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Intraplate seismicity in Brazil

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Abstract

We describe the development of the Brazilian earthquake catalogue and the distribution of seismicity in Brazil and neighbouring areas in mid-plate South America. This large mid-plate region is one of the least seismically active stable continental regions (SCR) in the world: the maximum known earthquake had a magnitude of 6.2 m_b and events with magnitudes 5 and above occur with a return period of 4 years. Several seismic zones can be delineated in Brazil, including some along craton edges and in sedimentary basins. Overall, the exposed cratonic regions tend to have half as many earthquakes compared to the average expected rate for all of mid-plate South America. Earthquakes tend to occur in Neoproterozoic foldbelts especially in areas of thin lithosphere, or near craton edges around cratonic keels. Areas with positive isostatic gravity anomalies tend to have more earthquakes, indicating that flexural stresses from uncompensated lithospheric loads are an important factor in explaining the intraplate seismicity. We also found that earthquakes are two to three times more likely to occur within 20 km of mapped neotectonic faults, compared to events at larger distances. On closer examination, however, we observe that most of these events occur near but not directly on the major neotectonic faults. This discrepancy could be explained by the model of stress concentration near intersecting structures. The Brazilian passive margin is also a region of higher than average seismicity. Although clear differences are found between different areas along the passive margin (extended crust in southeast Brazil having especially high seismicity compared to narrow continental shelves elsewhere), overall the Brazilian passive margin has 70% more earthquakes (magnitudes above 3.5) than the average stable continental region.

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3.1 Introduction

Explaining the genesis of intraplate seismicity is a great challenge. Several models have been proposed to explain the cause of earthquakes far away from the active plate boundaries. These can be broadly divided into two kinds of models: those involving weakness zones and those involving stress concentrations. Crustal weak zones are usually due to the last major orogenic process and involve ancient rifts or failed rifts (e.g., Sykes, 1978; Johnston and Kanter, 1990; Assumpção, 1998; Schulte and Mooney, 2005), or suture zones (i.e., around craton edges as shown by Mooney *et al.* [2012]). Stress concentrations can arise from lateral density variations (e.g., Stein *et al.*, 1989; Assumpção and Araujo, 1993; Zoback and Richardson, 1996; Assumpção and Sacek, 2013), contrasts of elastic properties (e.g., Campbell, 1978; Stevenson *et al.*, 2006), or fault intersections (Talwani, 1999; Gangopadhyay and Talwani, 2003, 2007). Quite often, weak zones and stress concentrations are linked in the same process. For example, lithospheric thin spots between ancient cratonic areas can be regarded as a weak zone but the seismicity is due to stress concentration in the elastic upper crust (e.g., Assumpção *et al.*, 2004). Evidence for higher seismicity along Phanerozoic suture zones in North America can be interpreted as concentration of stresses and deformation ("crumpling" zones) near craton edges (Lenardic *et al.*, 2000), which are ultimately caused by lateral variations of lithospheric thickness (Mooney *et al.*, 2012).

If lateral density variations are not isostatically compensated, flexural stresses can arise in the upper crust and reach large magnitudes to significantly contribute to intraplate seismicity (e.g., Cloetingh *et al.*, 1984; Stein *et al.*, 1989; Zoback and Richardson, 1996; Assumpção *et al.*, 2011; Assumpção and Sacek, 2013). Flexural stresses can be caused by ice-sheet retreat (e.g., Mazzotti *et al.*, 2005), sediment load in the continental margin (Stein *et al.*, 1989; Assumpção, 1998; Assumpção *et al.*, 2011), or intracrustal loads from past geological processes (e.g., Zoback and Richardson, 1996; Assumpção and Sacek, 2013).

As reviewed by Mazzotti (2007), it is usually agreed that several different factors can contribute to produce an intraplate seismic zone. However, one of the major difficulties with most models for intraplate seismicity is the fact that the same geological/structural features are also present in areas with no current seismic activity. For example, not all continental shelves are equally active, despite having similar geological structures and potentially the same sources of stress. This has contributed to the debate of whether long-term migration of intraplate seismic zones occurs, with significant implications for seismic hazard assessment (Stein *et al.*, 2009; Li *et al.*, 2009), and highlighted the importance of further studies of intraplate mechanisms and a more detailed comparison of seismicity patterns between different regions and continents.

Here we present the spatial distribution of seismicity in Brazil and discuss possible correlations with geological and geophysical features, trying to assess some of the proposed models mentioned above. Assessing the applicability of general models for intraplate seismogenesis is important to better delineate seismic zones in mid-plate South America.

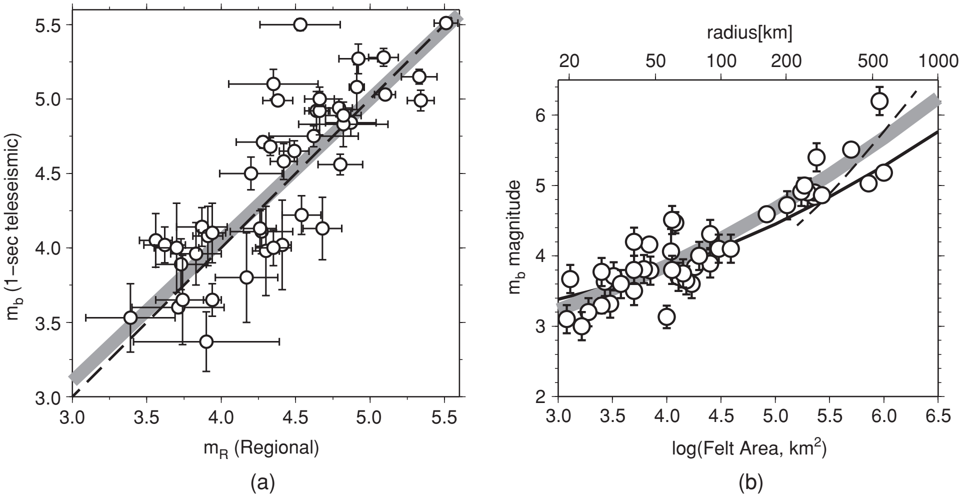

Figure 3.1 (a) Relationship between the regional magnitude scale m_R (Assumpção, 1983) and the teleseismic m_b scale (IASPEI). Error bars are standard deviations of the mean values. Grey line is the m_b:m_R regression, which is not statistically different than $m_b = m_R$ (dashed line). The regional scale is equivalent to the teleseismic magnitude. (b) Empirical relationship between total felt area (A_f) and magnitude. The magnitudes used in this plot are average of m_b and m_R values. The grey line is the regression $m = 2.44 - 0.015\log(A_f) + 0.0922[\log(A_f)]^2$; standard deviation = 0.35 magnitude units. The solid thin line is the empirical relation for Central and Eastern United States (Nuttli *et al.*, 1979) using magnitude $m_b(L_g)$. The dashed line is the approximate relationship between m_b and felt area from the worldwide compilation of Johnston *et al.* (1994). Top axis is the equivalent radius for the felt area.

3.2 Earthquake catalogue

The Brazilian earthquake catalogue is based mainly on the compilation of Berrocal *et al.* (1983, 1984) complemented since 1982 by the *Brazilian Seismic Bulletin* prepared jointly by the universities of São Paulo (USP), Brasília (UnB), Rio Grande do Norte (UFRN), and the Technological Research Institute (IPT) of the state of São Paulo. Other institutions (State University of São Paulo, UNESP, and National Observatory, ON) also contribute data to the Brazilian bulletin. Events in a neighbouring area just west of the Brazilian border (also characterized as SCR) are included to help establish correlation with intraplate geological and geophysical features – these events outside Brazil were taken from the literature, the ISC catalogue, as well as located by the Brazilian stations (e.g., Berrocal *et al.*, 1984).

The magnitude scale adopted in the catalogue is the 1-second P-wave teleseismic m_b, especially for events larger than about 5, and the regional magnitude (m_R) developed by Assumpção (1983) for earthquakes recorded between 200 km and 2000 km using the maximum P-wave particle velocity in the period range 0.1 to 1.0 s. Figure 3.1a shows that the regional magnitude m_R is equivalent to the teleseismic m_b scale in the range 3.5 to 5.5.

Magnitudes of historical earthquakes were estimated from felt area, as shown in Figure 3.1b. Both total felt area (inside isoseismal II MM) and A_{IV} (area inside isoseismal IV MM) were used. The relations between felt area and magnitudes are similar to those of the Central and Eastern United States as reported by Nuttli *et al*. (1979), and shown in Figure 3.1b. Our data are also consistent with the global compilation of Johnston *et al*. (1994) and Johnston (1996) for $m_b > 4.5$. An event with magnitude 5 is usually felt up to 200–500 km away. The new regression shown in Figure 3.1b is not significantly different from the one used by Berrocal *et al*. (1984). For historical events, m_b magnitudes can be estimated with a standard error of 0.35 units.

Completeness of the catalogue varies considerably according to the region. For the most populated areas, such as southeastern Brazil, magnitudes above 4.5 (which should be felt to 100 km distance or more; Figure 3.1) are believed to be complete since about 1850. For less populated areas such as the Amazon region, the threshold of 4.5 was only attained in the late 1960s with the installation of WWSSN stations in South America, and the array station in Brasilia, central Brazil.

3.3 Seismicity map

Figure 3.2a shows all epicentres of the Brazilian catalogue with magnitudes above 3.0 (a total of about 800 events) and the main geological provinces in Brazil (Almeida *et al*., 2000). Our seismic catalogue is relatively recent: the two earliest well-documented events with magnitude above 4 occurred in 1807 ($\sim$5 m_b in northeastern Brazil; Veloso, 2012) and 1861 ($\sim$4.4 m_b in southeastern Brazil). The maximum observed earthquake, with a magnitude of 6.2 m_b, occurred on 31 January 1955, in the northern part of the Parecis basin (Figure 3.2a). There are sparse historical data on a possibly large earthquake in the central Amazon basin in 1690, which could have magnitude $\sim$7 (Veloso, 2014), but no reliable accounts allow a confirmation.

Paleoseismological studies in northeastern Brazil (Bezerra *et al*., 2005, 2011; Rossetti *et al*., 2011) have described the collective occurrence of liquefaction structures in Quaternary gravels, which are consistent with magnitudes as high as $\sim$6.0–7.0. These paleoseismological studies are still patchily distributed in Brazil, but show that magnitudes up to 7 m_b should be considered in hazard estimates.

The distribution of epicentres in Figure 3.2a is much affected by the population distribution: the higher population density in southeastern and northeastern Brazil results in a large number of historical events reported in newspapers, old journals, and books. To be able to compare seismicity rates in different parts of the country a more geographically uniform coverage is necessary. For this reason, we filtered the Brazilian catalogue (Figure 3.2a) with time-variable thresholds to produce the "uniform" epicentral map of Figure 3.2b. We selected events with magnitudes higher than 6 since 1940 (probably detectable with the worldwide stations reporting to the ISS bulletin); magnitudes higher than 5.0 since 1962 due to the increased coverage of the WWSS network; magnitudes higher than 4.5 since 1968 due to the installation of the Brasilia array in 1967, the WWSSN

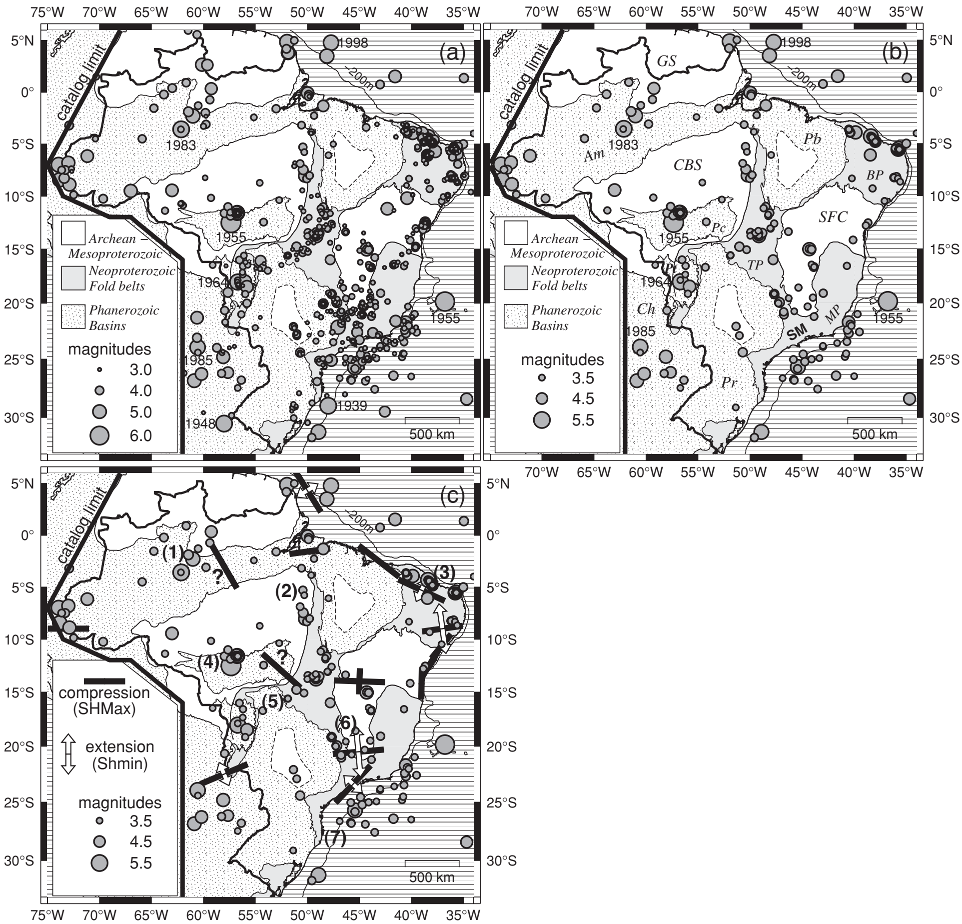

Figure 3.2 Intraplate epicentres in Brazil and neighbouring areas. (a) Raw catalogue, with crustal events only (depth < 50 km), and magnitudes ≥ 3.0. (b) "Uniform" catalogue with time-variable magnitude thresholds. Thick solid line is the approximate limit of the Brazilian catalogue. Shading denotes the main geological provinces in Brazil. Cratonic areas: Guyana shield (GS) and Central Brazil shield (CBS) as part of the Amazon craton; São Francisco craton (SFC); intracratonic basins: Amazon (Am), Parnaiba (Pb), Parecis (Pc), Chaco (Ch), Paraná (Pr) and Pantanal (Pt); Brasiliano fold belt provinces: Tocantins (TP), Borborema (BP), Mantiqueira (MP); SM denotes the "Serra do Mar" coastal ranges in southeast Brazil. Dashed white areas are proposed cratonic blocks in the middle of the Parnaíba and Paraná basins. Hatched area is the Atlantic Ocean where solid line (200 m bathymetry) denotes the edge of the continental shelf. Dates in (a) and (b) indicate magnitudes ≥ 5.3 m_b. (c) Epicentres of the uniform catalogue (open circles) and estimates of the stress field: grey bars are compressional principal stresses (S_{Hmax}); open arrows are extensional principal stresses (S_{hmin}); numbers denote main seismic zones as discussed in Section 3.3. For colour version, see Plates section.

station NAT in northeastern Brazil and general increase of seismological research in Brazil; magnitudes above 3.5 since 1980 due to the installation of several stations in various parts of the country by the University of Brasília (including the Amazon region) and the University of São Paulo. The magnitude thresholds defined above are our best estimates of the magnitude completeness of our catalogue. The geographically "uniform" catalogue (shown in Figure 3.2b) is not declustered. Both the raw (Figure 3.2a) and the uniform catalogues (Figure 3.2b) show several seismically active areas and large regions almost completely aseismic.

The stress field in Brazil is still poorly known due to the small number of well-determined focal mechanisms and few in-situ stress measurements. Data from the compilation of Assumpção (1992), other studies (Lima *et al.*, 1997; Ferreira *et al.*, 1998; Barros *et al.*, 2009, 2012; Chimpliganond *et al.*, 2010; Lima-Neto *et al.*, 2013), and recent unpublished results were combined to provide a preliminary estimate of the stress patterns in Brazil, shown in Figure 3.2c. Compressional stresses predominate with a trend of roughly east–west-oriented maximum horizontal stress (S_{Hmax}) in eastern Brazil, probably changing to a more NW–SE orientation in the Amazon region. A strong influence of the continental margin can be seen, making S_{Hmax} roughly parallel to the coast along most of the Atlantic shore. The effect of the continental margin has been explained as due to lateral density contrasts between continental and oceanic crust (e.g., Coblentz and Richardson, 1996) and flexural stresses (Assumpção, 1992, 1998).

Combining the distribution of seismicity (Figure 3.2a, b) with the estimated stress patterns (Figure 3.2c), the main active areas could be delineated as follows: (1) southern part of the Guyana shield and middle Amazon basin, the largest known event being a 5.5 m_b in 1983; (2) a north–south-trending zone along the eastern border of the Amazon craton; (3) northern part of the Borborema Province, in northeastern Brazil around the Potiguar marginal basin, with the largest known event occurring in 1980 with 5.2 m_b; (4) the Porto dos Gauchos seismic zone with activity known since the largest event of 1955 (Barros *et al.*, 2009); (5) a NE–SW zone in the Tocantins province possibly continuing towards the Pantanal basin; (6) southern Minas Gerais zone, in and around the southern tip of the São Francisco craton; and (7) the southeast offshore zone with activity concentrated along the continental slope from the Pelotas basin in the south to the Campos basin, from 33° S to 20° S (e.g., Assumpção, 1998; Assumpção *et al.*, 2011).

Remarkably, Branner (1912), on the basis of historical accounts, had already delineated the main seismic zones in Brazil (excluding the Amazon region) such as: northeastern Brazil (zone 3), Central Brazil and Mato Grosso (zone 5), and southeast Brazil (Minas Gerais and Rio de Janeiro; roughly zone 6). Most of the largest earthquakes (magnitude ~5) in the second half of the twentieth century occurred roughly in the same areas as defined by historical events in the late nineteenth and early twentieth centuries.

An interesting aspect of Brazilian seismicity is the different characteristics of the earthquake sequences in northeastern Brazil compared with other parts of the country. In northeastern Brazil, recurrent swarms and aftershock sequences, some lasting for several years, are very common (Takeya *et al.*, 1989; Ferreira *et al.*, 1998, 2008; Bezerra *et al.*, 2007), whereas large earthquakes (~5 m_b) in other parts of the country tend to occur as a single event with a short aftershock sequence.

We calculated the Gutenberg–Richter magnitude–frequency relation using the "uniform" catalogue for both continental and offshore earthquakes (Figure 3.2b), with the time-variable detectability thresholds above, using the method of Weichert (1980) for partially complete catalogues. This catalogue was declustered (reducing from 800 to 650 events) and a maximum magnitude of 7.0 was used. We obtained a *b*-value of 0.97 ± 0.06. The seismicity rate can best be evaluated for the cumulative frequency of earthquakes with magnitudes ≥5.0 m_b, for which we get a return period of 4 years, making this mid-plate area of South America one of the SCRs with the lowest seismicity rate in the world, as shown by Johnston *et al*. (1994).

3.4 Seismotectonic correlations

We now test the statistical significance of some general hypotheses and models regarding the distribution of seismicity in mid-plate South America, as seen in Figure 3.2. One must be aware, however, that the Brazilian historical and instrumental catalogue spans a very short time window and may not be representative of the long-term behaviour of intraplate seismicity, especially when events of magnitude 6+ have return periods of the order of a century. In addition, it has been suggested that long-term migration of activity in SCRs may be a common characteristic, such as in North America (Stein *et al*., 2009; Li *et al*., 2009) and Australia (Clark *et al*., Chapter 2, this book). Thus, the statistical tests below should be regarded as an initial study, and interpretation of the results should consider the relatively short time span of the catalogue.

3.4.1 Lower seismicity in Precambrian cratonic provinces

A first hypothesis to be tested is the possible lower seismicity of Mid-Proterozoic and older cratonic provinces. Cratons are usually regarded as more "stable" and rigid blocks, compared with the surrounding younger fold belts. We compared the distribution of continental seismicity only (east of the catalogue limit defined by the thick solid line in Figure 3.2), excluding the offshore area. For simplicity, we considered only the two exposed large cratonic areas in the Amazon and Atlantic shields, and have not included small cratonic blocks, such as the Luis Alves craton in Southern Brazil and the Apa block near the Brazil/Paraguay border, or cratonic blocks hidden beneath sedimentary basins such as the Rio de La Plata craton in northeast Argentina or the hypothesized cratonic blocks beneath the Parnaíba and Paraná basins. Figure 3.2b shows that the exposed cratons (Amazon and São Francisco cratons) correspond to 35% of the continental area (i.e., between the "catalogue limit" in Figure 3.2 and the coastline). If the seismicity distribution had no correlation with these large cratonic areas, we would expect about the same fraction of epicentres to be located in those cratonic areas. For the "whole" catalogue (Figure 3.2a) we would expect around 390 epicentres (35% of 1,118 epicentres) but we observe only 200. Getting half the expected rate is statistically highly significant. If we use the “uniform” catalogue, we get a similar result: about 40% of the expected rate (33 observed out of 82 expected).

We can then conclude that cratonic areas in mid-plate South America are about 50% less seismic than the average mid-plate seismicity in Brazil and neighbouring areas. Including smaller cratonic blocks (with areas less than 10% of the major Amazon and São Francisco cratons) would not change this result significantly. In fact, it would probably make the result even more clear, as most of these other small blocks have almost no earthquakes. We conclude that large cratonic areas are about four times less seismic than the other younger provinces: Brasiliano fold belts (~750–540 Ma) and intraplate basins. This may not seem surprising at first. Similar results can be found in other continents such as Australia, where Clark *et al*. (this volume) showed that cratonic crust is less seismic than non-cratonic areas.

The statistically significant result for Brazil could only be obtained on a continent-wide scale. Some cratonic areas can have high earthquake activity (such as in the middle of the São Francisco craton; e.g., Chimpliganond *et al*. [2010]) and regional comparisons of cratonic versus non-cratonic areas (such as done by Assumpção *et al*. [2004] for southeastern Brazil) had not produced statistically significant differences.

3.4.2 Intraplate seismicity and cratonic roots

Recently, Mooney *et al*. (2012) analyzed the global distribution of intraplate earthquakes and concluded that intraplate seismicity tends to concentrate around cratonic edges, especially for large magnitudes. The craton edges were defined by the S-wave anomalies from global-scale tomography. The global scale of that study included both mid-continent as well as passive margin earthquakes, and earthquakes more properly characterized by continental-shelf dynamics were included as “craton-edge” events. Here we compare the distribution of continental earthquakes with S-wave anomalies. We used the S-wave anomaly at 100 km, obtained from joint inversion of surface waves and receiver function point constraints (Assumpção *et al*., 2013), as a proxy for lithospheric depths (Figure 3.3).

The map of Figure 3.3a clearly shows a trend of higher seismicity above areas of low S-wave velocities, which is confirmed by the high frequency of epicentres above areas with S-wave anomalies between −1 and −4% (Figure 3.3c, d). This result confirms the findings of Assumpção *et al*. (2004), who showed that in Central Brazil higher seismicity is observed above areas of low P-wave velocities at lithospheric depths. This can be interpreted as stress concentrations in the upper crust due to lithospheric thinning.

Figure 3.3c, d also shows that the number of events above areas of very high S-wave velocities (anomalies ≥ +5% corresponding to cratonic cores or roots) is lower than expected. This is consistent with the finding above (Section 3.4.1) that cratonic areas tend to have lower seismicity. However, an interesting feature in these histograms is the peak of high seismicity above areas with anomalies in the range +3 to +5%. This seems to correspond to the cratonic edge effect found by Mooney *et al*. (2012) on a global scale.

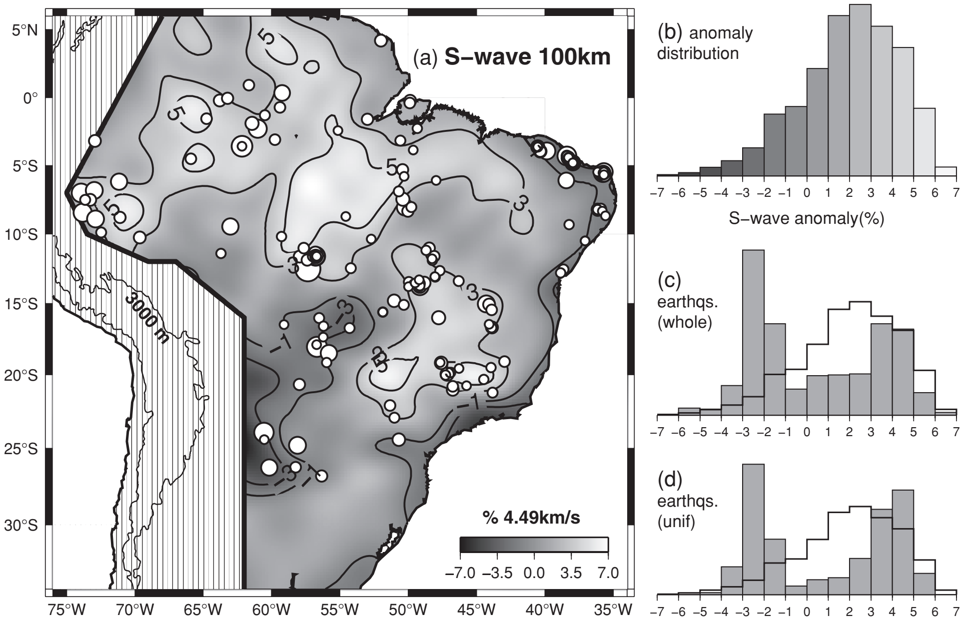

Figure 3.3 Comparison of S-wave anomalies with epicentral distribution. (a) S-wave anomalies at 100 km depth (Assumpção *et al.*, 2013) from joint inversion of surface waves and receiver function point constraints. White circles are epicentres from the "uniform" catalogue. (b) Histogram of the S-wave anomalies within the continent and east of the catalogue limit, corresponding to the grey-shaded area in (a). (c) Histogram of the S-wave anomalies beneath all continental epicentres of the "whole" catalogue. (d) Similarly for the "uniform" catalogue. The solid black lines in (c) and (d) indicate the distribution expected from (b) if the earthquakes had no correlation with lithospheric structure. For colour version, see Plates section.

Areas with "normal" lithospheric depths (anomalies between −1 and +3%) seem to be the least seismic.

3.4.3 *Passive margin seismicity*

Schulte and Mooney (2005) confirmed earlier findings (e.g., Sykes, 1978; Johnston and Kanter, 1990) that, on a global scale, intraplate earthquakes (M > 4.5) tend to occur preferentially in rifted crust, that is, in interior continental rifts (31%) or rifted continental margins (28%), compared with continental non-extended crust (41%). Considering that the area of non-extended crust in SCRs is several times that of rifted margins, it is clear that passive margins have a much higher seismicity rate. For magnitudes greater than 6, the preference for rifted crust is even stronger. Here we test if the extended crust along the Brazilian passive margin is significantly higher than the average continental area. The whole Brazilian margin was subjected to rifting during the Pangea breakup in the Jurassic–Cretaceous (Chang *et al.*, 1992). Therefore, we do not differentiate between interior rifts

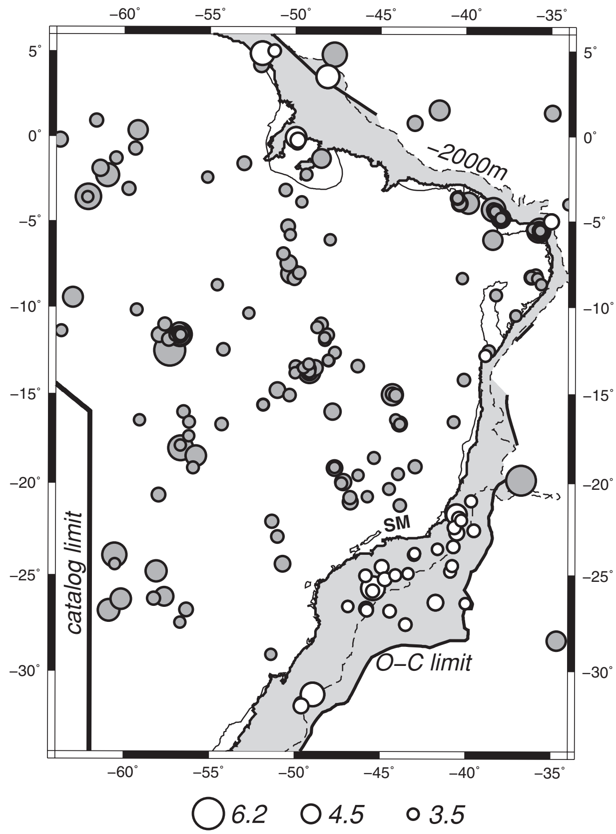

Figure 3.4 Comparison of seismicity between passive margin (shaded area, between the coastline and the oceanic–continental [O-C] limit) and interior SCR. The extension of the passive margin was defined using the mapped O-C limit, if available (thick solid line) offshore, or the 2,000 m bathymetric contour (dashed line) used as a proxy for the O-C limit. Thin solid lines near the coast indicate onshore marginal basins, not included in our definition of "passive margin". Open circles are epicentres in the passive margin, grey circles in the continental area (from the uniform catalogue of Figure 3.2b). "SM" in southeast Brazil denotes the presently aseismic "Serra do Mar" coastal ranges.

and non-extended crust along this margin, as this would require more extensive work to better define the area of influence of interior rifts.

A common definition of a "rifted continental margin" is the region of extended crust in the transition from normal continental to oceanic crust, in areas where extension led to seafloor spreading (e.g., Schulte and Mooney, 2005). For our statistical test, here we define "passive margin" as the area between the coastline and the oceanic–continental crustal limit (O-C limit), shown in Figure 3.4. The extension of the passive margin was defined using the mapped O-C limit, if available, or the 2,000 m bathymetric contour (used as a proxy for the O-C limit). Mapped O-C limits were taken from Houtz *et al.* (1977), Chang *et al.* (1992), Gomes (1992), Mohriak *et al.* (2000), Watts *et al.* (2009), and Zalan *et al.* (2011).

For simplicity, we did not include the onshore marginal basins, as different criteria could be used to define the onshore limit of the extended crust. We traded a more detailed and complex analysis for a simpler, more objective statistical test.

The continental region (Figure 3.2b) and the passive margin (Figure 3.4) have a total of 274 events with magnitudes 3.5 or greater in the uniform catalogue (238 in the continent and 36 in the passive margin). Taking into account the different sizes of both areas, we would expect only 21 events (7.8%) in the passive margin if the seismicity were uniformly distributed. The larger number of observed events (36) indicates that the Brazilian passive margin has a seismicity rate 70% higher than the average SCR seismicity, with a confidence limit better than 98%. A test using $m_b \geq 4.5$ also shows a larger number of events in the passive margin (six observed events compared to an expected number between two and three), but the small sample prevents a reliable measure of the statistical significance.

Although the Brazilian passive margin has a higher seismicity rate, on average, Figure 3.4 shows a high concentration in two areas: one in southeastern Brazil where the continental crust was subjected to an extreme degree of extension and thinning, and the other just north of the Amazon fan, both characterized by thick sedimentary sequences. Areas of short continental shelf (most of the eastern and northeastern margin), with generally thin sedimentary layers, have almost no earthquakes. This indicates that crustal weaknesses caused by high levels of extension, as well as flexural stresses, are important factors in defining seismicity rates in passive margins (e.g., Assumpção, 1998; Assumpção *et al.*, 2011). Concentration of seismicity in the continental margin is a common pattern of global seismicity, as shown by Schulte and Mooney (2005), but local conditions can cause significant variations along the margin, as shown by Sandiford and Egholm (2008) for Australia.

3.4.4 Influence of neotectonic faults

Neotectonic has been described as the period when young tectonic events have occurred and are still occurring in a given region after its last orogeny or after its last significant tectonic or stress field set up (e.g., Pavlides, 1989). The neotectonic period varies in different regions. There is no consensus on the onset of the neotectonic period in some passive margins, such as the Brazilian margin, where neotectonic studies are patchy. Therefore, we chose to analyze a preliminary neotectonic map of Brazil and show two examples of pre-existing fabric such as ductile shear zones and their relationship with the present-day seismicity.

Neotectonic activity in Brazil has been clearly observed in several areas (e.g., Riccomini and Assumpção, 1999; Bezerra and Vita-Finzi, 2000; Bezerra *et al.*, 2006, 2011), with observed geological faulting dated as recent as Holocene (e.g., Riccomini and Assumpção, 1999). A preliminary map of neotectonic faults in Brazil was presented by Saadi *et al.* (2002), with most of the mapped faults and lineaments likely to be active in the neotectonic period based on geomorphological criteria. While this compilation is still very preliminary and very few faults have geochronological dates, it is the only compilation spanning the whole country, and for this reason may be useful for some initial tests. For

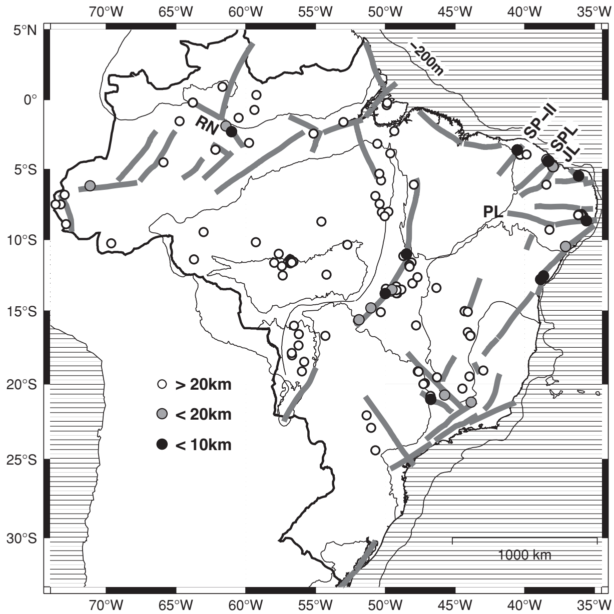

Figure 3.5 Correlation between neotectonic faults and epicentres of the "uniform" catalogue. Thick grey lines are the proposed neotectonic faults compiled by Saadi *et al.* (2002). Open circles are epicentres more than 20 km away from any fault segment; grey and solid circles denote epicentres in the range 20–10 km from any fault, and closer than 10 km, respectively. Thin solid lines are the limits of the major geological provinces as in Figure 3.2. Faults discussed in the text: RN, Rio Negro; PL, Pernambuco Lineament; SP-II, Sobral Pedro-II Lineament; SPL, Senador Pompeu Lineament; JL, Jaguaribe Lineament.

example, it is natural to wonder if the present seismicity tends to be close to the mapped neotectonic structures. Figure 3.5 shows a map of the neotectonic faults and lineaments as compiled by Saadi *et al.* (2002). We now test if the epicentres of the Brazilian catalogue (Figure 3.2) tend to lie close to the proposed neotectonic features. For these tests, we excluded the Samambaia fault (fault BR-38 in Saadi's compilation) because it had been defined only on the basis of the earthquake activity near João Câmara, northeast Brazil (5.5° S 35.5° W in Figure 3.2); the corresponding earthquakes were also removed from the database. In addition, we corrected the position of the fault BR-15 (Sobral Pedro-II in northeastern Brazil, labelled "SP-II" in Figure 3.5) because it was misplaced in Saadi's compilation.

Using the "uniform" catalogue (magnitudes above 3.5 m_b), we compared the number of observed epicentres closer than 20 km (or 10 km) to any fault segment, with the expected number assuming a random distribution of events in the continental area of Brazil. We used the criterion of 10 and 20 km distance because this is roughly the estimated epicentral accuracy of most events in the catalogue. Figure 3.5 shows the events closer than 20 km (and 10 km) from any fault segment. The chance of a random event being closer than 20 km to any fault segment is 8.8%. The uniform catalogue has 180 events, and 50 are closer than 20 km, which is about three times the expected number. For a 10 km distance, we would expect 8 events (4.3%) but observe 20 events closer than 10 km. This is highly significant (more than 99.9% confidence level). At a closer distance of 5 km, the results are similar. Both the "whole" (Figure 3.2a) and the "uniform" (Figure 3.2b) catalogues yield similar results. This indicates that areas close to the neotectonic faults mapped by Saadi *et al.* (2002) are two to three times more likely to have seismic activity, compared to areas far from the faults.

This is the case for northeastern Brazil, where seismicity is best known in the country due to many detailed studies of earthquake swarms and aftershocks using local networks. A clear example of the association of present-day seismicity with geological features is the Pernambuco Lineament, a ductile Brasiliano (~600 Ma) shear zone, reactivated in the brittle crust during the Pangea breakup in the Cretaceous. This feature was presented in the compilation of Saadi *et al.* (2002; "PL" in Figures 3.5 and 3.6a). Seismological studies indicated that this shear zone has been repeatedly reactivated in the past few decades (Ferreira *et al.*, 1998, 2008; Lopes *et al.*, 2010; Figure 3.6a). However, several other lineaments in this preliminary neotectonic map of Brazil do not have any evidence of paleoseismicity, historical or instrumental seismicity. For example, Ferreira *et al.* (1998) have shown that in northeastern Brazil most earthquakes have no direct correlation with large geological lineaments mapped at the surface, even when the epicentres are apparently very close to a major fault or shear zone. These are the cases of major shear zones shown in Figure 3.5, such as Jaguaribe Lineament (JL), Senador Pompeu Lineament (SPL), and the Sobral Pedro-II fault (SP-II).

The explanation for the reactivation of major lineaments, where others remain aseismic, is a matter of debate. For example, in northeastern Brazil, major shear zones were reactivated in the Pangea breakup and they form the boundaries of rifts (Chang *et al.*, 1992). The occurrence of pseudotachylyte in these mylonitic belts implies that they are exhumed paleoseismic zones (Kirkpatrick *et al.*, 2013). However, other continental-scale east–west-trending shear zones in northeastern Brazil (Figure 3.5) also present a long history of brittle reactivation and are also under the ~ east–west-trending maximum compression (S_{Hmax}) and ~north–south-trending extension (S_{hmin}), such as the Pernambuco shear zone (Figure 3.2c). A question remains as to why these other shear zones do not show present-day seismicity. Several processes have been proposed to explain mechanical fault weakness, such as the occurrence of low-friction material in the fault core (e.g., Morrow *et al.*, 1992) or the presence of high fluid pressure in the fault zone (e.g., Byerlee, 1990; Sibson, 1990). However, there is a paucity of evidence to support the idea that some of these processes can be responsible for the weakening of fault zones (Holdsworth *et al.*, 2001). As intraplate faults present long recurrence periods (e.g., Bezerra and Vita-Finzi, 2000), it is possible that these continental-scale features represent dormant structures. It follows that the short period of instrumental monitoring, poorly known historical seismicity, and lack of systematic paleoseismic investigations in Brazil indicate that further studies are necessary to address this problem.

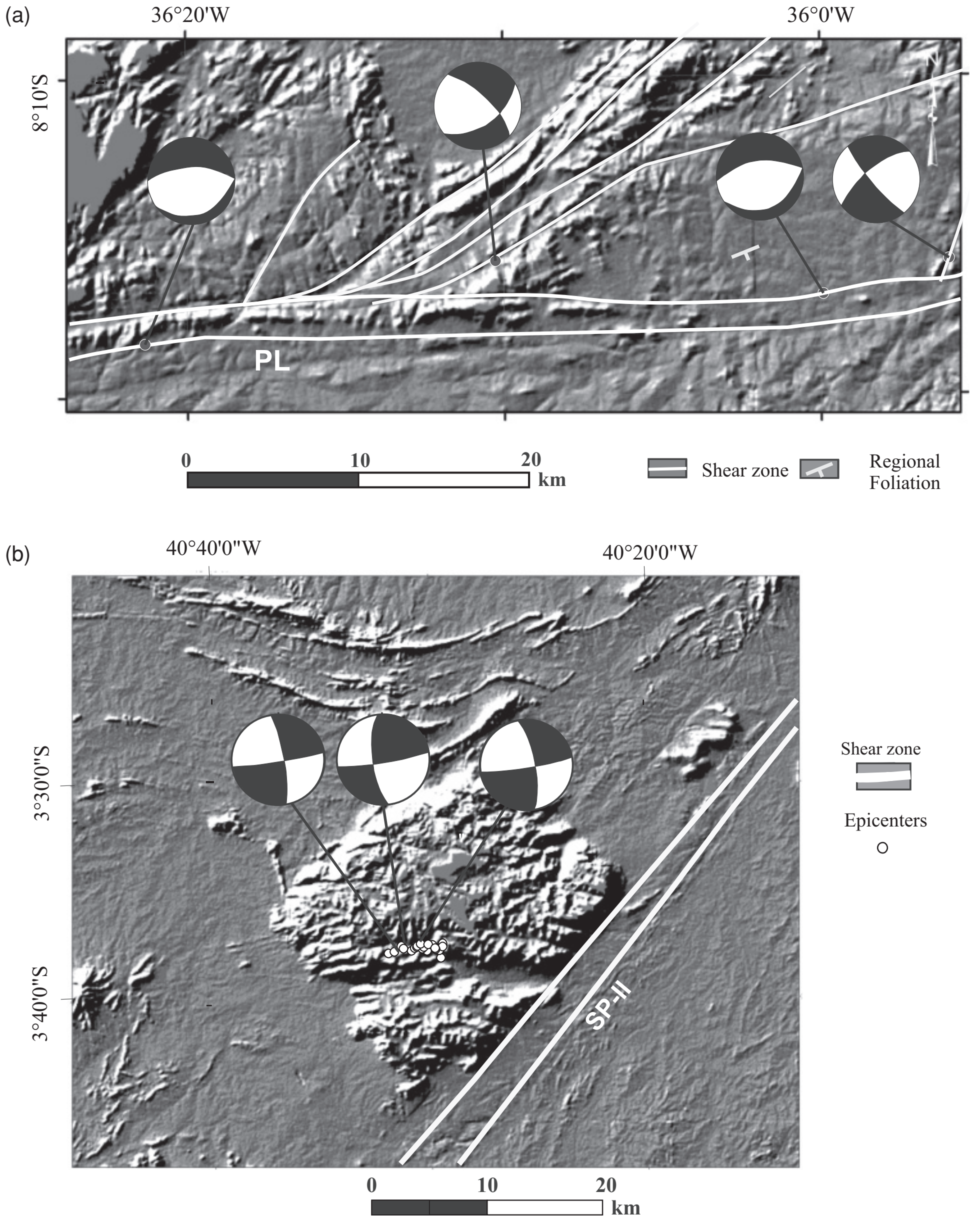

Figure 3.6 Examples of relationship of seismicity with major lineaments thought to be neotectonic features in northeastern Brazil. (a) Focal mechanisms in the present reactivation of the Pernambuco Shear zone ("PL" in this figure and in Figure 3.5). Note that events along the main E–W branch have E–W-trending normal faults, and events along the NE-trending branches are strike-slip because of the E–W compressional and N–S extensional principal stresses. Focal mechanisms from Lopes *et al.* (2010), Ferreira *et al.* (1998, 2008) and Lima-Neto *et al.* (2013). (b) Earthquake sequence in a small, E–W transcurrent fault about 10 km from the SW–NE-oriented Sobral Pedro-II Lineament ("SP-II" in Figure 3.5). The NW–SE regional maximum horizontal stress (Figure 3.2c) is not favorably oriented to reactivate the major lineament, but causes seismicity in a small previously unmapped fault nearby (Moura *et al.*, 2013).

The activity near the SW–NE-trending Jaguaribe Lineament (JL in Figure 3.5) actually occurs on an E–W-trending strike-slip seismogenic fracture ("Palhano" earthquakes in Ferreira *et al*. [1998]). The activity near the Senador Pompeu Lineament (SPL in Figure 3.5) occurs on a NW–SE-trending strike-slip fault ("Pacajus-Cascavel" activity in Ferreira *et al*., 1998). Finally, Moura *et al*. (2013) showed that the events close to the NE–SW-trending Sobral Pedro-II shear zone actually occur on a small E–W-trending fracture, as shown in Figure 3.6b. In the Amazon basin, a similar inconsistency can be found with the "Rio Negro" fault (BR-10 of Saadi *et al*., 2002; labelled "RN" in Figure 3.5): the event less than 10 km from the fault is the 5.1 m_b Manaus earthquake of 1963, 45 km deep, which had a well-determined reverse faulting mechanism with the two nodal planes oriented SW–NE (Assumpção and Suárez, 1988), clearly inconsistent with the SE–NW trend of the Rio Negro fault.

Our statistical tests showing higher seismicity up to about 20 km from faults interpreted as being neotectonic may, in fact, indicate a zone more prone to seismic activity, but not necessarily a direct relationship. The presence of a neotectonic feature might increase the chances of stress concentration in intersection zones involving other smaller fractures, such as proposed by Talwani (1999) and Gangopadhyay and Talwani (2003; 2007). In addition, the major lineament may not be favourably oriented with respect to the present stresses while other smaller faults may be optimally oriented, such as shown in Figure 3.6b.

3.4.5 Flexural stresses

Flexural stresses are known to contribute significantly to earthquakes in the continental shelf (e.g., Stein *et al*., 1989; Assumpção, 1998; Assumpção *et al*., 2011) as well as in the stable continental interior, such as in the Amazon basin (Zoback and Richardson, 1996).

Flexural stresses can reach high magnitudes, and even apparently small loads can contribute significantly to intraplate stresses as shown by Calais *et al*. (2010) by modelling the effect of Late-Pleistocene erosion in the New Madrid seismicity. In Brazil, the SW–NE-trending seismic zone in the Tocantins province (Figure 3.2) coincides with high gravity anomalies (Figure 3.7). Assumpção and Sacek (2013) showed that the uncompensated lithospheric load, which causes the high gravity anomalies, produces large compressional stresses in the upper crust (due to flexural bending of the lithosphere) and explained the seismicity distribution in Central Brazil. Here we test whether the correlation between gravity anomalies and seismicity can be extrapolated to all of the mid-plate area in South America.

We used the isostatic gravity anomaly map of South America (Sá, 2004), also used by Assumpção and Sacek (2013). Figure 3.7 shows the epicentres of the "whole" catalogue and the gravity anomalies. It can be seen that most epicentres tend to be located in areas of positive gravity anomalies, and large areas without seismicity (such as in the middle of the Paraná and Parnaíba basins, as well as in the Guaporé shield) tend to have negative gravity anomalies. The average isostatic anomaly in the continental area shown in Figure 3.7a is −13 mGal (Figure 3.7b). The distribution of gravity anomalies at the

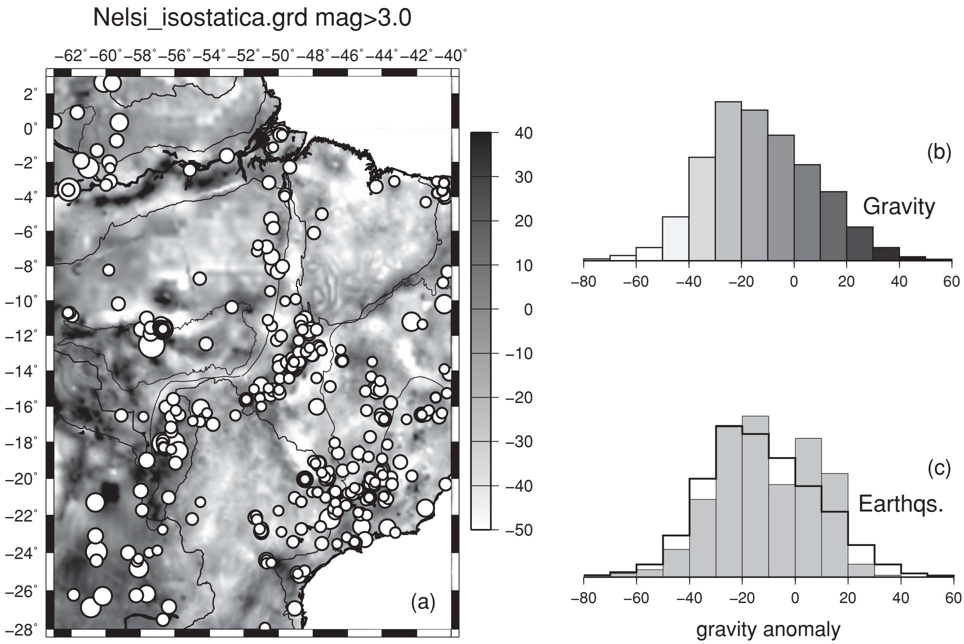

Figure 3.7 Isostatic gravity anomalies and epicentral distribution. (a) Map of epicentres of the "whole" catalogue, with magnitudes ≥ 3.0 and isostatic anomalies; scale in mGal. (b) Distribution of the gravity anomalies in the continental area shown in the map. (c) Grey bars are the gravity anomaly distribution at the epicentres. The thick solid line is the expected frequency, based on the gravity distribution, if the epicentres were uncorrelated with gravity anomalies. For colour version, see Plates section.

epicentres is shown by the grey histogram in Figure 3.7c. There are relatively more events in areas with high gravity anomalies (0 to 20 mGal) and fewer events in areas with low gravity (−50 to −30 mGal) compared to the expected numbers. This result shows that positive isostatic gravity anomalies are correlated with a higher seismicity rate, indicating that flexural stresses are an important factor in explaining intraplate seismicity in most of Brazil, and not only in the Tocantins province.

3.5 Discussion and conclusions

Mid-plate South America is less seismic than most other continental mid-plate regions such as Central and Eastern North America, Australia, India, and China. The largest known magnitude is 6.2 m_b, and the seismicity rate can be quantified by a return period of about 4 years for magnitude 5 and above. Despite this low rate of activity, it can be seen that earthquakes tend to occur in some seismic zones with large "aseismic" areas in between. No simple model can explain all the intraplate activity. Cratonic regions tend to have lower rates of seismicity, on average, but some magnitudes around 5 have been observed in old cratonic areas. In the cratons, seismicity tends to occur around deep lithospheric keels, or in craton edges, in agreement with similar findings on a global scale (Mooney *et al*., 2012).

Areas near proposed neotectonic faults (less than 20 km) also seem to be more prone to seismic activity compared with areas farther away from these features. However, this correlation only holds on a continental scale: several neotectonic faults have no evidence of seismic activity (Figure 3.5) and no neotectonic features have been mapped yet in several seismic zones, such as the northern Parecis and the Pantanal basins. The compilation of neotectonic faults by Saadi *et al*. (2002) is a preliminary result and many more active features still remain to be mapped. Also, the sampling of neotectonic features compiled by Saadi *et al*. may have been influenced by known regions of seismicity, such as the Codajás fault (BR-05) in the Amazon basin, and the Manga fault (BR-47) in the middle of the São Francisco craton. However, despite the uneven sampling of possible neotectonic faults, the correlation with epicentral distribution is statistically highly significant. On the other hand, comparisons of the fault-plane solutions of several events close to these faults (especially in northeastern Brazil) reveal inconsistencies between the earthquake fault planes and the geologically mapped structures. We propose that the statistical correlation between epicentres and neotectonic features is due to some other mechanism, such as stress concentration near intersecting structures, as proposed by Gangopadhyay and Talwani (2003, 2007), or unfavourable orientation of the main regional fault with respect to the current intraplate stresses. At any rate, the relationship of neotectonic features and intraplate seismicity deserves further studies.

Seismic zones such as the eastern border of the Amazon craton and the northern Parecis basin (zones 2 and 4 in Figure 3.2c) could be attributed to stress concentration due both to lateral density variation in cratonic keels and to flexural stresses from intracrustal loads. Seismicity in northeastern Brazil (zone 3) and in the Pantanal basin (zone 5) could be related to stress concentration in the upper crust in areas of thin and weak lithosphere, such as proposed by Assumpção *et al*. (2004) for central and southeastern Brazil. The seismic zone in the middle of the Amazon basin (zone 1) could be influenced by flexural stresses from intracrustal loads along the Amazon rift (Figure 3.7), as proposed by Zoback and Richardson (1996), but probably other causes are also necessary as no seismicity is observed directly above the gravity high.

An interesting aspect of the seismicity distribution in southeast Brazil is the complete lack of epicentres along the Serra do Mar coastal ranges ("SM" in Figure 3.2b and Figure 3.4). A system of Cenozoic continental rifts, together with the high topography of the coastal ranges, have been subjected to several neotectonic studies (e.g., Riccomini and Assumpção, 1999; Modenesi-Gauttieri *et al*., 2002; Cogné *et al*., 2012), which have mapped many faults, some with Holocene reactivation (carbon-14 dating). The compilation of Saadi *et al*. (2002) includes several neotectonic faults along the southeast coastal ranges (Figure 3.5). The extensive evidence of Quaternary activity and lack of epicentres in the Brazilian catalogue led Assumpção and Riccomini (2011) to propose the possibility of long-term seismic migration in southeast Brazil.

Clearly, no simple model seems to explain the location of all seismic zones, and a combination of several factors may be necessary to explain the concentration of activity in some areas. Stress concentration mechanisms from lateral density variations (at the edge of cratonic keels, and from flexural deformation) seem to be very effective in mid-plate South America. Zones of weakness are not easily defined and have not been tested properly in this chapter. However, the higher probability of earthquakes occurring near (but not exactly on) neotectonic faults (weak zones?) may indicate that the model of stress concentrations near intersecting structures may also be applicable to Brazil.

While the statistical correlation of the present seismicity with geological and geophysical features may shed some light on the mechanics of intraplate seismogenesis, especially when similar results are found in other SCRs, one must be aware of the short time window of the Brazilian historical and instrumental catalogue. Further studies are necessary to see if long-term seismicity migration could help explain the lack of epicentres near geological features that are seismically active in other areas.

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