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# INTERPRETATION OF THE GEOMAGNETIC ANOMALIES IN THE SÃO FRANCISCO CRATON REGION BASED ON CHAMP MISSION DATA

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**ABSTRACT.** This paper presents the results of the analysis of magnetic data from the CHAMP mission (CHAllenging Mini-satellite Payload), based on the MF4 (Magnetic Field) magnetic model of the lithosphere aiming at a better understanding of the lithospheric structure of the São Francisco Craton region. Geophysical studies have been conducted in this area since the 1970s, providing information on the crust and on the lithospheric/asthenospheric mantle with a reasonable degree of detail and reliability. Magnetometric maps constructed from the model discussed here show satisfactory results that allowed for the association of different tectonic events (orogeny, continental passive margins) that occurred during the geodynamic evolution of the lithospheric area in question.

**Keywords**: magnetometry, CHAMP mission, cratonic lithosphere, São Francisco Craton.

**RESUMO.** O presente trabalho apresenta as discussões dos resultados da análise de dados magnetométricos provenientes da missão CHAMP (CHAllenging Mini-satellite Payload), que constituem o modelo geomagnético da litosfera MF4 (Magnetic Field), visando o avanço no conhecimento da estruturação litosférica da região do Cráton São Francisco. Estudos geofísicos nesta área têm sido realizados desde a década de 1970, fornecendo um conhecimento da crosta e do manto litosférico/astenosférico com um razoável grau de detalhamento e confiabilidade. Os mapas magnetométricos baseados no modelo MF4 apresentaram resultados satisfatórios que possibilitaram associar as estruturações resultantes de alguns eventos tectônicos distintos de orogenias de núcleos continentais e para margens passivas, envolvidos na geodinâmica da porção litosférica em questão.

**Palavras-chave**: magnetometria, missão CHAMP, litosfera cratônica, Cráton São Francisco.

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## INTRODUCTION

The geophysical studies performed in the São Francisco Craton region have been carried out since the 70's under the Gravimetric Survey Program of the Bahia State (DNPM/CPRM Agreement).

Airborne geophysical surveys were conducted over extensive areas of the craton with simultaneous recording of magnetic and scintillometric data (K, Th, U and CT). Data from some of such surveys, investigated in greater detail, allowed for better understanding of the region's crust. In recent decades, geophysical investigations have been systematically conducted aiming at unveiling the structure and evolution of the Earth's lithosphere.

Data obtained with the use of potential methods (Gravimetry and Magnetometry) increase our knowledge of the crust and of the lithospheric/asthenospheric mantle of a certain region with a reasonable degree of detail and reliability, allowing both better knowledge of the crustal structure of the region in several scales and the determination of specific parameters of the rheology of the lithosphere, including its isostatic condition (eg. Blitzkow et al., 1979; Haralyi & Hasui, 1985; Ussami, 1986, Molina & Ussami, 1999; Oliveira, 2005, 2009).

Other studies involving seismology, magnetotelluric surveys and geothermal studies were performed on the craton, both in local and in regional scale (e.g. Assumpção et al., 2002; Pádua, 2005; Alexandrino & Hamza, 2008), adding to the knowledge of the region's crust and mantle.

In this context, it is here proposed to present and discuss the results of the geomagnetic mapping of the São Francisco Craton region derived from data obtained during the CHAMP – MF4 space mission (CHAllenging Mini-satellite Payload – Magnetic Field, Reigber et al., 2002) aiming at understanding the lithospheric structure and geodynamic evolution of the area. In addition to a short explanation of the magnetometry by satellite methodology, a geological interpretation of thematic maps will be presented, trying to correlate the patterns of geomagnetic anomalies with the main tectonic-structural features of this important segment.

## GEOLOGIC CONTEXT

The São Francisco Craton region is a geotectonic entity of higher order of the pre-Brasiliano (Pan African) consolidation, which comprises almost the entire state of Bahia and extends to the neighboring regions of Minas Gerais, Sergipe, Pernambuco and Goiás (Almeida, 1977) (Fig. 1).

Initially, the limits of the São Francisco Craton region were defined by Almeida (1977), according to craton delimitation criteria of the Russian-European school, classifying them into two categories: conventional and arbitrary.

The conventional limits were defined by the relevant structural discontinuities such as the more external faults of the folding belts. The arbitrary limits were identified on shield regions, on areas with Phanerozoic or Proterozoic cover without significant discontinuities, in areas of reworked basement, in segments of continuous folding within the belts and discontinuous folding within the cratonic area (Almeida, 1981).

In the inner portion of the craton, in most of its extension, Precambrian and Phanerozoic covers prevail, constituting three major morphotectonic units: São Francisco Basin, Paramirim Aulacogen and a great portion of the Recôncavo-Tucano-Jatobá Rift. Differently, both in the extreme southern and in the eastern portions, the basement outcrops. The protoliths of the Espinhaço (Mesoproterozoic) and São Francisco (Neoproterozoic) Super Groups were deposited on an aborted rift delineated by truncations in the N/S direction (Alkmim et al., 2003).

The tectonic evolution of the São Francisco Craton region features five stages of deforming events (Alkmim, 2004), where stage I is the Rio das Velhas/Jequié event (2.9–2.7 Ga) derived from distinct orogenic events of continental nuclei, aggregated by means of diachronic collisions, together with the juvenile arches and post-tectonic magmatic episodes. Later, once the continent was consolidated, the Craton region evolved towards the Minas passive margin, individualizing the Paramirim region (2.5 Ga) and making evident stage II of the Paramirim continent individualization. Stage III is marked by the Trans-Amazon event, where the Paramirim continent (Gavião block) collides with the Gabon continent as part of the Paleoproterozoic orogeny (2.1–1.9 Ga).

It is likely that those collisions lead to the formation of a supercontinent, on which the Staterian period developed. Stage IV is evidenced by the Staterian taphrogenesis (1.75 Ga), during which the development of continental sedimentary rifts occurred, interspersed with acid lava, capped by marine deposits from the Espinhaço Super Group. The Staterian rifts were reactivated, some evolved to passive margins and a new taphrogenesis occurred in the Macaúbas region, followed by glaciation in stage V, defined as the Tonian Taphrogenesis (950 Ma). During that period, the São Francisco – Congo Plate was individualized, outlining traces of the future São Francisco Craton.

## METHODOLOGY

The CHAMP mission was launched in July 2000 to measure the low altitude field under a circular orbit, with high accuracy

(Reigber et al., 2002). Recently, two models were incorporated to the new CHAMP datum: i) the Comprehensive Model (Sabaka et al., 2002), that includes geomagnetic field parameters taking into account the sources from the nucleus to the magnetosphere and, ii) the MF (Magnetic Field) models, focused strictly on the lithospheric magnetic field.

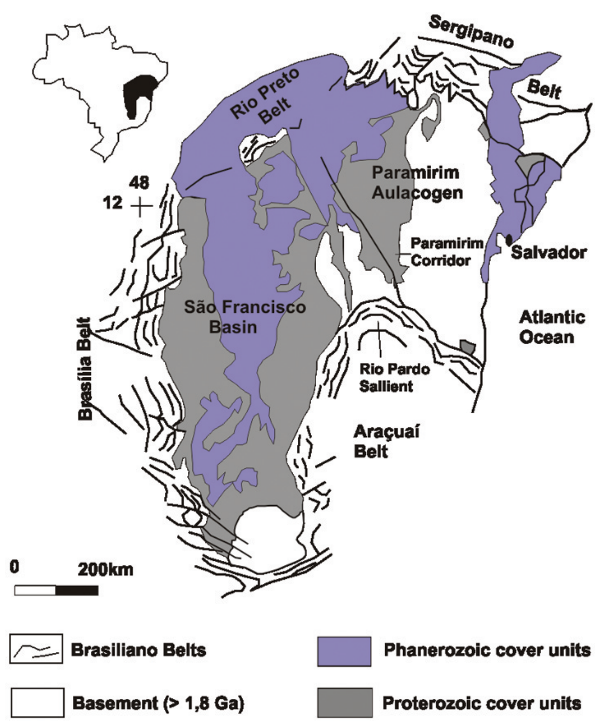


**Figure 1** – Simplified geologic map of the São Francisco Craton region (Cruz & Alkmim, 2006).

The initial model MF1 was determined based on scalar data (total intensity) surveyed in the first year of the CHAMP mission (Maus et al., 2002). Presently, the fourth generation model (MF4) is under development using improvements in the processing methodology, including correction for polar electrojet (PEJ) effects.

The MF4 field model represents part of the crustal geomagnetic field, derived from the scalar and vector data acquired during five years, between August 20, 2000 and April 2005. Data were acquired using an absolute Overhauser scalar magnetometer (OVM) with a 1 Hz sampling rate and a triaxial fluxgate magnetometer (FGM) with a 50 Hz sampling rate. CHAMP spatial orientation was based on an optical camera system that allowed the measurement of the vector field with an accuracy of a few seconds.

The model is obtained by the expansion of spherical harmonics (SH) for the grade 90 potential magnetic field and coefficients from 1 to 15. Input data were measured by the CHAMP satellite in an Earth orbit with an inclination of 87.3° and an initial altitude of 456 km. In five years the altitude decreased to 360 km, requiring two orbital maneuvers to increase the altitude and extending the mission's useful life.

In order to assess a model for the lithospheric geomagnetic field, it is necessary to consider some of its possible applications:

a) Subtract the lithospheric model from the measurements obtained by the satellite, to be able to study phenomena such as ionospheric currents (Ritter et al., 2004), pulsations (Sutcliffe & Lühr, 2003) and magnetic signals caused by ocean flow (Tyler et al., 2003);

b) Direct use of the model in geologic and geophysical interpretation (Hemant et al., 2004; Hemant & Maus, 2005);

c) Construction of a long wavelength lithospheric model, to be used in large-scale compilations of marine magnetic data and of data acquired in airborne surveys.

Processing also includes the subtraction of the values related to the main field, to the magnetospheric field and to corrections for effects arising from ocean tides. Magnetospheric fields still present, after this phase, are removed by adjustment, using a low-grade spherical harmonic function (Fig. 2).

The magnetometric maps of the São Francisco Craton region were generated via GMT – Generic Mapping Tools (Wessel & Smith, 1991, 1998), using data from the CHAMP – MF4 mission (Maus et al., 2006) with altitudes of 400, 100 and 50 km, to emphasize anomalies at lithospheric levels. The interpolation technique applied was the minimum curvature with a five-minute grid interval.

## RESULTS

Over the São Francisco Craton region, the total geomagnetic map at 400 km altitude allowed for the identification of the magnetic amplitude domains in different areas. The intermediate magnetic values appear associated to the Trans-Brazilian Lineament. Those of low magnetic amplitude are represented by the Rio Escuro Lineament with a preferential NE 45° direction. The higher values, also in the NE 45° direction, are related to the Serra do Mar mountain range (Fig. 3).

In the northern craton portion and its vicinities it was possible to identify the Paramirim Aulacogen and the Salvador Fracture Zone in the low magnetic amplitude domain. The Cadeia – Vitória – Trindade Lineament and the southern craton portion, such as the Altos Sete Lagoas and Parnaíba are highlighted by the negative magnetic values in the Analytic Amplitude Signal (AAS) map at 100 km altitude. The intermediate amplitudes were identified

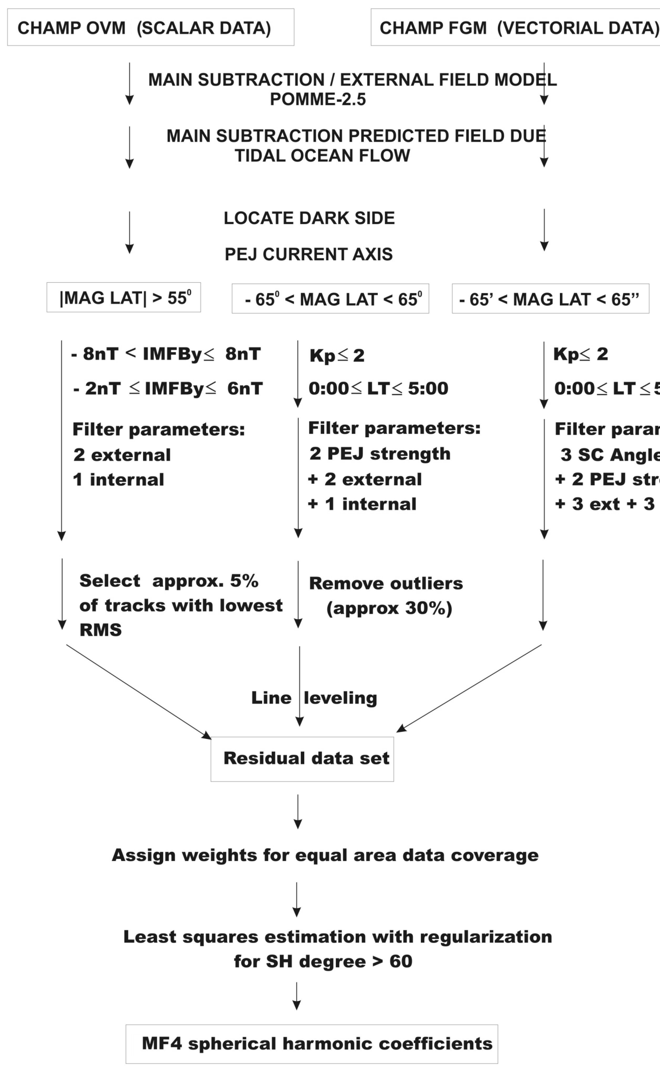


**Figure 2** – CHAMP – MF4 satellite data processing scheme. POMME-2.5: Potsdam Magnetic Model of the Earth; OVM: Overhauser scalar magnetometer; FGM: fluxgate magnetometer; PEJ: Polar Electrojets; SH: Spherical Harmonics; IMF: Interplanetary Magnetic Field; RMS: Root Mean Square; Kp: magnetic activity index (Maus et al., 2006).

in the Alto Januária, Serra do Mar and in the Tocantins Province, all of which are probably associated to orthognaisses related to the magmatic arch and ophiolitic mélange of the internal zone of the Brasília Belt. In the volcanic cones of the Cabo Frio High the higher anomalies and linear structures are, in general, oriented in the NE 45° direction (Fig. 4).

In the derivative Z at 100 km altitude map the low magnetic amplitudes associated with the internal zone of the Brasília, Alto Januária, Rio Escuro Lineament, Quadrilátero Ferrífero and Cabo Frio High are clearly shown. The high magnetic amplitudes are related to the Serra do Mar range, to the Tocantins Province magmatic arch and to intermediate amplitudes covering the remaining cratonic regions (Fig. 5).

The regions of the Cabo Frio High, Quadrilátero Ferrífero and Rio Escuro Lineament stand out by their lower magnetic values in the total field map at 50 km altitude, while those in the higher magnetic value domain are associated with the Serra do Mar range (Fig. 6). The magnetic domains are similar to those of the derivative Z at 100 km altitude map (Fig. 5).

The high magnetic value domains represented in the vertical 50 km component distinguishes the regions of the Quadrilátero Ferrífero, Araxá, Alto Januária, Cabo Frio High, and part of the Borborema and Tocantins provinces. The lower magnetic values are related to the Riacho do Pontal Belt and encompass the remaining spaced out areas with intermediate magnetic values. The Trans-Brazilian Lineament with a NE 45° direction is characterized by intermediate magnetic amplitudes in the total field at 50 km altitude map (Fig. 7).

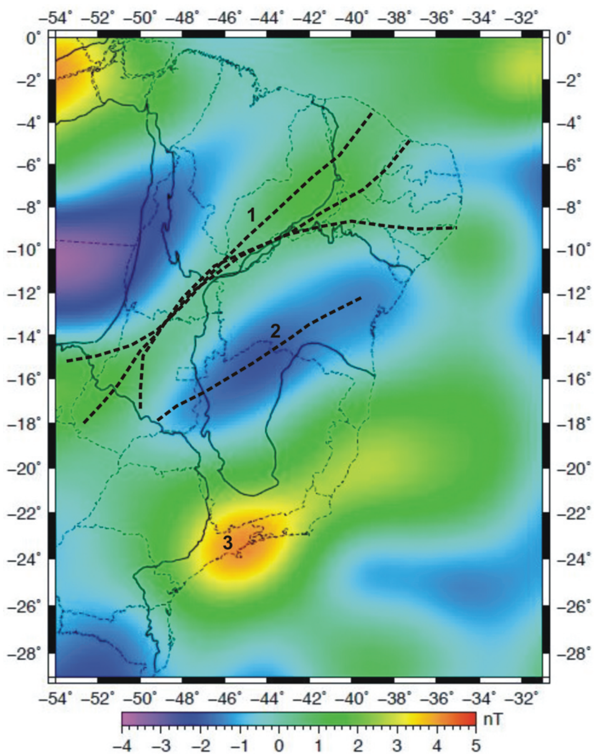


**Figure 3** – Geomagnetic anomalies map of the total field at 400 km altitude of the cratonic region and vicinities. 1 – Trans-Brazilian Lineament; 2 – Rio Escuro Lineament; 3 – Serra do Mar.

The Trans-Brazilian Lineament is composed of fragile transcurrent faults along the NE 30° direction and extends for more than 400 km to the African continent (Cordani et al., 2003). The Trans-Brazilian Lineament is the main regional feature present in the central portion of the Tocantins Province in Central Brazil and was highlighted in the total magnetic field at 400 km and 50 km altitude maps (Figs. 3, 6), and in the 100 km and 50 km Z derivate maps (Figs. 6, 7).

The cratonic lithosphere can be seen in the crust/mantle interface map (Oliveira, 2009) indicating a crustal thickening in the São Francisco Craton and in the Tocantins Province, mainly in the Brasília Belt, while the crust becomes thinner in the Quadrilátero Ferrífero region. In the northern craton portion, a crustal thinning in the East-West direction shows depths between 37 and 43 km. As to the southern region, it has a thickness between 35 and 40 km (Fig. 8). In the Brasília Belt and in the São Francisco Basin it is around 45 km, in agreement with the results obtained by Giese & Schutte (1975), Blitzkow et al. (1979), Ussami (1986), Soares (2005) and Oliveira (2009).

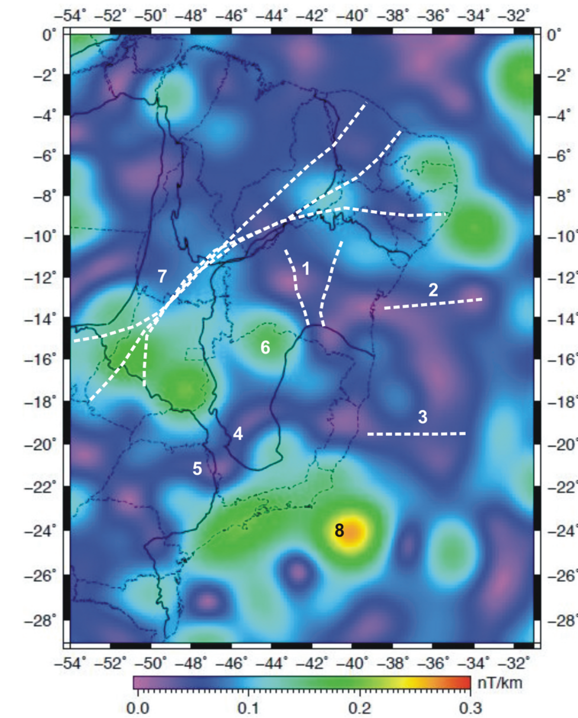


**Figure 4** – 100 km amplitude analytic signal of the cratonic region and environs. 1 – Paramirim Aulacogen; 2 – Salvador Fault Zone; 3 – Candeias Lineament – Vitória – Trindade; 4 – Alto de Sete Lagoas; 5 – Alto Parnaíba; 6 – Alto de Januária; 7 – Tocantins Province; 8 – Alto Cabo Frio.

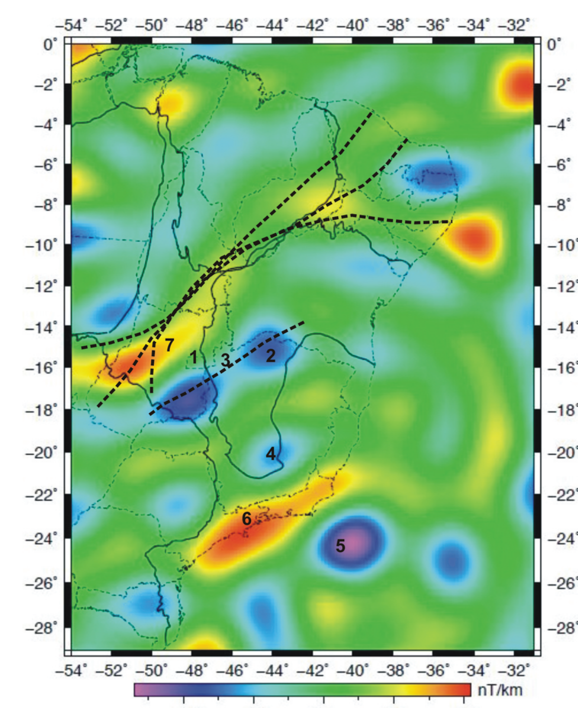


**Figure 5** – 100 km altitude Z derivative geomagnetic anomalies map of the cratonic region and environs. 1 – Brasília Belt; 2 – Alto Januária; 3 – Rio Escuro Lineament; 4 – Quadrilátero Ferrífero; 5 – Cabo Frio High; 6 – Serra do Mar; 7 – Tocantins Province Magmatic Arch.

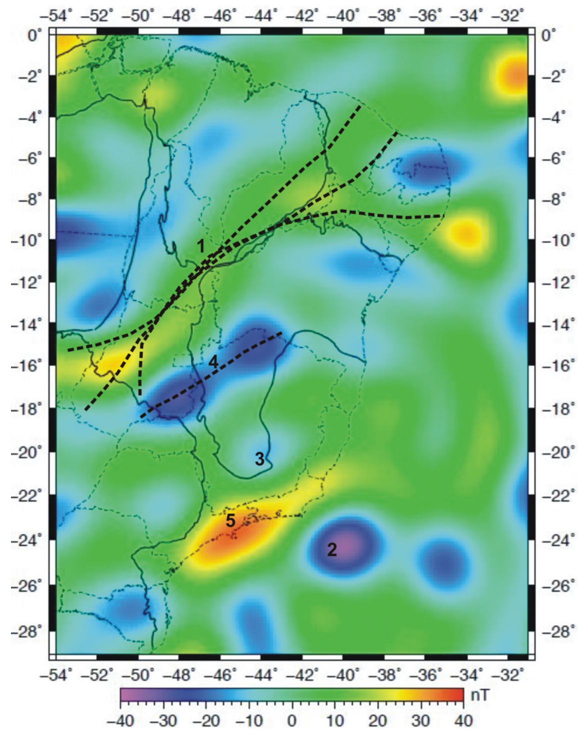


**Figure 6** – 50 km altitude total field geomagnetic anomalies map of the cratonic region and environs. 1 – Trans-Brazilian Lineament; 2 – Cabo Frio High; 3 – Quadrilátero Ferrífero; 4 – Rio Escuro Lineament; 5 – Serra do Mar.

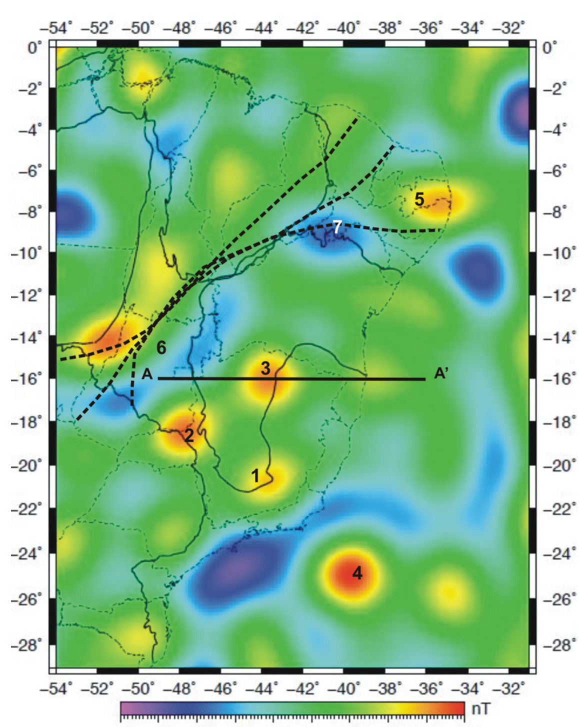


**Figure 7** – 50 km altitude vertical Z component geomagnetic anomalies map of the cratonic region and environs. 1 – Quadrilátero Ferrífero; 2 – Araxá Complex; 3 – Alto Januária; 4 – Cabo Frio High; 5 – Borborema Province; 6 – Tocantins Province; 7 – Riacho do Pontal Belt.

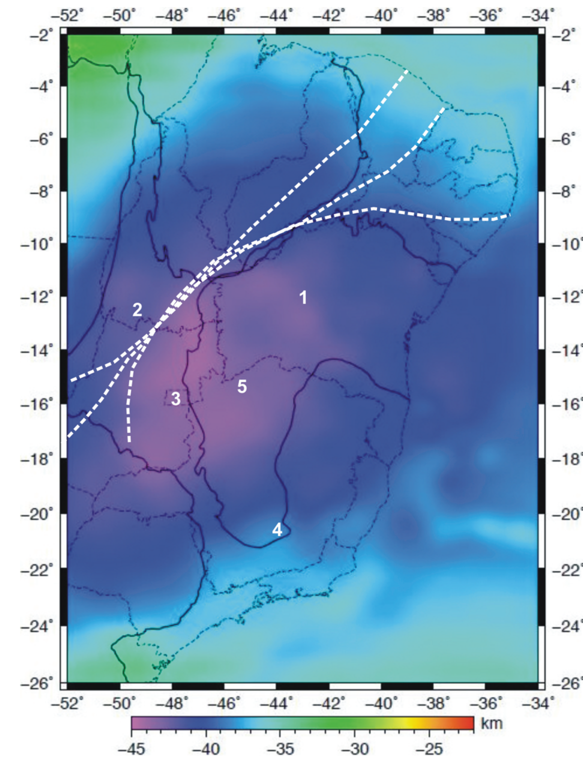


**Figure 8** – Moho map of the São Francisco Craton and environs. 1 – São Francisco Craton; 2 – Tocantins Province; 3 – Brasília Belt; 4 – Quadrilátero Ferrífero; 5 – São Francisco Basin (Oliveira, 2009).

Complementarily, the magnetic profile of the vertical Z component, together with the topographic profile, the crust/mantle interface and the thickness of the magnetic lithosphere (Fig. 9), supplied satisfactory information in relation to the magnetic lithospheric behavior of the craton region and its environs. To obtain this integrated profile, a compilation was conducted with data from the vertical Z component at 50 km altitude, from the topographic profile obtained from the digital landscape model DTM2006 (Oliveira, 2009), from the crust/mantle interface (Oliveira, 2009) and from the thickness of the magnetic lithosphere, obtained by 2D inversion of the vertical Z component, based on the methodology detailed in Dyment & Arkani–Hamed (1998) and Maule et al. (2005), where the top of the magnetic lithosphere is represented by the region's topography and its base by the *Curie* depth, where minerals lose their magnetic properties at a temperature of approximately 580°–600°C (Blakely, 1995). The variation of the magnetic lithosphere can be perceived in the São Francisco Craton region, where the base coincides with the *Curie* surface.

According to profile AA' (Fig. 9) the Brasília Belt presents altitudes of around 1 km, magnetic anomalies of intermediate amplitudes with the crust/mantle interface at approximately 45 km and magnetic lithosphere thickness between 80 and

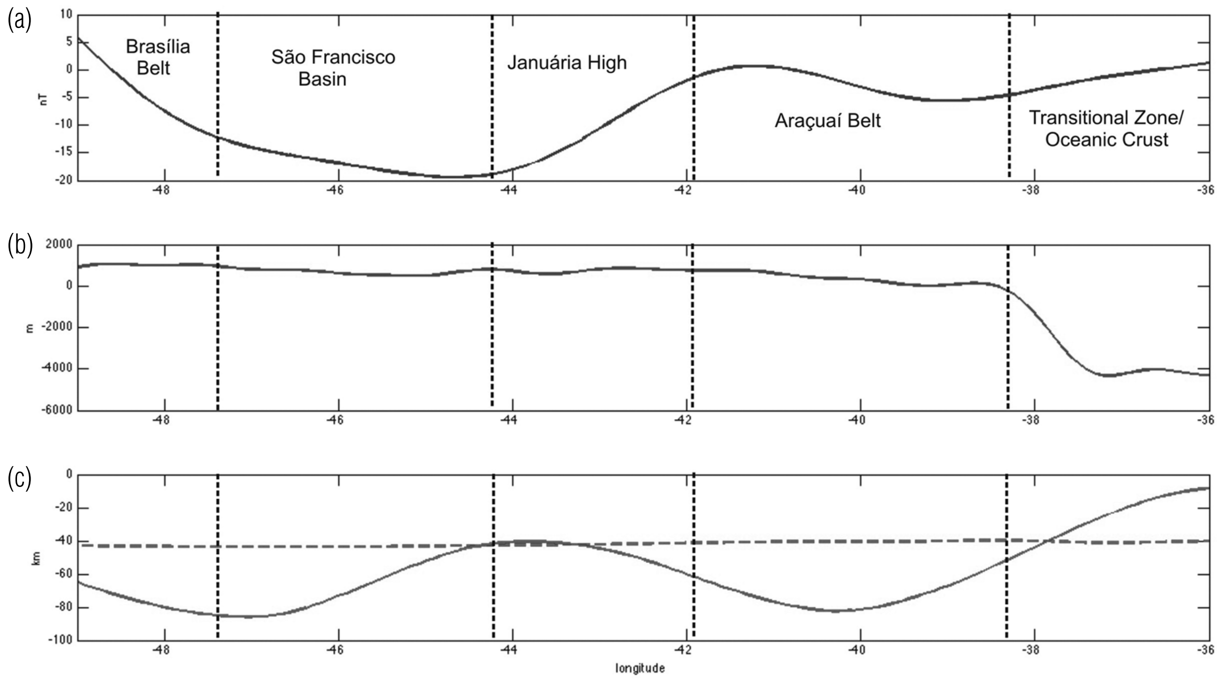


**Figure 9** – AA' profile representing 50 km altitude geomagnetic curves (a); topography (b); Moho: interface crust/mantle (dashed line in c); magnetic lithosphere from the *Curie* surface (continuous line in c).

90 km. The Araçuaí Belt presents a variety of altitude values and intermediate amplitudes; the crust/mantle interface is at around 38 km and a magnetic lithosphere thickness of 80 km. The transitional zone and the oceanic crust present intermediate amplitudes, with the bathymetry reaching 4,000 m below sea level, the crust/mantle interface reaching 37 km and the magnetic lithosphere thickness reaching 10 km (Fig. 9).

In the São Francisco Craton region, the São Francisco Basin presents intermediate amplitudes, a crust/mantle interface at 45 km and a magnetic lithosphere thickness of around 90 km. In the Alto Januária region, amplitude values are high, with a crust/mantle interface at 37 km and a magnetic lithosphere thickness of 40 km.

## CONCLUSIONS

The analysis of the geomagnetic anomalies of the São Francisco Craton region and vicinities, obtained by processing data acquired by the CHAMP – MF4 mission, allowed for its association with formations that probably resulted from major tectonic events, involving the lithosphere at the São Francisco Craton region.

The paleogeographic configuration of the Ectasian – Estenian ocean and the extensional phase, recorded by the remnants of the oceanic crust in the tectonic formations of the Brasiliano, around the São Francisco Province (Fig. 10), are evidenced in the total magnetic field maps at 400 and 50 km altitudes (Figs. 3, 6) and in the 100 km altitude vertical Z component maps (Fig. 5).

The magnetic lithosphere thickness of the cratonic region highlighted in profile AA' (Fig. 9), ranges between 40 and 90 km. That variation may be associated to the thermal contributions in the mantle, both by thermal flow and by the distribution of HPEs (Radiogenic Heat Producing Elements), to the *Curie* surface and to the chemical impoverishment of the mantle combined to the floatability effect of the cratonic lithospheric mantle, caused by its tendency to become chemically differentiated during geological times, with less Fe and Mg contents, due to successive magmatic episodes (Oliveira, 2009), can also account for the observed thickness variations.

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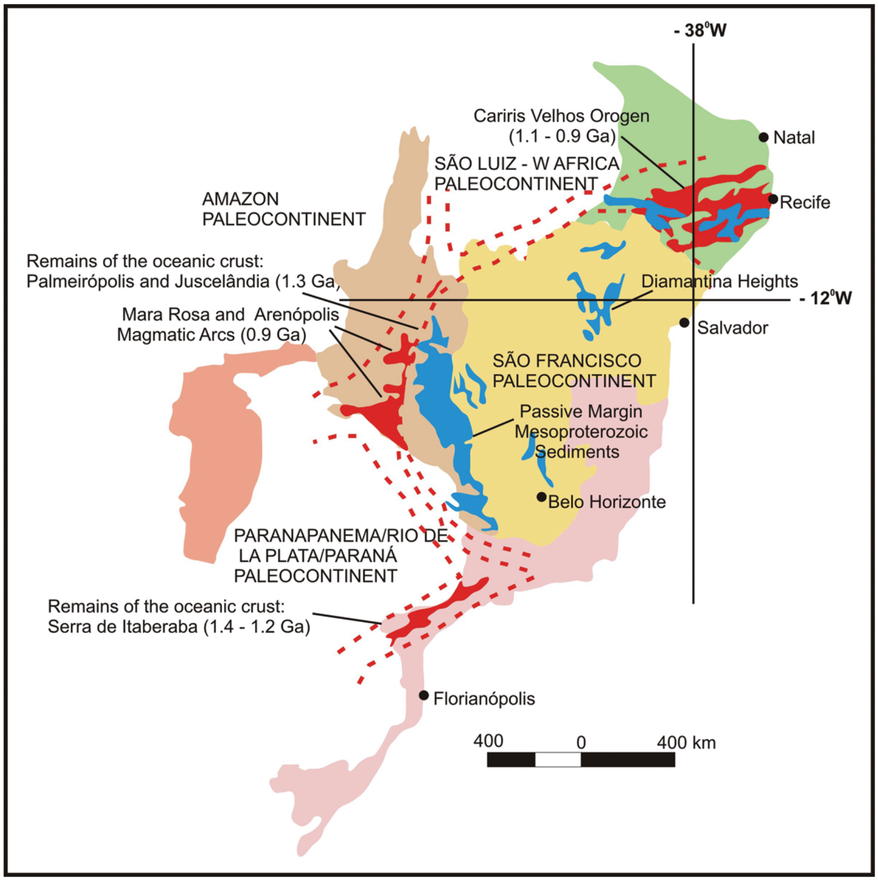


**Figure 10** – Paleogeographic reconstitution of the Ectasian – Estenian Ocean and their records during its expansion phase: remains of the oceanic crust, passive margins; compression phase: magmatic arches (Delgado et al., 2003).

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