

RESEARCH ARTICLE

3D Magnetic Inversion in Angola: Serra da Neve Alkaline Complex and Jamba Itabirites case studies

Inversión magnética 3D en Angola: estudios de caso del Complejo Alcalino de la Serra da Neve y de las Itabiritas de Jamba

 Ana Machadinho^{1,3,4*},  Patricia Repesas¹,  Daniela Alves¹,  Domingos Cordeiro²,  João Carvalho¹,
 Rui Lopes¹,  Paulo Caessa¹,  Luis Pereira¹,  André Osório¹

¹Laboratório Nacional de Energia e Geologia, Estrada da Portela-Zambujal, Apartado 7586 Alfragide, 2610-999 Amadora, Portugal. E-mails: patricia.represas@lneg.pt; danielapva@gmail.com; joao.carvalho@lneg.pt; rui Lopes88@gmail.com; pcaessa@gmail.com; lfrpereira@gmail.com; osorio.c.andre@gmail.com

²Instituto Geológico de Angola, IGEO, Rua 311, Centralidade de Kilamba, Belas, Luanda, Angola. E-mail: cordeiro9elica@gmail.com

³GeoBioTec, Nova School of Science and Technology, Campus da Caparica, 2829-516 Caparica, Portugal.

⁴Geociences Center, University of Coimbra, Rua Sílvio Lima, Pólo II, 3030-790 Coimbra, Portugal.

Corresponding author: ana.machadinho@gmail.com (Ana Machadinho)

Key point:

We evaluate the effectiveness of the magnetic method for the characterization of potential target areas for mineral exploration.

We show that strong magnetic anomalies are related to target areas, which can represent mineralization's host rocks.

Magnetic inversion technique allowed the obtention of the 3D geometry and MVI susceptibility values for the SNAC and Jamba itabirites.

ABSTRACT

Demanding and speculative economies make it imperative to search for new areas of mineral exploration. Angola's geological diversity presents an enormous potential for mineral resources. This potential can be assessed by applying different methods, such as geophysical prospecting, to discover new potential targets of areas to explore. For many years, the magnetic method has been successfully used in mineral exploration. In this work we apply a 3D magnetic inversion technique to aeromagnetic data in two different study areas. The Serra da Neve alkaline complex (SNAC) represents a potential source for rare earth elements (REE) and the Jamba itabirites provides metallic mineral deposits with iron and gold mineralizations. In both case studies, whether concerning alkaline intrusions or itabirites deposits, their magnetic properties are characterized by strong magnetic anomalies clearly delineated on magnetic anomaly maps. The high magnetic susceptibility (k) contrast between these target structures and the host rocks allowed us to obtain a coherent three-dimensional geometry for the SNAC structures and the itabirites deposits. The magnetic inversion technique also provided magnetic vector inversion (MVI) susceptibility values estimation for constituent lithologies, as well as the shape and size of the studied structures and deposits. The results demonstrate the effectiveness of the magnetic method for the detection and characterization of target areas, offering an innovative technique to identify potential areas in mineral resources exploration.

Keywords: 3D magnetic inversion; MVI susceptibility; Serra da Neve alkaline complex; Jamba itabirites.

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Puntos clave:

Evaluamos la eficacia del método magnético para caracterizar potenciales áreas de interés para la exploración mineral.

Mostramos que fuertes anomalías magnéticas están relacionadas con áreas de interés, que pueden representar

RESUMEN

Las economías exigentes y especulativas hacen imperativa la búsqueda de nuevas áreas de exploración minera. La diversidad geológica de Angola presenta un enorme potencial de recursos minerales. Esto se puede evaluar aplicando diferentes métodos, como la prospección geofísica para descubrir nuevas áreas potenciales a explorar. Durante muchos años el método magnético se ha utilizado con éxito en la exploración minera. En este trabajo aplicamos una técnica de inversión magnética 3D a datos aeromagnéticos en dos áreas de estudio diferentes. El complejo alcalino de la Serra da Neve (SNAC) representa una potencial fuente de elementos de tierras raras y las itabiritas de Jamba proporcionan depósitos de minerales metálicos con mineralizaciones de oro y hierro. En ambos casos, intrusiones alcalinas y depósitos de itabiritas, sus propiedades magnéticas se caracterizan por fuertes anomalías magnéticas que están bien definidas en los mapas de anomalías magnéticas. El elevado contraste de susceptibilidad

rocas con mineralizaciones. La inversión magnética permitió obtener la geometría 3D y los valores de susceptibilidad MVI para el SNAC y las itabiritas de Jamba.

magnética entre las rocas estudiadas y sus materiales encajantes nos permitió obtener una geometría tridimensional coherente para el SNAC y los depósitos de itabiritas. La técnica de inversión magnética también proporcionó una estimación de los valores de susceptibilidad MVI (*magnetic vector inversion*) para las litologías constituyentes, así como la forma y el tamaño de las estructuras y depósitos estudiados. Los resultados demuestran la efectividad del método magnético para la detección y caracterización de áreas de interés, ofreciendo una técnica innovadora para identificar áreas potenciales para la exploración de recursos minerales.

Palabras clave: Inversión magnética 3D; Susceptibilidad MVI; Complejo alcalino de la Serra da Neve; Itabiritas de Jamba.

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1. Introduction

Magnetic prospection is an indirect tool that has been successfully utilized in mineral exploration. Magnetic methods measure variations in the Earth's magnetic field caused by the presence of magnetic minerals in the ground. So, this method is effective for locating and mapping the distribution of magnetite-rich rocks or others magnetic minerals, which can be associated with different types of mineralization. Studies such as Sharma (1987) and Nabighian *et al.* (2005) prove the effectiveness of the magnetic method in mineral exploration.

In this work, we apply a 3D magnetic inversion, namely the magnetization vector inversion (MVI) technique (Sequent, 2019), to aeromagnetic data acquired in the scope of the PLANAGEO project. We present two case studies, the Serra da Neve alkaline complex (SNAC) and the Jamba itabirites.

Angola's landscape is distinguished by its enormous geological diversity and substantial mineral wealth. The Serra da Neve alkaline complex is formed by syenites, porphyries and peralkaline granites and volcanic and sub-volcanic terms, where rhyolites and trachytes predominate. Geochemistry and mineralogy of these complexes often translate into anomalous concentrations of Nb, REE, Ti, Zr, Ta, U, Th, apatite (phosphates), being related to the final stages of the magmatic evolution process (Lopes *et al.*, 2021). Alkaline igneous complexes currently represent one of the main sources of rare earth elements (REE), which represent one of the most economically important resources of heavy REE and Yttrium (Y) (Dostal, 2017). SNAC is a potential target for mineral exploration, not only as a source of REE, but also due to its favorable characteristics for ornamental rock production. However, its remote geographic location and the lack of an efficient road network, which allows products to flow are the main constraints to the valorization of resources in the region (Lopes *et al.*, 2021).

The Angolan substantial mineral riches are also prominently underlined by the Precambrian formations that span a significant portion of the country. The Jamba region, situated within the Cassinga domain in the southern part of Angola, is particularly noteworthy for its vast deposits of metallic minerals. Historically identified as one of the southern region's areas with the highest metallic mineral potential, Cassinga is renowned for its significant iron (Fe) and gold (Au) reserves. This region benefits from certain infrastructural advantages, such as railway access, which are not as prevalent across other parts of Angola, thereby heightening the interest in its mineral resource potential (Pereira *et al.*, 2022).

Due to the SNAC and the itabirites of Jamba mineral resources potential they can contribute significantly to the country's mining industry. In both cases, the magnetic properties of the geological units result in strong magnetic anomalies that are distinctly visible on magnetic maps.

The use of 3D magnetic inversion techniques allowed us to create detailed models of the subsurface, offering insights into the distribution, shape, and size of both the SNAC and the itabirite deposits, offering a new lens through which to evaluate their mineral potential. This work aims to contribute to

the exploration and assessment of mineral resources, supporting the development of mining strategies that are both efficient and aligned with sustainable practices.

2. Geological setting

2.1. Serra da Neve

The transangolan volcanic belt is an intra-continental rift with a NE-SW trend that crosses Angola and contains a major part of the alkaline-carbonatite magmatism of SW Angola. The emplacement of this alkaline-carbonatite complexes occurred mainly along active tectonic lineaments (Comin-Chiaramonti *et al.*, 2007), and is directly related to the breaking up of Pangea and the consequent South Atlantic opening during the Cretaceous (Pereira *et al.*, 2003). This NE-SW belt is intersected by several NW-SE lineaments, where alkaline magmas intruded NE-SW or in others inherited directions, such as WNW-ESE. This is the case of the Serra da Neve alkaline complex (SNAC) (Fig. 1a and 1b).

The SNAC has been studied by many authors, referring the work of Pereira & Moreira (1978), which carried out a detailed cartographic survey and described for the first time the SNAC and its sub-volcanic character. The SNAC is located on the geological maps of Chongóroi and Equimina (scale 1:250.000). This complex encompasses a large set of volcanic, sub-volcanic and plutonic alkaline rocks, which intrudes paleoproterozoic granitic and gneissic-migmatitic rocks within the Angolan shield (Fig. 1b). For these alkaline structures, a U-Pb age of 90.57 ± 0.25 Ma was reported in literature that indicates a crystallization age for a phonolite from the core of the Lutala structure (Jerram *et al.*, 2018). Recently, in the scope of the PLANAGEO project, a hyperalkaline granite of the Chieriunde structure was dated and provided a crystallization U-Pb age of 96.07 ± 0.81 Ma, with xenocrystals aged 108.7 ± 3.3 Ma and 114.1 ± 1.4 Ma. These data suggest a polyphase character for the Serra da Neve alkaline magmatism, with several episodes between the Aptian – Albian transition (Early Cretaceous) and the Turonian (Upper Cretaceous) (Ferreira *et al.*, 2021).

The main structure of the Serra da Neve complex has a sub-circular to elliptical shape and extends longitudinally for 45 km and transversely for 20 km. The SNAC is formed by several ring structures oriented according to the NW-SE (Goto-Pituaco-Malinde, Pongulué, Lutala, Chilelariva, Chitucubero structures) and to the WNW-ESE trends (Chai, Babaque, Lutala, Chilelariva and Chitucubero structures). Associated to this complex there is a network of important veins, and also some satellite structures, namely the Nejoio and Vicuio structures, aligned with the WNW-ESE trend, and the Chiuerinde and Lacache structures trending NE-SW (Fig. 1b). The ring structures of Serra da Neve form inselbergs over the level of the Angolan plateau. The Lutala structure reaches the highest altitude of 2489 m (Pereira, 1977).

Generally, the sub-circular structures are formed by a volcanic and sub-volcanic center (alkaline-carbonatitic volcanic to subvolcanic rocks, siliceous and ferruginous volcanic breccias, tuffs and trachytite to phonolitic flows) and/or by plutonic alkaline rocks (syenites, nepheline syenites, monzonites and ijolites) (Merino-Martínez & Rodrigues, 2021). In the border of some of the structures, a fenite aureole was formed, associated with the granitic and gneissic-migmatitic host rocks contact due to the metasomatic alteration of the alkaline rocks (fenitization process) (Pereira & Moreira, 1978). This occurs in the Chai, Lutala principal structure, Chitucubero and Nejoio structures (Fig. 1b).

2.2. Jamba

The Jamba itabirites are one of the components of the Jamba Group, situated within the Cassinga domain (Carvalho *et al.*, 2000), placed in the Precambrian basement of southwest Angola (Fig. 2). With a Neoproterozoic age (~ 2.72 - 2.47 Ga), these formations display complex structural benches characterized by robust folding and fracturing, closely associated with acidic volcanic rocks, phyllites, schists, and gneisses.

Within the broader geological context, the Jamba Group is situated in the southwest of Angola, placed in the geological terrain of the Central African Shield. This sequence is intruded by the Jamba-

Tchamutete granites, for which crystallization ages (U-Pb on zircon) between ca. 2.57 and 2.61 Ga were obtained (Pereira & Osório, 2021).

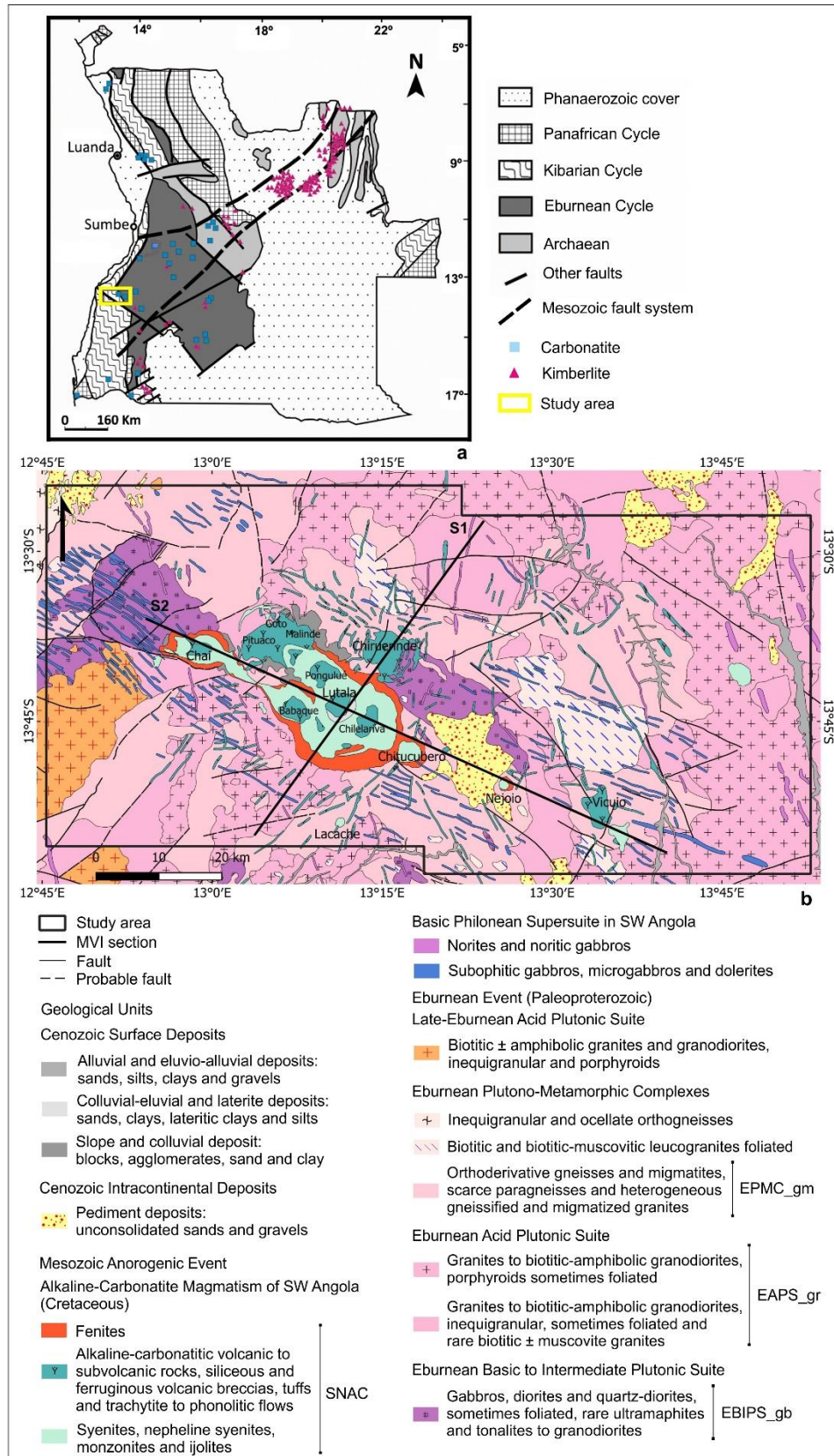


Figure 1. a) Simplified geological map of Angola showing the distribution of carbonatites and kimberlites. Adapted from Campeny *et al.* (2014). b) Geological map of the Serra da Neve area. Adapted from Merino-Martínez & Rodrigues (2021). Black lines indicate the location of MVI sections (S1 and S2).

Figura 1. a) Mapa geológico simplificado de Angola con la distribución de carbonatitas y kimberlitas. Adaptado de Campeny *et al.* (2014). b) Mapa geológico de la zona de la Serra da Neve. Adaptado de Merino-Martínez & Rodrigues (2021). Las líneas negras indican la ubicación de las secciones MVI (S1 y S2).

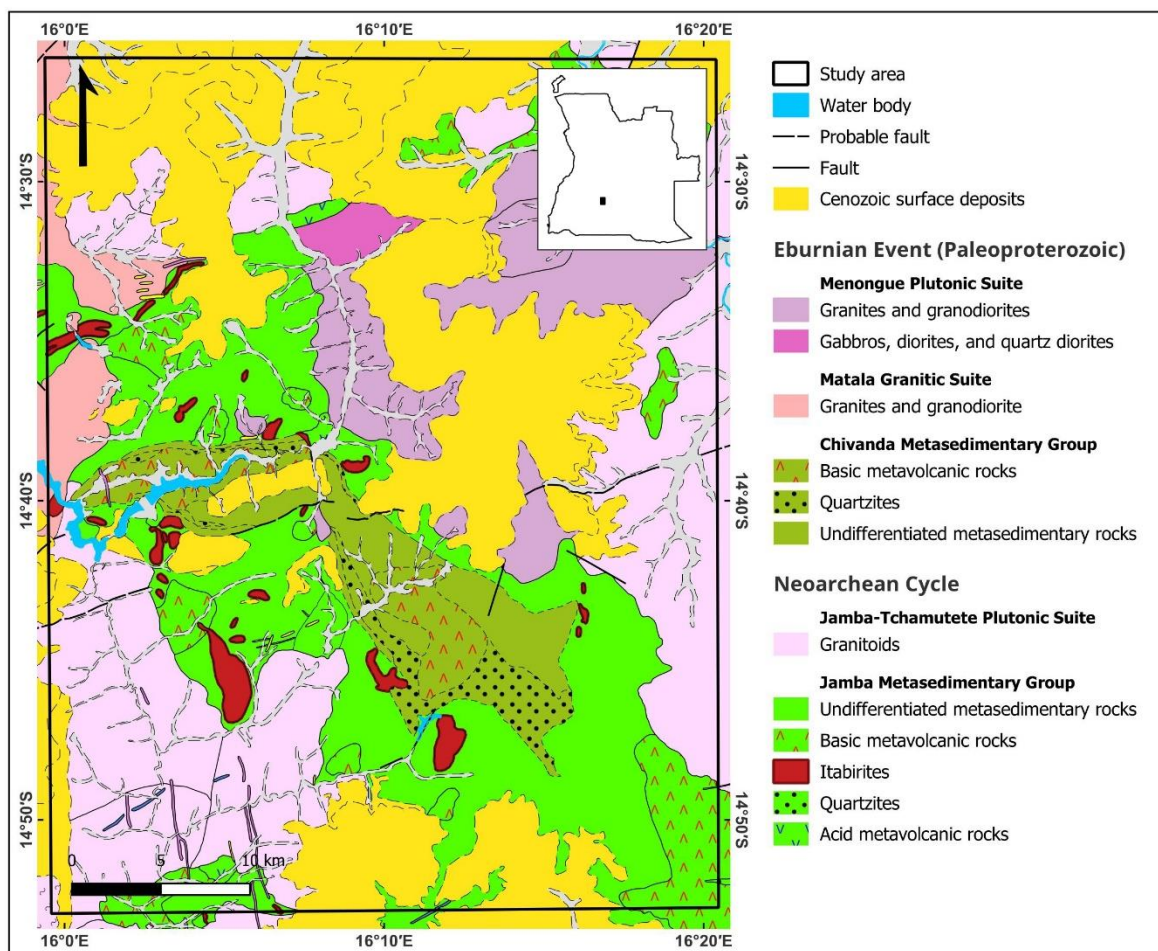


Figure 2. Geological map of the Jamba area. Adapted from Rodrigues *et al.* (2021).

Figura 2. Mapa geológico de la zona de Jamba. Adaptado de Rodrigues *et al.* (2021).

Consisting of siliciclastic and volcanic sequences that intrude the Jamba Group, the Chivanda Group deposited over this early Archaean nucleus. The subsequent magmatic episode is here represented by the Menongue Plutonic Suite, dated ca. 1.95-1.99 Ga, consisting of granodiorites, granites, porphyries, and lavas (Pereira & Osório, 2021). The complex intrudes the Jamba and Chivanda Groups and the Neoproterozoic granites of Jamba-Tchamutete.

This region has witnessed significant magmatic and tectonic events, shaping the Precambrian basement and intracontinental sedimentary basins of Southern Africa. Consequently, the Jamba itabirites serve as geological archives, recording the evolution of the Cassinga domain from the formation of an Archaean core, with magmatism and sedimentation, to the subsequent collision and accretion during the Eburnean and the events that followed. Bearing the imprint of this polyphase deformation, Jamba itabirites feature an intricate deformation composed by tight folds with steep axes, boudinage, foliation, cleavage, and fracturing. The Jamba itabirites also offer insights into the environmental conditions of the primitive Earth, characterized by low oxygen levels and intense hydrothermal activity, which facilitated the precipitation of iron oxides in ancient oceans.

Regarding the characteristics and composition of the Jamba itabirites, these formations exhibit compositional banding marked by iron oxides (hematite and magnetite) and siliceous material (quartz) (Pereira & Osório, 2021). Their chemical composition aligns with typical banded iron formations (BIFs), showcasing low contents of trace elements and rare earths.

3. Methodology

3.1. Magnetic survey

UTE-Planageo carried out an aeromagnetic and radiometric survey in southwest Angola aimed at enhancing geological understanding and supporting mineral exploration. Conducted by Xcalibur Geophysics Ltd from July 2014 to December 2016, the survey utilized a Geometrics G-823A magnetometer and a RS-501 spectrometer aboard an Airtractor 502B aircraft, at an altitude of 100 m. Flight lines were spaced 1000 m apart with tie lines every 10000 m. Quality control procedures ensured the reliability and accuracy of the acquired data. Preliminary validation confirmed data consistency for geological interpretation. Magnetic data was micro levelled and corrected, and the International Geomagnetic Reference Field (IGRF) was removed. The data was then gridded into a 200 m spaced grid by applying a bi-direction interpolation algorithm. A reduction-to-pole was also calculated to minimize the displacement of the anomalies resulting from low latitude effects. The processing and correction of the data was carried out using the software Oasis montaj (Seequent, 2019).

3.2. Magnetic inversion

3D magnetic modelling provides useful information about geometry, depth and physical properties of the source bodies. However, magnetic inversion is non-unique. This means that there are different magnetic susceptibility distributions that can produce the same measured magnetic anomalies. Therefore, it is important to consider the additional knowledge about the study area, such as the geological knowledge and magnetic properties distribution (magnetic susceptibility or rock magnetization). When available this data can be used to constrain the inversion models.

Inversions were performed using Oasis montaj software, with Voxi Earth Modelling extension (Seequent, 2019). Voxi allows a 3D voxel-based inversion in an area of interest, obtaining the magnetic susceptibility distribution. The magnetic susceptibility model can be determined by conventional magnetic inversion (CMI) or by magnetic vector inversion (MVI). While the CMI assumes that the magnetic response arises entirely from magnetic induction, the MVI considers the presence of induced and remanent magnetization, without any prior knowledge of the direction or strength of remanent magnetization. Therefore, for a more accurate interpretation of magnetic anomalies, it is recommended to use the MVI technique, particularly if remanent magnetization is suspected or when working in low latitudes (Ellis *et al.*, 2012).

The results of MVI model include three outputs that can be used to interpret the magnetic anomalies. These outputs are the amplitude of the magnetization, the earth field projection of the magnetization and the amplitude of the perpendicular to earth field component of the magnetization. These voxels are all normalized by the strength of the inducing field. The amplitude of magnetization is the most meaningful scalar and should be the primary quantity used in interpretations (Ellis *et al.*, 2012).

The scalar property returned by MVI inversion is the MVI susceptibility (MVI-k). These values can be used directly in the interpretation and can be compared and constrained by known measured rock susceptibility (MacLeod & Ellis, 2013).

To improve the MVI inversion results, namely the geometry and the amplitudes of the recovered physical properties, we applied two iterative reweighting inversion (IRI) iterations. Given the limited subsurface geological information, we employed the Voxi inversion algorithm without additional constraints, enabling an exploratory analysis of the magnetic data. This approach, reliant on the data itself and devoid of preconceived models, introduces a broad spectrum of potential interpretations due to the inherent non-uniqueness of the inversion process. Consequently, careful validation of the resulting models against other geological and geophysical evidence is very important.

To simplify the model interpretation, from the amplitude of magnetization voxel we created several isosurfaces, which represent different MVI susceptibility values (in S.I.).

4. Magnetic Data

4.1. Serra da Neve

The Serra da Neve total magnetic intensity (TMI) map is characterized by negative anomalies from -800 nT to positive anomalies, up to 2500 nT (Fig. 3). Strong positive anomalies are distributed in the WNW-ESE direction, surrounded by lower intensity positive anomalies, with values up to 1260 nT. These areas are mainly related to the SNAC lithologies. The remaining area of the map is characterized by negative anomalies mostly with values up to -300 nT. These negative values and low intensity positive values (up to 200 nT) are essentially related with the granitoid and gneissic-migmatitic host rocks, namely the Eburnean Acid Plutonic Suite, the Eburnean Plutono-Metamorphic Complex and the Late-Eburnean Acid Plutonic Suite. The Eburnean Basic to Intermediate Plutonic Suite is characterized by negative and positive anomalies between -150 nT and 300 nT (Fig. 1b and Fig. 3).

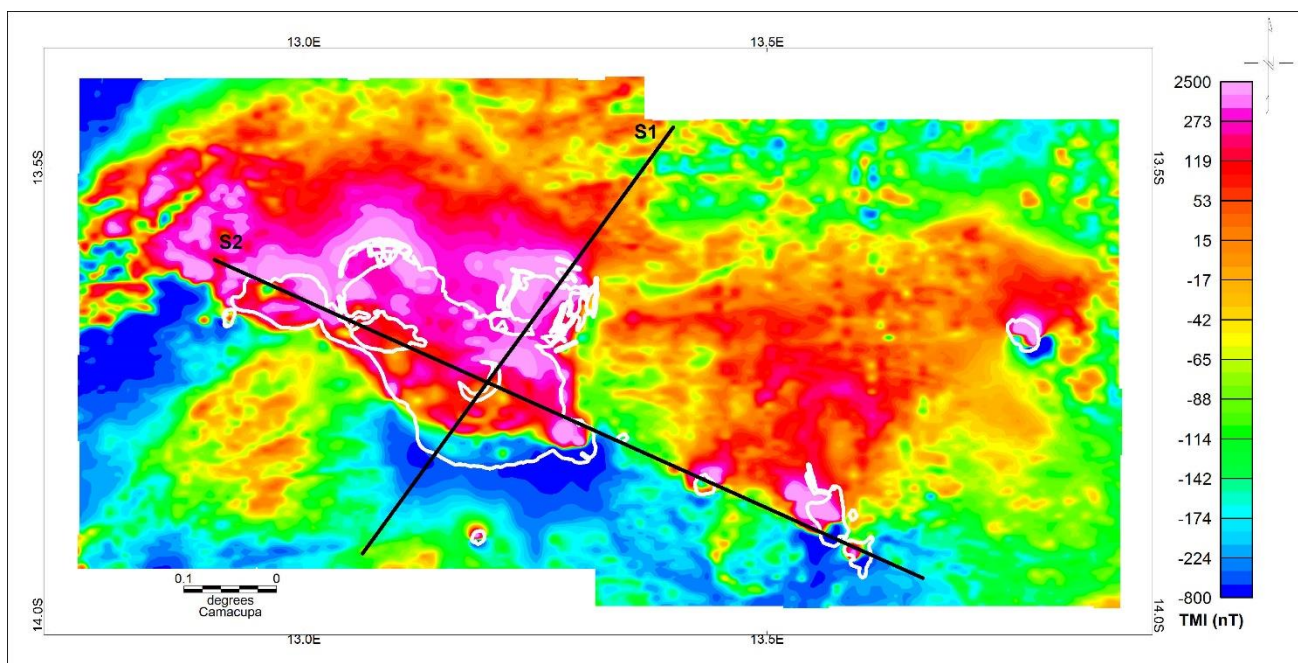


Figure 3. Serra da Neve total magnetic intensity (TMI) map. Black lines indicate MVI sections location (S1 and S2) and white line marks the geological contact of the units that form the Serra da Neve Alkaline Complex (SNAC).

Figura 3. Mapa de intensidad magnética total (TMI) de la Serra da Neve. Las líneas negras indican la ubicación de las secciones MVI (S1 y S2) y la línea blanca marca el contacto geológico de las unidades que forman el Complejo Alcalino de la Serra da Neve (SNAC).

4.2. Jamba

The magnetic anomaly map (reduced to the pole) of the Jamba region (Fig. 4) shows a complex magnetic field characterized by a wide range of anomalies. A range of magnetic field anomalies between -350 nT and 250 nT is indicative of typical variations within the region. However, notable deviations occur where the presence of intense magnetic dipoles elevates local values substantially, ranging between -8000 nT and 9000 nT. These anomalies delineate regions of heightened magnetic complexity.

The dominant magnetic signature within the region emanates from the Neoproterozoic granites of Jamba-Tchamutete, characterized by a subtle magnetic response, reflecting a magnetic susceptibility measuring around 8×10^{-3} S.I. (Represas *et al.*, 2018). Consequently, areas dominated by these geological units exhibit negligible magnetic anomalies, with reduced-to-pole magnetic field values predominantly falling between -100 nT and -50 nT. On the other hand, the occurrence of outcrops of Matala granites in the northwestern edge of the study area are coincident with localized variations in

the magnetic field, with occasional minor anomalies likely attributed to intrusive bodies from the Menongue Plutonic Suite. In fact, distinct positive anomalies, registering values of approximately 200 nT, mark the occurrence of the Menongue plutonic suite in the northeastern quadrant. These anomalies correlate with the magnetic susceptibility range of 1×10^{-2} to 5×10^{-2} S.I. measured within the geological formations of this suite (Represas *et al.*, 2018).

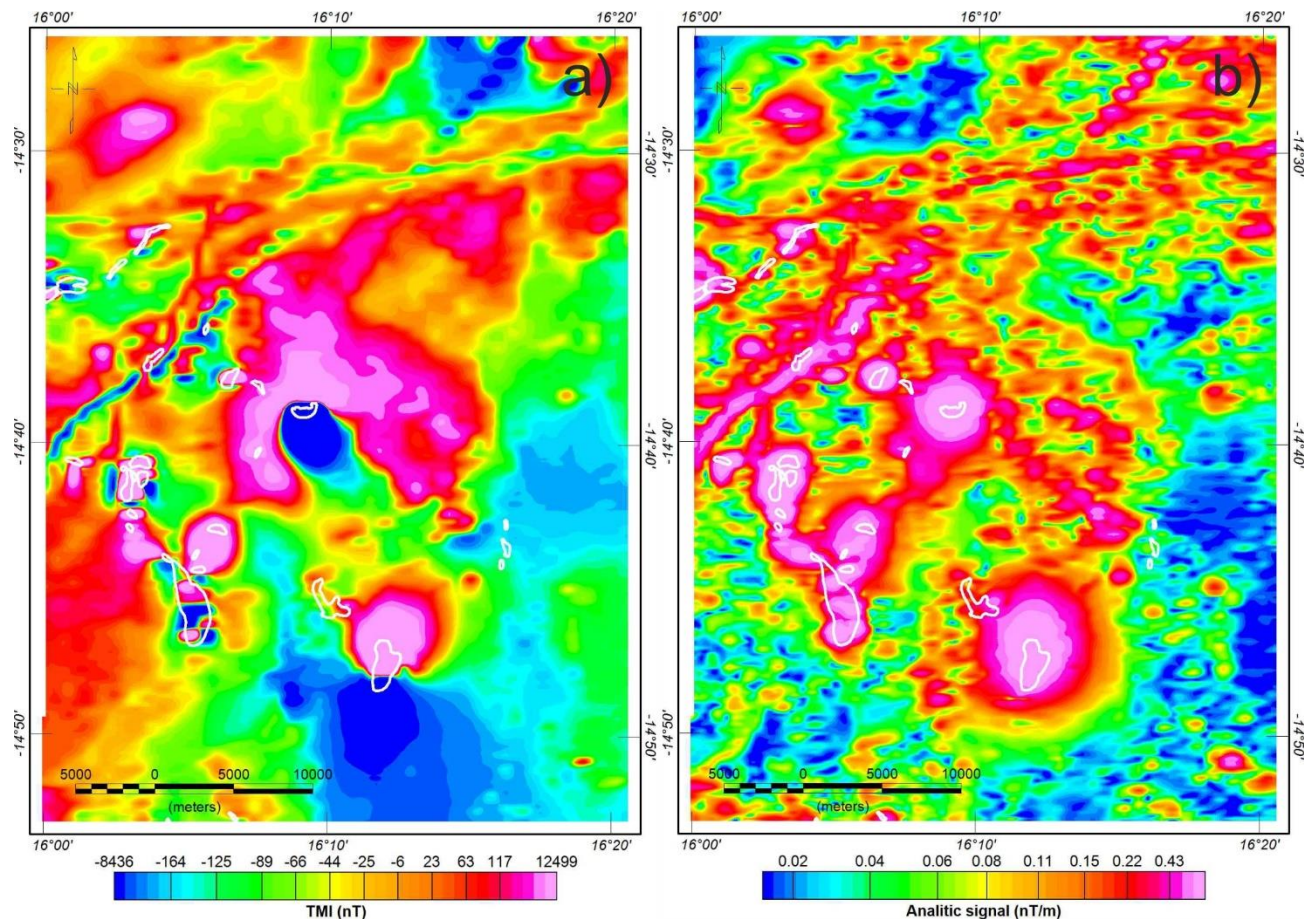


Figure 4. a) Jamba total magnetic intensity (TMI) map reduced to the pole ($I=-56.2^\circ$; $D=-5.9^\circ$). b) Analytic signal of Jamba TMI. White lines mark the geological contact of the Jamba Group itabirites.

Figura 4. a) Mapa de intensidad magnética total (TMI) de Jamba reducido al polo ($I=-56.2^\circ$; $D=-5.9^\circ$). b) Señal analítica de la TMI de Jamba. Las líneas blancas marcan el contacto geológico de los itabirites de Grupo Jamba.

Significant magnetic features are identified within the Jamba Group, manifested as intense dipolar magnetic anomalies. The analytic signal of the magnetic anomaly shown in Figure 4b provides a more accurate delineation of the sources of the anomalies, which frequently correspond to mapped outcrops of itabirites. These formations, characterized by a high iron content, exhibit a distinctive magnetic response. Comprising metavolcano-sedimentary sequences interspersed with BIFs (Gonçalves, 2010), the Jamba Group manifests a magnetic contrast between its base and upper sections. The lower strata, dominated by metagreywackes and phyllites, display relatively low to medium magnetic susceptibility (10^{-4} - 10^{-3} S.I.), possibly influenced by pyrite substitution in reducing conditions (Canfield & Berner, 1987; Pereira *et al.*, 2013). In contrast, the upper sequence, characterized by quartzites, schists, and itabirites, exhibits higher susceptibility (10^{-3} - 10^2 S.I.), indicative of oxidizing conditions and the presence of hematite-rich BIF layers.

The magnetic anomalies associated with the Jamba Group play a pivotal role in delineating mineralization zones, particularly exemplified by the North Cassinga region. Here, the presence of distinct and intense magnetic anomalies serves as a reliable indicator of possible mineral deposits characteristic of the Jamba Group.

5. Inversion results and discussion

Magnetic inversions were carried out on the two study areas, namely Serra da Neve and Jamba (Fig. 3 and Fig. 4), to produce three-dimensional models. The results are presented and discussed below.

5.1. Serra da Neve

Isosurfaces were created from the amplitude of magnetization voxel, representing different MVI susceptibility values in S.I. units. These MVI susceptibility values characterize the different lithologies that form the SNAC and the host rocks (Fig. 5). SNAC lithologies are related to positive magnetic anomalies and are characterized by MVI susceptibility isosurfaces from 0.5 to 0.007 S.I. units. Generically, fenites have the lowest values of MVI-k (0.02 to 0.007 S.I.) and alkaline-carbonatitic volcanic to subvolcanic and syenite rocks present the highest values of MVI-k (0.5 to 0.02 S.I.) (Fig. 5a). Host rocks are associated to negative and low positive anomalies and are characterized by MVI-k values below 0.007 S.I. (Fig. 3 and Fig. 5). Overall, the MVI susceptibility values we interpreted from inversion model are compatible with magnetic susceptibilities measured in similar lithologies (Schön, 2015).

We extracted two MVI susceptibility sections, S1 and S2, to simplify the interpretation of the inversion model (figs. 5b and 5c). Several magnetic lineaments were identified in the sections and their directions are in agreement with the mapped faults (Fig. 1).

S1 section runs from NNE to SSW for 62 km and intersects the Chiuerinde and Lutala SNAC structures. In S1 section, SNAC lithologies were interpreted from km 19 to km 53. The SNAC bodies present a medium-high susceptibility (0.007-0.5 S.I.). Chiuerinde structure thickness ranges from 4 to 6 km, while Lutala structure ranges from 2.5 to 6.5 km. Lower MVI-k values are observed from km 36 to km 43 in the Lutala structure (Fig. 1 and Fig. 5b). Host rocks were interpreted in the remaining section, namely the Eburnean Acid Plutonic Suite and the Eburnean Plutono-Metamorphic Complex (Fig. 1). Basically, granitoid and gneissic-migmatitic host rocks are characterized by MVI-k values below 0.007 S.I. (Fig. 5b).

S2 section runs from WNW to ESE for 90 km. This section intersects lengthwise the Serra da Neve alkaline complex. From WNW to ESE, it intersects the Chai, Lutala and Chitucubero structures, and two more satellite structures related to this complex, namely Nejoio and Vicuio (Fig. 1 and Fig. 5c). As in the previous section, in the S2 the SNAC bodies present a MVI-k between 0.007 S.I. and 0.5 S.I.. Chai structure was recognized between km 6 and km 18 with thickness ranging from 3 to 7 km. Lutala and Chitucubero structures thicknesses are 6 km and 4 km, respectively, and are present in S2 between km 27 and km 50. The satellite structures, Nejoio and Vicuio, are represented in S2 section between kms 61-66 and kms 73-84 and present a maximum depth of 6 km and 7 km, respectively. As in the S1 section, the Lutala structure located between km 33 and km 44 is characterized by lower MVI-k values (Fig. 5c). The Eburnean Acid Plutonic Suite and the Eburnean Plutono-Metamorphic Complex units were also interpreted in S2, being characterized by MVI-k values below 0.007 S.I. (Fig. 1 and Fig. 5c).

We observe a source body with an average thickness of 4 km in the edge of the WNW section. This is probably related to the gabbros, diorite and quartz-diorites sometimes foliated rare ultramaphites and tonalities to granodiorites mapped in this area and assigned to the Eburnean Basic to Intermediate Plutonic Suite (Fig. 1 and Fig. 5c).

In both sections (S1 and S2) we observe lower MVI-k values associated with the Lutala structure. This is probably due to the diversity of geological units and to the presence of surface/overlying deposits. As described in Caessa *et al.* (2021), the Lutala core is a caldera-shaped depression filled with eluvio-alluvial deposits, sometimes interspersed with tuffs, sparse outcrops of phonolites, syenitic porphyries and syenites.

The magnetic method proved to be very useful in the detection of the Serra da Neve structures and of the lineaments that control its emplacement. The observed high magnetic susceptibility contrast between the complex and the host rocks allowed us to obtain an accurate three-dimensional geometry for all SNAC structures. The positive magnetic anomalies related to SNAC structures allowed the definition of target areas, which can represent preferential host areas for REE mineralizations.

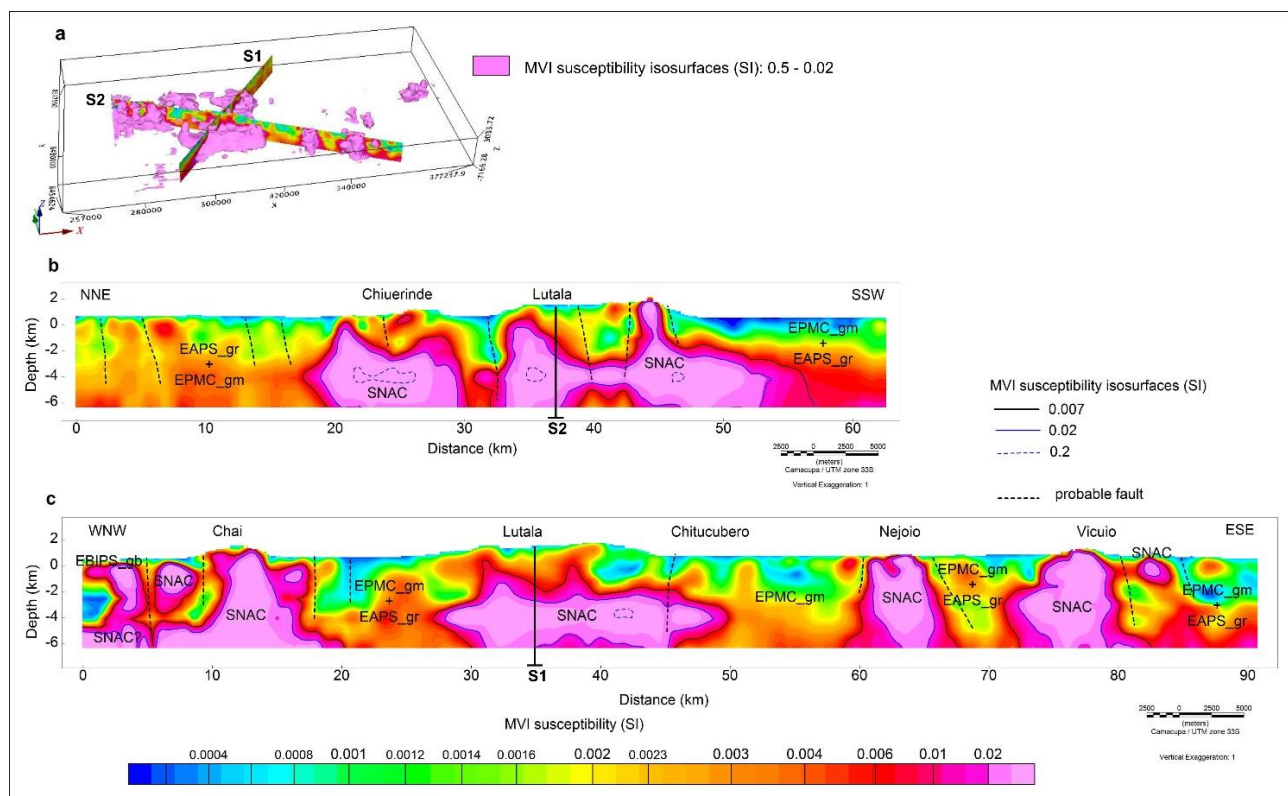


Figure 5. Serra da Neve MVI susceptibility model. a) MVI susceptibility isosurfaces (0.5 – 0.02 S.I.) representing the geological units that form SNAC and MVI susceptibility sections (S1 and S2) extracted from the amplitude of magnetization voxel. b) S1 section. c) S2 section. In the sections are represented MVI susceptibility contour lines (0.2, 0.02 and 0.007), probable faults and interpreted geological units: SNAC – Serra da Neve Alkaline Complex units; EPMC_gm - Eburnean Plutono-Metamorphic Complex: orthoderivative gneisses and migmatites, scarce paragneisses and heterogeneous gneissified and migmatized granites; EAPS_gr – Eburnean Acid Plutonic Suite: granites to biotitic-amphibolic porphyritic granodiorites, sometimes foliated and granites to biotitic-amphibolic granodiorites, inequigranular, sometimes foliated and rare biotitic ± muscovite granites; EBIPS_gb – Eburnean Basic to Intermediate Plutonic Suite: gabbros, diorites and quartz-diorites, sometimes foliated, rare ultramafites and tonalites to granodiorites.

Figura 5. Modelo de susceptibilidad MVI de la Serra da Neve. a) Isosuperficies de susceptibilidad MVI (0.5 – 0.02 S.I.) que representan las unidades geológicas que forman el SNAC y secciones de susceptibilidad MVI (S1 y S2) extraídas del voxel de amplitud de magnetización. b) Sección S1. c) Sección S2. En las secciones están representadas las líneas de contorno de las superficies de susceptibilidad MVI (0.2, 0.02 y 0.007), fallas probables y unidades geológicas interpretadas: SNAC – unidades del Complejo Alcalino de la Serra da Neve; EPMC_gm - Complejo Plutono-Metamórfico Eburneano: gneises y migmatitas ortoderivadas, escasos paragneises y granitos heterogéneos gneisificados y migmatizados; EAPS_gr – Suite Plutónica Ácida Eburneana: granitos a granodioritas biotítico-anfibólicas, porfiroides, a veces foliados y granitos a granodioritas biotítico-anfibólicas, inequigranulares, a veces foliados y raros granitos biotíticos ± moscovitos; EBIPS_gb – Suite Plutónica Básica a Intermédia Eburneana: gabros, dioritas y cuarzo-dioritas, a veces foliadas, raras ultramafitas y tonalitas a granodioritas.

5.2. Jamba

As shown in Figure 6, the inversion process carried out on the area around the Jamba itabirites revealed a model with well-defined volumes. These volumes exhibit diverse dimensions and shallow depths, with most of them outcropping. No preferred orientation or alignment is noticeable, with the volumes showing a radial symmetry. The process established a robust correlation between the calculated volumes and the geometries derived from the magnetic field's analytical signal.

The model was formed by a grid with cells sized at 250m x 250m. The vertical dimension begins at 125 m at the surface, increasing in depth by 8% with each row, extending to an exploration depth of approximately 7 km. Empirical assessment, aided by the examination of outcropping areas of itabirites and of the Menongue plutonic suite, led to the selection of isosurface thresholds of 0.006, 0.01, and 0.02 to provide readers with pertinent information on the distribution of magnetic susceptibility values.

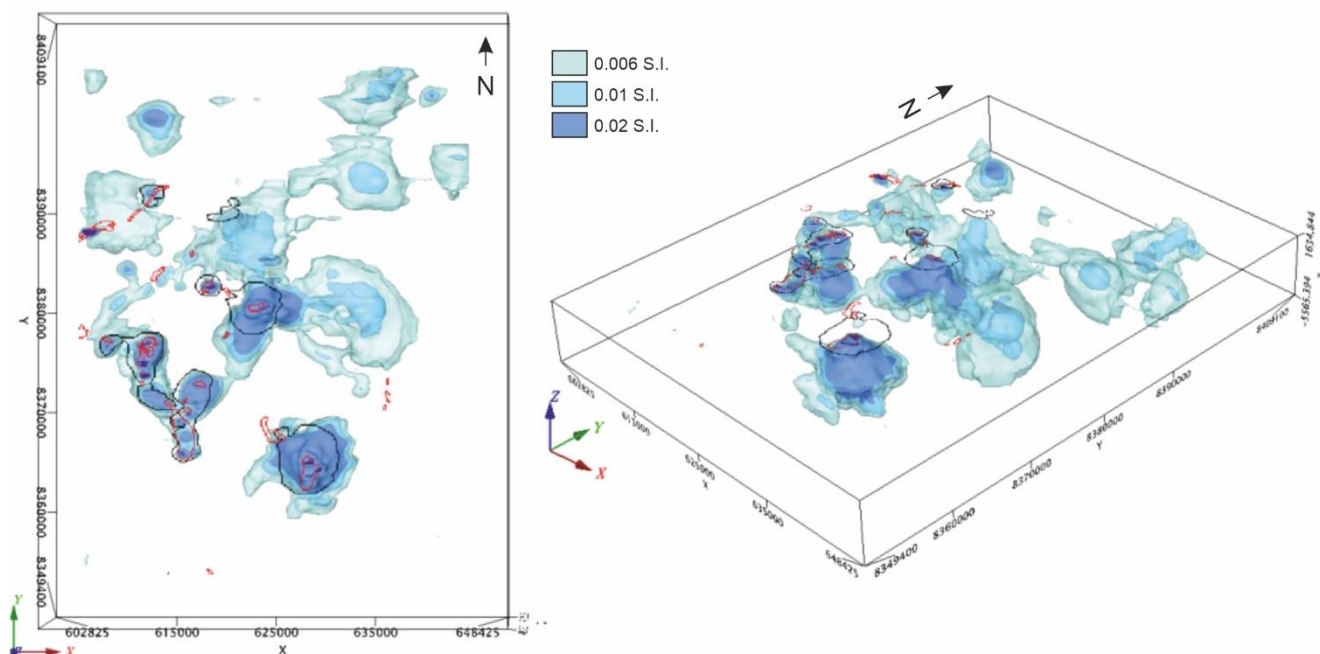


Figure 6. Jamba MVI susceptibility model. MVI susceptibility isosurfaces 0.006 (lighter blue), 0.01 and 0.02 (darker blue). Black lines mark the outline of the TMI analytic signal and red lines mark the itabirites outcrops.

Figura 6. Modelo de susceptibilidad MVI de la Jamba. Isosuperficies de susceptibilidad MVI 0.006 (azul más claro), 0.01 y 0.02 (azul más oscuro). Las líneas negras marcan el contorno de la señal analítica de la TMI y las líneas rojas marcan los afloramientos de las itabiritas.

The model exhibits magnetic susceptibility values significantly high, reaching up to 2.5 in S.I. units. Notably, all values above 0.07 S.I. are correlated with itabirite outcrops, which are consistent with the presence of magnetite and hematite in varying proportions, as these minerals significantly enhance the magnetic susceptibility of the rocks. In this analysis we highlighted the volumes identified by susceptibility values above 0.02 S.I. as representing itabirites. These predominantly exist as outcropping or sub-outcropping bodies, primarily situated above a depth of 3 km. The two large volumes in the centre and centre-south of the study area are the exceptions as these higher values root on the bottom of the model. The proximity of Menongue plutonic suite outcrops to these larger volumes necessitates consideration of potential magnetic signal interference or overlap. Such overlapping is likely to cause an overestimation of the itabirite volume within the calculated model, emphasizing the critical role of empirical evaluation in conjunction with geophysical modelling to accurately interpret subsurface structures.

Regions presenting elevated, albeit less high, susceptibility values above 0.006 S.I. are associated with the granites of the Menongue plutonic suite. This suite's mineralogical composition, abundant in plagioclase, quartz, hornblende, biotite, and particularly accessory magnetite, plays a pivotal role in its distinctive magnetic properties. The measured susceptibility values within the Menongue plutonic suite ranged from 1.87×10^{-3} to 2.55×10^{-2} S.I., averaging at 1.26×10^{-2} S.I. (Represas *et al.*, 2018) further highlighting the suite's significant contribution to the area's magnetic landscape.

The complex interplay between the mineralogical compositions of the Menongue plutonic suite and itabirites, especially in terms of their magnetic properties, underlines the challenges and considerations in geophysical inversion analysis. Only by integrating multidisciplinary datasets, including geological, petrological and the acquisition of more geophysical data with different methodologies, we can enhance subsurface structure understanding.

6. Conclusions

This study has successfully applied 3D magnetic inversion techniques in two different areas in Angola, namely SNAC and Jamba. The results allowed the estimation of reasonable MVI susceptibility values and the geometric characterization of intrusions/deposits in accordance with the available geological information of the study areas, providing a better understanding of its geological and mineralogical frameworks.

Notably, the study underscores the importance of employing iterative reweighting inversion (IRI) techniques to refine the geometry and amplitude of the recovered physical properties, thereby enhancing the accuracy of subsurface models.

The high magnetic susceptibility contrast between the SNAC and the host rocks allowed us to obtain a 3D geometry for all SNAC structures. The SNAC geometry derived from the inversion model is in conformity with the geometries of typical igneous intrusions, as well as with the existent geological knowledge of the Serra da Neve. However, in the future this model can be improved if we have more geological, geochemical or geophysical information available to constrain the magnetic inversion.

The positive magnetic anomalies related to SNAC lithologies have permitted the delineation of target areas. These areas can potentially host REE mineralization's that are an economically important resource commonly associated with these alkaline complexes. SNAC can therefore be an important target area for mineral exploration in Angola. Detailed geophysical and geochemical studies are recommended in the designed target areas to evaluate the mineral exploration potential with better detail.

Regarding Jamba itabirites, our findings reveal distinct, well-defined volumes with varying dimensions and depths, showcasing the potential of high-resolution magnetic surveys in identifying and delineating iron ore deposits. 3D magnetic inversion has allowed for a detailed interpretation of the subsurface distribution of Jamba itabirites, highlighting areas with significant iron ore potential. The inversion results, characterized by high magnetic susceptibility values, correlate strongly with known itabirite outcrops, validating the efficacy of the MVI method in this context. Furthermore, the identification of substantial magnetic anomalies associated with the Menongue plutonic suite adjacent to itabirite volumes underscores the complex interplay between geological formations in the region. This complexity necessitates a multidisciplinary approach, integrating geological, petrological, and geophysical data, to accurately interpret the subsurface structures and mineralization processes.

The implications of this research extend beyond academic interest, offering tangible benefits for the mining industry in Angola. The detailed subsurface models generated through this study provide a valuable tool for targeted exploration and efficient resources exploitation. Moreover, the methodology and findings contribute to the broader geophysical community by demonstrating the potential of 3D magnetic inversion in mineral exploration, particularly in regions with complex geological settings.

Future research should aim to extend the application of 3D magnetic inversion techniques to other mineral-rich regions within Angola, exploring the potential for uncovering new deposits. Incorporating additional geophysical data, such as gravity and seismic surveys, could further refine subsurface models and enhance the understanding of mineralization processes.

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Authorship contribution statement

Ana Machadinho: Writing - Original Draft, Investigation, Conceptualization, Data Curation, Formal analysis, Methodology, Visualization, Validation.

Patrícia Represas: Writing - Original Draft, Investigation, Conceptualization, Data Curation, Formal analysis, Methodology, Visualization, Validation.

Daniela Alves: Writing - Review & Editing, Investigation, Data Curation.

Domingos Cordeiro: Writing - Review & Editing, Data Curation.

João Carvalho: Writing - Review & Editing, Investigation, Formal analysis, Supervision.

Rui Lopes: Writing - Review & Editing, Investigation, Data Curation.

Paulo Caessa: Writing - Review & Editing, Investigation, Data Curation.

Luis Pereira: Writing - Review & Editing, Investigation, Data Curation.

André Osório: Writing - Review & Editing, Investigation, Data Curation.

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