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Joint modeling gravity, geoidal and geothermal of the Lithosphere in Sergipano Belt and tectonic implications, NE Brazil.

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Abstract

In this research paper were applied methods which integrate geophysical and petrological data to the crustal and lithospheric
10 structure in the Sergipano Belt, in the Southern Borborema Province, NE Brazil. These methods allowed us to unveil the main crustal features and their tectonic relationships with the crust-mantle interface (Moho), as well as the lithosphere-asthenosphere boundary (LAB) of this region. The crust structure was constrained by available geological, gravimetric and seismological data, and chemical composition for mantle bodies. Gravity, geoid and heat flow data integrated with existent geological and geophysical data provides to understand the evolution of the Southern Borborema Province. The modeling
15 method was based on local isostasy in which the first phase of the work consisted on the filtering of geoid anomaly and topography data using low-pass in the harmonic and frequency domains, respectively, to estimate the thickness of the crust and the lithosphere, and the second phase is characterized by geothermal modeling. The crustal structure was constrained by geological information, thermo-physical parameters, and gravity and magnetic data inversion results, while the lithospheric mantle was constrained by chemical composition of xenoliths. The results show that maximum depths of Moho and thermal
20 lithosphere (LAB) along the modeled profile are 34 - 42 km and 194-202 km observed, and temperatures are recorded with an average of 600° C in the Moho temperature at Sergipano belt. The results presented suggest a thinning lithospheric mantle below the Sergipano belt, with values varying between 168 to 180 km, excepting in Girau do Ponciano whose is 194 km and a moderate lithospheric thickening below the Rio Coruripe, and thicker lithosphere at Pernambuco-Alagoas terrains reached 202 km.

25 **Key words:** Gravity and geoid anomalies; Crustal and lithospheric structure; thermal modeling.

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1. Introduction

The understanding the tectonic evolution of Precambrian Terrans is complex due to their tectonic dynamics of their structures, either by erosion or overlapping of tectonic events. This difficulty resides in the reconstruction of the evolutionary
30   process that generated these terrains, as well as in the characterization of its lithosphere, its dynamics, heat production on the earth's surface and the location of the suture zones between the different blocks. Geothermal models have gained prominence these days, as they allow the interpretation of the current lithospheric characteristics of these terrains and for being an important tool to answer several questions arising from tectonic dynamism, in space and time, thus helping to provide the geological history in a region.

35   Gravity and geoid data, as well as magnetic, seismological and heat flow data have been recently successfully used to better understand and delineate geological terrains (eg, Kaban et al., 2014; Carballo et al., 2015; Afonso et al., 2016; Qashqaiet al., 2016; Sampaio et al., 2017; Abedi et al., 2018; Souza et al., 2019; Brown et al., 2020, Kumar et al., 2020). In this paper, we use gravimetric, geoid and topographic data associated with thermal properties, density distribution and seismological velocities to characterize the thermal structure of the lithosphere of the Southern Borborema Province, NE Brazil. Therefore,
40   this modeling allowed us to understand the geodynamic processes involved in the formation of the crust, crust-mantle interface and lithosphere-asthenosphere interface of the region.

The conception Southern Borborema Province (SBP) is related to the role of neoproterozoic orogen between South America and West Africa during the Gondwana supercontinent development, his conFiguretion was due to the convergence of the Amazonian Cráton, São Francisco Congo and São Luís - West Africa during the orogeny (Lima 2018; Brito Neves et al.,
45   2000). This is an area that attracts a lot of attention due to its complex geotectonic evolution, the collision generated a 1000 km long continental orogen on the north margin of the São Francisco Craton composed of the Rio Preto, Riacho do Pontal and Sergipano belts (Caxito et al., 2016 and references), in South America, extending across northwestern Africa, in the Oubanguides Orogen, on the northern margin of the Congo Craton (Trompette, 1997).

In the last few years, several geological and geophysical studies have been developed in this area in order to unveil the
50   crustal structure as Argollo et al. (2011) who studied the crustal model and heat flow in the Estância, Vaza-Barris and Macururé domains, based on the measurement of density, conductivity and estimation of the volumetric rate of heat production; Dutra et al. (2018), who developed a crust structure model and geothermal flow map for the adjacent region to the Sergipe-Alagoas basin; Araújo (2019) who studied the size of sources in the transition zone between of the Segipano belt and the Pernambuco-Alagoas domain; Dutra et al. (2017) which estimated the basement thickness and lateral variation of the
55   density contrast in the Estância, Canudos-Vaza-Barris, Macururé domains and Pernambuco-Alagoas Terrain; Fianco et. (2019) and Dutra et al. (2019) which estimated the moho thickness for Pernambuco-Alagoas terrain and also for the Sergipano belt; and Oliveira (2009) which proposes a less thick lithosphere in the Salvador-Esplanada-Boquím domain and

in most regions of the Sergipano belt, obtained through integrated 3D inversion of data from the Bouguer and geoid anomalies. On the other hand, studies about lithospheric structure, LAB depths, thermal modelling, mantle density and

60 seismic velocity distribution still need to be done.

The modeling of geophysical and petrological data, associated with its relationship with plate tectonics in the different geological domains, allowed to determine the structure in muti-layers of the Southern Borborema Province. This study integrates gravity anomaly (free-air and Bouguer anomalies), geoid anomaly, topography and heat flux, thermal conductivity and radiogenic heat rate data to produce a geothermal, density distribution and velocity model of the seismic waves (S and P)

65 for the crustal and lithosphere-asthenosphere structure up to 400 km depth.

2. Geological Settings

The SBP comprises one of the main tectonic segments of the Borborema Province. Many researchers infer the subdivision of the Borborema Province into three subprovinces: Northern, Central or Transversal and Southern (Brito Neves et al., 2000; Lima, 2018, Pereira et al., 2020). The Borborema Province is resulted from continental blocks that collided during the

70 amalgamation of Western Gondwana at the end of the Neoproterozoic. Therefore, the SBP results on the collision between the Pernambuco-Alagoas Massif and São Francisco Cráton to the north, this region is divided by the Sergipano belt (SB), Riacho do Pontal (RPD), Rio Preto and Pernambuco-Alagoas domains which show the lateral continuity and related geological features (Lima, 2018; Brito Neves et al., 2000, Oliveira et al., 2010; Santos et al., 2000).

Figure 1

75 The Pernambuco-Alagoas domain is limited to the north with the transversal subprovince by the Pernambuco lineament and to the south with the Sergipano belt by shear zones. The Pernambuco-Alagoas Domain is constituted with two large metamorphic complexes, the Belém complex of São Francisco represented essentially by granitic and granodioritic orthogaisse, and Cabrobró Complex, a metavolcanosedimentary unit composed of shales, gneiss, quartzite, marbles, calssilicics and amphibolites (Lima, 2018). These complexes present a transpressive tectonics showing regions of intense

80 deformation due to the Cariris Velho event (Santos, 1995). In this tectonic domain there are neoproterozoic plutonic intrusions which can be grouped into pre and post-collisional, these granitic intrusions were classified into five batholiths: Buique-Paulo Afonso, Águas Bela-Canindé, Maribondo-Correntes, Ipojucas-Atalaia and Jaboatao-Garanhuns.

The Sergipano belt comprises a sequence of metamorphosed supercustral rocks with characteristics of the passive continental margin and foreland basin (Oliveira et al., 2015). The belt is divisible from north to south into the Canindé,

85 Poço-Redondo-Marancó, Rio Coruripe, Macururé, Vaza-Barris, and Estância geotectonics domains (fig. 1) (Oliveira et al., 2010, 2017; Davison e Santos 1989; Dutra et al., 2019). The Marancó domain comprises on metasedimentary pelitic to psamitic rocks and intercalations of basalt, andesite, gabbro and amphibolite rocks. Peridotites and gabbros with varying degrees of serpentinization occur mainly as lenses in metasedimentary rocks or as intrusions to the south; they can be slices of lithospheric mantle under the orogen or fragments of ophiolite (Silva Filho, 2006); The Poço-Redondo subdomain is a

90 migmatitic gneiss complex dominated by granodioritic-tonalitic rocks that represent the base of the Marancó subdomain; The Canindé domain is between the Pernambuco-Alagoas domain and the Maraconó unit of the Poço-Redondo domain, morever, it is limited by the Macururé shear zone. It consists of metavolcanic-sedimentary rocks, calcissilicate rocks (Lima, 2018).   In these three domains (Marancó-Poço Redondo and Canindé) are the allochthonous accreted during the Neoproterozoic (Oliveira et al., 2017).

95 The Estância domain is one of the first domains of the Sergipano belt, from south to north is the Estância, which is basically constituted by sub-horizontal sedimentary rocks, deformed and undeformed (Oliveira et al., 2017; Argollo et al., 2011) . The Vaza-Barris domain is the most deformed when compared to the Estância, it contains several grouped formations in the Miaba, Simão Dias and Vaza-Barris groups (Oliveira, 2006; Silva and McClay, 199)). In the typical locality (Fazenda Capitão), the lower Miaba group comprises a basal quartzite unit (Itabaiana), by dolomite interspersed with stromatolite and

100 limestone (Jacoca Fm). The basal quartzites of the Miaba Group rest unconformable in the gneisses and migmatites of the basement of the Itabaiana and Simão Dias domes; The Macururé domain is basically composed of amphibolite facies, meta-turbidites containing garnets, schist mica with smaller intercalations of quartzite, marble and meta-volcanic rocks (Oliveira et al., 2006); The Rio Coruripe domain is located between the Macururé domain in the southeast and Pernambuco-Alagoas in the northeast, moreover, it is limited by the beautiful Monte Jeremoabo shear zone. It is constituted by gneissic metamorphic

105 rocks and migmatite with migmatitic structures. Its basement is essentially formed by amphibolitic and granulitic rocks (Sampaio, 2019; Lima, 2018).

The basement of the Sergipano belt is represented by the occurrence of gneissic domes of Girau do Ponciano, Simão Dias and Itabaiana, which are involved in the episode of regional metamorphisms and tectonic deformation. These deformations were studied by Oliveira et al. (2006); Oliveira et al. (2010) and Oliveira et al. (2015), which the structural evolution of the

110 belt was synthesized in four deformation phases. The first phase, called remaining structures from the pre-Brazilian deformation event, the second is characterized by nappes and pushes with south convergence, the third associated with the transpressive regime and the fourth expressed by the ductile and brittle character.

The other domain included in our study area is Salvador-Esplanada-Boquim, which belongs to the São Francisco Cráton and is represented by high-grade metamorphic rocks. The São Francisco Cráton represents a tectonic entity of the Brasilian cycle

115 and comprises most of Bahia State and extends to the Minas Gerais, Sergipe, Pernambuco and Goiás. The basement was consolidated at the end of the Transamazonic cycle. Its coverage comprises two complexes (De Almeida, 2017), the Archean and Paleoproterozoic terrains that constitute the basement of the São Francisco Cráton in the Bahia State, these can be grouped into four important Archean crustal segments, the Gavião, Serrinha, Jequié and Itabuna-Salvador-Curaçá Blocks, (Souza, 2013). The São Francisco Cráton is represented by high-grade metamorphic rocks - gneissic, migmatitic, granulitic

120 and granitoid rocks, in addition to having some dykes of correlated age. The Cráton is truncated by an aborted N-S oriented rift in which protoliths from the Espinhaço (Mesoproterozoic) and São Francisco (Neoproterozoic) Supergroups have deposited.

3. Material and Methods

We used orbital geophysical data, elevation (topography), gravity anomaly (Bouguer and Free-air), geoid anomaly, and
125   surface heat flow. The elevation data were extracted from ETOPO1, a global relief model, available on the National
Geospatial Intelligence Agency - Earth Gravitational Model (NGA, 2008) page, with 1×1 min arc resolution, which
integrates topography and ocean bathymetry. Figure 2 show the elevation map, the Pernambuco-Alagoas domain is
characterized by high elevation values and on the Sergipano belt the map show low elevation.

Figure 2

130   The gravity anomalies are of data base from International Center for Global Gravity Field Models (ICGEM) and from
International Gravimetric Bureau (BGI). The data base ICGEM used the European Improved Gravity model of the Earth by
New techniques - EIGEN-6C4 (Förste et al., 2014), (ICGEM: http://icgem.gfz-potsdam.de) . The data base BGI used the
Earth Gravitational Model geopotential model - EGM2008 (Pavlis et al., 2012), (BGI: https: //bgi.obs-mip.fr/). These
ICGEM and BGI models are widely used to studies related to Earth internal structure, as well as in lithosphere modeling.

135   In Figure 3a the Bouguer anomaly map the positive anomalies has amplitudes range from 12 to 60 mGal related to the rocks
of the basement with with higher density values, and negatives anomalies with amplitudes ranging −130 to −20 mGal
related sedimentary basins (Tucano, Jatobá and Sergipe-Alagoas). The Free-Air was used to interpret anomalies and to
model the lithosphere. Figure 3b show the free-air anomaly map and it can be seen that positive anomalies ranging from 22
to 80 mGal on Salvador-Esplanada-Boquim domain and on Sergipano belt (in the Estância, Vaza-Barris) and part of the
140   Macururé domain. Positive anomalies extend to the north of the study area, covering the Rio Coruripe and Pernambuco-
Alagoas domains, with amplitude 10 to 60 mGal.

Geoid anomaly data were extracted from International Center for Global Gravity Field Models (ICGEM: http://icgem.gfz-
potsdam.de) using the GECO model (Gilardoni et al., 2016), this complete model has a spherical harmonic degree and order
2190. Figure 3c show the residual geoid anomaly map (harmonics coefficients up to degree and order 10 removed) and it is
145   observed that maximum anomalies are recorded in the northern region of this study area with amplitude ranging -6 to -3 m,
while the southern region is characterized by low amplitude anomalies.

The surface heat flow data were obtained from terrestrial campaigns of the Geoterm project (IF-UFBA), and from National
Gravimetry Network through the ANP database (Petrobrás and other oil companies) and used in data modeling, the values
are in topography map in Figure 2.

150   **Figure 3: (a); (b) and (c)**

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3.1 Processing and Lithosphere Modelling

To develop this study, we first searched for a database that allowed us to get the proposed objectives, then, we filtered the topography data by applying low-pass filter in the frequency domain to remove high-frequency (low wavelength) effects associated to the sources. To apply this filter properly, we first developed a power spectrum analyze that allowed us to split

155 the sources into two wavelengths: low wavelength than 66.66km and long wavelength than 66.66 km, which low wavelength is associated with high-frequency while long wavelength is to low-frequency. We also removed the spherical harmonic coefficients up to 10 on the geoid anomaly data to get the residual geoid anomaly, by applying also low-pass filter but in the harmonic domain. These two filtered data were used to estimate automatically the crustal depths (Moho) and lithosphere-asthenosphere boundary (LAB) using method that integrates geoid anomaly and topography associate to thermal analyze

160 developed by Fullea et al. (2007).

This method is based on local isostatic compensation principle, and considers four layers: crust, sea water, lithosphere and asthenosphere. The density distribution in the lithosphere is dependent on temperature and varies linearly with depth, according to the equation:

$$\rho_m(z) = \rho_a\big[1 + \alpha\big(T_a - T_m(z)\big)\big] \tag{1}$$

165 Where α is the linear thermal coefficient expansion, T_a a is the temperature at the lithosphere-asthenosphere limit and $T_m(z)$ is the temperature at depth z in the lithosphere.

The geoid anomaly is calculated selecting the reference column, the one that allow obtaining the best fit and thicknesses. In this work the reference lithospheric column was selected according as described by the method (for details, Fullea et al., 2007). The table 1 show the physical input parameter used in our calculations. We applied improved LitMod2D_2.0 code

170 (Kumar et al., 2020) for lithospheric modeling, which is interactive software that integrates geophysical and petrological data in order to get the lithospherics models up to the 400 km depth. The improved LitMod2D_2.0 is based on the Afonso et al., 2008 code, that allows to determine 2D models, temperature, density and seismic waves velocities (P and S) distributions, in a consistent thermodynamic-geophysical environment, fitting also the geophysical data (Bouguer and free-air anomalies, geoid anomaly, heat flow and topography data). The physical parameters used in our modelling area in table 1.

175 **Table 1**

The model consists on set of crust and mantle bodies, each one characterized by its physical properties. The crust is characterized by thermo-physical parameters such as density, conductivity and radiogenic heat, while the mantle bodies are characterized by mantle chemical composition (for details about the method, Kumar et al., 2020; Afonso et al., 2008). The

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temperature in the lithosphere is calculated assuming stationary regime and solving the heat transport equation, and

180 considering fixed boundary conditions at the surface (0 ^{o}C) and at the LAB (1320 ^{o}C). The density distribution in the model is calculated using an iterative scheme that allows incorporating the effect of pressure, temperature and composition (Kumar et al., 2020; Afonso et al., 2008). Once the physical properties are determined for each mantle composition, gravity, geoid, elevation, surface heat flow, and P and S seismic velocities are computed and compared with the observed values. Gravity and geoid are calculated by using simple algorithms to each element of the mesh. Elevation is calculated assuming local

185 isostasy referenced to a mid-ocean ridge column with the compensation level at 410-km depth (Jiménez-Munt et al., 2019). The data processing workflow is represented by the Figure 4.

Figure 4

4. Results

In geophysical direct modelling are supposed an existence of an initial model composed of crustal bodies with physical

190 parameters each one and mantle bodies characterized by chemical composition. The model is modified as necessary to get be best fit of the observable data along the transects. In this section we present our modeling results, crustal and lithosphere structure, temperature and density distribution, as well as seismic wave's distribution.

4.1. Moho and LAB depths

The Moho and LAB depths has been estimated according to described on the section 3. The Figure 5a show the Moho map

195 obtained from our calculation. The results show crust varies 12 to 40 km, however, in Salvador-Esplanada-Boquím domain and in the Sergipano belt the crust is thinner varies 32 to 36 km, while in Pernambuco-Alagoas domain the crust is thicker, ranging from 37 to 42 km. These results are in agreement with Dutra et al. (2019) and Fianco et al. (2019). In relation to the lithosphere-asthenosphere boundary (LAB depth), the Figure 5b shows the map with the LAB values obtained from our calculation, where Pernambuco-Alagoas domain is thicker reaching 205 km, and thinning lithosphere in Sergipano belt and

200 in SEB domain, reaching 190-180km.

Figure 5: (a) and (b)

In relation to the crustal structure, the initial crustal geometry along the transects has been constrained by geological information extracted from different studies (e.g Brito Neves et al., 2000; Oliveira et al., 2010; Santos et al., 2000; Lima, 2018; Barbosa, 2012; Silva and McClay, 1995), that describe the tectonics unities and lithologies, and from seismic,

205 gravimetric and magnetic studies (e.g Araújo, 2019; Fianco et al., 2019; Dutra et al., 2019; Sampaio, 2019). We also used the seismological data from Geoterm project. The first transect, A-A', is oriented from the SW-NE, parallel to the strike of the

Sergipe-Alagoas Basin and crosses the Vaza-Barris, Macururé and Rio Coruripe domains that belongs to the Sergipano belt, and the PEAL domain to the north. The second transect, B-B', is oriented from south to north (S-N) of the study area. The physical parameters (density, radiogenic heat and thermal conductivity) were extracted from Boeker (2011); Dutra et al.
210 (2018), (2019); Kumar et al. (2013), Jiménez-Munt et al. (2019); Tunini et al. (2014) and Araújo (2019).

4.2. Mantle chemical composition

The mantle structure along of the profiles is constrained by the chemical composition and the LAB depth values. The chemical compositions, due to its influence on the density and on the seismic velocity waves, are important for our modelling as well as the LAB depth geometry. In this study we were used two chemical compositions (mantle 1 and mantle
215 2) as shown in table 2. The initial geometry of the LAB along the transects is inferred from the calculated values in section 4.1 through topography and geoid anomaly data associated to the thermal analyze, in a 1D approach.

c

In the transects we used two chemical composition (table 2). The mantle 1 has been extracted from Griffin et al. (2009) based on the age of the last thectono-thermal event that occurred in the study area, which is the Cráton do São Francisco
220 collision with Pernambuco-Alagoas domain. Geochronological information indicates that this collision occurred in the neoproterozoic, between 650-530 Ma (Lima et al., 2017). We used this composition to constrain the lithospheric mantle below the Salvador-Esplanada-Boquím domain and for part of the Sergipano Belt, while the second one, mantle 2, was extracted from Ngonge et al. (2019) based on continental mantle xenolith sample of the Borborema Province. This composition was used for the lithospheric mantle below the Rio Coruripe, Marancó, Poço-Redondo, Canindé domains and
225 the Pernambuco-Alagoas domain. The lithologies considered and the physical parameters are described in the table 3

Table 3

4.3. Crustal and Lithospheric Structure

The results of the crustal models obtained in the modeling along the transects A-A' and B-B' are shown in Figure 6. The
230 lithospheric models were elaborated using multilayer geometry, and correspond to the upper crust, middle crust, lower crust, lithospheric mantle and asthenosphere up to 400 km depth. The crystalline basement is represented by the middle and lower crust with maximum thicknesses of 23-25 and 37.5 km respectively. The Rio Coruripe (RC) and Pernambuco-Alagoas (PEAL) sources reach 18 and 11 km depth (fig. 6a), respectively. The dome structure (Itabaiana dome) in the Vaza-Barris domain reaches 6 km of depth, while the Jatobá Basin in the Pernambuco-Alagoas domain reaches 4.5 km depth (fig. 6b). A
235 significant variation of the upper crust, characterized by crustal thinning, is observed in Vaza-Barris and Macururé domains

8

(fig. 6a)   with a thickness of 20 km. The moho depths increases in the direction of the transects without great variations, starting 32 to 36 km on the Salvador-Esplanada-Boquím (SEB) domain and in the Sergipano belt, and in the Pernambuco-Alagoas domain the crust is so thicker, reaching 38 km. The sedimentary cover considered in the modeling is the most recent, that of the Cenozoic.

240   **Figure 6**

The figures 7e) and 8f) shows the best-fit lithospheric model. The calculates heat flow in Vaza-Barris domain are characterized by a low heat flow and do not trend to the observed along the transects, due to the influence of São Francisco Cráton rocks which are old structures (fig. 8a). On the other hand, in Estância domain trends to the observed in the transect A-A' (54.37-60.04) $m\,W/m^2$; The calculated gravity Bouguer and free-air anomalies and geoid anomalies matches to the observed trends to the the profile (figs. 7a, 7b, 7c, 8b, 8c and 8d), small misfits of geoid anomaly are observed in Vaza-Barris and in Pernambuco-Alagoas in order of 5 to 9 m, respectively, indicating that these domains are characterized by high densities. The calculated elevation presents a tendency very close to the observed, giving a good adjustment in major domains of Sergipano Belt, however, misfits in the order of 750 to 1200 m are observed from the Marancó domain to the Pernambuco-Alagoas and Macururé domains (figs. 8e and 7d). According to Kumar et al., 2013, in case of any discrepancy or incompatibility of the gravity and geoid anomalies data with the elevation data, preference is given to the adjustment of the first two. To evaluate the adjustment of the observed and calculated data (table 4), root mean square error (RMSE) has been calculated according to:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_1-x_2)^2}{n}}$$, where: x_1 and x_2 are observed and calculated data; n is the number of point along the profile.

The lithosphere-asthenosphere boundary (LAB) shows a marked variation below the SEB domain and Sergipano belt characterized by a thinning lithospheric mantle whose thickness is 175 on the SEB and Estância domains, small smooth changes in the LAB depth are observed in the Vaza-Barris and Macururé domains 169-180 km (figs. 7e and 8f). In the next part of Macururé domain, in Girau do Ponciano the lithosphere is thicker, reaching a value of 194.0 km (fig. 7e). An another important change is observed in the Marancó-Poço-Redondo-Canindé (MPRC) domain, characterized by an increase in the thickness of the lithosphere reaching 202 km in PEAL domain which is the maximum depth (fig. 8f).

260

4.4 Temperature and Density Distribution 2D

The temperature distribution model along the transects are displayed in the figures 7e and 8f. The Sergipano belt is characterized by horizontal isotherms in the lithospheric mantle, with Moho temperature about 600°C. Therefore a

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significant variation characterized by horizontal isotherms with upwards deflection and increases temperature, according to

265   the increase of the crustal thickness and of lithospheric mantle thickness (fig. 8f), is observed from Marancó up to the Pernambuco-Alagoas domain, with Moho temperature about 800°C. The geothermal gradient below the lithospheric mantle is justified by the LAB thickness variation and of the adiabatic gradient.

The density distribution in the mantle lithospheric is shown in the figures 7f and 8g, and it is dependent on the temperature-pressure and chemical composition. Laterally, low densities are found below the PEAL up to Marancó domain with values

270   about $3200 kg/m^3$ increasing toward to SEB domain ($3300 kg/m^3$), (fig. 8g). Vertically, the density increases with depth, varies from $3300 kg/m^3$ below the Moho toward to the lithosphere-asthenosphere boundary ($3400 kg/m^3$).

Figure 7

Figure 8

Table 4

275   *4.5 Mantle Seismic Velocity Distribution*

Figures 9 and 10 shows the calculated results of the velocity of the seismic waves. Seismic velocities are dependent on chemical composition and temperature-pressure. In depth, the P velocity waves increases from 7.9 km/s at PEAL domain beneath the Moho depth to 8.3 km/s in the LAB. Laterally, therefore, low velocities are found in PEAL domain the P increasing to SEB domain and to Sergipano belt (fig. 10a). In addition, the S velocities decrease with depth at the LAB and

280   then increase again to the 400km depth. Laterally, S waves low density are found also in PEAL ($4.53 km/s$) domain, increasing to SEB domain and Sergipano belt ($4.62 km/s$). It is important to notice that the seismic velocities increase in the opposite direction to the increase in the thickness of the lithospheric mantle (fig. 10b).

Figure 9

Figure 10

285

In order to evaluate how temperature varies more accurately in different depths of the modelled domain, we plote geotherms from two selected points represented by P1 and P2, in the temperature distribution models, one in the Vaza-Barris domain and the other one in the Rio Coruripe domain (figure 11a and 12a). In addition, it was possible to plote also the density and velocity (P and S waves) distribution curves for each selected point using the density and wave velocities models, and it's

290   important to notice that the density distribution and P waves increase from lithospheric mantle up to 400 km depth, while the S wave, decrease with depth from the lithospheric mantle to the LAB and then increase to 400 km depth (figure 11b and 12b).

Figure 11 : (a) and (b)

Figure 12 : (a) and (b)

295   **5. Discussion**

The present work aimed to study the lithospheric structure, providing temperature distribution models, density and seismic velocities distribution, representative for the Borborema Southern Province. The initial models were constrained using geological information, gravimetric and seismological data at some points. Based on the analysis of available potential data and modeling methods, it was possible to automatically determine the crustal and lithospheric thickness, using elevation and
300   geoid anomaly coupled with temperature and density distribution (Fullea et al., 2007 method), and we also obtain a more accurate 2D model of temperature, density distribution and seismic waves velocities to the lithosphere. Thermophysical parameter and geochemical composition information was coupled as a priori information in the models. We applied the improved LitMod2D_2.0 code (Kumar et al., 2020) to provide the models, and the geophysical data we used are topography, gravity anomalies (bouguer and free-air), and geoid anomaly and heat flow data.

305

The depths for the Rio Coruripe and Pernambuco-Alagoas sources obtained by Araújo (2018) through the modeling of gravimetric data reaches 21 and 9 km. These results shown small discrepancies to our along to the transects modeled (fig. 6) reaching 18 km for Rio Coruripe and 11 km for Pernambuco-Alagoas depth. In additional, the depths of the domes structures, the Itabaiana and Girau do Ponciano (Figs. 6b and 6a), reached 6 km and 10 km, in agreement with Sampaio
310   (2019) which suggests 6km and an uplift of the basement of the Itabaiana dome, as well as 8.0 km for the Girau do Ponciano dome. These small discrepancies observed are correlated to the difference of the methods applied in the two modeling situations.

The Moho depths in our models (fig. 6) suggest an attenuated crustal thinning for the SEB domain and Sergipano belt with values ranging from 32 to 36 km, and thicker crust for the Rio Coruripe and Pernambuco-Alagoas domains with a value of
315   38 km. Therefore, these results are in agreement to Dutra et al. (2019) and Fianco et al. (2019) which estimated the Moho depth from gravimetric and seismological data, both the Sergipano belt is characterized by a thinning crust ranging from 33 to 35 km, and in Pernambuco-Alagoas domain the crust is so thicker with values about 37-42 km.

Our calculates heat flow (fig. 8a) belongs to the range found by Dutra et al. (2018), which indicates heat flow varies from 38.0 to 90.0 mWm^2, although the SEB domains are characterized by a high geothermal gradient, estimated from
320   aeromagnetic and Curie surface data, and due to the methodology employed, has greater intervals than those found in this work.

In relation to the lithosphere-asthenosphere boundary (LAB), few studies have been carried out in this area, however, the results presented suggest a thinning lithospheric mantle below the SEB domain and Sergipano belt, with values varying between 168 to 180km, excepting in Girau do Ponciano whose is 194 km and a moderate lithospheric thickening below the Rio Coruripe (fig. 7e), and thicker lithosphere at Pernambuco-Alagoas domain reached 202 km. Therefore, these results are in agreement to Oliveira (2009) who proposes a thinning lithosphere in SEB domain and in most regions of the Sergipano belt with values ranging 160 to 180, and a mild thickening in the Rio Coruripe and Pernambuco domains -Alagoas whose thickness varies between 180.0 to 190.0 km, obtained through integrated 3D inversion of the Bouguer gravity and geoid anomalies. In addition, Feng et al. (2007) conducted a study in which developed a tomographic S wave velocity model for the upper mantle beneath South America, by simultaneous inversion of the regional S and Rayleigh waveforms and of the Rayleigh wave group velocities, to constrain the upper mantle and the Moho depth, therefore, it results indicate the São Francisco craton characterized by high upper mantle velocities $(3.5 - 7.0 \, km/s)$ in the first 200 km of depth. This trend extends to the northeast of Brazil. These results reinforce presented in our models, where the velocities of the S waves at the LAB range 4.47 to 4.50 km/s.

5.1 Tectonic Implications

Gravity, geoid and heat flow data interpretation integrated with existent geological and geophysical data provides to understand the evolution of the Southern Borborema Province. Distinctive gravity features suggest that the lithotectonic associations in the area correlate with different fault-bounded terranes that underwent subsequent amalgamation. These features include contrasting gravity and geoidal signature between terranes. Its origin is interpreted as a result of the oblique collision between Pernambuco-Alagoas domain with the São Francisco-Congo Cráton during the Brasilian/Pan-African orogeny. The structural evolution of the Southern Borborema Province is summarized in four deformation phases and the evolution has a better fit with a model that resembles the one proposed by Davison and Santos (1989). The Sergipano Belt was formed through the collage of distinct lithostratigraphic domains. Main shear zones that divide these domains would be thrust zones that juxtaposed geological units of different crustal levels. This is corroborated by Santos et al. (2014), Dutra et al. (2019) and our modeling. In this hypothesis, the SFC limit is represented by de Shear zone São Miguel do Aleixo as proposed by Oliveira and Medeiros (2018). The Macururé Domain is an allochthonous terrane accreted to the São Francisco paleoplate margin and the final suture is represented by the collision of the Marancó-Poço Redondo arc (Oliveira et al., 2010) and the closure of an ocean that is represented by the region dominated by high positive gravity (20 to 40 mGal) and geoidal (5.5 to 6.5 m) values located between PEAL and SB. Presents trough gravity relief, and comprises parts of Rio Coruripe and Canindé domains. Its lithotectonic domains are inserted to the northern portion of the Canindé, Poço Redondo-Marancó, Rio Coruripe and Macururé domains, which it is limited by extensive transpressional shear zones. These domains incorporate metavulcansedimentary rocks to mafic/ultramafic rocks. Collage of terranes is a characteristic feature of accretionary processes and, in fact, some authors propose the evolution of the Borborema Province as a progressive accretion

of terranes during the Neoproterozoic (Santos et al., 2000; Brito Neves et al., 2000). This proposal has been reinforced by
355   recent studies in the Northern and Transversal domains of the province such as those of Santos et al. (2018) and Pereira et al.
(2020). Thus, evidence points to an accretionary origin for the Sergipano Belt and highlights the importance of accretion
tectonics in the evolution of the Borborema Province and the amalgamation of Western Gondwana.

6. Conclusion

In this work, we provide lithospheric model for Southern Borborema Province were developed and presented along two
360   transects, by integrating geological, geophysical and petrological data. The observables geophysical data were calculated and
compared to the observed along the profiles. The models shown Moho depths in agreement obtained to the other authors
using different geophysical data, showing that the crust at SEB domain and Sergipano belt is thinner to the PEAL domain.
The transition zone occurs between the Macururé and Rio Coruripe domains, as can be seen in the moho and LAB maps,
also the LAB geometries in the models reveal a thinning a lithospheric mantle in the Sergipano Belt domains and a
365   thickening in the Pernambuco-Alagoas domain, in accordance with proposed by some researchers. The mantle chemical
composition has a very important for lithosphere modeling to fit the geophysical data. Its lateral variations, significantly
influence to the density distribution and to the seismic velocity waves, it is noticed in our second model in figure 9a, along
the transect B-B'. The obtained lithospheric structures are representative for Southern Borborema Province in agreement
with the evolutionary model. Our crustal thickness results show thinning crust for Salvador-Esplanada-Boquím domain
370   (SEB) and Sergipano belt with values varying 32-36 km and thicker for Pernambuco-Alagoas domain varying 38-40 km, in
agreement with seismic and gravimetric data. Results of lithosphere-asthenosphere boundary (LAB) show maximum values
in Pernambuco-Alagoas domain reaching ~201 km. The modeled transects show approximate geometries for the LAB. The
SEB domain and the Sergipe belt are characterized by LAB ranging 169 to 180 km, an abrupt change is observed in Girau do
Ponciano. These results are in agreement obtained by gravity data. Based on lateral variation of the chemical composition of
375   the lithospheric mantle, was possible to obtain the best fit of the seismic velocities waves P and S, and the density
distribution. Our results show that the PEAL domain has a different composition that extends to the Marancó, Poço-
Redondo, Canindé and Rio Coruripe domains, from the rest of the region due to collision with the São Francisco Cráton. The
crustal thickness results show that the Salvador-Esplanada-Boquím domain (SEB), Sergipano belt and Alagoas Sub-basin are
characterized by thinning crust with values varying 32-36 km, thicker crust for Pernambuco-Alagoas terrain varying 38-40
380   km, in agreement with seismic and gravimetric data. Results of lithosphere-asthenosphere boundary (LAB) in all two
profiles show maximum values in Pernambuco-Alagoas domain reaching ~201 km. profiles show approximate geometries
for the LAB. The SEB domain and the Sergipano belt are characterized by LAB ranging 169 to 180 km. These results are in
agreement obtained from gravity data. The chemical mantle composition and its lateral variation show that the chemical
composition of PEAL extends to the first three domains of the Sergipano Belt, and their respective adjustments in density

385 and velocity distribution (P and S). Our geometric model and our results are in agreement with the evolutionary model of the Southern Borborema Province, which is an important orogenic terrains in north-eastern Brazil.

Acknowledgement

Data Availability

The data used in this study come from different databases and it can be found at: http://icgem.gfz-potsdam.de/ for Bouguer and geoid anomaly; https://bgi.obs-mip.fr/ for Free-air anomaly; National Geoespatial-Inteligency Agency - Earth Gravitational Model (https://www.ngdc.noaa.gov/mgg/global/) for elevation and Geoterm project for surface heat flow.

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Physical Parameter	Numerical Value
Density crust (ρ_c)	$2770 \ kg/m^3$
Water density (ρ_w)	$1030 \ kg/m^3$
Asthenosphere density (ρ_a)	$3200 \ kg/m^3$
Thermal coefficient expansion α	$3.5. \ 10^{-5}$
Radiogenic heat (H)	$1.2 \ Wm^{-3}$
Crust thermal conductivity (k_c)	$2.92 Wm^{-1}K^{-1}$
Mantle thermal conductivity (k_m)	$3.2 \ Wm^{-1}K^{-1}$
Surface temperature (T_s)	$0^o C$
LAB temperature (T_a)	$1350^o C$

Table 1: Physical parameter used in our modelling to map crustal and lithosphere thickness.

Oxides	Mantle 1 (Griffin et al., 2009)	Mantle 2 (Ngonge et al., 2019)
SiO_2	44.5	43.12
Al_2O_3	3.5	4.25
FeO	8.0	9.29
MgO	39.78	38.76
CaO	3.1	3.0
Na_2O	0.23	0.28
Total	99.11	98.7

Table 2: Chemical composition used in our lithosphere modelling for mantle bodies.

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Bodies	$\rho(kg/m^3)$	$k(W/mK)$	$A(\mu W/m^3)$
Sediments	$2350 - 2550$	2.0	1.0
Amphibolite	$2730 - 2760$	$2.3 - 2.61$	$1.2 - 1.65$
Vaza-Barris domain	2600-2700	2.61	1.2
Itabaiana dome	2750	2.61	1.2
Girau do Ponciano	2740	2.63	1.65
SEB domain	2740	2.19	1.087
Estância domain	2770	2.5	0.98
Macururé domain	$2720 - 2770$	2.63	1.67
Granite	$2710 - 2820$	2.4	1.65
Marancó	2780	2.7	1.6
Poço-Redondo	2820	2.7	1.60
Canindé	2820	2.7	1.60
PEAL source	2680	2.4	1.65
RC source	$2750 - 2770$	2.4	1.67
Upper crust	$2780 - 2850$	2.7	0.7
Middle crust	$285 - 2870$	2.5	0.7
Low crust	$2950 - 2980$	2.2	0.2

Table 3: Physical parameter used in our modelling for crustal bodies. ρ: Density; k Thermal conductivity and A: Radiogenic heat.

Profile	Bouguer anomaly (mGal)	Free-air anomaly (mGal)	Geoid anomaly (m)	Elevation (m)
A-A'	4.67	4.69	0.57	124.0
B-B'	6.22	5.80	0.35	306.48

525 **Table 4:** The RMSE between calculated and observed data along the transects A-A' and B-B'

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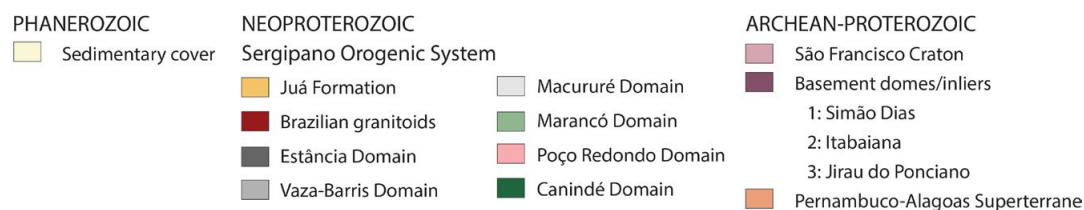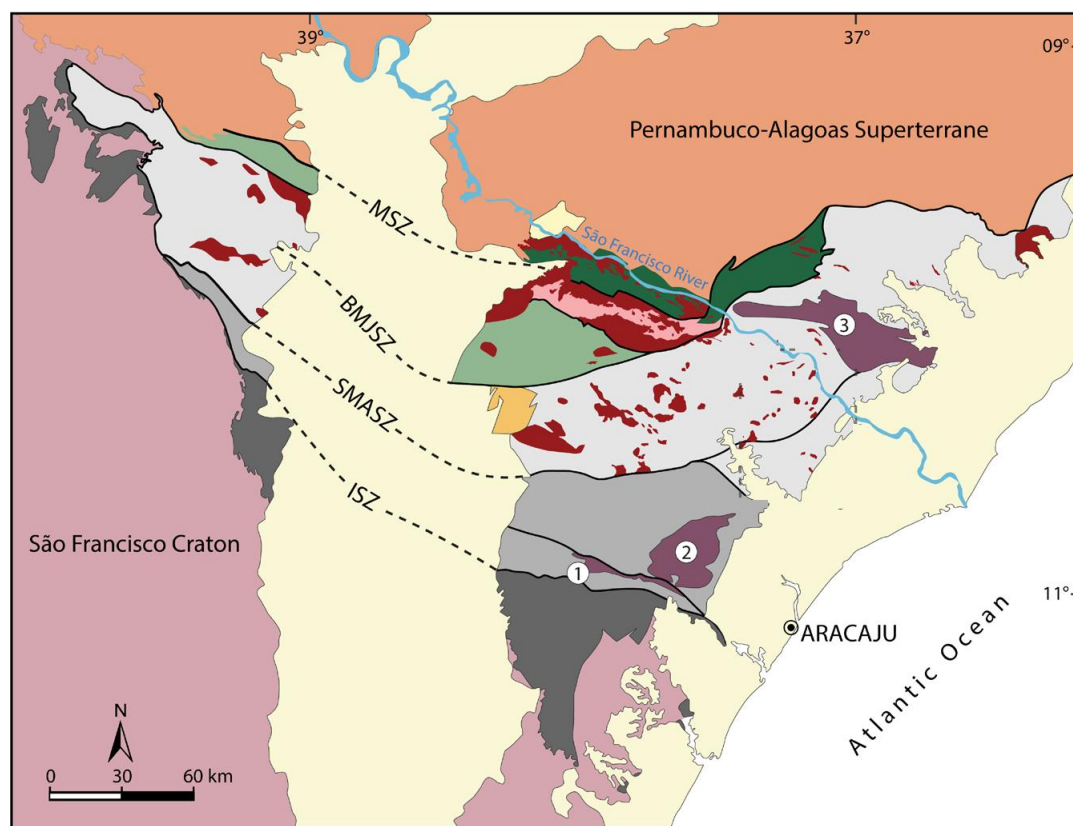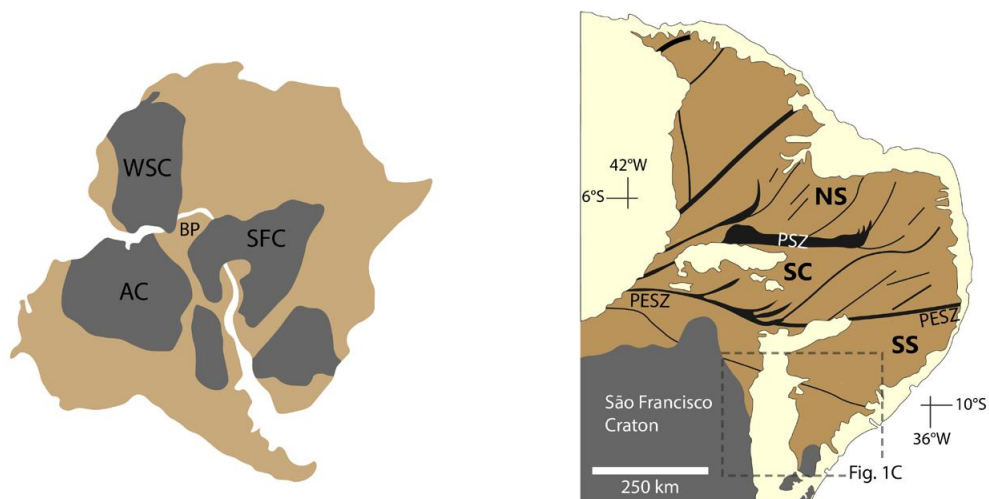
Figure 1: Geological context (Pereira et al., 20202). (A) Pre-drift reconstruction of South America-Africa showing the
530   location of Borborema Province (BP) and Amazonian (AC), West-Africa (WSC) and São Francisco-Congo cratons (SFC).
(B) Subdivision of Borborema Province in Northern (NS), Central (SC) and Southern (SS) subprovinces, limited by the
shear zones systems Patos (PSZ) and Pernambuco (PESZ), according to Van Schmus et al. (2008). (C) Simplified geological
map of the area outlined in (B) showing the tectonic compartmentation of the Sergipano Orogenic System according to
Davison and Santos (1989). The rectangle shows the location of the study area. MSZ: Macururé shear zone; BMJSZ: Belo
535   Monte-Jeremoabo shear zone; SMASZ: São Miguel do Aleixo shear zone; ISZ: Itaporanga shear zone.
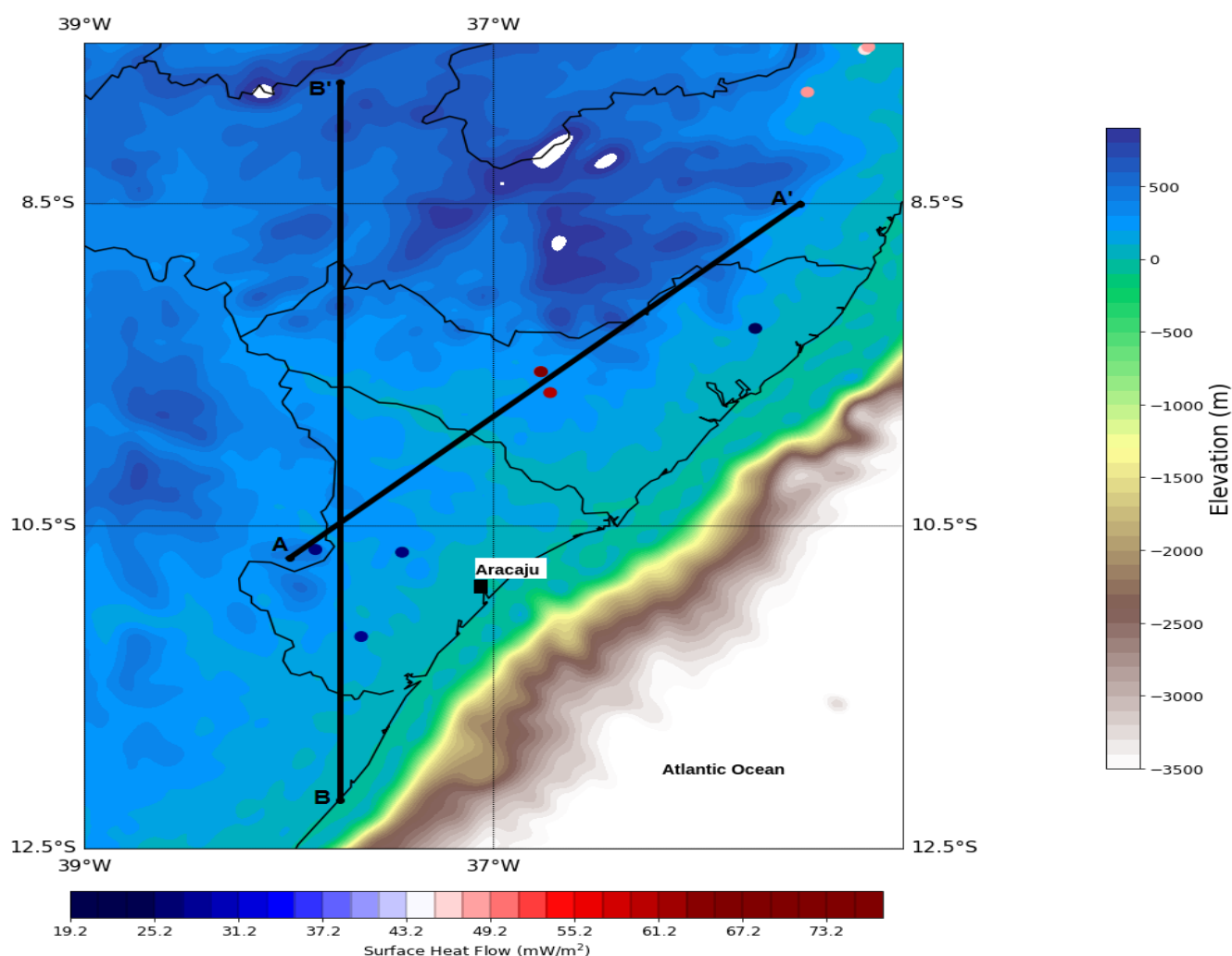
Figure 2: Elevation Database (m). The points are the surface heat flow.

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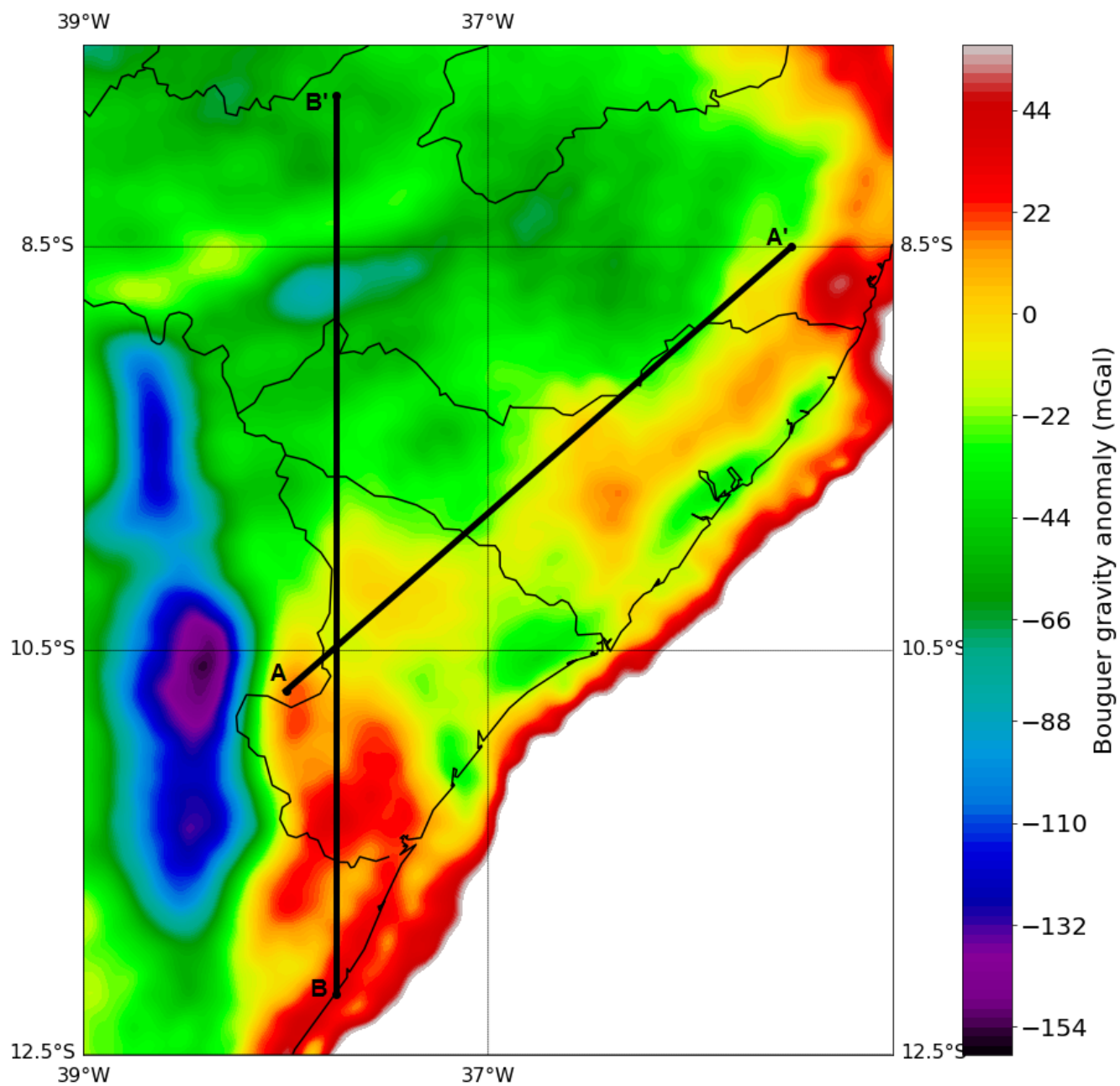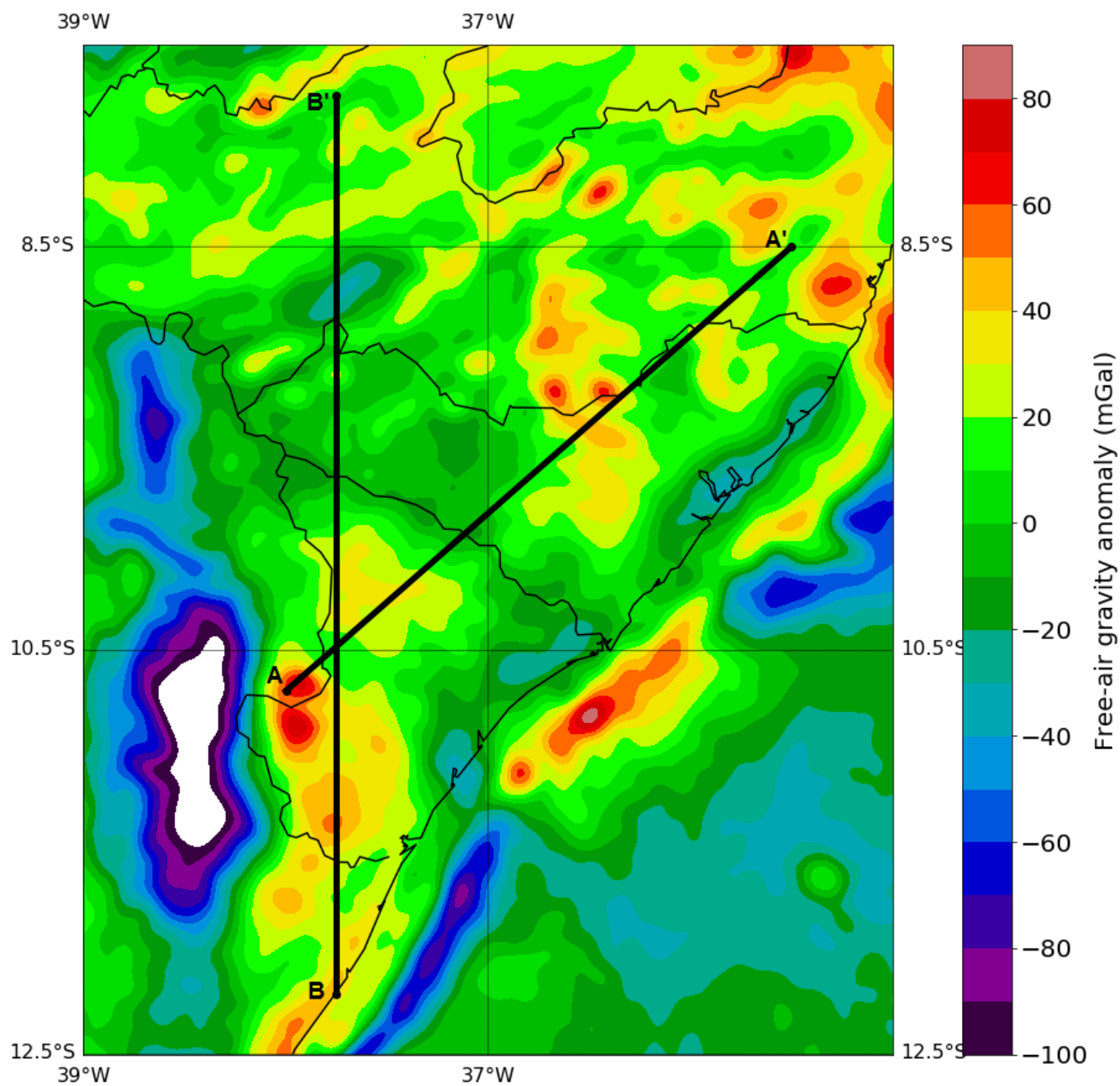
540   Figure 3(a)

Figure 3(b)
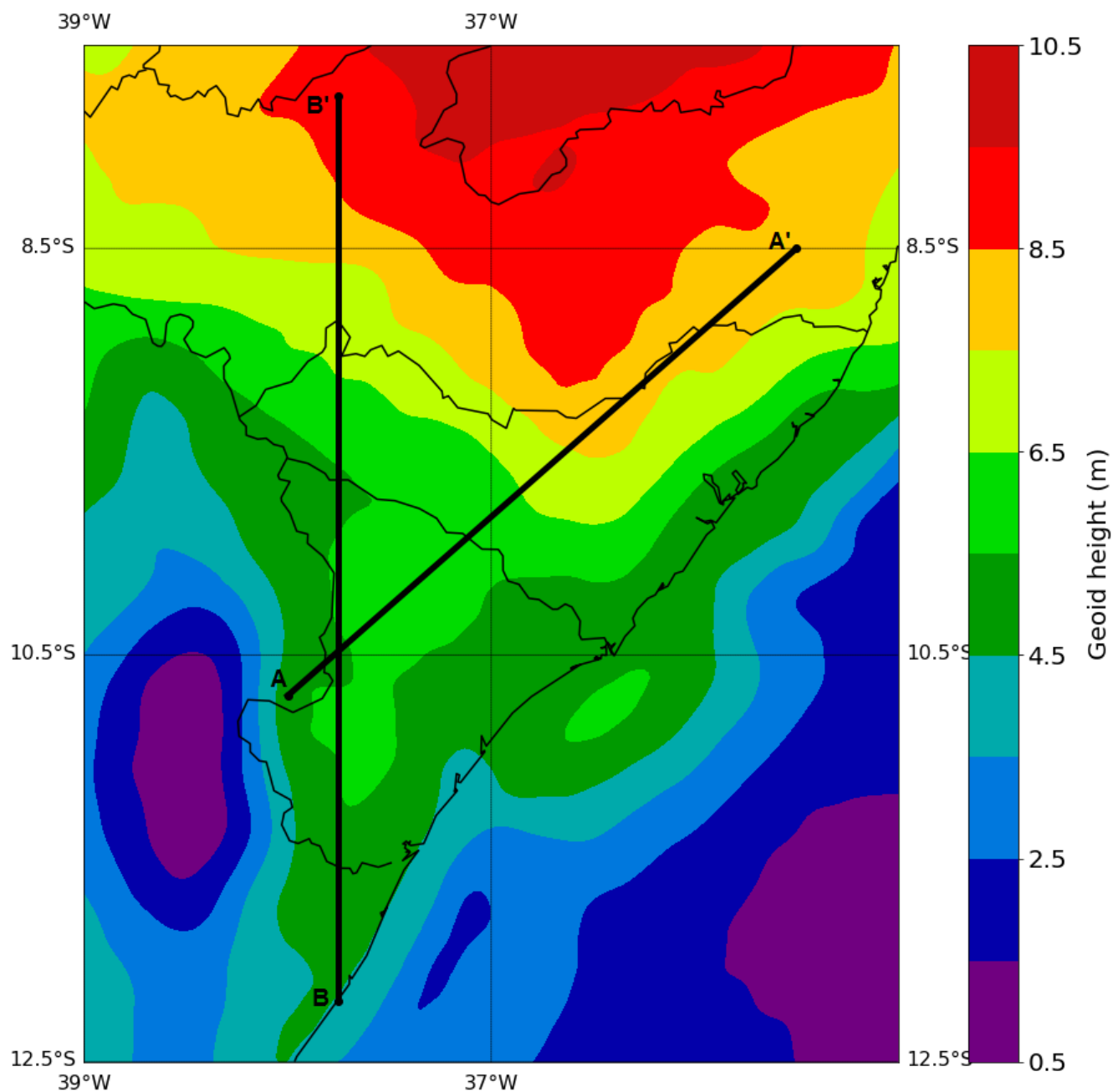
Figure3(c)

Figure 3: Geophysical Database: (a) Bouguer gravity anomaly (mGal), (b) Free-air gravity anomay (mGal), (c) Geoid anomaly (m).
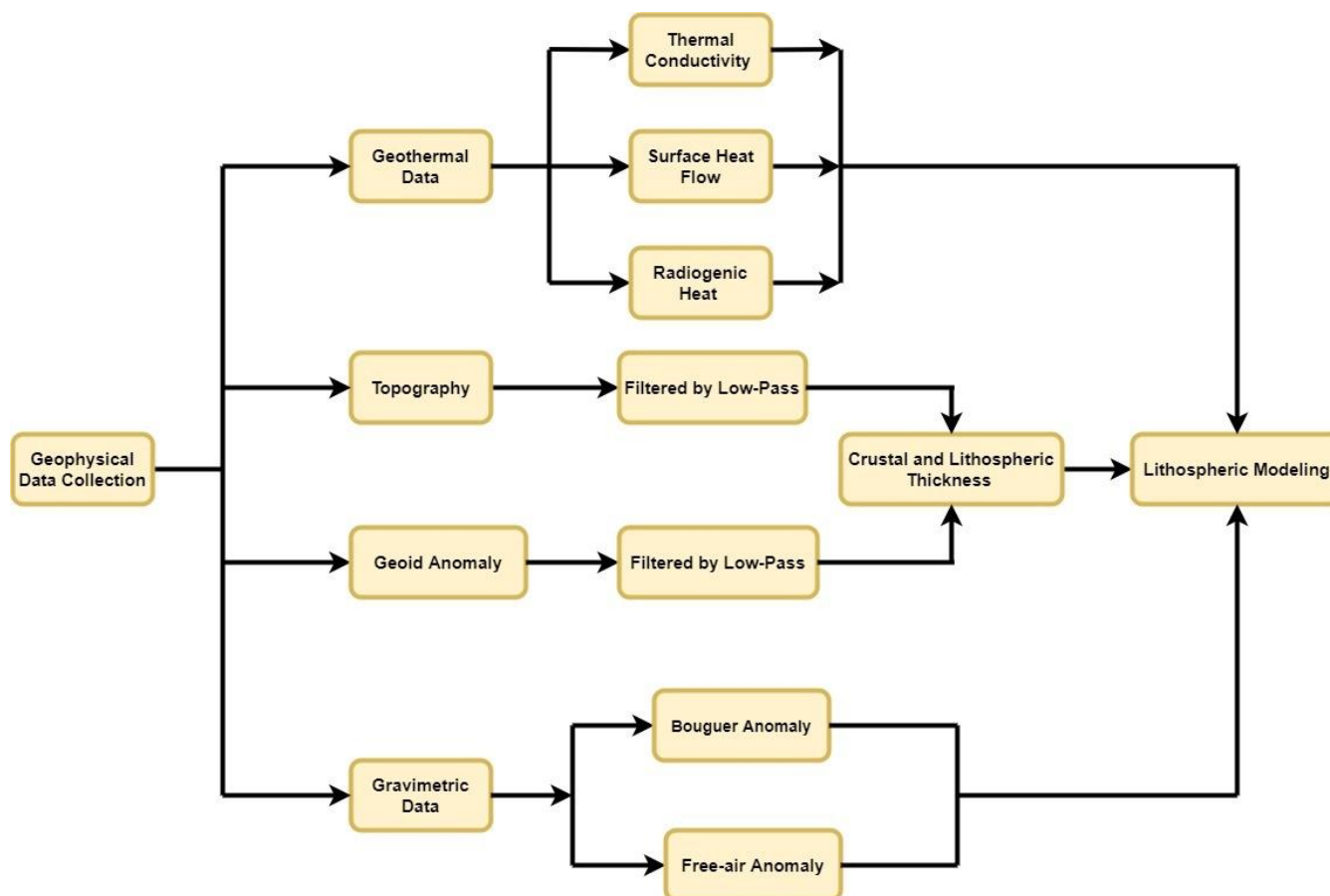
Figure 4: Description of the steps of the data processing up to lithosphere modelling (workflow).
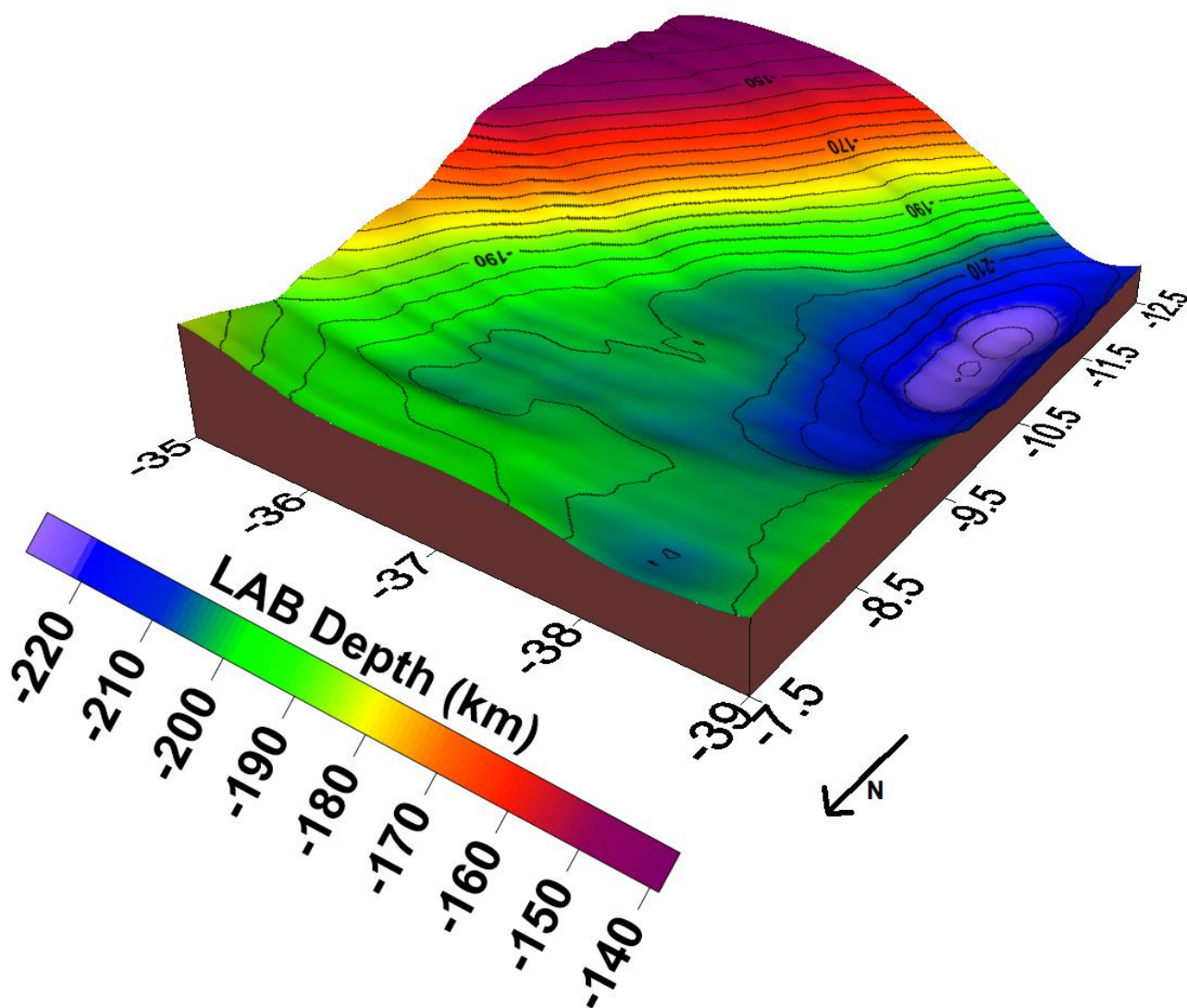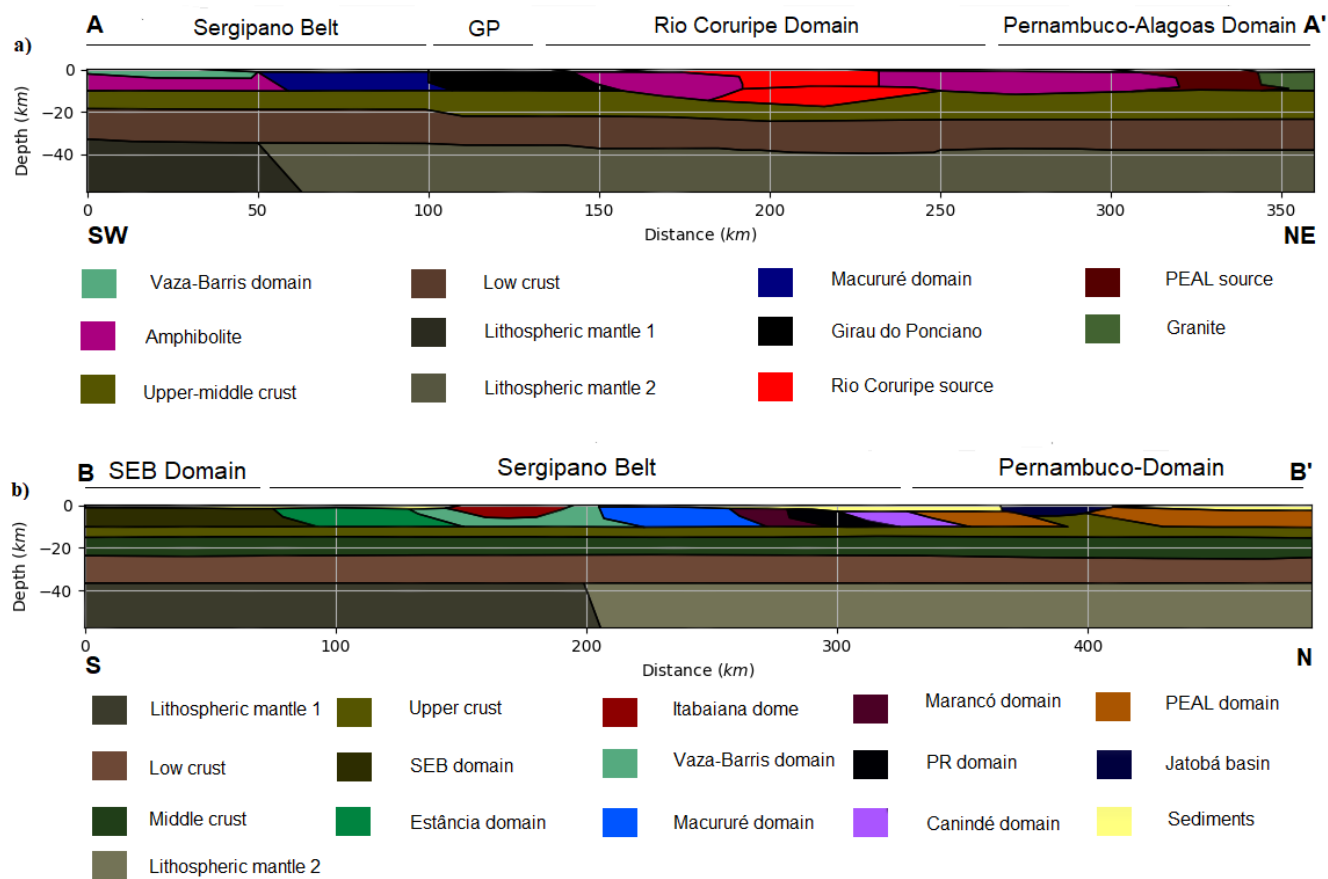
550

Figure 5(a)

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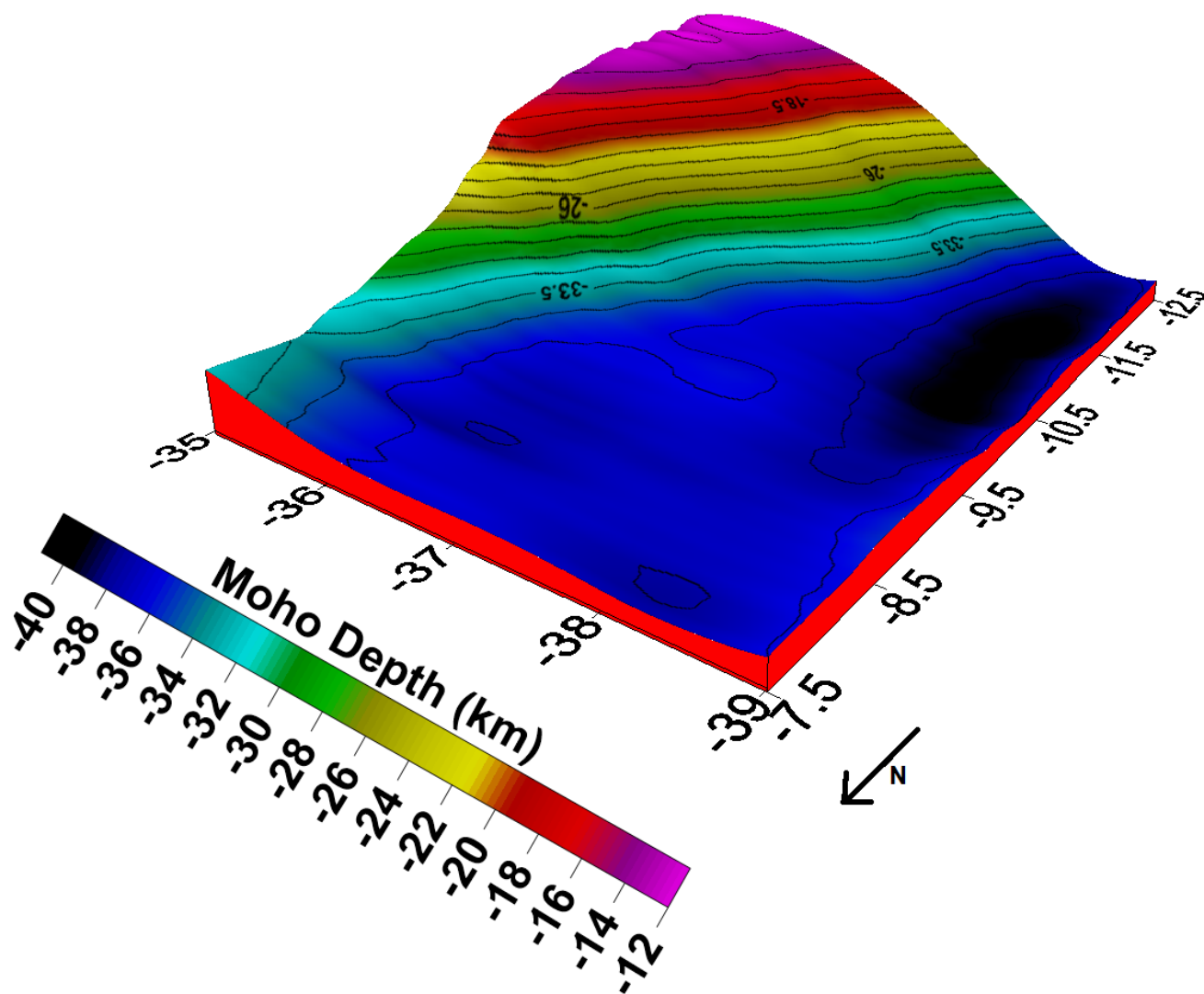
Figure 5 (b)

Figure 5: Results of Calculated Dephs: (a) Moho and (b) LAB.

555
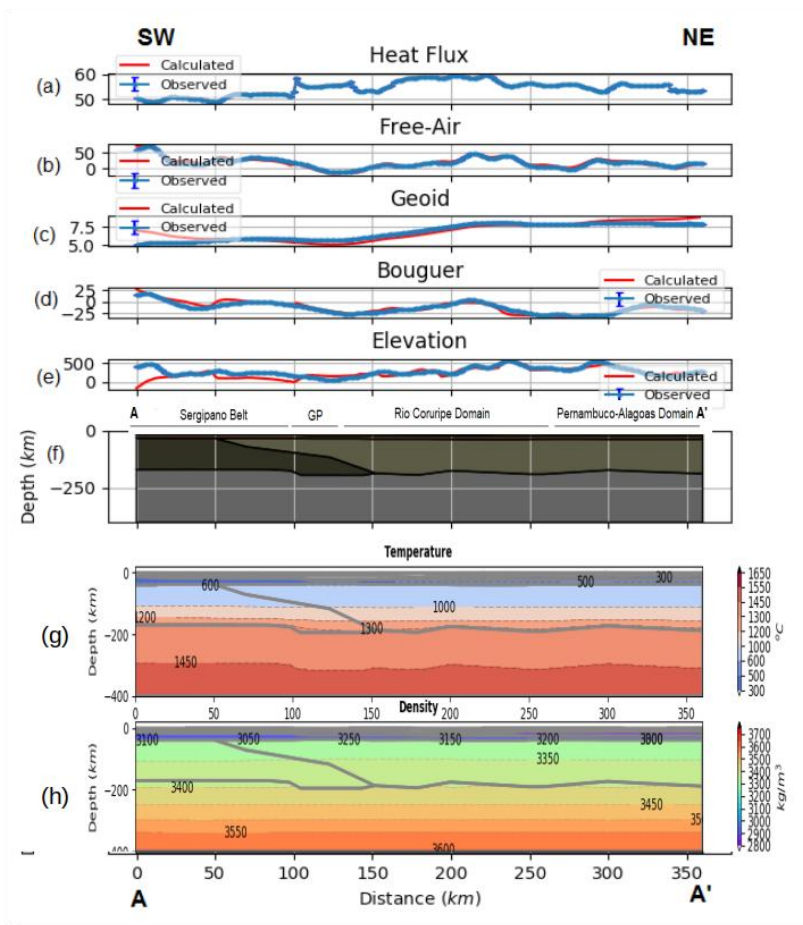
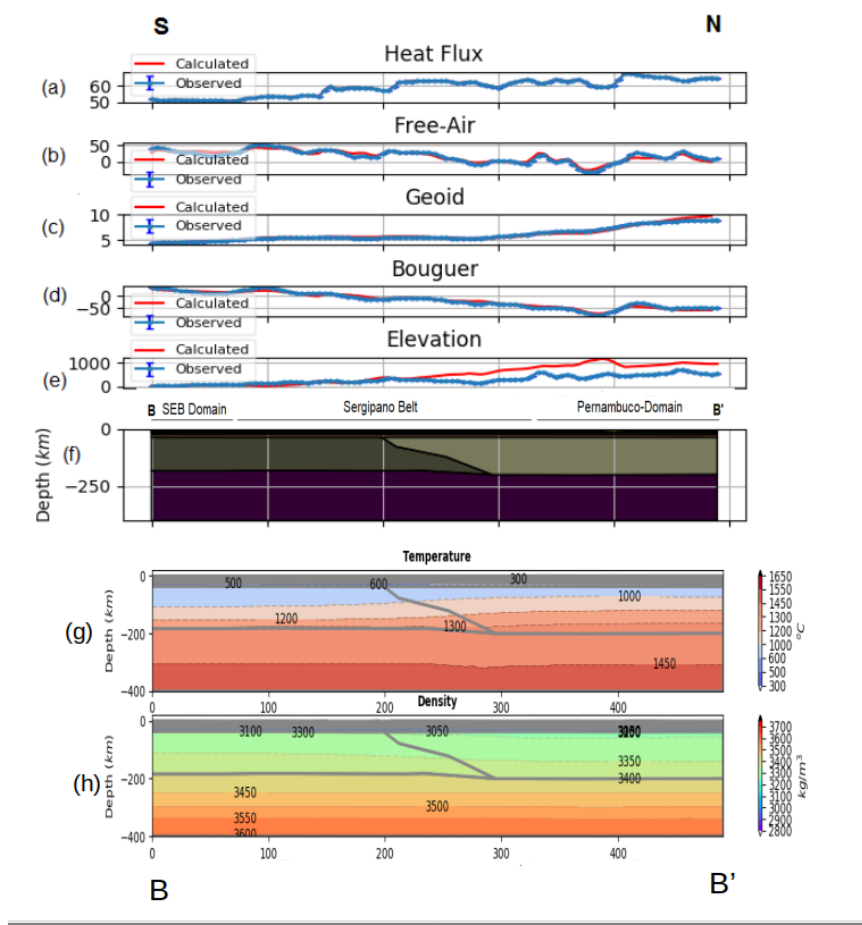**Figure 6**: Best fit of crustal models for transects A-A and B-B'.

Figure 7: Best fit of lithospheric model for the transects A-A. (a) Surface heat flow, (b) Geoid anomaly, (c) Bouguer anomaly, (d) Free-air anomaly, (e) Elevation, (f) Geometry of the profile, (g) Temperature distribution and (h)Density distribution. Red dots are measured values and Blue lines denote observed values
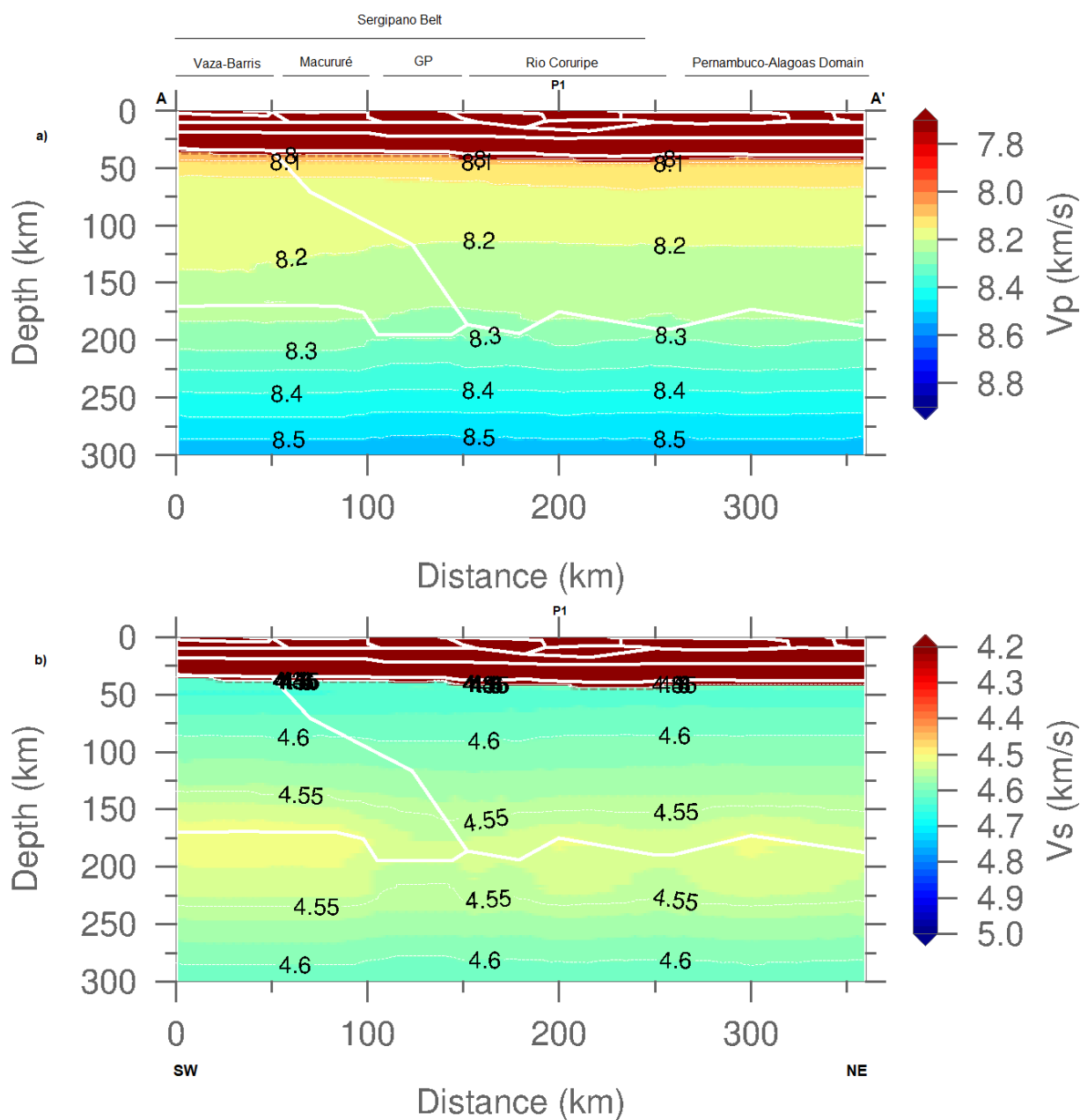
Figure 8: Best fit of lithospheric model for the transects B-B'. (a) Surface heat flow, (b) Geoid anomaly, (c) Bouguer anomaly, (d) Free-air anomaly, (e) Elevation, (f) geometry of the profile, (g) Temperature distribution and (h) Density distribution. Red dots are measured values and Blue lines denote observed values.

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Figure 9: Results of Transects A-A'. (a) *P*-wave and (b) *S*-wave mantle velocity distribution
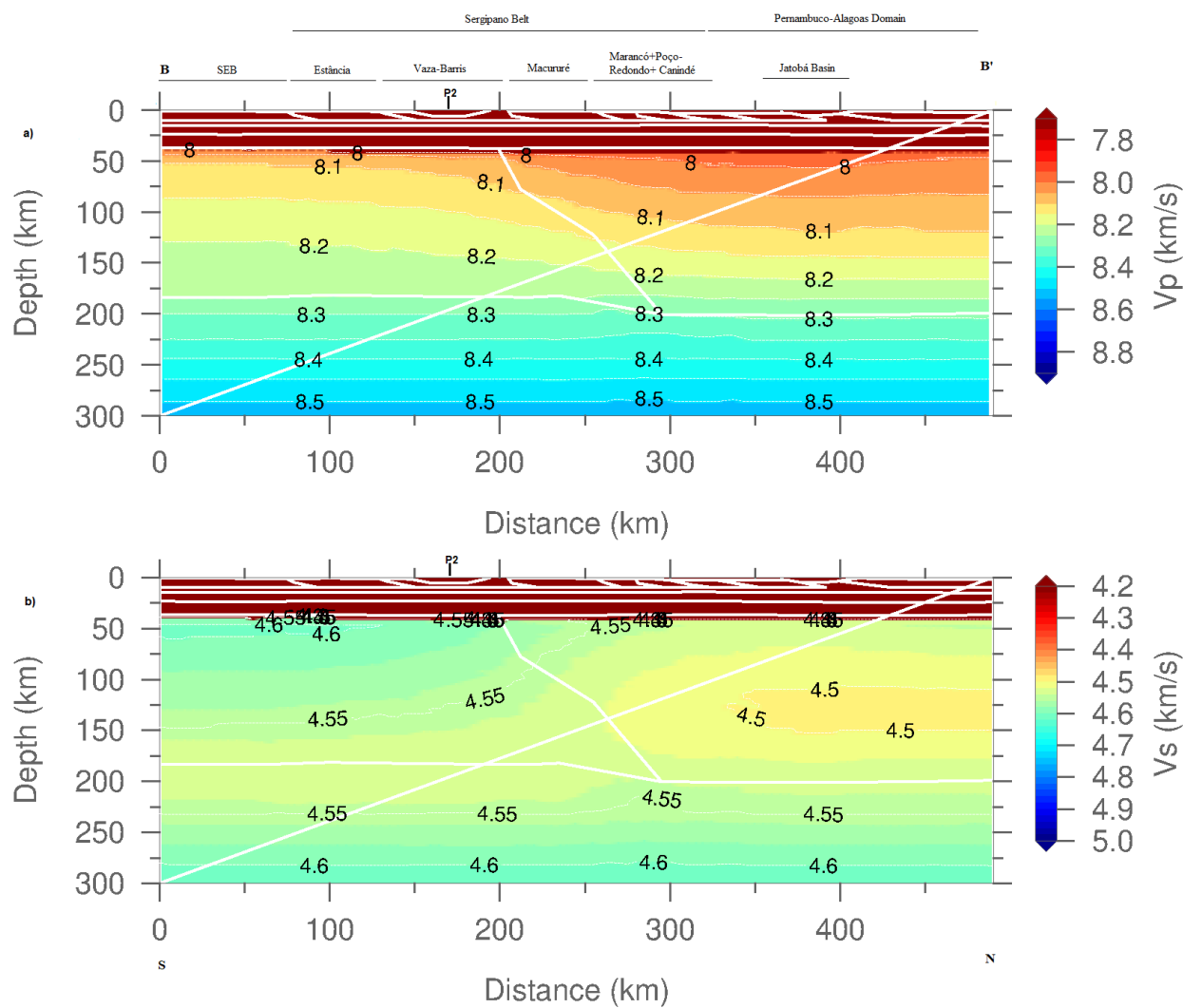
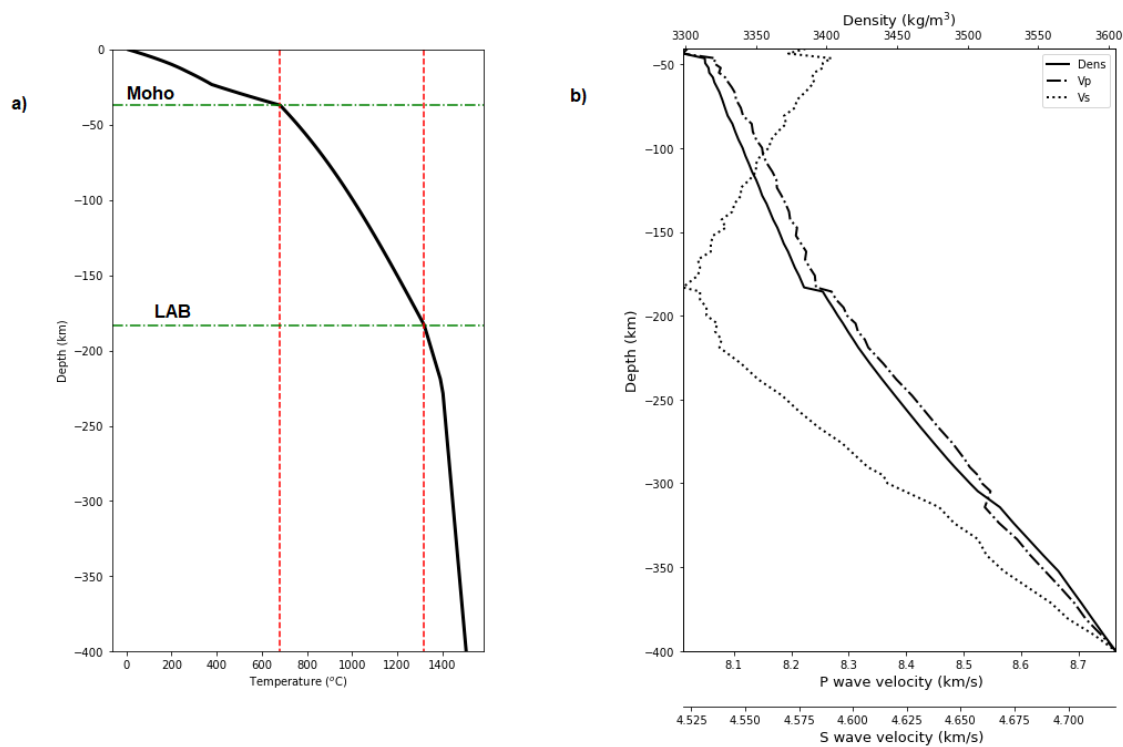**Figure 10:** Results of Transects B-B'. (a) *P*-wave and (b) S-wave mantle velocity distribution.

Figure 11: Geoterm (a) and density and seismic velocities waves (P and S) for the selected point P1.
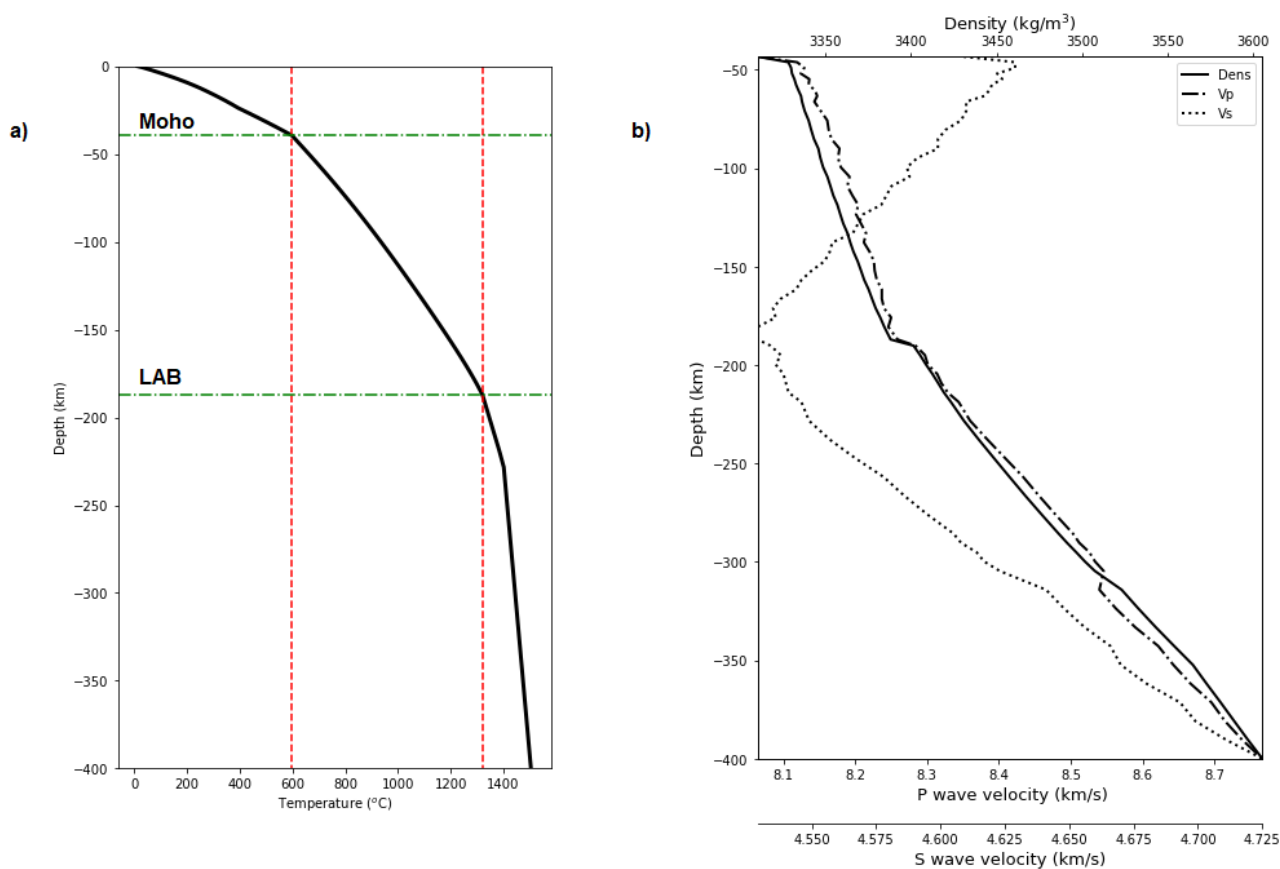
575

Figure 12: Geoterm (a) and density and seismic velocities waves (P and S) for the selected point P2