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MAPPING OF CHROMITE OCCURRENCE IN A META-ULTRAMAFIC COMPLEX BY MAGNETOMETRIC PROSPECTING, SUL-RIOGRANDENSE SHIELD (SOUTHERN BRAZIL)

MAPEAMENTO DE OCORRÊNCIA DE CROMITA EM COMPLEXO METAULTRAMÁFICO POR MEIO DE PROSPECÇÃO MAGNETOMÉTRICA, ESCUDO SUL-RIOGRANDENSE (SUL DO BRASIL)

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ABSTRACT - This study presents the use of terrestrial magnetometry method in the characterization of a metamorphic and chromium-mineralized ultramafic rocks in the São Sepé region (RS). The most preserved rocks are gray to dark green serpentinites and occasionally magnesian schists with folds and variable fracturing that occur as a lenticular body enclosed within the host meta-volcano-sedimentary rocks. The chromite present in serpentinites is associated with magnetite and occurs in the form of small lenses. 1677 reading lines were made perpendicular to the main direction of the meta-ultramafic rock, with 25m spacing between measurement points. The magnetometric maps revealed high-intensity anomalies related to meta-ultramafic rocks. The results revealed the existence of highly magnetic individualized lenses orientated according to NE/SW. The direct relationship between high magnetization and chromite/ferro-chromite concentrations allows relatively detailed mapping of potentially mineralized areas, revealing dimensions more significant than the limits of the meta-ultramafic sequence defined in the geological map. The results indicate that the analytical signal amplitude map is a highly recommended product for planning sampling actions and reserve quantification, improving classical geological mapping.
Keywords: Mineral research. Chrome. Meta-ultramafic. Magnetometry. Analytical signal amplitude.

RESUMO - Este estudo apresenta a utilização do método de magnetometria terrestre na caracterização de rochas ultramáficas metamórficas e mineralizadas com cromo na região de São Sepé (RS). As rochas mais preservadas são serpentinitos cinzentos a verde-escuros e ocasionalmente xistos magnesianos com dobras e fraturamento variável, que ocorrem como um corpo lenticular contido em rochas meta-vulcano sedimentares hospedeiras. A cromita presente nas serpentinitas está associada à magnetita e ocorre na forma de pequenas lentes. Foram feitas 1.677 linhas de leitura perpendiculares à direção principal da rocha meta-ultramáfica, com espaçamento de 25m entre os pontos de medição. Os mapas magnetométricos revelaram anomalias de alta intensidade relacionadas às rochas meta-ultramáficas. Os resultados revelaram a existência de lentes individualizadas altamente magnéticas orientadas conforme NE/SW. A relação direta entre a elevada magnetização e as concentrações de cromita/ferrocromita permite um mapeamento relativamente detalhado de áreas potencialmente mineralizadas, revelando dimensões mais significativas que os limites da sequência meta-ultramáfica definida no mapa geológico. Os resultados indicam que o mapa analítico de amplitude de sinal é um produto altamente recomendado para planejamento de ações de amostragem e quantificação de reservas, melhorando o mapeamento geológico clássico.
Palavras-chave: Pesquisa mineral. Cromo. Meta-ultramáfica. Magnetometria. Amplitude do sinal analítico.

INTRODUCTION

Mining is a term that covers the processes, activities, and industries that aim to extract minerals from deposits or mineral masses. As an industrial activity, mining is indispensable for economic and technological development (Arndt & Ganino, 2012). A mineral deposit is formed by the ore, surrounded by sterile parts corresponding to the host rocks. The ore is an economically usable mineral, while minerals without commercial value are denominated gangue (Pereira, 2003).

Chromite is considered one of the most important industrial minerals in the world. It is used as a metallic and nonmetallic mineral for metallurgical, chemical, and refractory industries and as sand for foundry processes. The metallurgical industry emerges as the largest consumer of chromite products compared to the others (Chatterjee, 2007). Chromium is the fifth metal element of major industrial consumption. The world's largest reserves of chromite are distributed as follows: Kazakhstan (26.1%), South Africa (15%), India (3.2%) and other countries (59%). The total Brazilian reserves are 15 million tons, equivalent to 4.992 thousand tons of Cr_2O_3 contained, distributed among the states of Bahia (69%), in the municipalities of Campo Formoso, Andorinha, Uauá and Santa Cruz; Amapá (31%), in the municipality of Mazagão (ANM, 2019).

Prospecting and mineral exploration studies are fundamental for recognizing and incurporating new reserves in response to a growing demand for the internal market and export and trade balance equilibrium. The available tools include direct methods (drilling, soil and rock sampling, chemical analysis) and indirect methods such as remote sensing analysis and geophysical methods (Dentith & Mudge, 2014).

Geophysical methods allow quick and low-cost surveys compared to direct methods, although with relatively more significant uncertainties and ambiguities. This tool enables detecting and delineating features and structures of potential interest in the subsurface without a precise definition of composition or contents (Moon et al., 2006). In mineral exploration, these methods are highly applicable, as the contrast of physical properties between a potentially mineralized target and the hosting rock allows the correlation to economically significant mineral accumulations (Telford et al., 1990; Dentith & Mudge, 2014).

Among the array of geophysical methods, magnetometry has been applied in the study of mafic-ultramafic rocks due to the content of magnetite, which results in high contrast with the surrounding rocks, as demonstrated by several researchers (e.g., Yungul, 1956; Hansen, 1966; Bosum, 1970; Ruy et al., 2006; Súarez et al., 2012).

In this paper, we applied the magnetometry method to delimitate the geometry of chromium mineralization within meta-ultramafic rocks of the Basic-Ultrabasic Complex, Sul-Riograndense Shield. The magnetic results proved a robust correlation between magnetization intensity and anomalous elemental contents in geochemistry analyses and contributed to new potential target characterization.

LOCATION OF THE STUDY AREA

The study area is located in the Rincão do Funcho locality, São Sepé municipally, central region of Rio Grande do Sul state. Access to the area is possible by secondary roads about 7 km away from the intersection between BR-392 and BR-290 (Figure 1).

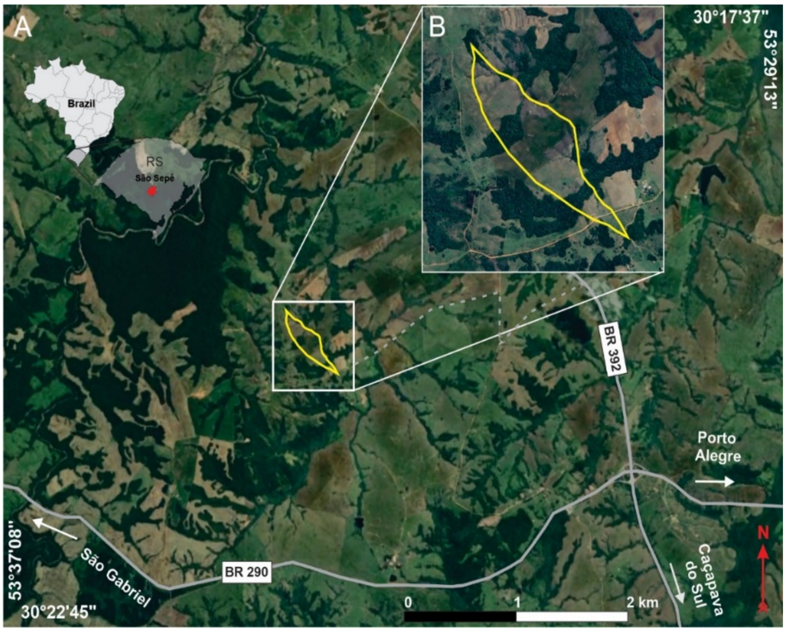

Figure 1 – Location of the study area (modified from Google Earth). A) Satellite image showing the access to the study area by secondary roads (dotted line) about 7 km from the intersection between BR-392 and BR-290 (gray lines). The inset shows the São Sepé municipality location in Rio Grande do Sul state. B) Detail of the study area showing the geological boundaries (yellow line) of meta-ultramafic rocks.

Semi-regional systematic studies on a scale of 1: 50,000 were carried out in the area, represented by geochemical prospecting in stream sediments and rock samples, as well as terrestrial and aerial geophysical studies, gathered in the Basic Geological Surveys Program (PLBG) Passo do Salsinho (SH.22-YAI-4). This study allowed the recognition of podiform chromite mineralization associated with the mafic-ultramafic bodies in the study area. The region is a target of many studies with applications of geophysical in mineral exploration in the occurrences of copper and gold (Moreira et al., 2012; Moreira & Ilha, 2011; Pereira et al., 2015; Cortês et al., 2016; Moreira et al., 2016).

GEOLOGICAL CONTEXT

The Sul-Riograndense Shield (Chemale Jr., 2000) is characterized by the pre-Cambrian rocks of the Rio Grande do Sul state, concerning the southern part of the Mantiqueira Province (Almeida & Hasui, 1984). According to Hartmann et al. (2007), the shield is the result of continental crust generation and deformation during two major orogenic cycles from 890 to 540 Ma, the Transamazonic (Paleoproterozoic) and the Braziliano cycles (Neoproterozoic).

The Sul-Riograndense Shield can be divided into four main geotectonic units (Chemale Jr., 2000): i) the Taquarembó block, which includes the cratonic basement of Paleoproterozoic and Archean ages (2.5 and 2.35 Ga); ii) the São Gabriel terrain, consisting of a Neoproterozoic juvenile crust; iii) the Tijucas terrain, formed by Paleoproterozoic nuclei and metamorphosed volcanic sedimentary rocks (Porongos Belt), and late to post-orogenic basins of Neoproterozoic to Eopaleozoic age (Camaquã Basin); and iv) the Pelotas Batholith, which corresponds to the post-collisional magmatism. The last three are part of the Dom Feliciano Belt (DFB), generated from the agglutination of the paleoplates Kahalari, Congo, and Rio de La Plata during the Braziliano orogenic system (Chemale Jr., 2000; Hartmann et al., 2007).

The study area is located at the São Gabriel Terrain, to the west of the DFB, which comprises granodioritic to tonalitic gneiss complexes, meta-volcanic-sedimentary associations, and meta-mafic-ultramafic rocks remaining from the ocean floor (Phillip et al., 2016). These rock associations correspond to the juvenile accreted island, magmatic arcs, passive and back-arc basins, and ophiolitic complexes (Chemale Jr., 2000; Hartmann et al., 2007). Such units are strongly controlled by N30-40°E trending shear zones that are easily recognized by magnetic anomalies (Hartmann et al., 2000; Phillip et al., 2016).

The study target corresponds to a discrete meta-ultramafic rock exposition related to the Basic-Ultrabasic Metamorphic Complex, located east of the Cambaí Gneissic Complex, and tectonically juxtaposed with the meta-volcano-sedimentary rocks of the Vacacaí Complex (Figure 2).

The Basic-Ultrabasic Metamorphic Complex consists of ophiolitic sequences composed mainly of metabasalts, amphibolites, and meta-ultramafic rocks, such as various magnesian schists (talc-tremolite and talc-chlorite schist, tremolite schist, olivine-talc schist) and serpentinites, with metamorphic facies from upper greenschist to amphibolite (Widner, 1990).

In the study area (Figure 2b), the Basic-Ultrabasic Metamorphic Complex outcrops as an elongated body bounded by low-angle NW-trending shear faults. It comprises mainly serpentinites involved by magnesian schists, characterized by an anastomosed NE-SW-trending schistosity marked by tremolite, serpentine, talc, and chlorite. Occasionally, olivine and amphibole relics are present on schists. The most preserved sites are grey to dark green rocks with open, moderately plunging folds trending to N-S to NE-SW, and locally NW-SE trending folds, and variable fracture cleavage. The most penetrative fracture cleavage presents NNE-SSW orientation, dipping 20º-45º to SE. Vertical veins filled with milky quartz are frequently associated with sub-vertical NW-trending fracture cleavage, especially near the body boundaries. Generally, chromite and magnetite occur as centimetric (1-5 cm) porphyroblasts in the serpentinites, along small lenses parallel to schistosity, located on the central parts of the meta-ultramafic body.

The Vacacaí Metamorphic Complex comprises a series of volcanic, volcanoclastic, and sedimentary rocks metamorphized on greenschist facies. It includes metapelitic rocks with subordinate unconsolidated meta-sandstone levels and, occasionally, ortho-derived rocks (Chemale Jr, 2000). The study area prenominates the meta-volcanoclastic rocks (Figure 2b), classified as meta-tuff with NE-SW-trending foliation parallel to sedimentary bedding. Structural features related

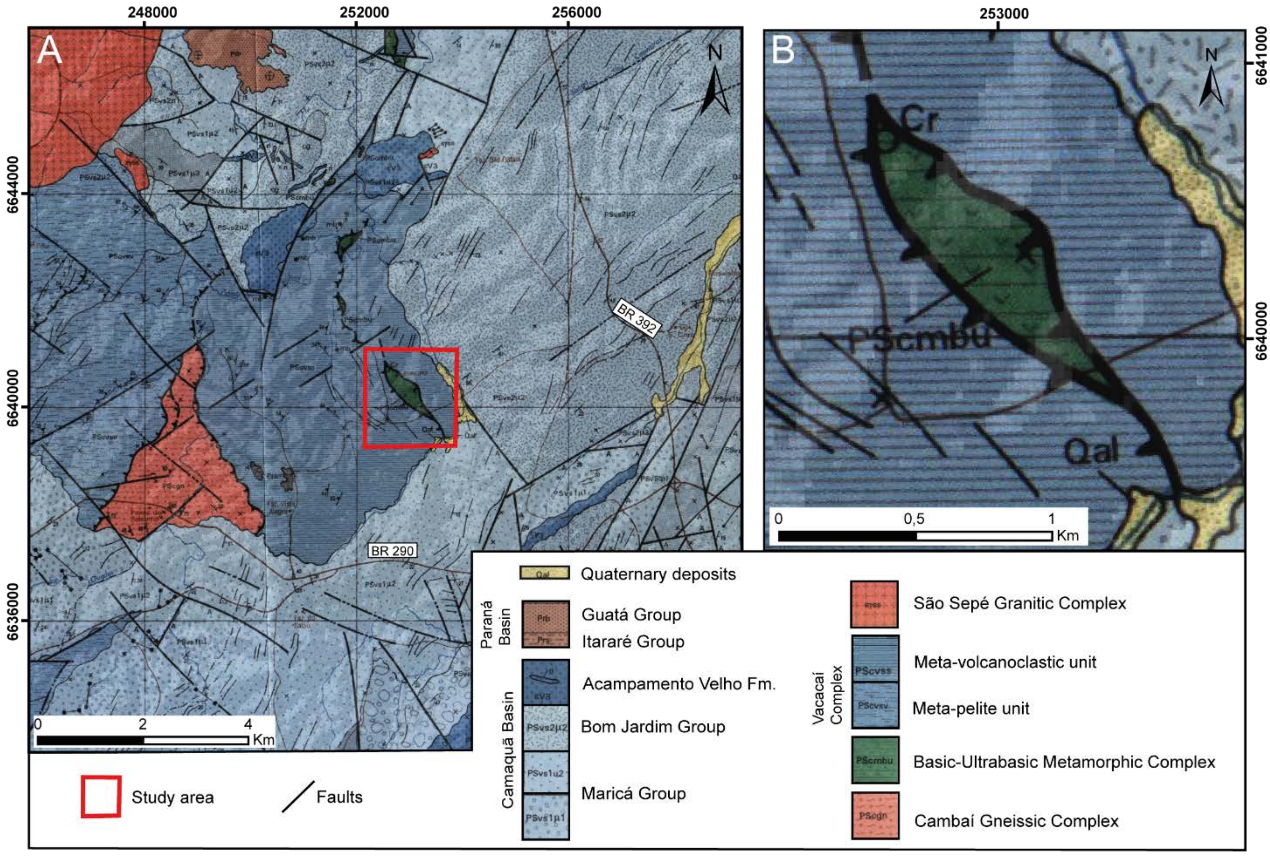

Figure 2 – Regional geological map of the study area based on the Passo do Salsinho chart (SH.22-YAI-4) (Modified from CPRM, 1995). A) Location of the Basic-Ultrabasic Metamorphic Complex enclosed within meta-volcano-sedimentary rocks of Vacacaí Complex. Note that the meta-ultramafic rocks occur as discontinuous bodies elongated from N-S to NW-SE. B) Detail of the meta-ultramafic rock studied. The outcrop is ~ 1.300 m long X 300 m wide and is located on the extreme south of the Basic-Ultrabasic Metamorphic Complex.

to the Vacacaí Complex suggest a tectonic evolution in which four deformational phases can be distinguished. The first three (D1, D2, and D3) generated coaxial NE-SW trending folds and are related to compressive stresses directed towards SE, where D1 and D2 reflect a tangential movement, while D3 is associated with a shear phase.

The Basic-Ultrabasic Metamorphic Complex thrusting is related to the SE-vergent thrust stack during D2 phase. Phase D4, which generated NW-SE trending folds, resulted from a drastic reorientation in the Sul-Riograndense Shield global strain regime (CPRM, 1995, 2000).

The Basic-Ultrabasic Metamorphic Complex thrusting is related to the SE-vergent thrust stack during D2 phase.

MATERIALS AND METHODS

The magnetometric method was applied to define the geometry of the Basic-Ultrabasic Complex through contrasting magnetic properties with the Vacacaí Complex and to identify small structures or chromite/iron-chromite concentrations within the meta-ultramafic sequence.

The GSM 19 (GEM SYSTEMS) magnetometer with proton nuclear precession was used for the magnetic survey. 1677 magnetic stations with ~25 m spacing were collected in 52 pick-up lines oriented at N45°, perpendicular to the meta-ultramafic body geometry (Figure 3). The lines have 50 m spacing and lengths from 50 m up to 1800 m.

All measurements were linked to a base station during the 10-h daily field campaigns to characterize the magnetic diurnal variation in the study area. This station was located far from the study target and anthropic noises like electrical networks, residences, and roads, and programmed to make measurements with 1 min time intervals (Figure 3).

A GPS Pathfinder Pro-XR differential receiver from Trimble Navigation Ltda was used to obtain the magnetometric stations' x,y, and z geographical coordinates (UTM, WGS-84 datum). Differential data correction was made using the Brazilian Institute of Geography and Statistics

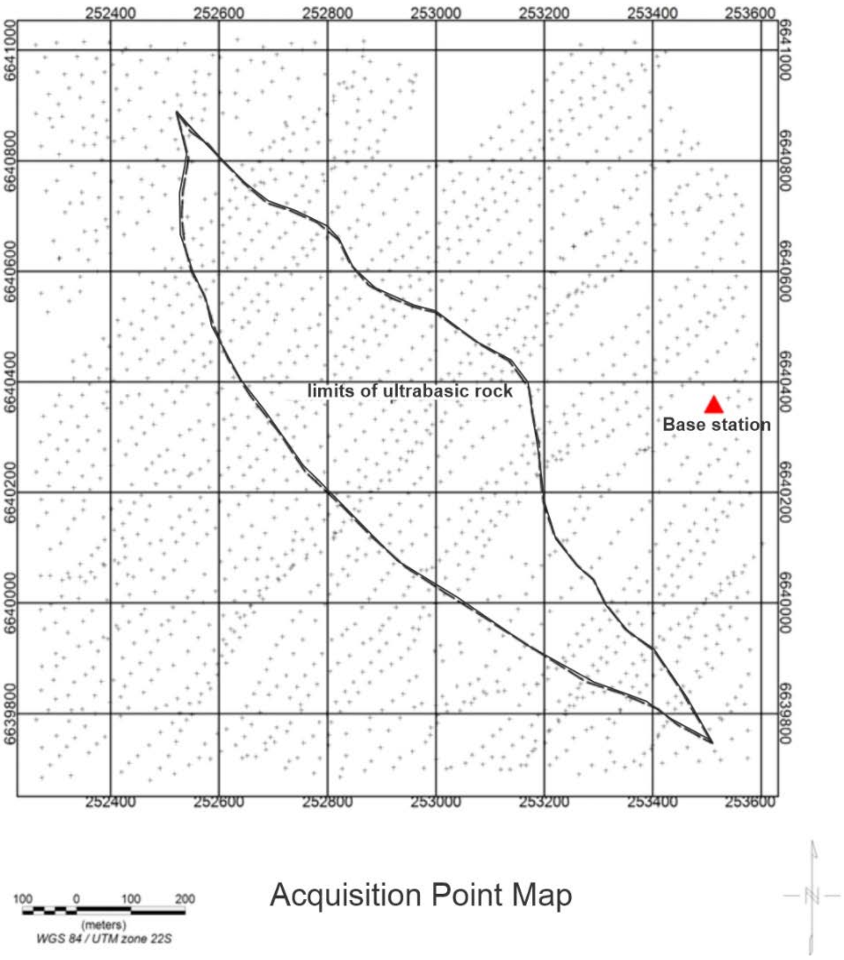

Figure 3 – Map of magnetometer survey stations (grey dots) and base station (red triangle) over the limits of the meta-ultramafic sequence.

(IBGE) reference station in Santa Maria - RS.

Data processing was performed in Geosoft Oasis Montaj software using a 15 m x 15 m cell grid based on the least curvature interpolation method. After daily corrections, a total magnetic field map was generated. Finally, pole reduction, analytical signal, and upward continuation algo-rithms were applied to construct the magnetic maps.

RESULTS AND DISCUSSION

The mineral content of meta-ultramafic sequences is generally associated with high magnetic susceptibility materials, which is helpful in geophysical exploration. The Basic-Ultrabasic Metamorphic Complex host rocks are mainly meta-volcano-sedimentary sequences of Vacacaí Complex, low magnetic susceptibility compared to minerals on the Basic-Ultrabasic Metamorphic Complex. There-fore, the magnetic anomalies could indicate the approximate geometry and geological boundaries of the meta-ultramafic rocks, although the interpretation of these products is frequently qualitative (Telford et al., 1990).

The magnetic survey indicated two main magnetic bodies in the study area, located at the central and northwestern domains (Figures 4, 5, and 6). These bodies present elliptical geometry (~ 400m long X 300 wide) and are arranged along the NW-SE direction. Although the magnetic results indicated that these bodies are discontinuous, they are similar to the geological boundaries of the Basic-Ultrabasic Metamorphic Complex (Figure 2B) but present more signi-ficant dimensions.

The Total Magnetic Field map showed two distinct high magnetic anomaly values within the meta-ultramafic sequence at the central and northwestern domains and a medium magnetic anomaly value in the southeast domain (Figure 4A). The high magnetic anomalies form magnetic dipoles, that is, areas of low intensity flank them. This feature indicates the presence of individual magnetic bodies or a set of small bodies gathered in two domains due to the smoothing of the interpolation algorithm. Such dipoles show

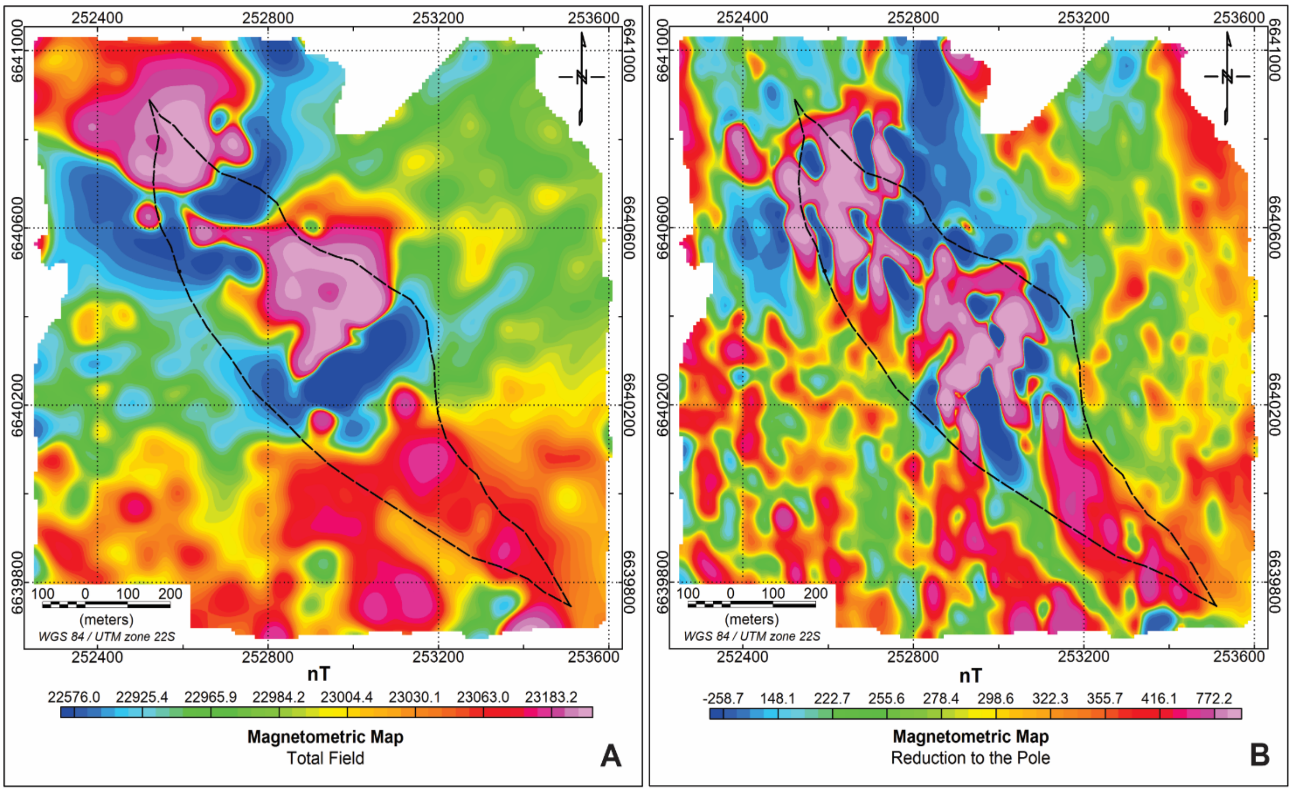

Figure 4 - Magnetometric maps of Total Field (A) and Reduction to the Pole (B).

principal orientation to NE-SW, similar to rock foliation. The medium magnetic anomaly presents lateral continuity beyond the domains of the meta-ultramafic sequence, which suggests a similarity in magnetic signal with the rocks of the Vacacaí Metamorphic Complex. Field evidence indicates that this domain comprises chlorite-talc schist with insipient serpentinization.

The Pole-reduction map also indicated the three previously individualized magnetic domains, although somewhat continuous and presenting a tendency of orientation towards N-S (Figure 4B). This filter has the purpose of displacing anomalies laterally, placing them on their respective sources, and changing their shape so that the symmetrical sources cause symmetrical anomalies. In this case, the three magnetic domains are contained within the limits of the meta-ultramafic sequence. However, this pattern likely reflects near surface positions since the meta-ultramafic rocks present variable SW dip-direction. It is also possible to recognize individualized bodies in the central and northwestern domains, although they tend to be oriented towards the N-S direction, something that does not match the structural pattern of the last deformation phases (NE and NW).

In contrast, the Analytic Signal Amplitude map highlighted only the central and northwestern magnetic domains within the meta-ultramafic sequence's limits and presented a strong attenuation in the southeast domain. In this map, a diffuse point interpolation predominates, merging eventual individualized bodies and gathering into two large bodies (Figure 5A).

The analytical signal filter works by positioning the resultant amplitudes above the limits of the structures (Nabighian, 1972). Therefore, the limited magnetic domains in this product should reflect the shallower positions of the magnetic bodies. The superimposition of the meta-ultramafic sequence boundaries defined by geological mapping over the analytical signal amplitude map (Figure 5A) reveals that the high-intensity magnetic anomaly in the northwest portion has continuity beyond the limits of geological mapping. This discrepancy can be attributed to the absence of rock exposures due to the thick soil cover.

The Regional Field magnetometric map (Figure 5B) indicated the three magnetic domains, of which the southeastern domain presents more attenuated values, similar to the total magnetic field and pole-reduction maps. In this case, the main magnetic domains do not allow the differentiation of individualized bodies, possibly due to smoothing effects related to the interpolation algorithm,

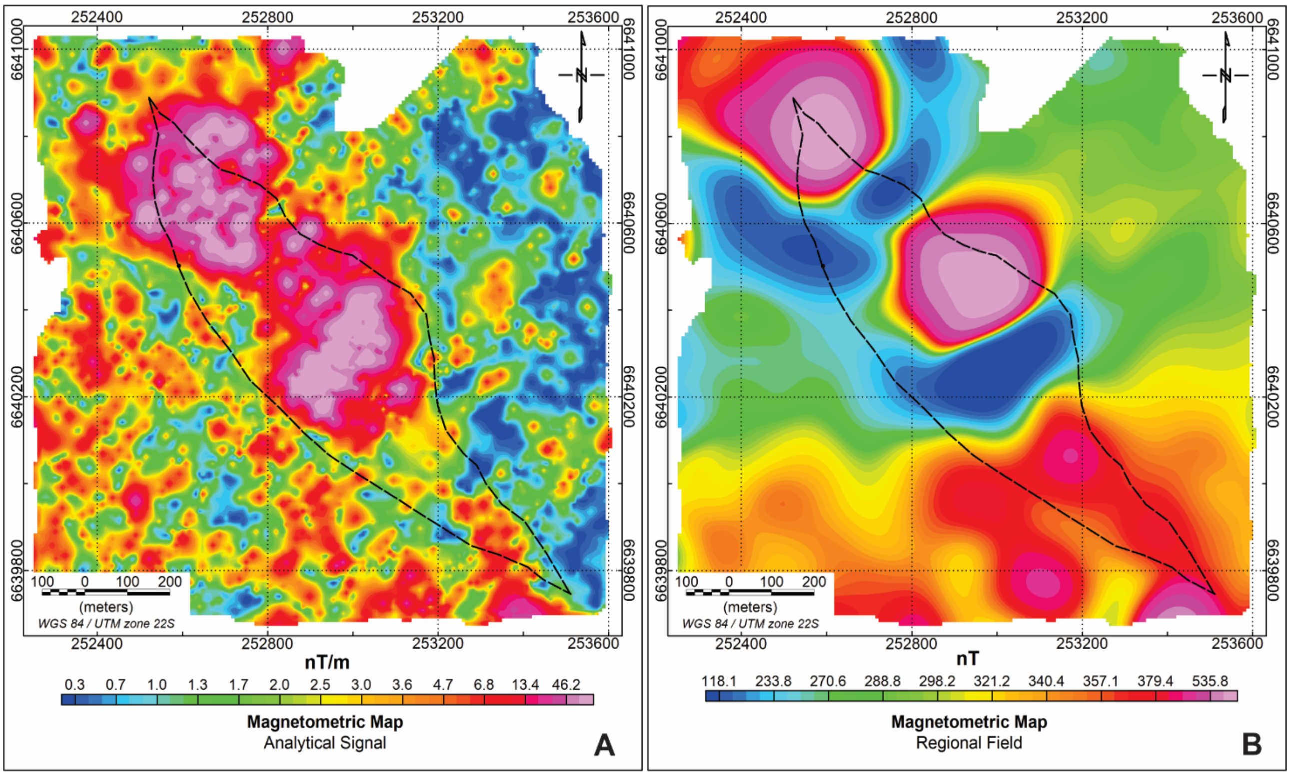

Figure 5 - Magnetometric maps of Analytical Signal (A) and Regional Field (B).

besides exceeding the limits of the meta-ultramafic sequence. This algorithm uses a low-pass filter that eliminates high-frequency signals to highlight deep structures or sources. However, the tendency of positioning the magnetic domains beyond the limits of the meta-ultramafic sequence, apparently displaced in the NE direction, conflicts with the structural reality of NE-foliation. Furthermore, in this region, outcrops the Vacacaí Complex, devoid of any magnetic structure recognized in the field or described in the literature

The residual magnetometric map revealed several individualized magnetic domains predominantly contained within the meta-ultramafic sequence boundaries, with marked attenuation in the southeast portion of the study area (Figure 6A).

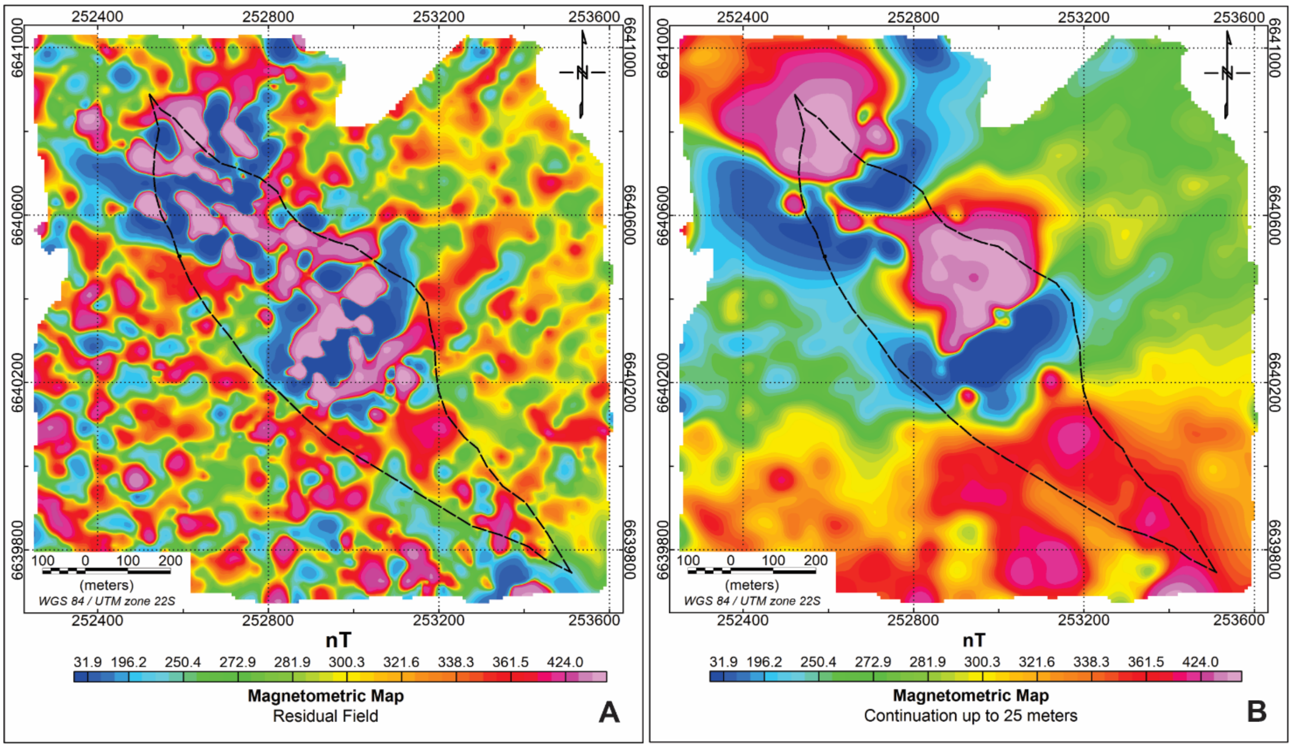

Figure 6 – Magnetometric maps of Residual Field (A) and Continuation up to 25m (B).

These bodies are highly discontinuous and present preferential orientation to NE at the central area, deflecting to NW-trend at the northwest portion. This orientation pattern is consistent with the third and fourth deformational phases (NE- and NW-trending, respectively) related to the Basic-Ultrabasic Metamorphic Complex structural evolution. However, it suggests that the influence of the fourth deformational phase is more accentuated towards the northwest of the area. The concentration of NW-trending folds in this region also corroborates with this interpretation (Figure 7).

The continuous magnetic map of up to 25 meters (Figure 6B) indicated the three magnetic domains previously described in other products, as well as signal attenuation in the southeast domain. The tendency of the central and northwest domains to exceed the limits of the metamorphic sequence is also observed. This map eliminates low frequencies and enhances structures to 12.5 meters deep. Thus, magnetic domains must reflect shallow bodies, although discordant to the lithological context, since the tendency of displacement beyond the limits of the meta-ultramafic sequence in the NE direction does not correspond to the geological reality of the area.

According to the field analysis and structural measurements, the high-intensity magnetic domains recognized in the central and northwestern portions have a clear relationship with areas of meta-ultramafic rocks occurrences, which reflect structural heterogeneities (Figure 7).

The central domain comprises serpentinites containing chromite-magnetite, with gently folded foliation predominantly in the NE-SW direction. The corresponding magnetic anomaly shows a remarkable NE-SW trend, following the foliation (Figure 7), as observed in the magnetometric maps, especially analytical signal and residual field maps (Figures 5A and 6A). Linear zones of chromite-magnetite mineralization strike in the NE-SW direction conformably to the trend of the central magnetic anomaly as a whole.

In turn, the northwestern domain is characterized by strongly folded serpentinites. Folds are predominantly NW-SE tight to isoclinal folds, moderately plunging (35°-44°). Consequently, the magnetic anomaly tends to NW-SE orientation, consistent with the hinge lines. This structural pattern suggests a reorientation during D4 deformational phase in the northwestern domain.

On the other hand, the moderate-intensity magnetic domain located southeast of the meta-ultramafic sequence is related to chlorite-talc-schists with relics porphyroclasts of olivine. The presence of olivine relics indicates an incipient serpentinization process, which probably produce a of lesser intensity magnetic signature than sites of complete serpentinization.

The low-intensity magnetic domains located at the northeast portion of the study area correspond to meta-volcanoclastic rocks of the Vacacaí Complex which predominate minerals with relatively low magnetic susceptibility compared to mafic-ultramafic minerals and hydrated magnesium and iron phyllosilicates (Figure 7).

The results showed that among the advantages and disadvantages of geophysical surveys applied to mineral research projects, the possibility of measuring parameters directly related to mineral occurrences is an excellent strategy for recognizing and sizing potentially mineralized areas, adding important subsurface information to the classic geological mapping.

The velocity of data acquisition, the absence of noise in the open field, and the multiple forms of processing make this tool essential in the search for mineral deposits of chromite/iron-chromite associated with ultramafic rocks. Furthermore, using a dense acquisition mesh allows the individualization of magnetic bodies directly related to chromium occurrences.

The geophysical data, especially the analytical signal maps, are practical methods for detailing targets in mineral research and planning sampling actions that depend on the location and limits of magnetic areas, regardless of the rock or material outcrop. In this case, the reserves estimate must be a more faithful expression of the deposit's reality and assertive than geological mapping. The papers of Yungul (1956), Shayestehfar et al. (2015), Parvar et al. (2018), Porras et al. (2021), Rezayee et al. (2023) involve the use of magnetometry and a combination of other geophysical methods in mapping chromite bodies in ultramafic sequences and present similar results in terms of discrimination of occurrences.

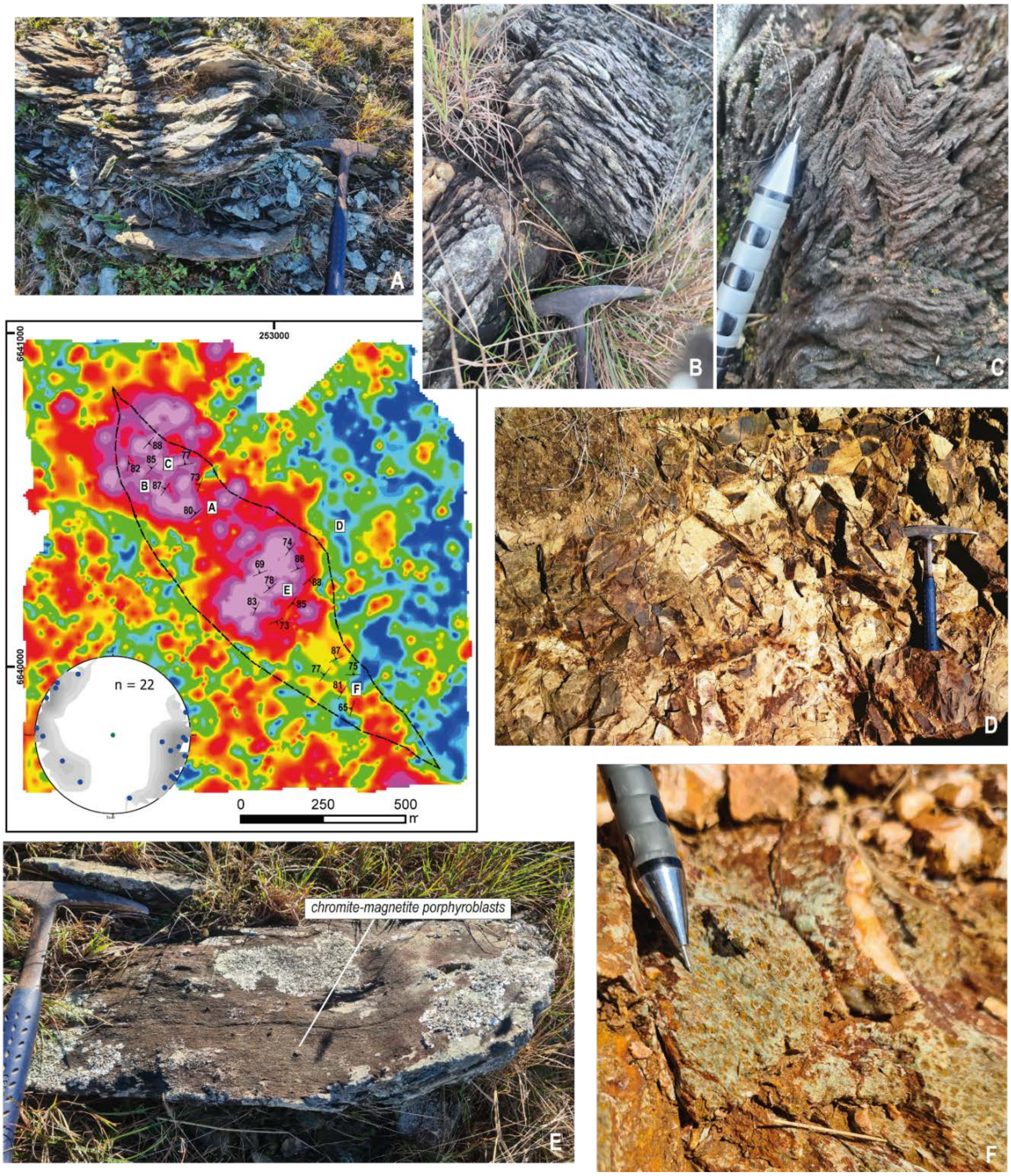

Figure 7 – Correlation between the main lithologies with the magnetic anomalies observed in the Analytical Signal Amplitude Map. Foliations are plotted on ASA map and the stereogram shows the pole of foliation planes. Location of field photographs is named A to F. A), B), and C) tight to isoclinal NW-SE folds observed in the northwest domain; D) Meta-tuffs of Vacacaí Complex; E) Gently folded serpentinites with chromite-magnetite porphyroblasts; F) chlorite-talc-schists with relics porphyroblasts of olivine.

CONCLUSIONS

This paper applied terrestrial magnetometric prospecting to delimitate the geometry of meta-ultramafic lenticular body of the Basic-Ultrabasic Complex and highlight potential chromite occurrences.

Two high-intensity magnetic domains (central and northwestern) were recognized in all magnetometric products, which in some cases were contained within the limits of the Basic-Ultrabasic Complex and occasionally exceeded the geological boundaries.

The processing products revealed heterogeneity of the meta-ultramafic sequence in its southeast portion, apparently related to heterogenous serpentinization process of ultramafic minerals, as olivine.

The low-intensity magnetic domain observed northeast of the area was interpreted as meta-volcanoclastic rocks of Vacacaí Complex. Such interpretation provides a more accurate positioning of the geological limits in the study area.

The results indicated highly magnetic individualized bodies with metric dimensions orientated according to NE-SW in central domain and NW-SE in northwestern domain. These magnetic bodies, especially the central, suggest zones with elevated concentrations of minerals with relatively high magnetic susceptibility, such as magnetite and chromite, demonstrating the efficacy of the magnetometric method in investigating mineralized targets in meta-ultramafic rocks.

The geophysical survey, especially the magnetic analytical signal amplitude map, revealed the continuity of magnetic targets beyond the limits of geological mapping. The direct relationship between magnetic anomaly and chromite/ferrochromite concentrations indicates that targets of high magnetic intensity are mineralized areas with economic potential to be defined by direct sampling and quantification of content. In this aspect, geophysical investigation demonstrates an assertive and accurate tool for detailing targets for estimating reserves in mineral research projects for chromite deposits.

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