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Strain rates estimated by geodetic observations in the Borborema Province, Brazil

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ABSTRACT

The strain rates for the Borborema Province, located in northeastern Brazil, were estimated in this study. For this purpose, we used GNSS tracking stations with a minimum of two years data. The data were processed using the software GIPSY, version 6.2, provided by the JPL of the California Institute of Technology. The PPP method was used to process the data using the non-fiducial approach. Satellite orbits and clock were supplied by the JPL. Absolute phase center offsets and variations for both the receiver and the satellite antennaes were applied, together with ambiguity resolution; corrections of the first and second order effects of the ionosphere and troposphere models adopting the VMF1 mapping function; 10° elevation mask; FES2004 oceanic load model and terrestrial tide WahrK1 PolTid FreqDepLove OctTid. From a multi annual solution, involving at least 2 years of continuous data, the coordinates and velocities as well as their accuracies were estimated. The strain rates were calculated using the Delaunay triangulation and the Finite Element Method. The results show that the velocity direction is predominantly west and north, with maximum variation of 4.0 ± 1.5 mm/year and 4.1 ± 0.5 mm/year for the x and y components, respectively. The highest strain values of extension and contraction were $0.109552 \times 10^{-6} \pm 3.65 \times 10^{-10}$/year and $-0.072838 \times 10^{-6} \pm 2.32 \times 10^{-10}$/year, respectively. In general, the results show that the highest strain and variation of velocity values are located close to the Potiguar Basin, region that concentrates seismic activities of magnitudes of up to 5.2 mb. We conclude that the contraction direction of strain is consistent with the maximum horizontal stress derived from focal mechanism and breakout data. In addition, we conclude that the largest strain rates occur around the Potiguar Basin, an area already recognized as one of the major sites of seismicity in intraplate South America.

1. Introduction

Several studies involving deformation analysis of the earth surface using geodetic observations have been conducted to understand the dynamics of the strain applied to intraplate regions. Among them, Li et al. (2001) established a model of rigid motion, elastic–plastic and strain for eight intraplate blocks and peripheral areas in China. The model was consistent with the strain parameters, obtained using geological and geophysical methods. Calais et al. (2006) combined independent geodetic solutions, using the continuous data from GPS stations covering the central and eastern regions of the US and showed that surface deformation in the North American Plate interiors is qualitatively consistent with that expected from GIA (Glacial Isostatic Adjustment). They also showed that, with 95% confidence level, no residual motion was detected in the New Madrid Seismic Zone. Cloetingh et al. (2006) combined seismicity data and strain indicators with geodetic and geomorphological observations to show that the deformation of the northern Alpine Foreland is still ongoing and will continue in the future. Banerjee et al. (2008) studied three of the major historic intraplate earthquakes (Magnitude > 7.5) that happened in the Indian subcontinent, which, considering the surface velocities

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determined from GPS data, suggest the possibility of significant intraplate deformation with shortening rate from north to south of $0.3 \pm 0.05 \times 10^{-9}$/year. Southward motion from 4 to 7 mm/year located over the Shillong plateau, in northeastern India, reflects the fast shortening and danger of a large earthquake associated with active thrust faults that limit the plateau.

Regarding the South American plate, most field models of active stresses suggest the presence of stress formed predominantly by the Mid-Atlantic ridge push, collision with the Nazca plate, intraplate density variations, drag or basal resistance exerted by the asthenosphere, and resistance associated to faults. According to Lima (2000), the South American plate is under horizontal compression and shortening, which can be demonstrated by a compilation of stress data, numerical field models of intraplate stresses and results based on geodetic observations. Based on the processing of GPS, SLR and DORIS data collected over the course of three years (1994, 1995 and 1996), Norabuena et al. (1998) and Crétaux et al. (1998) reported that about 10–15 mm/year of crustal shortening occur in the interior of the South American plate, thus indicating that the Andes region is still in a process of continuous formation. Marotta et al. (2013a) estimated deformation between pre- and post-seismic periods in Latin America using geodetic observations and from their results it was possible to analyze the interactions between lithospheric plates from the directions of contraction and extension between points located on separate plates.

Turning to the interior of the South American plate, the models of strain currently known are derived mostly from studies involving seismological and geological data, such as focal mechanisms and breakouts, according to work presented by Zoback (1992), Assumpção (1992, 1998), Coblentz and Richardson (1996), Lima et al. (1997), Ferreira et al. (1998, 2008), Bezerra et al. (2011), Heidbach et al. (2009), and Lopes et al. (2010a).

Recent studies about strain rates by geodetic observations seek to associate them to known strain models. From the coordinates and velocities estimated for a grid of points of geodetic network, Marotta et al. (2013b) estimated strain rates for the South American intraplate region and suggest that the large superficial motions occur in regions with more heterogenous geological structures and multiple rupture events; that large earthquakes are concentrated in areas with predominantly contraction strain rates, oriented southwest–northeast; and, that the change of direction in the movement of the geodetic points in the South American plate shows predominantly tectonic influence with some variations that can be attributed to the strain interactions with local geological characteristics. However, little is known about the relationship between strain rates and stress directions and structures in the upper crust in intraplate areas.

This work aims to determine the strain rates of the Borborema Province, northeastern Brazil, from velocity vectors estimated by GPS positioning methods using data of a geodetic network of continuous monitoring. We seek to understand these strain rates and their relationship with the present-day stress field and the structural framework of the region.

2. Tectonic strain at the Borborema Province

Brazil is located in the low seismic activity continental intraplate region of South America. However, there are some regions in Brazil characterized as active seismogenic zones, such as the Northeast, which features recurring seismic activity (Takeya et al., 1989; Ferreira et al., 1998; Lopes et al., 2010b; Rossetti et al., 2011) associated with recent tectonic activity (Fig. 1).

The Borborema Province is located in the eastern margin of the South American plate. The coastal areas of the mainland and the interior comprise a Precambrian crystalline basement overlain by Cretaceous and Cenozoic sedimentary basins Almeida et al. (2000). These basins were formed mainly by the reactivation of the shear zones during the breakup of Pangea in the Cretaceous de Castro et al. (2012). The Neogene record consists primarily of the Barreiras Formations, of Miocene age, and Quaternary sedimentary deposits Rossetti et al. (2011).

The Borborema Province constitutes the central part of a wide orogenic belt deformed during the Pan-African/Brasiliano orogeny (750–540 Ma), covering an area of 900 km long and 600 km wide. Ductile shear zones are among the most striking features of the Borborema Province. They form continental scale structures linked to Precambrian terrains. In some cases, they mark a collage of large Proterozoic crustal blocks. Several of the major shear zones continue in Africa, in a Pangea pre-breakup reconstruction.

Seismological and studies using data from the oil industry focused on the Borborema Province presented preliminary estimates of the stresses in the region. Assumpção (1992) presented a compilation of the lithospheric stress directions for the South American continent and the main patterns of the intraplate stress regional field. He also suggested that in northeastern Brazil, seismicity is characterized mainly by strike-slip earthquakes in the upper crust. A model was proposed for the region where the stress field would be the result of an overlapping of regional and local stress fields, characterized by E–W-trending compression and N–S-trending extension. Lima et al. (1997) studied the crustal stresses in Brazil and presented a detailed analysis of breakout data performed in 541 wells distributed in sedimentary basins throughout the country, from which 481 were from basins along the continental margin and 60 were from intracratonic basins. The authors verified in the Potiguar Basin that average orientation of maximum horizontal stresses (SH_{max}) by breakout is consistent with the orientation of the maximum horizontal stresses (SH_{max}) inferred from focal mechanisms around the basin. The breakouts also show that (SH_{max}) is approximately parallel to the northern coastline. From the results, they suggested that this pattern is also consistent with the model by Assumpção (1992).

In northeastern Brazil, indicated that earthquakes tend to occur around the border of the Potiguar Basin in the crystalline basement, with strike-slip focal mechanisms at depths between 1 and 12 km (Assumpção, 1998; Ferreira et al., 1998; Bezerra et al., 2007). These studies also suggested that the combination of regional stresses, local flexion effects of thick sediment loads and a presumably weaker crust, explains the main patterns of seismicity in the area.

While studying a series of earthquakes with local networks, Ferreira et al. (2008) and Lopes et al. (2010a) helped to increase the stress database in Brazil. From the analysis of clusters of seismic activities along the Pernambuco shear zone, included in the Borborema Province, the works showed the reactivation of Pernambuco shear zone with normal and strike-slip faults, thus indicating N–S-trending extension and E–W-trending compression.

3. Study area

The study area shown in Fig. 2 consists of the entire region covered by a network of geodetic points in the Borborema Province.

Among the points that make up the geodetic network are those belonging to Brazilian Continuous GNSS Network (RBMC) (<www.ibge.gov.br>, accessed on 01/02/2013), controlled by Brazilian Institute of Geography and Statistics (IBGE), and Potiguar GPS Network (RGP), controlled by the Federal University of Rio Grande do Norte (UFRN).

The geodetic points belonging to RBMC, besides being for civilian use, are also part of the SIRGAS-CON network, which is used to perform the Geocentric Reference System for the Americas