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DEFINING LITHOSPHERIC LIMITS WITH DEEP SOURCED GEOPHYSICS: THE CASE OF SÃO FRANCISCO CRATON AND BORBOREMA PROVINCE

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ABSTRACT. The East Brazilian Shield is a product of the Neoproterozoic convergence and collage of rigid Archean lithospheric blocks, which stabilized at the end of the Paleoproterozoic Trans-Amazonian event (2.0 Ga). The areal extent of the São Francisco Craton is well understood by regional gravimetric surveys, but its northern limit with the Borborema Province is not so clear. The integration of gravity, magnetics and seismic velocity anomaly maps allows mapping this northern limit to the Borborema Province. Applying the vertical integration low-pass filter to satellite magnetics yields a remarkable match to the probable lithospheric suture zone. This magnetic map identifies the deep response from thinner/thicker lithospheres of Neoproterozoic mobile belts or stable cratons. One potential microcraton is the NE extension of the Borborema Province, one site of the oldest rocks in South America, a residue of the Benino-Nigerian Craton, separated from the main occurrence by the opening of the Atlantic. The Sergipana, Riacho do Pontal and Rio Preto Neoproterozoic fold-and-thrust belts mark areas of the foreland tectonism, hundreds of kilometers inside the São Francisco Craton lithospheric block. The presence of younger rocks inside the deep geophysical limits may be evidence of a large detachment of younger continental crust over the old cratonic lithosphere.

Keywords: geodynamics, data integration, satellite magnetics, gravimetry, lithospheric studies.

INTRODUCTION

The main geodynamic feature of the Eastern Brazilian shield is the large Archean to Paleoproterozoic lithospheric block under the São Francisco Craton (Almeida, 1977). Alkmim et al. (1993) suggested the São Francisco Craton (SFC) could be either as small as the undeformed foreland cover by the Neoproterozoic tectonic event, or a larger tectonic plate (see Figure 1). The latter, the large plate, was named Paramirim Craton by authors working with regional gravimetric surveys (Davino, 1980; Almeida, 1981; Lesquer et al., 1981; Haralyi and Hasui, 1982).

According to Artemieva (2011), there are several definitions of lithosphere, one for each type of geophysical investigation method of choice. Rigid lithospheric blocks maintain their shape during continental collisional events and coincide with the main stable cratons. The discrimination of the lithosphere is based on physical properties such as seismic velocity, conductivity, magnetism and density, as well as from minerals present in kimberlite xenoliths (Artemieva, 2011). Lithospheric studies aim to map limits of the thick lithospheric blocks. On maps, it is common to integrate all suite of geophysical datasets to determine probable limits of main stable cratons and mobile belts (Begg et al., 2009; O´Reilly et al., 2009; Jessell et al., 2016; Rocha et al., 2019; Affonso et al., 2021).

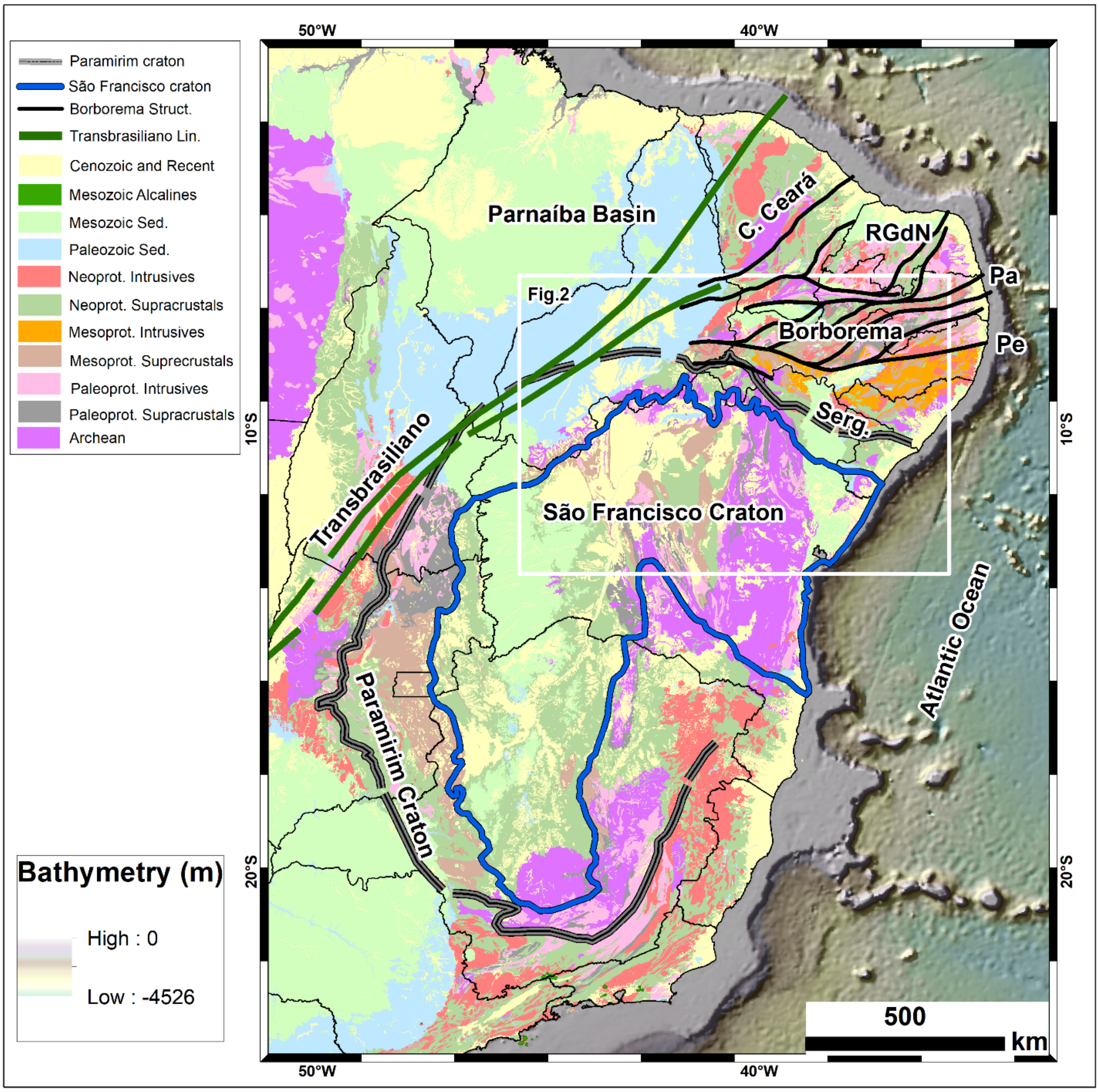


Figure 1: Geology map of Eastern Brazil and adjacent Atlantic Ocean. Current understanding of the tectonic limits of the SFC and Paramirim Craton summarized in Heilbron et al. (2017). Display of major cratonic boundaries within the Borborema Province, with special interest in the transcurrent Patos (Pa) and Pernambuco (Pe) lineaments and Sergipana Belt (Serg.), Rio Grande do Norte Domain (RGdN) and Central Ceará Domain (C. Ceará). The Transbrasiliano lineament is well defined from magnetic maps. Figure 2 area marked. Geology map compiled from CPRM GIS (Bizzi et al., 2003).

Several studies point to the fact that most prolific metallic ore deposits, like the giant provinces of nickel sulfides, Iron-Oxide Copper Gold (IOCG) and gold deposits, are situated in the junction of resilient lithospheric plates (Begg et al., 2010; Hronsky et al., 2012; Griffin et al., 2013; Groves et al., 2016; Costa et al., 2020). A plausible explanation for this is that deep roots are connected to pathways for ascending rich melts during the passage of mantellic plumes (Griffin et al., 2013).

Recently, new datasets and applications of long-wavelength geophysical surveys were produced for lithospheric studies in Brazil. Assumpção et al. (2017) reviewed the produced tomographic images and velocity depth sections, integrated with gravity, and defined limits and depths of the crust and lithosphere, describing the physical properties of the SFC. In a recent development, Rocha et al. (2019) worked with *P*-wave tomography, and presented the data of slices of the deep cratonic roots of the SFC, naming this high velocity lithosphere the São Francisco Paleocontinental Block.

In this work, we have processed gravimetric and magnetometric data, and combined them with recent developments in seismic tomography maps, in order to propose a delimitation of lithospheric blocks with emphasis on the limits between the SFC and the Borborema Province.

Borborema Province

The Borborema Province (Almeida, 1981; Brito Neves et al., 2000) is situated at the N-E corner of Brazil. It consists of very complex ductile tectonic units of poly-deformed metamorphic and magmatic associations, a product of the Brasiliano/Pan-African (640-500 Ma) orogenic event. A complex mixture of gneiss/migmatite with long-lived magmatism was deformed into fold and thrust belts, with large regional dextral strike-slip shear zones. The province is conventionally separated into three sectors (North, Transitional and South) by two large tectonic structures, the semi-parallel Patos and Pernambuco lineaments, of continental scale transcurrent geometry. The dextral kinematics are a result of a lateral-escape tectonics, consisting of thrust belts verging E/NE/SE, in a clockwise rotation along the lateral faults of Patos and Pernambuco, a result of the collision of the SFC and the Amazon Craton Parnaíba Basin (Archanjo et al., 2021; Neves, 2021).

The limit of the Borborema Province with the SFC is marked by crustal collisional sutures of the Rio Preto, Riacho do Pontal and Sergipana fold and thrust belts (Heilbron et al., 2017) (see Figure 2). Borborema sectors are divided into domains, according to lithology and age, from Archean to Paleoproterozoic, middle Proterozoic and Neoproterozoic (Brito Neves et al., 2000; Hasui, 2012). Oliveira et al. (2005) and Oliveira (2008) compiled those different domains with magnetometry and gravimetry to produce a geophysical-oriented map of the major crustal boundaries.

According to Neves (2015), there are four stages represented in zircons throughout Borborema: the Trans-Amazonian collages (2.25-1.95 Ga.), two extensional events at 1.8-1.6 Ga. and 1.0-0.9 Ga, and the Brasiliano Orogen 0.67-0.55 Ga. The 1.0-0.9 Ga event corresponds to what has been referred to as the "Mesoproterozoic Cariris Velhos collisional event" (Brito Neves et al., 1995, 2000; Santos et al., 2010), which is being reinterpreted as an intracratonic rifting event, later inverted during the Brasiliano Orogeny (Ganade et al., 2021; Neves, 2021).

It is evident that were this event collisional or intracratonic rift it would have affected the integrity of the SFC margin (Ganade et al., 2021). This effect has lead Santos (2016) and Santos et al. (2019) to propose a Borborema Metacraton, an old Archean crust with thinned lithosphere by a tectonic thermal event.

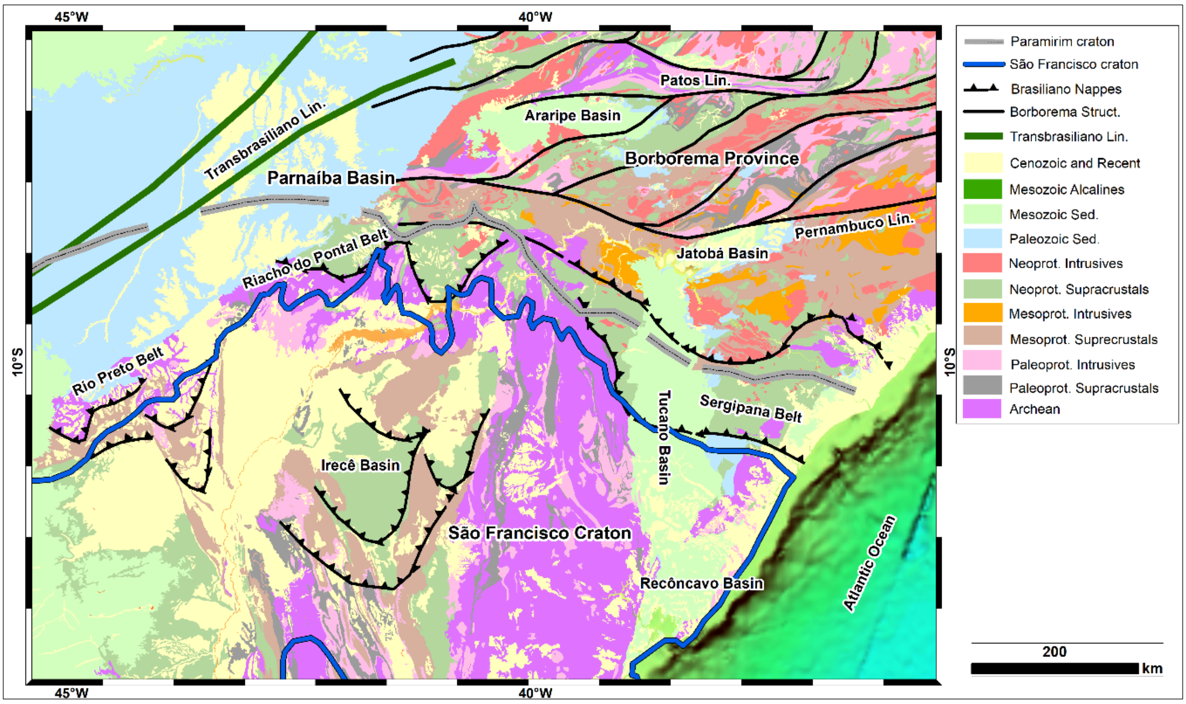
One of the oldest rock ages in Brazil occur at the São José do Campestre Massif in Rio Grande do Norte Domain of the Borborema Province, with zircon ages reaching 3.45 Ga (Dantas et al., 1998). Neves (2015) informs that the Rio Grande do Norte Domain may only have suffered late-stage orogenic processes due to the thicker lithosphere there, a central cratonic position in the Borborema Province block.

According to Ganade et al. (2021), two oceanization processes occurred during the Brasiliano, followed by continental collision at the margins of the Borborema Province. To the south, the SFC cratonic lithosphere, already weakened by Cariris Velhos Tonian extension, is better defined by the south verging Sergipana and Riacho do Pontal fold and thrust belts. To the west, the limits with the Parnaíba Basin block are understood as being located along the Transbrasiliano lineament. In both collisions, the Borborema block acted as the upper block in the subduction events. It is considered part of the Benino-Nigerian Craton left in South America during the rifting that resulted in the Atlantic Ocean (Ganade et al., 2021).

The Eastern portion of the Borborema Province and the SFC have thinned continental margin crust effect of the Mesozoic rifting and opening process of the Atlantic Ocean (Oliveira and Medeiros, 2012). This event is also represented by the series of rift basin such as Sergipe-Alagoas, Recôncavo, Tucano, Jatobá and Araripe Mesozoic basins (Milani and Thomaz Filho, 2000).

DATASETS AND METHODOLOGY

The application of datasets to investigate deep into the lithosphere has been summarized in the Lithospheric Architecture Mapping by Begg et al. (2009) and O´Reilly et al. (2009). The lithospheric mapping uses the integration of several investigation techniques focusing on the lithospheric mantle, such as seismic wave tomography, gravimetry, magnetics, magneto-telluric, SKS splitting, earth-quake locations, refraction seismic surveys, etc. (Jessell et al., 2016; Curtis et al., 2017).



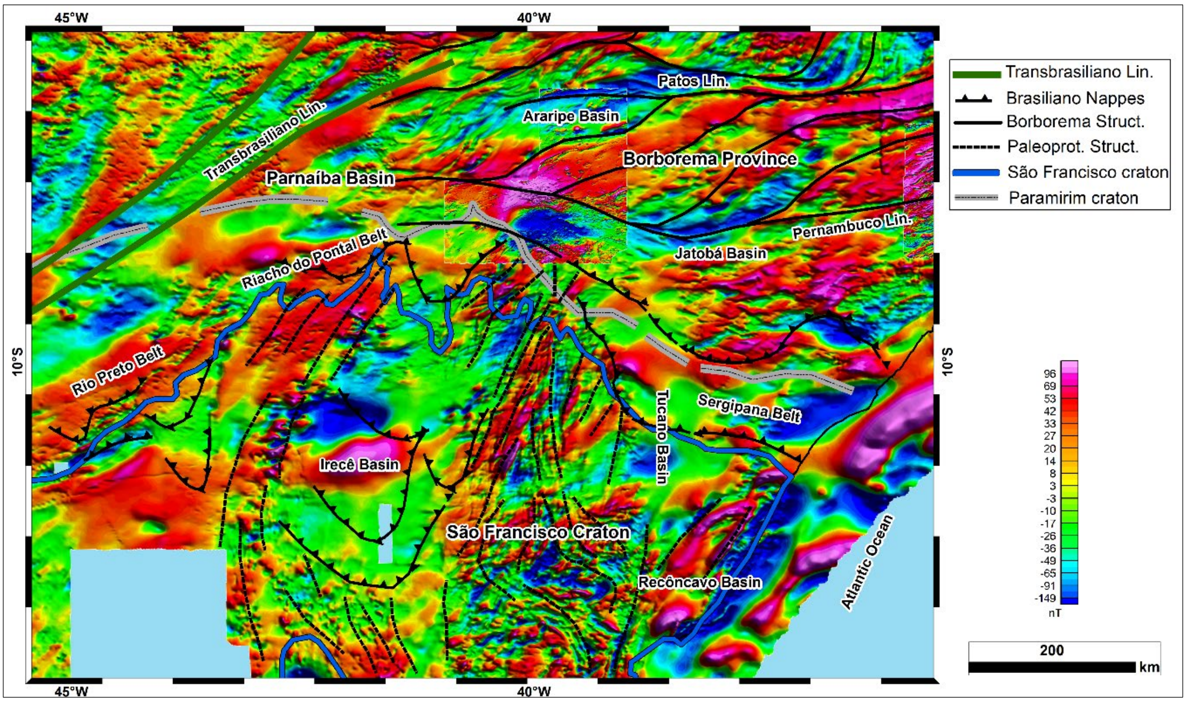


Figure 2: a) Main crustal tectonics, important lineaments and lithotectonic units of the SFC and Borborema Province boundary (Bizzi et al., 2003). The presence of foreland tectonic thrusts and nappes hundreds of kilometers inside the SFC is exemplified by the Irecê basin (Alkmim et al., 1993). b) Compilation of the magnetometric map from CPRM airborne data. The major crustal structures such as the regional transcurrent lineaments are well observed in the lineaments from the magnetic map (Oliveira, 2008). The E-W direction structures are of Brasiliano age. Paleoproterozoic magnetic lineaments within the SFC have preferential N-S directions.

All these materials are available to a certain extent in Eastern Brazil and recent developments are well summarized in Assumpção et al. (2017). In recent years, there have been several new publications on deep geophysical studies of the crust and lithospheric mantle in the Borborema Province and the SFC. We combined some of this published data into an interpretation of the probable architecture of the lithospheric blocks, trying to separate the mapping of crustal structures from lithospheric mantle features; therefore, the lithospheric block architecture may not be coincident with known major crustal boundaries from shallow geological and geophysical mapping.

Gravimetry

The outer shelf of the planet, the lithosphere, has a rigid nature and is buoyant over the viscous asthenospheric mantle (Artemieva, 2011). The Mohorovicic discontinuity (Moho) separates the lithosphere into the crust and the lithospheric mantle. The thickness of the crust in northeastern Brazil averages 35-44 kilometers, and is highly affected by the processes of Gondwana break up (Assumpção et al., 2017).

Under the crust of rigid continental shields, the Sub-Continental Lithospheric Mantle (SCLM) type of lithosphere is composed of depleted harzburgitic ultramafic rocks that are cold and buoyant, with a low Fe/Mg ratio. The thickness of the lithosphere can reach over 250 km under old cratons. At younger continental lithosphere, the average thickness is about 120 km, with predominance of fertile peridotites, which are hotter and denser (Artemieva, 2011).

Thus, regional continental gravity maps have a distinct large ellipse-like shaped blue pattern of gravimetric lows over thick cratonic lithosphere (Brito Neves and Alckmim, 1993; Pereira and Fuck, 2005; Artemieva, 2011). On the contrary, associated to long orogenic mobile belts, over the tectonic hinterland, an elongated positive gravimetric anomaly marks the edge of cratons (Lesquer et al., 1981; Haralyi and Hasui, 1982; Meissner et al., 1991; Pereira and Fuck, 2005).

After the SFC being defined as a stable piece of the shield in Eastern Brazil (Almeida, 1977) (see Figure 1), authors defined the Paramirim craton, larger area of stable crust, from the results of the first regional gravimetric surveys (Davino, 1980; Almeida, 1981; Lesquer et al., 1981; Haralyi and Hasui, 1982).

The gravity map we used was processed from a geoidal undulation model (GGM02C) from the gravity GRACE satellite, which is combined with the EGM96 surface information by Tapley et al. (2005). The geoid elevation surface is an equipotential surface of the gravitational forces of the Earth, and its variations reflect density anomalies of deep sources from the mantle. From the geoid grid, we took the first and second vertical derivatives, aiming to better define the limits of the SFC that correlate with the lithosphere, especially in its northern limits with the Borborema Province. This is shown in Figure 3.

Seismic velocity tomography

Seismic tomography provides one of the best bits of information on the structure of the sub-continental lithospheric mantle. It is based on variations of seismic velocities that reflect temperature and composition of the lithosphere (Grand, 2002; Deen et al., 2006; Artemieva, 2011). The continental lithosphere of cratons commonly has a positive velocity anomaly zone in the upper mantle depleted harzburgite material, with high Mg/Fe ratio, and lower temperature gradient, that increases the seismic wave transit velocity. On the other hand, the less rigid, hotter, thinner, juvenile lithospheric mantle is characterized by low velocity. Maps of Vp/Vs ratio show velocity associations of SCLM down to depths around 400 km over large cratonic blocks, which are ellipse-shaped, both in Africa and Australia (Deen et al., 2006; Begg et al., 2009; O´Reilly et al., 2009; Griffin et al., 2013; Fishwick and Bastow, 2014).

The pioneer work in the application of the methodology for the delimitation of the SFC confirmed the presence of a high velocity lithosphere compatible with a rigid and resilient lithosphere (Rocha et al., 2011; Assumpção et al., 2013, 2017; Azevedo et al., 2015). Recently, used *P*-wave travel-time tomography to define the positive velocity anomaly at the lower lithosphere associated to the São Francisco Paleocontinental Block. This block has its boundaries marked by low-velocity anomalies that demonstrate the existence of theses sutures at lithospheric depths.

The São Francisco Paleocontinental Block can be traced with depth slices and cross-sections through the craton from 75 to 300 km that show the keel geometry into the asthenosphere. In Figure 4 we used the 100 km depth slice from the supplementary data available from Rocha et al. (2019), which fits our interpretation range, showing the extent of the elastic SFC lithosphere. For all authors working with seismic velocity tomography (Azevedo et al., 2015; Assumpção et al., 2017; Rocha et al., 2019), the observed high velocity craton extends under the thrusted Brasília orogenic belt and the Araçuaí orogenic and magmatic belt.

Magnetics

Recent studies with xenolith minerals from deep origin from the mantle, laboratory experiments with mineral phase properties, and fractal amplitude spectra analysis of long wave-length magnetic anomalies from

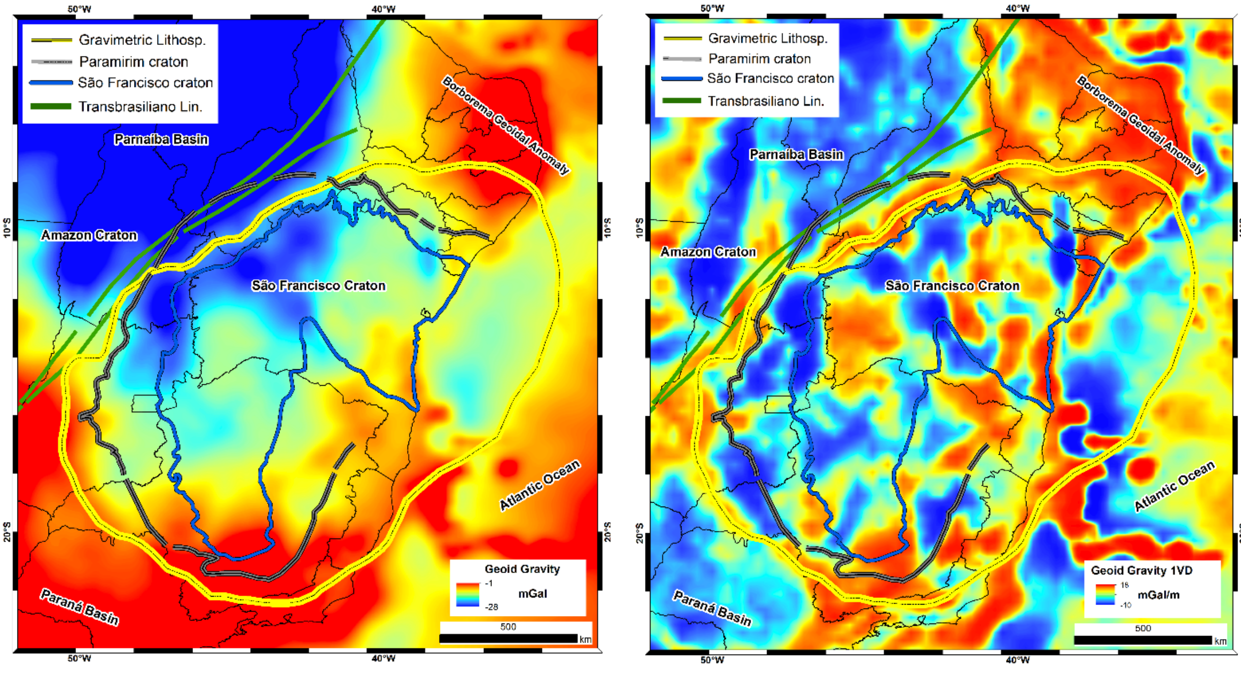


Figure 3: Extents of the SFC cratonic lithosphere defined by gravimetric methods. a) Geoidal Height model with low-density areas (blue) predominate over the Amazon Craton and Parnaíba Basin, and the SFC. b) The first vertical derivative of the geoid model in a. The semi-ellipse of low values is surrounded by important high amplitude First Derivative of the Geoid model in a. Positive anomalies are attributed to the deep lithospheric suture zone. The low-density areas adjacent to these gravity highs, in the cratons, are foreland fold and thrust belts.

magnetometry point all to the magnetic nature of rocks in the mantle since magnetization is present in areas of cold and hydrated lithospheric mantle environment (Ferré et al., 2021).

The Curie Depth relates to the temperature where the magnetization of a rock is zero (550ºC for magnetite) and varies from region to region, with non-conclusive application (Artemieva, 2011). Ferré et al. (2021) discuss the recent findings that in old and cold cratonic blocks, at least at the upper part of the lithospheric mantle, the calculated Curie depth is deeper than the seismological Moho, thus allowing the delimitation of cratonic lithospheric blocks.

New satellite derived magnetic models derived from measurements from magnetometric satellites, like Champ and Swarm systems, are available over all continent shields (Olsen et al., 2017). The satellite magnetic model (LCS-1 lithospheric total field model) has harmonics associated to Earth's total magnetic field with wavelengths compatible with depths down to 250 km deep.

In order to image the longest wave-length anomalies in this magnetic model over the SFC, we applied the low-pass filter of the vertical integration with FFT processing (Geosoft Magmap 2D FFT - Vertical Integration). The smooth low-pass image of the satellite magnetic is presented in Figure 5.

The same low-pass filtering procedure was adopted to the total magnetic intensity mosaic grid for the Borborema Province, made of several high-resolution airborne magnetic surveys (500 meters lines) from the Brazilian Geological Survey (downloaded from CPRM data repository, available at https://geosgb.cprm.gov.br/geosgb/downloads.html). In Figure 6, the low-pass filter of the vertical integration with FFT processing (Geosoft Magmap 2D FFT - Vertical Integration) is presented.

Sm-Nd Isotope Map

Ganade et al. (2021) explored the original methodology from Cassidy (2006), producing a map grid by isotopic model age from Sm-Nd for the Borborema Province to determine major geodynamic boundaries. From their published supplementary dataset, with a large compilation of available Sm-Nd model age in spreadsheet format, we produced a Sm-Nd isotope raster map using kriging interpolation in ArcGIS (Figure 7).

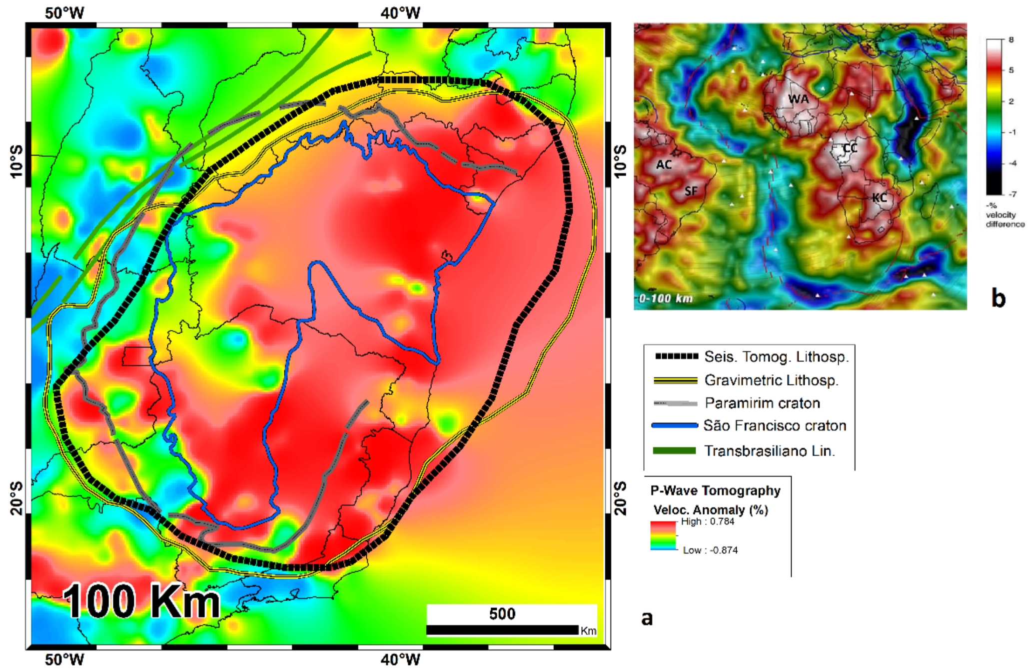


Figure 4: Adaptation of the dataset of the 100 km depth slice of P-wave travel-time tomography, originally supplementary data from Rocha et al. (2019), in which they identified the São Francisco Paleocontinental Block. The seismic tomographic lithospheric limits of the SFC with the Borborema Province to the North are well marked by a sharp fall on the velocity anomaly gradient. The red to green hue in the map marks the limits of the interpreted seismic tomographic lithosphere. b) The more regional map from O´Reilly et al. (2009), based on the tomographic model by Grand (2002), identifies high P-velocities associated to cratons in Africa and South America. Cratons in b: WA – West African Craton; CC – Congo Craton; KC – Kalahari Craton; AC – Amazon Craton; SF – São Francisco Craton.

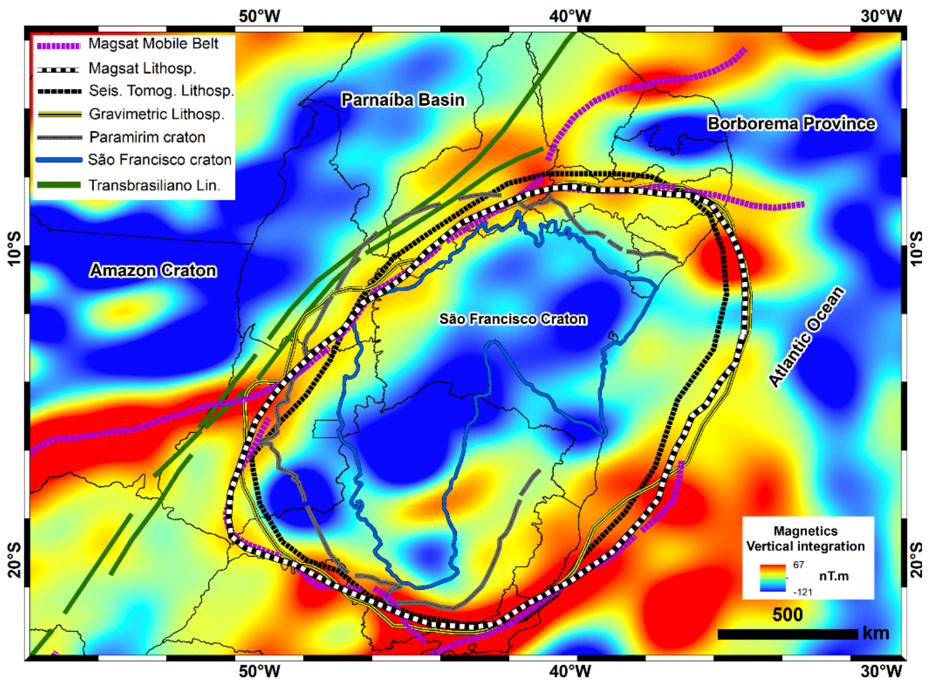


Figure 5: The SFC Lithospheric Block outline seen from the processed (vertical integration) satellite magnetometry (LCS-1 satellite data from Olsen et al., 2017). The magnetic lows (blue hues) are associated to cratonic centers, and the mobile belts are the positives (red hues). There is a possible cratonic lithosphere beneath the Borborema Province separated from another low pattern in the Parnaíba Basin by another magnetic high. The Transbrasiliano lineament mapped from high-resolution airborne magnetometry (shallow sources) has limited importance compared to the cratonic limits derived from satellite magnetometry.

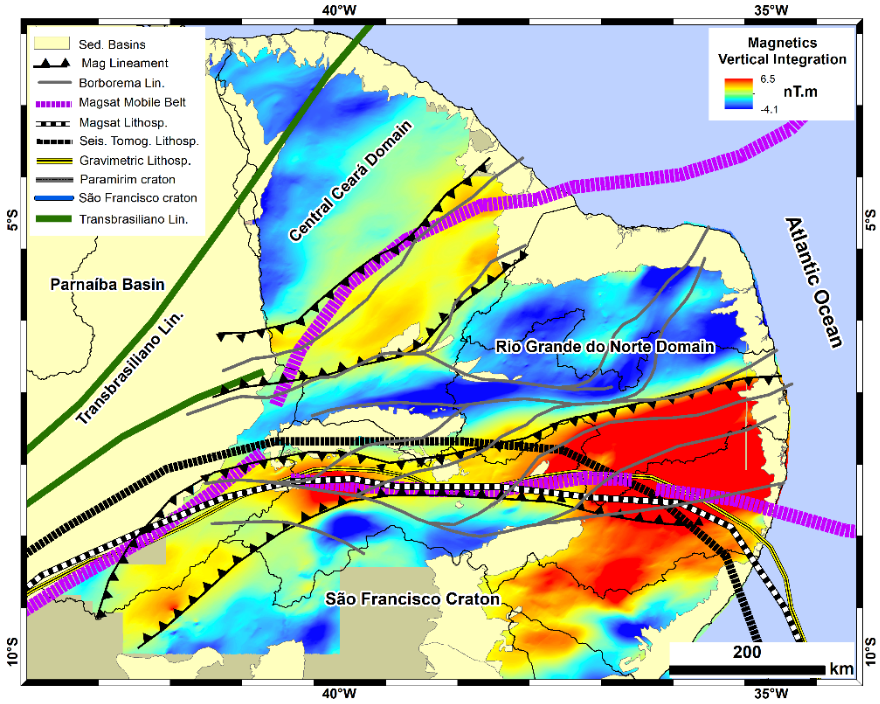


Figure 6: Low-pass filtered (vertical integration) on the total magnetic intensity mosaic grid for the Borborema Province, made of several high-resolution airborne magnetic surveys (500-meter lines) from the Brazilian Geological Survey. An important E-W discontinuity is observed at the approximate location of the lithospheric suture zone defined by satellite magnetics, gravimetry and seismic tomography. The figure shows a well marked magnetic low (blue hues) probably associated to a cratonic center in the Rio Grande do Norte Domain. The location of mobile belts is marked by the magnetic highs (red hues), the same observed from satellite magnetics.

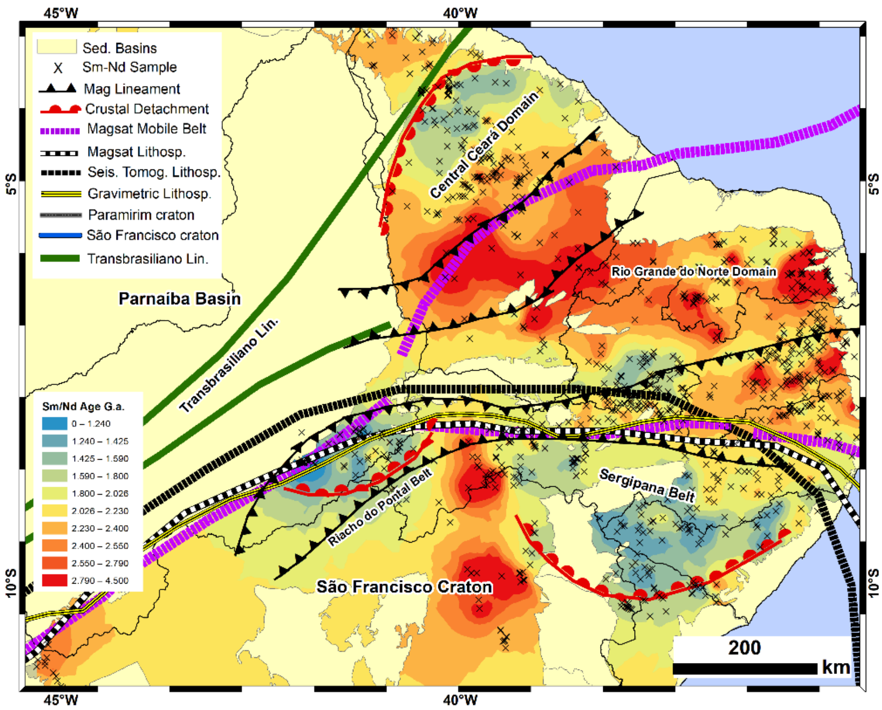


Figure 7: Grid map of isotopic Sm-Nd model age for N-E Brazil (data from Ganade et al., 2021). The raster map was produced using Arcgis kriging methods. The interpretation lines from integrated deep geophysical data define the Borborema Province nuclei as Paleoproterozoic to Archean, as it is possible to infer from the Sm-Nd isotopic map (red hues). The younger regions in the map mark the Sergipana/Riacho do Pontal belts, and the younger zone in the Central Ceará Domain (blue hues) depict collision belt crustal material, possibly detached into the cratonic areas of the SFC and Parnaíba Basin.

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RESULTS AND DISCUSSION

Different from other geologic/geophysical techniques for examining crustal tectonic evolution, this work is a contribution to the understanding of the Neoproterozoic evolution of the Borborema Province and the northern SFC by looking deeper into the lithospheric mantle.

To do this, we started by integrating magnetic and gravimetric continental scale data, recent developments on published seismic velocity tomography models and Sm-Nd geochronology compilation databases (Figure 8).

The original concept of the SFC (Almeida, 1977), a zone not deformed during the Neoproterozoic collision, has numerous exceptions (Alkmim et al., 1993). The thin-skin tectonism in foreland fold and thrust belt, with low grade metamorphism, is present at all sides of the craton, with tectonic horizontal displacement of hundreds of kilometers.

Conventional airborne magnetic survey maps differentiate crustal footprints of the collision with the southern Borborema Province. There, the magnetic fabric has a strong E-W orientation resulting from the Brasiliano tectonism, whilst the SFC Paleoproterozoic fabric has a N-S trend, which shows no sign of posterior reworking. This effect separates the thick-skin Brasiliano compressional tectonics from the thin-skin foreland fold and thrust nappes, in which the magnetic signal of the basement rocks is not deformed.

The concepts of the Paramirim Craton from Haralyi and Hasui (1982) or the Sanfranciscana Plate from Alkmim et al. (1993) are based on regional gravimetric maps, with a cratonic lithosphere footprint larger than the original SFC mapped by geochronology. It corresponds to a SCLM continental lithospheric block, a paleotectonic plate.

We used the geoidal height gravity large wavelength anomaly grid to make an image of the lithosphere (Figure 3). The low density of the cratonic continental block contrasts with the high gravity anomalies at its margins. With the derivatives of this surface, the strong lateral positive anomaly is more evident, with the gravimetric limits for the São Francisco Lithospheric Block, marked by a large ellipse-shaped lithospheric block with its low gravimetric center.

This results in the delimitation of the continental lithosphere is almost the same as the limits of the old Paramirim craton, defined by Haralyi and Hasui (1982), and the Neoproterozoic suture, by Heilbron et al. (2017). However, to the north of the craton, the limit with the Borborema Province at the Sergipana belt is not so obvious since it is a region affected by the Mesozoic thermal-tectonic events (Oliveira and Medeiros, 2012). Another development is the surprisingly small influence of the Transbrasiliano lineament, which does not present any significant deep sourced anomaly associated to a lithospheric suture zone. A good mapping of the areal distribution of the cratonic, resilient Archean lithosphere is achieved with the seismic velocitiy tomography technique. The SCLM type of lithosphere has high seismic wave velocities mapped under continents. There are several available published maps and depth slices of seismic velocity anomaly tomography for the Brazilian Eastern margin (Assumpção et al., 2017; Rocha, 2008; Rocha et al., 2011, 2019). The latest 100 km deep slice prepared from data from Rocha et al. (2019) was used to produce Figure 4 and is used as the image of the seismic lithosphere.

Deeper slice maps show the same positive velocity anomalies bellow 400 km, within the Asthenosphere, maintaining some differentiation under Archean cratons (Bédard et al., 2013). These results are very similar to the ones from other seismic derived models in other old continents such as Australia and Africa, with circular to ellipsoid shaped cratons (Deen et al., 2006; Begg et al., 2009; O´Reilly et al., 2009; Jessell et al., 2016).

Working with satellite magnetometry, Oliveira (2011) calculated the magnetic lithosphere depth of 60 to 110 km for the SFC, whilst the base of the crust presented an average of 37-44 km deep. Idárraga-García and Vargas (2018) described the difference of the base of crustal depth calculated from seismic wave studies for South America and compared it to the Curie temperature depth. The result is that from older

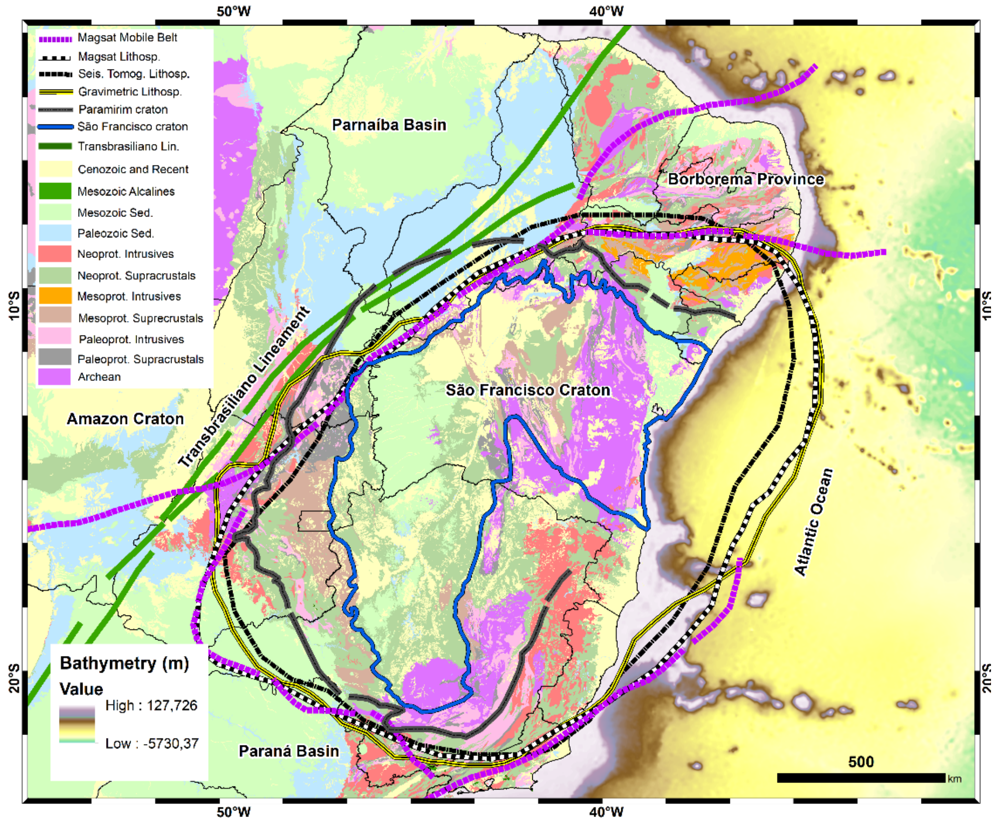


Figure 8: The summary of the SFC lithospheric block obtained from gravimetry, seismic velocity tomography and satellite magnetometry. Also shown are the historical SFC (Almeida, 1977) and the Paramirim craton (Haralyi and Hasui, 1982). The ellipse-like shape of the lithospheric block resembles other craton geometries from shields of Africa and Australia. The bathymetric map shows that volcanic cones in the Atlantic oceanic crust are developed external to the SFC continental lithosphere.

and colder lithospheres, like cratons of the Amazon and São Francisco, the Curie depth is deeper than the Moho depth.

The results from the integration of satellite magnetometry lithospheric model LCS-1 (Olsen et al., 2017) show remarkable coincidence with the limits of the SFC lithospheric block, as discussed from gravity and seismic velocity (Figure 5). A very well-defined ellipse-shaped block of low magnetic value is surrounded by high magnetic anomalies, at the margins of the SFC, in the predicted location of the center of mobile belts or lithospheric suture zones.

The elongated positive anomalies of the mobile belts could mark the presence of hotter and thinner lithospheres contrasting with the low magnetic anomaly centered in the SFC. The fact that the magnetics the magnetics differentiate between types of lithosphere suggests that the SCLM has temperatures in the lithospheric mantle that allow it to still maintain magnetic properties (Ferré et al., 2021).

The same results are reported in other cratons of the globe like West Africa, Yilgarn and Gawler in Australia, and in the North America shield (Hastings, 1985; Toft et al., 1992; Purucker et al., 2002; Chopping and Kennett, 2015; Wang and Li, 2015; Kennett et al., 2018; Williams and Gubbins, 2019).

Ganade et al. (2021) discuss the existence of a remnant from the Benino-Nigerian Craton within the Borborema Province. The satellite magnetics indeed shows a signal corresponding to a small piece of lithosphere, a cratonic lithosphere below the Borborema Province. This small Borborema lithospheric block is separated from the SFC by the Sergipana and Riacho do Pontal orogenic belts and from the Parnaíba Basin lithospheric block to the west by a probable suture in the Central Ceará Domain. Pitombeira et al. (2021) included in the West Gondwana Orogeny the Central Ceará Domain Neoproterozoic mobile belt.

Main tectonic elements of the lithosphere are also evident in airborne magnetometric data when the vertical integration filter is applied (Figure 6). From this vertical integration map, we can observe an important E-W discontinuity very close to the Patos lineament, at the approximate location of lithospheric suture zone as defined by satellite magnetics, gravimetry and seismic tomography. The two elongated positive anomalies lateral to the Borborema Province correspond to the ones observed from satellite magnetics, but in higher resolution, and are in close association to the position of the suture zone in the lithospheric mantle.

The Archean nucleus of the São José do Campestre Massif (3.45 Ga - U/Pb) is at the center of the Borborema Lithospheric block. The Sm-Nd model age map of Figure 7, made after the compilation of geochronology data available from Ganade et al. (2021), clearly shows the Archean and Paleoproterozoic areas within the Borborema Province, surrounded by two younger belts.

There are several remnants of older Archean and Paleoproterozoic crust within the Borborema Province immersed in the strongly sheared ductile tectonism of Brasiliano supra-crustal units and granitoids. However, the preponderance in the isotopic map is of a large old, reworked Archean craton in the Borborema Province. This seems to be corroborated by the findings of Ngonge et al. (2019), which used Re–Os isotope to postulate an earlier Paleoproterozoic sub-continental lithospheric mantle beneath the N-E Borborema Province.

The Brasiliano tectonism has been described as responsible for the lateral-escape tectonics with transport of mass to the south over the SFC, in response to the Amazon Craton and Parnaíba Basin block collision (Archanjo et al., 2021; Ganade et al., 2021; Neves, 2021). Caby and Arthaud (1986) discuss Brasiliano age nappe tectonics in the Central Ceará Domain, with vergence to the west.

A regional seismic reflection 20-second survey line crossing the Parnaíba Basin and the Central Ceará Domain shows that the crust there is thrusted to the west and also observed on the crustal basement under the Paleozoic sedimentary basin (Daly et al., 2014).

It is likely that the Transbrasiliano lineament has no function in separating the Parnaíba Basin and Borborema blocks, as observed from satellite gravimetry and magnetometry, despite being a long duration trans-lithospheric lineament. Our maps also suggest that under the oceanic crust, out of Eastern Brazil, lies part of a continental lithosphere belonging to the SFC. O'Reilly et al. (2009) and Wang et al. (2017) also claim the existence of continental lithospheric mantle under the oceanic crust in some parts of the Atlantic Ocean.

The Sm-Nd map shows a clear separation of the Archean/Paleoproterozoic central cratonic terrains from middle to Neoproterozoic associations, which appear as elongated belts. There are two consistent Sm-Nd model age nuclei; the most obvious is the SFC block, the other at Parnaíba basin block. Another very well-defined old block is located in the northern Borborema Province, mainly in the Rio Grande do Norte Domain. This is an important observation since at the center of the Borborema Province one of the oldest rocks in South America is situated, dated at 3.45 Ga by U/Pb geochronology, the São João do Campestre Massif, of the Rio Grande do Norte Domain (Dantas et al., 1998). Two younger aged linear belts occur in the juxtaposition of these 3 blocks, the Sergipana and Riacho do Pontal mobile belts, and another one located in the Central Ceará Domain (Figure 7).

Although the Sergipana and Riacho do Pontal belts represent the continental collision events of the Brasiliano tectonics, they do not coincide with the geophysical lithospheric suture. In order to justify younger isotopic-age crust over the Archean blocks, a large horizontal detachment of the Sergipana and Central Ceará fold and thrust belts would be necessary.

The final result of this integration of deep sourced geophysical datasets is a map of the lithospheric blocks showing the limits of the larger São Francisco Lithospheric Block, the limits with the Amazon Craton and Parnaíba Basin block, the Borborema Lithospheric Block and the suture belts from the Brasiliano Orogeny (Figure 9).

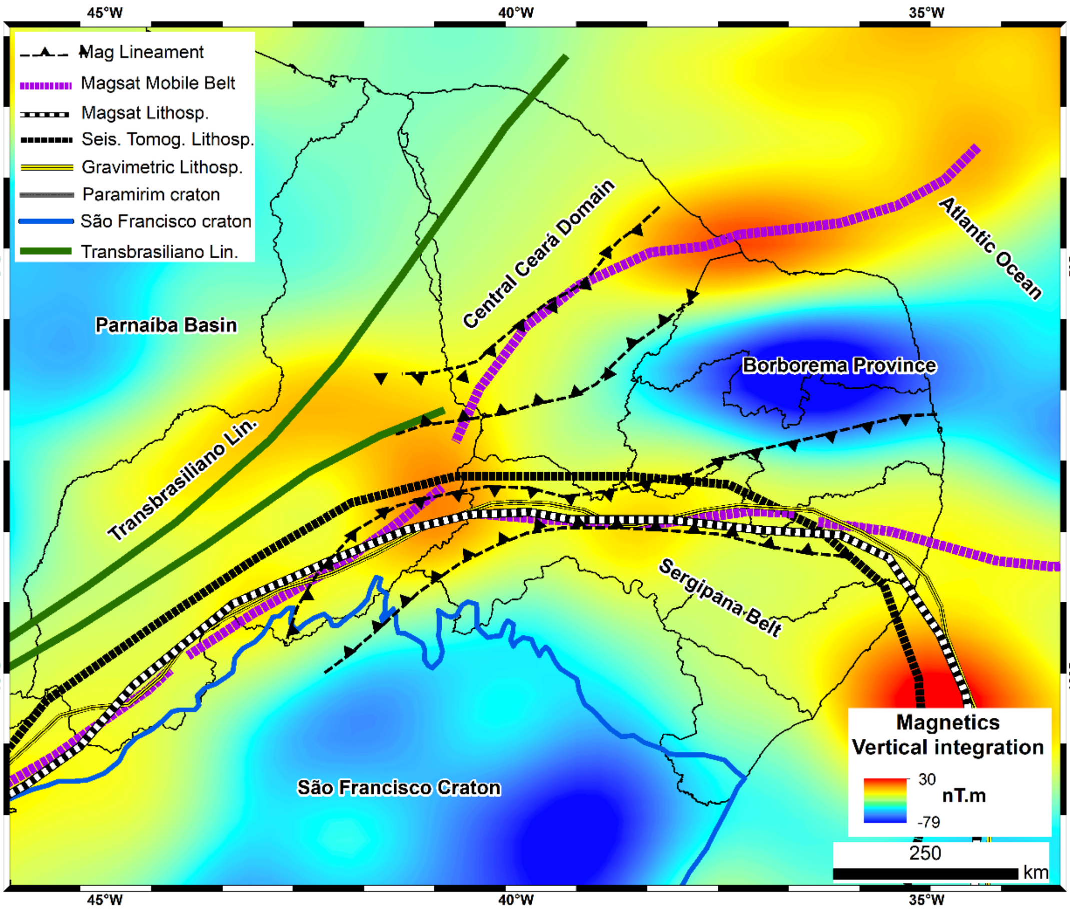
CONCLUSIONS

The integration of regional geophysics such as gravity, satellite magnetics and seismic wave tomography helps dealing with the lithospheric framework of the northern SFC and Borborema Province. Using gravity maps derived from geoidal model, we aim to look at the deepest source of gravity anomaly. The application of high-pass filters to image the lithospheric blocks and centers of suture zone proved to be satisfactory.

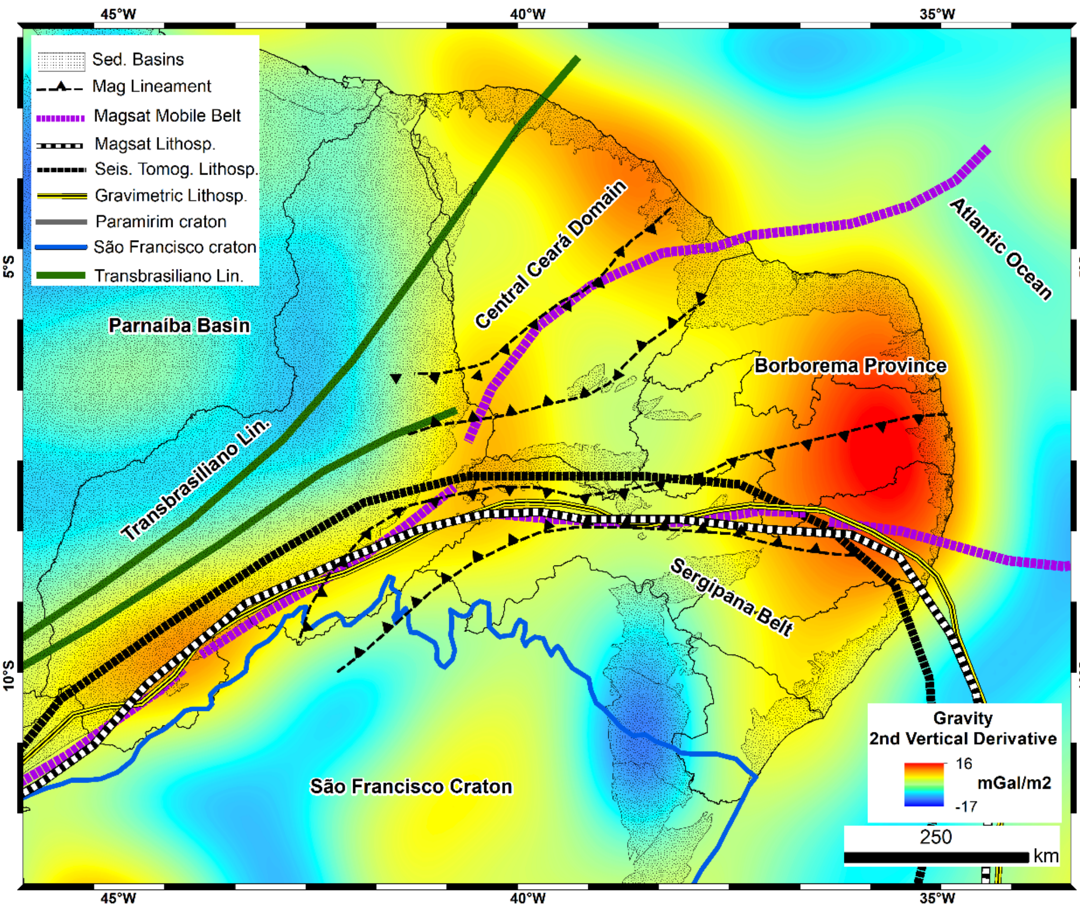
In addition, various digital forms of the most recent publications on seismic wave tomography of velocity anomalies were compiled. Depth slices at 100 km fit the expected slowing of velocity for the transition of craton lithosphere to mobile belts and associated suture zones.

Low-pass filter applied to satellite magnetic proves to be a good match to currently favored craton delimitation techniques such as gravimetry and seismic wave tomography. It also provides information on the deep architecture of mobile belts and defined very consistently a Borborema Lithospheric Block, likely a piece of the Benino-Nigerian Craton.

a


Mag Lineament
Magsat Mobile Belt
Magsat Lithosp.
Seis. Tomog. Lithosp.
Gravimetric Lithosp.
Paramirim craton
São Francisco craton
Transbrasiliano Lin.
Parnaíba Basin
Central Ceará Domain
Atlantic Ocean
Borborema Province
Transbrasiliano Lin.
Sergipana Belt
São Francisco Craton
Magnetics
Vertical integration
30
nT.m
-79
250
km
45°W
40°W
35°W
5°S
10°S

b


Sed. Basins
Mag Lineament
Magsat Mobile Belt
Magsat Lithosp.
Seis. Tomog. Lithosp.
Gravimetric Lithosp.
Paramirim craton
São Francisco craton
Transbrasiliano Lin.
Parnaíba Basin
Central Ceará Domain
Atlantic Ocean
Borborema Province
Transbrasiliano Lin.
Sergipana Belt
São Francisco Craton
Gravity
2nd Vertical Derivative
16
mGal/m2
-17
250
km
45°W
40°W
35°W
5°S
10°S

(continue)

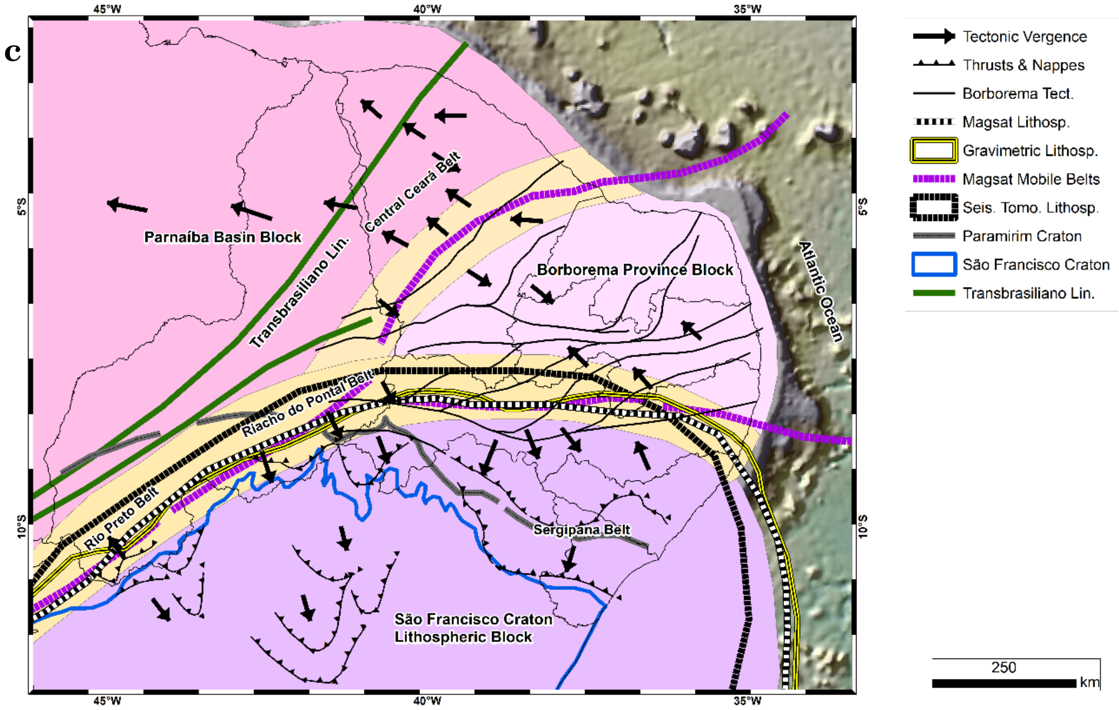


Figure 9: a) Low-pass filter of the vertical integral applied to the LCS-1 satellite magnetic model by Olsen et al. (2017). The low magnetic areas correlate well with cratonic centers and high magnetic anomalies to mobile zones. Lines are the summary of the lithospheric boundaries mapped from different techniques. b) Second vertical derivative of the Geoid model by Tapley et al. (2005). Large gravity lows are the cratonic lithospheres, the SFC and Parnaíba Basin. The Borborema Province gravimetric response is affected by a large, buried load in the Borborema uplift zone (Oliveira and Medeiros, 2012). c) Possible configuration of the lithosphere in the northeastern region of Brazil. Three Archean to Paleoproterozoic lithospheric blocks sutured by two mobile zones, the Sergipana / Riacho do Pontal / Rio Preto belt and the Ceará Central belt. The crustal structure geometry denotes large horizontal detachments of material in direction of the cratonic nuclei.

Large horizontal displacements over the SFC are evident with vergence to the center of the craton. The same happens to vergence in the Parnaíba and Borborema blocks. From the Sm-Nd grid map, we encountered a mismatch of the limits of the cratons and younger fractionated plutons. We interpreted that as an effect of large crustal detachments towards the SFC and Parnaíba blocks.

This work suggests the SFC is a large ellipse-shaped structure that corresponds to an Archean continental lithospheric block, SCLM-type, like several examples worldwide, with probable extent bellow the southern Borborema Province and under the oceanic crust of the Atlantic NE Brazil basins.

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