Lithospheric Features of the São Francisco Craton

2

Marcelo Assumpção, Paulo A. Azevedo, Marcelo P. Rocha, and Marcelo B. Bianchi

Abstract

Studying the thick lithosphere of cratons is important to help understand their formation and the mechanisms for their preservation. We present a synthesis of the information available for the deep structure in Eastern Brazil, from seismological and gravity data, to characterize the São Francisco Craton (SFC) and help better define its lateral boundaries at depth. Crustal thicknesses of the SFC, known mainly from receiver function studies, range from 38 to 42 km, except for a localized thickening (up to 44 km) in the northern part, and crustal thinning towards the Atlantic continental margin in Bahia state. Overall, the crust is slightly thicker near the geologically-defined surface boundaries (40–42 km) and slightly thinner in the center (38–40 km), which is consistent with generally low Bouguer anomalies and high topography to the East and to the West of the craton probably defining the suture zones during the Gondwana amalgamation. Modeling of gravity anomalies with some seismic constraints indicates a relatively low-density lithospheric mantle for the SFC, despite higher Pn velocity, which is consistent with a Fe-depleted, buoyant lithosphere, which helps preserve the cratons's root. Surface-wave continental-scale tomography suggested the thickest lithosphere, around 200 km, to be in the Archean southern part of the SFC, consistent with regional P- and S-wave tomography. Both the surface-wave and the body-wave tomographies show high upper mantle velocities beneath the Brasilia fold belt, next to the SFC's surface limits, which is interpreted as a continuation at depth of the craton's lithosphere, beneath the low-grade external metamorphic domain of the Brasilia fold belt. Analysis of the SFC seismicity shows that most earthquakes now occur on shallow (<2 km) normal faults formed during the formation of the Brasiliano continental margin, now reactivated under the present E–W compressional stresses.

Keywords

Tomography • Receiver functions • Cratonic lithosphere • Gravity anomaly

M. Assumpção (✉) · M.B. Bianchi
Geophysics Department, Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo, Rua Do Matão 1226, São Paulo, SP 05508-090, Brazil
e-mail: marcelo.assumpcao@iag.usp.br

P.A. Azevedo · M.P. Rocha
Seismologial Observatory, Institute of Geosciences, University of Brasília, Brasilia, DF 70910-000, Brazil

M. Heilbron et al. (eds.), *São Francisco Craton, Eastern Brazil*, Regional Geology Reviews, DOI 10.1007/978-3-319-01715-0_2

2.1 Introduction

Studying the thick lithosphere of cratons is important to help understand their formation and the mechanisms for their preservation. The study of the deep crustal structure, which resulted from a long evolution of the lithosphere, is the key to understand the geological processes that shaped the lithosphere (e.g., Artemieva and Meissner 2012). Early compilations of results from deep seismic refraction lines worldwide (Durrheim and Mooney 1991, 1994) suggested that Archean cratons, when compared with Proterozoic provinces, would have thinner and slightly more felsic crust, coupled with a lower density and Fe-depleted upper mantle (Durrheim and Mooney 1994; Hawkesworth et al. 1990; Artemieva 2009). However, more recent global compilations seem to indicate a large variability in crustal properties of Archean provinces (Artemieva 2009; Artemieva and Meissner 2012), with apparently no significant systematic difference from Proterozoic crust.

Here we summarize and discuss the available information regarding crustal thickness (mainly from receiver function studies) and upper mantle seismic velocities from regional tomography studies to characterize the lithosphere of the São Francisco craton and its surrounding belts.

2.2 Crustal Thickness

The first attempt to study the deep crustal structure in the São Francisco craton (SFC) was the recording of an unreversed seismic profile using quarry blasts from Itabira mine (Quadrilátero Ferrífero mining district, see Alkmim and Teixeira, this book) in the early 1970s by Giese and Schutte (1975). No refraction from the upper mantle (Pn phase) was recorded, but the reflections from the Moho indicated a normal crustal thickness of about 40 km. Other unreversed seismic refraction studies in the 1980s, using quarry blasts recorded near the northern limit of the SFC (e.g., Knize et al. 1984), indicated crustal thicknesses greater than 40–42 km (Fig. 2.1).

To compensate for the lack of other active refraction lines, passive seismological methods have been used to estimate crustal thicknesses in SE and Central Brazil using teleseismic receiver functions (RF). Initial studies of RF in SE Brazil (Assumpção et al. 2002) indicated a generally thinner crust in the southern part of the SFC in comparison with the Paraná Basin of southern Brazil (Fig. 2.1). Figure 2.1 shows the crustal thickness map obtained from a compilation by Assumpção et al. (2013a, b), with some additional points from RF analyses of recently deployed stations of the Brazilian Seismographic Network. As shown on Fig. 2.1, the SFC crust exhibits an average thickness of 40 km, a value that approaches 41 km, the average thickness estimated for the Brazilian portion of the South American platform (Assumpção et al. 2013a, b). Thicker crust (exceeding 45 km) occurs in the northern part of the Paraná Basin. A thinner crust is observed in the central part of the Tocantins Province, especially along the Goiás Magmatic Arc, where it is accompanied by high gravity anomalies (Fig. 2.1).

The sparse distribution of data points prevents a more detailed discussion of the observed patterns, but a domain of larger thicknesses can be recognized near the surface limits of the SFC, more or less following the higher topography (Fig. 2.1a) and lower Bouguer anomaly (Fig. 2.2a).

The first detailed study of seismic structure in the SFC was obtained by a 530 km long, E–W deep seismic refraction line, shot in 1998 across the Tocantins Province and the western part of the craton, at 13°–14°S (Berrocal et al. 2004; Soares et al. 2006). The model obtained by Soares et al. (2006) has four crustal layers in the western part of the SFC with Moho depth at about 42 km. Three suture zones (separating blocks with different structures) were identified: one at Minaçu (between the Goiás massif and the external metamorphic zone of the Brasilia belt), one near Cavalcante (in the Brasilia belt external zone) (see Fuck et al. this book), and another near Posse at the edge of the SFC surface limit. All these "collision zones" were modeled as dipping to the west. Another interesting finding was that the upper mantle velocity (Pn) was high (8.2–8.3 km/s) beneath the SFC as well as beneath the external zone, compared to the 8.0–8.1 km/s beneath the Goiás Massif and Magmatic Arc (Berrocal et al. 2004; Soares et al. 2006). All these characteristics led Soares et al. to place the western limit of the craton's deep crust, i.e., the edge of the São Francisco plate, near the boundary between the Goiás massif and the Brasilia belt (near coordinate 230 km in the profile of Fig. 2.2b).

2.3 Gravity Modeling

Modeling of crustal layers from interpretation of deep seismic refraction lines can be non-unique because of different interpretations of weak arrivals. For example, the transition between a thick crust beneath the Araguaia belt to a thin crust beneath the Brasilia belt magmatic arc had been placed between shot points 2 and 3 (coordinate 90 km, as in Fig. 2.2b). Based on gravity modeling and a re-interpretation of Moho reflected phases, Ventura et al. (2011) placed this transition ~40 km to the east, beneath shot point 3. The Moho was modeled about 5 km deeper (~50 km instead of 45 km) based on receiver function analysis at a station near Porangatu. Towards the east, (beneath shot point 7, Fig. 2.2b), the differences in crustal thicknesses are smaller, less than 4 km. Ventura et al. (2011) did not interpret the eastern section of the seismic experiment, so here we used the model of Soares et al. (2006), which covers part of the SFC, as a basis to extrapolate the crustal structure beneath the central and eastern part of the craton.

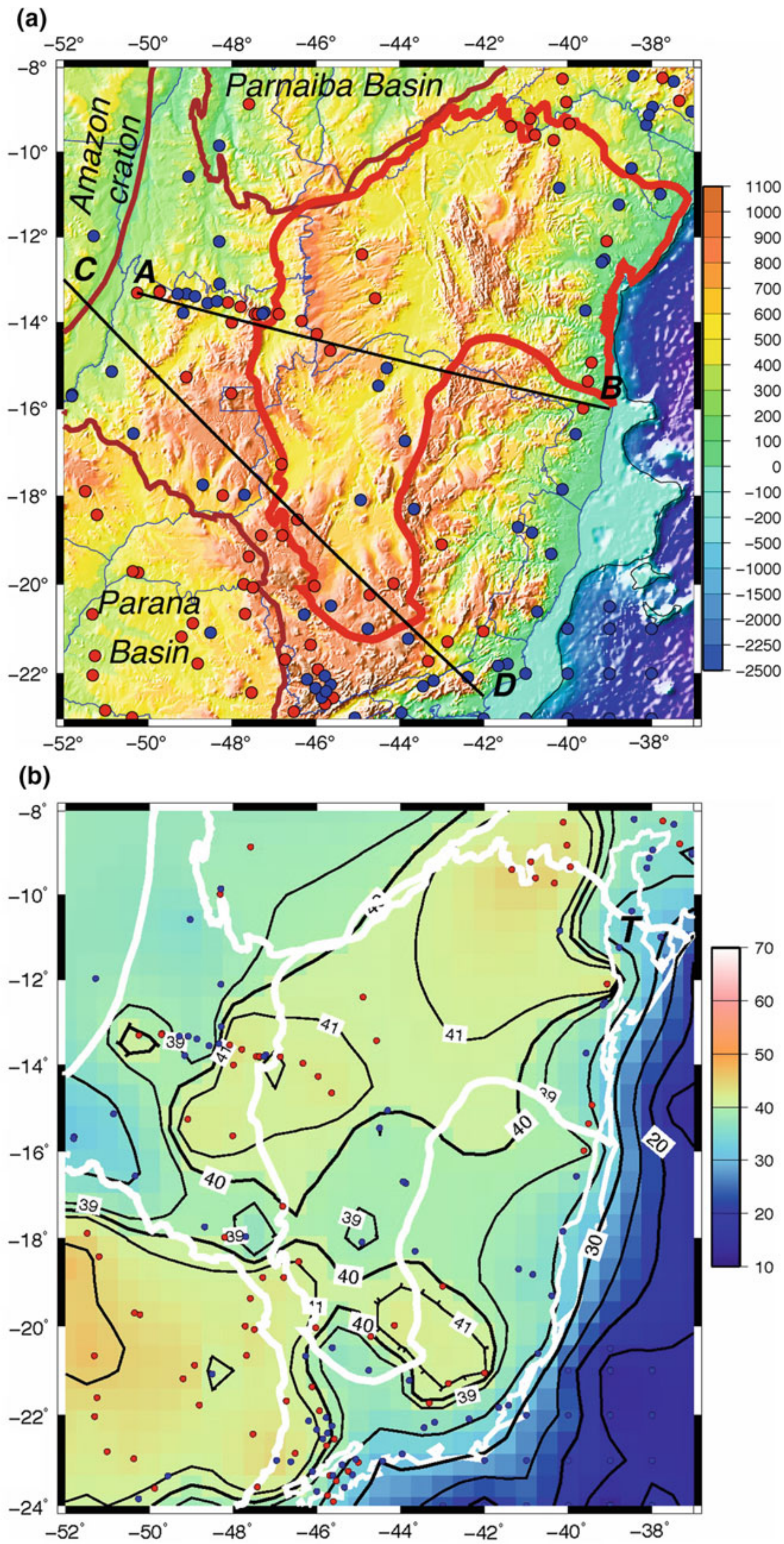

Fig. 2.1 **a** Topography in SE Brazil. *Red/Blue* dots denote crustal thickness more/less than 40 km. Profiles AB and CD refer to Figs. 2.2c and 2.3c, respectively. **b** Contours of crustal thickness from seismic data only. *Red and Blue dots* in the continent are locations where crustal thickness (including topography) were estimated from receiver functions at seismographic stations or from active experiments such as the deep refraction line across the western border of the São Francisco Craton (roughly along 13°–14°S). The data comes from the compilation of Assumpção et al. (2013a, b) complemented with some additional receiver function analyses. "*T*" indicates the Recôncavo–Tucano Basin

We extended the crustal seismic model of Soares et al. (2006) across the SFC to estimate possible variations of crustal thickness as well as to see if the gravity data indicated any changes in upper mantle density. We used the GOCE satellite Bouguer anomalies, which are smoothed enough for the modeling of major regional variations. The P-wave velocities of the seismic model were converted to densities using the linear relation of Christensen and Mooney (1995). The upper mantle density was fixed throughout the profile at 3360 kg/m^3 (corresponding to an average Pn velocity between the 8.05 and 8.23 km/s in the seismic model). The numbers shown in the crustal section of Fig. 2.2b are the density contrasts of the crustal layers relative to the uniform-density upper mantle.

The few Moho depths available in the central part of the profile, obtained from RF studies, indicate an average value of 40 km, slightly less than the 42 km at the easternmost part of Soares et al. (2006) model, but probably within the uncertainty of each method. The low Bouguer anomaly along the eastern limit of the SFC (Fig. 2.2a) could be modeled by a crustal thickening (perhaps reaching 44 km). The high topography along the eastern side of the SFC is consistent with a major boundary, whose limits could be placed around coordinate 900 km in the profile of Fig. 2.2b. Clearly, the few seismic constraints available in Eastern Brazil do not allow a more detailed modeling of the SFC, but the main features observed at the western limit (crustal thickening beneath the low Bouguer and high topography) are also present in the eastern limit. The extension of the crustal limit of the SFC, at depth, beneath the Brasilia belt internal zone, seems to be accompanied by a similar extension in the East beneath part of the Araçuaí belt, thereby placing the boundaries of the São Francisco plate (see Heilbron et al. this book).

2.4 Lithospheric Properties

2.4.1 Surface-Wave Tomography

Seismic tomography is normally used to estimate lateral variations of upper mantle properties. Although direct determination of the lithosphere/asthenosphere boundary, with good resolution, is not usually possible in surface-wave studies, the lateral variations of S-wave velocities help map relative variations of lithospheric thicknesses. Feng et al. (2007) carried out a surface-wave tomography of South America with a method combining both waveform fitting as well as group-velocity measurements. An updated model with additional dispersion data was presented by Assumpção et al. (2013b) and shown on Fig. 2.3. The maximum period of the surface-waves was 150 s, which limits the resolution of the surface-wave tomography down to about 250 km depth. In addition, only features larger than about ~300 km or so can be mapped in such continental-scale surface-wave tomography. At 100 km depth (Fig. 2.3a), the regional pattern shows two main areas with high S-wave velocities: one beneath the southern part of the SFC (where Archean rocks are exposed) and another block beneath the northern part of the Paraná basin, usually attributed to a cratonic nucleus beneath the basin (Cordani et al. 1984; Julià et al. 2008).

At 150 km depth (Fig. 2.3b), the region of high S-wave velocity is concentrated in the southern half of the SFC, which indicates the region of thickest lithosphere. Studies of S-wave receiver functions at station BDFB (Brasília) by Heit (2007) indicated the lithosphere/asthenosphere boundary at about 160 km, shown in the map and profile of Fig. 2.3b. The lithosphere of the SFC is thinner in eastern Bahia, which could be an effect of lithospheric thinning during the South Atlantic opening in the Lower Cretaceous. However, resolution of the surface-wave tomography also decreases considerably towards the coast, where fewer ray paths are observed (Feng et al. 2007; Assumpção et al. 2013b). A thicker lithosphere around the craton's surface limits beneath parts of the Brasilia and Araçuaí belts is also apparent. However, part of this "extended" lithosphere could be an artificial effect due to smoothness constraints used in the tomography inversion. A global map of lithospheric thickness, based on long-period (>50 s) surface waves with ~250 km lateral resolution (McKenzie et al. 2015) also indicated a lithosphere about 200 km thick in the central part of the SFC, and a thinning towards the coast and the Recôncavo–Tucano basin in northern SFC (Fig. 2.1b), similar to the image of Fig. 2.3d.

The limit of the SFC high-velocity region towards the Amazon craton (across the so-called Transbrasiliano Lineament, see Cordani et al. this book) is not well resolved in the surface-wave tomography, but is a relatively sharp transition seen in the P-wave tomography, as described in the next section.

2.4.2 P-Wave Tomography

Teleseismic P-wave tomography (using periods of around 1 s) has potentially better lateral resolution at depths below 100 km, as shown on Fig. 2.4. Previous P-wave tomography in SE Brazil (Schimmel et al. 2003; Assumpção et al. 2004; Rocha et al. 2011) had all shown generally higher velocities beneath the SFC and lower velocities beneath the Cretaceous igneous provinces (Iporá, Alto Paranaíba, and Serra do Mar) emplaced along the orogenic belts that fringe the craton to the south. High velocities have also been observed beneath the northern part of the Paraná basin, not in a single block, but in separate patches.

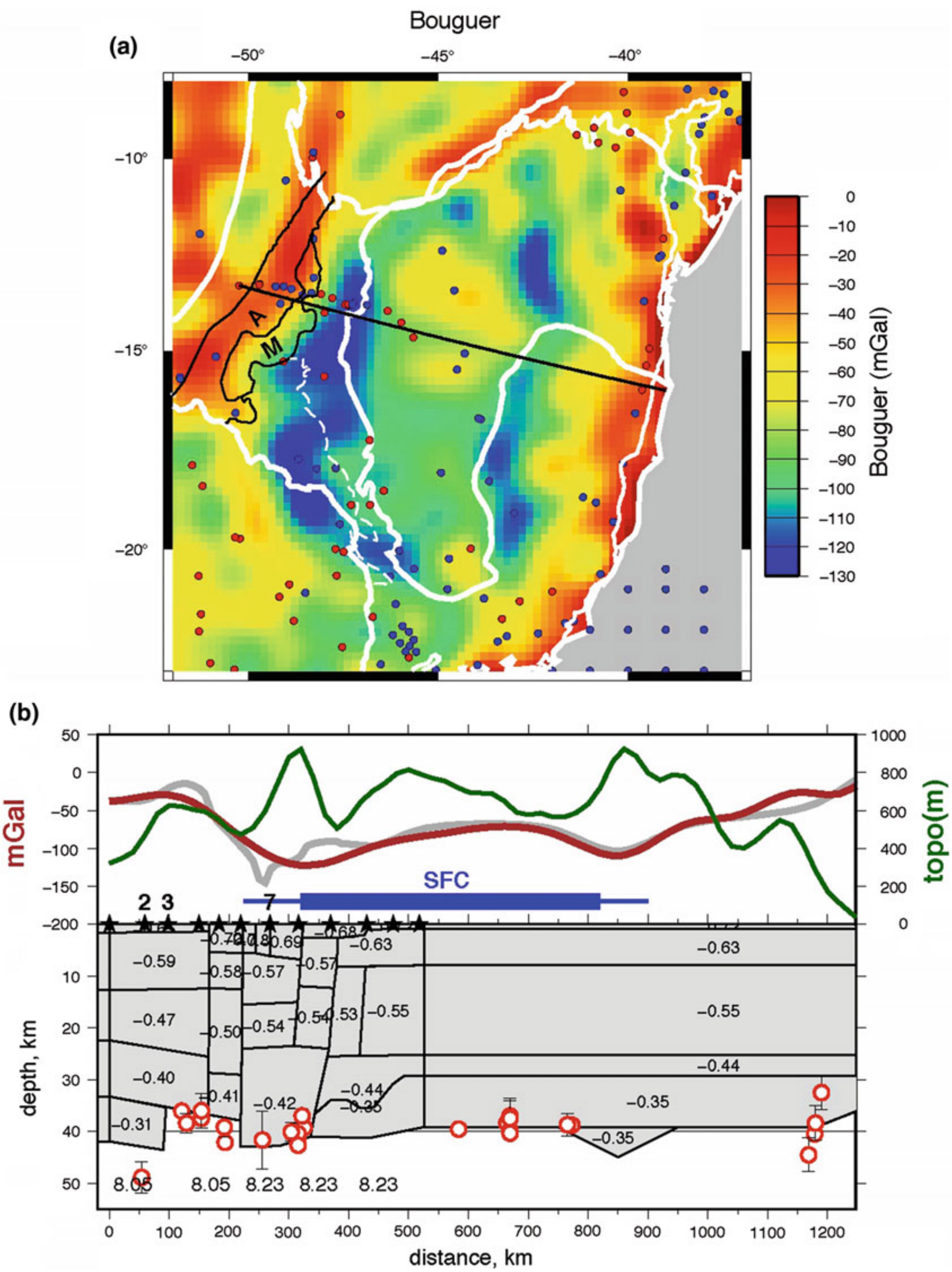

Fig. 2.2 Crustal thickness model across the central part of the SFC. **a** Bouguer map (GOCE) showing low gravity anomalies along the western and eastern borders of the SFC. *Red/blue* dots are Moho depths deeper/shallower than 40 km. *White dashed line* west of the SFC is the separation between external and internal metamorphic zones of the Brasilia Belt. *Black solid lines* indicate limits of the Magmatic Arc ("A") and the Goiás Massif ("M"). **b** Crustal model along the WNW-ESE profile shown in **a**. The *lines* are topography (*green*), observed gravity (*brown*) calculated gravity (*gray*). The *bottom* section from 0 to 530 km is the seismic model of Soares et al. (2006) obtained from 12 explosions (*stars on the left side* of the profile), some of which are numbered as referred to in the text. *Numbers* in the crustal section (*gray area*) are density constrasts relative to a constant density of the upper mantle taken at 3360 kg/m^3. *Numbers* below the crust are the P-wave velocities from Soares et al. (2006). The seismic refraction model was extrapolated across the whole profile—only the Moho depth was changed to fit the low Bouguer anomaly to the east of the craton. *Open red circles* are Moho data points from receiver function studies (as in the map) up to ±200 km from the profile line. The *blue line* indicates the limits of the SFC: *thick line* for the surface limit, and *thin line* for the extrapolated extension at depth

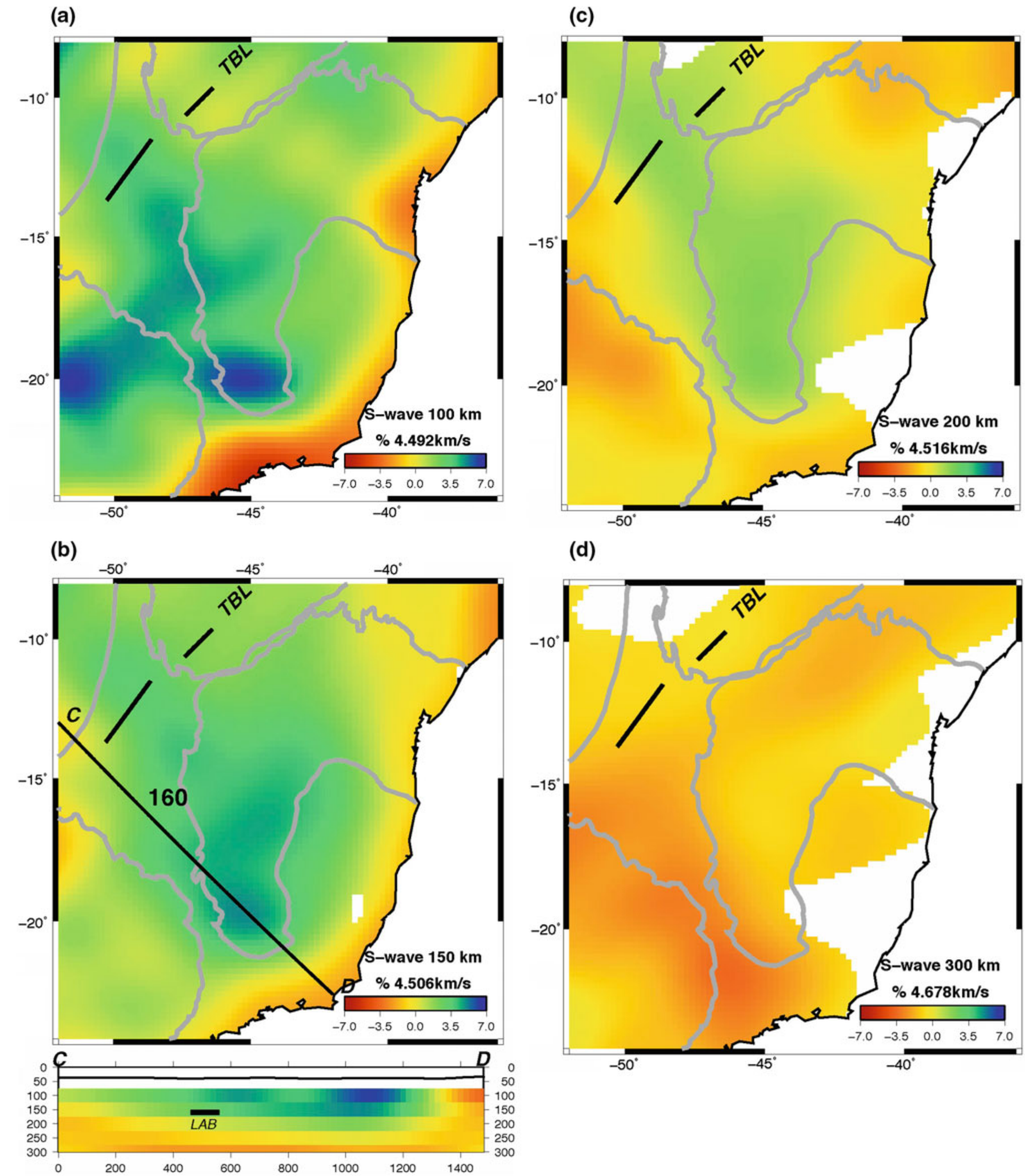

Fig. 2.3 S-wave anomalies from surface-wave tomography using the joint inversion method (waveform + group dispersion) of Feng et al. (2007) presented by Assumpção et al. (2013b) with additional dispersion data. **a**–**d** Anomalies at depths of 100, 150, 200 and 300 km, respectively. Resolution is poor below 250 km depth. For the 150 km depth (**c**), a vertical NW-SE profile is also shown. Note higher S-wave velocities in the southern part of the SFC, and lower velocities in the northern part, indicating thicker lithosphere in the central and southern parts of the SF craton. The high velocities outside the surface limits of the SFC, especially at 150 km depth, indicate possible extension of the craton beneath the low-grade metamorphic margins of the Brasilia and Araçuaí belts. In the profile "*C-D*" the horizontal bar *LAB* denotes the Lithosphere/Asthenosphere boundary at 160 km depth (Heit 2007)

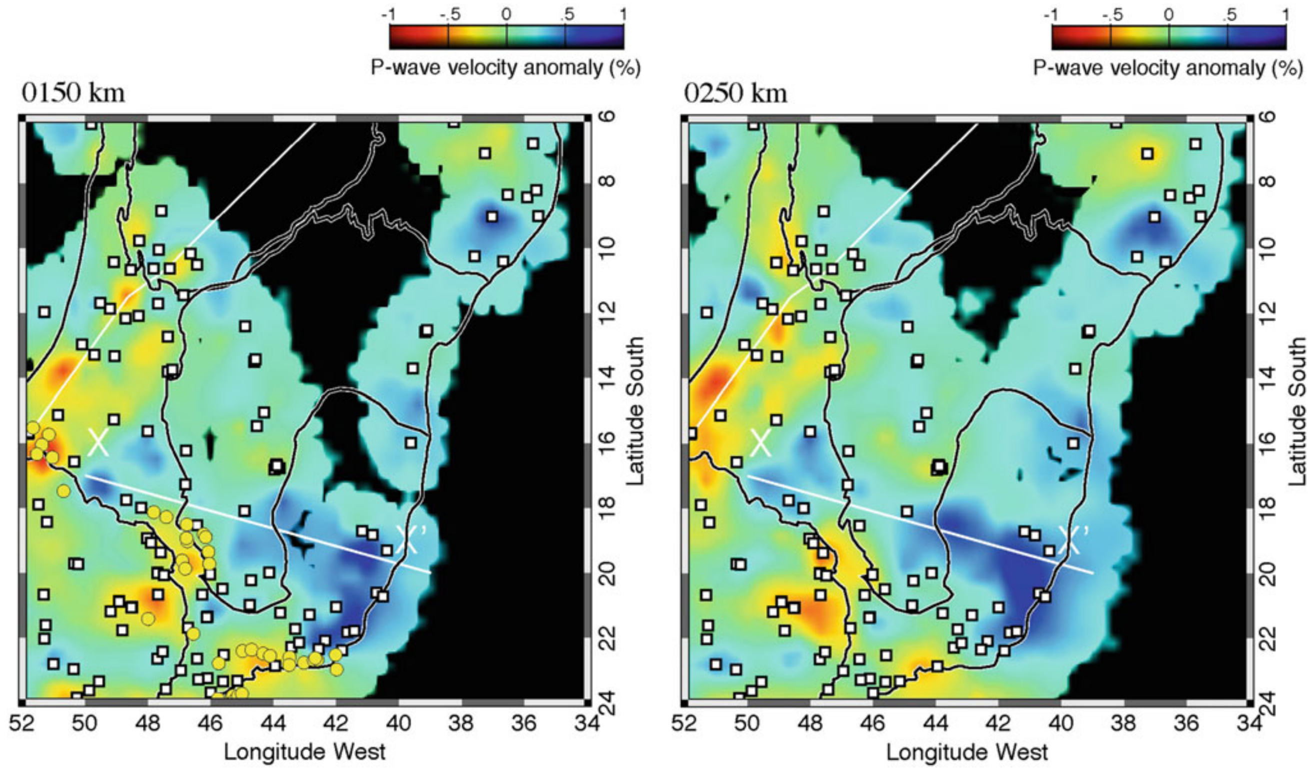

Fig. 2.4 P-wave anomaly at 150 km (*left*) and 250 km (*right*). *White squares* are seismic stations used in the tomography. *Yellow circles* are Cretaceous pipes of the Iporá, Alto Paranaíba (APIP) and Serra do Mar igneous provinces

Here we show an updated P-wave tomography inversion adding more data from the Tocantins Province (Azevedo et al. 2015), as well as from recently deployed stations of the Brazilian Seismographic Network in SE Brazil (Fig. 2.4). The resolution varies considerably because of highly non-even distribution of stations and ray-paths. Where station density is higher, such as in the southern part of the SFC, high velocities can be seen in the southern extreme of the SFC as well as in the Brasilia belt, generally consistent with the larger-scale surface-wave tomography. The Late Cretaceous alkaline intrusions of the Alto Paranaíba Igneous Province (APIP) (Fig. 2.4) correlate with low upper mantle P-wave velocity—consistent with the SFC being "eroded" by metasomatism and losing part of its deep root (Artemieva 2009).

The eastern limit of the high-velocity lithosphere is not well resolved because of few seismic stations in the Araçuaí belt. However, high velocities are suggested all along the coast from Rio de Janeiro northwards. The SFC northern boundary is not resolved with the few stations presently available. The type of tomography method employed here, using relative arrival times, is more suited to map lateral variations in the upper mantle but does not provide good absolute constraints on depths to the bottom of the lithosphere (e.g., Schimmel et al. 2003; Rocha et al. 2011). This is seen in the profile of Fig. 2.5.

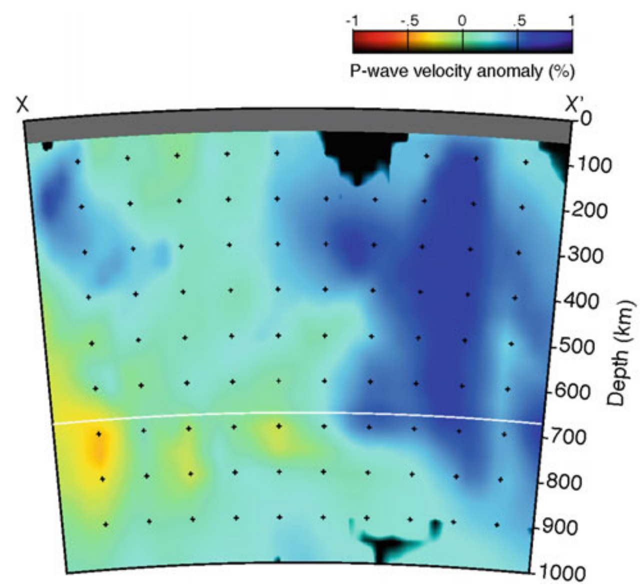

Fig. 2.5 XX′ profile suggesting ~200–300 km lithospheric depth for the Brasilia belt, and maybe 300–400 km for the southern part of the SFC. Depth resolution is very poor in this type of tomography. High velocities beneath the Ribeira belt are poorly resolved because of few stations

The high velocities beneath the Ribeira belt do not seem to be consistent with the surface-wave tomography results. However, the P-wave tomography has poor resolution near the coast north of 22°S due to the few available stations.

2.5 Seismicity and Stresses

Although cratonic areas in Brazil tend to be on average relatively less seismic, when compared to Neoproterozoic Brasiliano belts (Assumpção et al. 2014; Agurto-Detzel et al. 2015a), the southern part of the São Francisco craton has significant seismicity with magnitudes up to about 5 mb (Chimpliganond et al. 2010; Assumpção et al. 2014), as seen on Fig. 2.6a. An interesting feature is that seismicity is concentrated near the central and southern part of the SFC, where the lithosphere is thicker. Although intraplate seismicity occurs at shallow depths in the brittle upper crust, it results from stress concentration that can be caused by deeper structures, especially lateral variations of crustal and lithospheric thicknesses. An analysis of worldwide moderate to large intraplate earthquakes (magnitudes larger than 5) by Mooney et al. (2012) indicated a trend of seismicity to occur near craton edges around cratonic keels. Some evidence of similar features in the Amazon craton was suggested by Assumpção et al. (2014) and can be seen in Fig. 2.6a with epicenters roughly around the tomographic keel in the southern part of the SFC.

Intraplate stresses in Eastern Brazil are not uniform. The southern part of the SFC is characterized by E–W compressional and N–S tensional stresses (Assumpção, 1998; Assumpção et al. 2014). Stresses change in the central part of the craton towards E–W compression (Agurto-Detzel et al. 2015b). In the Tocantins fold belt province, stresses are also compressional but the orientation of the major compressional axis rotates towards SE–NW, as seen from inversion of focal mechanisms (Carvalho et al. 2016) as well as in situ measurements of hydraulic fracturing (Caproni and Armelin 1990). The regional trend, roughly E–W to SE–NW maximum horizontal compression, is probably caused by plate-wide forces such as Mid-Atlantic ridge-push and convergence between the Nazca and South American plates. However, local stress components (probably due to lateral variations of deep structure) are superimposed on the regional component.

Earthquakes in the SFC tend to occur at very shallow depths (less than 5 km), around the cratonic keel in the southern and central parts of the craton (Fig. 2.6a). The few earthquakes with focal mechanisms and hypocentral depths well determined by local stations occur in very shallow (less than 2 km depth) east-dipping faults (Fig. 2.6b). This indicates reactivation of Proterozoic normal faults under the present intraplate compressional stresses. It is not clear yet how exactly the high stresses in the upper crust of the SFC are generated by lateral variations of the craton's deep structure, but models of weak lithospheric mantle at craton's edge and flexural stresses (Assumpção et al. 2004, 2014) are possible candidates.

2.6 Discussion

Despite the few available data on deep crustal structure of the SFC some patterns can be recognized. On the western (Brasilia belt) and eastern border (Araçuaí belt) low Bouguer anomalies, high elevation and receiver function analyses (Figs. 2.1 and 2.2) indicate generally thick crust (down to ~44 km). The central part of the SFC seems to be characterized by slightly thinner crust (~39 km). High velocities in the lithospheric mantle (observed with P- and surface-wave tomographies, Figs. 2.3 and 2.4) are seen extending outside the SFC surface limits. All these features confirm the interpretation of the Tocantins seismic refraction line by Soares et al. (2006), who placed the main suture zone about 50–100 km outside the surface limit of the craton beneath the Brasília belt. A similar feature is proposed for the eastern limit beneath the Araçuaí belt.

On the other hand, the southern limit of the SFC, near the Ribeira belt, despite the high elevations, have high Bouguer anomalies and relatively thin crust. This could be due to the escape tectonics involved with the Ribeira belt (Vauchez et al. 1994), as opposed to collisional tectonics as in the western and eastern borders. Also, the relatively thin crust of the southern part of the SFC could be less dense (more felsic average crustal composition) allowing the crust to be balanced at higher elevations (Assumpção et al. 2002).

Although no direct determination of the depth to the lithosphere-asthenosphere boundary (LAB) has been made, S-wave velocities determined by surface-wave tomography (Fig. 2.3) suggest that the deepest part of the craton, about 200 km deep, lies in its southern part (Minas Gerais state). This is consistent with the expected range of 150–300 km for Archean lithosphere observed worldwide (Artemieva 2006).

In contrast, the northeastern part of the craton (towards the coast of Bahia) seems to have a thinner lithosphere. This is consistent with higher temperatures extrapolated from the geothermal gradient and also with the depths to the Curie temperature derived from spectral analyses of magnetic anomalies (Guimarães et al. 2014). The depths to the Curie temperatures range from 30 to 40 km in the Tocantins province, and from 38 to 44 km in the central part of the craton. At the NE part of the craton the Curie depth becomes shallow again (~30–32 km), consistent with an increase of the geothermal gradient and lithospheric thinning towards the coast of Bahia.

Near the Late Cretaceous Alto Paranaiba igneous province (APIP), the seismic velocities are lower than the

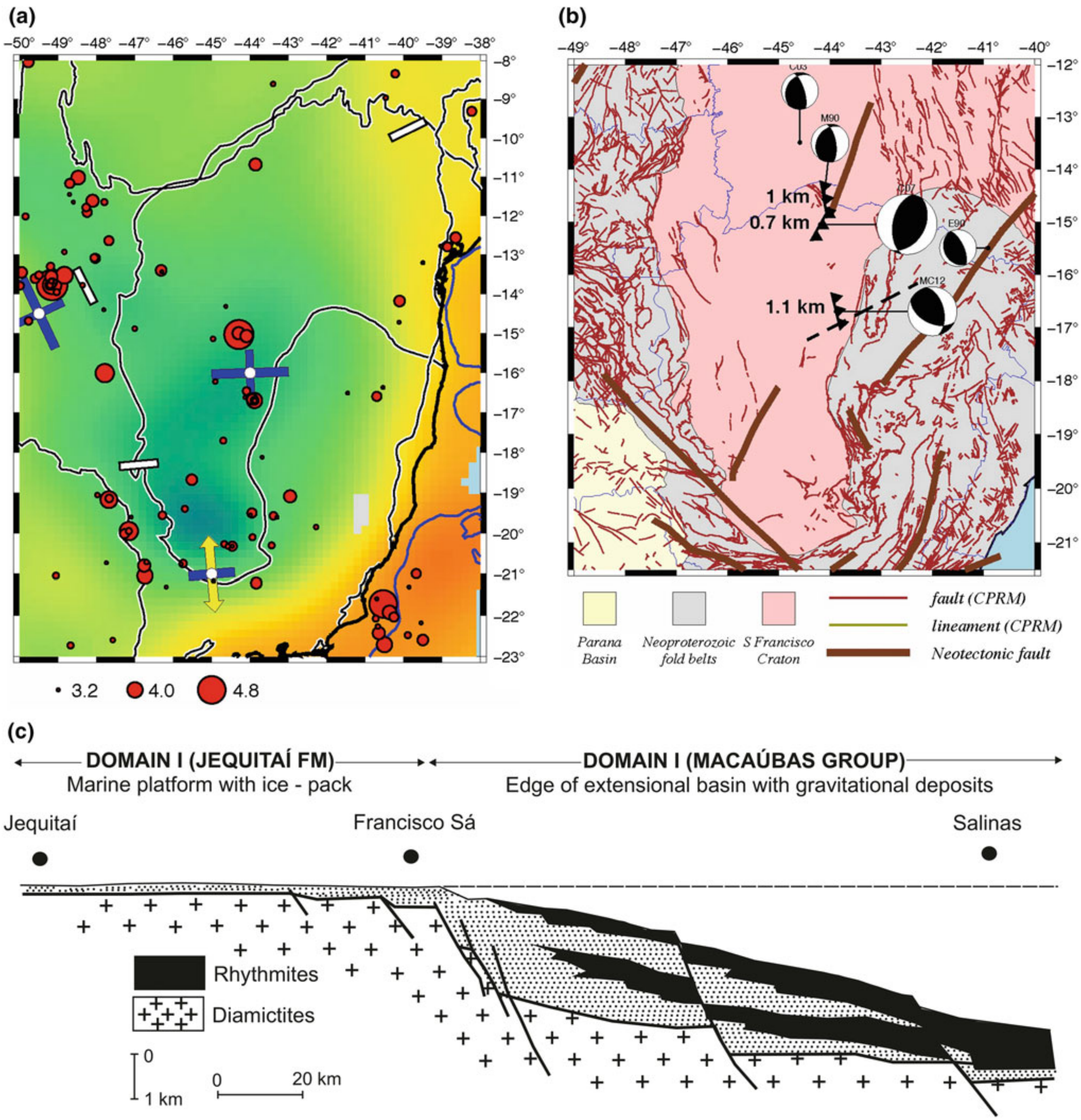

Fig. 2.6 **a** Epicenters and stresses in the SFC region. *Red circles* are epicenters from the uniform catalog of Assumpção et al. (2014). Stress tensors from earthquake focal mechanisms are indicated by *blue bars* (maximum and intermediate compressional stresses) and *yellow arrows* (horizontal tensional deviatoric stress). *Open white bars* are SHmax orientation from in situ measurements (Caproni and Armelin 1990; Magalhães 1999). *Background colors* are S-wave anomalies at 150 km depth from the surface-wave tomography as shown in Fig. 2.3b. *Blue line* offshore is the 200 m bathimetry. **b** Earthquake focal mechanisms and depths in the central part of the São Francisco craton. Events occur in E dipping reverse faults, as reactivation of ancient normal faults formed during the evolution of the craton's margin. *Thin brown lines* are geological faults from CPRM; *thick lines* are lineaments/faults interpreted as neotectonic features (Saadi et al. 2002). **c** Geological profile across the eastern border of the craton between Jequitaí and Salinas, indicated as *dashed line* in the map (Uhlein et al. 1998)

average lithospheric mantle (Fig. 2.4). Several interpretations are possible, such as (1) the original cratonic lithosphere was already thin (and consequently hotter), which facilitated pounding of partially melt material from a deep plume in the Cretaceous (e.g., Gibson et al. 1997), or (2) metasomatism in the Cretaceous, which decreased the seismic velocities, facilitated partial melting and pipe emplacement. Cratonic lithosphere tends to have lower upper-mantle velocities in areas with alkaline intrusions (Artemieva 2009). Both these models are consistent with a weak lithosphere (either due to higher temperature or due to a wet mantle lid) being responsible for higher seismicity near the APIP as well as the Iporá igneous provinces (Assumpção et al. 2004; Azevedo et al. 2015).

Although higher seismic velocities in the SFC lithospheric mantle—compared to the Brasilia belt—have been observed in the seismic refraction line (Fig. 2.2b), as well as in tomographic studies (Figs. 2.3 and 2.4), the gravity modeling did not require a corresponding higher density. If the 2 % higher velocity (8.25 compared with 8.05 km/s) was accompanied by higher density (0.05 g/cm^3 higher), a 50 km lithospheric lid would produce an extra Bouguer anomaly of 100 mGal, clearly incompatible with the observed data (Fig. 2.2b). This means that the craton's lithospheric mantle has higher P- and S-wave velocities (~2–3 % higher), but roughly the same density, or even slightly lower density as modeled by Koosah et al. (2007) and Ventura et al. (2011). This is consistent with a Fe-depleted composition for Archean cratons (e.g., Hawkesworth et al. 1990; Durrheim and Mooney 1991; Artemieva 2009) and lower temperatures, which account for the buoyancy of the craton's root allowing stability over its entire evolution.

2.7 Conclusions

Few geophysical data on the deep structure of the São Francisco Craton is available. However, some patterns can be recognized. The central part of the craton has normal to slightly thin crust (average of 39–40 km), and the western and eastern borders are thicker, generally correlating with higher topography. Surface- and P-wave tomography suggest a thicker lithosphere in the central and southern parts, reaching perhaps ~200 km. Surface-wave tomography suggests thinner lithosphere in the NE part, towards the coast of Bahia and Tucano basin.

Gravity modelling using the few available seismic point-constraints on crustal thicknesses shows that the lithospheric mantle in the central and southern parts of the craton has about the same density as the surrounding Neoproterozoic belts. This is consistent with an Fe depleted Archean lithospheric mantle, which, despite its lower temperature, is buoyant enough to remain stable throughout its evolution.

Seismicity in the SFC shows that the present E–W compressional stresses are reactivating old, shallow faults, which were formed during the evolution of the Brasiliano marginal basins. Variations of the crustal stresses indicate that strong local components, probably due to deep structure of the SFC, are superimposed on the plate-wide stress components generated at plate boundaries.

Acknowledgments We thank Petrobras Geotectonic Program for supporting the Brazilian Seismographic Network and the Transbrasiliano Project, which allowed new crustal thickness estimates and better tomographic coverage at recently deployed stations. We used results from several temporary experiments carried out with instruments from the Pool of Geophysical Equipment (PEG-BR, National Observatory, Rio de Janeiro). We also thank FAPDF and INCT (Estudos Tectônicos) for supporting geophysical projects in central Brazil. Work carried out with CNPq Grant 30.6547/2013-9 (M.A.) and CAPES PhD scholarship (P.A.A).

References

Agurto-Detzel, H., M, Assumpção, M. Bianchi, and M. Pirchiner, 2015a. Intraplate seismicity in mid-plate South America: correlations with geophysical lithospheric parameters. Geol. Soc. London, Special Publication in "Seismicity, Fault Rupture and Earthquake Hazards in Slowly Deforming Regions". 432, first published on November 2, 2015, doi:10.1144/SP432.5.

Agurto-Detzel, H., M. Assumpção, C. Ciardelli, D.F. Albuquerque, L. V. Barros, G.S.L., França, 2015b. The 2012–2013 Montes Claros earthquake series in the São Francisco Craton, Brazil: new evidence for non-uniform intraplate stresses in mid-plate South America. *Geophys. J. Int.*, 200, 216–226. Doi:10.1093/gji/ggu333.

Azevedo, P.A., M.P. Rocha, J.E. Soares, R.A. Fuck, 2015. Thin lithosphere between the Amazon and São Francisco Cratons, in Central Brazil, revealed by seismic P-wave tomography. *Geophysical J. Int.*, 201, 61–69. doi:10.1093/gji/ggv003

Artemieva, I.M., 2006. Global 1°x1° thermal model TC1 for the continental lithosphere: Implications for the lithosphere secualr evolution. *Tectonophysics*, 416, 245–277.

Artemieva, I.M., 2009. The continental lithosphere: reconciling thermal, seismic and petrological data. *Lithos*, 109, 23–46.

Artemieva, I.M., & R. Meissner, 2012. Crustal thickness controlled by plate tectonics: a review of crust-mantle interactions processes illustrated by European examples. *Tectonophys*., 530–531, 18–49.

Assumpção, M., 1998. Focal mechanisms of small earthquakes in SE Brazilian shield: a test of stress models of the South American plate. *Geophys. J. Int*., 133, 490–498.

Assumpção, M., D. James, A. Snoke, 2002. Crustal thicknesses in SE Brazilian shield by receiver function analysis: implications for isostatic compensation. J. *Geophys. Res*., 107(B1), ESE2-1—ESE2-14, 2006, doi:10.1029/2001JB000422.

Assumpção, M., M. Schimmel, C. Escalante, M. Rocha, J.R. Barbosa & Lucas V. Barros, 2004. Intraplate seismicity in SE Brazil: Stress concentration in lithospheric thin spots. *Geophysical J. Int.* , 159, 390–399. doi:10.1111/j.1365-246X.2004.02357.x

Assumpção, M., M.B. Bianchi, J. Julià, F.L Dias; G.S. França, R.M. Nascimento, S. Drouet, C.G. Pavão, D.F. Albuquerque, A.V. Lopes, 2013a. Crustal thickness map of Brazil: Data compilation and main features. *J. South Am. Earth Sci*., 43, 74–85. doi:10.1016/j.jsames.2012.12.009.

Assumpção, M., M. Feng, A. Tassara, J. Julià, 2013b. Models of crustal thickness for South America from seismic refraction, receiver functions and surface wave dispersion. *Tectonophys*., 609, 82–96, doi:10.1016/j.tecto.2012.11.014.

Assumpção, M., J. Ferreira, L. Barros, F.H. Bezerra, G.S. França, J.R. Barbosa, E. Menezes, L.C. Ribotta, M. Pirchiner, A. Nascimento, J. C. Dourado, 2014. Intraplate Seismicity in Brazil. In *Intraplate Earthquakes*, chapter 3, ed. P. Talwani, Cambridge U.P., ISBN 978-1-107-04038-0.

Berrocal, J., Y. Marangoni, N.C. Sá, R. Fuck, J.E.P. Soares, E. Dantas, F. Perosia, and C. Fernandes, 2004. Deep seismic refraction and gravity crustal model and tectonic deformation in Tocantins Province, Central Brazil, *Tectonophysics*, *388*, 187–199.

Caproni, N., J. Armelin, 1990. Instrumentação das escavações subterrâneas da UHE Serra da Mesa. In *Simpósio sobre Instrumentação Geotécnica de Campo - SINGEO-90*, Assoc.Bras.Geol. Eng., São Paulo, vol 1, p 249–257.

Carvalho, J.M., L.V. Barros, and J. Zahradnik, 2016. Focal mechanisms and moment magnitudes of micro-earthquakes in Central Brazil by waveform inversion with quality assessment and inference of the local stress field. *J. South Am. Earth Sci*., 71, 333–343, doi:10.1016/j.jsames.2015.07.020

Chimpliganond, C., M. Assumpção, M. von Huelsen & G.S. França, 2010. The intracratonic Caraíbas-Itacarambi earthquake of December 09, 2007 (4.9 mb), Minas Gerais State, Brazil. *Tectonophysics*, 480, 48–56.

Christensen, N.I., Mooney, W.D., 1995. Seismic velocity structure and composition of the continental crust: a global view. *J. Geophys. Res*. 100 (B6), 9761–9788.

Cordani, U.G., B.B. Brito Neves, R.A. Fuck, R. Porto, A.T. Filho, and F.M.B. Cunha, 1984. Estudo preliminar de integração do pré-Cambriano com os eventos tectônicos das bacias sedimentares brasileiras. *Rev. Ciência Técnica Petróleo*, 15, Petrobrás, CENPES, Rio de Janeiro.

Durrheim, R.J., Mooney, W.D., 1991. Archean and Proterozoic crustal evolution: Evidence from crustal seismology. *Geology*, 19, 606–609.

Durrheim, R.J., Mooney, W.D., 1994. Evolution of the Precambrian lithosphere: seismological and geophysical constraints. *J. Geophys. Res*. 99 (B8), 15359–15374.

Feng, M., S. Van der Lee and M. Assumpção, 2007. Upper mantle structure of South America from joint inversion of waveforms and fundamental-mode group velocities of Rayleigh waves. *J. Geophys. Res.,* 112, B04312, doi:10.1029/2006JB004449.

Gibson, S.A., Thompson, R.N., Weska, R.K., Dickin, A.P. & Leonardos, O.H., 1997. Late Cretaceous rift-related upwelling and melting of the Trindade starting mantle plume head beneath western Brazil, *Contrib. Mineral Petrol.*, 126, 303–314.

Giese, P., J. Schutte, 1975. Preliminary report on the results of seismic measurements in the Brazilian coastal mountains. Unpublished Report, Free Univ. of Berlin, Berlin, Germany.

Guimarães, S.N.P., D. Ravat, & V.M. Hamza, 2014. Combined use of the centroid and matched filtering spectral magnetic methods in determining thermomagnetic characteristics of the crust in the structural provinces of Central Brazil. *Tectonophys.*, 624–625, 87–99 , doi:10.1016/j.tecto.2014.01.025

Hawkesworth, C.J., Kempton, P.D., Rogers, N.W., Ellam, R.M., van Calsteren, P.W., 1990. Continental mantle lithosphere, and shallow level enrichment processes in the earth's mantle. *Earth Planet. Sci. Lett*. 96, 256–268.

Heit, B., F. Sodoudi, X. Yuan, M. Bianchi, and R. Kind, 2007. An S receiver function analysis of the lithospheric structure in South America. *Geophys.Res.Lett., 34, L14307, doi:*10.1029/2007GL030317.

Julià, J., M. Assumpção & M.P. Rocha, 2008. Deep crustal structure of the Paraná Basin from receiver functions and Rayleigh-wave dispersion: Evidence for a fragmented cratonic root. *J. Geophys. Res.,* 113, B08318, doi:10.1029/2007JB005374.

Knize, S., Berrocal, J., Martins, D., 1984. Modelo Preliminar de Velocidades Sismicas da Crosta Atraves de Explosões Locais Registradas Pela Rede Sismográfica de Sobradinho,BA. *Rev. Bras. Geoc.*, 2, 95–104.

Koosah M., Vidotti R., Soares J.E.P., Fuck R.A. 2007. Gravimetric and seismic data integration in a 2D forward gravimetric modeling for the crust and lid mantle beneath northern Brasilia Belt. In: SBGf, Internat. Cong. of the Brazilian Geophys. Soc., 10th, Rio de Janeiro, Expanded Abstract Volume, CD-ROM.

Magalhães, F.S., 1999. Tensões regionais e locais: Casos no território brasileiro e padrão geral. *PhD Thesis*, Escola de Engenharia de São Carlos, USP, 225 pp.

McKenzie, D., M.C. Daly, and K. Priestley, 2015. The lithospheric structure of Pangea. *Geology*, doi : 10.1130/G36819.1

Mooney, W.D., J. Ritsema, and Y. Hwang (2012), Crustal seismicity and maximum earthquake magnitudes (Mmax) in stable continental regions (SCRs): correlation with the seismic velocity of the lithosphere, *Earth Planet. Sci. Lett.,* 357–358, 78–83, doi:10.1016/j.epsl.2012.08.032.

Rocha, M.P., Schimmel, M., and Assumpção, M., 2011. Upper-mantle seismic structure beneath SE and Central Brazil from P- and S-wave regional traveltime tomography. *Geophysical Journal International*, 184, 268–286, doi:10.1111/j.1365-246X.2010.04831.x.

Saadi, A., M.N. Machette, K.M. Haller, R.L. Dart, L.-A. Bradley, and A.M.P.D. Souza, 2002. Map and Database of Quaternary Faults and Lineaments in Brazil. USGS Open-File Report 02-230 (2002).

Schimmel, M., M. Assumpção & J. VanDecar, 2003. Upper mantle seismic velocity structure beneath SE Brazil from P- and S-wave travel time inversions. *J. Geophys. Res*., 108(B4), 2191, doi:10.129/2001JB000187.

Soares, J.E., J. Berrocal, R.A. Fuck, W.D. Mooney, and D.B.R. Ventura (2006), Seismic characteristics of central Brazil crust and upper mantle: A deep seismic refraction study, *J. Geophys. Res*., *111*, B12302, doi:10.1029/2005JB003769.

Uhlein, A., R.R. Trompette and M. Egydio-Silva, 1998. Proterozoic rifting and closure, SE border of the São Francisco Craton, Brazil. *J. South Am. Earth Sci*., 11(2), 191–203.

Vauchez, A., A. Tommasi, & M. Egydio-Silva, 1994. Self-indentation of a heterogeneous continental lithosphere. *Geology*, 22, 967–970.

Ventura, D.B.R., J.E.P. Soares, R.A. Fuck & L.C.C. Caridade, 2011. Caracterização sísmica e gravimétrica da litosfera sob a linha de refração sísmica profunda de Porangatu, Província Tocantins, Brasil Central. *Rev. Bras. Geoc*., 41(1), 130–140.

http://www.springer.com/978-3-319-01714-3

São Francisco Craton, Eastern Brazil
Tectonic Genealogy of a Miniature Continent
Heilbron, M.; Cordani, U.G.; Flecha de Alkmim, F. (Eds.)
2017, VIII, 331 p. 164 illus., 148 illus. in color.,
Hardcover
ISBN: 978-3-319-01714-3