Geophysical characterization of the remanent anomaly in the Paleo/Mesoproteozoic Araí Intracontinental Rift, Brazil

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SUMMARY

We investigated a remanent anomaly in the main part of a Brazilian intracontinental Paleo/Mesoproterozoic rift using different geophysical methods. To enhance the anomaly signature at different depths we used RTP, DZ, THDR, 3D-AS, and UpCon techniques, generating a magnetic-structural interpretation of the main non-mapped features of the region. To identify the presence of non- induced magnetization in this particular anomaly and its total magnetization direction, we used the Maxi-Min, Magnetic Vector Inversion and Helbig's Magnetic Moment Analysis techniques. We found total magnetization inclination and declination (I, D) of (49.10, -25.10), (46.30, -10.05) and (43.94, -19.53), respectively. Based only on the TMI, we modelled this anomaly considering remanence using Magnetic Vector Inversion technique. Two bodies of great extension were identified at depths ranging between ~9 and 20 km. The anomaly was interpreted as a within-plate mafic pluton representing a magma chamber of continental tholeiitic association with associated feeder conduits. These results are crucial to understand the tectonic evolutional framework from this region affected by several superimposed events, including the Neoproterozoic Brasiliano Orogeny.

Key words: remanent, rift, inversion, Proterozoic, magnetic.

INTRODUCTION

The Araí Rift comprises a Paleo/Mesoproterozoic intracontinental rift located in the north-eastern portion of the Brasília Fold Belt, Brazil, that was affected by the Neoproterozoic Brasiliano/Pan-African Orogeny (Fuck et al., 2014) (Figure 1). The main faults of the rift follow the NE direction from Niquelândia through Cavalcante and Teresina towns, extending to Campos Belos town, confirmed by mapped conglomerate layers along these faults. The area investigated in this study comprises a magnetic dipole observed in the main portion of the rift. This anomaly is located at low magnetic latitudes and seems to have a strong remanence component, initially confirmed by its inverted nature when compared to the behaviour expected for a purely induced anomaly in the same geographic location (Figure 2). The anomaly has a length of approximately 60 km in the NW direction and is characterized by a major negative in the northwest and a slightly reduced positive in the southeast, oriented N42E. The amplitude of the anomaly is approximately 70 nT. The main anomaly is followed by some other small normal and inverted dipolar anomalies in the same area and it was previously observed by Almeida (2009) in the region of the Pedra Branca Suite (Figure 3), referring to a probably deep source.

To study this particular magnetic signature, we compared and interpreted different functions that are calculated directly from the TMI: (1) reduction to the pole (RTP) by the Maxi-Min technique proposed by Fedi et al. (1994), Magnetic Vector Inversion (MVI) (MacLeod and Ellis, 2013) and Helbig's Magnetic Moment Analysis (HMMA) (Helbig, 1963) in order to identify remanence by comparing the total magnetization direction with the induced magnetization direction; (2) the first vertical derivative (DZ), upward continuation (UpCon), the 3D analytic signal (3D-AS), the total horizontal derivative (THDR) and the RTP grids in order to characterize the anomaly and its boundaries, comparing results between each other; (3) a 3D model of the vector of magnetization from MVI, in order to recognize the total magnetic vector behaviour in the main portion of the rift and the causative sources characteristics and susceptibility range. The main aim of this study is to suggest hypotheses that help to understand the geologic processes responsible for generating this anomaly and to suggest a regional tectonic framework from the region over the main portion of the Araí Rift that will be useful to future scientific studies and exploration.

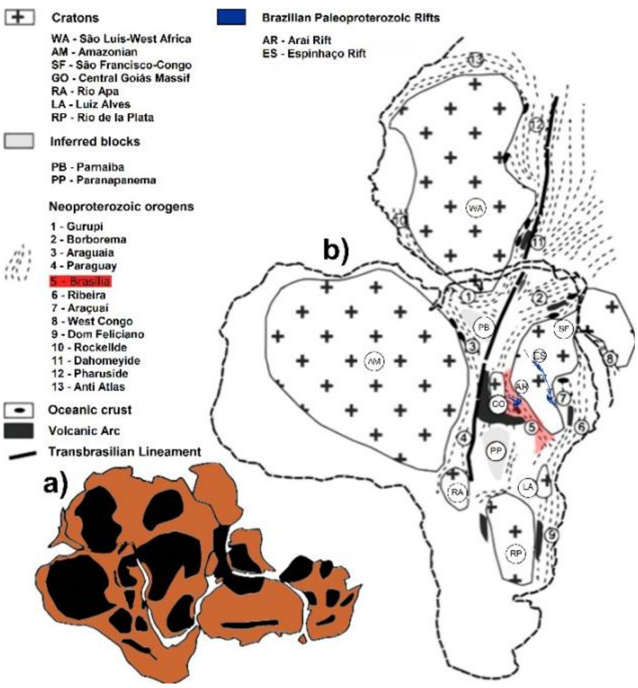

Figure 1. (a) Gondwana reconstruction adapted from Unrug (1996) and (b) Neoproterozoic disposition of the geologic units during Brasiliano/Pan-African Orogeny in Brazil adapted from Klein and Moura (2008).

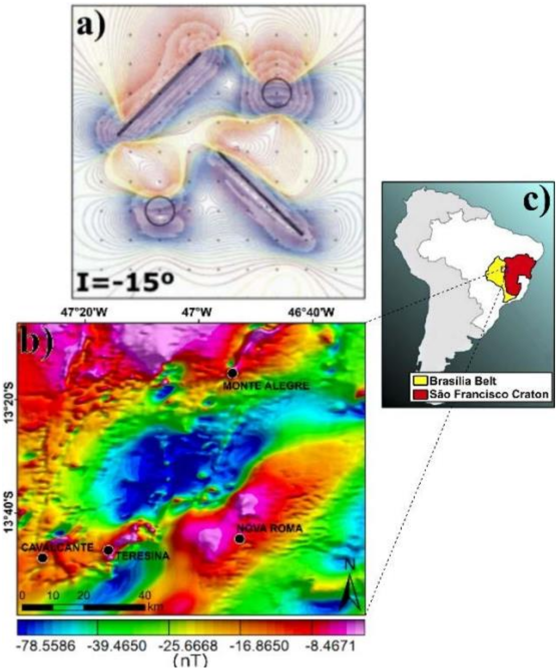

Figure 2. (a) A 15º inclination in the magnetic field for the southern hemisphere in the geometry recognition of causative sources (adapted from Isles and Rankin, 2013), inverted dipolar anomaly and (c) location of the study area in Brazil.

GEOLOGIC SETTING

The 1: 100,000 geological maps of the study area (Figure 3) (Alvarenga *et al.*, 2007a; Botelho *et al.*, 2007) depict the main stratigraphic units of this region (Alvarenga *et al.*, 2007b), being these: (i) Ticunzal Formation, (ii) Aurumina Suite, (iii) Nova Roma Quartz-Diorite (namely Nova Roma pluton by Cuadros *et al.* 2017a), (iv) Pedra Branca Suite, (v) Araí Group and (vi) Bambuí Group. The sedimentary cover is represented by the Paleo/Mesoproterozoic rift-sag metavolcanic and metasedimentary rocks of the Araí Group and the Neoproterozoic foreland siliciclastic/carbonatic rocks of the Bambuí Group. The basement portion within this study area was referred to by Fuck *et al.* (2014) as the Cavalcante-Arraias domain and is composed of the 2.12 – 2.18 Ga peraluminous granites and tonalites of the Aurumina Suite (Botelho *et al.*, 2006; Fuck *et al.*, 2014; Sousa *et al.*, 2016), concordantly intruding medium-grade schists and paragneisses of the Ticunzal Formation (Marini *et al.*, 1984). Cuadros et al. (2017b) constrained the age of the latter between 2.16 and 2.19 Ga, based on zircon U-Pb data. Ticunzal Formation TDM ages range between 2.19 and 2.80 Ga (Pimentel *et al.*, 2004; Botelho *et al.*, 2006; Fuck *et al.*, 2014; Cuadros et al., 2017b). This basement domain is marked by the intrusion of tin-bearing A-type rapakivi granites of the Pedra Branca Suite and is partially covered by the green-schist facies metamorphic sequences of the Araí Group, with protoliths including siliciclastic rocks, rhyodacites and basalts. Both units are interpreted as the result of a rifting event that took place at ~1.77 Ga (Pimentel *et al.*, 1991; 1999). The rift-related volcanism is characterized by a bimodal association, typical of continental setting. The felsic lavas are similar to the granites of the Pedra Branca Suite, showing an intraplate magmatism signature, whilst the mafic lavas show continental tholeiitic signature (Alvarenga *et al.*, 2007b). A later anorogenic magmatic event at ~1.58 Ga is represented by the tin-bearing granites of the Serra da Mesa Suite, to the west of the studied area (Pimentel *et al.*, 1999; Pimentel and Botelho, 2001), corresponding to rift reactivations. The Nova Roma pluton is referred to by Cuadros *et al.* (2017a) as an undeformed composite body that intruded mica-graphite schists of the Ticunzal Formation and Au2 muscovite-biotite granites of the Aurumina Suite. In some instances, a progressive assimilation of the host rocks can be observed in outcrop, yielding a hybrid rock type between metaluminous and peraluminous. Alvarenga *et al.* (2007b) reported a U-Pb zircon age of ~2.14 Ga with a TDM of 2.48 Ga and an εNdT value of -3.9 for this unit.

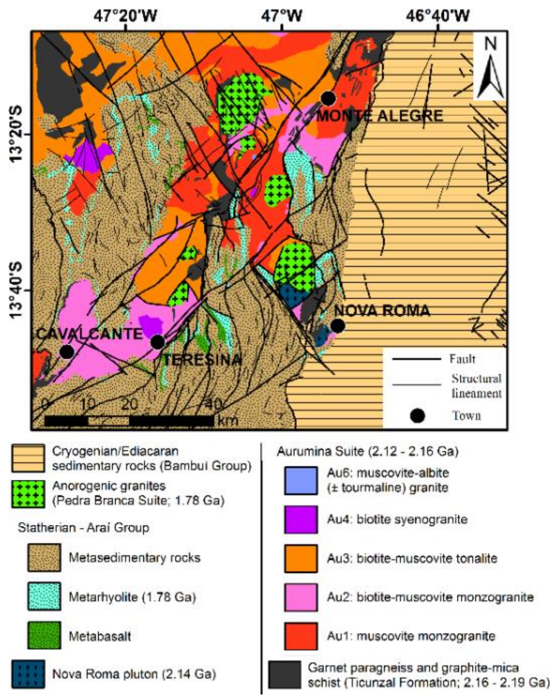

Figure 3. Geological map of the studied area. Modified from Cuadros et al. (2017a; 2017b).

METHODOLOGY

Edge Detection of Magnetic Sources

By visual inspection of the RTP, DZ, THDR, 3D-AS, and UpCon, we identified the position and the edges of magnetized bodies at different depths over the main anomaly, delineating contacts, and comparing the individual response of each product. Then, we associated these responses to the known geology (Figures 4 and 5).

First order derivatives-based products were chosen to enhance details in magnetic data caused by high frequency anomalies (Nabighian *et al.*, 2005) while Upward Continuation was used to emphasize the field with a deeper origin by recalculating and increasing the height of the observation plane of the anomaly (Jacobsen, 1987). The first vertical derivative emphasizes features close to the surface and narrows the width of the anomaly, thus locating sources more precisely (Cooper and Cowan, 2004). THDR filter is useful to distinguish abrupt lateral changes in magnetic susceptibility, represented by higher gradients. The peaks of the anomalies are located at the edges of the bodies or close to them. The shift between the anomaly peak and the edge of the magnetic source increases with increasing source-sensor distance (Pilkington and Tschirhart, 2017). This edge detection filter is given by Cordell and Grauch (1985) as the square root of the sum of the squares of first horizontal derivatives of the magnetic field. Since THDR is based on the TMI first order derivatives, one can conclude that THDR is more effective in imaging shallower bodies than deeper one. 3D-AS can be expressed as the magnitude of the vector sum of the three-component directional first derivatives of the magnetic field (Roest *et al.*, 1992). The resulting shape of the anomaly is expected to be centred above the magnetic body, but some factors (such as varying magnetization directions, terrain effects, 3D corners on body edges, etc) can produce slight offsets from its true location (Li, 2006). If more than one magnetic source is presented, the result of the 3D-AS is dominated by shallow sources.

Magnetisation estimates and data inversion

We applied the Maxi-Min technique developed by Fedi et. al (1994) for both the calculation of the total magnetization and for an efficient RTP at low latitudes considering remanence. Maxi-Min method is based on the successive application of the RTP operator on the measured magnetic data for different total magnetization parameters. The correct (I, D) pair is the one that maximizes the minimum of the magnetic anomaly reduced to the pole (Cordani and Shukowsky, 2009). The results are a grid of the TMI reduced to the pole and an estimate of the direction (I, D) of the total magnetization of the anomaly.

Using Helbig's integrals, total magnetization directions can be estimated in small data windows centred on each grid node of the magnetic vector field component grids. If the central grid node lies over an isolated compact source that can be represented by a magnetic dipole, then the calculated magnetization direction will accurately predict the total magnetization direction of the dipole, and the direction will remain relatively constant as the window size is increased in small steps. On the other hand, if the central grid node does not lie over an isolated source, the calculated total magnetization direction will change with increasing window size (Phillips, 2005; Phillips *et al.*, 2007). We estimated total magnetization directions using HMMA technique within a finite data window on the TMI grid centred over its main dipolar anomaly, based on the observation of the RTP map (Figure 4a), to produce the total magnetization direction result. We applied a second order low-pass filter with a cut off wavelength of 10 km to isolate the main anomaly and removed a planar surface from each magnetic vector component within the window in order to assure that the mean values of the components are zero within the window, and that the two vanishing moments are approximately zero.

The MVI technique (Ellis *et al.*, 2012), performs magnetic data inversions considering both remanent and induced magnetization without prior knowledge of the direction or strength of remanent magnetization. The majority of current voxel-based magnetic inversions assume anomalous magnetization in the direction of the inducing earth's field (Li and Oldenberg, 1993). However, as observed in this study, the direction of rock magnetization, particularly in strongly magnetized rocks, is often in a direction different from the primary geomagnetic field. Assuming that there is a component of remanence in this area, we used the MVI to directly model the vector of magnetization based only on the TMI data. We used a voxel cell size of 500m x 500m x 2516m (x, y, z), with mesh points of 198 x 157 x 24 (746,064 cells). After the application of these techniques, if the total magnetization does not coincide with the induced magnetization (parallel to the known IGRF direction), we confirm that there is a non-induced magnetization associated, possible due to remanence.

RESULTS AND INTERPRETATION

Qualitative Interpretation

From the observation of the TMI, RTP, 3D-AS and THDR maps in conjunction with the DZ and UpCon maps (Figures 2, 4 and 5), the total magnetic anomaly results from the interaction of a deep anomaly of large wavelength and inverse polarization with shallow anomalies, most of them with a normal polarization.

Contour lines corresponding to high values (from visual inspection) above 24 nT, 0.009 nT/m and 0.007 nT/m were applied to the RTP, AS and THDR maps, respectively (Figure 4). From the geometry observed by these contour lines, it is possible to notice that the RTP map shows a circular anomaly crossed by a linear anomaly of NE direction, the latter related to a probably deep fault. Analysis of the 3D-AS and THDR confirm that the circular anomaly found in the RTP map does not relate just to one spherical body of great dimension, but to the interaction between this body's anomaly with smaller anomalies oriented NS and structures predominantly oriented N34E. These NE structures are related to reactivated transpressive faults. The north-south fold-belt trends to the west and east of this cluster of anomalies are deflected around intrusive bodies. The majority of the circular bodies observed in the AS and THDR are associated with granitic intrusions of the Pedra Branca Suite, and lead to localized positive highs in these maps along the rift main axis, adding to the linear high produced by a major basement fault, that can be observed inthe THDR map (Figure 4c). A well-defined boundary between zones with noticeable different degrees of magnetic relief observed on the TMI map (Figure 2) confirms this behaviour.

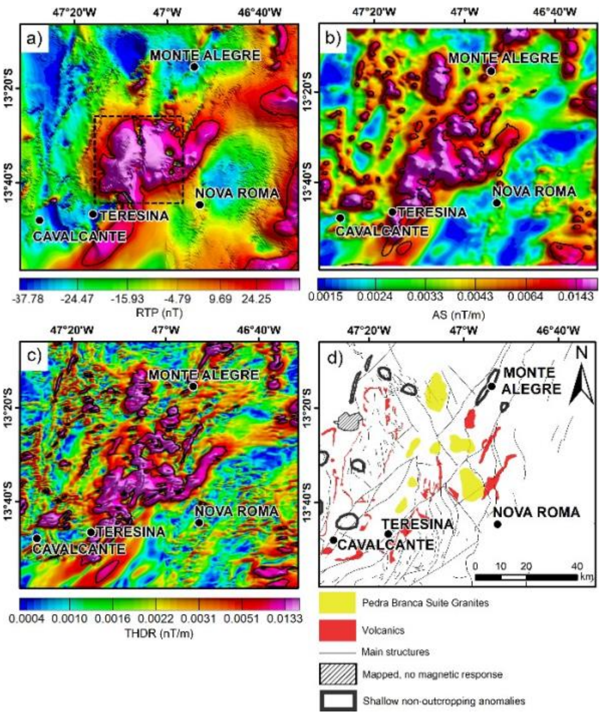

Figure 4. (a) RTP, (b) 3D-AS and (c) THDR maps with solid black contour lines of respectively 24 nT, 0.009 nT/m, and 0.007 nT/m, indicating high values in the signal. The dashed square in the RTP map represents the chosen window for the application of the HMMA technique. (d) Magnetic interpretation of the studied area. The main structures are based on the 1:1,000,000 map by Souza *et al.* (2004).

Part of the peaks in the 3D-AS and THDR maps correlate with previously mapped plutons of the Pedra Branca Suite. However, the deep anomaly observed in the TMI and UpCon maps (Figure 2 and 5b, 5c, 5d) is most likely related to magnetite-rich basaltic rocks of the Araí Group. This body would represent a chamber of stalled magma from which extracted lavas were subsequently erupted, forming the basalt flows mapped on the surface of the surrounding areas. Smaller linear non-outcropping anomalies (Figure 4) might be interpreted as basalt dykes related to the main body that represent feeder structures that channelled the extracted lavas to the surface. These dykes are likely to have crystalized more rapidly than the body responsible for the main anomaly, thus carrying a direction of magnetization that differs from the latter.
Part of the Aurumina Suite units interact with N30E structures, modified in the Brasiliano Orogeny into large dextral transpressive shear corridors followed by intense mylonitization and silicification and by the development of a pervasive mylonitic foliation (Alvarenga *et al.*, 2007b). Part of the outcropping Pedra Branca plutons are aligned with Brasiliano N40W structures, positioned between weakness zones, while most of the non-outcropping plutons are NS oriented.

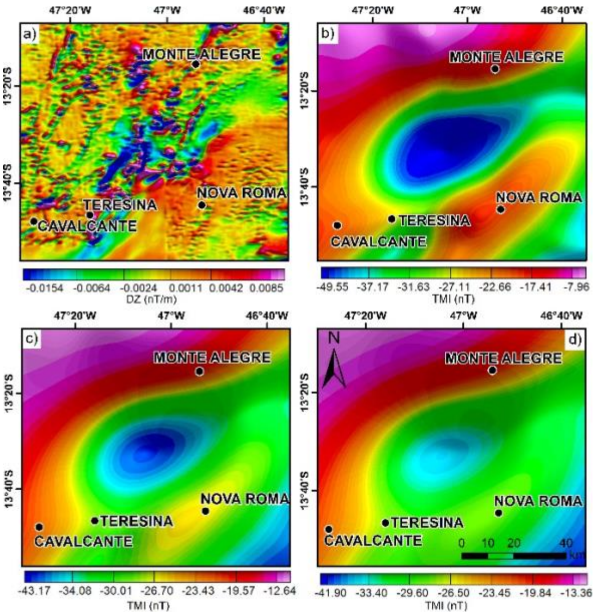

Figure 5. (a) DZ map showing anomalies due to shallow sources, UpCon map with an observation height of (b) 7 km, (c) 15 km and (d) 20 km showing a deep source anomaly.

Quantitative Interpretation
After the application of the Maxi-Min algorithm, MVI and the HMMA techniques we have found the following results for the total magnetization vector of the study area

Position		IGRF		Total Magnetization		Technique
Latitude	Longitude	I	D	I	D	
13 33' 00'' S	47 03' 36'' W	-20.18	-20.78	49.10	-25.10	Maxi-Min
				46.30	-10.05	MVI
				43.94	-19.53	HMMA

Table 1. Location, IGRF and direction of the total magnetization from the application of different techniques on the magnetic anomaly.

Since the direction of the total magnetization does not coincide with the IGRF, we can infer that there is associated non-induced magnetization (possibly due to remanence) in the region. Paleomagnetic studies are necessary to establish the exact cause of the remanent magnetization observed, thus allowing to resolve with good precision the age and the geological event that generated such magnetization. Nevertheless, through inferences made from the observation of different geophysical and geological features in this work, we will establish a preliminary hypothesis for this remanence.
Figure 6 shows a 3D model with the estimates for the total magnetization from MVI, with a cell size of 500 m in the XY direction and 2516 m in Z direction. It is possible to notice the presence of spherical and tabular bodies between 9.2 and 20 km deep approximately, with magnetic susceptibility values varying from 0.032 to 0.083 SI. The extension of the main body is ~30 km, with a secondary body spanning ~13 km.

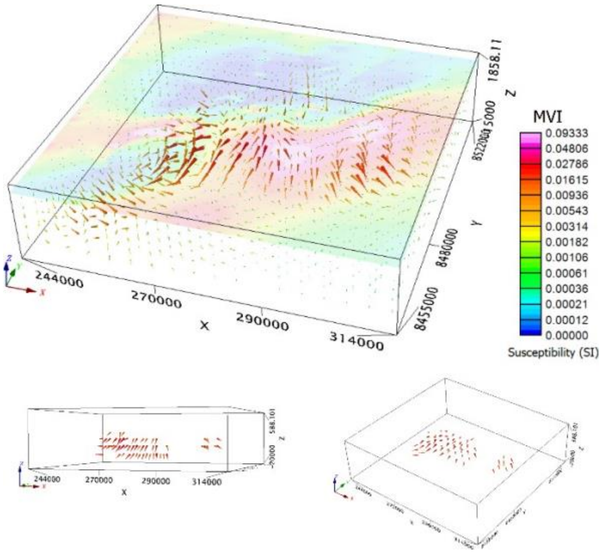

Figure 6. Total Magnetization vector of the study area from MVI and susceptibility response.

CONCLUSIONS

Based on the interpretation of different geophysical methods, along with previously-generated geological data, we characterized a magnetic anomaly with remanent signature in the main portion of the Araí Intracontinental Rift. It is very likely that the recorded magnetization found in the main anomaly of the study area corresponds to thermoremanent magnetization of a mafic pluton representing a magma chamber with associated feeder conduits that was emplaced within the main portion of the rift, acquired at the time of intrusion of these rocks. A second hypothesis would be that the magnetization recorded in these plutons represents a remagnetization acquired during the Brasiliano Orogeny.
Most of the outcropping units have normal polarization, including most of the metavolcanics rocks associated with felsic magmatism (verified from the TMI grid, after the application of a high pass filter (DZ)), indicating that the remanence modelled in MVI belongs to bodies at greater depths (between 9.2 and ~ 15 km – Figure 6) positioned vertically in the same region as the outcrops (see RTP compared to AS and UpCon maps – Figures 4 and 5). Thus, the magnetic bodies modelled in this work are interpreted as within-plate mafic rocks of continental tholeiitic association. There may be other bodies associated at greater depths, but they cannot be detected because, in this region, rocks lose their magnetization at depths of approximately 20 km (Curie surface according to Blum,

1999 and Moro et al., 2018).

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