Chapter 2

https://doi.org/10.32685/pub.esp.35.2019.02
Published online 17 April 2020

Contribution of New Airborne Geophysical Information to the Geological Knowledge of Eastern Colombia

Ismael Enrique MOYANO–NIETO[1]*, Renato CORDANI[2], Lorena Paola CÁRDENAS–ESPINOSA[3], Norma Marcela LARA–MARTÍNEZ[4], Oscar Eduardo ROJAS–SARMIENTO[5], Manuel Fernando PUENTES–TORRES[6], Diana Lorena OSPINA–MONTES[7], Andrés Felipe SALAMANCA–SAAVEDRA[8], and Gloria PRIETO–RINCÓN[9]

1 imoyano@sgc.gov.co
Servicio Geológico Colombiano
Dirección de Recursos Minerales
Diagonal 53 n.° 34–53
Bogotá, Colombia

2 rcordani@reconsult.com.br
RECONSULT Geofisica
Cerqueira César, Rua Augusta, 2690–loja 322,
CEP 01412–100
São Paulo–SP, Brasil

3 lopaca7@gmail.com
Carrera 8 n.° 58–67
Cali, Colombia

4 nlara@sgc.gov.co
Servicio Geológico Colombiano
Dirección de Recursos Minerales
Diagonal 53 n.° 34–53
Bogotá, Colombia

5 orojas@sgc.gov.co
Servicio Geológico Colombiano
Dirección de Recursos Minerales
Diagonal 53 n.° 34–53
Bogotá, Colombia

6 mpuentes@sgc.gov.co
Servicio Geológico Colombiano
Dirección de Recursos Minerales
Diagonal 53 n.° 34–53
Bogotá, Colombia

7 dcospina@sgc.gov.co
Servicio Geológico Colombiano
Dirección de Recursos Minerales
Diagonal 53 n.° 34–53
Bogotá, Colombia

8 asalamanca@gidco.com
Gidco SAS
Carrera 20 n.° 70ª–21
Bogotá, Colombia

9 gprieto@sgc.gov.co
Servicio Geológico Colombiano
Dirección de Recursos Minerales
Diagonal 53 n.° 34–53
Bogotá, Colombia

* Corresponding author

Abstract Airborne geophysics is an easy way to increase and complement the geological knowledge of large areas, especially very remote areas like the Colombian Amazonia. For this objective and to identify areas of interest for mineral resources, the Colombian government has made extensive efforts to fly the Andean and eastern parts of the country, collecting more than 400 000 linear km of magnetic and gamma spectrometric information over the Colombian Amazonia. This document focuses on describing the potential of these data to increase the geological knowledge of the Amazonian region. It presents a methodology to interpret the geophysical data and its application over a specific area in the eastern Guainía Department. It was possible to identify Paleoproterozoic to Mesoproterozoic igneous and metamorphic rocks of the Guiana Shield (Mitú Complex, Parguaza Granite) and several lineaments and structural trends that have not been previously reported. These crystalline basement rocks are partially covered by Miocene sedimentary rocks, recent alluvial deposits, and dense rainforest coverage, which make geological mapping very difficult. The results increase the relevance of this type of geophysical interpretation to the geoscientific knowledge about Colombia. This paper also highlights the training of Colombian geoscientists in modern geophysical interpretation techniques.
Keywords: *geophysical interpretation, magnetics, gamma spectrometry, Colombian Amazonia.*

Resumen Usar la geofísica aerotransportada es una forma sencilla de aumentar y complementar el conocimiento geológico de grandes áreas, especialmente si son muy remotas como la Amazonia colombiana. Para lograr este objetivo y además identificar áreas de interés para recursos minerales, el Gobierno colombiano realizó esfuerzos para sobrevolar las zonas andina y oriental del país y adquirió más de 400 000 km lineales de información magnetométrica y gamma espectrométrica sobre la Amazonia colombiana. Este documento se centra en describir el potencial de estos datos geofísicos para aumentar el conocimiento geológico sobre la región Amazónica. Presenta la metodología que se utilizó para la interpretación de los datos geofísicos adquiridos y

Citation: Moyano–Nieto, I.E., Cordani, R., Cárdenas–Espinosa, L.P., Lara–Martínez, N.M., Rojas–Sarmiento, O.E., Puentes–Torres, M.F., Ospina–Montes, D.L., Salamanca–Saavedra, A.F. & Prieto–Rincón, G. 2020. Contribution of new airborne geophysical information to the geological knowledge of eastern Colombia. In: Gómez, J. & Mateus–Zabala, D. (editors), The Geology of Colombia, Volume 1 Proterozoic – Paleozoic. Servicio Geológico Colombiano, Publicaciones Geológicas Especiales 35, p. 17–36. Bogotá. https://doi.org/10.32685/pub.esp.35.2019.02

su aplicación en un área específica ubicada al oriente del departamento de Guainía, donde la interpretación geofísica permitió diferenciar las rocas ígneas y metamórficas paleoproterozoicas a mesoproterozoicas del Escudo de Guayana (Complejo Mitú y Granito de Parguaza) y varios lineamientos y tendencias estructurales que no han sido reportados anteriormente. Estas rocas cristalinas del basamento se encuentran parcialmente cubiertas por rocas sedimentarias del Mioceno, algunos depósitos aluviales recientes y una densa cobertura vegetal, la cual hace muy difícil el mapeo geológico. Los resultados aumentan la relevancia de este tipo de interpretaciones geofísicas para el conocimiento geocientífico de Colombia. Adicionalmente, en este trabajo se resalta el entrenamiento de geocientíficos colombianos en las técnicas modernas de interpretación geofísica.

Palabras clave: *interpretación geofísica, magnetometría, gamma espectrometría, Amazonia colombiana.*

1. Introduction

Modern geophysical techniques are commonly used by geological surveys, academia, and industry around the world to aid in geological mapping, provide basic information about mining prospects, and strategic information to geological surveys even in areas where mining is restricted or prohibited (Dods et al., 1989; Geological Survey of Ireland, 2017; Nakamura, 2015; Oliveira, 2014a; Oliveira, 2014b; Silva, 2014).

For these objectives, the easiest and most inexpensive way to cover large areas with geophysical data at regional to semi–detailed resolutions is the use of fixed wing aircraft equipped with specific geophysical sensors suitable for the purposes of the survey (Table 1; Dentith & Mudge, 2014; Reeves, 2005), such as magnetic and gravimetric sensors over sedimentary basins and offshore regions for hydrocarbon exploration (Graterol & Vargas, 2010a, 2010b) and magnetic and gamma spectrometric sensors for mineral resource and geological mapping (Oliveira, 2014a; Oliveira, 2014b; Silva, 2014).

To increase the geological knowledge of the country and identify areas of interest for mineral resources, the Servicio Geológico Colombiano, in collaboration with external experts of the World Bank, selected areas of the country where geological, geochemical, and metallogenical information could be integrated with geophysical data to evaluate the mineral resource potential of these areas (Andean region) and other ones where the lack of geoscientific information could be complemented with the same geophysical information, such as the Orinoquia and Amazonian regions of eastern Colombia (Moyano et al., 2016).

Airborne magnetometry and gamma spectrometry data acquisition surveys were designed for selected areas. The surveys were distributed in parallel lines at 500 to 1000 meter spacings to attain a good resolution for the areal coverage (Reeves, 2005) and to acquire multi–purpose geophysical data (Oliveira, 2014a; Oliveira, 2014b; Silva, 2014). This survey design represents more than 1 million line kilometers of geophysical information, of which nearly 400 000 line kilometers are in the Amazonian region (Figure 1).

Table 1. Geophysical methods commonly used in the exploration of several important types of mineral deposits.

Deposit type	Gravimetry	Magnetometry	Resistivity	Radioactivity
Iron formation	M D	M D	D	M
Coal		M D		
IOCG	M D	M D	D	D
Magmatic	M D	M D	D	
Primary diamonds	M	M		
Uranium	M	M	M	D
Porphyry Cu, Mo	M	M D	D	D
SEDEX Pb–Zn	M	M	D	
Placer deposits	M		M	
Skarns	M	M D		
Groundwater			M D	
Petroleum	M	M	M	

Source: Data modified from Dentith & Mudge (2014).

Note: M—geological mapping of prospective terrains; D—detection/delineation of the mineral environment.

Regionally, the geological basement in eastern Colombia (Orinoquia and Amazonian regions; Figure 2) is composed of rocks of the Amazonian Craton (Tassinari & Macambira, 1999) and within Colombia corresponds to the Mitú Migmatitic Complex (PP–Mmg1 sensu Gómez et al., 2015) or the Mitú Complex (Celada et al., 2006; López & Cramer, 2012; López et al., 2007; Rodríguez et al., 2011). These rocks include gneisses and amphibolites with migmatites, granitoids of different compositions and alkaline and calc–alkaline affinities, and doleritic dikes (Bruneton et al., 1982; Celada et al., 2006; Galvis et al., 1979; López & Cramer, 2012; Rodríguez et al., 2011). The rocks of this complex outcrop in the Guainía, Vaupés, and Caquetá Departments. The U–Pb SHRIMP and Sm–Nd ages for

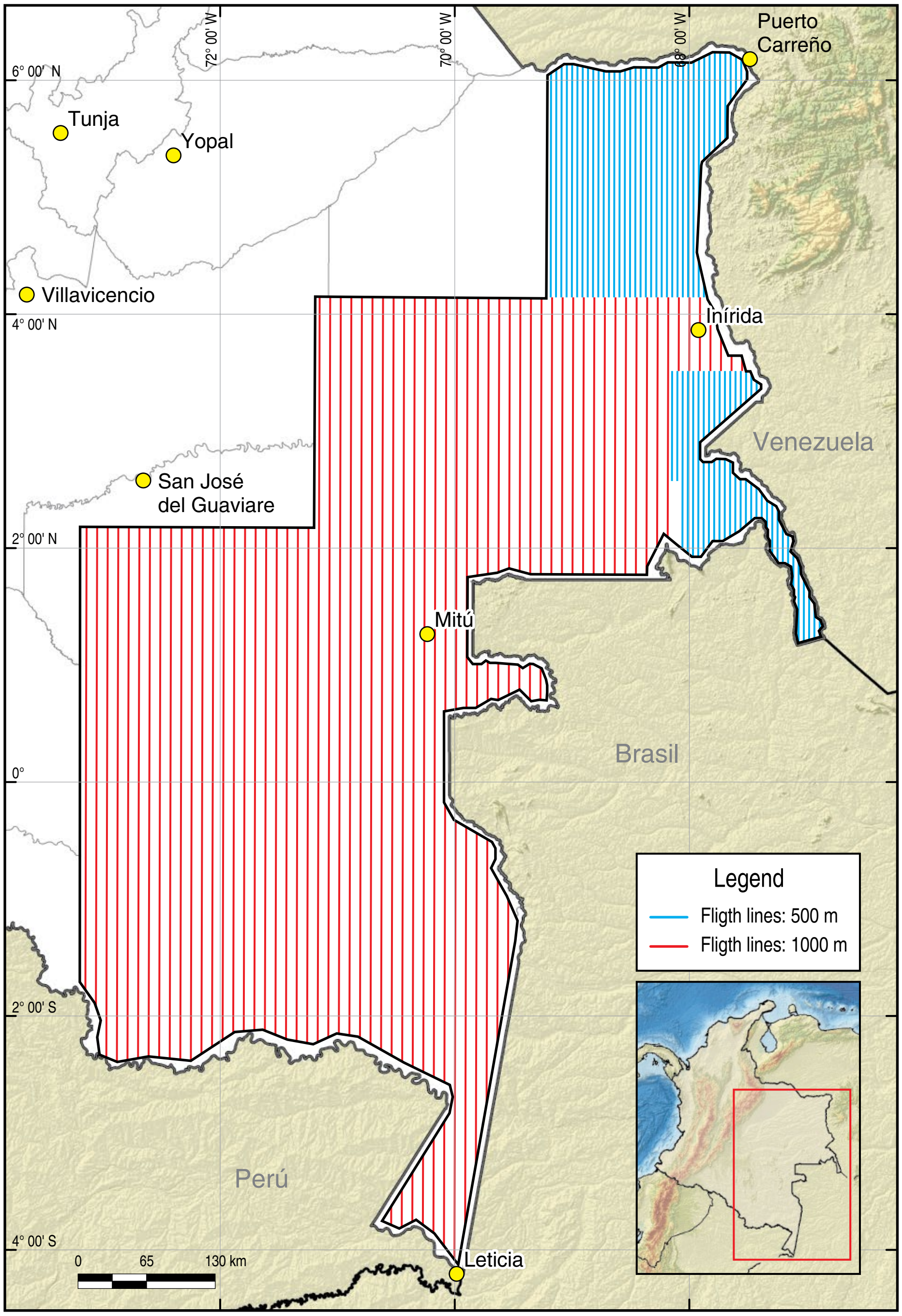


Figure 1. Location and line spacing of the airborne geophysical surveys.

the rocks of the Mitú Complex range from 2.2 Ga to 1520 Ma (Cordani et al., 2016; Tassinari et al., 1996).

The Roraima and Pedrera Formations (MP–Mvlg1 sensu Gómez et al., 2015), which were introduced by Gansser (1954), are a sequence of oligomictic conglomerates with alternating shales and ferruginous conglomerate sandstones that unconformably overlies the Mitú Complex. It has been identified in the Naquén and Caracanoa mountain ranges (Santos et al., 2003) and along the Vaupés and Guaviare Rivers (Julivert, 1968). Galvis et al. (1979) identified outcrops in the central and southeastern areas of the Guainía Department (Ingeominas, 1988). Acid subvolcanic dikes in the Roraima Formation metasedimentites have a 1496 ± 30 Ma Rb–Sr whole–rock age and an age of 1045 ± 19 Ma – 1293 ± 18 Ma K–Ar for several muscovite schists (Pinheiro et al., 1976). A maximum age of 1895 ± 15 Ma was derived from U–Pb SHRIMP dating (Santos et al., 2000).

The Parguaza Granite (MP–Pf1) is characterized as a granite with alkaline affinity (González & Pinto, 1990) that outcrops as isolated bodies in the plains in the eastern parts of the Vichada and Guainía Departments (Celada et al., 2006) and along the western margin of the Orinoco River. Numerous dikes with

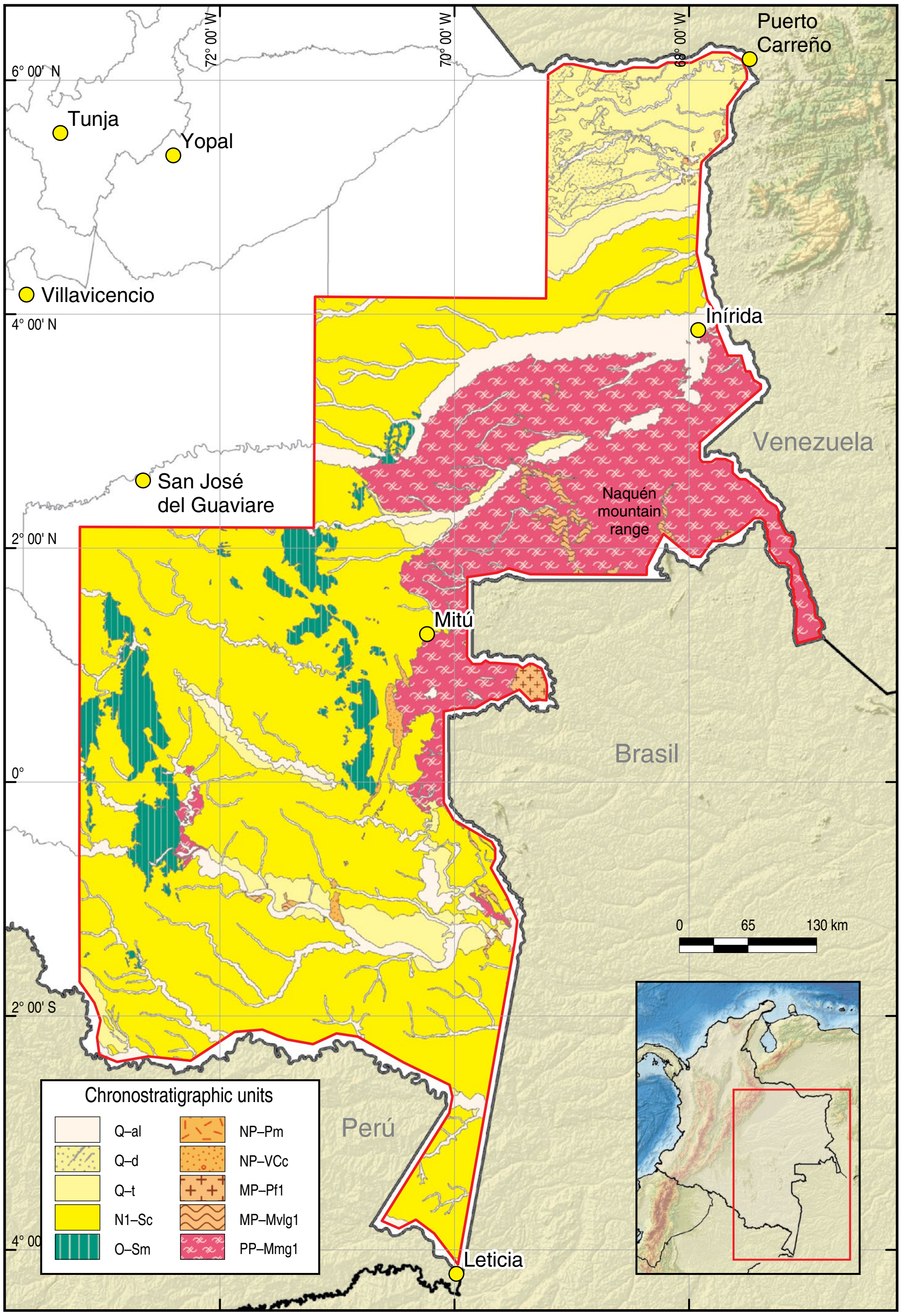
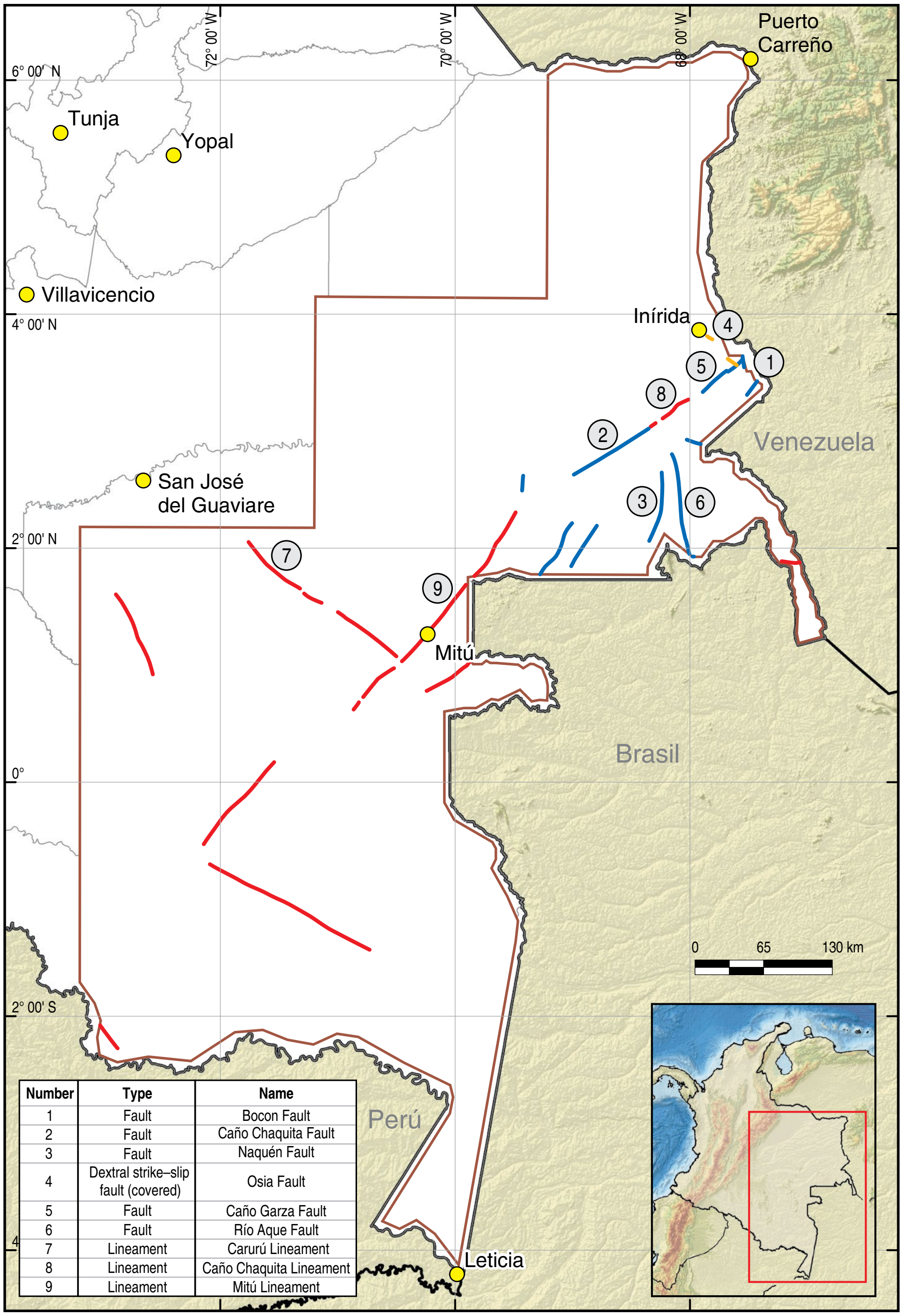


Figure 2. Geological framework of eastern Colombia (simplified from Gómez et al., 2015).

lenticular and tabular shapes, irregular bodies of microgranites, quartz and K–feldspar pegmatites, and quartz dikes intrude the Parguaza Granite (Celada et al., 2006). The geochronological data of Priem et al. (1982) suggest an age of 1575–1450 Ma for the emplacement of the Parguaza Granite (López & Cramer, 2012), whereas U–Pb ages of zircons by LA–ICP–MS give an age of 1401 ± 2 Ma (Bonilla–Pérez et al., 2013).

The Piraparaná Formation (NP–VCc) is composed of rhyodacitic lava flows toward the base with pyroclastic deposits mixed with polymictic conglomerates and arkosic sandstones that grade into quartz sandstones toward the top (Celada et al., 2006). It is represented by a folded sedimentary to metasedimentary sequence that outcrops at Yaca–Yaca on the Vaupés River and on the Piraparaná River to the south (Galvis et al., 1979). Preliminary Rb/Sr whole–rock isotopic dating results give the Piraparaná Formation an age of 1200 Ma (Priem et al., 1982).

The sedimentary rocks (O–Sm) form non–continuous plateaus that trend north–south and include a sequence of marine siltstones, shales, limonites, metasiltstones, feldspar metasandstones, and fine–grained metasandstones with marble lenses.



Number	Type	Name
1	Fault	Bocon Fault
2	Fault	Caño Chaquita Fault
3	Fault	Naquén Fault
4	Dextral strike–slip fault (covered)	Osia Fault
5	Fault	Caño Garza Fault
6	Fault	Río Aque Fault
7	Lineament	Carurú Lineament
8	Lineament	Caño Chaquita Lineament
9	Lineament	Mitú Lineament

Figure 3. Structural features of the study area (simplified from Gómez et al., 2015).

Thery (1982) and Bogotá (1982) proposed an Ordovician age for this unit. Finally, several Cenozoic and Quaternary deposits (N1–Sc, Q–t, Q–d, Q–al) composed of eolian sandstones, lateritic terraces, and recent alluvial sediments cover the area.

The Quaternary deposits and dense vegetation coverage of the area make it difficult to identify structural features, but regional lineaments that affect the sedimentary cover and control the drainage can be identified in the area (Figure 3). The faults in the Naquén mountain range affect the Mitú Complex and can be related to regional structural features (Ingeominas, 1989). The Carurú Lineament (Gómez et al., 2015) strikes approximately N30°W and was described by De Boorder (1980) as a lineament drawn from scarps in the Roraima and Pedrera Formations that also controls the channels of the Inírida and Vaupés Rivers in some areas (Celada et al., 2006). To the south of this area, other lineaments that strike approximately N30°W control the upper portions of the Caquetá and Apaporis Rivers. Furthermore, a lineament that strikes N40°E between the Caquetá and Apaporis Rivers also controls portions of their channels.

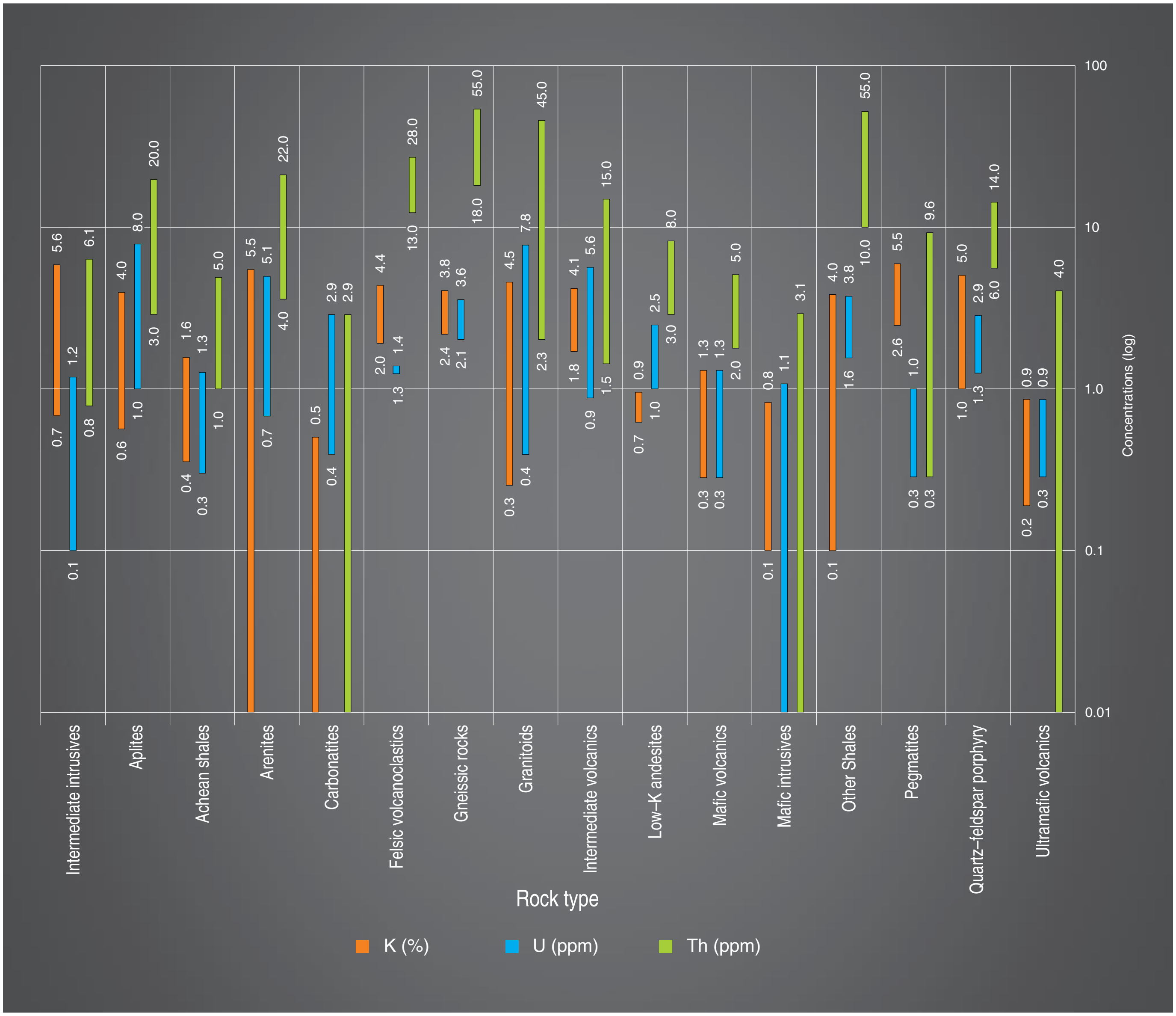


Figure 4. K, U, and Th isotope concentrations in different types of rocks (modified from Dickson & Scott, 1997).

The Mitú Fault is described by Galvis et al. (1979) as part of a fault system that strikes N40°E to N60°E (Celada et al., 2006) and was identified as a lineament by Gómez et al. (2015). Another fault of this system that affects the Mitú Complex is the Caño Chaquita Fault, which extends to the SW and may be a continuation of the Mitú Fault (Celada et al., 2006). The Naquén Fault is described by De Boorder (1980) as a fault with a dip–slip component where the rocks associated with the Roraima and Pedrera Formations are in contact with the Mitú Complex. This fault was later called the "Maimachi Fault System" by Ingeominas (1989) (Celada et al., 2006). The Río Aque Fault is located on the eastern side of the Naquén mountain range and is considered to be a fault with a dip–slip component that was reactivated from the Precambrian to the Cenozoic (Ingeominas, 1989). The Río Aque and Naquén Faults define the wedge that is composed of the Naquén mountain range (Galvis et al., 1979).

2. Geophysical Methods Used

2.1. Gamma Ray Spectrometry

Gamma ray spectrometry is a geophysical method used to measure the energy spectrum and intensity of the radiation emitted from the materials at the earth's surface. Radioactive isotopes of the elements potassium (^{40}K), uranium (^{231}U, ^{238}U, and their daughters), and thorium (^{232}Th and its daughter) are the only ones that produce sufficient intensities to be used in radiometric mapping (International Atomic Energy Agency, 1991).

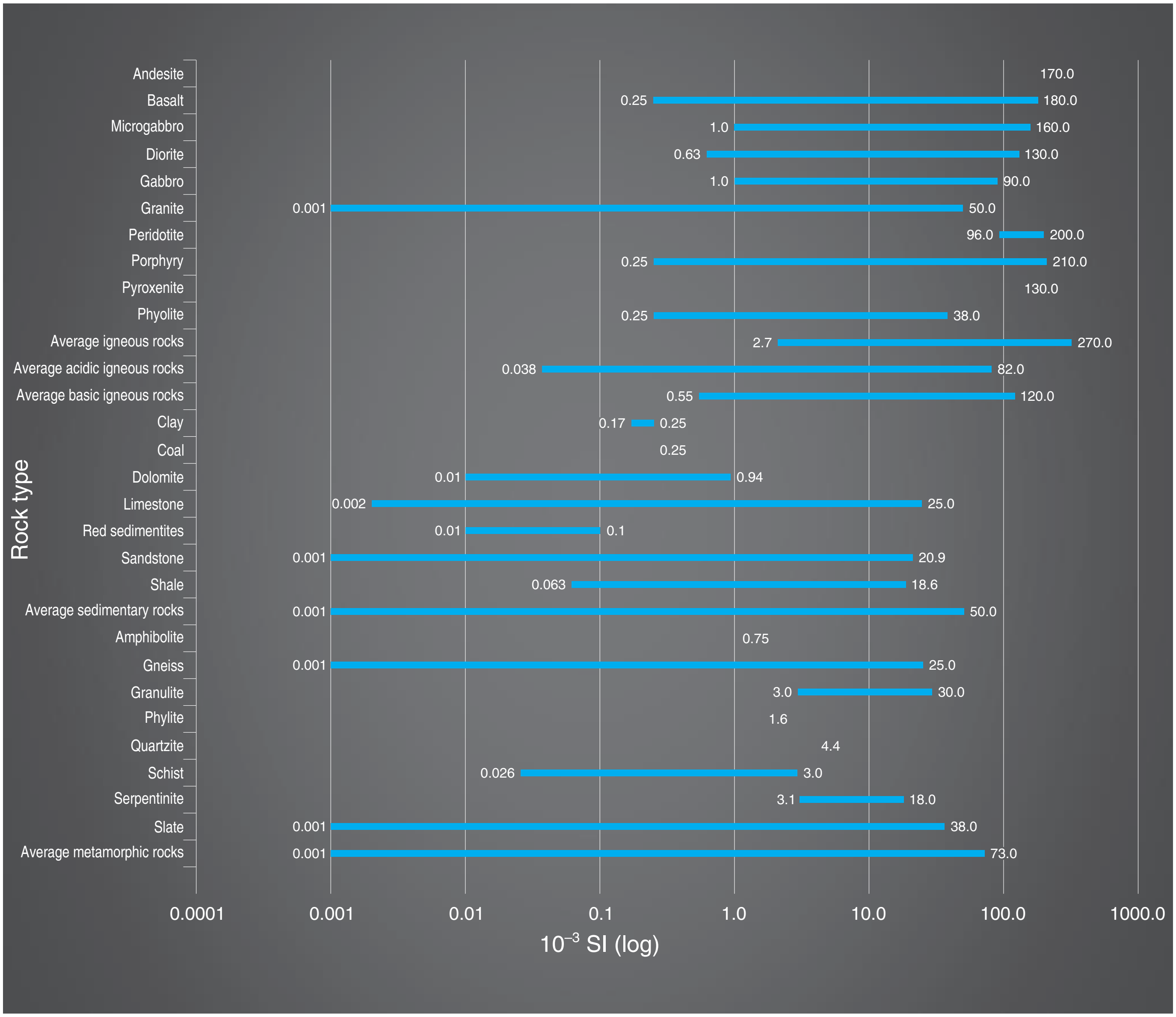


Figure 5. Magnetic susceptibilities of common rock types (modified from Hunt et al., 1995).

Gamma ray spectrometry is a passive method, which means that no external signal is necessary to generate a response from the source. Its applications include geological mapping (Nakamura, 2015; Oliveira, 2014a; Oliveira, 2014b; Silva, 2014), taking into account the variation on the concentrations of K, U, and Th isotopes according to the type of rock (Figure 4), detection of zones with hydrothermal alteration (Fueg, 2010), particularly in the identification of potassic alteration related to porphyry–type, silver and hydrothermal gold deposits and in volcanic massive sulfides (Shives et al., 1997).

The acquisition equipment includes a gamma ray spectrometer, which is composed of crystal detectors of NaI (thallium activated) that are sensitive to gamma radiation and generate pulses that pass through a photomultiplier that convert them into an electrical signal that can be counted, discriminated, and compiled into an energy spectrum (California State University, 2014). This energy corresponds to isotopes from many sources, so it is necessary to perform pre–processing to remove noise from the raw data. The reduction process involves several parameters and coefficients that must be calculated in a calibration range (International Atomic Energy Agency, 1991) using calibration pads of known K, U, Th and background concentrations and also by test lines performed before and after every data acquisition flight.

From the raw database of the counts per unit time of each element (whose energy levels are known), several corrections must be applied, including the dead time (small gaps of time when the equipment registers the number of counts and does not measure data), aircraft and cosmic radiation background removal, radon removal, Compton scattering (influence of de-

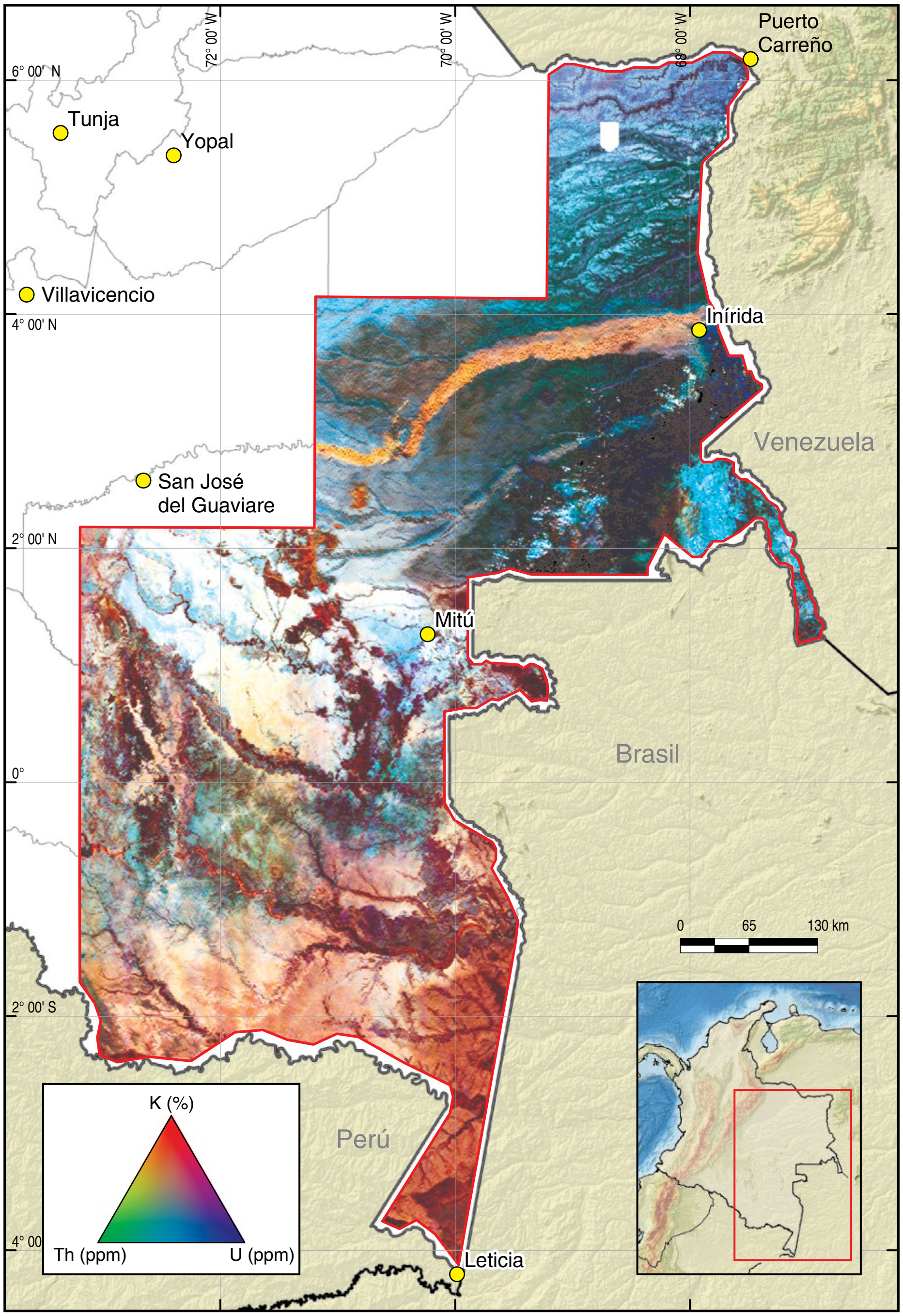


Figure 6. Radiometric ternary image (U, Th, K) of eastern Colombia (modified from Moyano et al., 2016).

caying isotopes from higher energy isotopes into lower energy isotopes), and atmospheric attenuation related to the flight height above the ground. Finally, these corrected counts per unit time are transformed into grids of the relative concentrations of K (%), U (ppm), and Th (ppm) (International Atomic Energy Agency, 2003).

2.2. Magnetometry

Magnetometry is a potential field method (Telford et al., 1990) that measures the variations of the Earth's magnetic field. The variations from the International Geomagnetic Reference Field (IGRF) (National Oceanic & Atmospheric Administration, 2018) are considered "anomalies" that are responses to changes in the magnetic properties (magnetic susceptibility) of the rocks (Figure 5) and materials of the Earth's crust. This total magnetic field anomaly (TFA) map is the basis of the processing and interpretation of magnetometry data.

The acquisition equipment for aeromagnetic surveys consists of a magnetometer that measures the intensity of the magnetic field along each flight line. Before calculating the TFA, the raw data must be compensated for and reduced from noise

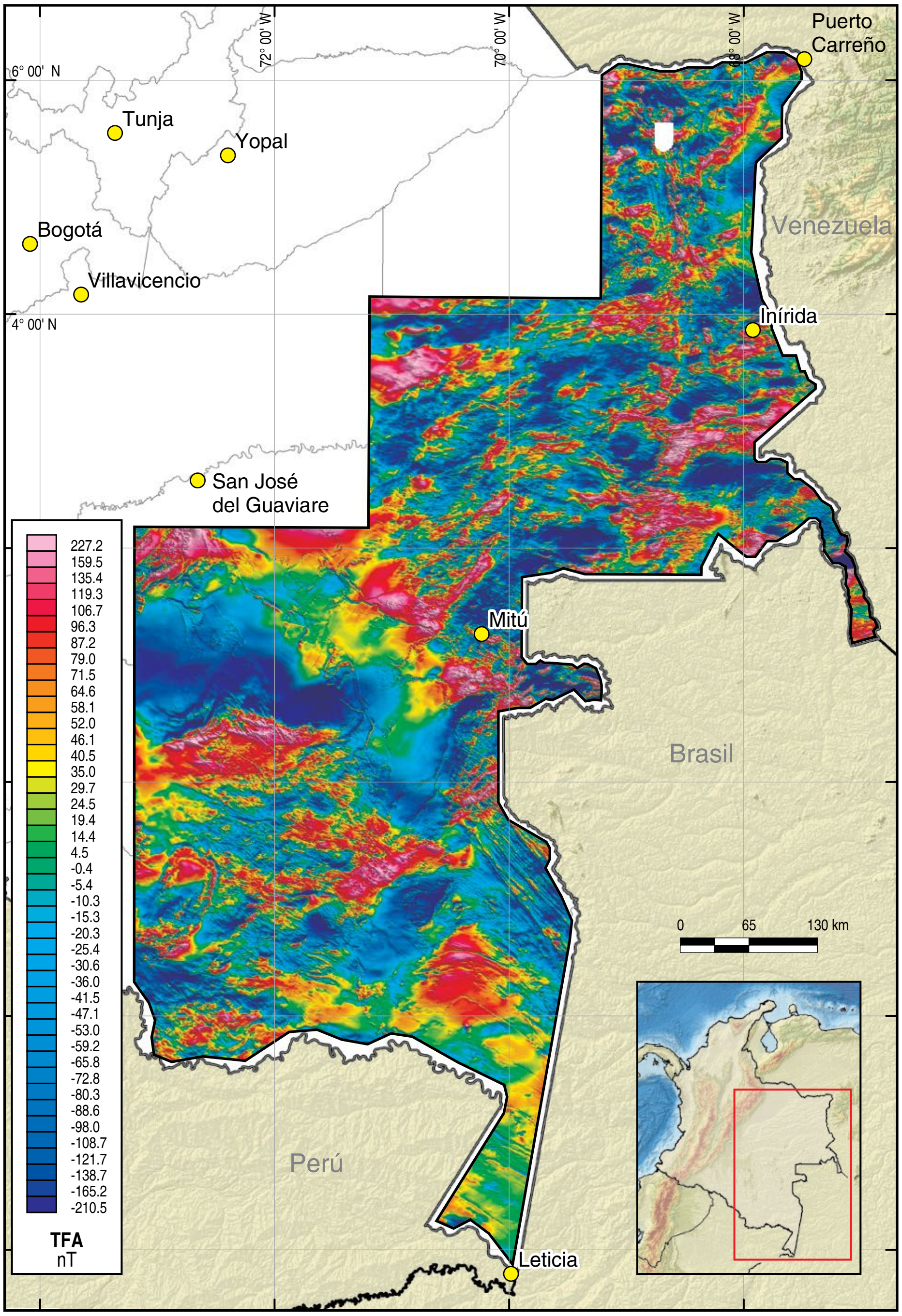


Figure 7. TFA map of eastern Colombia (modified from Moyano et al., 2016).

and variations related to the acquisition itself, including lag correction, heading, diurnal variations, levelling, and micro–levelling (Reeves, 2005). After these corrections are performed, the resulting measured magnetic field grid is subtracted from the IGRF to obtain the TFA.

Aeromagnetic surveys provide magnetic anomaly maps (Corrêa et al., 2017; Dentith & Mudge, 2014; De Sousa–Moro et al., 2018). Large areas can be mapped quickly, without interpretation bias, irrespective of surface cover and with minimal terrain restrictions (Reeves, 2005). Most importantly, the geologic and structural information that can be gleaned from aeromagnetic data (Dentith & Mudge, 2014; Reeves, 2005) make magnetometry a unique tool for earth scientists.

The main applications of magnetometry are (Table 1) geological mapping (Oliveira, 2014a; Oliveira, 2014b; Silva, 2014), delineation of geological structures (De Sousa–Moro et al., 2018; Ramos et al., 2014), studies of porphyry copper/gold deposits and related hydrothermal alteration/mineralization (Heithersay & Walshe, 1995; Jhon et al., 2010), direct searches for iron oxide copper–gold (IOCG) systems, alkaline bodies containing diamonds and iron deposits (Nannini et al., 2017), and studies on continental–scale geotectonic trends (Kronenberg & Reeves, 2011).

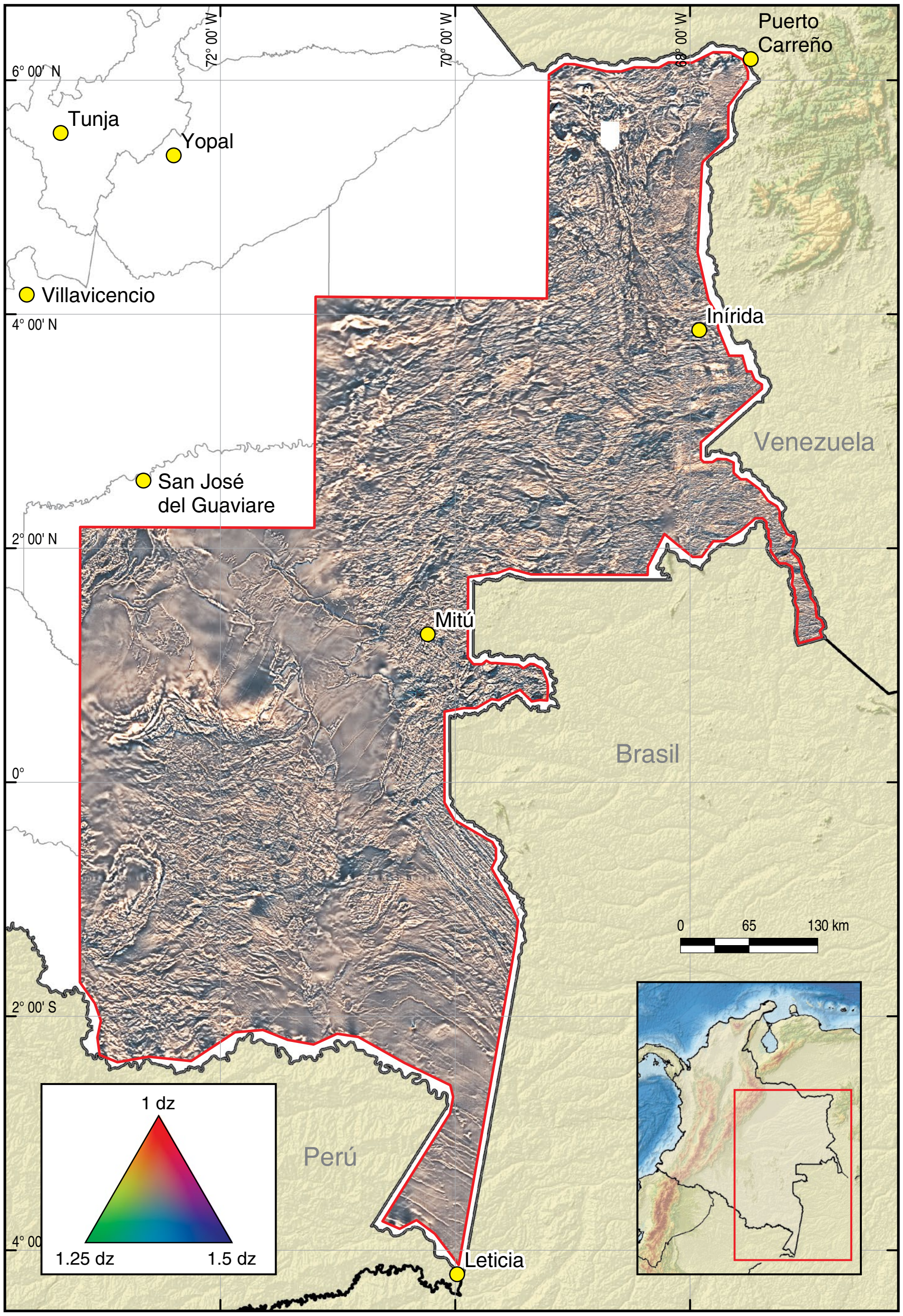


Figure 8. Ternary image of partial derivatives (1 dz, 1.25 dz, 1.5 dz) of the TFA for eastern Colombia.

3. Processing the Geophysical Datasets

The principal objective of these airborne surveys was to evaluate the potential for mineral resources in Colombia using high–resolution geophysical data processing for target selection and characterization over selected areas of the country. In addition, the acquisition of this type of broad coverage geophysical information for the first time in the history of the country provides data with a resolution that was not previously available (Graterol & Vargas, 2010a, 2010b; Kronenberg & Reeves, 2011). The data provide a tool to enhance the geological knowledge about areas of limited accessibility and dense vegetation and soil coverage, like the Amazonian region.

This gamma spectrometric and magnetometric information (Figures 6, 7) provides the Colombian government with high quality geophysical data suitable for surface geological mapping and mineral resource exploration and also for the research of the geology and evolution of the Amazonian Craton because the magnetometry method is more sensitive to the higher magnetic susceptibilities of the metamorphic and igneous rocks of

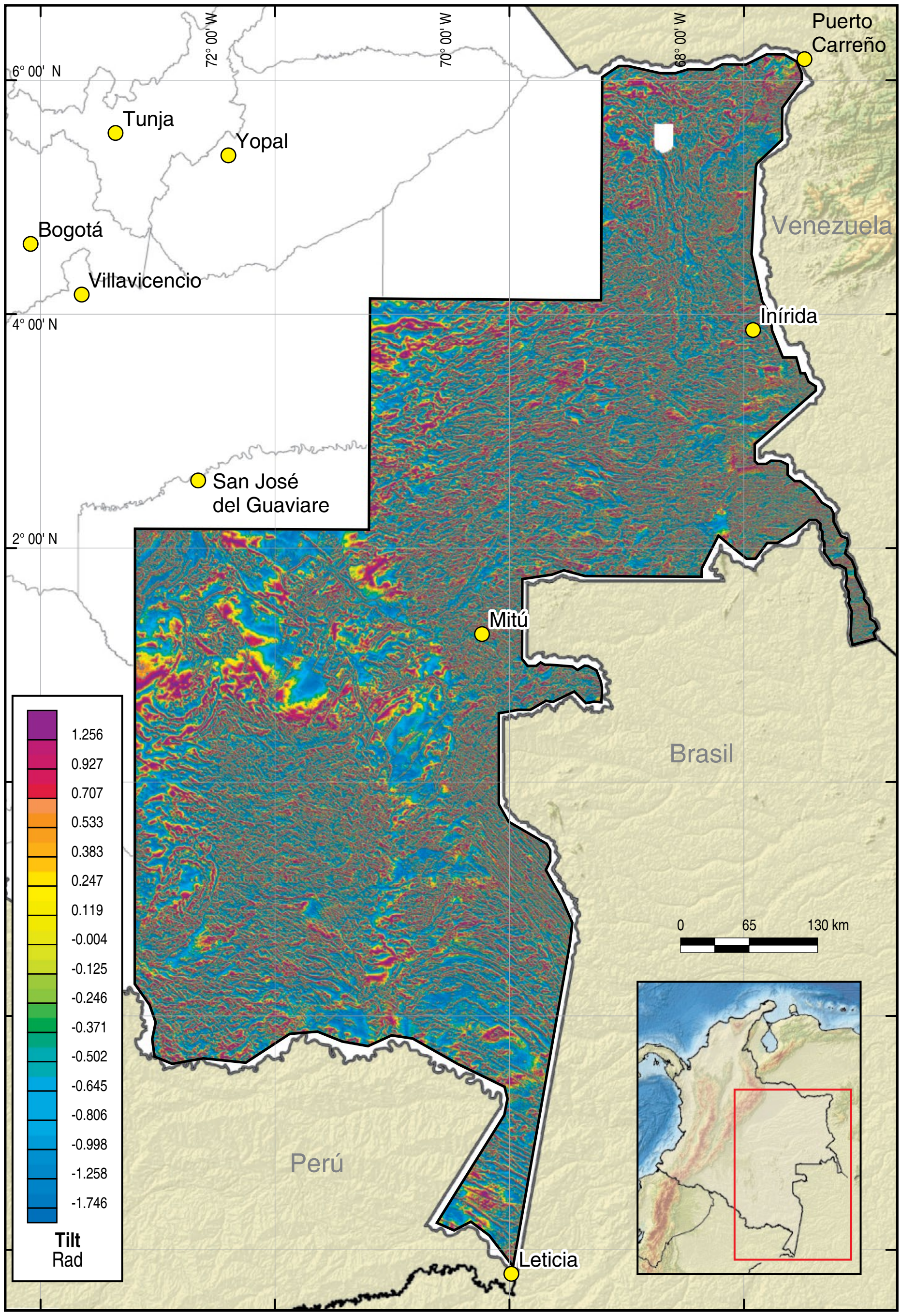


Figure 9. Tilt derivatives of the RTP (TFA) for eastern Colombia.

the basement than to the low–magnetic susceptibility of the sedimentary rocks and soil in the study area (Graterol, 2006, 2009; Graterol & Vargas 2007).

A procedure was developed to process the airborne geophysical data to generate information that will help geoscientists increase the geological knowledge and to select areas of interest for mineral resource exploration over remote areas. The steps of this procedure are:

- Construct a ternary image (International Atomic Energy Agency, 2003) that represents the surface distribution of radioactive isotopes over the survey area as a combination of the relative concentrations of K (red), Th (green), and U (blue). Qualitative regional to semi–detailed litho–geophysical maps can be constructed that show different radiometric domains based on the variability on the proportions of the three isotopes, which provide information to improve the geological cartography (Dentith & Mudge, 2014; Ford et al., 2008; International Atomic Energy Agency, 2003; Martelet et al., 2006; Minty, 1997; Oliveira, 2014a; Oliveira 2014b; Ramos et al., 2014) as shown in Figure 6.

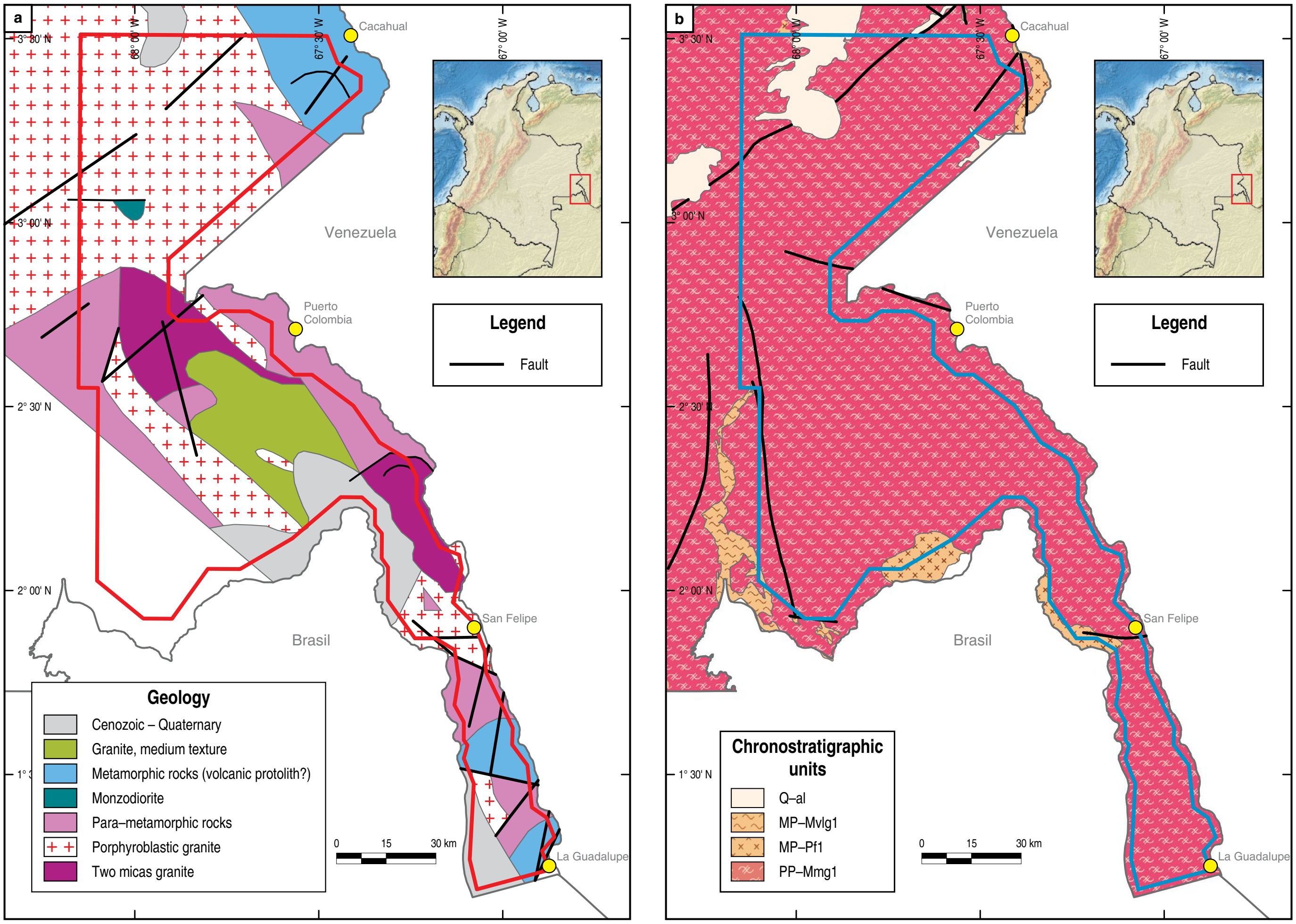


Figure 10. Regional geology of the study area. **(a)** Modified from Bruneton et al. (1982). **(b)** Simplified from Gómez et al. (2015).

- Calculate the vertical derivatives (1 dz, 1.25 dz, and 1.50 dz) of the TFA (Dentith & Mudge, 2014) and display it on a ternary image (Figure 8). This representation provides a coverage suitable for delineating magnetic domains (Dentith & Mudge, 2014) because it enhances the high frequency attributes of the magnetometric data and their lateral variations, which allows the interpreter to separate different textures that could be related to variations in the magnetic susceptibility of the basement rocks and hence to possibly discriminate different lithologies.
- Calculate the tilt angle derivative (Salem et al., 2015) and display it on a grid (Figure 9). The tilt image results from the arctangent of the vertical derivative divided by the total horizontal derivatives (x, y) of the reduction to magnetic pole (RTP) (Baranov & Naudy, 1964) of the TFA. Tilt derivative calculation provides an image that enhances the borders and linear features of magnetic data that are useful for identifying magnetic lineaments of geological interest, such as fractures, faults, and dikes (Curto et al., 2013; Fairhead et al., 2004).

4. Results

To illustrate the potential of the geophysical data and the interpretation procedure for geological interpretation, an area of the Guainía Department near the Venezuela and Brasil border was selected due to the regional geology (Bruneton et al., 1982, Celada et al., 2006; López et al., 2007; López & Cramer, 2012; Gómez et al., 2015), which can be correlated with the geophysical features to extend the geological/geophysical interpretation (Figure 10).

Figure 11 shows the ternary image of the gamma spectrometric data for the east Guainía area. The northern part of this area contains low values of the relative concentrations of radioactive elements (domain 3; see Figure 11b), which are reflected by the darker colors on the ternary image (Figure 11a). In the central and southern parts of the area, the relative concentrations of the radioactive elements increase (light colors; see Figure 11a). From these gamma spectrometric domains, it is possible to differentiate a group of domains with relatively high counts of radioactive isotopes (e.g., 1, 4, 6, 7, 10; see Figure 11b) and others with lower radioactive element contents (e.g., 3, 8, 9;

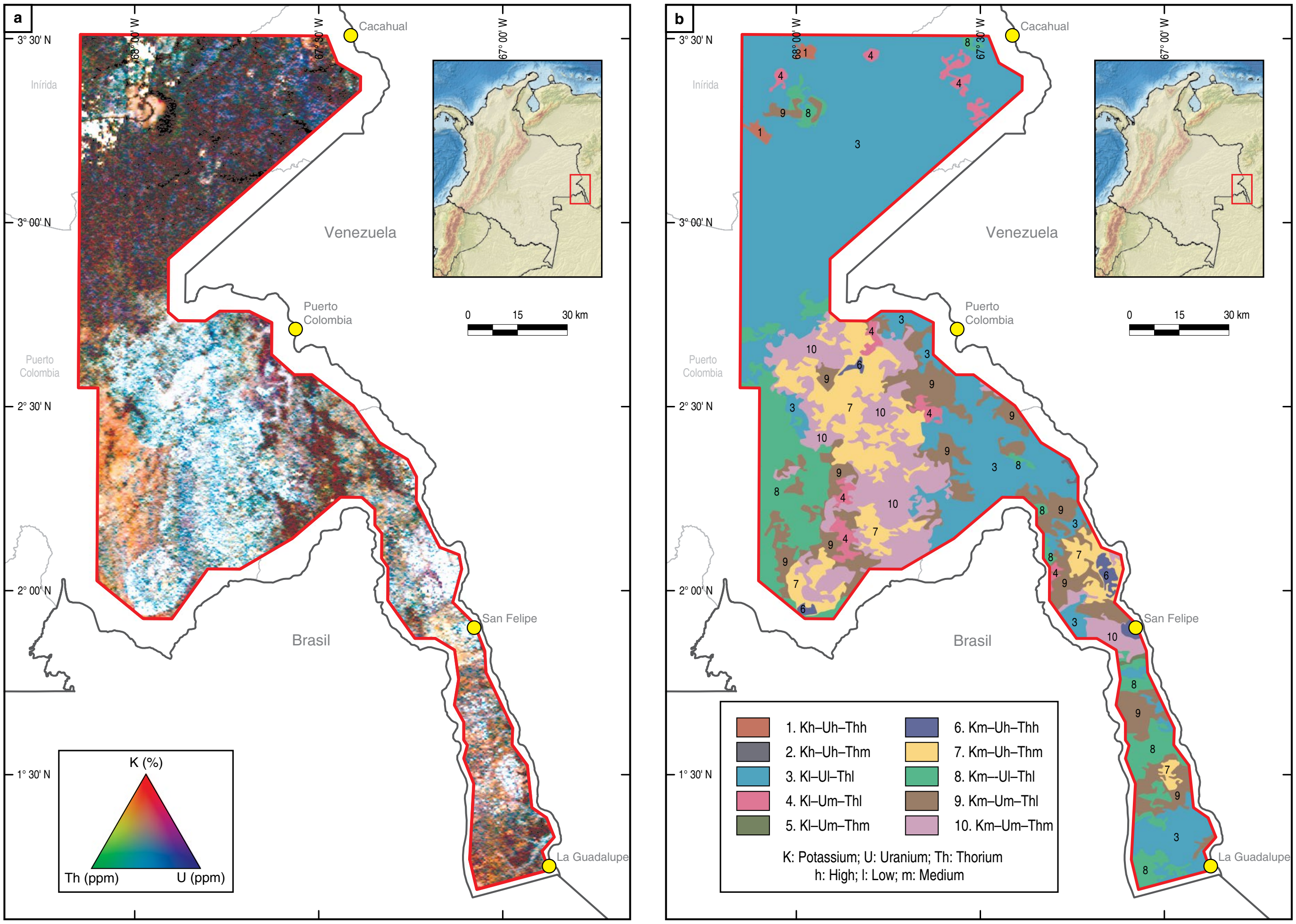


Figure 11. (a) Ternary gamma spectrometric image of the Guainía area. **(b)** Delineated radiometric domains of the Guainía area.

see Figure 11b). A comparison with the geological information (Figure 10a; Bruneton et al., 1982) shows a correlation between the groups with high radioisotope contents and areas with more igneous rocks and between the groups with lower radioisotopes contents and areas with more metamorphic lithologies.

Figure 12 shows the ternary image for the magnetometry data. The qualitative contrasts in the texture and intensity of the magnetic responses over the area indicate several magnetic domains (Figure 12b) that can be grouped into high magnetic responses (e.g., 1, 2; see Figure 12b) and low magnetic responses (e.g., 3, 4; see Figure12b). Based on the average magnetic susceptibilities of common rock types (Figure 5), the magnetic response of igneous rocks will be higher than that of metamorphic rocks. Furthermore, a comparison of the magnetic domains with the available geological information (Bruneton et al., 1982) shows an association between high to medium magnetic domains and igneous lithologies and between low to medium magnetic domains and metamorphic lithologies.

The magnetic lineaments extracted from the tilt derivative image (Figure 13b) show three different patterns. The first includes N50°E to N60°E lineaments that affect the structure at a large scale and are parallel to the Caño Chaquita Lineament to the north of the study area and that were also identified in Brasil to the south (Almeida et al., 2004). The N50°E lineaments are closely related to another group of major lineaments that strike N40°W to form a nearly orthogonal family that is present over the entire area. Several dike– or pegmatite–like lineaments along the southeastern border of the Guainía Department are similar to the N40°W trends (Figure 13). Finally, an incipient pattern with trends of N10°E to N15°E was delineated from the magnetic and radiometric images (Figure 14).

5. Discussion

Based on the available geological data, in the eastern part of the Guainía region, approximately 80% of the total area corresponds to granitoids (Bruneton et al., 1982). The area also contains metamorphic rocks of high amphibolite facies, such as orthogneisses and paragneisses with high potassium contents due to metasomatism (Bruneton et al., 1982; Galvis et al., 1979). However, the absence of outcrops in the region did not allow the boundaries between the granitoids and the metamorphic rocks to be estab-

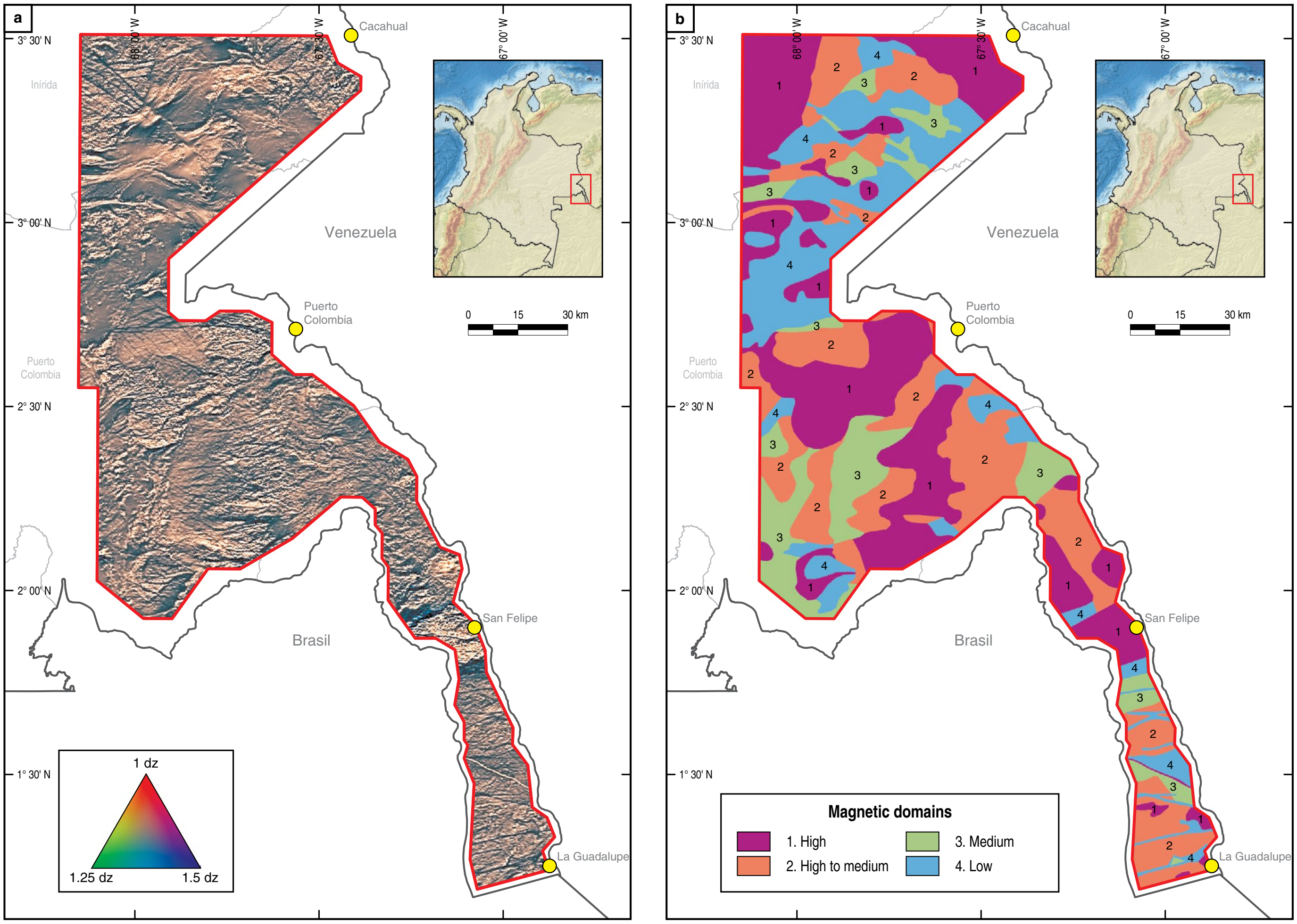


Figure 12. (a) Ternary image of the magnetic derivatives for the Guainía area. **(b)** Delineated magnetometric domains for the Guainía area.

lished accurately. For this reason, the geological mapping can be improved by the use of the geophysical domains and lineaments obtained in this study, which were interpreted as variations in the physical properties of the different types of rocks identified in the area. Using the new geophysical data, the magnetic and radiometric domains, and magnetic lineaments defined here are linked with some of the lithologies of the Mitú Complex, Parguaza Granite, and other igneous rocks (Figure 14).

The geophysical signatures of the localities in which Parguaza–type granitoids have been described include polygonal areas with low magnetism and sharp magnetic borders. In addition, relatively high K, Th, and U contents (Figure 4) are commonly related to this type of granitoid. Consequently, low magnetic and high gamma spectrometric domains with these polygonal shapes were mapped in the southwestern Guainía area as Parguaza–type granitoids (Figure 14).

The San Felipe–type porphyroblast granite and the biotite granite, mapped by Bruneton et al. (1982) as porphyroblastic granite and two micas granite, respectively (Figure 10a), are correlated with high magnetic responses (Figure 12a), medium K contents and medium to high Th–U contents (Figure 11a). For that reason, the geophysical domains with the same characteristics were mapped as San Felipe–type and biotite granites. For example, in the northern part of the study area, several highly magnetic bodies are associated with biotite granites, although they do not have the same gamma signature. Also in the north, an intrusive body was mapped based on its circular shape, high K content, and high magnetic response.

Several low magnetic responses with low to medium K–U contents and low Th contents are correlated with metamorphic rocks mapped by Bruneton et al. (1982). These metamorphic rocks continue into Brasil as the "Complexo Cumati, Fácies Tonu" (Almeida et al., 2004) as a sequence of locally migmatitic biotite orthogneisses. These rock types also contain magnetic lineaments (Figure 13) with prevalent E–W and N70°E–N80°E strikes, which could be related to foliations and/or fractures that also bend in some locations.

6. Conclusions

The Servicio Geológico Colombiano, in collaboration with external experts from the World Bank, designed an airborne

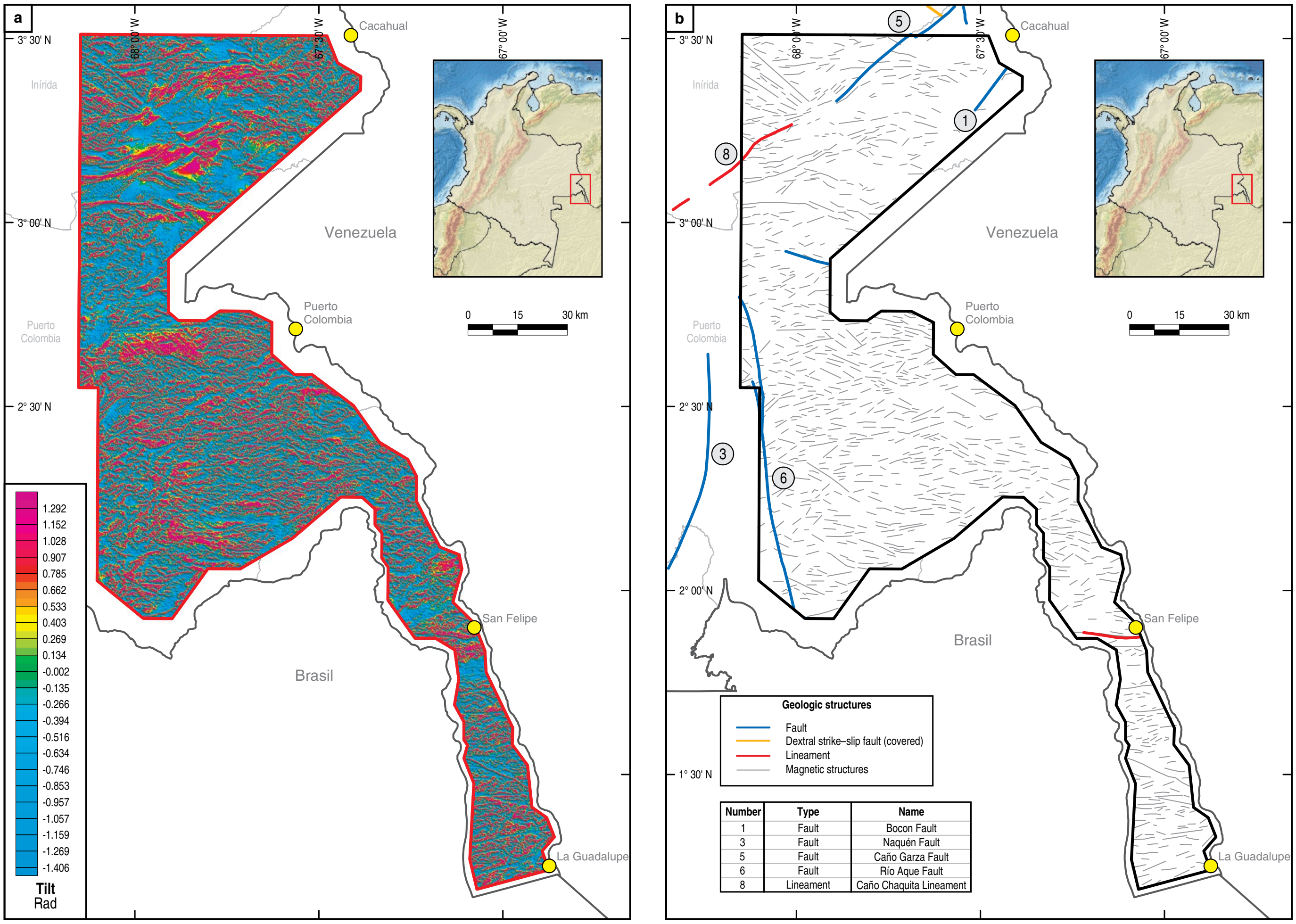


Figure 13. (a) Tilt derivatives of the RTP of the TFA. **(b)** Delineated magnetic lineaments and geological structures.

magnetometry and gamma spectrometry data acquisition survey to collect multi–purpose geophysical data to evaluate the mineral resource potential of the country and to increase the geoscientific knowledge of remote areas like the Amazonian region. For this purpose, a methodology for processing geophysical information to generate datasets and images with an emphasis on geological mapping was presented.

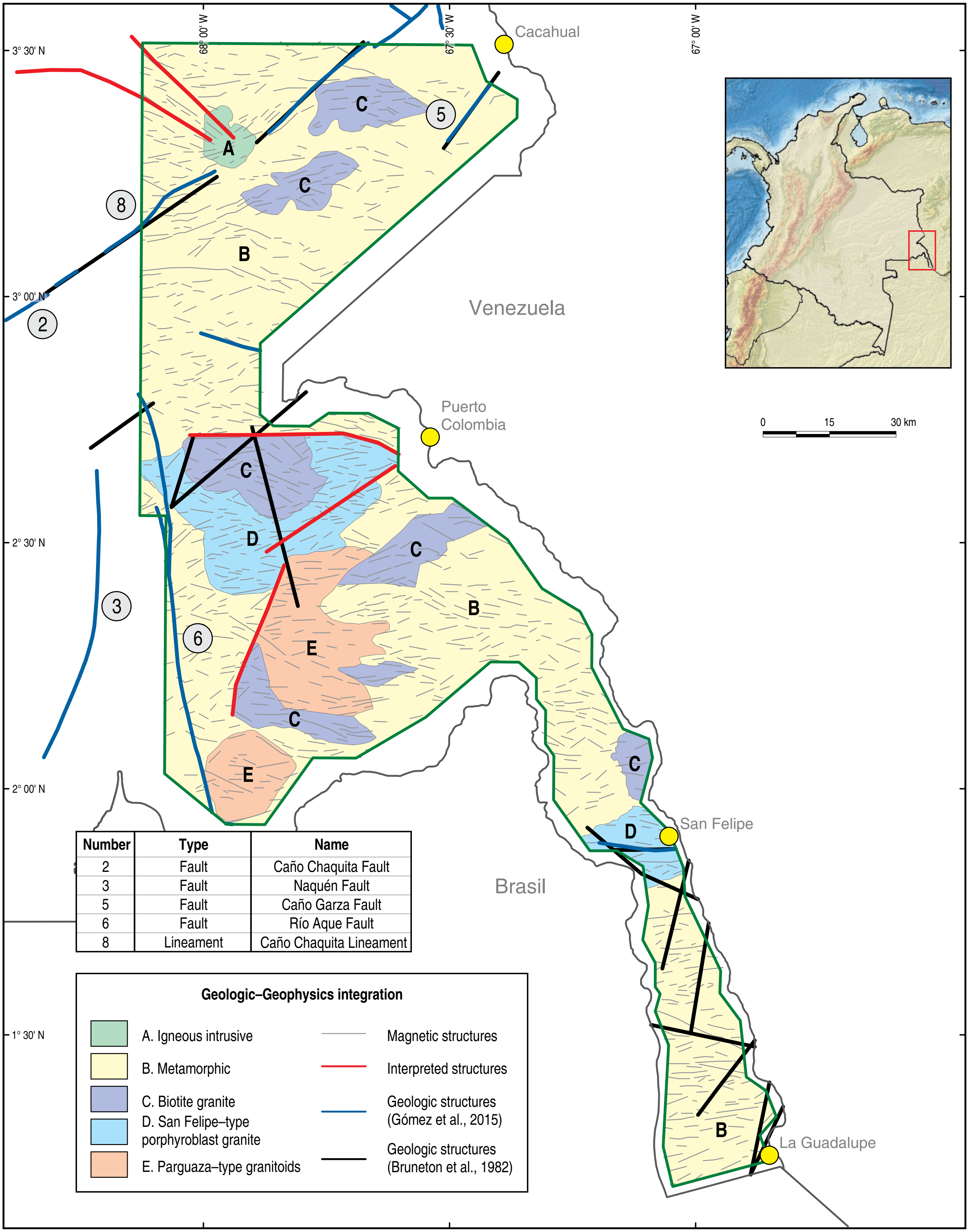
To illustrate the applicability of the methodology, the procedure was applied to an area in the Guainía Department. The geophysical domains and lineaments were compared and integrated with the available geological information, which allowed these domains to be classified into geological units and also allowed new units with similar geophysical signatures to be delineated. All of these data were incorporated into a litho–geophysical map of the study area (Figure 14).

The lineaments and faults identified on the available geological maps were also identified in the magnetic images. For example, the Caño Chaquita Lineament and the lineament near the town of San Felipe are clearly identifiable in the tilt derivative image and the ternary diagram of the derivatives. The Río Aque Fault is also easily recognizable to the southwest of the study area. In addition, several other linear features share the same orientation with lineaments mapped in Brasil.

This example demonstrates that this methodology of interpreting gamma spectrometric and magnetometric data is a good complement for early stage geological mapping in remote areas like the Amazonian region, where the collection of regional scale cartography will require several decades. Using the data collected in this survey, costs and time can be optimized by distinguishing prominent control localities to identify and map geological contacts and structural elements, which will have a significant effect on further mapping.

Acknowledgments

The authors would like to thank the Servicio Geológico Colombiano for allowing the use of the geophysical data from ongoing contracts and for the time to write this paper.



Number	Type	Name
2	Fault	Caño Chaquita Fault
3	Fault	Naquén Fault
5	Fault	Caño Garza Fault
6	Fault	Río Aque Fault
8	Lineament	Caño Chaquita Lineament

Figure 14. Map showing the integration of geophysical and geological information of the Guainía area.

References

Almeida, M.E., Luzardo, R., Pinheiro, S.S. & Oliveira, M.A. 2004. Folha NA.19–Pico da Neblina. Scale 1:1 000 000. In: Schobbenhaus, C., Gonçalves, J.H., Santos, J.O.S., Abram, M.B., Leão–Neto, R., Matos, G.M.M., Vidotti, R.M., Ramos, M.A.B. & De Jesus, J.D.A. (editors), Carta geológica do Brasil ao milionésimo, Sistemas de Informações Geográficas–SIG. Programa Geologia do Brasil, Companhia de Pesquisa de Recursos Minerais–Serviço Geológico do Brasil. Brasília.

Baranov, V. & Naudy, H. 1964. Numerical calculation of the formula of reduction to the magnetic pole. Geophysics, 29(1): 67–79.

Bogotá, J. 1982. Estratigrafía del Paleozoico inferior en el área amazónica de Colombia. Geología Norandina, (6): 29–38.

Bonilla–Pérez, A., Frantz, J.C., Charão–Marques, J., Cramer, T., Franco–Victoria, J.A., Mulocher, E. & Amaya–Perea, Z. 2013. Petrografía, geoquímica y geocronología del Granito de Parguaza en Colombia. Boletín de Geología, 35(2): 83–104.

Bruneton, P., Pallard, B., Duselier, D., Varney, E., Bogotá, J., Rodríguez, C. & Martín, E. 1982. Contribución a la geología del oriente de las comisarías del Vichada y del Guainía (Colombia). Geología Norandina, (6): 3–12.

California State University. 2014. Gamma ray spectroscopy using a NaI (Ti). Scintillation Counter, 3 p. Stanislaus, USA.

Celada, C.M., Garzón, M., Gómez, E., Khurama, S., López, J.A., Mora, M., Navas, O., Pérez, R., Vargas, O. & Westerhof, A.B. 2006. Potencial de recursos minerales en el oriente colombiano: Compilación y análisis de la información geológica disponible (fase 0). Servicio Geológico Colombiano, unpublished report, 165 p. Bogotá.

Cordani, U.G., Sato, K., Sproessner, W. & Santos–Fernandes, F. 2016. U–Pb zircon ages of rocks from the Amazonas territory of Colombia and their bearing on the tectonic history of the NW sector of the Amazonian Craton. Brazilian Journal of Geology, 46(1): 5–35. https://doi.org/10.1590/2317-4889201620150012

Corrêa, J.W., Corrêa, J.W. & Bokelmann, G. 2017. Lateral variation of crustal properties from aerogeophysical data in northern Brazil. Geophysics, 82(5): J39–J60. https://doi.org/10.1190/geo2016-0206.1

Curto, J.B., Vidotti, R.M., Fuck, R.A., Blakely, R.J., Alvarenga, C.J. & Dantas, E.L. 2013. Unveiling the Transbrasiliano Fault System in northern Paraná Basin using airborne magnetic data. 13th International Congress of the Brazilian Geophysical Society and EXPOGEF. Proceedings, p. 452–456. Rio de Janeiro, Brazil. https://doi.org/10.1190/sbgf2013-095

De Boorder, H. 1980. Contribución preliminar al estudio de la estructura geológica de la Amazonia colombiana. Revista CIAF, 5(1): 49–96.

Dentith, M. & Mudge, S. 2014. Geophysics for the mineral exploration geoscientist. Cambridge University Press, 454 p. New York.

De Sousa–Moro, P., Vidoti, R.M. & Dantas, E.L. 2018. Structural framework from gravity and magnetic data in the Paleo/Mesoproterozoic Araí rift–sag Basin, central Brazil. Geophysics, 83(4): B195–B207. https://doi.org/10.1190/geo2017-0627.1

Dickson, B.L. & Scott, K.M. 1997. Interpretation of aerial gamma–ray surveys–adding the geochemical factors. AGSO Journal of Australian Geology & Geophysics, 17(2): 187–200.

Dods, S.D., Teskey, D.J. & Hood, P.J. 1989. Magnetic anomaly map of Canada. Canadian geophysical atlas, map 11. Scale 1:10 000 000. Geological Survey of Canada. Ottawa.

Fairhead, J.D., Mackenzie, C., Green, C.M & Verduzco, B. 2004. A new set of magnetic field derivatives for mapping mineral prospects. 17th Geophysical Conference and Exhibition. Australian Society of Exploration Geophysicists Extended Abstracts, 2004(1), p.1–4. https://doi.org/10.1071/ASEG2004ab042

Ford, K., Harris, J.R, Shives, R., Carson, J. & Buckle, J. 2008. Remote predictive mapping 2. Gamma–ray spectrometry: A tool for mapping Canada's north. Geoscience Canada, 35(3–4): 109–126.

Fueg, J. 2010. The airborne geophysical survey of the Greens Creek area. In: Taylor, C.D. & Johnson, C.A. (editors), Geology, geochemistry, and genesis of the Greens Creek massive sulfide deposit, Admiralty Island, Southeastern Alaska. U.S. Geological Survey, Professional Paper 1763, p. 109–121. Reston, USA.

Galvis, J., Huguett, A. & Ruge, P. 1979. Geología de la Amazonia colombiana. Boletín Geológico, 22(3): 3–86.

Gansser, A. 1954. The Guiana Shield (South America): Geological observations. Ecologae Geologicae Helvetiae, 47(1): 77–112.

Geological Survey of Ireland. 2017. Tellus A3 & A4 airborne. Geological Survey of Ireland, geophysical technical report, 89 p.

Gómez, J., Montes, N.E., Nivia, Á. & Diederix, H., compilers. 2015. Geological Map of Colombia 2015. Scale 1:1 000 000. Servicio Geológico Colombiano, 2 sheets. Bogotá. https://doi.org/10.32685/10.143.2015.936

González, C.F. & Pinto, H. 1990. Petrografía del Granito de Parguaza y otras rocas precámbricas en el oriente de Colombia. Geología Colombiana, 17: 107–121.

Graterol, V. 2006. Programa aerogravimétrico y aeromagnético de la Cuenca del Yarí–Caguán, Colombia. Contrato No. 2052332. Agencia Nacional de Hidrocarburos, informe final de interpretación, 50 p. Bogotá.

Graterol, V. 2009. Levantamiento aerogravimétrico y aeromagnético de los sectores norte y oriental de la Cuenca de los Llanos Orientales, Colombia: Contrato n.° 034. Agencia Nacional de Hidrocarburos, informe final de interpretación, 51 p. Bogotá.

Graterol, V. & Vargas, A. 2007. Levantamiento aerogravimétrico y aeromagnético de la Cuenca de los Llanos Orientales, Colombia: Contrato n.° 036–2007. Agencia Nacional de Hidrocarburos, informe final de interpretación, 48 p. Bogotá.

Graterol, V. & Vargas, A. 2010a. Mapa de anomalía de intensidad magnética total (IMT) de la República de Colombia. Scale 1:2 500 000. Agencia Nacional de Hidrocarburos. Bogotá.

Graterol, V. & Vargas, A. 2010b. Mapa de anomalía de intensidad magnética total reducida al polo (IMTRP) de la República de Colombia. Scale 1:2 500 000. Agencia Nacional de Hidrocarburos. Bogotá.

Heithersay, P. & Walshe, J. 1995. Endeavour 26 north: A porphyry copper–gold deposit in the Late Ordovician, Shoshonitic Goonumbla Volcanic Complex, New South Wales, Australia. Economic Geology, 90(6): 1506–1532. http://dx.doi.org/10.2113/gsecongeo.90.6.1506

Hunt, C.P., Moskowitz, B.M. & Banerjee, S.K. 1995. Magnetic properties of rocks and minerals. In: Ahrens, T.J. (editor), Rock physics and phase relations: A handbook of physical constants, AGU reference shelf series 3. American Geophysical Union, p. 189–204. Washington D.C.

Ingeominas. 1988. Memoria explicativa: Mapa geológico de Colombia. Scale 1:1 500 000, p. 1–71. Bogotá.

Ingeominas. 1989. Exploración geológica preliminar de la serranía de Naquén, comisaria del Guainía. Ingeominas, unpublished report, 112 p. Bogotá.

International Atomic Energy Agency. 1991. Airborne gamma ray spectrometer surveying. Technical report series N° 323, 116 p. Vienna, Austria.

International Atomic Energy Agency. 2003. Guidelines for radioelement mapping using gamma ray spectrometry data. Technical report series N° 1363, 179 p. Vienna, Austria.

Jhon, D.A., Ayuso, R.A., Barton, M.D., Blakely, R.J., Bodnar, R.J., Dilles, J.H., Gray, F., Graybeal, F.T., Mars, J.C., McPhee, D.K., Seal, R.R., Taylor, R.D. & Vikre, P.G. 2010. Porphyry copper deposit model. Scientific Investigations Report 2010–5070–B. U.S. Geological Survey, 186 p. Reston, USA.

Julivert, M. 1968. Lexique Stratigraphique Internacional, Amérique Latine. Colombie (première partie), Précambrien, Paléozoïque, Mésozoïque, et intrusions d'âge mésozoïque–tertiaire. Centre National de la Recherche Scientifique 5, fascicule 4 a, 651 p. Paris.

Kronenberg, S. & Reeves, C.V. 2011. Vaupés and Amazonas Basins. In: Cediel, F. (editor), Petroleum geology of Colombia: Geology and hydrocarbon potential, 15. Agencia Nacional de Hidrocarburos and Universidad Eafit, 103 p. Medellín.

López, J.A. & Cramer, T. 2012. Ambiente geológico del Complejo Mitú y perspectivas de ocurrencias minerales de niobio y tantalio en el territorio colombiano. Geología Colombiana, 37: 75–93.

López, J.A., Khurama, S., Bernal, L.E. & Cuéllar, M.A. 2007. El Complejo Mitú: Una nueva perspectiva. XI Congreso Colombiano de Geología. Memoirs CD ROM, p 16. Bucaramanga, Santander.

Martelet, G., Truffert, C., Tourlière, B., Ledru, P. & Perrin, J. 2006. Classifying airborne radiometry data with agglomerative hierarchical clustering: A tool for geological mapping in context of rainforest (French Guiana). International Journal of Applied Earth Observation and Geoinformation, 8(3): 208–223. https://doi.org/10.1016/j.jag.2005.09.003

Minty, B.R.S. 1997. Fundamentals of airborne gamma–ray spectrometry. AGSO Journal of Australian Geology & Geophysics, 17(2): 39–50.

Moyano, I.E., Lara, N.M., Puentes, M.F., Rojas, O.E. & Cárdenas L.P. 2016. Mapa de anomalías geofísicas de Colombia para recursos minerales: Anomalía magnética de campo total (nT); Distribución ternaria de la concentración de K, U y Th; Señal analítica de la anomalía magnética de campo total (nT/m). Scale 1:1 500 000. Servicio Geológico Colombiano, 3 sheets. Bogotá.

Nakamura, A. 2015. Radiometric map of Australia (3rd edition). Scale 1:15 000 000. Geoscience Australia. Canberra.

Nannini, F., Cabral–Neto, I., Silveira, F.V., Cunha, L.M., Oliveira, R.G. & Weska, R.K. 2017. Informe de recursos minerais: Programa geologia do Brasil: Áreas kimberlíticas e diamantíferas do estado do Mato Grosso. Série Pedras Preciosas N° 12. Programa Geologia do Brasil, Companhia de Pesquisa de Recursos Minerais–Serviço Geológico do Brasil, 46 p. Brasilia.

National Oceanic & Atmospheric Administration. 2018. Magnetic Field Calculators. https://www.ngdc.noaa.gov/geomag-web/#igrfwmm (consulted in August 2018).

Oliveira, A.C. 2014a. Carta interpretativa geofísica–geológica folha NA.20–Z–B Caracaraí. Scale 1:250 000. Companhia de Pesquisa de Recursos Minerais–Serviço Geológico do Brasil, 1 sheet. Manaus, Brazil.

Oliveira, V. 2014b. Carta interpretativa geofísica–geológica folha NA.20–X–D Boa Vista. Scale 1:250 000. Companhia de Pesquisa de Recursos Minerais–Serviço Geológico do Brasil, 1 sheet. Manaus, Brazil.

Pinheiro, S.S., Fernandes, P.E.C.A., Pereira, E.R., Vasconcelos, E.G., Pinto, A.C., de Montalvão, R.M.G., Issler, R.S., Dall'Agnol, R., Teixeira, W. & Fernandes, C.A.C. 1976. Geologia. In: Divisão de Publicação. (editor), Projeto RADAMBRASIL. Levantamento de recursos naturais: Folha NA. 19 Pico da Neblina, 11, p. 19–137. Rio de Janeiro.

Priem, H.N.A, Andriessen, P.A.M., Boelrijk, N.A.I.M., De Booder, H., Hebeda, E.H., Huguett, A., Verdumen, E.A.T. & Verschure, R.H. 1982. Geochronology of the Precambrian in the Amazonas region of southeastern Colombia (western Guiana Shield). Geologie en Mijnbouw, 61(3): 229–242.

Ramos, L., Pires, A. & Benfica, C. 2014. Airborne gamma–ray spectrometric and magnetic signatures of Fazenda Nova region, east portion of Arenópolis magmatic arc, Goiás. Revista Brasileira de Geofísica, 32(1): 123–140. https://doi.org/10.22564/rbgf.v32i1.401

Reeves, C. 2005. Aeromagnetic surveys: Principles, practice & interpretation. GEOSOFT, 155 p. Delft, the Netherlands.

Rodríguez, G., Sepúlveda, J., Ramírez, C., Ortiz, F.H., Ramos, K., Bermúdez, J.G. & Sierra, M.I. 2011. Unidades, petrografía y composición química del Complejo Migmatítico de Mitú en los alrededores de Mitú. Boletín de Geología, 33(1): 27–42.

Salem, A., Williams, S., Fairhead, D., Smith, R. & Ravat, D. 2008. Interpretation of magnetic data using tilt–angle derivatives. Geophysics, 73(1): L1–L10. https://doi.org/10.1190/1.2799992

Santos, J.O.S., Hartman, L.A., Gaudette, H.E., Groves, D.I., McNaughton, N.J. & Fletcher, I.R. 2000. A new understanding of the provinces of the Amazon Craton based on integration field mapping and U–Pb and Sm–Nd geochronology. Gondwana Research, 3(4): 453–488. https://doi.org/10.1016/S1342-937X(05)70755-3

Santos, J.O.S., Potter, P.E., Reis, N.J., Hartmann, L.A., Fletcher, I.R. & McNaughton, N.J. 2003. Age, source, and regional stratigraphy of the Roraima Supergroup and Roraima–like outliers in northern South America based on U–Pb geochronology. Geological Society of America Bulletin, 115(3): 331–348. https://doi.org/10.1130/0016-7606(2003)115<0331:ASARSO>2.0.CO;2

Shives, R.B.K., Charbonneau, B.W. & Ford, K.L. 1997. The detection of potassic alteration by gamma–ray spectrometry–recognition of alteration related to mineralization. Geophysics and Geochemistry at the Millenium, Exploration 97, p. 1–17.

Silva, M. 2014. Carta interpretativa geofísica–geológica folha NA.20–Z–C Rio Demini. Scale 1:250 000. Companhia de Pesquisa de Recursos Minerais–Serviço Geológico do Brasil, 1 sheet. Manaus, Brazil.

Tassinari, C.C.G. & Macambira, M.J.B. 1999. Geochronological provinces of the Amazonian Craton. Episodes, 22(3): 174–182.

Tassinari, C.C.G., Cordani, U.G., Nutman, A.P., van Schmus, W.R., Bettencourt, J.S. & Taylor, P.N. 1996. Geochronological systematics on basement rocks from the Río Negro–Juruena province (Amazonian Craton) and tectonic implications. International Geology Review, 38(2): 161–175. https://doi.org/10.1080/00206819709465329

Telford, W.M., Geldart, L.P. & Sheriff, R.E. 1990. Applied geophysics, 2nd edition. Cambridge University Press, 770 p. Cambridge, UK.

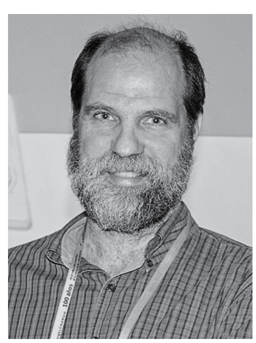
Thery, J.M. 1982. Constitution du Nord–Ouest du continente Sud Américain avant les tectoniques Andines. Doctoral thesis, Université Bourdeaux II, 3 volumes, 221 p. Burdeous, France.

Explanation of Acronyms, Abbreviations, and Symbols:

dz	Vertical derivative
IGRF	International Geomagnetic Reference Field
IOCG	Iron oxide copper–gold
LA–ICP–MS	Laser ablation multi–collector inductively coupled plasma mass spectrometry
MP–Mvlg1	Pedrera and Roraima Formations
MP–Pf1	Parguaza Granite
NaI	Sodium iodide
NP–Pm	Neoproterozoic alkaline gabbros
NP–VCc	Piraparaná Formation
N1–Sc	Miocene sedimentary rocks
O–Sm	Ordovician sedimentary rocks
PP–Mmg1	Migmatitic Complex of Mitú
Q–al	Alluvial and alluvial plains deposits
Q–d	Aeolian deposits
Q–t	Alluvial terraces
RTP	Reduction to magnetic pole
SHRIMP	Sensitive high–resolution ion microprobe
TFA	Total magnetic field anomaly

Authors' Biographical Notes

Ismael Enrique MOYANO–NIETO graduated in geology in 2002, earned a MS in geophysics (2015) and currently is a PhD student at the Universidad Nacional de Colombia. He works as a geologist–geophysicist for the research group in applied geochemistry and geophysics at the Dirección de Recursos Minerales of the Servicio Geológico Colombiano (2009–present).



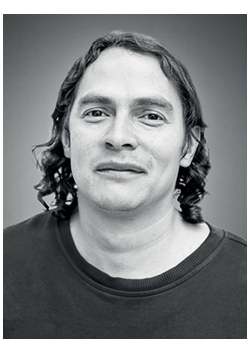
Renato CORDANI graduated in geophysics in 1994 and earned an MS (1997) and a PhD (2008) at the Institute of Astronomy and Geophysics of the Universidade de São Paulo (IAG/USP). Renato has contributed to finding several mineral deposits around the globe and has published several technical papers related to mineral exploration and airborne surveys. He collaborates as a reviewer for the *RBGf* (*Brazilian Jour-*

nal of Geophysics) and *RBG* (*Brazilian Journal of Geology*). Renato is a member of the council of the Brazilian Geophysical Society (SBGf) (2009–present).

Lorena Paola CÁRDENAS–ESPINOSA graduated in physics in 2011 and earned a MS in geophysics at the Universidad Nacional de Colombia. She worked at the Dirección de Recursos Minerales of the Servicio Geológico Colombiano (2013–2018) and teached geophysics at Universidad de Ciencias Aplicadas y Ambientales (environmental engineering) (2016–2018).

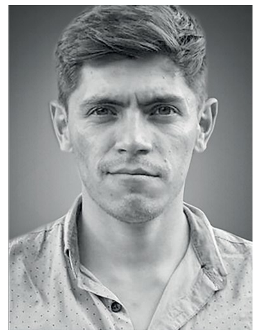
Norma Marcela LARA–MARTÍNEZ graduated in cadastral engineering and geodesy at the Universidad Distrital Francisco José de Caldas (2005) and earned a specialization degree in geomatics at the Universidad Militar Nueva Granada (2018). She has 10 years of experience in geomatics topics and has worked at the Dirección de Recursos Minerales of the Servicio Geológico Colombiano in the area of geophysical exploration since 2013.

Oscar Eduardo ROJAS–SARMIENTO graduated in mining engineering in 2006 from the Universidad Nacional de Colombia (Medellín) and earned an MS in geophysics at the Universidad Nacional de Colombia (Bogotá) in 2012. Oscar has contributed to geophysical exploration for geothermal energy, geological characterization using resistivity methods, and mineral exploration using airborne magnetometry and gamma spectrometry.



Manuel Fernando PUENTES–TORRES graduated in physics from Universidad Distrital Francisco José de Caldas of Bogotá in 2014. Since 2011, he has worked in the Servicio Geológico Colombiano in the Dirección de Recursos Minerales in the field of geophysics for mineral resources. Since 2014, he has contributed to the processing and interpretation of airborne magnetometric and gamma spectrometric data.

Diana Lorena OSPINA–MONTES graduated in geology from Universidad de Caldas (2007) and earned a MS in geophysics at the Universidad Nacional de Colombia (Bogotá). She works in the geophysics section of the Dirección de Recursos Minerales of the Servicio Geológico Colombiano (2017–present).



Andrés Felipe SALAMANCA–SAAVEDRA graduated in geology from the Universidad Nacional de Colombia (2013) and geophysics (MS) from the Universidad Nacional de Colombia, Bogotá. Andrés has worked on seismic processing and signal analysis. He worked on the interpretation and processing of radiometric and magnetometric anomalies at the Dirección de Recursos Minerales of the Servicio Geológico Colombiano until December 2019.

Gloria PRIETO–RINCÓN is the current technical director of the Dirección de Recursos Minerales of the Servicio Geológico Colombiano. She studied chemistry at the Universidad Nacional de Colombia and earned DSc in geochemistry and petrology. She has completed training courses in environmental management, mineral resource processing, and prospecting, exploration and management of mineral resources. She has developed research and directed projects in geochemical characterization, multipurpose geochemical mapping, medical and environmental geochemistry, and mineral prospection and exploration. Gloria has published reports and scientific papers in national and international journals. She is member of the Editorial Committee of the journal *Geochemistry: Exploration, Environment, Analysis* (*GEEA*) and a representative for South America in the IUGS/IAGC Task Group on Global Geochemical Baselines. She is also a member of the Scientific Committee and part of the Governing Council of the UNESCO International Centre on Global–Scale Geochemistry.