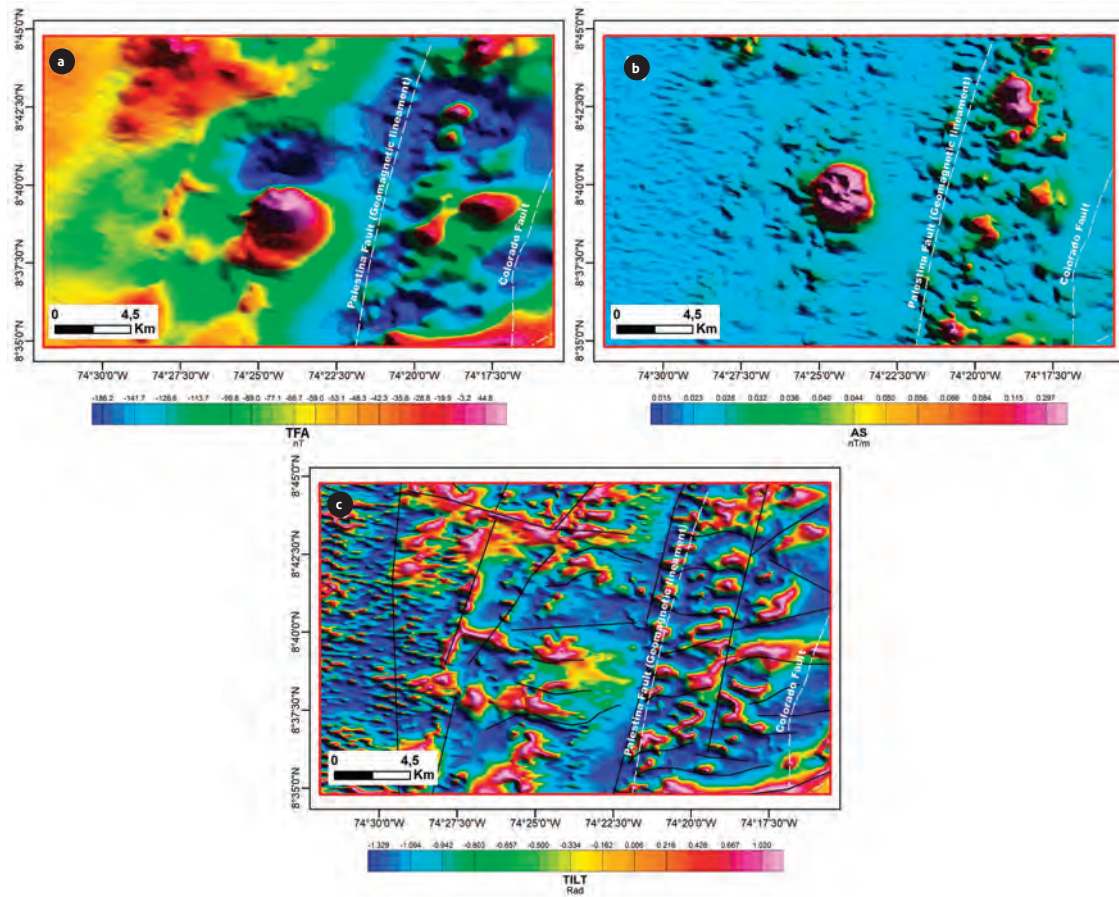
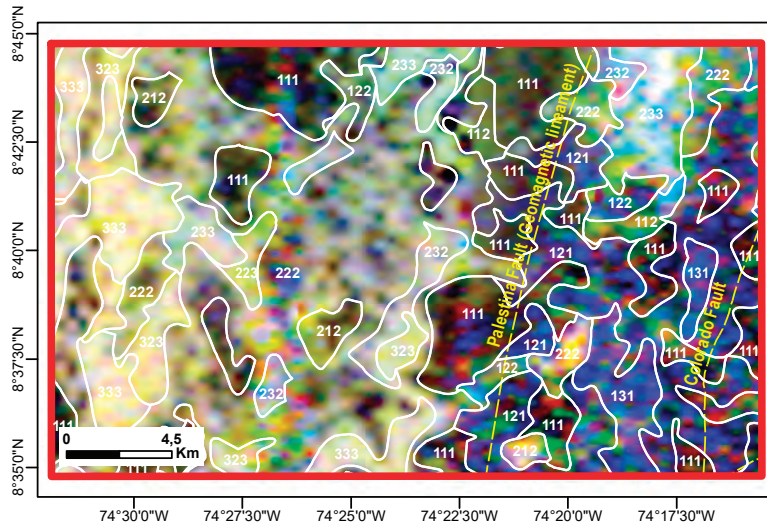


Figure 10. Magnetometry images of the San Lucas anomaly: a) Total field anomaly (TFA), b) analytical signal of the TFA, c) tilt derivative image with magnetic lineaments (black lines) and Palestina Fault (yellow line)



K	U	Th	Combination	Code
Low	Low	Low	Kl-Ul-Thl	111
Low	Low	Medium	Kl-Ul-Thm	112
Low	Medium	Low	Kl-Um-Thl	121
Low	Medium	Medium	Kl-Um-Thm	122
Low	High	Low	Kl-Uh-Thl	131
Medium	Low	Low	Km-Ul-Thl	211
Medium	Low	Medium	Km-Ul-Thm	212
Medium	Medium	Medium	Km-Um-Thm	222
Medium	Medium	High	Km-Um-Thh	223
Medium	High	Medium	Km-Uh-Thm	232
Medium	High	High	Km-Uh-Thh	233
High	Medium	High	Kh-Um-Thh	323
High	High	High	Kh-Uh-Thh	333

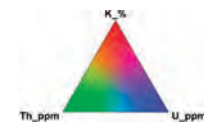


Figure 11. Ternary radiometric image of the San Lucas anomaly with contoured radiometric domains



Since there are no outcrops and no topographic or radiometric expressions, magnetic 3D modeling is the only choice to estimate the parameters of a possible buried body of interest. The MVI model with a cutoff magnetic susceptibility of 0.03 SI shows a “pipe-like” body of 2 x 3 km (Figures 12a and 12b), located at 100 m depth.

### 5.2.3 Mineral resource potential

The San Lucas anomaly is located 25 km to the west of the Au-(Ag) metallogenic district of Barranco de Loba (López et al., 2018). This district is characterized by the presence of Au/Cu porphyries such as the San Carlos Project and intrusion-related and epithermal deposits (Figure 13). The metallogenic context of the area and the semicircular pipe-like shape of the magnetic source allows us to estimate that the corresponding target of this anomaly is more likely to be a porphyry system than a kimberlite/carbonatite-related body. Therefore, additional exploration programs for this anomaly should be airborne gradiometric gravity or ground gravity and airborne or ground EM.

## 5.3 Amazonas anomaly

This anomaly is found in the southeastern part of Colombia, in an area of low relief with a drainage system that

flows into the Amazon River and is covered by a dense tropical rainforest.

### 5.3.1 Geology

The surface geology corresponds to nonmagnetic Neogene rocks with ferruginous matrixes (conglomerates, sandstones, claystone, and in some cases coal) that are poorly consolidated and dissected by the principal drainages of the area (Figure 14). The magnetic basement rock can be related to the Mitú Complex (Rodríguez et al., 2011), composed of subalkaline high-potassium rocks, in some places with enrichments in rare earth element (REE) minerals.

### 5.3.2 Anomaly description and 3D modeling

This single magnetic anomaly has a very strong (2,000 nT) peak-to-peak amplitude (TFA) and lacks surface expression (Figures 15a and 15b). Through a flight with 1,000 m line spacing, it appears in four flight lines. Because such anomalies are not expected in the sedimentary rocks that crop out and because there is neither radiometric signature nor geological evidence of a causative body coincident with the magnetic anomaly (Figure 16), 3D modeling of the magnetometry is used to estimate the shape, depth and other parameters of the subsurface body.

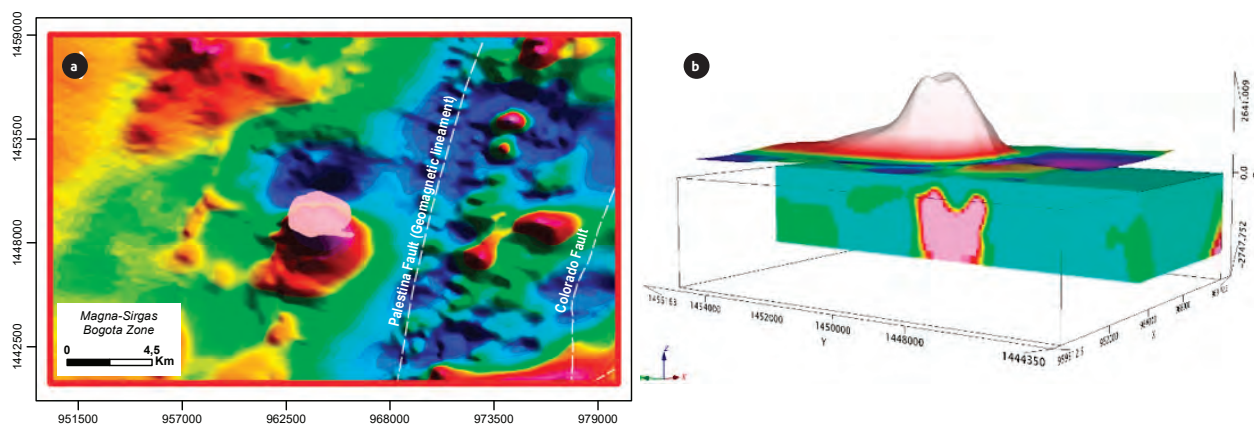
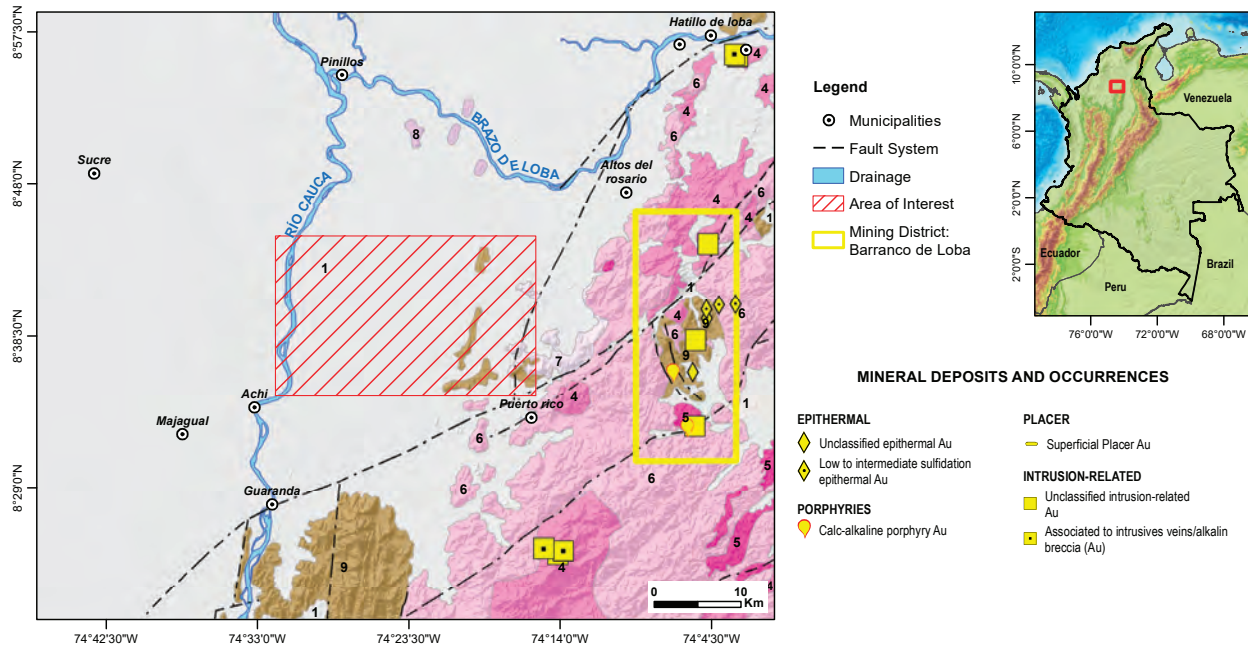
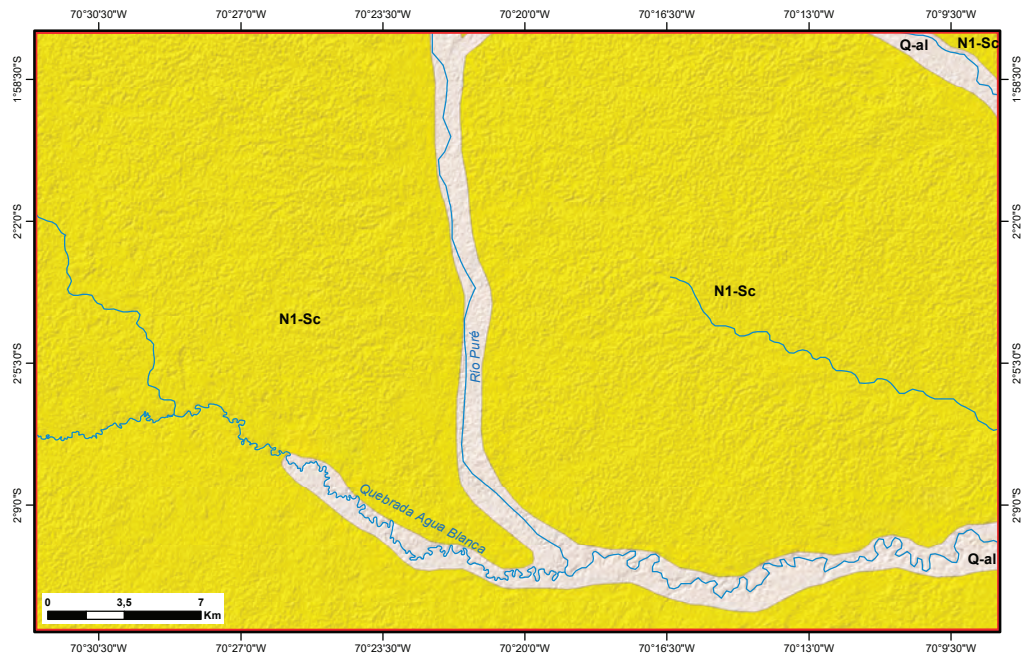


Figure 12. 3D model of the San Lucas anomaly: a) TFA superimposed with the 3D framework of the susceptibility model with a cutoff of 0.3 SI, b) cross section of the magnetic susceptibility model from 3D MVI inversion with the 3D image of the RTP



**Figure 13.** Mineral deposits and occurrences near the San Lucas anomaly (red box); the numbers represent the local geology: 1) Surface deposits (Quaternary), 2) Cenozoic sedimentary rocks (Paleocene-Pliocene), 3) Cretaceous sedimentary rocks (Berriasian-Albian), 4) felsic igneous rocks (Jurassic), 5) subvolcanic rocks (Jurassic), 6) volcanic and volcanic-sedimentary rocks (Permian–Upper Jurassic), 7) continental siliciclastic rocks (Triassic?), 8) metamorphic rocks (Triassic), 9) high-grade metamorphic rocks (Proterozoic)  
 Modified from López et al. (2018)



**Figure 14.** Geology of the Amazonas anomaly: Neogene deposits with ferruginous matrix (N1-Sc), alluvial and alluvial plain deposits (Q-al)  
 Modified from Gómez et al. (2015)

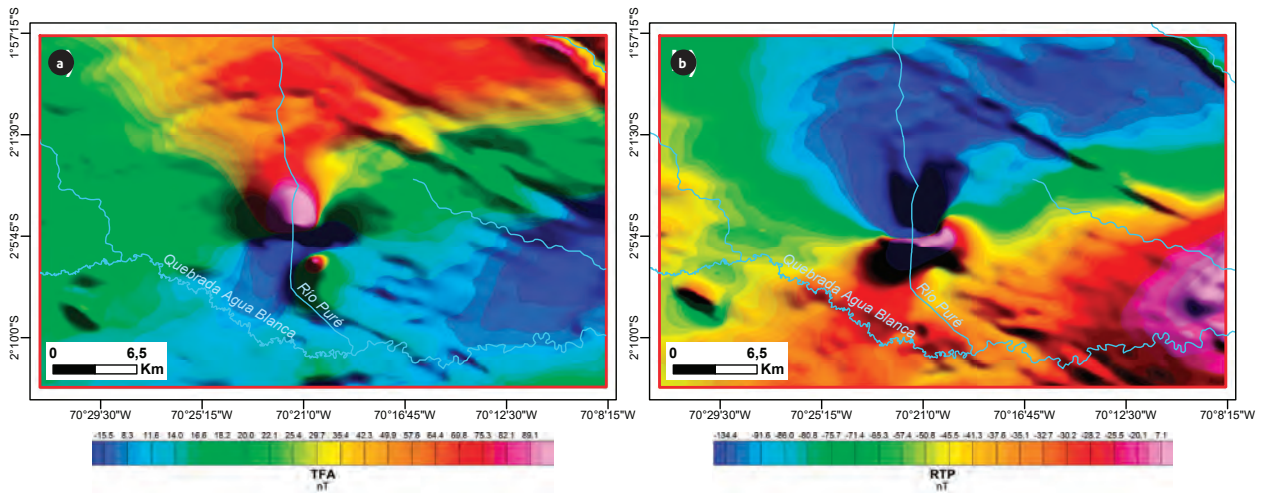


Figure 15. Magnetometry images of the Amazonas anomaly: a) Total field anomaly (TFA), b) reduction to magnetic pole (RTP) of the TFA

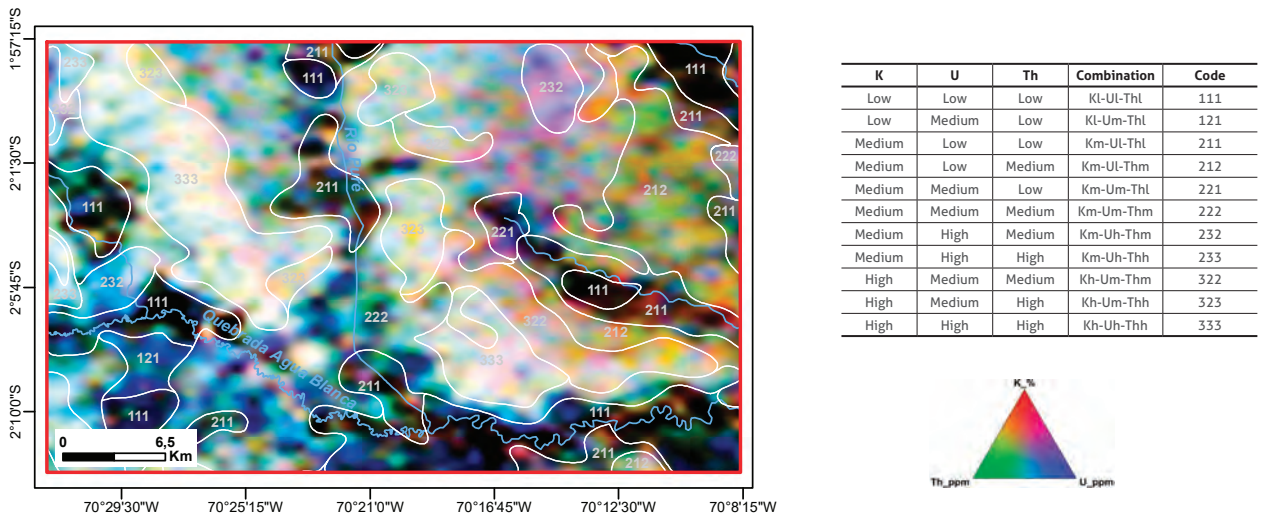
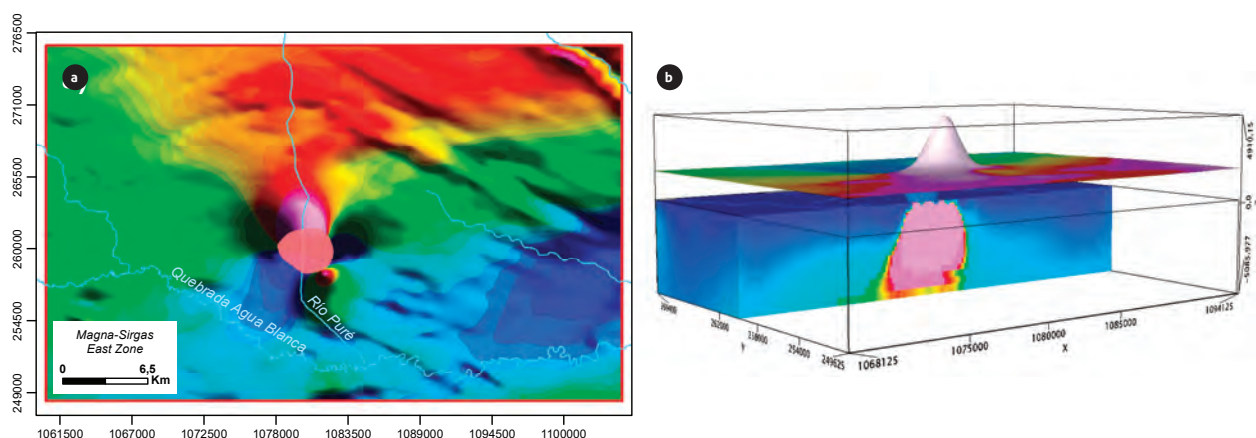


Figure 16. Ternary radiometric image of the Amazonas anomaly with contoured radiometric domains

Figures 17a and 17b show the results of the 3D MVI inversion with a magnetic susceptibility cutoff of 0.003 SI. The isosurface shows a 4 km x 3.5 km magnetic source located close to the surface. Additionally, the shape of the

dipole in the TFA anomaly (Figures 15a and 17b) could indicate that the magnetic body has a complex magnetization (remanence).





**Figure 17.** 3D model of the Amazonas anomaly. a) TFA superimposed with the 3D framework of the susceptibility model, b) cross section of the magnetic susceptibility model from 3D MVI inversion and the 3D image of the RTP

### 5.3.3 Mineral resource potential

The average depth of the modeled source (top of the body) is 40 m, and it is not possible to determine either the source petrology of the source or the economic value. Additionally, the anomaly is in an area with poor geological knowledge due to the dense rainforest coverage and lack of infrastructure.

However, isolated magnetic bodies located within the sedimentary cover in the Amazonian Craton have the potential to be alkaline rocks. Kimberlites (diamonds) and carbonatites (phosphate, niobium, and REEs) are the main economic targets of anomalies. In this case, rocks of the Mitú Complex have REEs, niobium (Nb), and tantalum (Ta) minerals associated principally with granitic pegmatites, dikes and acidic stocks, which intrude the complex and could also be the source of tin (Sn) and tungsten (W) (López and Cramer, 2012).

A mineral exploration program should apply other methods and then drill the anomaly to find the source. The additional methods suggested for this anomaly are i) ground magnetics and ii) airborne gradiometric gravity or ground gravity.

## 6. DISCUSSION

As explained above, the metallotectonic environment and known mineral deposits in the NW Andes and Colombia reflect a subduction-related affinity with magma generation and emplacement. For exploration purposes in this

kind of geological setting, magnetometry has advantages over other geophysical methods due to the strong correlation between magnetic mineral contents and ore-deposit generation. In this work, the processing and interpretation of the magnetometric data focus on going beyond the anomaly detection itself to more specialized modeling of the magnetic source geometrical parameters and structural framework, integrated with gamma spectrometry and available geological, geochemical and metallogenic data. This integration methodology helps in the identification, characterization and fieldwork prioritization of the magnetic anomalies found in the blocks covered by the airborne surveys.

The Andes anomaly is located at the northern edge of the Antioquia Batholith. The MVI magnetic susceptibility model shows a nearly 7 km E-W elongated body located mostly at depth but with some possible outcrops related to a radiometric signature. The local geology identifies a Qz-rich dacitic porphyry (Kda, Figure 4) in the area of the anomaly, so it is possible that the magnetic source corresponds to the subsurface extent of this intrusive rock. This indication should increase the potential for mineral resource exploration beyond the outcropping portion of the rock. The presence of 144,000 ppb gold value in a vein sample that is located at the center of the magnetic source also suggests important potential but demands more detailed work. The location of intrusion-related/VMS Au/Cu deposits close to the anomaly and the delimitation of a metallogenic district in the area are key facts to priori-

tize the study of this anomaly. The data processing also allows the identification of NE-SW lineaments that represent a structural control on a possible fluid migration and/or emplacement of a potential ore.

The San Lucas Range anomaly is covered by non-magnetic fluvial and lacustrine deposits of recent age. To the east of the anomaly, separated by the Palestina Fault (NNE-SSW), metamorphic rocks of the San Lucas gneiss (MPsl, Figure 9) crop out. There is no surface or gamma spectrometric expression related to the anomaly, which supports the idea that the magnetic source is buried under recent sediments. Magnetometry interpretation marks predominantly NNE-SSW lineaments such as the Palestina Fault trend and suggests possible structural control on the emplacement of the magnetic source, which appears to be limited by these lineaments to the west and by the Palestina Fault to the east. The MVI magnetic susceptibility model shows a 2 km x 3 km “pipe-like” body located close to the surface, which could indicate that the magnetic source is not related to the magnetic igneous-metamorphic basement and probably is a magmatic body intruded within less magnetic rocks. There is no direct evidence of fertile rocks or mineralization over the anomaly, but 25 km to the east, the Barranco de Loba metallogenic district is delimited, characterized by the presence of several Au (Cu) porphyry, intrusion-related and epithermal deposits and occurrences. The size and shape of the MVI model of the magnetic source and the regional metallogenic context allow us to estimate that this anomaly could be related to an intrusive body with exploration potential for porphyry, intrusion-related and/or epithermal deposits.

The Amazonas anomaly is located in a very remote area of the Amazon rainforest where geological and metallogenic knowledge is restricted to regional extrapolation from sparse observation points. There is no surface or gamma spectrometry evidence that can be related to the anomaly. The magnetic anomaly shows a complex dipole with a very strong (2,000 nT) amplitude that suggests that the magnetic source could have strong remnant magnetization and be located within almost nonmagnetic rocks. Additionally, the dipole shows sharp lobes, suggesting that the source is buried very close to the surface. The MVI magnetic susceptibility model shows a 2.5 km x 3 km source located close to the surface. Even in the ab-

sence of detailed geological, geochemical or metallogenic information, it is possible to extrapolate the evidence and deposits discovered in other cratonic areas (Brazil and Venezuela) and expect that this kind of nearly cylindrical and isolated magnetic anomaly is related to alkaline rocks, kimberlites or carbonatites.

It is important to remember that geophysical data, for mineral exploration purposes, imply the estimation of physical properties of the rocks and materials of the subsurface by indirect measurement of the perturbation of a natural field or an induced signal due to contrasts in these properties. Furthermore, the use of mathematical modeling to quantitatively estimate the distribution of the selected physical property that corresponds to the observed perturbation has almost infinitely many different solutions (the nonuniqueness principle) that can be reduced to more geologically related models when integrated with field data.

In this context, the magnetic susceptibility cutoff used to represent the dimension and geometry of each of the magnetic sources (0.03 SI for the Andes and San Lucas anomalies and 0.003 SI for the Amazonas anomaly) from the MVI are estimated with the analytical signal (AS) of the TFA. The AS is a mathematical transform that reduces the dipolar signature of a magnetic anomaly and has the effect of strengthening at the edges of the magnetic source (Nabighian, 1972). Using this attribute, the magnetic susceptibility from the model is chosen so that the surface expression of the isosurface is close to the borders of the AS of the anomaly. For this reason, the magnetic susceptibility used for this work must be considered only a reference parameter estimated by mathematical criteria and has to be compared with petrophysical data. However, it is still a reliable and useful approximation in the absence of petrophysical data collected from rocks in the field.

For the anomalies and models presented in this work, the Andes anomaly has strong geological, geochemical and metallogenic controls that allow us to demonstrate the mineral potential in this area, and the 3D modeling of the magnetic source reinforces this potential. For the San Lucas and Amazonas anomalies, the lack of other geoscientific data must encourage exploration in these areas because geophysical modeling shows that there are magnetic sources that have to be explained, and given our

actual knowledge of the area, there is no evidence of potential other than the geological setting and, in the case of the San Lucas anomaly, the known mineral deposits in the surroundings.

The results presented in this work illustrate the methodology used to manage geophysical data (magnetometry and gamma spectrometry) for the evaluation of the mineral resource potential in Colombia. The three anomalies presented are located in different geological contexts within the country and represent strong evidence that the integration of available geological, geochemical and metallogenic data with advanced geophysical modeling will provide a better understanding of the nature, geometry and subsurface distribution of potential targets and hence optimize efforts and resources in the fieldwork phase.

## 7. CONCLUSIONS

The acquisition of high-resolution airborne magnetometry and gamma spectrometry generates valuable information to increase the geoscientific knowledge of Colombia and allows target identification and interpretation for mineral resource exploration. For this purpose, three magnetic anomalies were selected to illustrate the data processing methodology used for the identification of areas of interest for future investigation.

The Andes anomaly is interpreted as a magnetic (0.03 SI) source 3.5 km x 7 km wide and located at depth with some surface expression correlated with gamma spectrometry. The geological data correlate this anomaly at the surface with a Qz diorite porphyry, suggesting that the subsurface extent of the intrusion is wider. This anomaly is located within the Guadalupe (Au/Ag) metallogenic district and is a potential target for intrusion-related, epithermal or VMS deposits. The evidence of magnetic lineaments and a vein sample with gold suggest structural control for fluid migration and ore deposition.

The San Lucas anomaly is modeled as a magnetic (0.03 SI) "pipe like" source 2 km x 3 km wide, located close to the surface and surrounded by almost nonmagnetic rocks. There is no surface expression related to the anomaly, and the geological data indicate the presence of recent fluvio-lacustrine deposits. The magnetometry suggests a possible control by NNE-SSW lineaments on the

emplacement of the source; one lineament is correlated with the Palestina Fault in the east. The presence of the Barranco de Loba Au (Cu) metallogenic district 25 km to the east and the regional metallogenic context mark this anomaly as a target for porphyry/intrusion-related and epithermal deposits.

The Amazonas anomaly MVI model (0.003 SI) shows a nearly cylindrical 2.5 km x 3 km body, surrounded by almost nonmagnetic rocks and located close to the surface but with no topographic or gamma spectrometric correlation. Geological knowledge about the area is minimal, but evidence from deposits identified in other areas of the Amazonian Craton and the potential estimated for rocks of the Mitú complex allow us to consider this anomaly a potential target for carbonatite/kimberlite deposits.

Considering that there must be very few outcrops of mineral deposits yet to be found, the supply for the mineral market must be obtained from underground deposits. This fact, added to the global requirements of environmental protection, means that geophysical methods are increasingly fundamental in mineral prospecting.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the Servicio Geológico Colombiano (SGC) for allowing the use of airborne geophysical data from ongoing surveys and the interpretations presented in this document.

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