Causes of intraplate seismicity in central Brazil from travel time seismic tomography

Marcelo Peres Rocha, Paulo Araújo de Azevedo, Giuliano Sant’Anna Marotta, Martin Schimmel, Reinhardt Fuck

A R T I C L E   I N F O
Article history:
Received 16 September 2015
Received in revised form 1 May 2016
Accepted 3 May 2016
Available online 11 May 2016

Keywords:
Seismic tomography
Intraplate seismicity
Tocantins Province
São Francisco paleocontinent
Amazonian Paleocontinent
Parnaíba Basin

A B S T R A C T
New results of travel time seismic tomography in central Brazil provide evidence that the relatively high seismicity in this region is related to the thinner lithosphere at the limit between the Amazonian and São Francisco paleocontinents. The transition between these paleocontinents is marked by low velocity anomalies, spatially well correlated with the high seismicity region, which are interpreted as related to the lithospheric thinning and consequent rise of the asthenosphere, which have increased the temperature in this region. The low-velocity anomalies suggest a weakness region, favorable to the build-up of stress. The effective elastic thickness and the strain/stress regime for the study area are in agreement with tomographic results. A high-velocity trend is observed beneath the Parnaíba Basin, where low seismicity is observed, indicating the presence of a cratonic core. Our results support the idea that the intraplate seismicity in central Brazil is related to the thin lithosphere underlying parts of the Tocantins Province between the neighboring large cratonic blocks.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

1.1. Motivation

Most of the seismically active regions on Earth, including where the largest earthquakes occur, coincide with the limits of tectonic plates. Over 90% of the world earthquakes occur at the edge of oceanic and continental plates. Unlike plate boundary regions, where the seismicity is relatively concentrated and the causes are well understood, intraplate seismicity represents diffuse deformation in relatively stable tectonic regions (Zoback, 1992), and their origins cannot be explained simply, given that they depend on the local tectonic context (Assumpção et al., 2014).

Most common models proposed to explain intraplate seismicity are related to pre-existing weak zones, such as extended crust in aborted rifts or continental margins (e.g. Johnston, 1989; Schulte and Mooney, 2005), or stress concentration in the upper crust due to structural inhomogeneities (e.g. Sykes, 1978; Talwani, 1989; Talwani and Rajendran, 1991; Kenner and Segall, 2000). Liu and Zoback (1997) showed that stress concentration in the upper crust of the New Madrid seismic zone is the result of a weaker subcrustal lithosphere. Based on seismic tomography results, Assumpção et al. (2004) proposed that lithospheric thinning could provide favorable conditions for stress concentration in the brittle upper crust, which may explain the epicentral distribution within the South American Platform.

In the South American continent, the regional stress field is dominated by E-W compression (Zoback, 1992). The origin of this stress regime is mainly due to forces related with spreading in the Mid-Atlantic Ridge and the resistive forces exerted by the Caribbean plate to the north and the Nazca plate subduction to the west (Mendiguren and Richter, 1978; Coblenz and Richardson, 1996). Intraplate seismicity in Brazil is clearly not uniform and a few areas of higher activity have been identified (Assumpção et al., 2004, 2014). An example of the high seismic concentration can be observed in central Brazil. Significant seismicity, with preferential epicenter distribution in the SW–NE direction, is observed in the Tocantins Province. This is known as the Goiás-Tocantins Seismic Zone — GTSZ (Berrocal et al., 1984; Fernandes et al., 1991). The seismicity of central Brazil may be related to the limits between the São Francisco and Amazonian paleocontinents, which could represent a region of lithospheric thinning. According to Assumpção et al. (2004), in regions of tectonic lithospheric thinning, stress tends to focus on the crust, while in regions of thicker lithosphere the stress is more distributed within the upper mantle.
In seismic tomography results, regions with thinner lithosphere appear as low-velocity anomalies (Assumpção et al., 2004; Zhang et al., 2009; Rocha et al., 2011), which can be interpreted as regions of relatively higher temperature. Regions with thicker lithosphere, such as cratons, are characterized by stability and low temperatures, and normally appear as high-velocity anomalies in tomographic results. In this context, our objective is to relate new results of P-wave seismic tomography in central Brazil (Tocantins Province) with the seismicity distribution, in order to understand the causes of the high seismicity of the GTSZ.

1.2. Study area

The study area is located mostly in the Tocantins Province, in central Brazil, covering also the southeastern part of the Amazonian Craton, the western part of the São Francisco Craton, the southern part of the Parnaíba Basin and northeastern part of the Parana Basin. The area is crossed by the Transbrasiliano Lineament (TBL), a major lithospheric discontinuity in the region, which defines the boundary of different crustal domains (Cordani and Sato, 1999; Cordani et al., 2013; Brito Neves and Fuck, 2014). Here, we focus on the area marked by the dashed rectangle (Fig. 1). The black and white triangles are the seismic stations which have been added to the study carried by Rocha et al. (2011) for this purpose.

Central Brazil, and especially the Tocantins Province, is one of the most complex tectonic regions in South America. The most important event related to the formation of the Tocantins Province is the collision between the Amazonian and the São Francisco cratons and a third stable area, the Paranapanema block hidden beneath the Paraná Basin (Pimentel et al., 2000, 2004), giving rise to the Neoproterozoic Araguaia, Paraguai and Brasilia fold belts (01, 02 and 03 in Fig. 1). To the north of Tocantins Province lies the Parnaiba Basin. This is one of the largest cratonic basins of South America (like the Paraná, Solimões and Amazonic basins). This basin occupies an area of more than 600,000 km² (Brito Neves, 1998), and covers a rigid lithosphere block, which probably represents its craton core (Brito Neves et al., 1984; Gões et al., 1993; Nunes, 1993; Castro et al., 2014; Daly et al., 2014).

2. Data and method

For this study, new data were acquired through a permanent network recently installed in Brazil – Brazilian Seismographic Network (BSN) – with more than 80 stations distributed throughout the country (black triangles in Fig. 1) and providing, for this study, data between 2011 and 2015. We used also data from a temporary network with 15 stations (white triangles in Fig. 1), with events recorded between 2007 and 2013 (Azevedo et al., 2015). These new data were included in a database previously assembled by prior works (VanDecar et al., 1995; Schimmel et al., 2003; Rocha et al., 2011). We used records of P and PKIKP phases for events with minimum magnitudes larger than 4.6 and 5.4 (mb), respectively. Events were chosen in the epicentral distance range of 30° to 95° for P-waves and 150° to 180° for PKIKP.

**Fig. 1.** Study area with stations distribution. Black triangles are new stations, white triangles are the stations included by Azevedo et al. (2015) and gray triangles are old stations used by Rocha et al. (2011). Dashed rectangle is the interpreted area. The solid lines in gray and black are the boundaries of the countries and geological provinces, respectively. Dashed and dotted line is the Transbrasiliano Lineament (TBL). PRB — Paraná Basin; PB — Parnaíba Basin; TP — Tocantins Province; SFC — São Francisco Craton; AC — Amazonian Craton; (01) Araguaia Fold Belt; (02) Paraguay Fold Belt; (03) Brasilia Fold Belt.
waves, to avoid phase misidentification due to triplications, caused by the mantle transition zone or inner core. The final database for all of Brazil consists of 27,665 time measurements for phases P and PKIKP from 6,141 events.

The tomographic method used is the linearized inversion approach of VanDecar et al. (1995), which is based on the ACH inversion method (Evans and Achauer, 1993). This method has been successfully used in different regions (VanDecar et al., 1995; Sol et al., 2002; Wolfe et al., 2002; Schimmel et al., 2003; Bastow et al., 2005, 2008; Benoit et al., 2006; Lees et al., 2007; Schmid et al., 2008; West et al., 2009; Rocha et al., 2011; Azevedo et al., 2015). In this method, travel-time relative residuals (see Evans and Achauer, 1993) of teleseismic waves are inversed simultaneously for three-dimensional velocity structure, earthquake relocations, and station terms. Observed times are obtained by phase picking of the seismograms, and theoretical travel times have been computed for spherically symmetric Earth model IASP91 (Kennett and Engdahl, 1991). In order to obtain more accurate picks, we used the Multi-Channel Phase Cross Correlation (MCPC) developed by Schimmel et al. (2003). This method is an extension of the Multi-Channel Cross Correlation approach (VanDecar and Crosson, 1990), and provides an amplitude unbiased phase cross-correlation rather than the classical cross-correlation (Schimmel, 1999).

The parameter model has been discretized in a dense grid of knots interpolated with splines under tension (Cline, 1981; Neele et al., 1993). This interpolation scheme provides a smooth slowness distribution and therefore permits an accurate ray tracing. The grid for the whole Brazil is composed of 449,625 knots: 33 knots in depth, 109 knots in latitude and 125 knots in longitude. The spacing between the knots increases from the center to the border of the grid, and in depth. The parameterization model extends outside the area of the stations to minimize the mapping of noise and inconsistencies, as unrealistic structures into the central area. Further details about the inversion and data processing procedures can be obtained in VanDecar et al. (1995), Schimmel et al. (2003), Rocha et al. (2011) and Azevedo et al. (2015).

We used in our results (Figs. 2 and 3) earthquake data of the Brazilian Seismic Bulletin (BSB, http://rsbr.gov.br/catalogo sb.html), BSB includes historical and instrumental events from 1724 to December/2013 (Version 2014.11), with magnitudes from 2.0 to 6.2. The completeness of the BSB is variable in time and space, mainly due the inhomogeneous station density, which increased significantly only from the late 1970s with the installation of many stations in areas of hydroelectric reservoirs, and with another significant increase from 2011, with the installation of permanent stations of the BSN (Assumpção et al., 1997). According to Assumpção et al. (1997) theMagnitude of Completeness value for the BSB is 3.2 for events starting from 1980 and 2.8 for events starting from 1990 being higher for prior periods (e.g. 4.5 for 1968, when beginning the operation of the stations arrangement in the capital, Brasília). We used events with a minimum magnitude of 3.0 for our study area, considering that the majority of stations in that region started operation from the 1990s.

3. Results and discussion

Our results (Figs. 2 and 3) are velocity perturbations with respect to the IASP91 reference model (Kennett and Engdahl, 1991). The anomalies represent mainly lateral structure, where higher than average velocities are indicated by cold colors and lower than average velocities by hot colors. Areas without data are shown in black.

From the installation of new stations, it was possible to observe a new low-velocity anomaly in central Brazil, elongated in the SW–NE direction (Fig. 2) concurrent with the trend of the Tranbrasiliano Lineament. This anomaly is well resolved as shown by resolutions tests carried out by Azevedo et al. (2015). Further, this lineament is accompanied by high seismicity, mainly in its central portion. The seismicity decreases significantly at the boundary of the Parnaíba Basin, which is practically aseismic. The low-velocity anomaly at the southern portion of the Parnaíba Basin seems to be divided in two branches. It is possible that these low-velocity anomalies indicate the limits of a cratonic block that would represent the basement of this basin (see Castro et al., 2014), explaining the seismicity absence in its interior.

Based on the assumption that low-velocity anomalies, interpreted as higher temperatures, could result in weakness zones (Assumpção et al., 2004), we could consider that the low-velocity anomaly in central Brazil is a weaker region, and represents a lithospheric thinning and consequent asthenosphere rising, leading to the Tranbrasiliano Lineament reactivation, and consequent seismic activity in that region. However, we observe a high-velocity anomaly in the southwestern portion of the Tocantins Province, exactly in a region with absence of seismicity. According to Alkimim et al. (1993) and Ussami (1993), based in gravimetric anomalies, the São Francisco Craton extends beyond its surface boundary to the west, below the Brasilia Belt Fold. This pattern is confirmed by the results of seismic tomography (Azevedo et al., 2015; Rocha et al., 2011). Therefore, the lithosphere in that region has cratonic characteristics, not being a weakness region, not favoring the occurrence of high seismicity.

In Fig. 3 we show the vertical tomographic profile Z-Z′ (Fig. 3c), as indicated in Fig. 2, and the model to summarize our interpretation of the inhomogeneous seismicity in the E-W direction in central Brazil (Fig. 3b). This model is based on our seismic tomography results and on the model for the lithosphere structure in the region proposed by Soares et al. (2006) based in deep refraction results. The cumulative event number over a range of 200 km width is shown on Fig. 3a, centered in profile Z-Z′. Clearly, most seismic events occur over the low-velocity anomaly.

Fig. 2. Tomographic horizontal image at 150 km depth, and the seismicity of central Brazil. The thick lines indicate geological boundaries and the white circles represent epicenters (Brazilian Seismic Bulletin, Magnitudes > = 3.0). The dashed-dotted line is the Transbrasiliano Lineament. White line Z-Z′ indicates the vertical profile shown in Fig. 3c and the white square indicates the region that contains the events used in Figs. 3a and 5a.
The depth of the Lithosphere/ASThenosphere Boundary (LAB) in Fig. 3c was based on the maximum depths of cratons and mobile belts indicated in the literature (e.g. Veeraswamy and Raval 2004), where LAB in cratonic and mobile belt regions can reach depth intervals of 180 and 250 km and 70 and 150 km, respectively. Heit et al. (2007) indicate a value of 160 km for the LAB depth beneath Tocantins Province. Red dashed line represents the Lithosphere–Asthenosphere Boundary (LAB). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Some events occur within the São Francisco Craton, consistent with diffuse nature of the intraplate seismicity (Zoback, 1992). If the South American Platform was formed by a single continental block, existing seismicity would probably be diffusive as observed within the São Francisco Craton. However, as this is not the case, it is expected that the stress distributed across all of the South American Platform, can be concentrated in the lithospheric mantle, while in regions of lithospheric thinning, stress is concentrated mainly in the crust, allowing conditions for the occurrence of the seismic events. Also, the crust in the region of Tocantins Province is thinner (Soares et al., 2006) and weaker, probably due to the lithospheric thinning in the region and increasing of the temperature, which favors the occurrence of earthquakes there instead of the neighboring thicker cratonic crust regions.

Based on gravity results and modeling, Assumpção and Sacek (2013) proposed that the cause of the seismicity in the Tocantins Province is flexural deformation. The arguments presented by those authors are based on numerical modeling, and indicate that the stress reaching ~100 MPa, generated by flexure in central Brazil, due to a density contrasts in the lithosphere and topographic load, is sufficient to generate earthquakes. This result does not eliminate the possibility that the seismicity in central Brazil can also be generated by regional stress accumulation. Therefore, based on our results, we believe that the combination of weakness zones, caused by lithospheric thinning, and regional stress concentration, bears significant influence on the causes of seismicity in central Brazil.

To corroborate our tomographic results, Fig. 4 shows the effective elastic thickness (Te), available from Bizzi et al. (2003) and the strain/stress regime in the study area, available from Assumpção et al. (1985, 1997), Lima et al. (1997), Assumpção (1998), Chimiliganond et al. (2010), Marotta et al. (2013), and Agurto-Detzel et al. (2015).

Fig. 4a shows that most of Tocantins Province presents Te between 20 and 55 km. This area is between two stronger regions (blue), located on the Amazonian (NW) and São Francisco (SE) cratons, which have Te values above 55 km. In the southern Tocantins Province (between Paraná basin and São Francisco craton), we observed high Te values (coincident with high-velocity anomalies), which may be related to the part of São Francisco Palaeocontinent, as explained above. The smallest Te values (between 10 and 20 km) can be observed in part of Paraná and Parnaiba basins and northernmost São Francisco Craton. Most seismic events occur over regions with low-velocity anomaly and Te down to 55 km.

Regarding the strain and stress regime in the studied area, the principal strain rate (Fig. 4b) is concentrated on the SW–NE direction, and the stress (Fig. 4c) is concentrated in the E–W direction. According to Marotta et al. (2013), these directions corroborate the finding that the regional stress field, on the passive margin of South American Platform, is related mainly with spreading in the Mid-Atlantic Ridge and the resistive forces exerted by Nazca plate subduction.

If we consider only the Z-Z’ profile region, the Te values shown in Fig. 4a (low to intermediate values) and the direction of the stresses and principal strain rate on Fig. 4d (SW–NE direction), corroborate the model presented in Fig. 3, which shows that the stress concentration in lithospheric thinning regions is a favorable context for the occurrence of high seismicity.

We calculated cross-correlations between Seismicity, Te, Tomographic Anomalies and Crustal Thickness pairs (Fig. 5d, e, f, g, h, i), and made a comparison between the values of these parameters, along profile Z-Z’ (Fig. 5a, b, c). We observe reasonable correlation (over 67%) between different pairs of measurements, with the exception of the pair Te × Crustal Thickness (about 41%). Probably the crustal thickness has low correlation with the Te, since Te measures contain influences on the deformation in central Brazil, due to a density contrasts in the lithosphere and topographic load, is sufficient to generate earthquakes. This result does not eliminate the possibility that the seismicity in central Brazil can also be generated by regional stress accumulation. Therefore, based on our results, we believe that the combination of weakness zones, caused by lithospheric thinning, and regional stress concentration, bears significant influence on the causes of seismicity in central Brazil.

From visual correlation (Figs. 4 and 5) it can be seen that the seismicity coincides with Te values smaller than 50 km in Tocantins Province, especially with values near this limit. From the Te map, one can observe that the greater seismicity region (intermediate Te) is in regions where the deformation is greater and consequently where the stress is...
Thus, for the occurrence of seismicity in regions of lower Te, the existence of stress would be necessary. Apparently, the boundary between the Amazonian and São Francisco cratons is a favorable area for concentration of stress. Perhaps the two cratons may be serving as a kind of director of regional stress, and the boundary between them would be the most affected region.

4. Conclusions

In the South American Platform, tomographic low-velocity anomalies coincide with relatively high seismicity, mainly in central Brazil. These low-velocity anomalies likely indicate lithospheric thinning. Tomographic anomalies can be related with changes in Te values, where, higher Te values (>55 km) are generally related with high-velocity anomalies (mainly in cratonic regions), and smaller and intermediate Te values (between 10 and 55 km) are related with low-velocity anomalies, generally interpreted in our study area as weakness regions.

Regional stresses may be distributed evenly in the lithosphere, and in thinner regions, they tend to be more intense in the crust when compared with thicker regions. The boundary between the Amazonian and the São Francisco paleocontinents is a favorable area for concentration of stress.

The relative absence of high seismicity in the adjacent cratonic regions could be related to the concentration of the most part of the diffusive regional stress in the upper mantle.

Cross-correlation analysis between Seismicity, Te, Tomographic Anomalies and Crustal Thickness pairs suggests that the variation of each one has the same origin, with exception of the Te × Crustal Thickness pair that shows low cross-correlation coefficient, probably due to the fact that Te does not have the same information with that of Crustal Thickness.

The almost total absence of seismicity in the Parnaíba Basin can be related to the presence of a cratonic core that represents its basement. More stations need to be deployed in the Parnaíba Basin to confirm this assertion.

Acknowledgments

The authors thank Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and the Instituto Nacional de Ciência e
Fig. 5. Comparison and cross-correlations between the values of the Seismicity, Te, Tomographic Anomalies and Crustal Thickness. (a) Cumulative epicenter distribution in Z-Z profile over a range of 200 km for each side. (b) P-wave velocity anomaly along the profile Z-Z for a depth of 150 km. (c) Dashed and solid lines are the Crustal Thickness and Te values along Z-Z profile, respectively. (d), (e), (f), (g), (h) and (i) Calculated cross-correlations and distributions of the pairs of the analyzed parameters.

References


Cline, A.K., 1981. FITPACK: A Software Package for Curve and Surface Fitting Employing Splines under Tension. Dep. of Computer Sciences – University of Texas, Austin.


