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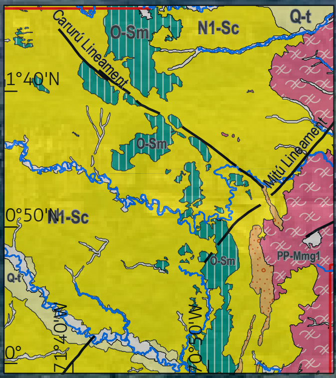

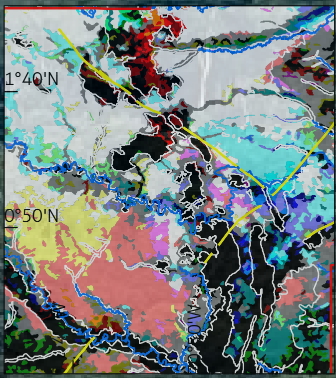

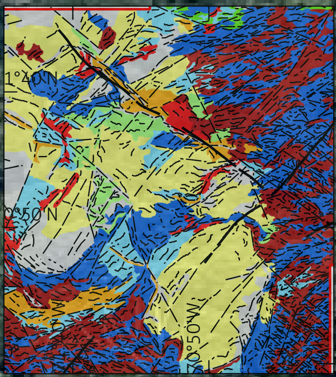

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Foto de cubierta
Serranía de La Lindosa, una formación rocosa que pocos han tenido la posibilidad de conocer, ubicada a unos 100 km al sur oriente de la población de San José del Guaviare, Colombia. Su belleza se realza con cuerpos de agua presentes en las cercanías, un infinito mar verde se puede observar desde su punto más alto, incontable vegetación y miles de aves de diferentes especies, sin olvidar su fauna terrestre que engalanan, aún más, su inmensa belleza.
Fotografía de Andrés Pinzón y Andrés Hernández, pilotos de la aeronave.

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Serranía de La Lindosa, Guaviare, Colombia
Fotografía de Andrés Pinzón y Andrés Hernández

Boletín Geológico

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EDITORIAL

Boletín Geológico publishes the special issue 48 (Spl.1), 2021, on airborne geophysics with the following articles:

Moyano et al. present in this data article the airborne magnetometry and gamma-ray spectrometry datasets that the Servicio Geológico Colombiano has made available. The information was acquired in 15 blocks that cover approximately 520 000 square kilometers of Colombian territory, representing more than 850 000 linear km of information. The data were collected along flight lines separated by 500 m or 1000 m, depending on the area, with sampling rates of 10 Hz (8 m) and 1 Hz (80 m) for the magnetometry and gamma-ray spectrometry data, respectively.

Puentes et al. present a synthesis of the *Map of Geophysical Anomalies of Colombia for mineral resources, MAGC 2020 version*. This map compiles the geophysical information acquired, processed, and interpreted by the Servicio Geológico Colombiano since 2013. This information was collected via airborne platforms (aircrafts) using magnetometry and gamma spectrometry. This version covers approximately 547 960 km^2 of the national territory in the Andean (North and Central), Eastern (Eastern Plains and Amazon) and Caribbean zones (Perijá mountain range).

Lara et al. disclose two case studies about the interpretation of geological features using airborne geophysical information in the Serranía de San Lucas – Antioqueño Batholith and eastern Colombia areas. The variations observed in airborne magnetic and gamma spectrometric data are used mainly to support the differentiation of geological units, to delimitate structures and to define compositional/lithological changes. In this context, the goal of this study is to support geological mapping through airborne magnetometry and gamma spectrometry geophysical data.

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Data article

Magnetic and gamma-ray spectrometric airborne geophysical data for investigating potential mineral resources and generating geoscientific knowledge in Colombia

Datos geofísicos aerotransportados de magnetometría y gama espectrometría para investigación del potencial de recursos minerales y generación de conocimiento geocientífico en Colombia

Ismael **Moyano**[a], Renato **Cordani**[b], Marcela **Lara**[a], Óscar **Rojas**[a], Manuel **Puentes**[a], Diana **Ospina**[a], Hernán **Arias**[a], Ernesto **Gómez**[a], Sergio **Torrado**[a], Adriana **Robayo**[a], Gloria **Prieto**[a]

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Abstract

The Servicio Geológico Colombiano has made available several airborne magnetometry and gamma-ray spectrometry datasets. The information was acquired in 15 blocks that cover approximately 520,000 square kilometers of Colombian territory, representing more than 850,000 linear kilometers of information. The data were collected along flight lines separated by 500 meters or 1000 meters, depending on the area, with sampling rates of 10 Hz (8 meters) and 1 Hz (80 meters) for the magnetometry and gamma-ray spectrometry data, respectively. The information is stored in 30 databases separated for each block and for each of the geophysical methods used. The Servicio Geológico Colombiano has provided a web portal that provides detailed specifications for each database and allows interested parties to see the terms and conditions to access the datasets and to check possible restrictions on access to information. To date, there is no geophysical database in Colombia with the coverage and resolution of these data sets, which will be very useful for geological research and research on potential mineral resources and to support geohazard monitoring, land-use planning and providing a baseline dataset for environmental monitoring.

Keywords: Airborne geophysical data, magnetometry, gamma-ray spectrometry, geological and mineral resource research.

Citation: Moyano, I., Cordani, R., Lara, M., Rojas, O., Puentes, M., Ospina, D., Arias, H., Gómez, E., Torrado, S., Robayo, A., & Prieto, G. (2021). Magnetic and gamma-ray spectrometric airborne geophysical data for investigating potential mineral resources and generating geoscientific knowledge in Colombia. *Boletín Geológico, 48* (Spl.1), 5-11. https://doi.org/10.32685/0120-1425/bol.geol.48.Spl.1.2021.574

Resumen

El Servicio Geológico Colombiano presenta la información geofísica de magnetometría y gamma espectrometría adquirida mediante plataforma aerotransportada. La información fue adquirida en 15 bloques que cubren alrededor de 520 000 kilómetros cuadrados del territorio colombiano, representando más de 850 000 kilómetros lineales de información. Los datos fueron levantados en líneas de vuelo separadas cada 500 metros o 1000 metros, según el área, con una tasa de muestreo de 10 Hz (8 metros) y 1 Hz (80 metros) para magnetometría y gamma espectrometría, respectivamente. La información se encuentra almacenada en 30 bases de datos por cada bloque y por cada uno de los métodos geofísicos utilizados. El Servicio Geológico Colombiano ha dispuesto un portal web que muestra las especificaciones detalladas para cada base de datos y permite a terceros ver los términos y condiciones para acceder a la base de datos y consultar las condiciones y posibles restricciones de acceso a la información. Hasta la fecha no existía en Colombia una base de datos geofísicos con la cobertura y resolución de los presentes datos, que serán de gran utilidad para la investigación geológica, y sobre el potencial de recursos minerales, así como sobre el apoyo en el monitoreo de amenazas de origen geológico y la toma de decisiones sobre planificación y el uso del territorio.

Palabras clave: Datos geofísicos aerotransportados, magnetometría, gamma-ray espectrometría, investigación geológica y en recursos minerales.

1. Description of the data

The data correspond to approximately 850,000 linear kilometers of geophysical information obtained by magnetometry and gamma-ray spectrometry instruments on an airborne platform. The information was acquired by the Servicio Geológico Colombiano (SGC) through several projects executed between 2013 and 2018 that cover an approximate area of 520,000 square kilometers of Colombian territory, distributed in 15 blocks (Figure 1). The data are stored in 30 databases (GDB-Oasis montaj, Seequent), one for each surveyed block and one for each geophysical method used, and the databases contain information pertaining to the flight lines (date of acquisition, coordinates and flight height) and the processed and levelled data corresponding to total-field magnetic anomalies (TFMA), total gamma-ray count and relative concentration of equivalent uranium (eU, measured in ppm), equivalent thorium (eTh, measured in ppm) and potassium (K, measured in %). Information about queries for coverage and instructions for requesting access to the data for a specific area are detailed below.

2. Importance of the data

- The airborne geophysical information related to the Colombian territory has a resolution and regional coverage greater than previously available.
- The availability of digital data allows any researcher with an interest in geophysics to apply their own processing, modeling and interpretation methods.
- The geophysical data will be useful for the regional exploration of potential mineral resources, tectonic studies, regional geological mapping of difficult-to-access areas, land-use planning and management, geohazard research and provide a baseline dataset for environmental monitoring.

3. Access to data

For access to the airborne geophysical data, a link has been provided in the SGC portal (Table 1) which details the requirements, terms and conditions and potential restrictions for access to the data. The SGC will include new databases as new blocks become available.

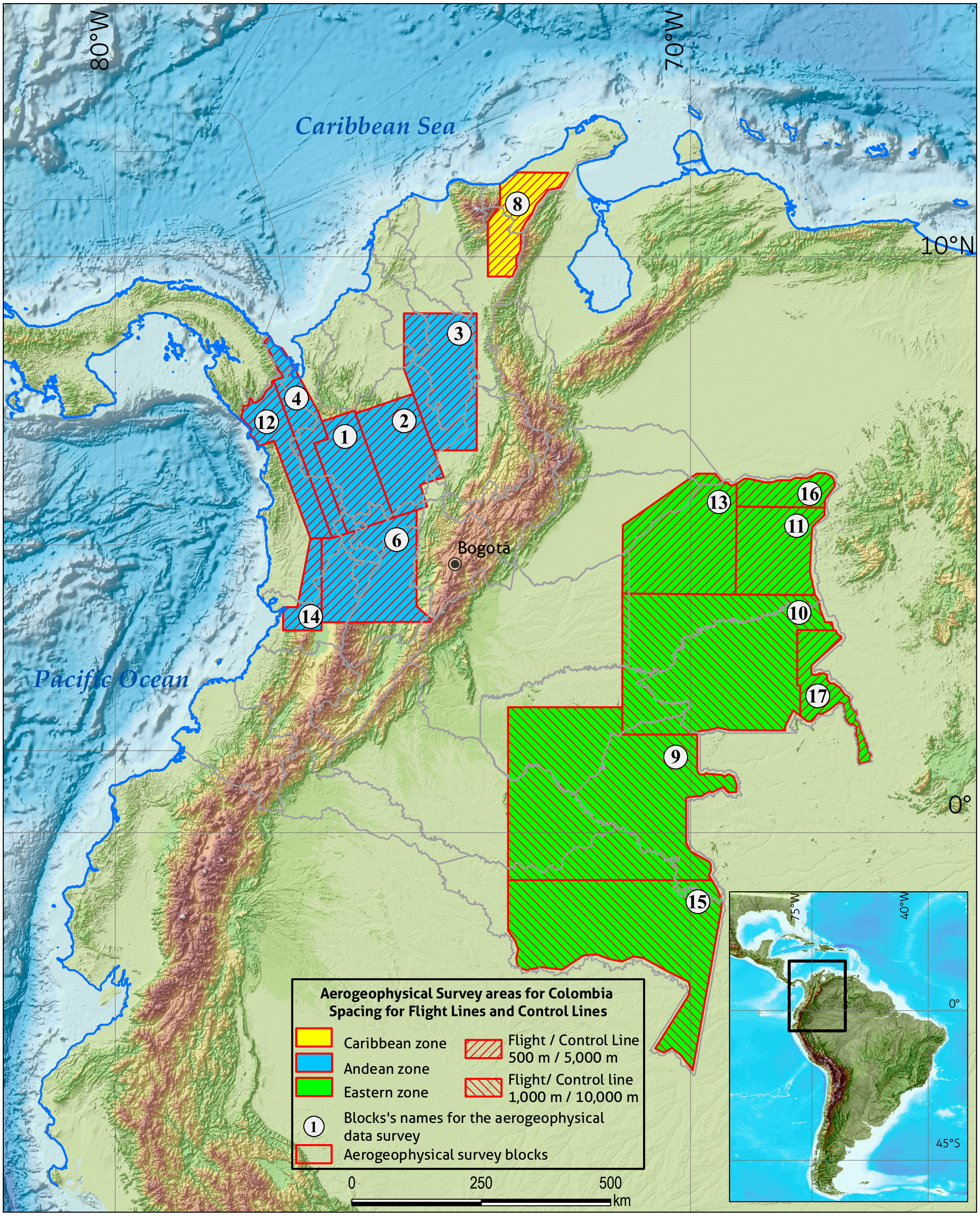

Figure 1. Location of the 15 blocks that contain airborne information
The color of each block corresponds to the geographical region (green: Amazonas-Orinoquía; blue: Andean; yellow: Caribbean), and the hatching details show the distance between the flight lines (NE-SW: 500 m, NW-SE: 1000 m). Block names: Antioquia W (1), Antioquia E (2), Bolívar (3), Urabá (4), Andes N (6), Amazonas N (9), Guainía (10), Vichada (11), Darién (12), Vichada W (13), Buenaventura (14), Amazonas S (15), Vichada N (16), Guainía E (17).

Table 1. Data specifications

Subject	Geophysics
Specific subject area	Geology, mineral resources.
Type of data	Magnetometry and gamma-ray spectrometry data.
How the data were acquired	Survey using an airborne platform.
Data format	The levelled data provided in GDB/XYZ/GRD format (compatible with Seequent Oasis montaj)
Parameters for data collection	The data were acquired in 15 blocks with flight lines separated by 500 m or 1000 m, depending on the area covered. Data sensors were 100 m above the ground (where safety and topography allowed it), and sampled at a rate of 10 Hz for the magnetometry data and 1 Hz for the gamma-ray spectrometry data.
Description of the data collection	The data are stored in a magnetometry geodatabase and a gamma-ray spectrometry geodatabase for each of the 15 blocks surveyed.
Location of the data source	Server at the headquarters of the Servicio Geológico Colombiano, Bogotá, Colombia.
Data accessibility	https://www2.sgc.gov.co/ProgramasDeInvestigacion/DireccionTecnicaRecursosMinerales/Paginas/consulta-informacion-geofisica.aspx
Additional information related to the data sets.	Authors: Moyano, I., Lara, N., Ospina, D., Salamanca, A., Arias, H., Gómez E., Puentes, M., & Rojas, O. (2018). Title: *Mapa de anomalías geofísicas de Colombia para recursos minerales, versión 2018 (Geophysical anomalies map of Colombia for mineral resources, 2018 version).* Metadata link: http://adminmiig.sgc.gov.co/Lists/RecursosSGC/DispForm.aspx?ID=67421 Authors: 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) Title: Interpretation of geophysical anomalies for mineral resource potential evaluation in Colombia: Examples from the northern Andes and Amazonian regions. Journal: *Boletín Geológico*, (46), 5-22. DOI: https://doi.org/10.32685/0120-1425/boletingeo.46.2020.514 Authors: 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). Title: Contribution of new airborne geophysical information to the geological knowledge of eastern Colombia. Book: *The Geology of Colombia* DOI: https://doi.org/10.32685/pub.esp.35.2019.02

4. Materials and methods

Data collection in all blocks was carried out using airborne platforms (fixed-wing aircraft) at a nominal height of 100 meters above the ground, where topographic conditions (particularly in the Andean zone) and operational safety conditions allowed it. Each aircraft was equipped with a high-precision global navigation satellite systems (GNSS) sensor used to navigate and position the aircraft as well as magnetometers and gamma-ray spectrometers configured to record variations in the terrestrial magnetic field and count the radiogenic particles at rates of 10 Hz and 1 Hz, respectively. This configuration ensured a magnetic field sampling density of 8 meters and spectrometric gamma-ray counts every 80 meters along each flight line.

The distance between the flight lines in 12 of the 15 blocks was 500 meters (the blocks with NE-SW hatching on Figure 1). For the remaining three blocks in the Colombian Amazon, the distance between the flight lines was 1000 meters (blocks with NW-SE hatching). The direction of the traverse lines varied depending on the geologic strike, being N 20 W in the Darién, Urabá, Antioquia W and Antioquia E blocks (the blue blocks labelled 1, 2, 4 and 12 in the north-west part of Figure 1) and N-S in the other blocks. For levelling the magnetic data, control lines (tie-lines) perpendicular to the traverse lines were established, with distances of 5000 m (blocks with flight lines every 500 m) and 10,000 m (blocks with flight lines every 1000 m).

Quality control was performed daily during data acquisition to ensure that the data was within the survey specifications (Table 2). Similarly, quality control was performed after final levelling of the magnetic data and conversion of the gamma-ray spectrometry data to maps of the relative concentrations of eU, eTh, and K.

The data in the databases for each block are in the .GDB format of the Oasis montaj software (Seequent). The databases are accessed in montaj and contain the following non-geophysical data: the traverse line number, fiducial (seconds after UTC midnight), date, coordinates (latitude, longitude) and flight height. The geophysical data in the databases include raw (measured magnetic field & energy spectrum for gamma-ray), pre-processed (ex. mag compensated, diurnal, levelled) and final processed data for the magnetometry (TFMA) and for the spectrometry database the total count and relative concentrations of eU (ppm), eTh (ppm) and K (%), after noise reduction by noise–adjusted singular-value decomposition (NASVD).

5. Uses of the data

The magnetic and gamma-ray data can be used for a variety of purposes. The magnetic data, shown in Figure 2a, can be used to identify the strike of geological features, the dips, any brittle structures that might have displaced the geological features, igneous intrusions, and locations where metamorphism or hydrothermal alteration may have created or destroyed mag-

Table 2. Technical specifications of the geophysical equipment used

Onboard magnetometer	
Sensitivity	0.01 nT
Absolute accuracy after compensation	± 10 nT
Dynamic range	20000-100000 nT
Heading effect	< 2.0 nT
Sampling interval	0.1 s (10 Hz)
Noise level (fourth difference)	<± 0.05 nT for more than 10% of readings in each interval of 120 s
Ground magnetometer	
Sensitivity	0.01 nT
Recording interval	< 3 s
Noise level	0.1 nT. The diurnal variation cannot exceed 5 nT in 5 minutes
Gamma-ray spectrometer	
Volume	Minimum of 32 liters (2048 in3) (downward detector)
Channels	256, 512 or 1024
Sampling interval	1 s (1 Hz)

netite (Dentith and Mudge, 2014). Gamma-ray spectrometry data (Figure 2b) can be used to map lithologies, drainage features and alteration, such as potassic alteration (Dentith and Mudge, 2014). The large-scale magnetic features can be used to better understand large-scale tectonic features and to infer the geological history of the area. The lithologies, structures and alteration in the area can be used to assist in looking for mineral deposits, such as the Titiribí, Quebradona, Marmato, Caramanta, La Cabaña-Río Dulce and Murindó porphyry-type deposits and Cerromatoso (Ultramafic lateritic Ni-Fe deposit) deposits (Sepúlveda et al., 2020). These deposits, among others, have clear magnetic expression that can be used as an example to identify new areas for detailed exploration (Moyano et al., 2018).

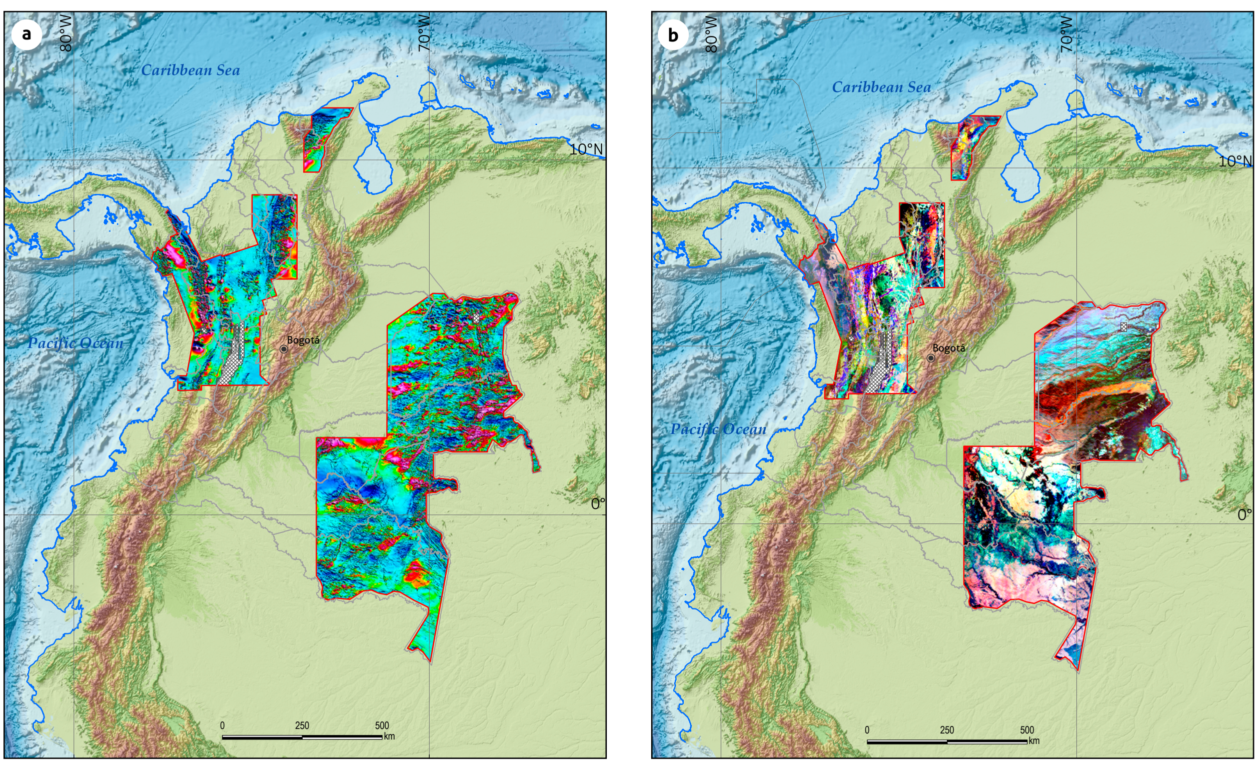

Figure 2. a) Image of TFMA. b) Ternary image distribution of the equivalent concentration of U, Th, and K. ▨: area not covered

The gamma-ray spectrometry data is useful for mapping near surface soils, so this can be used for land-use planning and for providing a baseline dataset to mapping changes to the environment that may result from future development. This type of geophysical data can also be used for mapping geohazards (Chen and Chan, 2002; Boonya and Bhongsuwan, 2013).

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Conflict of interest

The authors declare that they have no competing economic interests or personal relationships that could have influenced the work reported in this document.

References

Boonya, M., & Bhongsuwan, T. (2013, March 21-23). *Application of Airborne Gamma-Ray Spectrometric Data to Study Weathering of Rocks in Songkhla Province*. Siam Physics Congress SPC2013.

Chen, M., & Chan, L. (2002). In-situ gamma-ray spectrometric study of weathered volcanic rocks in Hong Kong. *Earth Surface Processes and Landforms*, *27*(6), 613-625. https://doi.org/10.1002/esp.336

Dentith, M., & Mudge, S. (2014). *Geophysics for the mineral exploration geoscientist*. Cambridge University Press. https://doi.org/10.1017/CBO9781139024358

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). Interpretation of geophysical anomalies for mineral resource potential evaluation in Colombia: Examples from the northern Andes and Amazonian regions. *Boletín Geológico*, (46), 5-22. https://doi.org/10.32685/0120-1425/boletingeo.46.2020.514

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Moyano, I., Lara, N., arias, H., Gómez, E., Ospina, D., Puentes, M., Robayo, A., Rojas, O., & Torrado, S. (2020). *Mapa de anomalías geofísicas de Colombia para recursos minerales: Fuentes magnéticas modeladas a partir de la inversión del vector magnético*. *Escala 1:1'500.000*. Servicio Geológico Colombiano.

Moyano, I., Lara, N., Ospina, D., Salamanca, A., Arias, H., Gómez, E., Puentes, M., & Rojas, O. (2018). *Mapa de anomalías geofísicas de Colombia para recursos minerales, versión 2018, escala 1:1.500.000*. http://adminmiig.sgc.gov.co/Lists/RecursosSGC/DispForm.aspx?ID=67421

Sepúlveda, J., Celada, C. M., Gómez, M., Prieto, D., Murillo, H., Rodríguez, A., Rache, A., Jiménez, C. A., Velásquez, L., Luengas, C., Torres, C., García, D., Prieto, G., Peña, L., Leal-Mejía, H., & Hart, C. (2020). *Mapa metalogénico de Colombia versión 2020. Escala 1:1'500.000*. Servicio Geológico Colombiano. https://srvags.sgc.gov.co/Jsviewer/Mapa_de_Anomalias_Geofisicas_de_Colombia_2020/

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Case study article

Regional integration and 3D modeling of airborne geophysical data: Map of Geophysical Anomalies of Colombia for mineral resources, 2020 version

Integración regional y modelado 3D de datos geofísicos aerotransportados: Mapa de anomalías geofísicas de Colombia para recursos minerales, versión 2020

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Abstract

The *Map of Geophysical Anomalies of Colombia for mineral resources, MAGC 2020 version* compiles the geophysical information acquired, processed and interpreted by the Servicio Geológico Colombiano (SGC) since 2013. This information was collected via airborne platforms (aircrafts) using magnetometry and gamma spectrometry. This version covers approximately 547 960 km^2 of the national territory in the Andean (North and Central), Eastern (Eastern Plains and Amazon) and Caribbean zones (Perijá mountain range). This information consists of 17 blocks of geoscientific interest, covered by flight lines separated by 500 and 1000 m, for a total of more than 907 566 linear km of airborne information, acquired at a nominal altitude of 100 m above the ground, with a sampling resolution that was not previously available at this scale and coverage. This document presents the methodology for compiling, processing and representing the thematic coverage included in MAGC 2020: Map of *Total field magnetic anomaly* (TFMA), *Map of the analytic signal (AS)* and *radiometric ternary map of the distribution of the relative concentrations of uranium, thorium and potassium*. Furthermore, the work identifies 1079 magnetometric anomalies of interest, which were subsequently analyzed and modeled in the *Map of magnetic sources modeled from magnetization vector inversion*, which contains a total of 1297 magnetic bodies interpreted from these anomalies. Integration of available geological and metallogenic information with each of these bodies allow the suggestion of possible geological sources and possible exploration targets. The objectives of this study were

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to generate and integrate geophysical information to identify new areas of interest with regards to potential mineral resources, and to generate new geoscientific knowledge about Colombia for land-use planning.

Keywords: Magnetic anomaly, magnetometry, gamma spectrometry, total-field magnetic anomaly (TFMA), analytic signal (AS), 3D inversion, 3D modeling.

RESUMEN

El *Mapa de anomalías geofísicas de Colombia* para recursos minerales, versión 2020 (MAGC 2020), compila la información geofísica adquirida, procesada e interpretada por el Servicio Geológico Colombiano (SGC) desde el año 2013. Esta información se ha levantado mediante plataformas aerotransportadas (aviones), utilizando magnetometría y gamma espectrometría y, para esta versión, abarca cerca de 547 960 km^2 del territorio nacional, distribuidos en la zona andina (norte y centro), zona oriental (Llanos orientales y Amazonía) y zona caribe (Serranía del Perijá). Esta información representa 17 bloques de interés geocientífico, que fueron cubiertos con líneas de vuelo separadas entre 500 y 1000 m, para un total de más de 907 566 km lineales de información aerotransportada, adquirida a una altura nominal de 100 m sobre el terreno y con una resolución de muestreo que hasta la fecha no estaba disponible a esta escala y cubrimiento. Este documento presenta la metodología de compilación, procesamiento y representación final de las coberturas temáticas incluidas en el MAGC2020: *Mapa de anomalía magnética de campo total* (ACT), *Mapa de señal analítica* (SA) de la ACT y *Mapa radiométrico de distribución ternaria de la concentración relativa de uranio, torio y potasio*. Además, la identificación de 1079 anomalías magnetométricas de interés, cuyo posterior análisis y modelamiento 3D están representados en el Mapa de fuentes magnéticas modeladas a partir de la inversión del vector de magnetización, que contiene un total de 1297 cuerpos magnéticos interpretados a partir de estas anomalías. El objetivo de este trabajo es generar e integrar información geofísica para identificar nuevas áreas de interés con potencial en recursos minerales y generar nuevo conocimiento geocientífico de Colombia que sirva como herramienta para la toma de decisiones en planeación y del ordenamiento territorial colombiano.

Palabras clave: Anomalía magnética, magnetometría, espectrometría gamma, anomalía magnética de campo total (TFMA), señal analítica (AS), inversión 3D, modelado 3D

1. Introduction

Since 2012, the Servicio Geológico Colombiano (SGC) has been advancing the acquisition of geophysical information using magnetometry and gamma spectrometry, with a regional coverage and spatial resolution that were previously not available for Colombia (Moyano et al., 2016). Although prior to this geophysical survey, government entities such as Ecopetrol and the Agencia Nacional de Hidrocarburos (ANH) had conducted airborne geophysical studies, the regional nature and technical parameters of these surveys (altitude, sampling density and resolution) were not detailed enough to detect magnetic anomalies originating from relatively small geological bodies, because as the altitude increases, the magnetic intensity of the latter decreases and is masked by larger regional anomalies. In contrast, the information acquired by the SGC and represented in the *Map of Geophysical Anomalies of Colombia for mineral resources – MAGC 2020 (*Moyano et al., 2020*)* reflects acquisition parameters at a much more detailed scale, allowing us to identify and characterize new deposits of minerals and to complement geological mapping.

The survey of airborne geophysical information is based on the need to expand the geoscientific knowledge of the national territory, generate useful information to identify potential mineral resources, provide basic information for better land-use planning, generate geological cartography and advance geoscientific research. Anomalies in the magnetic field are related to variations in the physical properties (magnetic susceptibility) of the materials which compose the earth's crust, which in turn directly reflect the concentration of magnetic minerals in the rocks that constitute them. From a geological-geophysical perspective, magnetic anomalies can be related to a wide variety of geological sources, such as intrusive bodies, dikes, hydrothermal alteration zones and volcanism.

All the geophysical airborne information collected since the first SGC survey in 2012 was processed and integrated, and then presented as four layers of information, including: 1) the total field magnetic anomaly map, 2) the analytical signal map

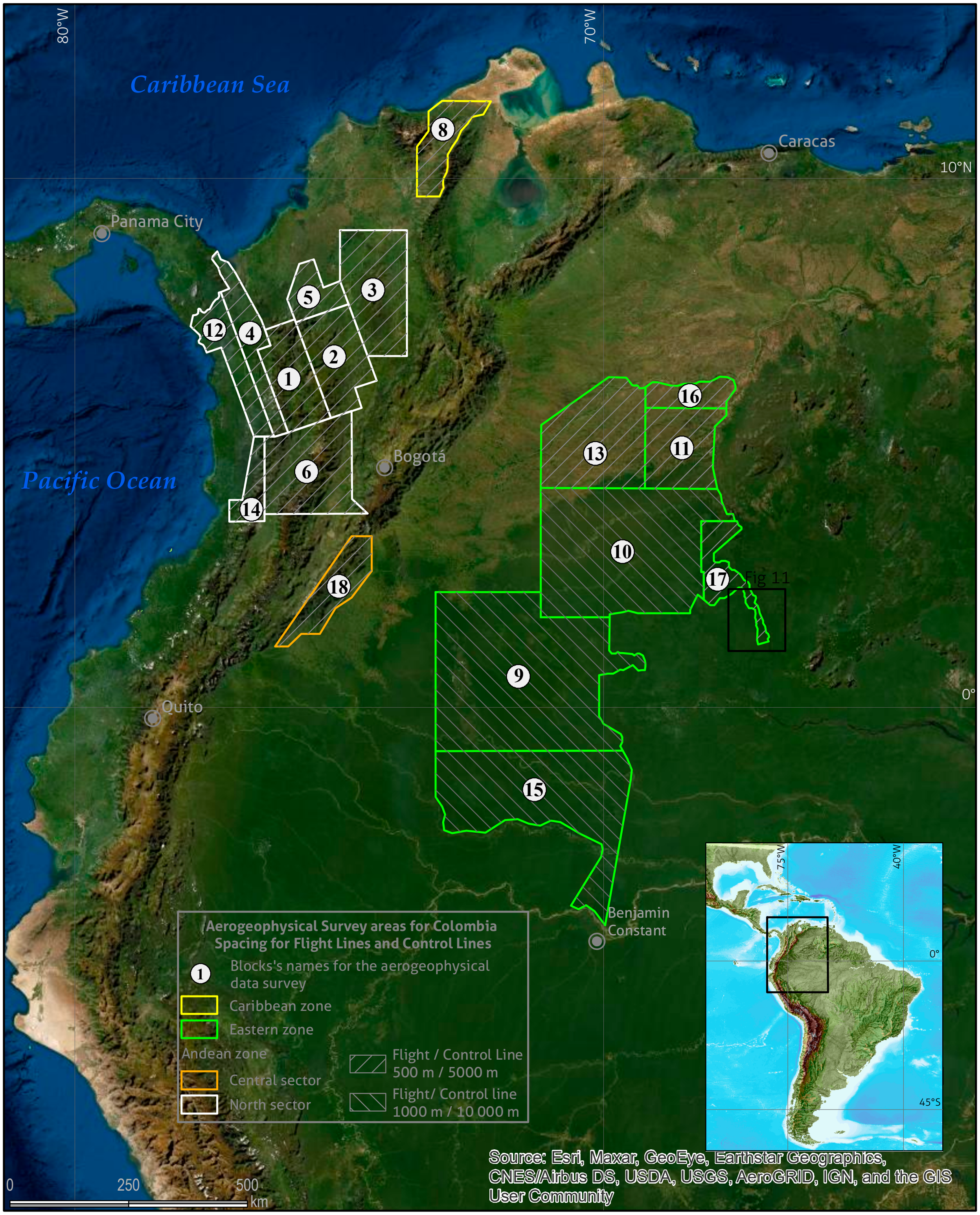

Figure 1. Location of the 17 blocks containing the airborne geophysical information
The color of each block corresponds to the geographical region (green: Amazonas-Orinoquía; blue: North Andean; Orange: Central Andean; Yellow: Caribbean) and the hatching indicates the distance between flight lines (NE-SW: 500 m, NW-SE: 1000 m).

of the total field magnetic anomaly, 3) the ternary radiometric map of the concentration distribution of uranium, thorium and potassium and 4) the map of possible geological sources, based on modeled magnetic sources, 2018 version (Moyano et al., 2018), which includes magnetic sources from the Córdoba and Garzón blocks for the 2020 version. The possible geological sources were identified and interpreted according to their geophysical attributes during modeling and characterized as being in a geological and/or metallogenic environment, information available from the *Metallogenic Map of Colombia 2020* (Sepúlveda et al., 2020) together with the *Geological Map of Colombia 2015* (Gómez et al., 2015).

The four layers generated allowed us to produce the 2020 version of the MAGC (Moyano et al., 2020), featuring magnetometry and gamma ray spectrometry information collected for 17 blocks (Figure 1). This map shows magnetic and gamma ray spectrometric anomalies. One of the blocks (Cesar-Perijá) is located in the Caribbean area, in the departments of Cesar and La Guajira, in the area of influence of the Sierra Nevada de Santa Marta, with heights ranging between 0 and 3000 meters above sea level. Eight blocks (Antioquia-W, Antioquia-E, Bolívar, Urabá, Andes-N, Darién, Córdoba and Buenaventura) are located in the northern part of the Andean zone. One block (Garzón) is located in the central part of the Andean Zone. In general, the Andean region is located in the departments of Antioquia, Bolívar, Boyacá, Caldas, Cesar, Córdoba, Cundinamarca, Chocó, Huila, Risaralda, Santander, Sucre, Tolima and Valle del Cauca, in Central and Western mountain ranges confluence area, with altitudes ranging from 0 to 5200 m. The seven remaining blocks (Amazonas-N, Guainía, Vichada, Vichada-W, Amazonas-S, Vichada-N and Guainía-E) are located in eastern Colombia, in the departments of Amazonas, Arauca, Caquetá, Casanare, Guainía, Guaviare, Meta, Vaupés and Vichada, areas of gentle slopes and heights that range between 50 and 800 meters above sea level.

1.1. Survey Specifications

All the blocks were surveyed via airborne platforms fixed wing aircrafts that flew at a nominal altitude of 100 m above the ground, where topographic (particularly in the Andean zone) and operational safety conditions allowed. Each aircraft was equipped with a high-precision positioning system and magnetic and gamma spectrometry sensors configured to record variations in the earth's magnetic field, and count radiogenic particles at rates of 10 Hz and 1 Hz respectively. The magnitude of the total magnetic field was measured every 7m to 9m, and the intensity of the natural gamma radiation from the ground was measured every 70 to 90 m. The distance between flight lines for 14 of the 17 blocks was 500 m. The remaining three blocks, located in the Colombian Amazon, were overflown with a distance between flight lines of 1000 m, and crossed by perpendicular control lines separated by 5000 or 10 000 m. The direction of the flight lines was N20W in the Córdoba, Darién, Urabá, Antioquia W and Antioquia E blocks, and N-S in the other blocks. To level the magnetic data, control lines perpendicular to the flight lines were established at distances of 5000 (blocks with flight lines every 500 m) or 10 000 m (blocks with flight lines every 1000 m).

The magnetometry data were acquired using cesium vapor magnetometers in the aircraft in a *tail stinger* installation. This type of assembly requires compensating for the aircraft movements during flights. The following are the technical specifications for the magnetometers installed in the aircraft:

- Sensitivity 0.01 nT
- Absolute accuracy ± 10 nT
- Dynamic range 20 000 and 100 000 nT
- Sampling interval 0.1 seconds (10 Hz)
- Heading effect < 2 nT

Diurnal variations in the magnetic field were recorded by a ground base station, with a sampling interval of no more than 3 seconds, synchronized with the magnetometer in the aircraft. The diurnal variations had a maximum tolerance of 3 nT (peak to peak) for a period of one minute for the magnetic base station. Fluctuations above these values and persisting for more than one hour are considered a possible solar storm, meaning flights were cancelled.

Likewise, 2048 cubic inch NaI Tl (sodium iodide crystals treated with thallium) gamma ray spectrometers were used onboard the aircraft to record the full spectrum of gamma rays between 512 and 1024 channels, at a sampling rate of one per second (1Hz). In addition, upward-looking NaI scintillator detectors were used to record the concentration of atmospheric radon. The K, U and Th counts were extracted from the full spectrum during processing according to their energy levels.

In some areas with special topographic or safety characteristics, the aircraft had to be flown at higher altitudes than the nominal flight value. This higher altitude resulted in progressive deterioration and a loss of sensitivity of the gamma spectrometry equipment, which is reflected as noise in the generated data and can lead to erroneous interpretations. For this reason, an analysis of the relative concentrations of the uranium (U), thorium (Th) and potassium (K) channels was performed directly from each block's database. From this analysis, data acquired at an unusual height above the nominal 100 meters showed discordant or even negative values of one or all the radioelements, and can be recognized as along-flight line strips of very high or low counts. These noise measurements were represented independently on the ternary gamma spectrometry map, with a warning regarding the interpretation of these areas.

The airborne magnetometry and gamma ray spectrometry information was compiled, integrated, and processed to generate thematic layers (images) with a spatial resolution of 125 m in the Caribbean and Andean zones and 250 m in the Eastern zone (Amazonas and Orinoquía).

2. Method

This section describes the methodology and processing to generate the thematic layers for the Caribbean, Andean (North and Central) and Eastern zones. Interpolation methods and micro leveling (MIC) techniques were applied to the 17 selected blocks, which were grouped along the Caribbean, Andean (North and Central) and Eastern zones. From this processing, three thematic images were generated: *total-field magnetic anomalies* (TFMA), *analytic signal* (AS) and the Ternary map of the distribution of potassium (K), thorium (Th) and uranium (U) concentrations. Subsequently, the magnetic anomalies were identified using magnetometry data. Therefore, to determine spatial characteristics and magnetic susceptibility, the magnetization Vector Inversion (MVI) algorithm was used to process magnetic field data acquired. From the intensity of the magnetic field data (TFMA) of detected anomalies, the MVI generates a mathematical modeling of a volume of data that represents the variations and the values of magnetic susceptibility in the field. Ideally, the inversion of the magnetic anomaly generated by this magnetic susceptibility model is matched to the geometry by the observed TFMA values, and the analytical signal. Finally, a layer was produced with the selected and modeled anomalies.

2.1. Interpolation method for thematic layers

For the interpolation of the magnetometry and gamma ray spectrometry data, a cell size between ¼ and ⅛ was chosen for the spacing of the flight lines, to avoid information loss and recover all frequencies. An appropriate algorithm that maintains the values of the original points while generating a continuous and smoothed surface must be chosen. The most commonly used interpolation algorithms are bidirectional, minimum curvature, weighted inverse distance and kriging methods (Watson and Philip, 1985; Briggs, 1974) algorithms.

For the interpolation of the magnetometry data, the bidirectional algorithm was used. This method correlates data taken line by line, by applying cubic splines both along and through the flight lines following a defined grid interval. Additionally, a low-pass filter is applied to remove high frequencies that generate artifacts in the information. This interpolation method is suitable for this type of survey, in which the data are distributed in parallel lines, because it interpolates first in one direction and then in the orthogonal directions, thus fitting an unlimited number of data points. This algorithm cannot be used for data with a random distribution.

The weighted inverse distance method was applied to the gamma spectrometry data. The sampling points values were calculated using their weighted average in a defined search radius. The weight assigned to each value is inversely proportional to its distance. The weighting of each value is assigned by a power parameter that modulates the influence of each data value as a function of distance. The higher the power parameter is, the more influence it will have on the closest points. In addition, the method adds a weighted slope factor that moderates the sharpness of the values' weights, preventing said values from leaving their range in the vicinity of their points.

2.2. Micro leveling of the thematic layers

Micro leveling is the elimination of residual errors produced in the regular course of a process such as leveling. These errors are manifested as corrugations along lines that are false artefacts (i.e., non-geological effects), creating distorted images identified as noise, while some data points appear in the same direction as the flight lines. This type of noise was removed from the interpolated grids using directional filters applied to the flight and control lines. The micro-leveling technique developed by Minty (1991) removes the non-geological effects caused by residual and leveling errors without affecting the data frequency spectrum.

2.3. Processing of magnetic images

To process and generate the magnetometric layers, it was necessary to apply frequency range filters in the areas, to com-

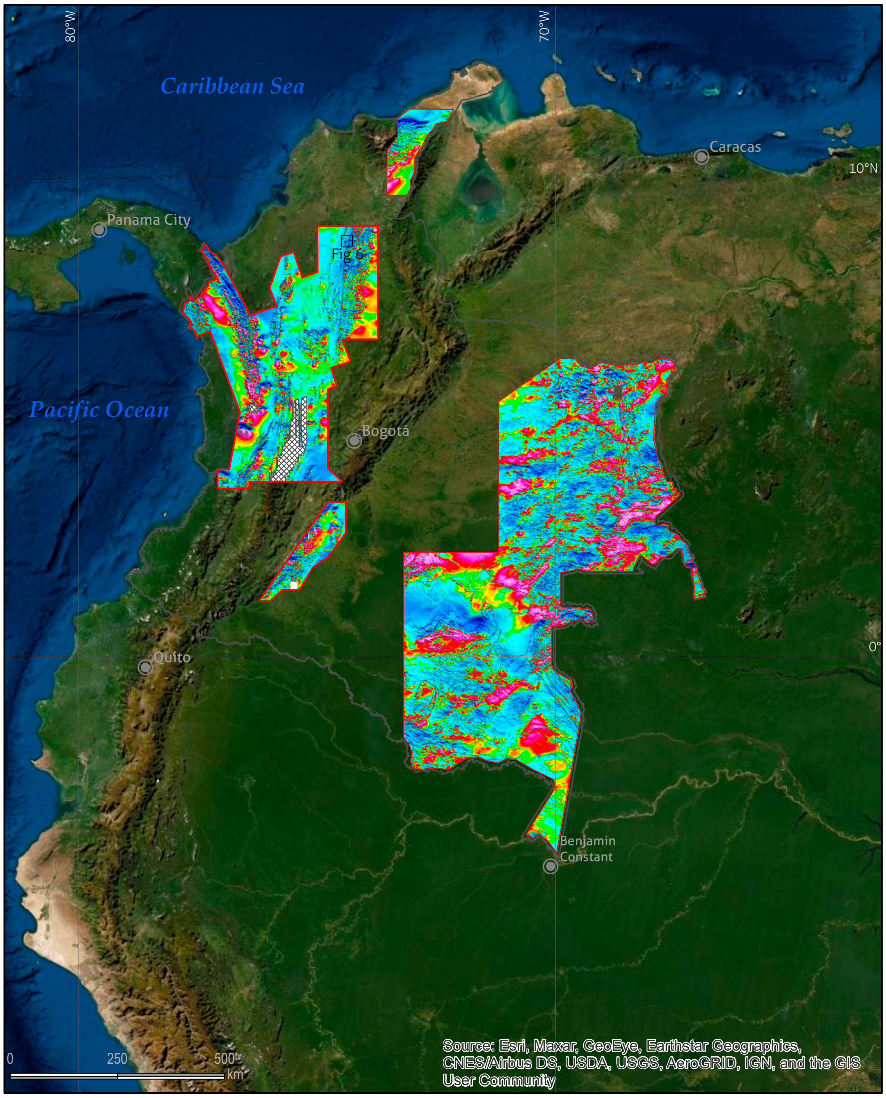

Figure 2. Geophysical anomalies map of Colombia for mineral resources: total-field magnetic anomaly (TFMA)
▨: area not covered.

pensate for noise effects in the leveling and in the combination of some images. The Andean zone (north sector) is the result of combining the images of Antioquia-W, Antioquia-E, Bolívar, Urabá, Andes-N, Darién, Buenaventura and Córdoba. Its processing was more exhaustive, as its leveling was more complex due to the steep topography of the area. For processing, directional and frequency range filters were applied to compensate for the combining of the images. For the Eastern zone, which is composed of the Amazonas-N, Guainía, Vichada, Vichada-W, Amazonas-S, Vichada-N and Guainía-E blocks, the images were combined to generate the TFMA image in this area.

2.3.1. Total-field magnetic anomaly map

The TFMA map (Figure 2) is obtained by removal of temporal variations and geomagnetic field model data (International Geomagnetic Reference Field (IGRF)) (Thébault et al., 2015) from the observed magnetic field. Thus, the TFMA map shows variations in the magnetic field produced by the presence of magnetic sources in the subsurface. However, to generate this image, each zone was processed differently according to the topographic characteristics and the location of the blocks.

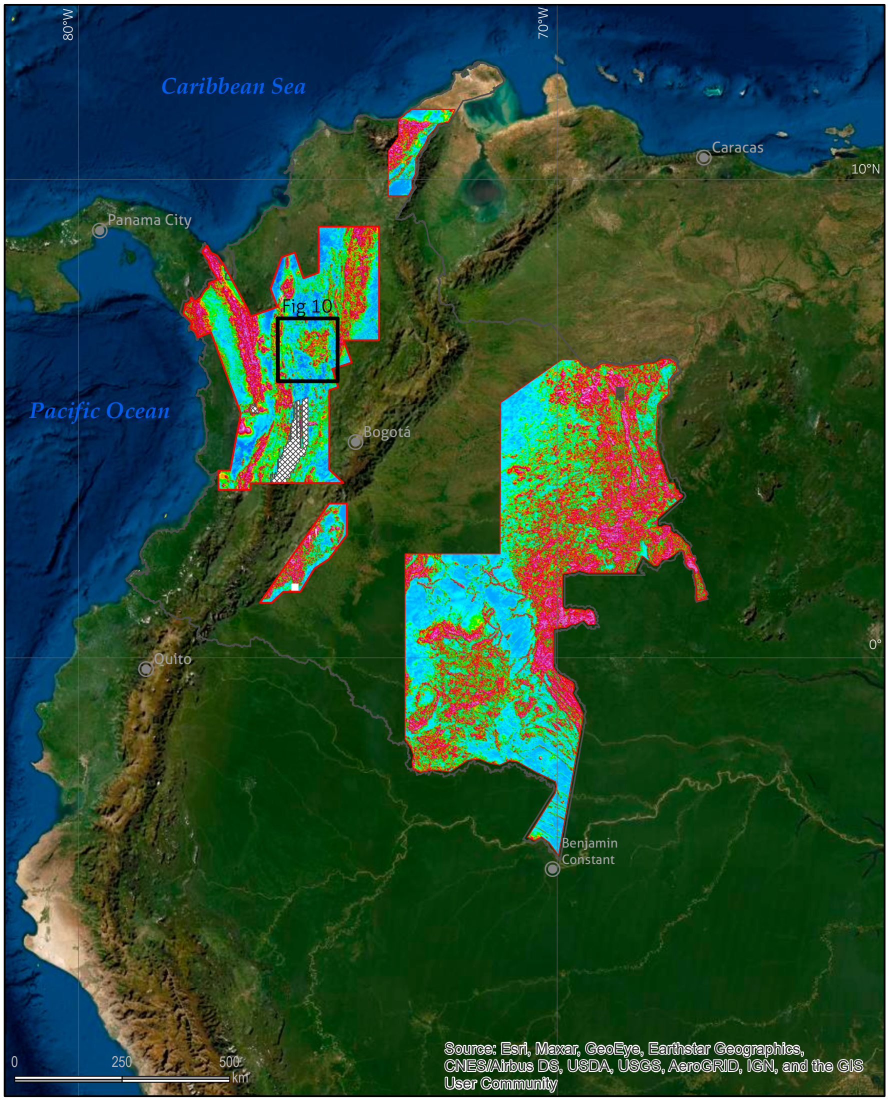

Figure 3. Map of geophysical anomalies of Colombia for mineral resources: analytic signal of the TFMA
▧: area not covered.

2.3.2. TFMA analytic signal

The TFMA analytic signal map (Figure 3) was obtained by applying a mathematical algorithm to the total magnetic field. The variations in the three spatial components in relation to depth were calculated (Roest et al., 1992). This mathematical process was used to highlight the edges of the magnetic sources and to directly locate magnetic anomalies, as this filter is independent of the direction of magnetization.

2.4. Preparation of thematic layers for gamma spectrometry data

To generate this coverage, the weighted inverse distance interpolation method was used for each block's gamma spectrometry data. The images were generated with a spacing of 125 m in the Caribbean and Andean zones (North and Central) and 250 m in the Eastern zone. All the images had a power parameter of 2 and a weighting slope of 1. The gamma spectrometry distribution ternary map shows the composition, in RGB colors, of the relative concentration of the three radioelements potassium (red), thorium (green) and uranium (blue). This composite image was generated from the normalization of the counts of each of these three elements in the gamma ray spectrometry data, generating the modulation of the red, green and blue colors in proportion to the concentration of potassium, uranium and thorium. The ternary image reduces the effects of gamma ray attenuation by vegetation or soil moisture (International Atomic Energy Agency, 2003). These colors are quantitatively related in a color triangle that indicates the composition of each radioelement channel to which it belongs (see Figure 4).

The processing of the images generated in the Caribbean, Andean (North and Central) and Eastern zones used a multiplication factor to level some images and join them. This factor was applied as the aircraft measurement systems for each block had a different calibration, yielding differing gamma ray counts. In some areas, aircraft were unable to maintain the nominal altitude due to abrupt topography, which reduced the

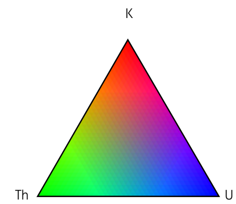

Figure 4. RGB composition of gamma spectrometry data
Red: potassium indicator; green: thorium indicator; blue: uranium indicator. Modified from International Atomic Energy Agency (2003).

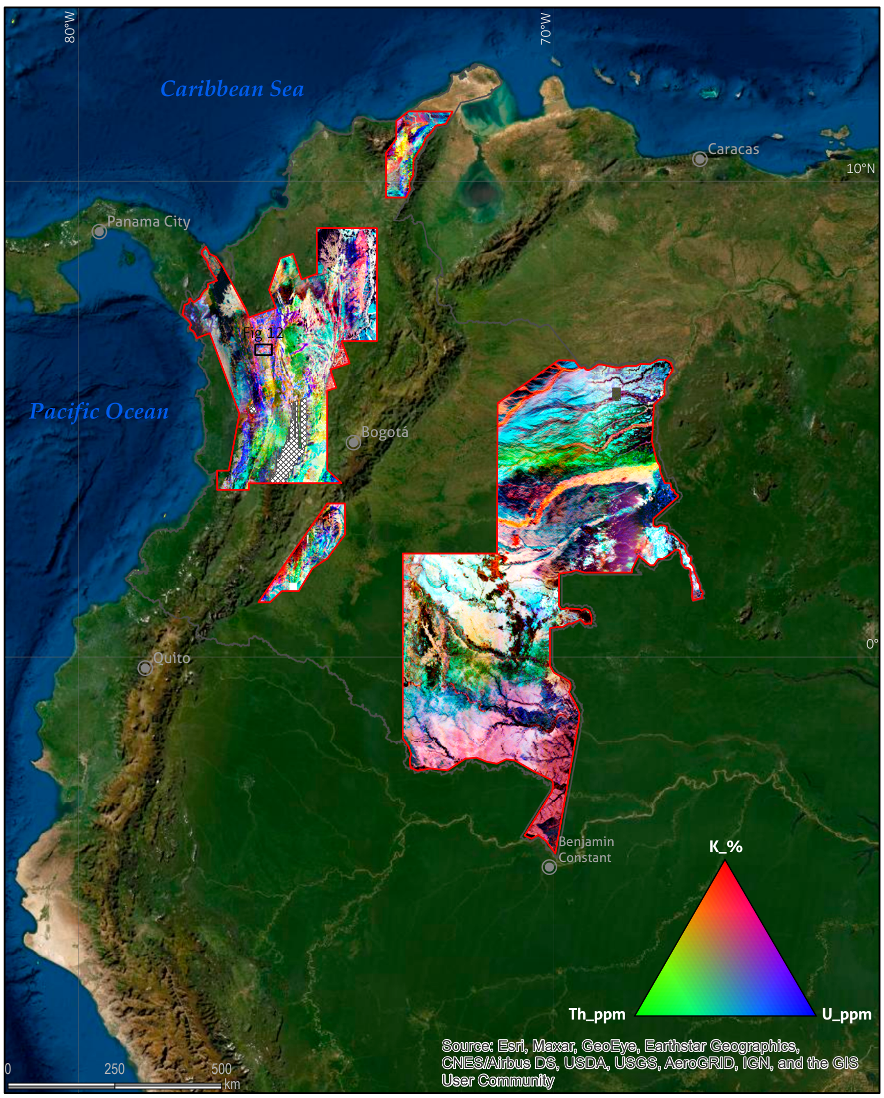

Figure 5. Geophysical anomalies map of Colombia for mineral resources
Ternary map showing the distribution of the potassium (K), thorium (Th) and uranium (U) concentrations.
▨: area not covered.

counts of radioelements potassium (K), thorium (Th), and uranium (U) on the ground. This problem was corrected using deconvolution and height correction techniques to avoid topography effects (Gunn and Almond, 1997). Figure 5 presents the *Ternary map of the distribution of K, Th and U concentrations compiled for Colombia*.

2.5. Selection of magnetic anomalies, 3D modeling and integration of magnetic sources

One of the main objectives of magnetometry information analysis is the identification of areas displaying characteristics associated with the presence of more magnetic bodies than the background. These magnetic anomalies are identified by characteristic attributes in the magnetic information, such as the presence of dipoles in the TFMA map (Figure 6a), areas with magnetic highs in the reduction to pole (RTP) of the TFMA (Baranov, 1957) (Figure 6b) and strong amplitudes of the TFMA analytic signal (Nabighian, 1972) (Figure 6c).

Magnetic anomalies are related to a wide variety of geological sources. Therefore, their geometric and physical parameters must be determined. For this, the magnetization Vector Inversion (MVI) algorithm was used to process acquired magnetic field data affected by remanent magnetization as well as induced magnetization. Remanent magnetization changes the intensity and direction of the total magnetization vector, and thus the magnetic susceptibility. Therefore, remanent magnetization can distort the inversion, if it is assumed that the source is only generated by induced magnetization (Ellis et al., 2012). From the intensity of the magnetic field data (TFMA) for detected anomaly, the MVI generates a mathematical modeling of a volume of data that represents the variations and the values of magnetic susceptibility in the field. Ideally, the inversion of the magnetic anomaly generated by this magnetic susceptibility model is matched to the geometry as observed with TFMA values and the analytical signal.

Finally, the integration of the information on magnetic sources in the blocks of interest was carried out to identify and interpret a possible geological source and exploratory target. For this reason, modeled magnetic sources for each of the 17 blocks were designated following a code consisting of four uppercase alphabetic characters. To identify the geophysical anomalies, a consecutive 3-digit numeric code was used, whilst an alphabetic code (consisting of capital letters, from the letter A to the letter Z) was used for anomalies that required subdividing due to having more than one body. This code is reset for each work block (Table 1). For example: BOLI002, ANTW002A or ANDN002B.

Table 1. Coding of the blocks produced by the airborne geophysical survey

N.° block	Block	Code
1	Antioquia-W	ANTW
2	Antioquia-E	ANTE
3	Bolivar	BOLI
4	Urabá	URAB
6	Andes-N	ANDN
8	Cesar-Perijá	CSPR
9	Amazonas-N	AMZN
10	Guainía	GUAI
11	Vichada	VICH
12	Darien	DARI
13	Vichada-W	VICW
14	Buenaventura	BVNT
15	Amazonas-S	AMZS
16	Vichada-N	VICN
17	Guainía-E	GUAE
18	Garzón	GARZ
19	Córdoba	CORD

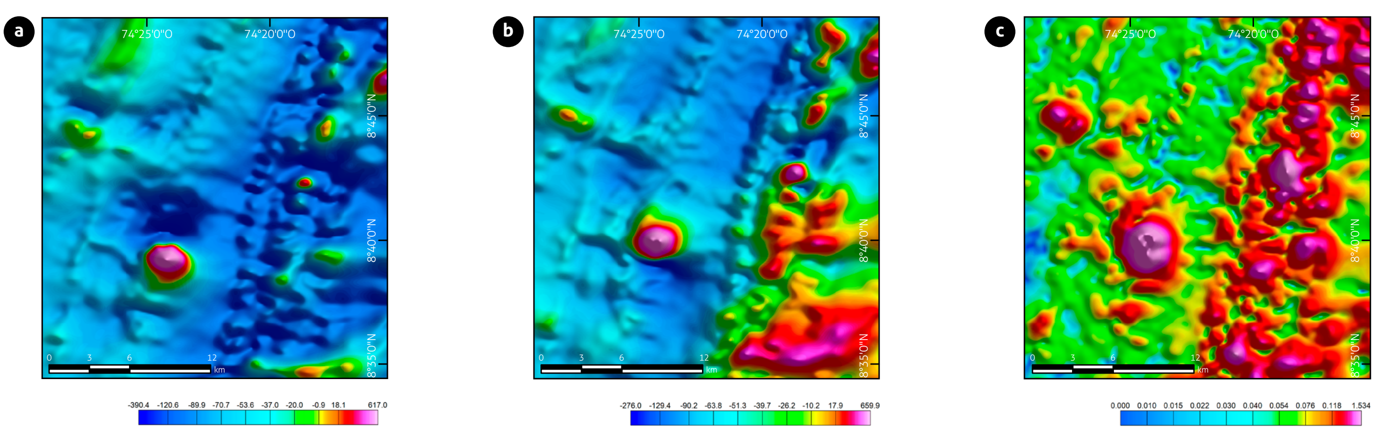

Figure 6. Magnetic source: BOLI022, characterization of the magnetic coverage attributes
a) TFMA; b) RTP; c) AS. See general location in Figure 2

3. Results

3.1. Interpretation of possible geological sources and exploration targets

The resulting compilation of the modeled magnetic sources for each of the 17 blocks is presented in the *Map of magnetic sources modelled by magnetization vector inversion (MVI)* (Moyano et al., 2020). The map presents the magnetic sources identified, characterized by their geophysical attributes during modeling and their geological and/or metallogenic environment (Figure 7). Accordingly, the integration of the magnetic sources for the MAGC 2020 was carried out taking into account the geophysical and geological attributes of the deposits, as per the Metallogenic context provided by the Metallogenic Map of Colombia (MMC), version 2020 (Sepúlveda et al., 2020). Within this context, each anomaly may be correlated with either some identifiable surface geological feature, or with a deep geological source devoid of surface expression (intrusive bodies, dikes, hydrothermal alteration zones, volcanism, faults, among others).

In accordance with the above, the interpretation of a possible geological source for each identified magnetic source refers to the available geological cartography, as per the Geological Map of Colombia (Gómez et al., 2015) for the evaluated area, from which the lithological correlation of the evaluated anomaly is established. As an example of the above, Figure 8 shows the 3D inversion model of the ANTW37B magnetic source, a shallow source associated on the surface with porphyritic basalt, and andesites. Similarly, although the magnetic sources do not have a surface geological expression, the existence of common characteristics to a source with geological correlation allows us to infer a possible similar geological origin. As an example of the above, Figure 9 shows the response in the ACT map and the 3D susceptibility model of the ANTW041 deep magnetic source defined as intrusive.

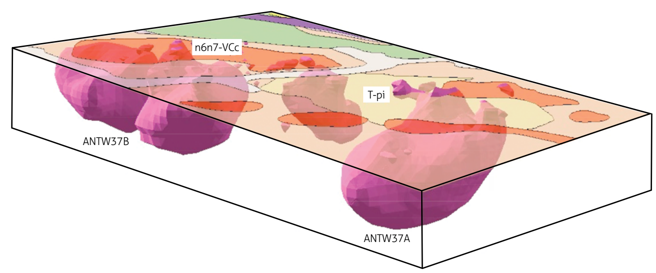

Figure 8. 3D susceptibility model for the magnetic source ANTW37B associated on the surface with the basalts of the Combia Formation (n6n7-VCc)

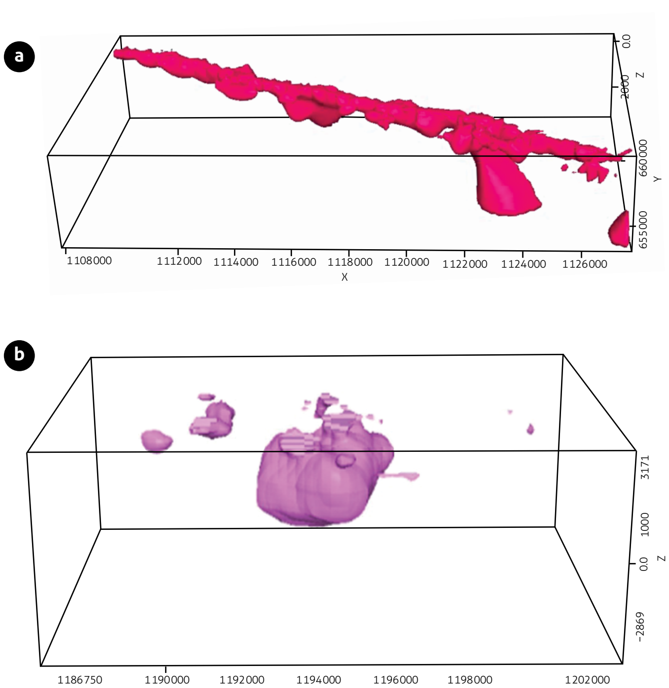

Figure 7. Example of possible geological sources (a) Dike, (b) Intrusive

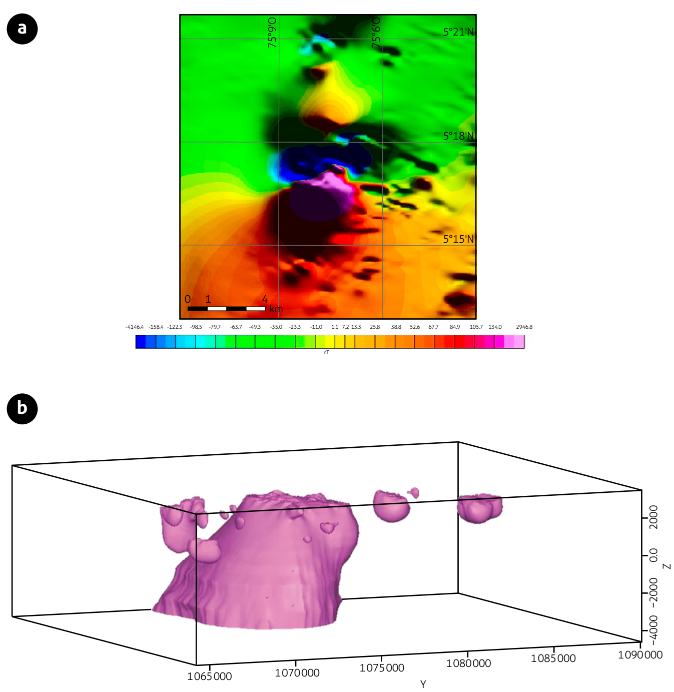

Figure 9. a) Plan view ACT map of the magnetic source ANDN011 b) 3D susceptibility model for the magnetic source ANDN011

Based on the integration of the geological and metallogenic contexts and the response or geophysical signature of each of the magnetic sources modeled**,** five possible geological sources are proposed for the MAGC 2020 (Moyano et al., 2020): dike (faults, veins and structural pattern), Intrusive, lithological, sedimentary and deposit model (DM). Thus, it is possible to advance the hypothesis that magnetic sources with geophysical characteristics and a similar geological-metallogenic context to those identified as DM may offer an exploratory potential similar to that already established based on the current geological knowledge of the existing deposits.

The differentiation of the possible exploration targets was based mainly on the identified deposit models (DM), and also taking into account parameters of the magnetic sources, such as magnetic susceptibility, depth and vertical extension, geometry and other geophysical attributes observed during the geophysical interpretation, together with the information from the MMC 2020 (Sepulveda et al., 2020) and the 2015 version of the Geological Map of Colombia (Gómez et al., 2015).

Seven possible exploratory targets were defined: intrusive, porphyry, mafic and ultramafic rocks (including laterites), carbonatites, kimberlites and placer deposits. Magnetic sources associated with a surface lithological response, and identified as such in the field as a possible geological source, were not considered.

4. Discussion

The maps were generated by processing the airborne geophysical magnetometry and gamma spectrometry data acquired in 17 blocks between 2018 and 2020. Magnetic anomalies were selected based on the TFMA map dipoles, and 3D inversion models of each were created. This process resulted in a distribution of magnetic susceptibilities related with magnetic bodies in deep and shallow zones with induced and remnant magnetization, defined as *magnetic sources*, while at the surface, the radioelement ternary gamma spectrometry data enhanced the lithological contrasts.

The maps obtained from the TFMA (Figure 2) of the different zones show the variation in the magnetic field due to the different geological structures. The magnetic anomalies of the Eastern zone are, for the most part, broader than the anomalies of the Andean and Caribbean zones. This finding indicates a clear differentiation of lithologies between the eastern region and the others.

Similarly, the AS shows the location of the bodies causing the magnetic anomalies (Figure 3), in addition to their plan shape. Therefore, the AS shows the extent of the rock formations and the limits of the heterogeneous geological formations and tectonic characteristics (faults). Thus, the AS of the Andean and Caribbean zones shows marked trends in the orientation of their magnetic structures, as is evident in the Urabá-Antioquia West and Bolívar and Cesar-Perijá blocks, in which tectonic activity is present. In addition, the analytic signal shows important geological structures, such as the Antioquia Batholith, which is located in the Antioquia west and East blocks, as in in Figure 10.

The AS of the eastern zone reveals a varied orientation and broad magnetic structures. The high AS values indicate a high gradient in three spatial components and strong contrasts in the magnetic susceptibility of the crystalline basement rocks. Magnetic structures such as extensive dikes are also observed, as shown in Figure 11.

These modeled sources have an estimated susceptibility ranging from 0.0001 to 0.09 SI and can estimate the shape of the source. According to the MVI models, the minimum magnetic susceptibility values were found mainly in the Amazonas S, Amazonas N, Vichada N and Buenaventura blocks (values lower than 0.0005 SI), while the highest susceptibility values were found in the GUAE, GUAINIA, ANTW and URABÁ blocks (values greater than 0.06 SI).

Let us note that the magnetic susceptibility model obtained by inversion represents only one of the several possible solutions that satisfy the predicted mathematical fit. Therefore, the susceptibility on which the geometric parameters of each magnetic source are estimated presents an uncertainty that can be progressively reduced, as long as there are control parameters over the area of interest, such as geological controls and magnetic susceptibility measurements of the rocks present in the area (petrophysics). With regards to the map of Colombian magnetic sources, the geophysical anomalies were interpreted during the early stages of evaluating the mineral resource potential, and as a guide to identifying those areas in which detailed field work may be carried out. Indeed, this type of control information is not always available, therefore the selected magnetic susceptibility has been estimated via parameters such as the anomaly geometry in layers, e.g., the analytic signal layer.

The possible geological source defined for each of the magnetic sources shows that most of them (82.3%) are of an intrusive type distributed throughout all zones, while 8.3% are

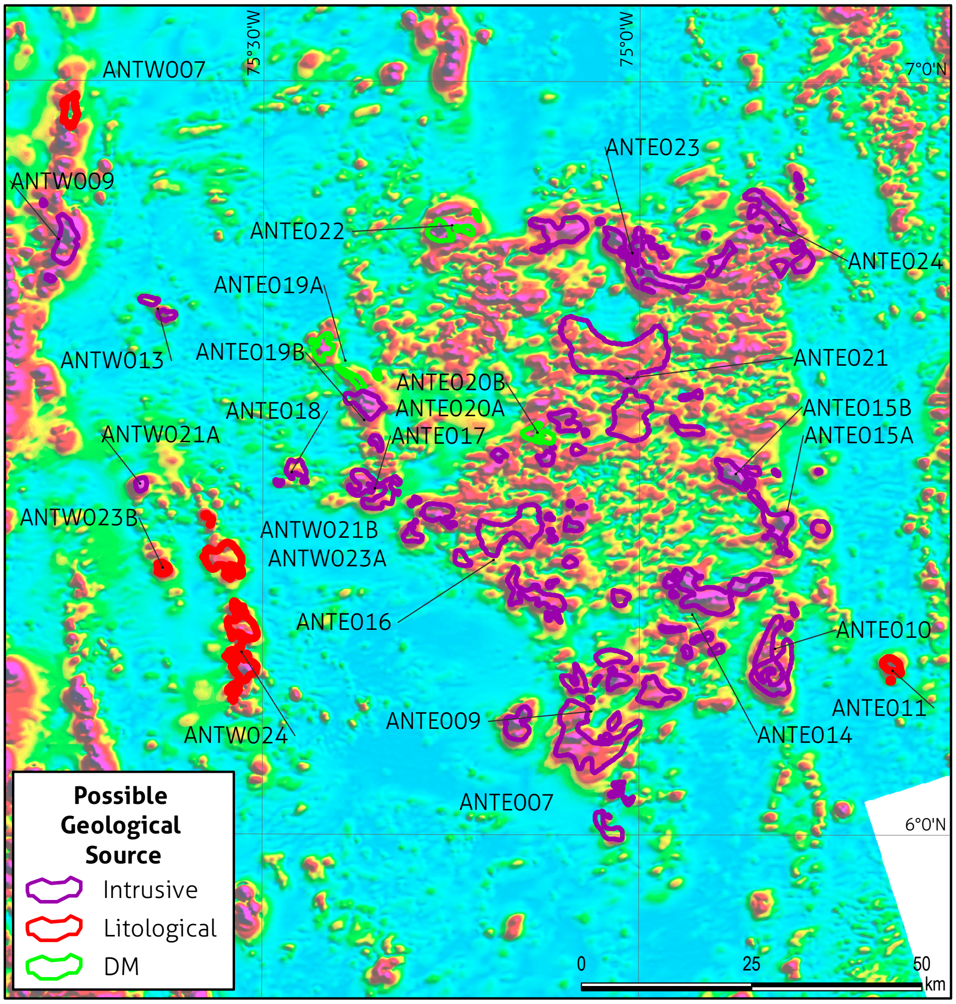

Figure 10. Possible geological sources in Antioquia Batholith
See general location in Figure 3.

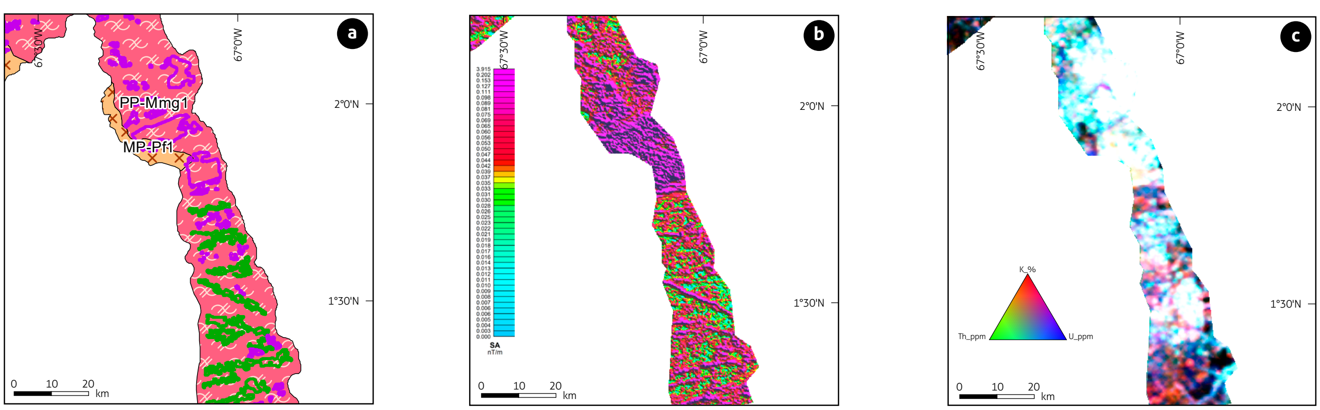

Figure 11. Left: Distribution of possible geological sources, intrusive (purple), and dike (green) of the eastern zone. Right: Analytic signal (AS) with magnetic sources of the eastern zone
a) Distribution of possible geological sources: Intrusive (purple), Dike (green), Chronostratigraphic units: PP-Mmg1: Complejo migmatítico de Mitú; MP-Pf1: Granito tipo Parguaza. b) Analytic signal map (AS) with distribution of possible geological sources: Intrusive (purple), Dike (green); c) Ternary map distribution of the potassium (K), thorium (Th) and uranium (U). See general location in Figure 1.

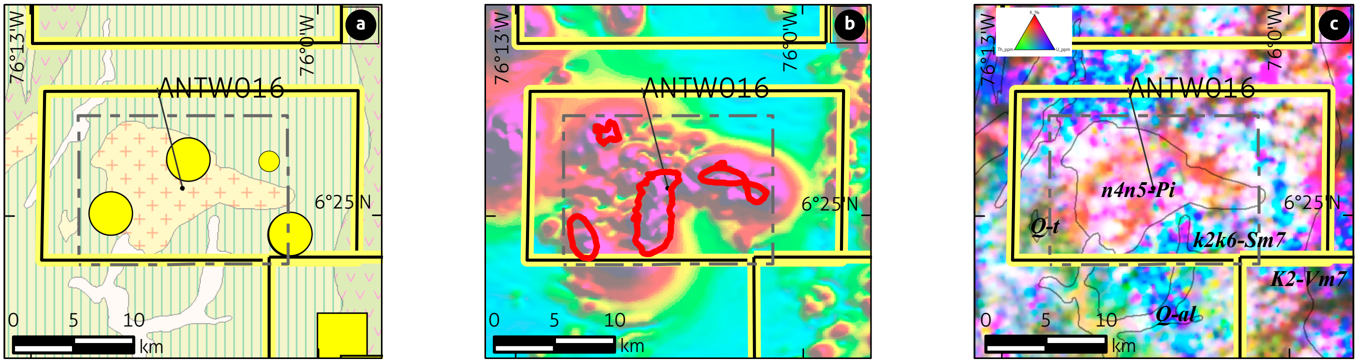

Figure 12. Magnetic source ANTW016 located in Antioquia W block, Páramo de Frontino area, identified as possible lithological geological source, and its distribution concentrations for radiometric elements of surface potassium (K), thorium (Th) and uranium (U)
a) Magnetic source: ANTW016 n4n5-Pi (La Horqueta Monzodiorite). Metallogenic District: Páramo de Frontino. Yellow circles: unclassified gold deposits; b) Analytical signal map (AS) with localization of magnetic source: ANTW016. Metallogenic District: Páramo de Frontino; c) Ternary map of the distribution potassium (K), thorium (Th) and uranium (U) n4n5-Pi La Horqueta Monzodiorite. Metallogenic District: Páramo de Frontino. See general location in Figure 5.

lithological and 1.7% are deposit models (DM). These magnetic sources are located mainly in the Andean and Caribbean zones. Finally, 7.6% are of the dike type and 0.1% of the sedimentary type, and are located mainly in the eastern zone.

Similarly, intrusive exploration targets constitute a higher proportion than other targets (54.6%). The porphyry type and mafic and ultramafic rocks comprise respectively 12% and 25.4% of the targets, and are associated with possible targets for kimberlites, carbonatites and veins, while the remaining 8% comprises the possible exploration targets of the placer, veins and lithologic types.

In addition, gamma spectrometry information shows different combinations of radiometric element concentrations for surface potassium (K), thorium (Th) and uranium (U). The gamma spectrometry RGB composite ternary map reflects the chemical composition of rocks and soil and may indicate lateral changes in said composition (Figure 5). These changes can be related to different lithologies (igneous, metamorphic and sedimentary), which reflect the regional tectonic processes and events that occurred in the area under consideration. Similarly, the ternary map may help to identify areas that have experienced alterations owing to the action of fluids during mineral accumulation processes. These alterations may be related to areas of high or low concentrations of radioelements, identified as light or dark areas in the ternary map, respectively. An example of the above is the magnetic source ANTW016 located in Antioquia W block, sector Páramo de Frontino shown in Figure 12. Additionally, areas enriched with potassium as a result of hydrothermal alteration are identified by red tones in this same map.

The gamma spectrometry data of the Eastern zone can be correlated with the lithological units already described and mapped, or with unidentified geological units. However, the limits between contrasts may not correspond to contacts between different lithostratigraphic units, but to variations or alterations within the same geological unit. It should be noted that gamma spectrometry data are sometimes of low resolution as a result of flight altitude issues owing to the steep topography of the Andean and Caribbean zones.

5. Conclusions

Magnetometry and gamma spectrometry data processing techniques were effective in producing geophysical coverage maps that can provide new geological information and detect the potential existence of mineral resources. These techniques are also a valuable tool for land-use planning related to the national territory.

The acquisition and processing of magnetometry data in 17 airborne geophysical blocks enabled the identification and modelling of 1297 magnetic sources associated with bodies with induced magnetization and magnetization perpendicular to the magnetic field. Based on the magnetic sources, potential mineral deposit sites were identified, either covered or outcropping, based on their distribution, depth, size, shape, and modeled magnetic susceptibility.

From the gamma spectrometry data, a ternary map showing the distribution of potassium (K), thorium (Th) and uranium was generated. This map can be used to identify new outcropping geological units according to the concentrations of these radioelements, and to generate and interpret new information, such as lithogeophysical maps. To do so, it is necessary to integrate this information with geological data to complement the geological mapping information of the country.

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References

Baranov, V. (1957). A New Method for Interpretation of Aeromagnetic Maps: Pseudo-Gravimetric Anomalies. *Geophysics, 22*(2), 359-383. https://doi.org/10.1190/1.1438369

Briggs, I. C. (1974). Machine contouring using minimum curvature. *Geophysics*, *39*(1), 39-48. https://doi.org/10.1190/1.1440410

Ellis, R., Wet, B., & Macleod, I. (2012). Inversion of Magnetic Data from Remanent and Induced Sources. *ASEG Extended Abstracts, 2012*(1). https://doi.org/10.1071/ASEG2012ab117

Gómez, J., Montes, N. E., Nivia, A., & Diederix, H. (2015). *Mapa geológico de Colombia 2015, Escala 1:1 000 000*. Servicio Geológico Colombiano.

Gunn, P. J., & Almond, R. (1997). A method for calculating equivalent layers corresponding to large aeromagnetic and radiometric grids. *Exploration Geophysics, 28*(1-2), 72-79. https://doi.org/10.1071/EG997072

International Atomic Energy Agency. (2003). *Guidelines for radioelement mapping using gamma ray spectrometry data*.

Minty, B. R. S. (1991). Simple micro-levelling for aeromagnetic data. *Exploration Geophysics*, *22*(4), 591-592. https://doi.org/10.1071/EG991591

Moyano, I., Lara, N., Arias, H., Gómez, E., Ospina, D., Puentes, M., Robayo, A., Rojas, O., & Torrado, S. (2020). *Mapa de anomalías geofísicas de Colombia para recursos minerales. Escala 1:1 500 000*. Servicio Geológico Colombiano.

Moyano, I., Lara, N., Puentes, M., Rojas, O., & Cardenas, L. (2016). *Mapa de anomalías geofísicas de Colombia para Recursos Minerales, versión 2016. Escala 1:1 500 000.* Servicio Geológico Colombiano.

Moyano, I., Lara, N., Ospina, D., Salamanca, A., Arias, H., Gómez E., Puentes, M., & Rojas, O. (2018). *Mapa de anomalías Geofísicas de Colombia para Recursos Minerales, Versión 2018. Escala 1:1 500 000*. Servicio Geológico Colombiano.

Nabighian, M. N. (1972). The analytic signal of two-dimensional magnetic bodies with polygonal cross-sections: it´s properties and use for automated anomaly interpretation. *Geophysics*, *37*(3), 5074-517. https://doi.org/10.1190/1.1440276

Roest, W. R., Verhoef, J., & Pilkington, M. (1992). Magnetic interpretation using 3-D Analytic Signal. *Geophysics*, *57*(1), 116-125. https://doi.org/10.1190/1.1443174

Sepúlveda, J., Celada, C. M., Gómez, M., Prieto, D., Murillo, H., Rodríguez, A., Rache, A., Jiménez, C. A., Velásquez, L., Luengas, C., Torres, C., García, D., Prieto, G., Peña, L., Leal-Mejía, H., & Hart, C. (2018). *Mapa metalogénico de Colombia versión 2020. Escala 1:1 500 000*. Servicio Geológico Colombiano.

Thébault, E. et al. (2015). International Geomagnetic Reference Field: the 12th generation. *Earth, Planets and Space*, *67*, 79. https://doi.org/10.1186/s40623-015-0228-9

Watson, D., & Philip, G. M. (1985). A Refinement of Inverse Distance Weighted Interpolation. *Geoprocessing*, *2*(4), 315-327.

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Case study article

Integration of geophysical information with geological cartography for mineral resources research and other applications in Colombia: examples from the Serranía de San Lucas, Antioquia Batholith and eastern Amazonia

Integración de información geofísica con cartografía geológica para investigación en recursos minerales y otras aplicaciones en Colombia: ejemplos en la serranía de San Lucas, Batolito Antioqueño y el oriente de Amazonía

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Abstract

Airborne geophysical information is used in the interpretation of geological features. The variations observed in airborne magnetic and gamma spectrometric data are used mainly to support the differentiation of geological units, to delimitate structures and to define compositional/lithological changes. In this context, the objective of this study is to support geological mapping through airborne magnetometry and gamma spectrometry geophysical data. Examples from two regions of the Colombian territory: a) the Serranía de San Lucas-Antioqueño Batholith and b) eastern Colombia are presented. Gamma spectrometric data are used to generate images of the K, U and Th channels in a ternary (RGB false color) map for the purpose of delimitate geological-geophysical domains. The magnetometry information was processed to highlight anomalous magnetic features and provide information about the structural framework of each of the areas of interest.

In the Serranía de San Lucas and Antioquia Batholith areas, 27 gamma spectrometric domains were interpreted primarily from the ternary composition images. Within these domains, a good correlation with each of the chronostratigraphic units was obser-

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ved, which enabled the identification and delimitation of areas with high or low concentrations of radioelements. In addition, the correlation of magnetic domains with high and low magnetic intensities and textures showed contrasts between igneous rocks, metamorphic rocks and sedimentary rocks. In the eastern zone, due to its fairly generalized geology, the geophysical information gained from both gamma spectrometry and magnetometry serves as a support to refine and delimitate the present geological units as well as their structural framework.

Keywords: airborne geophysics, gamma spectrometric data, magnetic data, chronostratigraphic units, ternary composition.

Resumen

La información geofísica aerotransportada es una herramienta para la interpretación de características geológicas. Las variaciones que se observan en los datos magnéticos y gamma espectrométricos aerotransportados son utilizados, principalmente, como apoyo para diferenciar unidades geológicas, delimitar estructuras y limitar cambios composicionales. En este contexto, el objetivo de este estudio es dar soporte al mapeo geológico a partir de los datos de geofísica aerotransportada de magnetometría y gamma espectrometría en dos regiones del territorio colombiano: a) serranía de San Lucas-Batolito Antioqueño, y b) oriente colombiano. El procesamiento de los datos gamma espectrométricos consiste en generar imágenes de los canales de K, U y Th, además de una composición ternaria en falso color RGB de estos tres canales, con la finalidad de delimitar dominios geológicos-geofísicos. De otro lado, la información de magnetometría se procesa para resaltar características magnéticas anómalas y proveer información acerca del marco estructural de cada una de las áreas de interés.

En la zona comprendida en la serranía de San Lucas-Batolito Antioqueño se delimitaron 27 dominios gamma espectrométricos, interpretados especialmente a partir de las imágenes de composición ternaria; en ellos se observa una buena correlación con la composición de cada una de las unidades litoestratigráficas, lo que permite identificar y delimitar zonas con altas o bajas concentraciones de radioelementos. Además, la correlación de dominios magnéticos con altas y bajas intensidades y texturas magnéticas muestra contrastes entre rocas ígneas, rocas metamórficas y rocas sedimentarias. Por su parte, en la zona oriental, por tener una geología bastante generalizada, la información geofísica, tanto de gamma espectrometría como de magnetometría, sirve de apoyo para depurar y delimitar con mayor exactitud temática las unidades geológicas presentes, así como su marco estructural.

Palabras clave: geofísica aerotransportada, datos gamma espectrométricos, datos magnéticos, unidades cronoestratigráficas, composición ternaria.

1. Introduction

Currently, high-resolution airborne geophysical data are available and also it is possible to process and interpret large amounts of data, which has increased the volume of geological information supported by geophysical information (Isles and Rankin, 2013). This results in maps and products that allow to establish the continuity and to defining with greater precision the boundaries between geological units when considering the interpretation of geophysical features.

Different types of data are used to produce geological maps. Some data are obtained during geological data collection campaigns in the field, while others consist of geochemical data, aerial photographs and satellite images. The integration of geological and geophysical data helps to improve the visualization of geological and structural features, from which structures and lineaments are identified, in addition to serving as support data for the delimitation of rocks.

Since 2012, the Servicio Geológico Colombiano (SGC) has advanced airborne surveys for the collection of geophysical data in areas of interest in the Colombian territory through magnetometry and gamma spectrometry; as a result, large regional coverage with high spatial resolution data was achieved (Moyano et al., 2020). Until 2020, the information obtained in these surveys was compiled in seventeen blocks that cover approximately 520 000 square kilometers of Colombian territory, distributed in the Caribbean, Andean, Amazonian and Orinoquia areas (Figure 1).

For the present work, two study areas were selected for the integration of geophysical information with the available geological cartography, these areas are: the Serranía de San Lucas-Antioquia Batholith and the eastern Colombian zone.

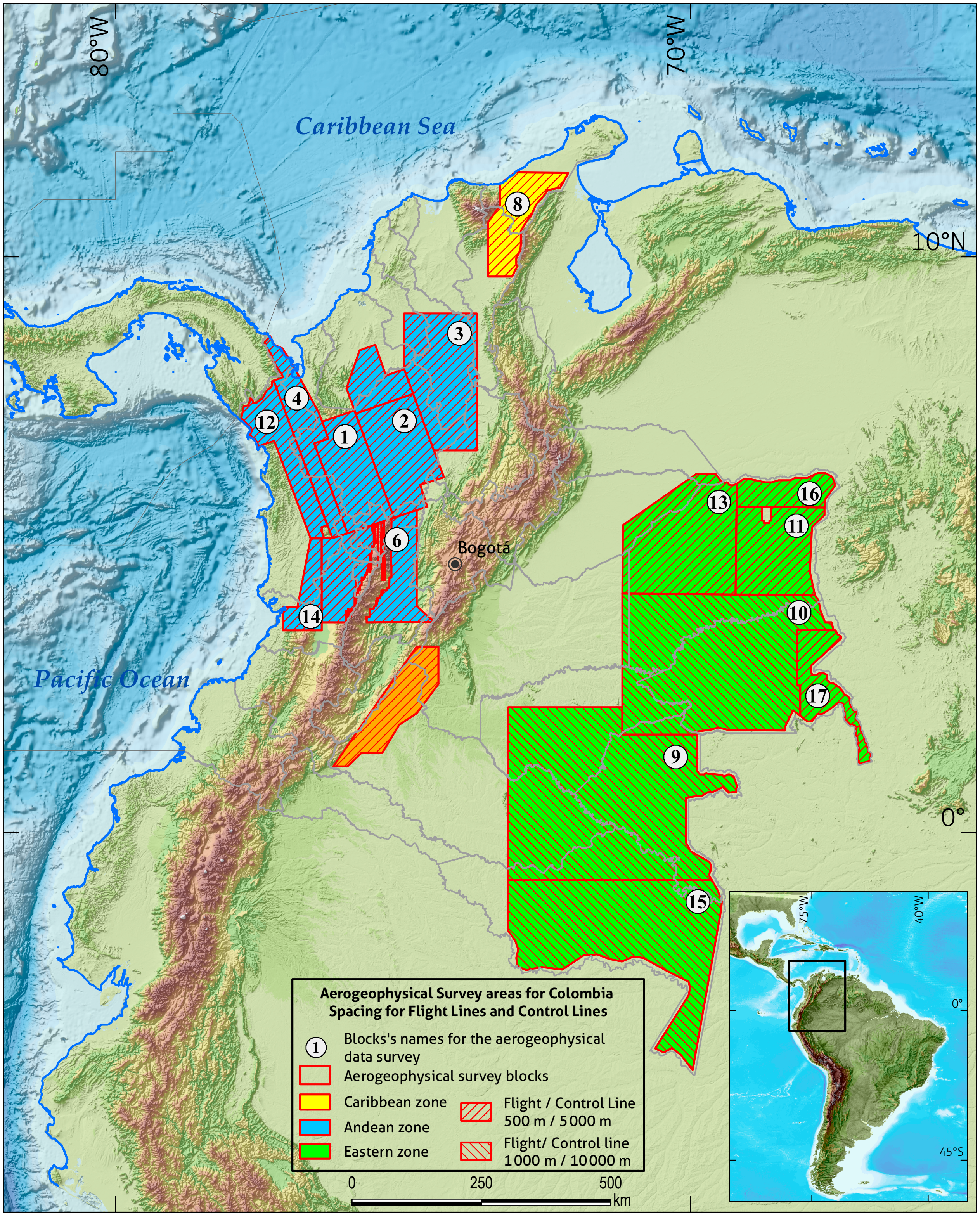

Figure 1. Ariborne geophysical blocks of Colombia, 2020
1. Antioquia_W, 2. Antioquia_E, 3. Bolívar, 4. Urabá, 6. Andes_N, 8. Cesar-Perijá, 9. Amazonas_N, 10. Guanía, 11. Vichada, 12. Darién, 13. Vichada_W, 14. Buenaventura, 15. Amazonas_S, 16. Vichada_N, 17. Guainía_E, 18. Garzón, 19. Códoba.

The magnetometry data were processed qualitatively and semiquantitatively by the application of supervised classification methodologies for the delimitation and characterization of geophysical features domains. Magnetic structures were characterized through techniques for the automatic detection of lineaments, and gamma spectrometric domains were generated with radiometric information and multivariate spatial analysis. The layers of information obtained were integrated with the available regional geological cartographic data (Gómez et al., 2015) for the purpose of obtaining information to identify areas with the potential existence of mineral resources and other applications, such as the validation and complementation of geological cartography.

2. Geological framework

2.1. Area 1. Serranía de San Lucas-Antioquia Batholith

The area of the Serranía de San Lucas-Antioquia Batholith is located in the northwest of Colombia, in the departments of Antioquia, Bolívar, Boyacá, Caldas, Cesar, Córdoba, Magdalena and Sucre. The region is in the confluence zone of the Central and Western mountain ranges, and has heights that vary between 0 m.a.s.l. and 3700 m.a.s.l. The area is dominated by two topographically abrupt regions: in the central northern part, by the Serranía de San Lucas mountain range, and toward the southwestern part, in the Antioquia area, by the Central Cordillera. The study area is framed by the Cauca River to the west and Magdalena River to the east (Figure 2).

2.2. Area 2. Eastern Colombia

The area of eastern Colombia is located in the eastern part of the country and includes the departments of Amazonas, Arauca, Caquetá, Casanare, Guainía, Guaviare, Meta, Vaupés and Vichada. The area includes the Guiana Shield, with heights varying between 0 m.a.s.l. and 900 m.a.s.l. The area is characterized by a flat topography, to the north dominated by the savannas of the Llanos Orientales; in the central area present the hills of Mapiripana, El Tigre and Caño Minas, and the Serranía de Naquén; and for the Amazon area, the mountains of Chiribiquete, Araracuara and La Trampa. The study area is framed by large bodies of water, such as the Meta, Orinoco, Guaviare, Vichada, Inírida, Vaupés, Apaporis, Caquetá and Putumayo rivers (Figure 3).

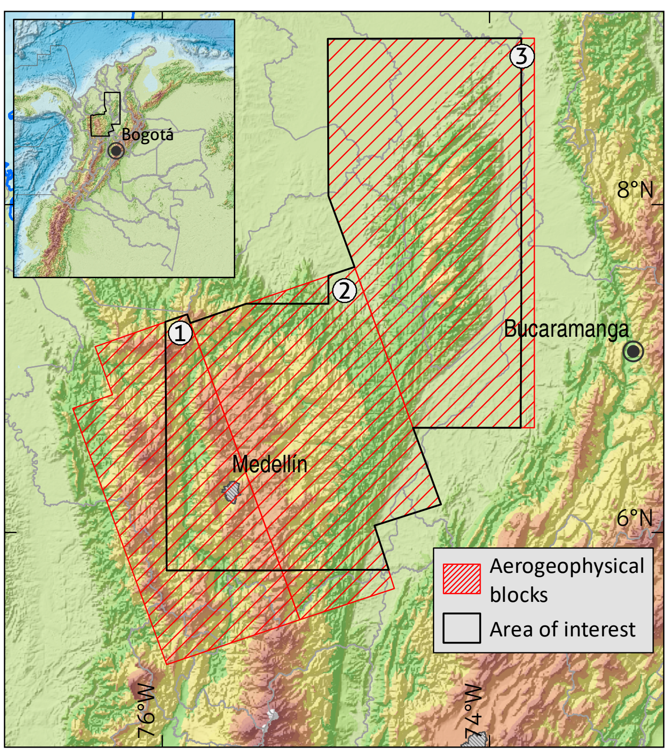

Figure 2. Geographic location of area 1: the Serranía de San Lucas-Antioquia Batholith

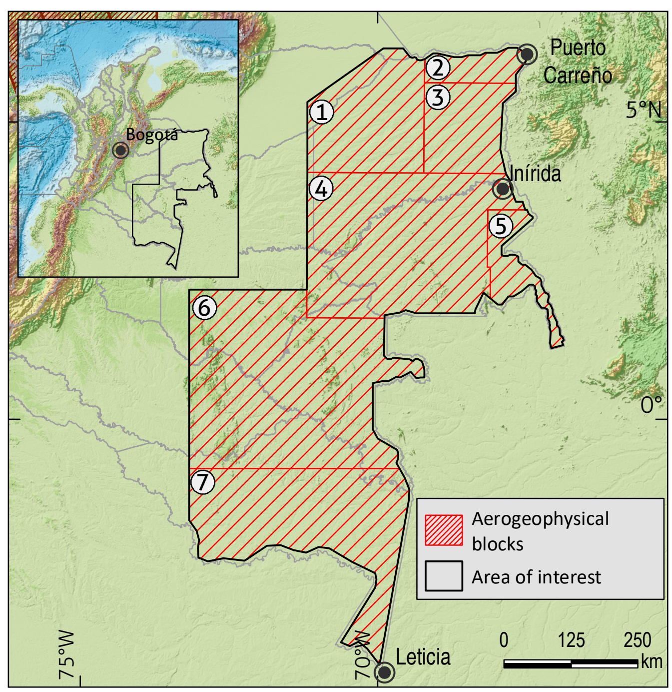

Figure 3. Geographic location of area 2: eastern Colombia

Table 1. Parameters for the acquisition of airborne geophysical information for each of the areas of interest

	Aerogeophysical block	Sampling interval	Flight lines/dir. flight lines	Control lines/dir. control lines	Flight altitude	Acquisition date	Area (km²)	
Serranía de San Lucas-Antioquia Batholith	Antioquia_W	80 m (gamma) 8 m (mag)	500 m/N20W	5000 m/N70E	100 m	18-10-2014	7967	58393
	Antioquia_E					15-08-2014	20710	
	Bolivar		500 m/NS	5000 m/EW		14-12-2013	29716	
Eastern Colombia	Amazonas_N	80 m (gamma) 8 m (mag)	1000 m/NS	10000 m/EW	100 m	25-07-2014	114393	369617
	Amazonas_S					23-06-2015	72510	
	Guainia					15-11-2014	92616	
	Guainia_E		500 m/NS	5000 m/EW		16-09-2016	12414	
	Vichada					24-06-2014	25080	
	Vichada_N					12-03-2016	9724	
	Vichada_W					17-06-2016	42881	

3. Materials and methods

3.1. Airborne geophysical information

Since 2012, the SGC acquired airborne geophysical data by magnetometry and gamma spectrometry geophysical methods in areas of interest in the Colombian territory. This information has been collected using an airborne platform (airplanes) at a height of 100 meters above the ground, as allowed by the topography and safety precautions. Table 1 presents general information on the blocks covered. Additional details about this information and characteristics of the data are found in Moyano et al. (2020).

3.2. Data processing

Initially, the spatial distribution of the data was reviewed to verify the continuity and coupling between the different blocks. Subsequently, the gamma spectrometry data were refined to exclude the areas where a greater flight height affected the quality of the information by exceeding the sensitivity limit of the instruments.

The final images were processed by 2D interpolation in regular grids through minimum curvature for the gamma data and bidirectional gridding for the magnetometry data (Moyano et al., 2020). The cell size used followed the recommendations of Gunn et al. (1997) with respect to using cell values between one quarter (¼) and one eighth (⅛) of the nominal spacing of the flight lines; this aims to avoid loss of information and, therefore, to recover all frequencies.

According to the specifications of the blocks in each work area (Table 1), the cell size was defined as a quarter (¼) of the distance between the flight lines, as follows:

1. *Serranía de San Lucas-Antioquia Batholith*. The cell size for the interpolation of the images was sellected at 125 m, since all the aerogeophysical blocks involved in the area have a flight line spacing of 500 m.
2. *Eastern Colombia*. The cell size used for the interpolation of the data was 250 m. In this area, there are three aerogeophysical blocks for which information was acquired in lines with spacing of 1000 m. Although information on the four blocks in this area was acquired with a spacing of 500 m, the information was generalized so as not to force an interpolation that would result in artifacts in the interpolated data.

3.2.1. Gamma spectrometry data

The airborne gamma spectrometric method is based on the detection of the natural gamma radiation emitted due to the process of stabilization of the nuclei in the radioactive elements in the materials and rocks on the Earth's surface. Among these elements, potassium (K), uranium (U) and thorium (Th) are the only natural elements with radioisotopes that produce gamma rays of sufficient energy and intensity to be measured in airborne geophysics surveys (International Atomic Energy Agency, 2003). Given that gamma rays are strongly attenuated in rocks, soil and air, most of the radiation emanates from shallow soil (approximately 90% of the measured gamma rays are received from 30 cm to 50 cm below the surface).

Because the three radioelements measured have specific chemical affinities, their distributions in rocks vary as a function of parameters such as mineralogy, oxidizing conditions, hydrothermalism and weathering. For this reason, K, U and Th can have very variable concentrations in rocks, which can be used to support geological cartography (Martelet et al., 2006).

The gamma spectrometry layers generated correspond to maps of equivalent concentrations of K, U and Th (Figures 4 and 5). From these three maps, a ternary composition was made in false RGB color (R: *red*, associated with channel K; G: *green*,

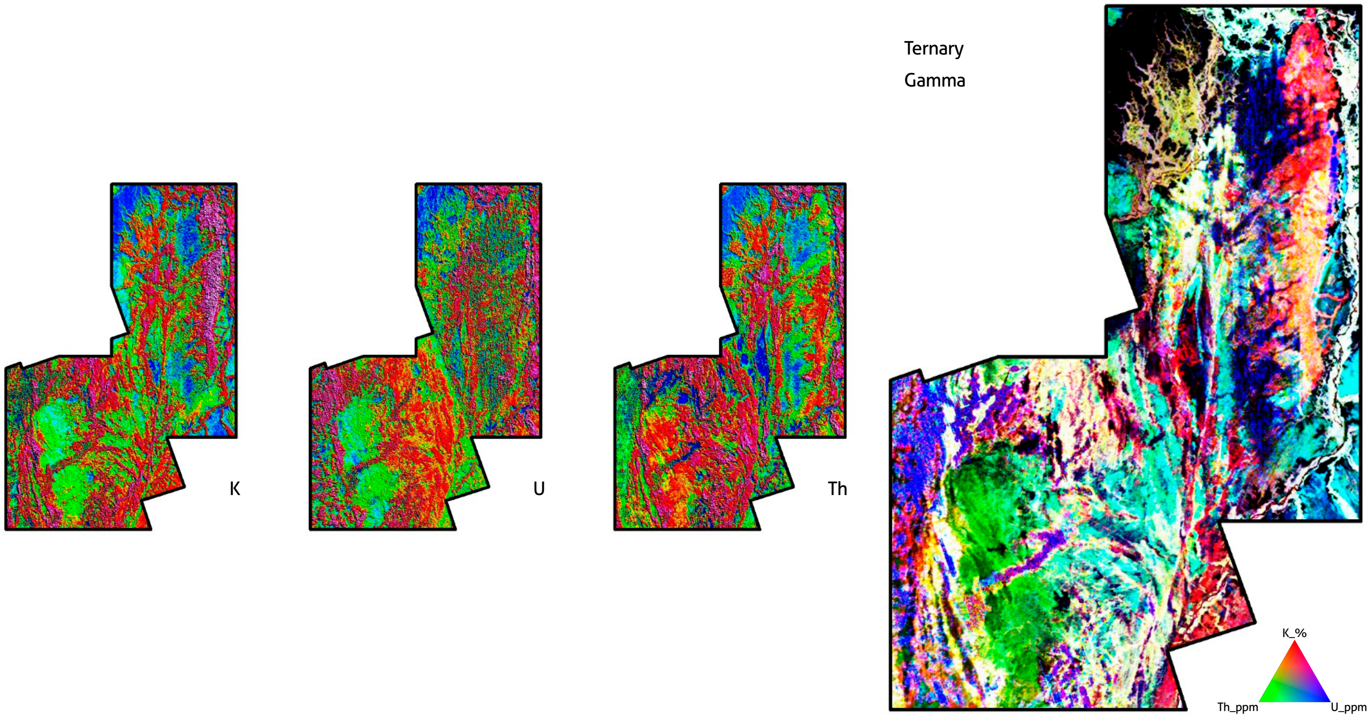

Figure 4. Flowchart of the gamma spectrometric data of area 1: Serranía de San Lucas-Antioquia Batholith
K: Potassium; U: uranium; Th: thorium; ternary gamma: RGB false color ternary composition of the K, U and Th channels.

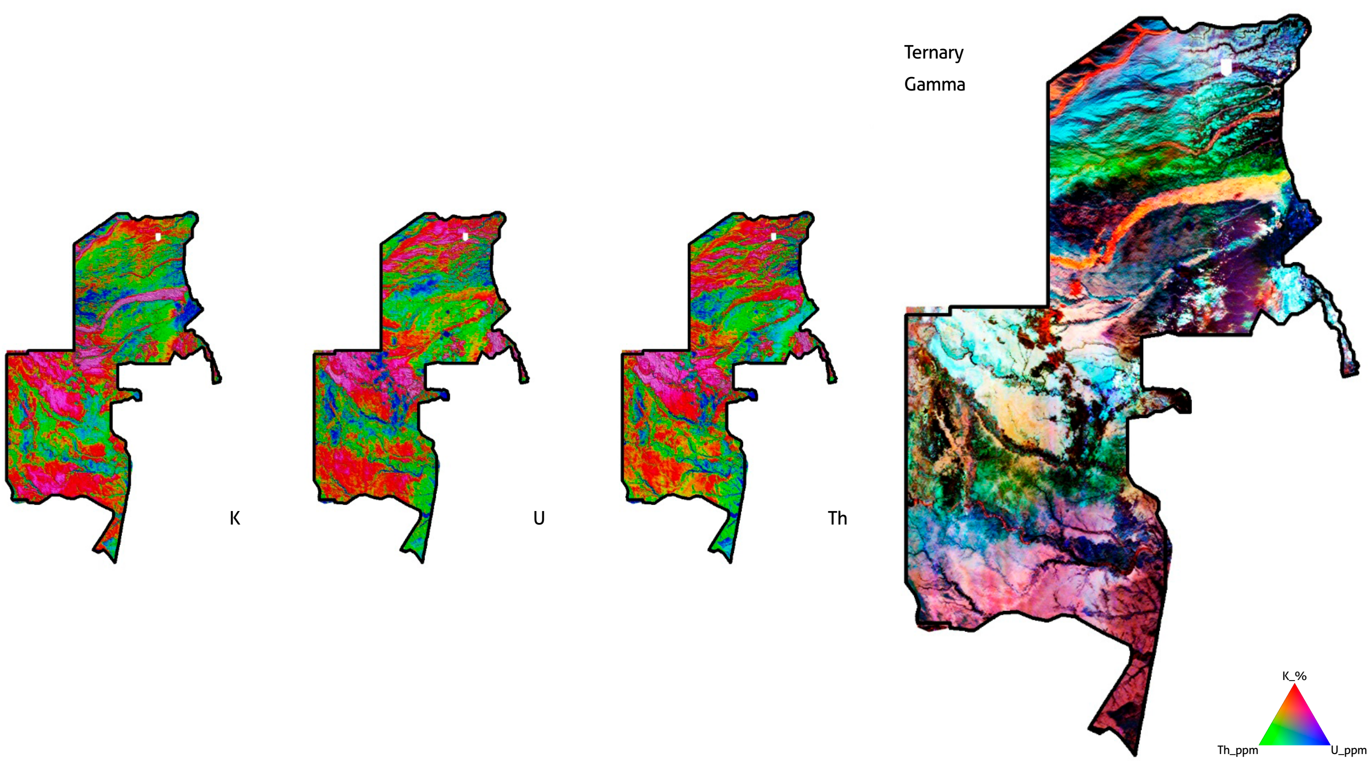

Figure 5. Flowchart of the gamma spectrometric data obtained in area 2: eastern Colombia
K: Potassium; U: uranium; Th: thorium; ternary gamma: ternary composition in false color RGB of the K, U and Th channels.

associated with channel Th; B: *blue*, associated with channel U). This ternary composition map is very useful, since the combination of the colors represents the average concentration of the three elements: white colors show areas that are high in the three radioelements, while dark brown or black colors indicate areas that have low contents. Low radiometric values are generally associated with rocks with low contents of radioactive elements or the presence of water masses or saturated soil. In addition, the radiometric images were integrated with a digital terrain model (DTM), generated from the altimetry data obtained during the survey of geophysical information, to observe the effect of the topography on the distribution of the radioelements.

3.2.2. Magnetometry

The total field magnetic anomaly (TMA) represents the portion of the observed magnetic field that does not correspond to the Earth's magnetic field reference model (International Geomagnetic Reference Field [IGRF]) (Thébault et al., 2015) nor to external temporal effects such as solar storms and diurnal variation. Therefore, the TMA can be associated with the effects of t he geomagnetic field due to variations in the distribution of magnetization in the Earth's crust caused by changes in the concentration of magnetic minerals in the rocks that comprise it.

Due to the dipolar nature of the magnetic field, the TMA represents magnetic anomalies (areas where the concentration of magnetic minerals is higher or lower than that in the environment) as dipoles. To establish a monopolar analog, transformations such as reduction to the magnetic pole (RTP) transform the dipole anomaly into a single peak on the body that is causing it, as if it were located in a magnetic pole. The RTP then transforms the asymmetric anomalies into symmetrical anomalies and locates them on the causative bodies (Marangoni, 2014). Other transformations used are the analytical signal (AS), which highlights the lateral contrasts (contours) of the anomalous source; the tilt derivative (Tilt), which highlights linear features of the information; and vertical derivatives (Dz), which, according to their magnitude, enhance progressively shallower attributes in the information. All these data processing steps are proposed to enhance features of the original information, such as structures and lateral changes, in support of the structural interpretation of the area.

An additional processing step used is the creation of a ternary composition (RGB) image from images of vertical derivatives in three different orders. That composite image allow to discriminate different *magnetic domains* (MD) from the delineation of areas of high magnetization (or high frequencies) and areas of low magnetization (or low frequencies), as well as lateral contrasts in the texture (e.g., high content of high frequency or *rough* anomalies). For the area of the Serranía de San Lucas-Antioquia Batholith, the orders generated correspond to 0.5 Dz-0.75 Dz-1 Dz (Figure 6), and for the eastern Colombian zone, they correspond to 0.75 Dz-1 Dz-1.25 Dz (Figure 7). The difference in the orders of the derivatives for the two areas is due to the greater amount of high frequencies associated with the topography of the Andean zone.

For the characterization of the structural framework of the areas of interest (magnetic lineaments), the images of the tilt derivative (Tilt) and the analytical signal were used. The first highlights the lineaments and detects the edges of the geological features that may be associated with fractures, faults, or geological contacts. In addition, it is very useful to delimit both shallow and deep sources (Miller y Singh, 1994). The analytical signal better defines the limits of the magnetic source, which contributes to the geometrical and spatial characterization of the various magnetic sources, according to the intensity of the magnetic field.

4. Results

4.1. Gamma spectrometric domains

Geological mapping techniques have progressively evolved toward the combination of field observations and remote sensing approaches. The use of techniques such as gamma ray spectrometry allows the identification of radioelement concentration patterns in combination with geological observations in the field. In addition, the continuous coverage of these geophysical data is crucial to extrapolate point observations of the soil to an entire region.

As the use of geographic information systems (GIS) software has become widespread, allowing better analysis of spatial relationships between datasets (geological, geophysical, geochemical, etc.), which has made it possible for geological mapping to present greater thematic precision. However, with the increase in the number of available data layers, this qualitative approach has become difficult to apply and requires the implementation of automated procedures, such as multivariate analysis, which was developed for aiding interpretation in cases in which the number of available variables increases progressively as more information is collected.

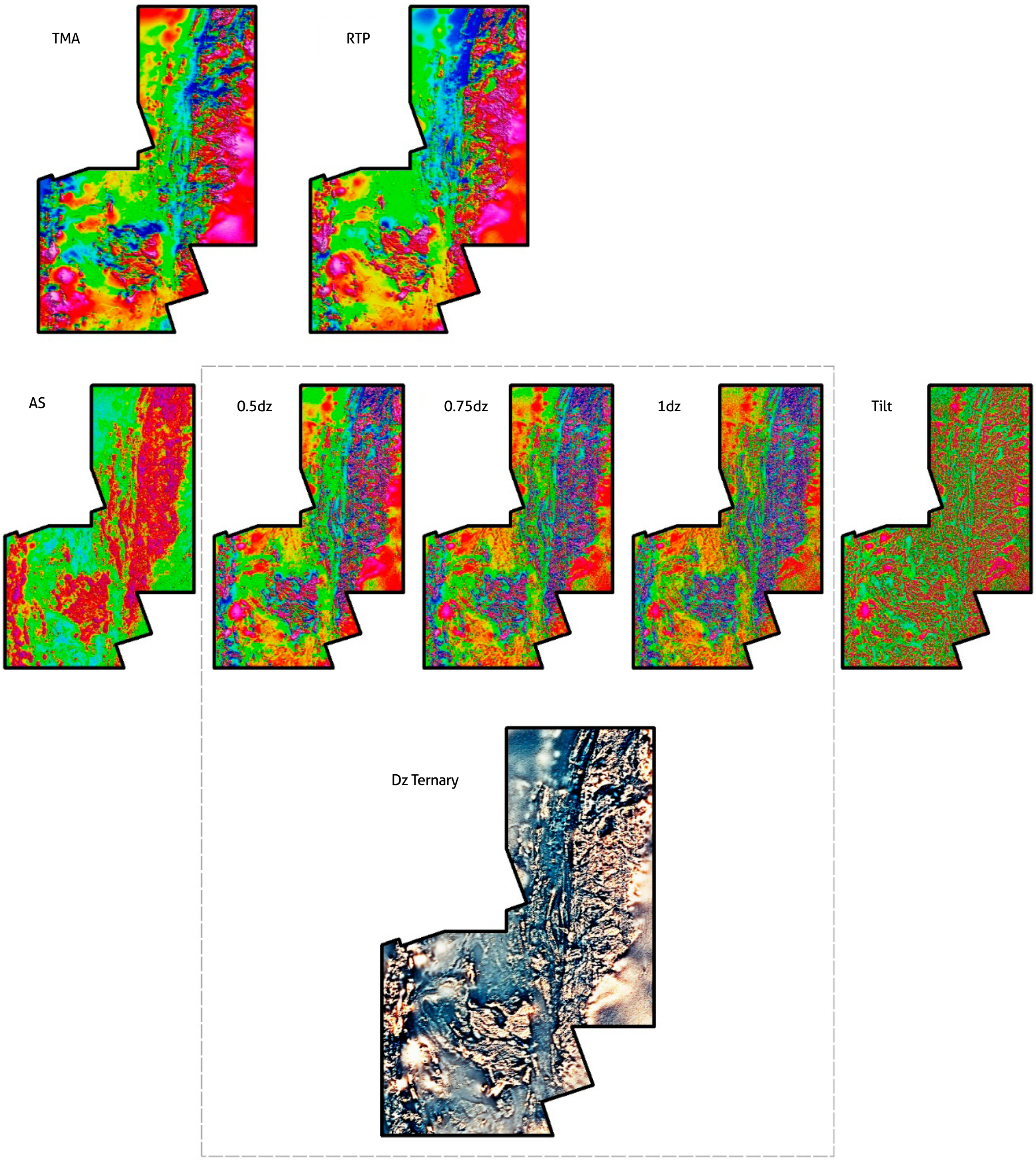

Figure 6. Flow diagram of the magnetic data of area 1: Serranía de San Lucas-Antioquia Batholith
TMA: total field magnetic anomaly; RTP: reduction to the pole of the total field magnetic anomaly; AS: analytical signal of the RTP; Dz: Ternary image from the 0.5, 0.75 and 1 vertical derivatives form the RTP; TILT: Tilt derivative; ternary Dz: ternary RGB composition of the vertical derivatives 0.5-0.75-1.

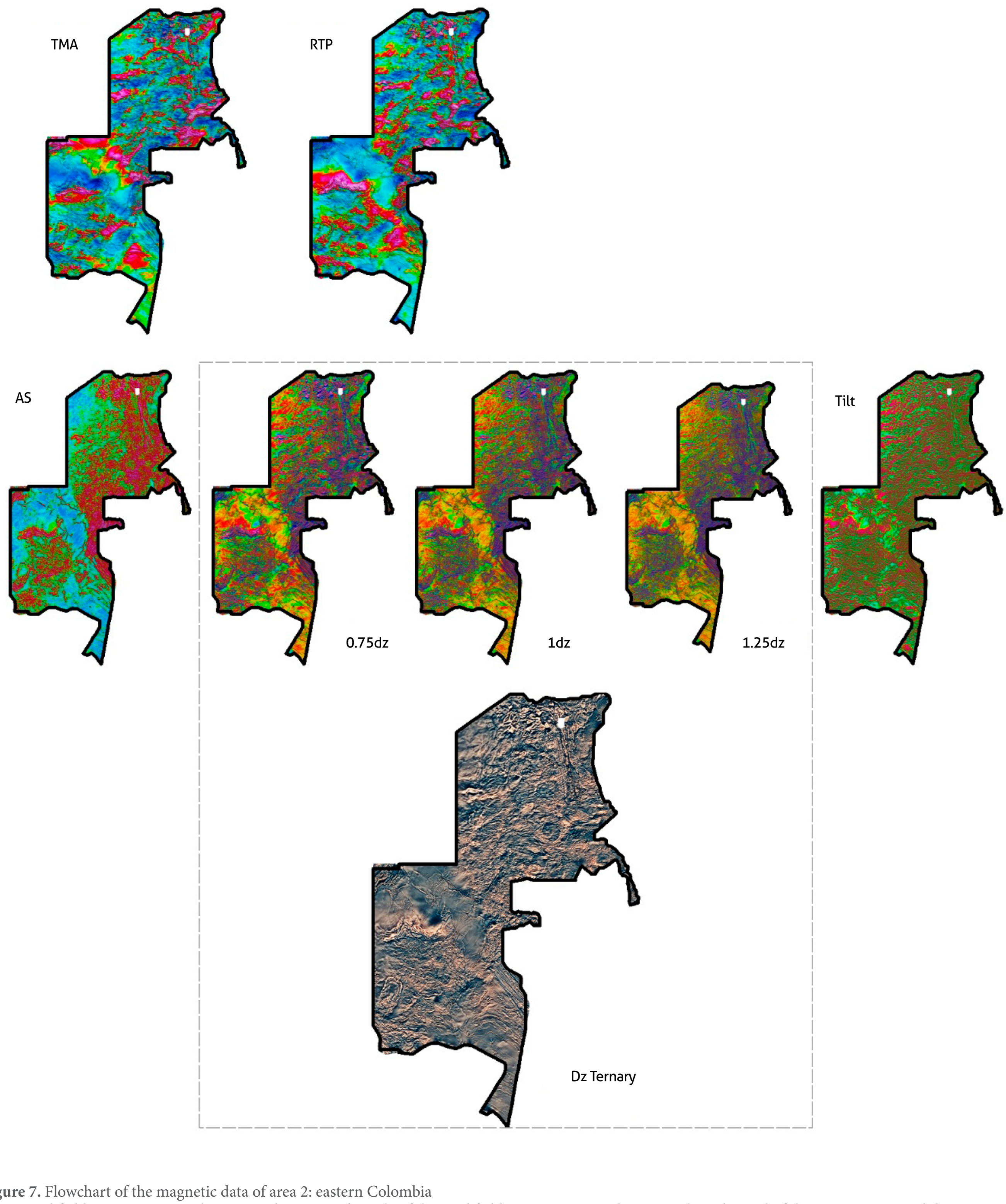

Figure 7. Flowchart of the magnetic data of area 2: eastern Colombia
TMA: total field magnetic anomaly; RTP: reduction to the pole of the total field magnetic anomaly; AS: analytical signal of the RTP; Dz: vertical derivatives from the RTP; TILT: Tilt derivative; ternary Dz: ternary RGB composition of the vertical derivatives 0.75-1-1.25.

4.1.1. Multivariate spatial analysis: classification methods

Among the widely known *classification algorithms,* two approaches are established: supervised and unsupervised classifications. In unsupervised classification, or *clustering*, image processing software automatically computes the values of different coverages and groups them according to their spectral values. In supervised classification, the spectral values of different covers are computed through training zones, which generally correspond to sites previously sampled in the field or for which there is previous knowledge (Richards, 2013)

Supervised classification requires a set of classes defined by an analyst, in addition to the characteristic spectral signatures of the classes. The approach developed for the two areas of interest relied on a supervised classification approach that is based on statistics, in which each class was assigned the highest probability in the dataset (supervised classification of maximum likelihood). Patterns of high, medium and low contents of each of the radioelements (K, U, Th) were previously identified in the interpolated images, and these patterns were used as training zones (Killeen et al., 2015).

4.1.2. Supervised maximum likelihood classification method

The supervised maximum likelihood classification method is one of the most frequently used classification methods. In this approach, a pixel is assigned to the class with the highest probability, according to its spectral characteristics previously defined by the analyst. The maximum likelihood algorithm is trained by control points, which it considers parameters. Subsequently, the algorithm selects the values of a finite set of data (in this case, the processed and interpolated gamma spectrometry images) with a greater probability of approaching the parameter defined in advance and then groups these data into clusters, with the same values reclassified into topics or classes; that is, the parameters that maximize the likelihood function are clustered.

The classification of maximum likelihood is also known as *classification by the Bayesian algorithm*, since *a priori* probabilities can be assigned by means of Bayes's theorem, which expresses the probability of a random event *A* occurring in *B* (Japan Association on Remote Sensing, 1993), according to (1):

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{\sum_{(k=1)}^{n} P(B|A_k)P(A_k)} \quad (1)$$

The maximum likelihood method has an advantage from the point of view of probability theory, but care must be taken with the following issues (Japan Association on Remote Sensing, 1993):

1. The samples used as training sites should be sufficient to allow the estimation of the mean vector and the variance-covariance matrix of the population.
2. The inverse matrix of the variance-covariance matrix becomes unstable when there is a very high correlation between two bands or the terrain data are very homogeneous. In these cases, the number of bands must be reduced by principal component analysis.

4.1.3. Application of the supervised maximum likelihood classification method

In the images created by minimum curvature interpolation (Yang et al., 2004) for each of the elements (K, U and Th), three main classes were defined: high concentrations, medium concentrations, and low concentrations. Once defined, the training zones were established in each image, with sufficiently high and homogeneous sampling in each image so that the spectral signatures were well defined. Subsequently, the maximum likelihood algorithm was applied, and it was verified that there was low correlation in the variance-covariance matrices. In this way, the maximum statistical probability was established for each cell of the images (K, U and Th), and the class to which the cells belonged was defined.

The steps involved in the processing and analysis of the data to generate the spectrometric gamma domains (GDs) are detailed in Figure 8. The processing software was *ArcGIS* 10.6 (the "Spatial Analysis" tool was used).

Once each image was classified, the gamma spectrometric domains of the areas of interest were defined. Given that there are three elements (K, U and Th) and that each element was assigned to three classes (high, medium, and low), it was possible to establish up to twenty-seven possible combinations in the area of interest (Figures 9 and 10; Table 2).

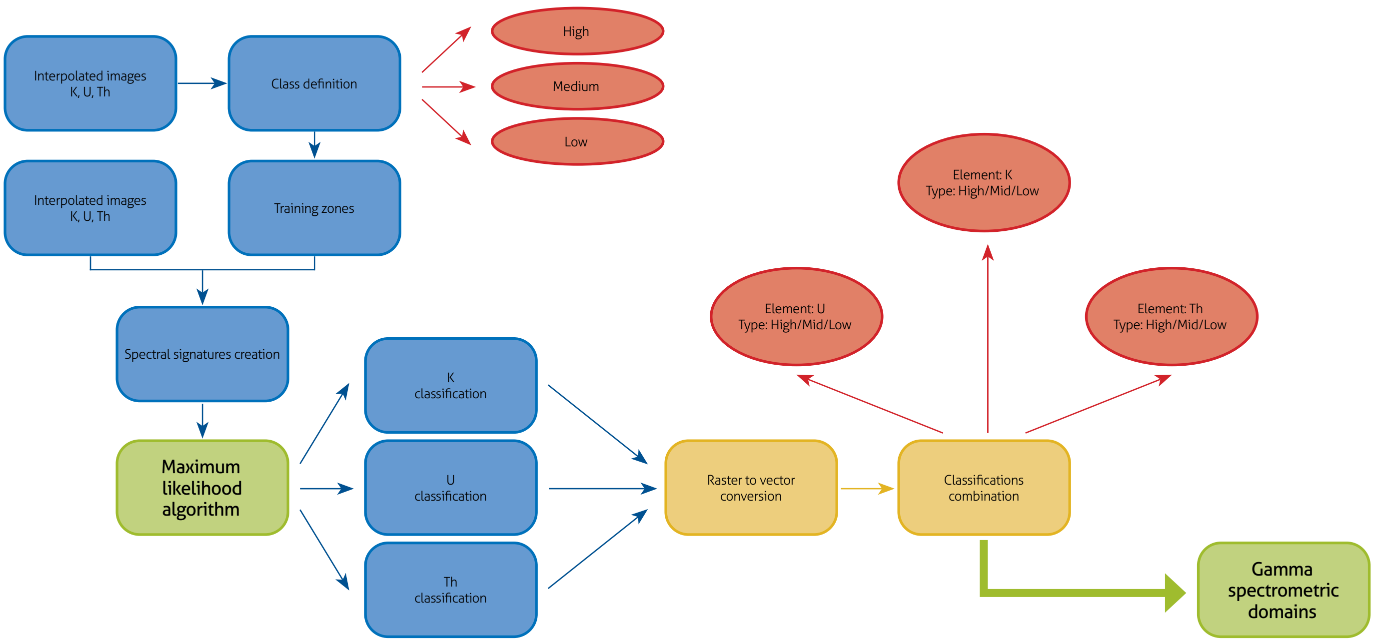

Figure 8. Flowchart of the application of the supervised classification method to obtain gamma spectrometric domains in the areas of interest: Serranía de San Lucas-Antioqueño Batholith and eastern Colombia

Table 2. Description of the gamma spectrometric domains generated for the areas of interest: Serranía de San Lucas-Antioquia Batholith and eastern Colombia

Domain	Combination	Detail			Code	Color
		Potassium (K)	Uranium (U)	Thorium (Th)		
1	Kh-Uh-Thh	High	High	High	333	
2	Kh-Uh-Thm	High	High	Medium	332	
3	Kh-Uh-Thl	High	High	Low	331	
4	Kh-Um-Thh	High	Medium	High	323	
5	Kh-Um-Thm	High	Medium	Medium	322	
6	Kh-Um-Thl	High	Medium	Low	321	
7	Kh-Ul-Thh	High	Low	High	313	
8	Kh-Ul-Thm	High	Low	Medium	312	
9	Kh-Ul-Thl	High	Low	Low	311	
10	Km-Uh-Thh	Medium	High	High	233	
11	Km-Uh-Thm	Medium	High	Medium	232	
12	Km-Uh-Thl	Medium	High	Low	231	
13	Km-Um-Thh	Medium	Medium	High	223	
14	Km-Um-Thm	Medium	Medium	Medium	222	
15	Km-Um-Thl	Medium	Medium	Low	221	
16	Km-Ul-Thh	Medium	Low	High	213	
17	Km-Ul-Thm	Medium	Low	Medium	212	
18	Km-Ul-Thl	Medium	Low	Low	211	
19	Kl-Uh-Thh	Low	High	High	133	
20	Kl-Uh-Thm	Low	High	Medium	132	
21	Kl-Uh-Thl	Low	High	Low	131	
22	Kl-Um-Thh	Low	Medium	High	123	
23	Kl-Um-Thm	Low	Medium	Medium	122	
24	Kl-Um-Thl	Low	Medium	Low	121	
25	Kl-Ul-Thh	Low	Low	High	113	
26	Kl-Ul-Thm	Low	Low	Medium	112	
27	Kl-Ul-Thl	Low	Low	Low	111	

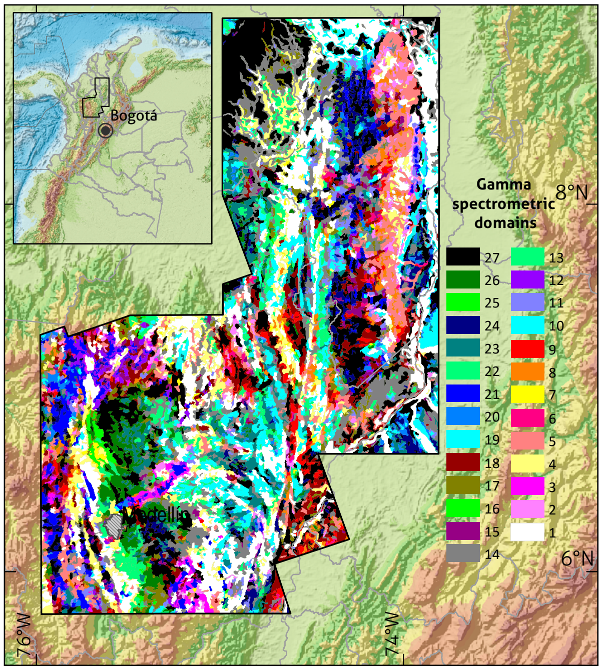

Figure 9. Gamma spectrometric domains in the Serranía de San Lucas-Antioquia Batholith area

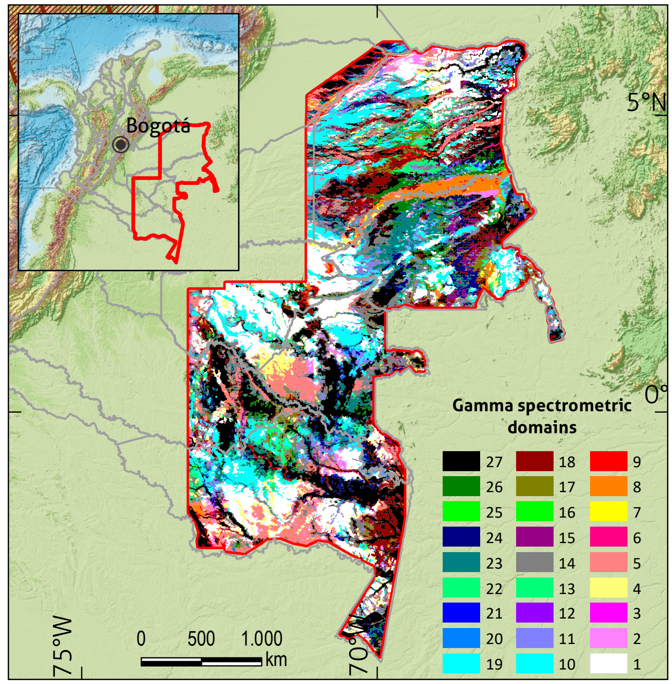

Figure 10. Gamma spectrometric domains in eastern Colombia

4.2. Magnetic domains (MDs)

Magnetic domains are areas with similar magnetic features, delimited by taking into account two magnetic characteristics: texture and intensity. Magnetic domains are delineated from the vertical gradient of the magnetic field, called the *vertical derivative* (Dv). This transformation enhances shallow magnetic sources while attenuating or suppressing the deep sources as the order of the derivative increases (Reeves, 2005).

The magnetic characteristics that allow the delimitation of the magnetic domains (MD) are: a) the magnetic intensity, related to the amplitude of the signal, and defined in three classes: high, medium, and low intensity; b) the magnetic texture, with which the *roughness* of the magnetic clusters in each image is discriminated. The magnetic texture is related to the power spectrum of the magnetic signal: high frequencies produce rough textures, and low frequencies produce smooth textures.

Once the domains were obtained by grouping the intensity and magnetic texture, the information was combined by means of cartographic generalization procedures and delimitation of domain borders. The combination of the two attributes resulted in the delimitation of nine MDs (Figures 11 and 12), the details of which are shown in Table 3.

Table 3. Description of the magnetic domains generated for the areas of interest: Serranía de San Lucas-Antioqueño Batholith and eastern Colombia

Domain	Detail				Code	Color
	Intensity		Texture			
	Class	Code	Type	Code		
1	High	3	Rough	3	33	
2	High	3	Medium	2	32	
3	High	3	Soft	1	31	
4	Medium	2	Rough	3	23	
5	Medium	2	Medium	2	22	
6	Medium	2	Soft	1	21	
7	Low	1	Rough	3	13	
8	Low	1	Medium	2	12	
9	Low	1	Soft	1	11	

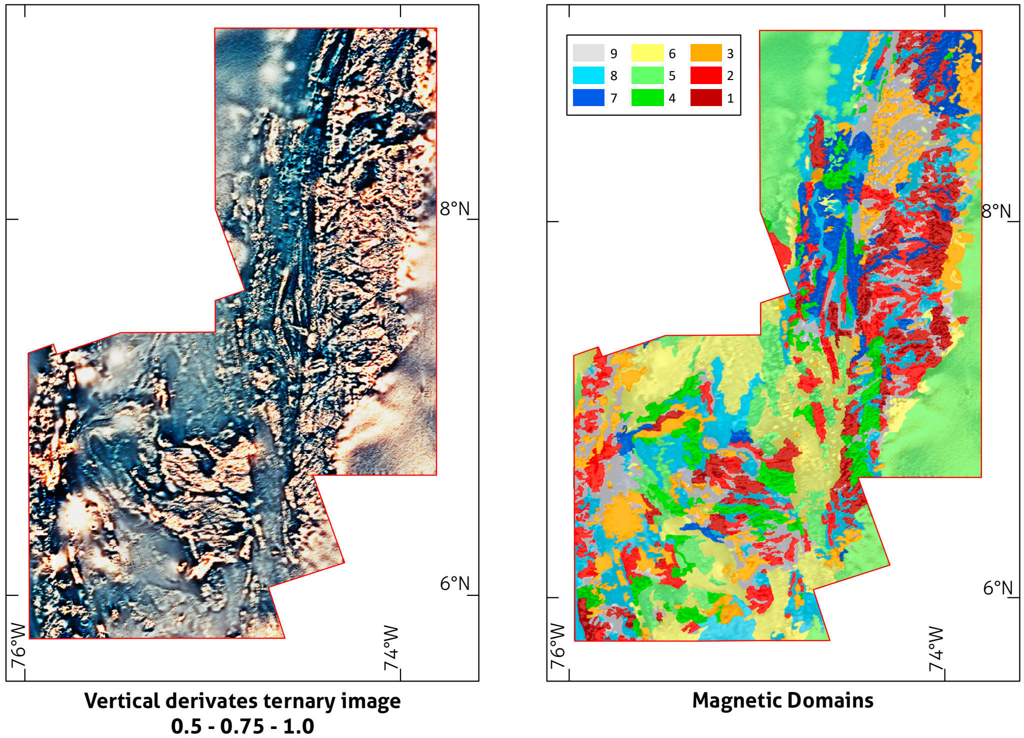

Figure 11. Magnetic domains of the Serranía de San Lucas-Antioquia Batholith area

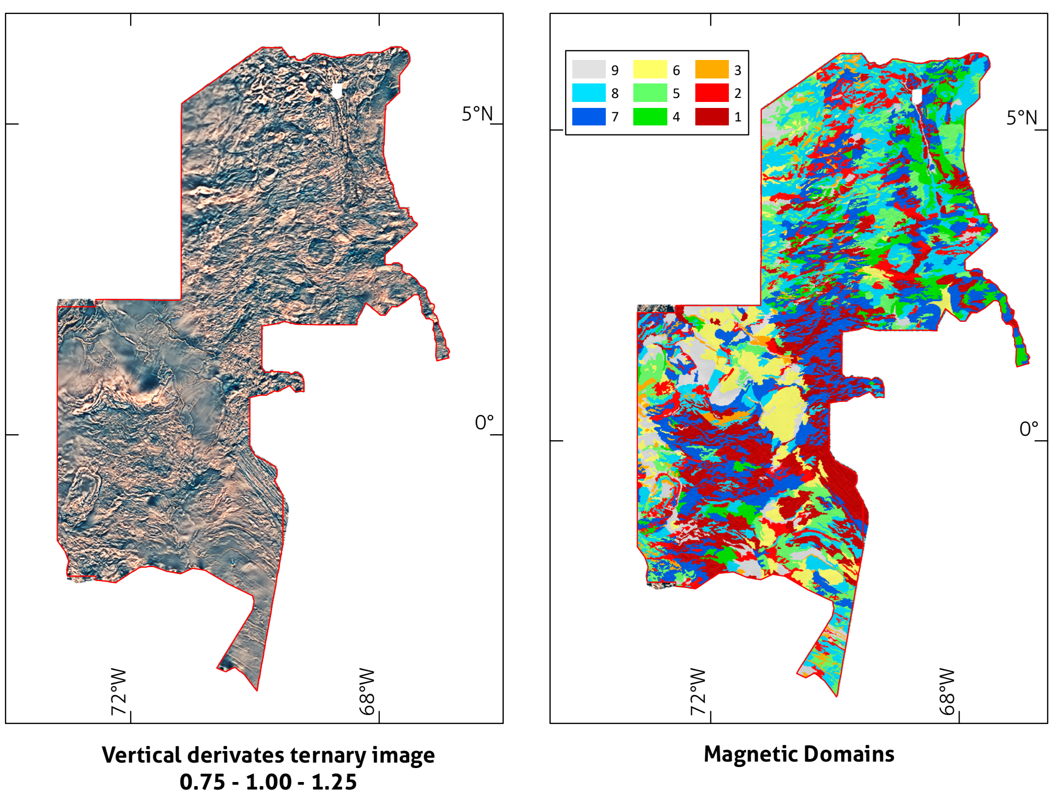

Figure 12. Magnetic domains of eastern Colombia

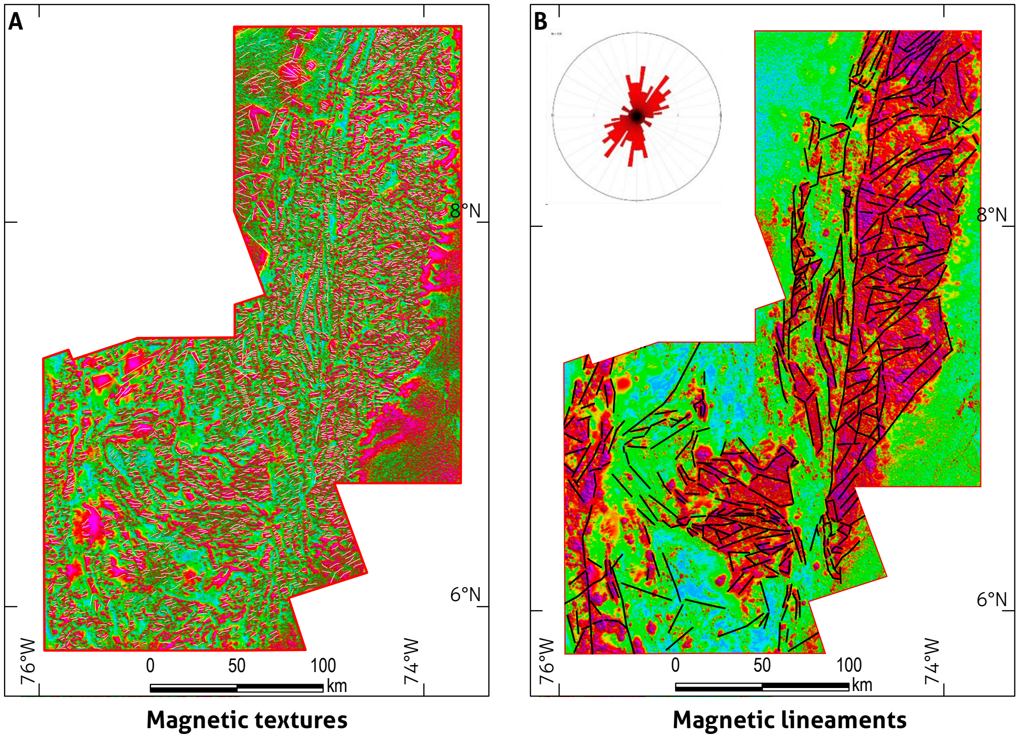

Figure 13. a) Magnetic lineaments on the analytical signal image and b) Rose diagram corresponding to the area of the Serranía de San Lucas-Antioquia Batholith

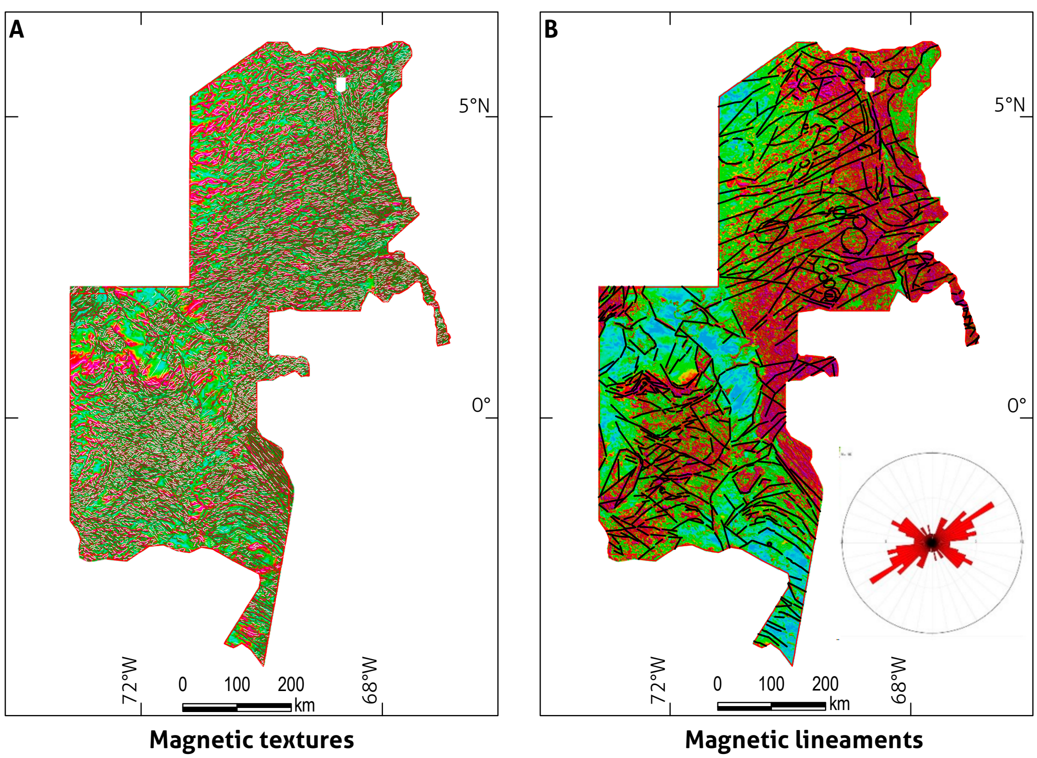

Figure 14. a) Magnetic lineaments on the analytical signal image; b) Rose diagram corresponding to eastern Colombia

4.3. Magnetic lineaments

From aeromagnetic data, magnetic lineaments that delineate the lateral changes in the magnetic field and represent the structural trends of each zone were selected. The lineaments are attributable to changes in the magnetic susceptibility of the rocks, possibly limited by structural and lithological controls, such as faults and fractures, among others.

The determination of the magnetic lineaments was performed through a quantitative and semiautomated process with the use of the CET (Center for Exploration Targeting) Grid Analysis tool (Abbass y Mallam, 2013). This allowed the automatic detection of lineaments through texture analysis while suppressing low values and preserving the orientation and local maximum amplitude values. In addition, it delimited the edges of the magnetic anomalies. The phase analysis detects regions with continuous linear trends and estimates of trend lines from the information detected by the phase analysis can reveal lithological and structural contrasts, mainly from the image created by the Tilt derivative. The result is a set of vectorized linear segments that show changes in orientation and regional structures within the area.

Once the magnetic lineaments were obtained from the CET, the digitization, interpretation, and categorization of the magnetic lineaments into three classes was performed: a) local lineaments generated by the CET algorithm called *magnetic texture*; b) lineaments that cross MDs and show trends in length and shape, identified as *first-order lineaments;* and c) regional lineaments that separate MDs, called *magnetic lineaments*. Magnetic coverages, such as the tilt derivative, the total field magnetic anomaly (TMA), the reduction in the pole of the TMA and the MDs, were used as support.

Rose diagrams to evaluate the orientation of the lineaments were generated; these plots represent the direction of bearing and show the percentage of distribution of the data, according to the length of each lineament. This allows for the analysis and comparison of the characteristics of the magnetic lineaments identified in each area of interest (Figures 15 and 16).

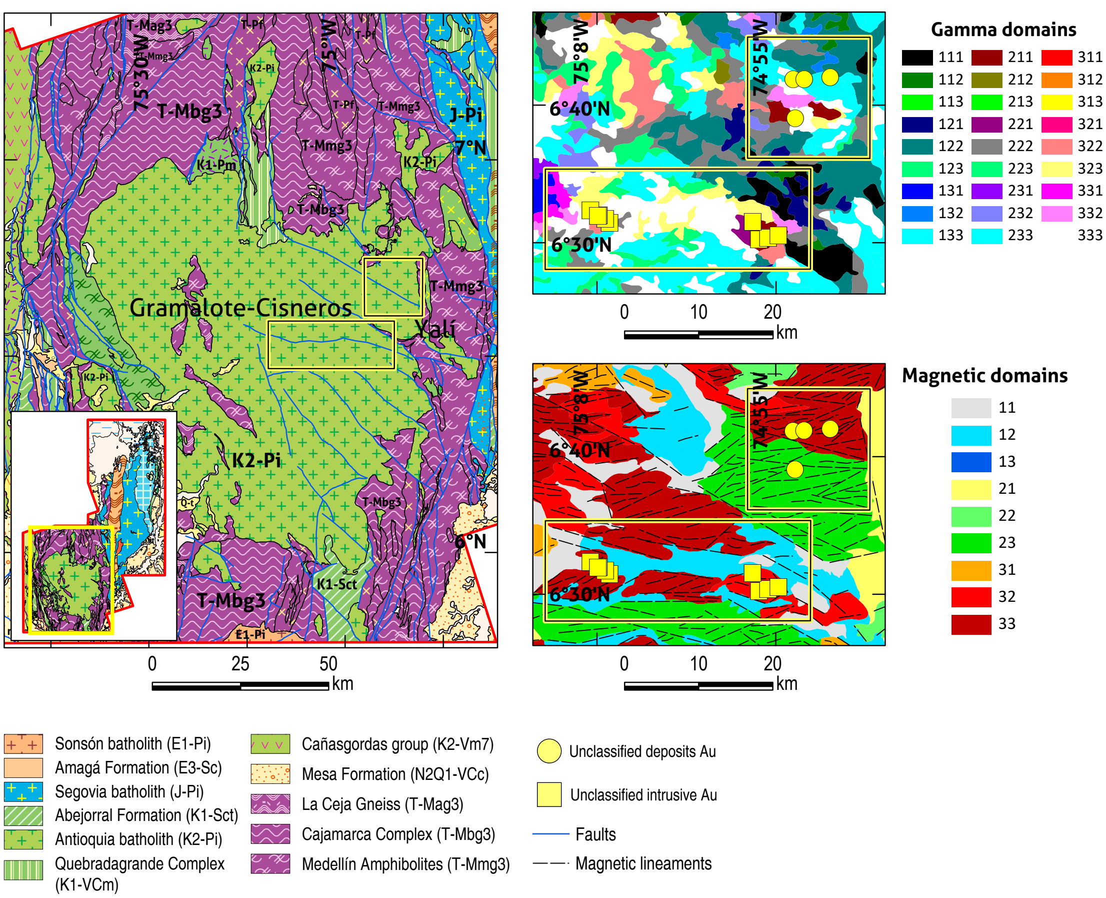

Figure 15. Geological-geophysical integration in the Gramalote and Yalí metallogenic districts
Left: geological units; right: gamma domains and magnetic domains.

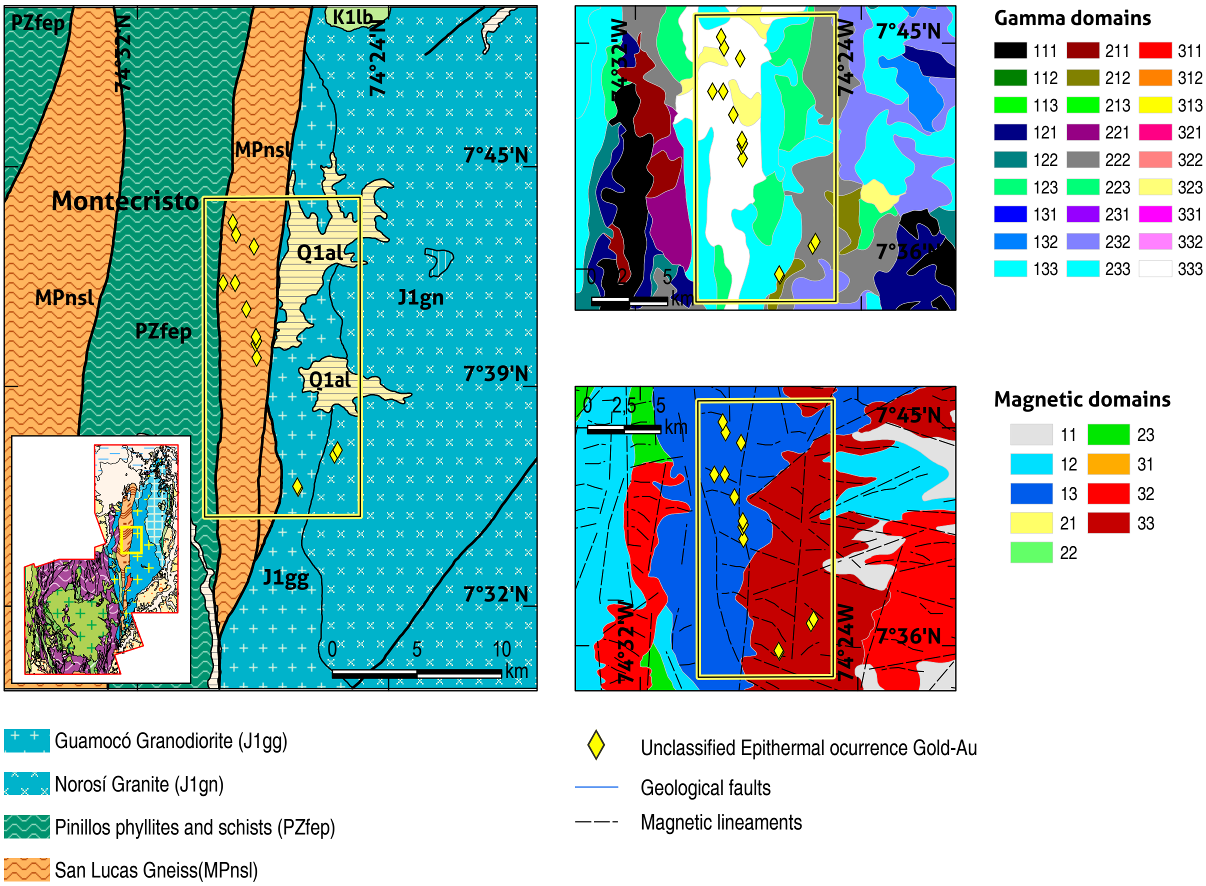

Figure 16. Geological-geophysical integration in the Monte Cristo metallogenic district
Left: San Lucas Gneiss (MPnsl), right: gamma domains and magnetic domains.

5. Discussion and examples of integration with geological information

The integration of geophysical and geological data from the gamma spectrometric and magnetic domains with geological data for the Serranía San Lucas-Antioquia Batholith area and eastern Colombia (covered in large parts by sedimentary substrate) shows the contrast of a series of geophysical attributes associated with the different geological units. This information contributes to the geological knowledge, helps in the identification of areas with the potential to host mineral resources, and supports geological mapping. Some examples of this potential are presented below.

5.1. Hydrothermal alteration zones: Antioquia Batholith, Serranía de San Lucas and Middle Magdalena Valley

To the southwest of the study area is the Antioquia Batholith (K2-Pi) outcrops, composed predominantly of tonalite-granodiorites. The radiometric counts for K vary from medium to low and are high in U-Th. The GDs highlight some regions that present high K values (GD-322 and GD-311); these regions are probably associated with potassium alteration zones that coincide with unclassified gold deposits and intrusive rocks included in the Metallogenic Map of Colombia (Sepúlveda et al., 2020) in the metallogenic gold districts of Gramalote and Yalí (Figure 15). On the other hand, the MDs in this area show high intensities, with rough to intermediate textures (MD-33 and MD-32). These values could be associated with more recent intrusions within the Antioquia Batholith.

Figure 16 shows the Monte Cristo metallogenic district located in the Serranía de San Lucas. In this area, several gold deposits are present (unclassified epithermal type (Sepúlveda et al., 2020)); these deposits are located in the San Lucas Gneiss (MPnsl) that consist of hornblendic and biotitic quartz-feldspathic gneisses. The area in which this unit is found includes the Palestina and Tigüí faults and coincides with high GD values (GD: 333, GD: 323). To the west of this unit, there are low GD values that coincide with phyllites and Pinillos schists. To the east of the Tigüí Fault, the Guamocó Granodiorite (J1gg) shows high values of U and Th. The MDs show a strong contrast between low magnetic intensities associated with the San Lucas Gneiss and high intensities associated with the Guamocó Granodiorite.

In the El Vapor metallogenic district, located in the Middle Magdalena Valley (Figure 17), gold occurrences (associated with unclassified intrusive rocks) were identified, oriented north-south between the El Bagre and Nus faults, which coincides with the GDs with high K values. This area has a good lithological contrast. For example, to the east, the Antioquia Batholith shows low gamma domains, and the graphite schists of muscovite quartz have high U values in contrast to the high K values of the Segovia Batholith, which are delimited by the Palestina Fault. To the east, the San Lucas Gneiss coincides with high U. On the other hand, the MDs indicate high intensities with medium textures, and there is evidence of wedging in the magnetic lineaments west of the Palestina Fault, where the rocks with unclassified gold intrusions are located.

5.2. Magnetic lineaments and geological structures: Antioquia Batholith and Serranía de San Lucas

The magnetic lineaments in the Serranía de San Lucas area shows different trends. The most representative are the regional lineaments with azimuths between 0° and 30° located in the central part of the Serrania de San Lucas. These lineaments coincide with the Palestina Fault, whose general direction is north-south, and to the west, with the El Bagre Fault and the Nus Fault. Some of these lineaments seems to be included in the general orientation of the Palestina Fault and form a braided system of structures in this orientation.

To the east of the Palestina Fault, smaller magnetic lineaments are observed with azimuths that vary between 30° and 60°; these could correspond to satellite faults-detected features

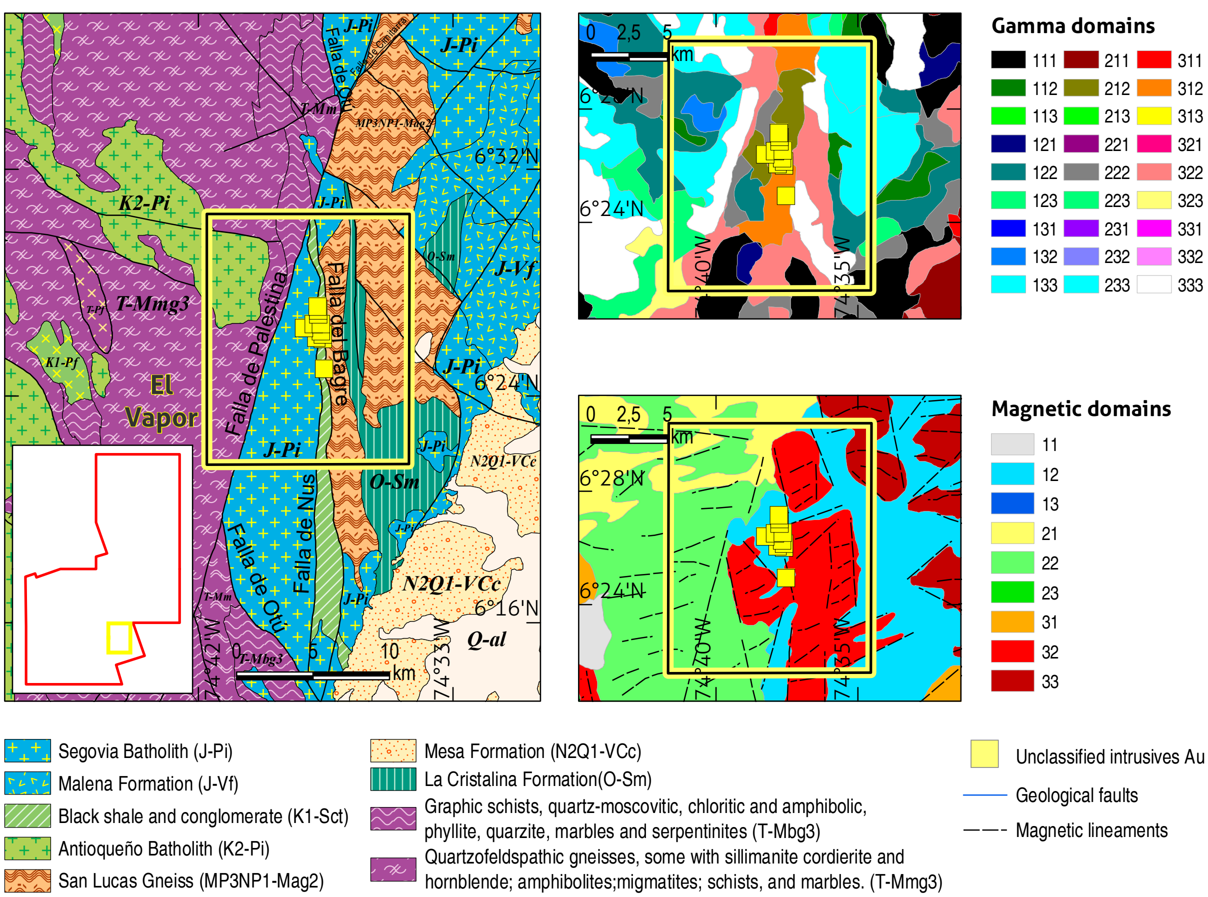

Figure 17. Geological-geophysical integration in the El Vapor metallogenic district
Left: chronostratigraphic units; right: gamma domains and magnetic domains.

of the Palestina Fault and are associated, from south to north, with the Cimitarra, San Blas, Las Brisas and Ororia faults. To the southwest of the Serranía de San Lucas, the trend of these lineaments' changes toward the northwest, consistent with the outline of the Otú Fault (Figure 18).

To the southwest of the area, three types of trends are identified. Magnetic lineaments with a northeasterly orientation that are concentrated in the eastern part of this batholith, with azimuths that vary between 10° and 20°, consistent with the Palestina Fault. A series of parallel lineaments (northwesterly) with azimuths from 300° to 330°, associated with the Antioquia Batholith and the Bizcocho and Balseadero faults to the east and the Riachón Fault to the north. Lineaments with azimuths of 340° to 350°, which are limited to the east and west by the Antioquia Batholith, correlated with the Silvia Pijao Fault to the southwest, and with the Miraflores Fault in the central region (Figure 18).

5.3. Geological knowledge and metallogenic potential in eastern Colombia

Eastern Colombia is composed of different types of igneous or metamorphic rocks (gneisses, migmatites) and sedimentary rocks that vary in age from the Mesoproterozoic to the present. The study area was analyzed based on the chronostratigraphic units of Colombia proposed in the *Geological Map of Colombia* (Gómez et al., 2015). Figure 19 shows Ordovician rocks (O-Sm), consisting of sedimentary rocks that form an outcrop in the central part of the study area and show good gamma spectrometric contrast, with low K, U and Th contents; to the north, higher relative content of K were observed, that can be intepreted as a rock alteration area or change in the composition of the sediments. Additionally, there is a so-*called Carurú* NW-SE lineament located northeast of the Mesa de Cubiyú and Cerro de Mandí. These areas present medium-intensity MDs, with smooth textures in the central region, while to the northeast of the Mesa de Cubiyú, a wedging with high magnetic intensity is evidenced, limited to the southwest by the Carurú lineament. On the other hand, to the east of Mitú, there is a strong contrast of MDs where there is an alternation of low and high intensities with rough texture that coincides with the Mitú Migmatitic Complex.

These units show a good correlation with the MDs that emerge. However, it is not possible to attribute a MD to a specific geological unit due to the heterogeneity and contrasts in the magnetic properties of the rocks or intrusions into the roc-

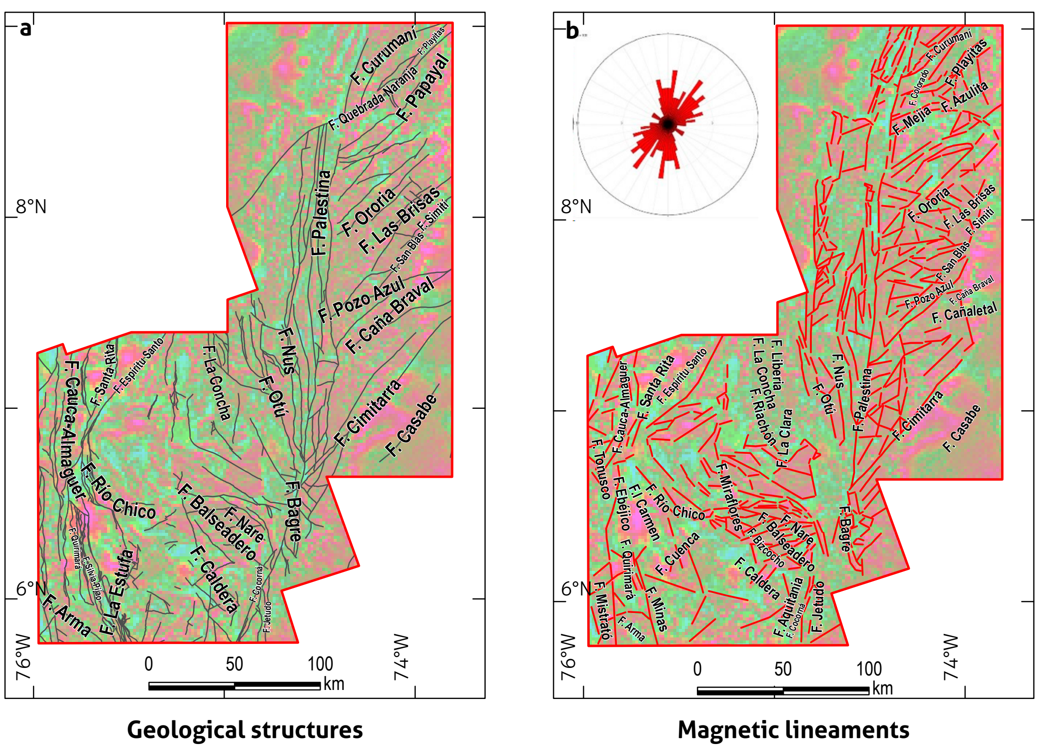

Figure 18. Structural configuration of the Serranía de San Lucas-Antioquia Batholith a) Geological faults, b) magnetic structures.

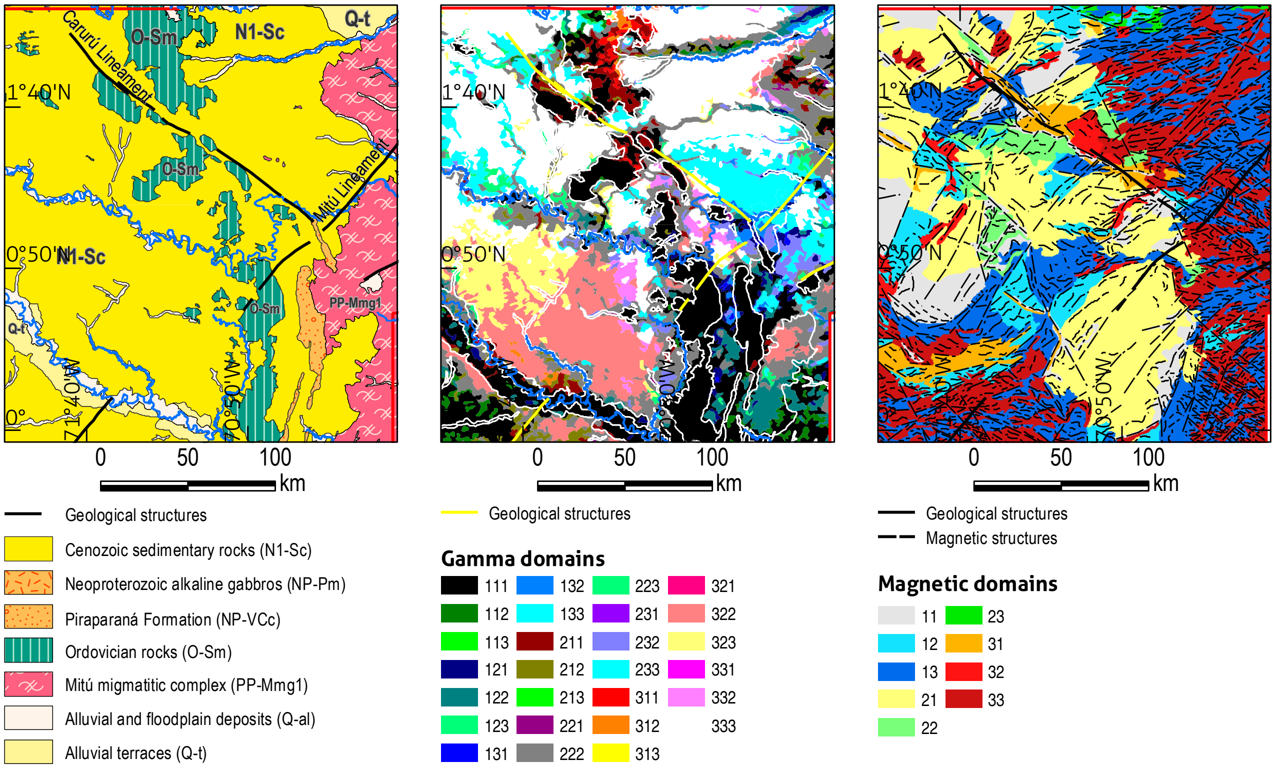

Figure 19. Geological-geophysical integration detailing the Ordovician units, gamma domains, and magnetic domains

ks within a unit. On the other hand, the gamma domains show the characteristics of the rock surfaces, which in many sectors indicate consistencies with the geological cartography and suggest that the rocks are good lithological markers.

6. Conclusions

Airborne geophysical data provides homogeneous coverage of the evaluated areas and enables the correlation of the geophysical responses of surface rocks and materials (Gamma spectrometry) and the subsoil (magnetometry) with the geological units and structures differentiated thus far in each unit.

The application of semiautomatic classification methodologies in the delimitation of magnetic domains and gamma spectrometric as well as for the automatic detection of lineaments is of great value in the integration and interpretation of large volumes of information that cover large areas. This is the case for the two areas evaluated here.

The integration of magnetic domains and gamma spectrometric domains with the regional geology of the area of the Serranía de San Lucas and Antioquia Batholith allowed to correlate the presence of regional faults, such as the Palestina Fault, and lateral contrasts in geochronological units known as the Antioquia Batholith and San Lucas gneiss. However, based on the interpretation of the geophysical domains, it is possible to point out changes and contrasts not reported in the geological cartography; these can be attributed to compositional changes in rocks, which in turn can indicate geological processes of alteration responsible for the accumulation of minerals of interest. An example of this was found in areas such as the El Vapor and Monte Cristo metallogenic districts.

Structural analysis was performed based on magnetometric information integrated with the geological cartography of the area of Serranía de San Lucas and the Antioquia Batholith. The correlation of lineaments and domains with main faults and variations in the orientation of secondary magnetic structures allowed the identification of different domains or blocks that must be explained from the point of view of geological evolution.

For eastern Colombia, information from gamma spectrometric domains represents a key tool in the review and adjustment of geological cartography. In addition, the lineaments and magnetic domains reflect high complexity and variation in the predominantly magnetic rocks that make up the basement, both toward the easternmost part of the study area (where rocks are exposed) and toward the center of the study area (where basement rocks are covered by sedimentary rocks and recent deposits). Therefore, similar to the observations and correlations established in the San Lucas area, it is important to identify the interaction between structures of varying geological origin and possible compositional changes in response to the presence of rock units or alteration zones that have geological potential or metallogenic objects in more detailed studies.

The observations and interpretations presented in this work are based on the management of geophysical information and the preparation of thematic layers that can contribute to the geological mapping of the metallogenic potential of Colombia. Therefore, it is recommended to carry out complementary studies aimed at establishing the relationship between geophysical domains and geological units as well as identifying alteration zones, diagnostic features, or mineral accumulation processes.

References

Abbass, A., & Mallam, A. (2013). Investigating the structures within the Lower Benue and Upper Anambra Basins, Nigeria, using first vertical derivative, analytical signal and (CET) Centre for Exploration Targeting plug-in. *Earth Sciences*, *2*(5), 104-112. https://doi.org/10.11648/J.EARTH.20130205.11

Gómez, J., Montes, N. E., Nivia, A., & Diederix, H. (comp.). (2015). *Mapa geológico de Colombia 2015. Escala 1:1 000 000*. Servicio Geológico Colombiano. https://doi.org/10.32685/10.143.2015.935

Gunn, P. J., Maidment, D., & Milligan, P. R. (1997). Interpreting aeromagnetic data in areas of limited outcrop. *AGSO Journal of Australian Geology and Geophysics*, *17*(2), 175-185.

International Atomic Energy Agency. (2003). *Guidelines for radioelement mapping using gamma ray spectrometry data*. IAEA-TECDOC-1363.

Isles, D. J., & Rankin, L. R. (2013). *Geological interpretation of aeromagnetic data*. Society of Exploration Geophysicists and the Australian Society of Exploration Geophysicists. https://doi.org/10.1190/1.9781560803218

Japan Association on Remote Sensing. (1993). *Remote sensing note*.

Killeen, P. G., Mwenifumbo, C. J., & Ford, K. L. (2015). Tools and techniques: Radiometric methods. *Treatise on Geophysics*, *11*, 447-524. https://doi.org/10.1016/B978-0-444-53802-4.00209-8

Marangoni, Y. R. (2014). AGG0324 - Métodos Potenciais. Parte 3: O Campo Magnético Conceitos e aplicações em Geofísica. In G. e. Universidade de São Paulo. Instituto de Astronomia, AGG0324 - *Métodos Potenciais* (pp. 24-33). São Paulo: Universidade de São Paulo.

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

Miller, H. G., & Singh, V. (1994). Potential field tilt—a new concept for location of potential field sources. *Journal of Applied Geophysics*, *32*(2-3), 213-217. https://doi.org/10.1016/0926-9851(94)90022-1

Moyano, I., Lara, N., Arias, H., Gómez, E., Ospina, D., Puentes, M., Robayo, A., Rojas, O., & Torrado, S. (2020). *Mapa de anomalías geofísicas de Colombia para recursos minerales, versión 2020*. Servicio Geológico Colombiano.

Reeves, C. (2005). *Aeromagnetic surveys: Principles, practice, and interpretation*. Geosoft.

Richards, J. A. (2013). Supervised classification techniques. In *Remote sensing digital image analysis*. Springer. https://doi.org/10.1007/978-3-642-30062-2_8

Sepúlveda, J., Celada, C. M., Leal-Mejía, H., Murillo, H., Rodríguez, A., Gómez, M., Prieto, D., Jiménez, C. A., Rache, A., & Hart, C. (2020). *Mapa metalogénico de Colombia 2020*. Memoria explicativa. Servicio Geológico Colombiano.

Thébault, E., Finlay, C. C., Beggan, C. D., Alken, P., Aubert, J., Barrois, O., Bertrand, F., Bondar, T., Boness, A., Brocco, L., Canet, E., Chambodut, A., Chulliat, A., Coïsson, P., Civet, F., Du, A., Fournier, A., Fratter, I., Gillet, N., … Zvereva, T. (2015). International Geomagnetic Reference Field: the 12th generation. *Earth, Planets and Space*, *67*, 79. https://doi.org/10.1186/s40623-015-0228-9

Yang, C., Yang, C., Kao, S., Lee, F., & Hung, P. (2004). Twelve different interpolation methods: A case study of Surfer 8.0. In *Proceedings of the XXth ISPRS Congress* (pp. 778-785). http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.183.7288

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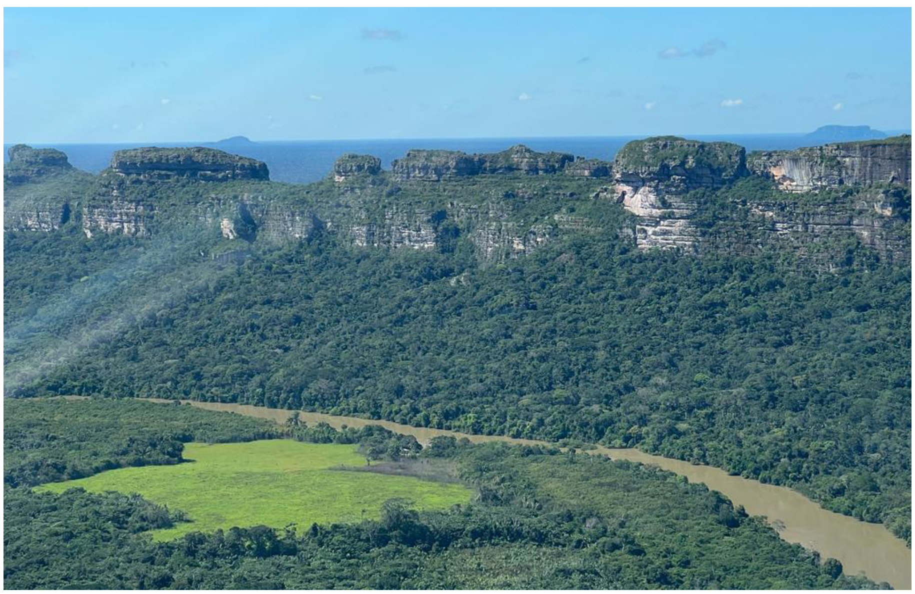

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