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AIRBORNE GEOPHYSICAL SURVEYING OF MAFIC-ULTRAMAFIC BODIES: A STUDY CASE FROM JACURICI COMPLEX (BAHIA)

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Abstract

The Jacurici mafic-ultramafic Complex hosts the largest chrome deposit in Brazil. This deposit is characterized by the presence of a massive chromitite layer that occurs in a single intrusion tectonically fragmented that, currently, outcrops in different segments along an N-S belt. The present work investigates the characteristics of these bodies through remote sensing techniques and airborne geophysical surveys, describing the geophysical and landform responses of economic targets. The study area presents magnetic anomalies when using 1st derivative filters and tilt derivative of the total magnetic field, whereas eU/K and eTh/K ratios define the best delimitations of igneous bodies using the gamma-spectrometric method. The information presented serves as a prospective parameter in the discovery of new lateral bodies in order to provide a guide for the discovery and analysis of similar deposits by Brazil.

Keywords: Jacurici mafic-ultramafic complex; Mineral prospecting; Regional geophysics.

ANÁLISE PROSPECTIVA DE CORPOS MÁFICOS-ULTRAMÁFICOS ATRAVÉS DE AEROGEOFÍSICA: CASO DE ESTUDO DO VALE DO JACURICI/BAHIA

Resumo

O Complexo máfico-ultramáfico Jacurici abriga o maior depósito de cromo do Brasil. Esse depósito é caracterizado pela presença de uma camada maciça de cromitito que ocorre em uma única intrusão tectonicamente fragmentada que, atualmente, aflora em diferentes segmentos ao longo de uma faixa N-S. O presente trabalho investiga as características desses corpos através de técnicas de sensoriamento remoto e levantamentos aerogeofísicos, descrevendo as respostas gamaespectrais, sucessibilidade magnética e de relevo dos alvos econômicos. A área de estudo apresenta anomalias magnéticas quando se utilizam filtros de 1ª derivada e tilt derivativo do campo magnético total, ao passo que razões eTh/K e eU/Kapresentam as melhores delimitações dos corpos ígneos utilizando o método gamaespectrométrico. As informações apresentadas servem como parâmetro prospectivo na descoberta de novos corpos laterais, a fim de prover guia para a descoberta e análise de corpos similares.

Palavras-chave: Complexo máfico-ultramáfico Jacurici; Prospecção mineral; Geofísica regional.

ANÁLISIS PROSPECTIVO DE CUERPOS DE MÁFICOS-ULTRAMÁFICOS MEDIANTE AEROGEOFÍSICA: ESTUDIO DE CASO DE VALE DO JACURICI / BAHIA

Resumen

El Complejo Máfico-Ultramáfico Jacurici alberga el mayor depósito de cromo de Brasil. Este depósito se caracteriza por la presencia de una capa masiva de cromitita que se presenta en una sola intrusión tectónicamente fragmentada que, actualmente, aflora en diferentes segmentos a lo largo de un cinturón N-S. El presente trabajo analiza las características de estos cuerpos mediante técnicas de teledetección y levantamientos aerogeofísicos, describiendo las respuestas geofísicas y de relieve de los objetivos económicos. El área de estudio presenta anomalías magnéticas al utilizar filtros de 1ª derivada y derivada de inclinación del campo magnético total, mientras que las relaciones eU / K y eTh / K definen las mejores delimitaciones de cuerpos ígneos mediante el método gamma-espectrométrico. La información presentada sirve como parámetro prospectivo en el descubrimiento de nuevos cuerpos laterales con el fin de proporcionar una guía para el descubrimiento y análisis de depósitos similares por Brasil.

Palabras-clave: Complejo máfico-ultramáfico Jacurici; Prospección mineral; Geofísica regional.

1. INTRODUTION

The Jacurici Complex host the largest Brazilian chromium-rich deposit (MARINHO *et al.*, 1986), and the exploration occurs since the 70s by FERBASA, with current production of approximately 300 T of chromite (35 a 40 w% of Cr_2O_3). Chromium (Cr) is a chemical element with wide use in the metallurgical, chemical, and refractory industries (KOLELI; DEMIR, 2016). This element is mainly found in Chromespinel (CLARK, 1978; IRVINE, 1967).

Mining is located in the municipality of Andorinha, in Bahia, belonging to the Piemonte Norte territory of Itapicuru, home to approximately 260 thousand inhabitants (SEPLAN, 2013). Despite the social advances achieved in the region over the last 20 years, the territory still has high illiteracy rates and low adherence to basic sanitation systems (SEPLAN, 2013). From this perspective, industrial enterprises, such as mining, under strict environmental protocols, serve as economic vectors for the social development of regions of human vulnerability.

The present work seeks to characterize and obtain prospective guides for deposits associated with mafic-ultramafic rocks, using the Jacurici Complex as an example. Aware of the high mineral potential in the Brazilian territory, the study applied in the area can help identify new bodies and delimit known deposits. Similar studies were applied to identify mineral deposits, such as the deposit of platinoids and chromium in the Carajás Province (FILHO *et al.*, 2007) or the ultramafic-associated deposits of the Morro Feio (SILVA; DUQUE; ALVES, 2019) in Brazil. Additionally, geophysical techniques have been applied to the identification of mineral prospects around the world, such as the Ni-Cu sulfide deposits of the Longshoushanna China group (VAN DER MEER; LIHUI; BODECHTEL, 1997), the kimberlite rocks of western Greenland (TUKIAINEN; THORNING, 2005), the Ni-Cu sulfide deposits of the Eastern region from Arunta in Australia and ultramafic rocks from Northern Norway (KARLSEN; OLESEN, 1996). To attend the aim, regional airborne geophysical surveys– gamma spectrometry and magnetic susceptibility – were used to identify the intensity of the different types of geophysical signals in the bodies classifying their effectiveness in the identification of mafic-ultramafic bodies possibly enriched in Cr.

2. GEOLOGIC CONTEXT

2.1. Regional Geology

The Mafic-ultramafic Jacurici Complex occurs in the northeastern portion of the São Francisco Craton (Figure 1). This craton consists of high-grade Archean to Paleoproterozoic gneiss (migmatitic-granulitic) terrains and granite-greenstone supracrustal terrains, covered by Meso- to Neoproterozoic continental shelf-type terrains (OLIVEIRA; MCNAUGHTON; ARMSTRONG, 2010; TEIXEIRA *et al.*, 2010). Specifically for basement rocks, the studies in the area were carried out by (OLIVEIRA; MCNAUGHTON; ARMSTRONG, 2010) and (SILVEIRA *et al.*, 2015). Currently, discussions are focused on the regional and temporal positioning of the Jacurici Complex magmatism in relation to its basement areas, which is a matter of debate. The mafic-ultramafic rocks have been interpreted as intrusive either in the Serrinha Block (KOSIN *et al.*, 2003; OLIVEIRA; MCNAUGHTON; ARMSTRONG, 2010; OLIVEIRA; CARVALHO; MCNAUGHTON, 2004), Salvador-Curaçá Belt (BARBOSA; SABATÉ, 2003; MISI *et al.*, 2012; TEIXEIRA *et al.*, 2010), or in both (SILVEIRA *et al.*, 2015) during the Paleoproterozoic.

The most recent geological mapping in the area was carried out by CPRM (COSTA, 2014). In this map, the area was considered as fully inserted in the Santa Luz Complex, of Mesoarchean age, and belonging to the Serrinha Block (Figure 2). The basement units are metasomatized migmatitic orthogneisses, tonalitic to granodiroritic migmatitic orthogneisses, calcitic to dolomitic marbles and garnet biotite gneiss. According to this map, the Mafic-Ultramafic Jacurici Complex is hosted in the biotite gneiss garnet unit (3085 ± 6 Ma, OLIVEIRA et al. 2002), although in a more detailed scale there is an wider diversity of lithologies. To the west, intrusive Rhyacian granitoids occur, represented by the Itiúba Sienitic Massif (2084 ± 10 Ma, (OLIVEIRA; CARVALHO; MCNAUGHTON, 2004)). The Salvador-Curaçá Belt rocks, represented by the Caraíba Complex (granulite orthogneisses, 2695 ± 12 Ma, SILVA et al. 1997) and the Tanque Novo-Ipirá Complex (aluminous, calc-silicate gneisses, quartzites and metacalcareous), outcrop in the extreme northwest of the area. For the mafic-ultramafic rocks of the Jacurici, U-Pb SHRIMP dating (OLIVEIRA; CARVALHO; MCNAUGHTON, 2004) in zircons of norites indicated an age of 2085 ± 6 Ma, currently being interpreted as the time of the crystallization of the Jacurici Complex. However, (SILVEIRA *et al.*, 2015) obtained a LA-ICP-MS U-Pb age of 2102 ± 5 Ma in zircons from metanorites and concluded that it could represent the first pulses of mafic-ultramafic magmatism of the Jacurici Complex. Nevertheless, all ages should be carefully evaluated, considering that they could be, alternatively, related to regional metamorphism instead.

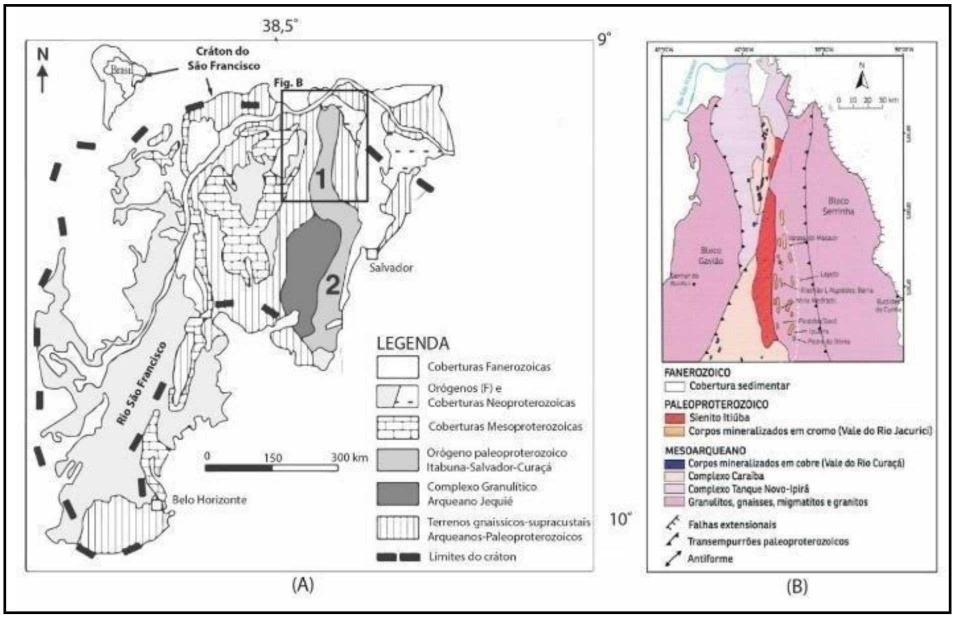

Figure 1 - (A) São Francisco Craton map showing the North (1) and South (2) segments of the Itabuna-Salvador-Curaçá Belt. (B) Detail of the North segment of the Itabuna-Salvador-Curaçá Belt showing the location of the Cr-rich bodies of the Jacurici Complex. Modified from MENEZES LEAL; BARBOSA; CORRÊA-GOMES, 2012; OLIVEIRA; MCNAUGHTON; ARMSTRONG, 2010).

The structural and metamorphic evolution of the area is available in few works, and MARINHO et al. (1986) remain the main reference. The following events were reported: (1) Deformation event D1, responsible for isoclinal folding and transposition, having the foliation S1 parallel to S0 well preserved in the host supracrustal rocks (Garnet Biotite Gneiss) and in the granodiorite orthogneisses (G1); (2) Deformational event D2, which tightly folds the S1 foliation of banded gneisses up to isoclinal. Coeval to this event, granodiorites and tonalites intrude (G2); (3) Deformational event D3, responsible for structuring the regional trend from NNE to NNW. During this event, occur intrusions of granitic to syenitic (G3) rocks, main represented by the Itiúba Sienite. Regarding metamorphism, only G3 intrusions were submitted to metamorphism into amphibolite facies; the others were metamorphosed into granulite facies conditions. According to Marinho et al. (1986), the Jacurici Complex was positioned in event D1, before the granodiorite orthogneisses (G1).

2.2. Geology of the Mafic-Ultramafic Jacurici Complex

The Mafic-Ultramafic Jacurici Complex (Figure 2) is constituted by more than 15 layered intrusive bodies oriented in the N-S direction. The complex hosts one of the main chromite reserves in Brazil, estimated to be more than 40 Mt, currently explored by the Mineração Vale do Jacurici S.A., FERBASA. It also hosts a Ni-Cu sulfide mineralization in its northern portion. The Jacurici Complex was studied in detail in the southern part of the Complex (Ipueira-Medrado segment, BARBOSA de DEUS and VIANA (1982), MARQUES and FILHO (2003), MARQUES et al. (2003)), and, more recently, other studies have investigated the central (Monte Alegre Sul segment, FRIEDRICH et al. (2020)) and the northern part (Várzea do Macaco segment, (DIAS *et al.*, 2014). MARQUES et al. (2017) review the geology and introduces new concepts about the Complex. The mineralized bodies that compose the Jacurici Complex have several characteristics in common, with an average of less than 300 m thick and the occurrence of a thick chromitite layer in all bodies, called Main Chromite Layer. This layer has been used as a stratigraphic marker for correlation between the different tectonically disrupted segments and allowed the estimate that the mineralized bodies were a single intrusion previously, although the magmatic province is considered much wider (MARQUES *et al.*, 2017). The mafic-ultramafic bodies are deformed, folded, faulted and metamorphosed into upper amphibolite to granulite facies, although they locally preserve many features and original magmatic mineralogy(FRIEDRICH *et al.*, 2020; MARQUES; FILHO, 2003).

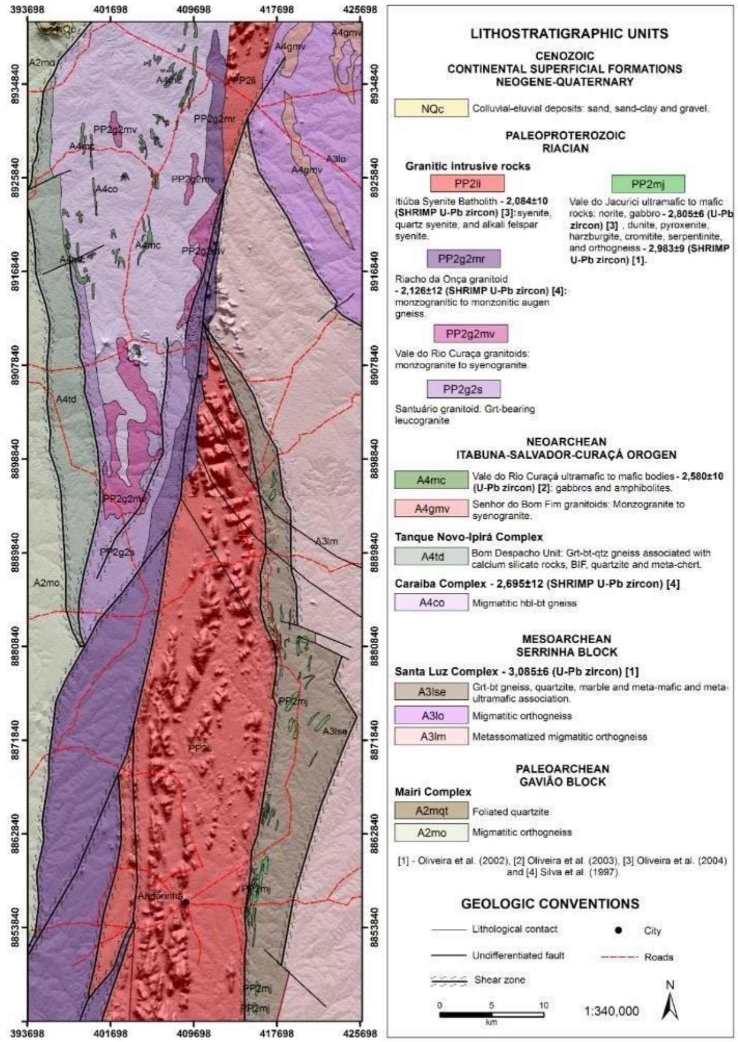

Figure 2 - Simplified Geological Map of the Vale do Jacurici and Vale do Curaçá regions (modified from COSTA, 2014).

Marques e Filho (2003) subdivided the intrusion into 3 main zones based on the rock composition in the Medrado-Ipueira segment, from the bottom to the top, into Marginal zone, composed of pyroxene-rich gabbros; Ultramafic Zone, subdivided into Lower Ultramafic Unit, Main Chromite Layer and Upper Ultramafic Unit; and, lastly, the Mafic Zone, composed of norites with variable proportions of orthopyroxene and plagioclase (Figure 3). The authors, based on the cryptic variation of olivine and orthopyroxene, identified a complex petrological evolution (Figure 3). An open magmatic regime was recognized in the interval that precedes the formation of the Main Chromite Layer, with a cyclic contribution of primitive magma in the magmatic chamber, while, after this layer, a closed regime occurs marked by normal fractional crystallization. Below the Main Chromite Layer, along with the Lower Ultramafic Unit, a gradual increase in the Mg content of the minerals was observed and, above this layer, along with the Upper Ultramafic Unit, there was a rapid evolution towards a more differentiated composition enriched in Fe (Figure 3). This demonstrated that the massive chromite layer must have formed during a drastic change of the magmatic evolution. Regarding sulfide mineralization, it was observed that the contents of forsterite and Ni in olivines are positively correlated throughout the stratigraphy of the Ipueira-Medrado segment, which added to the absence of sulfides at this location, demonstrates that no early sulfur saturation has occurred in the system. It is a favourable aspect for the possibility of sulfide mineralization in the region.

The formation of such a thick chromitite layer (5-8 m), as the Main Chromite Layer of the Jacurici Complex, is difficult to explain considering current models. For this reason, (FRIEDRICH *et al.*, 2020; MARQUES *et al.*, 2003) studied in detail the formation of the chromitite and concluded that the interval of the Main Chromite Layer is characterized by important changes in the physicochemical conditions of the magmatic chamber. Such changes are marked by the change of the magmatic regime and by an increase in the amount of amphibole during and after the layer formation. This information, together with mineral chemistry data and Nd and Os isotopic data, provided strong evidence that the chromitite may have formed after a very primitive magma, enriched in Mg and Cr, suffered crustal assimilation (MARQUES *et al.*, 2003).

Trace element geochemistry data showed that both the Upper Ultramafic Unit and the Lower Ultramafic Unit crystallized from similar parent magmas. This magma was enriched in LREE and LILE, depleted in Ta and enriched in Zr. These features, along with other factors (e.g. large amount of fluids), suggest two possibilities: (1) the parent magma was similar to a high-Mg basalt or komatiite generated by partial fusion of a convective mantle, subsequently enriched in LREE and LILE by interaction with some ancient Archean crustal component; or, (2) the parental magma originated from an ancient metasomatized subcontinental lithospheric mantle, probably the roots of an Archean Craton. In the latter case, the parent magma would not be contaminated by crustal material before intruding, with the enrichment in LILE and LREE and the low Ta and high Zr contents being explained by some residual Ti-rich phase in the enriched mantle (MARQUES *et al.*, 2003).

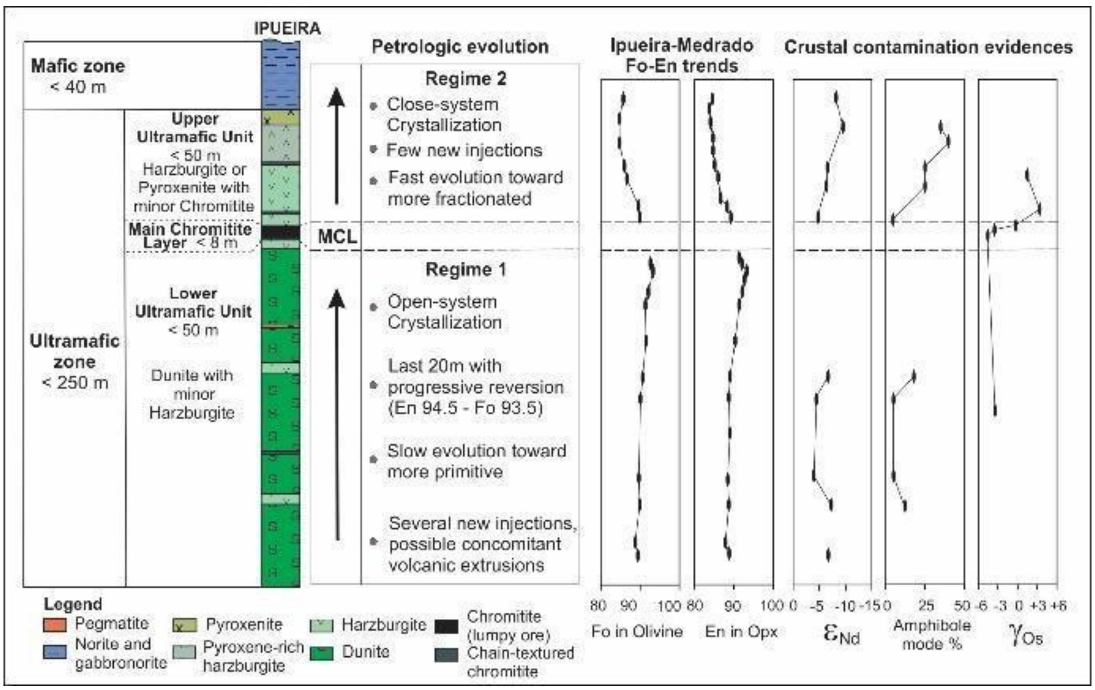

Figure 3 – Cryptical variation of (Ce/Sm), εNd, amphibole modal composition and γOs in the Ipueira-Medrado area. Stratigraphic variations of (Fo) in olivine and (En) and orthopyroxene are also represented. LUU, Lower Ultramafic Unit; MCL, Main Chromitite Layer; UUU, Upper Ultramafic Unit (Data from Marques et al., 2003)

Marques et al. (2003) carried out, together with the trace element studies, a careful isotopic study of Nd and Os. The results showed negative initial ε_{Nd} values for all samples, the most negative being those enriched in amphibole. Such data are consistent with a parent magma contaminated initially with crustal material or derived from an ancient metasomatized subcontinental lithospheric mantle source enriched in LREE. However, negative γ_{Os} values below the Main Chromite and positive above this layer, and in the Upper Ultramafic Unit, combined with more negative ε_{Nd} values in samples with more abundant amphibole in these intervals, suggest that the magma was contaminated in the magmatic chamber during crystallization, exactly in the interval forming the chromitite.

Therefore, the likely parental magma for Jacurici Complex is a high-Mg (picritic or U-type basalt of the Stillwater Complex) generated from a Re-depleted subcontinental lithospheric mantle (ancient), with the presence of a rich residual Ti phase, or metasomatized by a fluid deficient in HFSE. The magma was later contaminated with up to 30% of Archean continental crust, possibly within the magma chamber, triggering the crystallization of the Main Chromitite (MARQUES *et al.*, 2003).

However, the anomalous thickness (up to 8 m-thick) of the Main Chromite is a major mass balance problem. Considering the Cr_2O_3 content reported for mafic magmas and the volume of silicate rock observed, such a thick chromitite could only be explained if the intrusion acted as a conduit in which a large volume of magma flowed through. Thus, better understanding the regional context and evaluating other magmatic expressions possibly correlated to this magmatism is crucial for understanding the chromium deposit and can help in the prospecting of new targets.

3. MATERIALS AND METHODS

The data for the study area were obtained from the Companhia Baiana de Pesquisa Mineral (CBPM), from the airborne geophysical survey of the Riacho Seco-Andorinha sector. A total of 11030 km2 were surveyed by the company LASA Engenharia e Prospecções SA. For this purpose, an aircraft with a fixed wing, a system coupled with gamma spectrometry and magnetic sensors were used. The survey of the area consisted of transects every 250 m in the E–O direction, with control lines every 2500 m in the N-S direction, with a flight height of 250 m. Geophysical sensors collect samples every 0.1 and 1.0 s (magnetic and gamma spectrometry, respectively), with a Cs vapor sensor and a resolution of 0.001 nT (magnetic) and 256 spectral channels (gamma spectrometry) (LASA, 2002). The geological delimitation of the Jacurici bodies was based on the geological survey of the Bahia State (CBPM/CPRM, 2003), although, in detail, the Jacurici Complex is characterized by several discontinuous segments included in the location area (Figure 4). The segments here called North and South include bodies from the Monte Alegre Sul and Ipueira-Medrado area, respectively, as well as other adjacent bodies already detailed in other studies. The bodies located in the far North, including Várzea do Macaco, are outside the studied area here.

Magnetic and gamma spectrometric data are usually dismembered, through transformations and filters, in order to obtain different facets of the same data. From the total magnetic field (figure 5B), the derivative tilt, analytical signal and 1st derivative of the magnetic field were obtained. The analytical signal is defined as the magnitude of the sum of the three directional derivatives of the magnetic bodies, serving as a parameter in the delimitation of the bodies by recovering angular variations in the margins of the bodies (NABIGHIAN, 1972). The 1st derivative of the magnetic field consists of a high-pass filter that removes high-frequency signals in order to obtain anomalies with more defined edges (ISLES; RANKIN, 2013). The derivative tilt is obtained by the arctan of the ratio between 1st derivative and total lateral derivative, resulting in a filter similar to the 1st derivative, but with deeper information (MILLER; SINGH, 1994). For airborne gamma spectrometry data, three natural sources of gamma radiation are obtained, resulting from the decay of U-Th-K elements (MINTY, 1997), calibrated in order to obtain quantifiable values (notation "e” indicating equivalent). Additionally, the radioactive responses of the elements are applied to the ratios between elements, to highlight certain types of lithologies and the RGB ternary composition, synthetically coloring the values of red, green and blue with the values of potassium, thorium equivalent and uranium equivalent, respectively.

Nine maps were created from these data (Figures 4, 5 and 6) and, from them, the magnetic, gamma-spectrometric and landform responses were qualitatively analyzed. Variations of the geophysical signal were established, and the application of each one for the identification and delimitation of ultramafic bodies was described, evaluating their effectiveness as prospective parameters. Table 1 compiles the results.

4. RESULTS AND DISCUSSION

The study area (Figure 4) is located in the North of the State of Bahia, in the municipality of Andorinha, about 420 km from Salvador. The satellite image demonstrates a flat landform in the area, without indicative textures, contrasting with the adjacent granitic terrains located to the west.

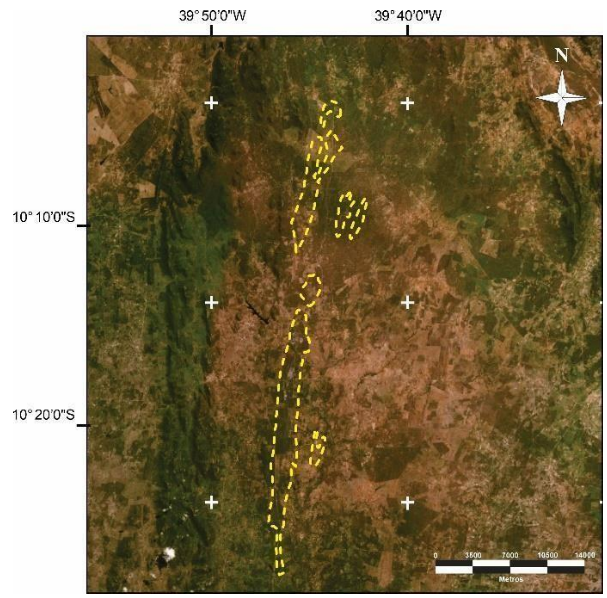

Figure 4 - Sattelite image showing a flat landscape in the studied area and no significant geomorphological features. Image extracted from ESRI (2021) and delimitation of mafic-ultramafic bodies-bearing areas is from Costa et al. (2014).

The magnetic susceptibility data of the study area reveal heterogeneous results in the identification of the Jacurici Complex. Figure 5 presents the maps for: (1) total magnetic field derivative tilt; (2) total magnetic field; (3) analytical signal of the total magnetic field; (4) 1st derivative of the total magnetic field. The derivative tilt interaction presents high to intermediate values for the segments, showing higher values, especially in the northern sectors (Figure 5A). Additionally, this filter identifies N-S lineaments in the studied area. The total magnetic field (Figure 5B) illustrates the lineaments of the studied area, but it does not give any type of anomaly or variation in magnetic values for the bodies. The analytical signal filter for the total magnetic field (Figure 5C) gives positive attributes in the identification of bodies, presenting high values with good delimitation, especially for the South area. However, the maps show similar magnetic responses for the group of rocks adjacent to the interest area, limiting its effectiveness. The filter of the 1st derivative of the total magnetic field (Figure 5D) satisfactorily demonstrates the regional structures, but does not describe the bodies in any way.

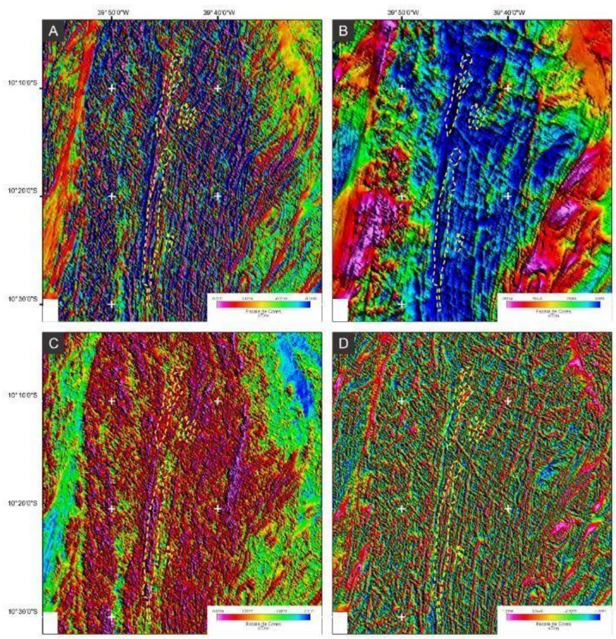

Figure 5 - Magnetic susceptibility maps for the Jacurici Complex region, showing the magnetic anomalies for the (A) Tilt type interactions derivative of the total magnetic field; (B) Total magnetic field; (C) Analytical signal of the total magnetic field; (D) 1st derivative of the total magnetic field.

The gamma spectrometry data in the studied area show diverse responses to the following filters: (1) eU, (2) eTh, (3) K, (4) total, (5) eU/eTh, (6) eU/K, (7) eTh/K and (8) ternary. Element K (Figure 6A) presents a strong anomaly related to the Itiúba alkaline complex, adjacent to the interest area, limiting the elements potential in identifying the mineralized body. The eU element (Figure 6B) is characterized by low content, not presenting any anomaly in the area of the bodies, only showing, in an incipient way, the regional lineament. The Th element (Figure 6C) presents values from intermediate to high, along with consistent N/S structures and good demarcation of bodies, especially in North area. The total count (Figure 6D) demonstrates a behaviour similar to K, showing intermediate values in the North area and low values in the South area. Despite the significant anomaly of the Itiúba Complex, it is possible to define the bodies in the North. The eU/eTh ratio (Figure 6E) presents intermediate values, with partial delimitation of the bodies, but marks the N-S lineament. The eU/K channel (Figure 6F) presents intermediate values for the area, showing good differentiation in relation to the background but with limited ability to identify the boundaries of the bodies. The eTh/K channel (Figure 6G) satisfactorily shows the N-S lineament, with good background differentiation, especially in the South. In the RGB composition (Figure 6H), the bodies do not present differentiation in relation to the background.

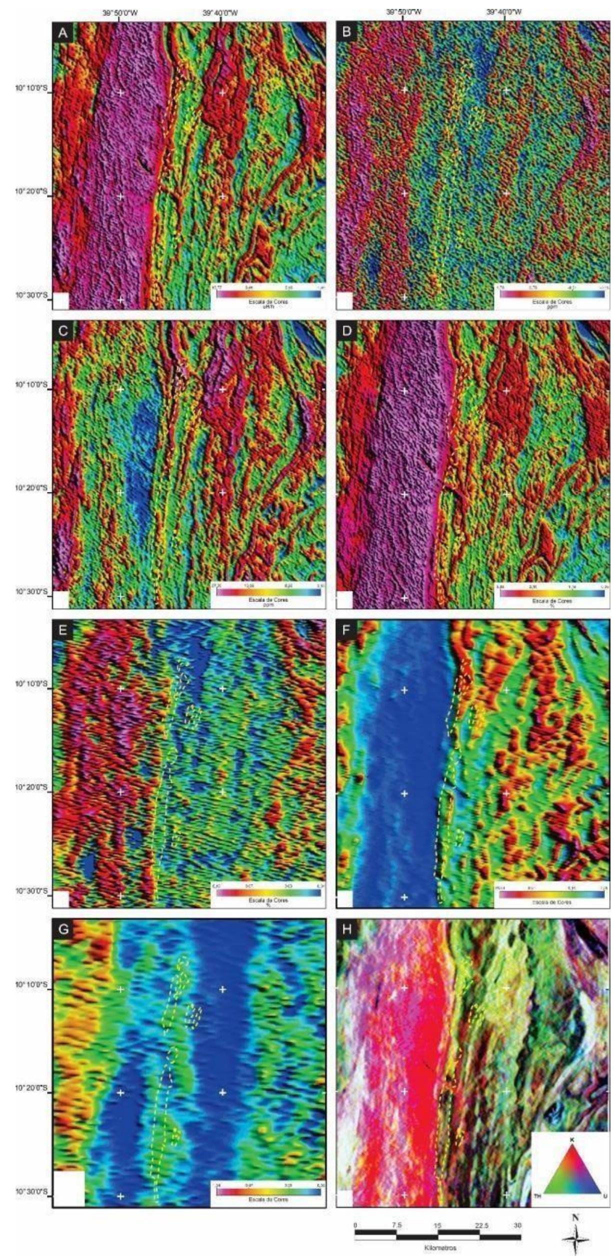

Figure 6 - Gamma spectrometry maps for the Jacurici Complex region, showing the radiometric anomalies for A) K content (%); B) U content (ppm); C) Th content (ppm); D) Total count values; E) eU/eTh ratio; F) eU/K ratio; G) eTh/K ratio; H) ternary RGB composition with values of U, Th and K.

Table 1 compiles the results presented for each remote sensor, presenting a simplified description, the variation of the values found (nTm-1 for the magnetic signal and % and ppm for gamma spectrometry) and their effectiveness in identifying and delimiting the segments with large mafic-ultramafic bodies of the Jacurici Complex.

Table 1- Compilation of the remote sensing responses in áreas with mineralized bodies (data from 1- ESRI database; 2 e 3 – CPBM geophysical survey).

	Remote Sensor	Description	Range values	Efficiency
Geomorphology and relief	Satellite imaging[1]	Low relief, without lumps or indicative textures	-	Low
Magnetic anomaly	Derivative tilt [2]	Display the N-S lineament; however, it lacks the detailing to delimitate the segments	from -1.3 to 1.3 nT/m	Medium
	Analytic signal[2]	Positive signal in the segment area, displaying the N-S lineation, delimiting the segment margins with good accuracy. Similar results are found in lateral granitic bodies, undermining their regional prospective potential	from 0.24 to 0.44 nT/m	High-medium
	1ª derivative[2]	Display the N-S lineament, with anomaly from N to S segments. Overall, it presents a heterogeneous signal	from -0.2 to 0.2 nT/m	Low
	Total magnetic field[2]	Low magnetic signal, without clear lineaments/structural identification	from 2489 to 2505 nT/m	Low
Gamaspectrometry	eU[3]	Low U concentrations limits the results	from -0.15 to 0.4 ppm	Low
	eTh[3]	High Th signal displays the N-S lineation but with an overall heterogeneous signal	from 9 to 27 ppm	Medium-low
	K[3]	Intermediary K signal, partially displaying the bodies lineation and delimiting the segments. However, the K signal is related to the lateral granitic bodies, undermining the segments delineations.	From 1.0 to e 3.0 %	Medium-low
	Total[3]	High-to-medium signal, with N well-defined segments in N region, but with an overall heterogeneous answer	from 5 to 10 uR/h	Medium
	eU/eTh[3]	Intermediary homogeneous ratio, but with limited potential to delimiting the segments	around 0.4	Medium-low
	eU/K[3]	Intermediary ratio with homogeneous distribution, with intermediary delimitation segment potential.	around 24	Medium-high
	eTh/K[3]	Intermediary ratio with homogeneous distribution, with intermediary delimitation segment potential.	from 5 to 10	Medium
	K, Th and U ternary composition [3]	Heterogeneous signal, with delimitation segment potential	Intermediary U, Th, and K values	Low

GALBRAITH and SAUNDERS (1983) present the distribution of elements measured by gamma spectrometry in rocks, identifying values around 7 ppb for U, 20 ppb for Th and 0.01% for K for ultrabasic igneous rocks, similar to other deposits found in Brazil such as the Morro Feio Complex (SILVA; DUQUE; ALVES, 2019). The alkaline granitic bodies of the Jacurici region, especially the Itíuba Sienite, tend to dominate the positive anomalies of the gamma spectrometry, especially in the K channel. Anomalies of this magnitude can mask the effects of smaller bodies, such as those of the Jacurici Complex. The high contrast between the Sienite Itiúba and its basement rocks blur the low levels of K and U of the Jacurici Complex, producing an indistinct signal in relation to the local background. The resolution of the geophysical sensors and the low areal extension of the mafic-ultramafic bodies of the Jacurici impose uncertainties on the signals found. However, SILVA, DUQUE and ALVES (2019) characterize the Morro Feio Ultramafic Complex as delimited by the K/Th and U/Th ratios. A similar result was also observed in the areas where the bodies of the Jacurici Complex occur. Thus, these parameters can be considered as an auxiliary tool in the delimitation of areas with greater prospective interest. Additionally, variations in the results of the North and South areas may indicate differences in the local geology, possibly in basement rocks.

In summary, it is possible to verify the greater efficiency of the derivative tilt and magnetic signal methods in the magnetic susceptibility survey and the eTh/K, eU/eTh, and U/K in the gamma spectrometry data as a combined local method for delimitation of areas with mafic-ultramafic bodies of the Jacurici Complex, constituting the most appropriate parameters for regional prospecting when using these sensors.

4. CONCLUSIONS

The study characterizes the geophysical and landscape responses of mafic-ultramafic bodies in the Jacurici Complex, through the petrophysical attributes of magnetic susceptibility and gamma spectrometry. Eleven maps of the studied area were generated using the mentioned remote sensors, and, subsequently, we have elaborated a table with the main attributes observed. The data show that: (1) landscape and geomorphology information based on satellite images give poor results for the bodies; (2) the magnetic tilt and analytical signal interactions demonstrate the best potential for identifying and delimiting the segments hosting the bodies, due to the higher and more prominent values in relation to the background; (3) the eTh/K, eU/eTh ratios present the best results for the segments with bodies and could help the prospection. Additionally, our results suggest that the segment located to the North present variations in the geophysical responses in relation to the South, as shown in figures 5B and C and 6. The identification and delimitation of similar segments hosting mafic-ultramafic bodies should use combined remote sensors, such as those used here, in order to eliminate noise and differentiate targeting areas from the background.

5. REFERÊNCIAS

BARBOSA DE DEUS, P.; VIANA, J.D.S. Jacurici valley chromite district. *In*: , 1982, Salvador. *INTERNATIONAL. SYMPOSIUM ON ARCHEAN AND EARLY PROTEROZOIC GEOLOGIC EVOLUTION AND METALLOGENESIS*. Salvador: [*s. n.*], 1982. p. 97–107.

BARBOSA, J.S.F.; SABATÉ, P. Paleoproterozoic collage of Archean plates of the São Francisco Craton in Bahia. *Rev Bras Geoc*, [*s. l.*], v. 33, n. 1, p. 7–14, 2003.

CLARK, T. Oxide minerals in the Turnagain ultramafic complex, northwestern British Columbia. *Canadian Journal of Earth Sciences*, [*s. l.*], v. 15, n. 12, p. 1893–1903, 1978. Disponível em: https://doi.org/10.1139/e78-201

COSTA, I.G.V. *Carta Geológica Preliminar - Folhas Andorinha (SC.24-Y-B-II) e Pinhões (SC.24-V-D-V)*. Salvador: [*s. n.*], 2014.

DIAS, J.R.V.P. *et al.* O corpo Várzea do Macaco e as mineralizações de cromo, níquel e cobre, Complexo Máfico-ultramáfico Jacurici, Cráton São Francisco, Bahia. *Brazilian Journal of Geology*, [*s. l.*], v. 44, n. 2, p. 289–308, 2014. Disponível em: https://doi.org/10.5327/Z2317-4889201400020009. Acesso em: 30 jan. 2021.

FILHO, C.R.S. *et al.* Spatial analysis of airborne geophysical data applied to geological mapping and mineral prospecting in the Serra Leste Region, Carajás Mineral Province, Brazil. *Surveys in Geophysics*, [*s. l.*], v. 28, n. 5–6, p. 377–405, 2007. Disponível em: https://doi.org/10.1007/s10712-008-9031-5

FRIEDRICH, B.M. *et al.* Petrogenesis of the massive chromitite layer from the Jacurici Complex, Brazil: evidence from inclusions in chromite. *Mineralium Deposita*, [*s. l.*], v. 55, n. 6, p. 1105–1126, 2020. Disponível em: https://doi.org/10.1007/s00126-019-00917-0. Acesso em: 7 jan. 2021.

IRVINE, T. N. CHROMIAN SPINEL AS A PETROGENETIC INDICATOR: PART 2. PETROLOGIC APPLICATIONS. *Canadian Journal of Earth Sciences*, [*s. l.*], v. 4, n. 1, p. 71–103, 1967. Disponível em: https://doi.org/10.1139/e67-004

ISLES, D.J.; RANKIN, L.R. *Geological Interpretation of Aeromagnetic Data*. [*S. l.*]: Society of Exploration Geophysicists and Australian Society of Exploration Geophysicists, 2013. Disponível em: https://doi.org/10.1190/1.9781560803218. Acesso em: 19 abr. 2021.

KARLSEN, T.A.; OLESEN, O. Airborne geophysical prospecting for ultramafite associated talc, Altermark, northern Norway. *Journal of Applied Geophysics*, [*s. l.*], v. 35, n. 4, p. 215–236, 1996. Disponível em: https://doi.org/10.1016/0926-9851(96)00026-2

KOLELI, N.; DEMIR, A. Chromite. *In*: ENVIRONMENTAL

MATERIALS AND WASTE: RESOURCE RECOVERY AND POLLUTION PREVENTION. [*S. l.*]: Elsevier Inc., 2016. p. 245–263. Disponível em: https://doi.org/10.1016/B978-0-12-803837-6.00011-1

KOSIN, M. *et al*. Guia De Excursão - Geologia Do Segmento Norte Do Orógeno Itabuna-Salvador-Curaçá. *Revista Brasileira de Geociências*, [*s. l.*], v. 33, n. 1, p. 27–32, 2003. Disponível em: https://doi.org/10.25249/0375-7536.200333s12732

LASA, Prospecções. *Projeto Levantamento Aerogeofísico da Área Riacho Seco –Andorinha, Relatório final*. Rio de Janeiro: SICM/CBPM, 2002.

MARINHO, M.M. *et al*. Geologia e potencial cromitífero do Vale do Jacurici-Bahia. *In*: XXXIV CONGRESSO BRASILEIRO DE GEOLOGIA. GOIÂNIA. [*S. l.: s. n.*], 1986. p. 2074–2088.

MARQUES, J. C. *et al*. Re-Os and Sm-Nd isotope and trace element constraints on the origin of the chromite deposit of the Ipueira-Medrado Sill, Bahia, Brazil. *Journal of Petrology*, [*s. l.*], v. 44, n. 4, p. 659–678, 2003. Disponível em: https://doi.org/10.1093/petrology/44.4.659. Acesso em: 30 jan. 2021.

MARQUES, J.C. *et al*. Thick chromitite of the Jacurici Complex (NE Craton São Francisco, Brazil): Cumulate chromite slurry in a conduit. *Ore Geology Reviews*, [*s. l.*], v. 90, p. 131–147, 2017. Disponível em: https://doi.org/10.1016/j.oregeorev.2017.04.033. Acesso em: 30 jan. 2021.

MARQUES, J.C.; FILHO, C.F.F. The Chromite Deposit of the Ipueira-Medrado Sill, Sao Francisco Craton, Bahia State, Brazil. *Economic Geology*, [*s. l.*], v. 98, n. 1, p. 87–108, 2003. Disponível em: https://doi.org/10.2113/gsecongeo.98.1.87. Acesso em: 30 jan. 2021.

MILLER, H.G.; SINGH, V. Potential field tilt—a new concept for location of potential field sources. *Journal of Applied Geophysics*, [*s. l.*], v. 32, n. 2–3, p. 213–217, 1994. Disponível em: https://doi.org/10.1016/0926-9851(94)90022-1

MINTY, B. R.S. Fundamentals of airborne gamma-ray spectrometry. *AGSO Journal of Australian Geology and Geophysics*, [*s. l.*], v. 17, n. 2, p. 39–50, 1997.

MISI, A. *et al*. Principais Domínios Metalogéneticos. Ouro do Greenstone Belt do Rio Itapicuru. *Companhia Baiana de Pesquisa Mineral*, Texto Explicativo., Salvador, v. 1, n. 1, p. 109–126, 2012.

NABIGHIAN, M.N. The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: Its properties and use for automated anomaly interpretation. *Geophysics*, [*s. l.*], v. 37, n. 3, p. 507–517, 1972. Disponível em: https://doi.org/10.1190/1.1440276

OLIVEIRA, E.P.; CARVALHO, M.J.; MCNAUGHTON, N.J. Evolução do segmento norte do orógeno Itabuna-Salvador-Curaçá: cronologia da acresção de arcos, colisão continental e escape de terrenos. *Geologia USP. Série Científica*, [*s. l.*], v. 4, n. 1, p. 41–53, 2004. Disponível em: https://doi.org/10.5327/S1519-874X2004000100003. Acesso em: 30 jan. 2021.

OLIVEIRA, E. P.; MCNAUGHTON, N. J.; ARMSTRONG, R. Mesoarchaean to Palaeoproterozoic growth of the northern segment of the Itabuna–Salvador–Curaçá orogen, São Francisco craton, Brazil. *Geological Society, London, Special Publications*, [*s. l.*], v. 338, n. 1, p. 263–286, 2010. Disponível em: https://doi.org/10.1144/SP338.13. Acesso em: 30 jan. 2021.

SEPLAN, Secretaria do Planejamento do Estado da Bahia. ***Diálogos territoriais II: Piemonte Norte do Itapicuru***. [*S. l.: s. n.*], 2013.

SILVA, A.B.; DUQUE, T.R.F.; ALVES, F.M. Interpretation of radiometric ratios and magnetic anomalies from Morro Feio ultramafic complex, central-western Brazil. ***Revista Brasileira de Geofisica***, [*s. l.*], v. 37, n. 3, p. 309–324, 2019. Disponível em: https://doi.org/10.22564/rbgf.v37i3.2010

SILVEIRA, C.J.S. *et al*. Geocronologia U-Pb em zircão de rochas intrusivas e de embasamento na Região do Vale do Jacurici, Cráton do São Francisco, Bahia. *Brazilian Journal of Geology*, [*s. l.*], v. 45, n. 3, p. 453–474, 2015. Disponível em: https://doi.org/10.1590/2317-488920150030233. Acesso em: 7 jan. 2021.

TEIXEIRA, J.B.G. *et al*. Depósitos de cobre do Vale do Rio Curaçá, Bahia. *In*: R.S.C., Brito; M.G., Silva; R.M, Kuyumijan (org.). *São Paulo : modelos de depósitos de cobre no Brasil e sua resposta ao intemperismo. Brasília, Serviço Geológico do Brasil*. [*S. l.: s. n.*], 2010. p. 218.

TUKIAINEN, T.; THORNING, L. Detection of kimberlitic rocks in West Greenland using airborne hyperspectral data: The HyperGreen 2002 project. *Geological Survey of Denmark and Greenland Bulletin*, [*s. l.*], v. v. 7, n. 7, p. 69–72, 2005. Disponível em: https://doi.org/10.34194/geusb.v7.4845

VAN DER MEER, F.; LIHUI, F.; BODECHTEL, J. MAIS imaging spectrometer data analysis for Ni-Cu prospecting in ultramafic rocks of the Jinchuan group, China. *International Journal of Remote Sensing*, [*s. l.*], v. 18, n. 13, p. 2743–2761, 1997. Disponível em: https://doi.org/10.1080/014311697217314

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