Anais da Academia Brasileira de Ciências (2016) 88(3): 1253-1264
(Annals of the Brazilian Academy of Sciences)
Printed version ISSN 0001-3765 / Online version ISSN 1678-2690
http://dx.doi.org/10.1590/0001-3765201620140507
www.scielo.br/aabc

The 2009 earthquake, magnitude m_b 4.8, in the Pantanal Wetlands, west-central Brazil

FÁBIO L. DIAS[1], MARCELO ASSUMPÇÃO[1], EDNA M. FACINCANI[2], GEORGE S. FRANÇA[3], MARIO L. ASSINE[4], ANTÔNIO C. PARANHOS FILHO[5] and ROBERTO M. GAMARRA[5]

[1]Universidade de São Paulo/USP, Departamento de Geofísica, IAG, Rua do Matão, 1226, Cidade Universitária, 05508-090 São Paulo, SP, Brasil
[2]Universidade Federal de Mato Grosso do Sul/UFMS, Campus de Aquidauana/CPAq, Av. Oscar Trindade de Barros, s/n, Serraria, 79200-000 Aquidauana, MS, Brasil
[3]Universidade de Brasília/UnB, Observatório Sismológico, Instituto de Geociências, Campus Universitário Darcy Ribeiro, Asa Norte, 70910-900 Brasília, DF, Brasil
[4]Universidade Estadual Paulista/UNESP, IGCE, Departamento de Geologia Aplicada, Campus de Rio Claro, Av. 24 A, 1515, Bela Vista, 13506-900 Rio Claro, SP, Brasil
[5]Universidade Federal de Mato Grosso do Sul/UFMS, Faculdade de Engenharias, Arquitetura e Urbanismo e Geografia/FAENG, Cidade Universitária, s/n, Caixa Postal 549, 79070-900 Campo Grande, MS, Brasil

Manuscript received on June 8, 2015; accepted for publication on August 15, 2015

ABSTRACT

The main goal of this paper is to characterize the Coxim earthquake occurred in June 15th, 2009 in the Pantanal Basin and to discuss the relationship between its faulting mechanism with the Transbrasiliano Lineament. The earthquake had maximum intensity MM V causing damage in farm houses and was felt in several cities located around, including Campo Grande and Goiânia. The event had an m_b 4.8 magnitude and depth was 6 km, i.e., it occurred in the upper crust, within the basement and 5 km below the Cenozoic sedimentary cover. The mechanism, a thrust fault mechanism with lateral motion, was obtained by P-wave first-motion polarities and confirmed by regional waveform modelling. The two nodal planes have orientations (strike/dip) of 300°/55° and 180°/55° and the orientation of the P-axis is approximately NE-SW. The results are similar to the Pantanal earthquake of 1964 with m_b 5.4 and NE-SW compressional axis. Both events show that Pantanal Basin is a seismically active area, under compressional stress. The focal mechanism of the 1964 and 2009 events have no nodal plane that could be directly associated with the main SW-NE trending Transbrasiliano system indicating that a direct link of the Transbrasiliano with the seismicity in the Pantanal Basin is improbable.

Key words: Earthquake, neotectonics, intraplate stress, Pantanal basin, focal mechanism.

INTRODUCTION

The Pantanal Basin has been regarded as one of the seismic regions of Brazil (Branner 1912, Berrocal et al. 1984) as shown in Fig. 1. According Sykes (1978) and Talwani and Rajendran (1991), intraplate earthquakes are the result of ruptures along pre-existing zones of weakness, located near structural inhomogeneities, which may concentrate local stress and, added to regional stress, are

Correspondence to: Fábio Luiz Dias
E-mail: fabioludias@gmail.com

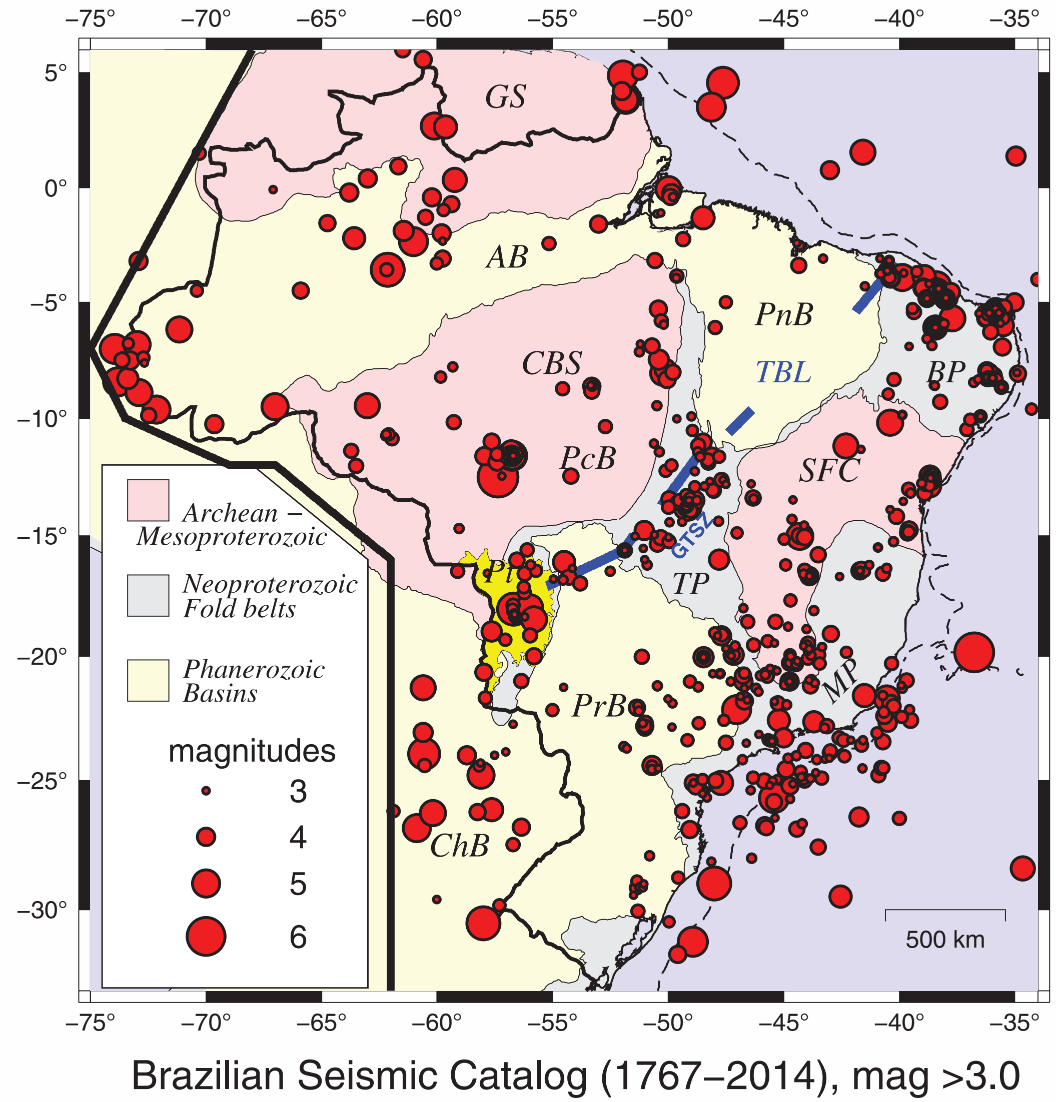

Figure 1 - Epicenters known in Brazil (Assumpção et al. 2014) and the main geological provinces of the country: *GS* = Guyana shield, *CBS* = Central Brazil shield, *SFC* = São Francisco craton; *AB* = Amazon basin, *PnB* = Parnaiba Basin, *PcB* = Parecis Basin, *BP* = Borborema Province, *ChB* = Chaco Basin, *TP* = Tocantins Province, *PrB* = Paraná Basin, *MP* = Mantiqueira Province. The total area of the Pantanal (*Pt*) is shown is highlighted. The bold line shows the strongest traits of Transbrasiliano Lineament (*TBL*) and Goiás-Tocantins Seismic Zone (*GTSZ*) is also indicated.

capable of generating earthquakes. Riccomini and Assumpção (1999), Mazzotti 2007 and Assumpção et al. (2014) proposed a range of possible causes of neotectonics in Brazil and their relations with the seismicity. In the Pantanal case, the cause of the seismicity is not well known.

The reasons for intraplate seismicity and its relation with geology are not easy to explain. The "resurgent tectonics" (Hasui 1990) and its possible relation with seismicity in the center-west region are marked by the Transbrasiliano Lineament (TBL) with average direction N30°E (Schobbenhaus et al. 1975, Curto et al. 2014). These Neoproterozoic brittle structures have been reactivated in the Paleozoic, Mesozoic and Cenozoic. The lineament is a striking feature with continental dimensions

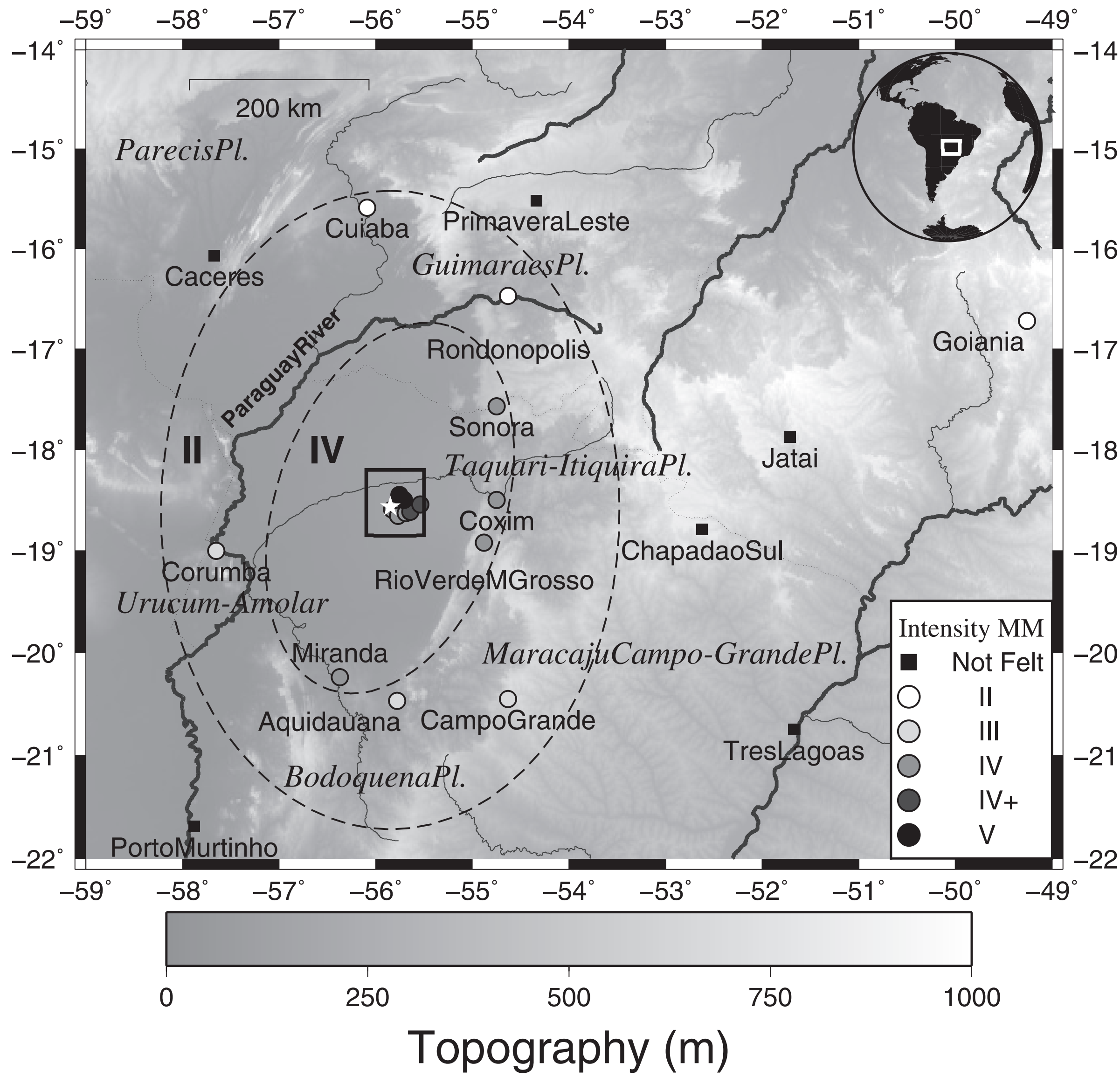

Figure 2 - Map of earthquake intensity Coxim earthquake (star). The color of the circles represents the different intensities felt by the population. The large and small ellipses are lines isoseismal MM II and MM IV, respectively. Black squares are major cities in the region where the tremor was not felt. The principal plateaus (Pl.) and the hydrography are also shown. The square in epicentral region corresponds to Fig. 3.

in central and northeast of Brazil and extending into Africa. The possible role of the structures associated with the TBL in the evolution of the sedimentary basin of the Pantanal was discussed by Soares et al. (1998), Assine and Soares (2004), Facincani (2007) and Facincani et al. (2011).

Close to the TBL, there is SW-NE-oriented earthquake zone with magnitude up to m_b 5 called Goiás-Tocantins seismic zone (GTSZ), inside of Tocantins province (Fig. 1). Earthquakes in the Pantanal seem to form a seismic zone linked to this seismic zone, which could suggest a relationship with the TBL (Assine 2003) (Fig. 1). Barros et al. (2015) used first-motion P-wave polarities and full waveform modelling to study the focal mechanism of an mb 5.0 event in GTSZ occurred in 2010. The

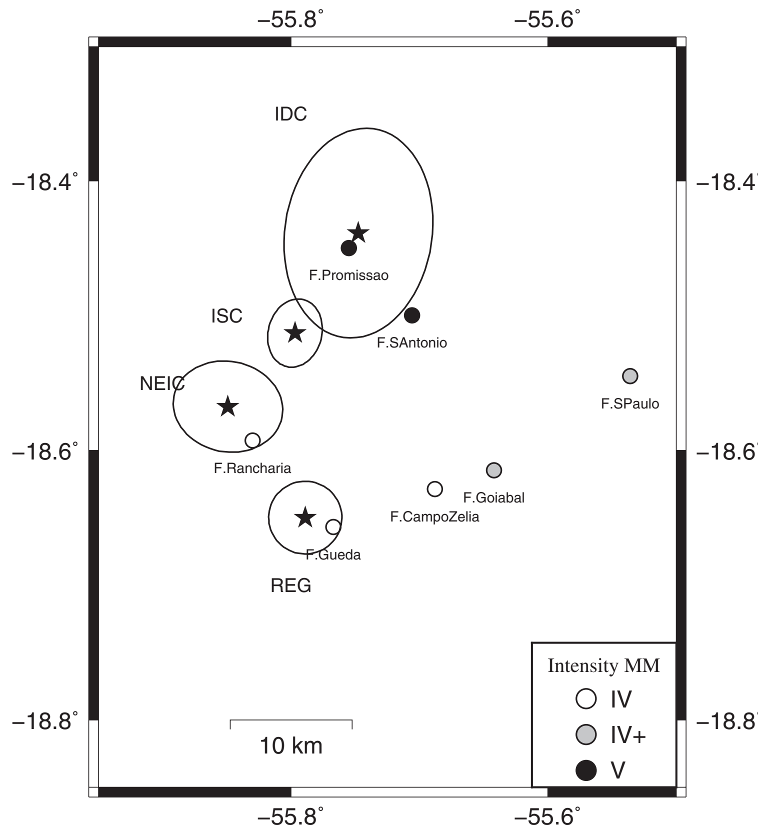

Figure 3 - Macrosseimic survey in the epicentral area. The maximum intensity was MM V near Promissão and Santo Antônio farms. The epicenters of different international agencies (ISC, IDC, USGS/NEIC) and this paper (REG) are represented by the stars, with ellipses showing their 95% confidence region.

authors propounded a thrust mechanism with a SW-NE faulting and they associated this earthquake with the TBL.

On the other hand, the TBL is accompanied by seismic activity in Goiás and Tocantins, but there is no seismicity associated with the TBL in the Parnaíba Basin. For this reason, Assumpção and Sacek (2013) suggested that the seismic activity in Central Brazil could be a result of compressional stress in the upper crust due to lithosphere flexural deformation caused by crustal thickness variations. In this case, the proximity of the TBL would only be a coincidence.

The objectives of this paper are to characterize the earthquake occurred in the Pantanal Nhecolândia, Taquari Fan on June 15th, 2009 at 22:14:45 UTC highlighting its location, magnitude, intensity and the possible relationship between the faulting mechanism of the event with the TBL.

TECTONIC SETTING

The Pantanal wetland is a sedimentary basin of Quaternary age, tectonically active, located in the Upper Paraguay River Basin, Central-West of Brazil. The basin is surrounded by the Maracaju-Campo Grande and Taquari-Itiquira plateaus in the east, Guimarães and Parecis plateaus in the north, Urucum-Amolar in the west and Bodoquena plateau in the south (Fig. 2). The Paraguay River collects water from several megafan rivers, situated in its left margin (Assine and Soares 2004). The basin is structured by faults and it is the main neotectonics feature in the state of Mato Grosso do Sul (Facincani et al. 2011). The Pantanal basin is a tectonic depression located at the left margin of the Paraguay River.

The basin was a result of tectonic reactivation of the forebulge in the last Andean compressive stage approximately at 2.5 Ma (Ussami et al. 1999). Studies performed at the basin such as oil company drill holes (Weyler 1962), shallow water wells, and reflection seismic data (Catto 1975), indicate that the maximum Cenozoic sediment thickness (500 m) is located in the center of the basin and the basement is mainly composed by low-grade metamorphic rocks of the Neoproterozoic Alto Paraguay folded belt.

Subsidence rate of the basin has not been measured so far. A rough estimate of the subsidence rate could be made based on the maximum sedimentary thickness (about 500m from seismic reflection surveys). Assuming the model of Ussami et al. (1999), considering the start of subsidence at about 2.5 Ma as a result of the Andean forebulge migration, we would get a value of the order of 0.2 mm/year.

EPICENTER, INTENSITY, MAGNITUDE

Figs. 2 and 3 show the most affected areas by the earthquake and the reported intensities are in the Modified Mercalli (MM) scale values. The macroseismic survey began 17 days after the earthquake. Residents in the surveyed farms answered standard questions like if there were falling or swinging objects, damage to tiles, walls, noise, etc. Information published in newspapers and on the Internet about the effects in neighboring towns was also used. The event was felt in the towns of Coxim, Sonora, São Gabriel do Oeste, Miranda, Rio Verde, Rio Negro, Alcinópolis, Corguinho, Rondonópolis, Nioaque, Aquidauana, Rochedo, Corumbá, Pedro Gomes, Campo Grande, Cuiabá as far as 300 km. The result of this compilation is shown in Figs. 2 and 3.

Two small aftershocks were felt by some residents in the Promissão and Santo Antônio farms (Facincani et al. 2011), but they were not large enough to be recorded by regional seismographic stations, situated more than 800 km away from the epicentral area.

The maximum effect was characterized by fall of objects to the ground, damage to plaster and fall of roof tiles in the Santo Antônio and Promissão farms (Fig. 3), which corresponds to intensity MM V. This fact suggests that the macroseismic epicenter is closer to these farms.

The epicenter of the earthquake was determined by several agencies (Fig. 3): ISC (International Seismological Centre), IDC (International Data Centre in Vienna) and USGS/NEIC (U.S. Geological Survey/National Earthquake Information Center). The uncertainties indicated in Fig. 3 refer to the consistency of the data for a 1D model of the Earth structure because it was not taken into account lateral heterogeneities in the Earth. Anyway, the ISC and IDC epicenters are more compatible with the highest observed intensity of MM V.

The best epicenter is the one determined by IDC (-18.57°, -55.85°). The epicentral area was about 100 km W of Coxim, near Santo Antônio and Promissão farm (-18.4°, -55.7°), within the Pantanal wetland (Facincani et al. 2011). ISC location was obtained using 447 stations with azimuthal gap of 36° and fixed depth of 10 km. The closest station of this location was ~600 km away, located in Bolivia.

A determination with 19 Brazilian regional stations (between 630 and 1440 km distance), using the Regional Seismic Travel Time (RSTT) velocity model (Myers et al. 2011) resulted in an epicenter ~ 40 km south of the probable (macroseismic) epicenter. This error is probably also due to lateral variations in the structure of the Brazilian lithosphere, and inaccuracy of the model, which affected the epicentral location.

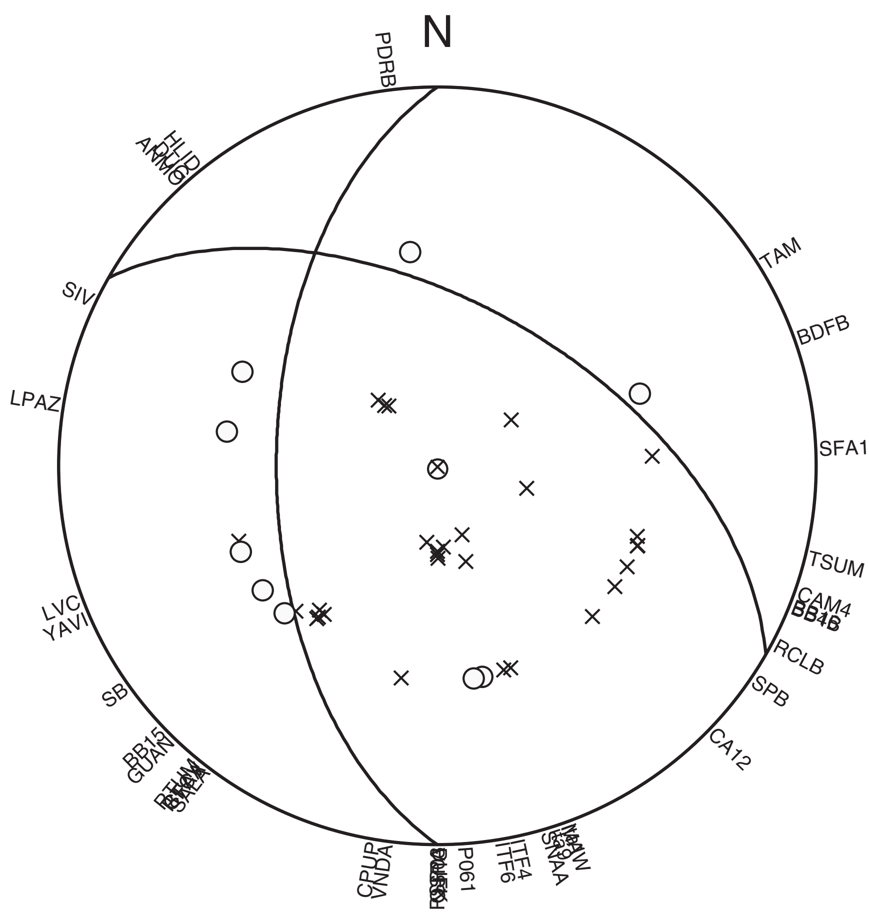

Figure 4 - Stereographic projection (lower hemisphere) of the focal mechanism of the Coxim earthquake of 2009. Crosses indicate compressional P-wave first motion; circles are dilatational motion. The two nodal planes are the two possibilities for the fault plane: N-S or NW-SE. The name of the seismographic stations and the north are also indicated. This mechanism is a reverse fault with transcurrent component.

Different magnitude scales can be used to quantify the size of an earthquake. The regional magnitude, used for earthquakes in Brazil (Assumpção 1983), is calculated by the maximum peak-to-peak amplitude of the P-wave particle velocity (V, μm/s), using Eq (1).

$$m_R = \log V + 2.3 \log R - 2.28 \qquad [1]$$

where R is the epicentral distance in km. This relation was established for distance range $200 \leq R \leq 1500$ km.

Using 11 stations, located in Brazil, Argentina, Paraguay and Bolivia, the m_R magnitude was determined as 4.82 ± 0.12, similar to the teleseismic P-wave magnitude m_b 4.8 published by the ISC.

The M_s magnitude (Rayleigh surface waves) is defined by Eq. (2).

$$M_s = \log (V_{max}/2\pi) + 1.66 \log \Delta + 0.3 \qquad [2]$$

where V is the maximum amplitude of the Rayleigh wave (in nm/s) with a period T between 3 and 60 s and distance in degrees (Δ) between 2° and 160° (Bormann et al. 2013). For Coxim earthquake, the M_s magnitude was estimated at 4.87 ± 0.03, by using 20 stations, located in Brazil, Argentina, Paraguay, Bolivia and Venezuela.

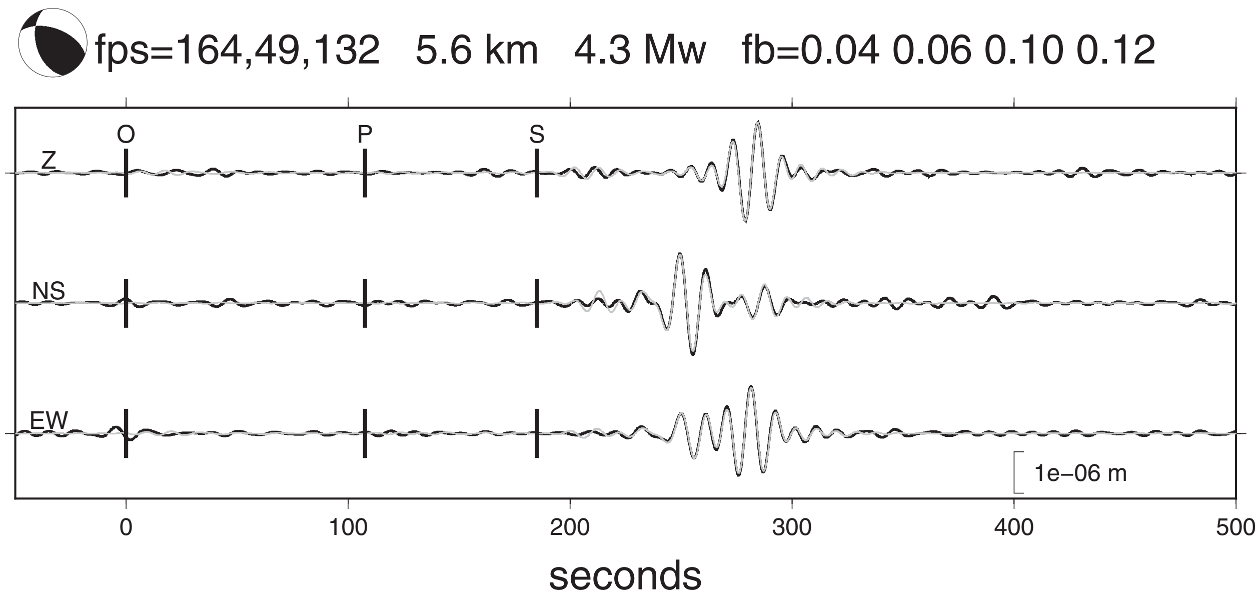

Figure 5 - Coxim event surface waves modeling using ISOLA program with CPSP methodology from Fojtíková and Zahradník (2014). In order, we have Z, NS and EW components in displacement (m) from BEB4B station (~ 800 km distance) with origin time (O), P and S-waves arrival marked. Observed data is the black line and synthetic is gray. The focal mechanism is shown in the top left with the depth, magnitude Mw and the frequency band used.

Although there is no direct relationship between the intensity and magnitude, some empirical relationships can be used to estimate the magnitude from the felt area. In Brazil, we can use the relations developed by Assumpção et al. (1980):

$$m_b = 1.63 + 0.60 \log (A_{II}) \qquad [3]$$

$$m_b = 2.29 + 0.55 \log (A_{IV}) \qquad [4]$$

where A_{II} and A_{IV} are the areas enclosed by MM II and MM IV isoseismal lines respectively

Fig. 2 shows that $A_{II} \sim 410000$ km^2 and A_{IV} ~130000 km^2 indicate inferred magnitudes of 5.1 and 5.0, respectively. These values show that the size of the affected areas is consistent with the instrumental magnitude m_b 4.8, especially considering the standard deviation of the order of 0.3 magnitude units of the empirical relationships (Eq. 3 and 4). We also determined an M_w 4.3 magnitude, as discussed in the next section.

FOCAL MECHANISM AND DEPTH

We use the P-wave first motion polarity data from regional and teleseismic stations to adjusting the fault planes (Fig. 4). We used regional waveform modelling as an independent check of the focal mechanism obtained by the P-wave first motions. We modelled the surface waves with the ISOLA code (Sokos and Zahradník 2008, 2013) for BEB4B station located in Bebedouro-SP city, approximately 800 km away from the event, using a 1D velocity earth model obtained by analysis of Love and Rayleigh surface-wave dispersion as shown by Dias et al. (in press). All nodal planes satisfying the polarity data of Fig. 4 were tried with the CPSP (Cyclic Scanning of the Polarity Solutions) method of Fojtíková and Zahradník (2014) and the solution that fits better both the polarities and the waveform is shown in Fig. 5.

We have a good fit between observed and synthetic data with a fit greater than 80%. Besides the waveform, as it was used in Fig. 6, the

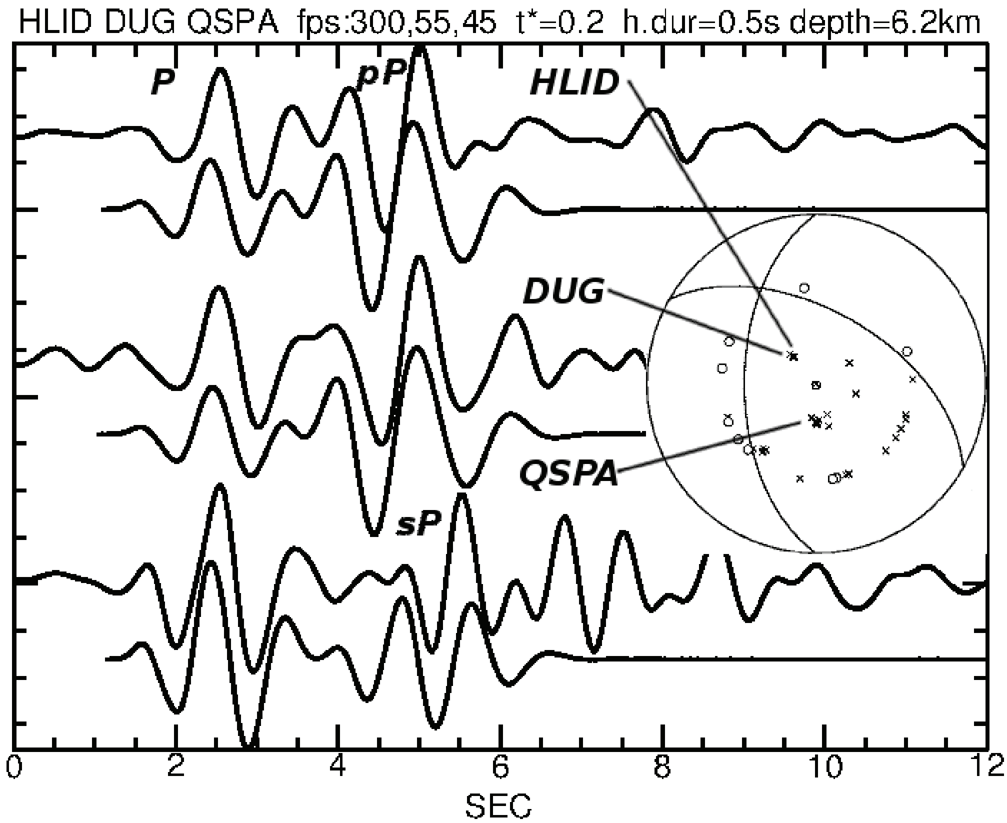

Figure 6 - Teleseismic P-wave modeling to determine the depth, with three stations (top to bottom): HLID, DUG (both in the United States) and QSPA (South Pole). The upper/lower traces are observed/calculated seismograms. Seismograms converted to WWSP response and modeled with a triangular source-time function with total duration 1.0 s and t* 0.2. The pP phase appears 2.0 s after the P, with reversed polarity and sP phase appears 4.0 s after the P in QSPA station.

seismogram amplitude was also modelled, so it was possible to obtain an Mw magnitude of 4.3. The mechanism obtained from the regional waveform modelling (Fig. 5) is similar to the one obtained with P-wave polarities (Fig. 4). This shows that the mechanism from first-motion polarities is reliable. Furthermore, the focal solution was confirmed by the Frequency Range Test developed by Dias et al. (in press).

The focal mechanism (Fig. 4) was predominantly a reverse fault with a component of strike-slip movement. It is not possible to define which nodal plane is the seismogenic fault. The mechanism shows an orientation of the P-axis which is approximately NE-SW. None of nodal planes (P-wave polarity solution Fig. 4, or regional waveform inversion of Fig. 5) have SW-NE orientation parallel to the TBL. This means that it is very unlikely that the Coxim event could be directly associated to any SW-NE structure of the main TBL system.

International agencies have not determined the depth of the event because, for shallow earthquakes, it is not always possible to identify the pP phase (P-wave surface reflection at the source). The depth was determined by forward modelling the waveform of stations at teleseismic distances (Fig. 6) using the previous mechanism from polarity data. In the waveform modelling, a triangular source time function of 1.0 s total duration, an average upper mantle attenuation of t*=0.2 s, and the focal mechanism from Fig. 4 were used. The

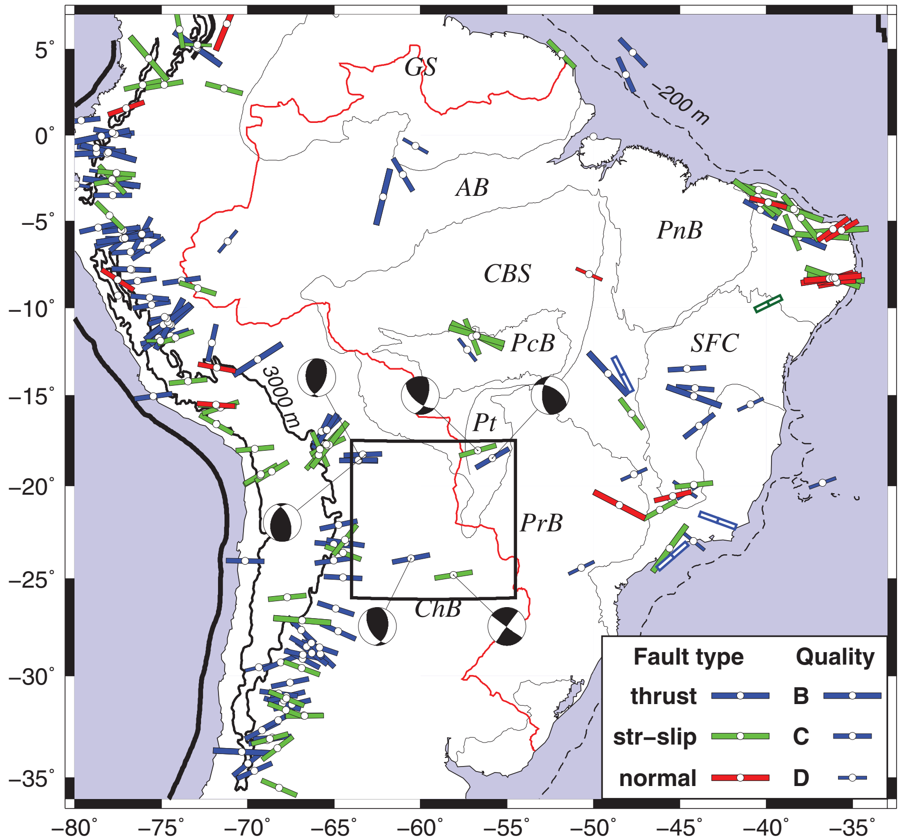

Figure 7 - Maximum horizontal stress direction from focal mechanism. The colors are the mechanism type and the size of bars (B, C and D) indicates the quality of the fault plane solution conform WSM – Project criteria (site: http://dc-app3-14.gfz-potsdam.de/index.html). The bar direction corresponds to compressional axis (P-axis) in thrust and strike-slip and null axis (B-axis, the intersection of the two nodal planes) in normal faults. The rectangle shows the mechanisms used in the stress inversion in Fig. 8. The main geological provinces are the same as Fig. 1. Data from Assumpção et al. 2016.

synthetics were calculated by including only the direct P-wave and the surface reflexions pP, sP. The pP phase appears 2.0 s after the P, with reversed polarity and sP phase appears 4.0 s after the P in QSPA station.

The focal depth that best reproduces the waveforms is about 6 km. This means that the earthquake occurred in the upper crust, within the Precambrian basement and 5 km below the Cenozoic sediment deposits of the Pantanal basin.

DISCUSSION

The two largest earthquakes recorded in the Pantanal sedimentary basin were a) Miranda, February 13th, 1964, magnitude m_b 5.4 (Assumpção and Suárez 1988), and b) Coxim, of June 15th, 2009, with magnitude m_b 4.8. Both events were the result of reverse faults with some strike-slip component (see the beachballs in Fig. 7). The focal solution of Coxim event (strike=300°, dip=55°, rake=45°) was obtained with first-motion polarities using the more sensitive stations in Brazil, South and North America and Africa and was confirmed with regional surface wave modelling (Figs. 4 and 5). Modelling of depth phases (pP and sP) from distant stations (Fig. 6), showed a focal depth of 6 km, i.e., in the upper crust beneath the sediments of the Pantanal Basin and the focal mechanism indicates a

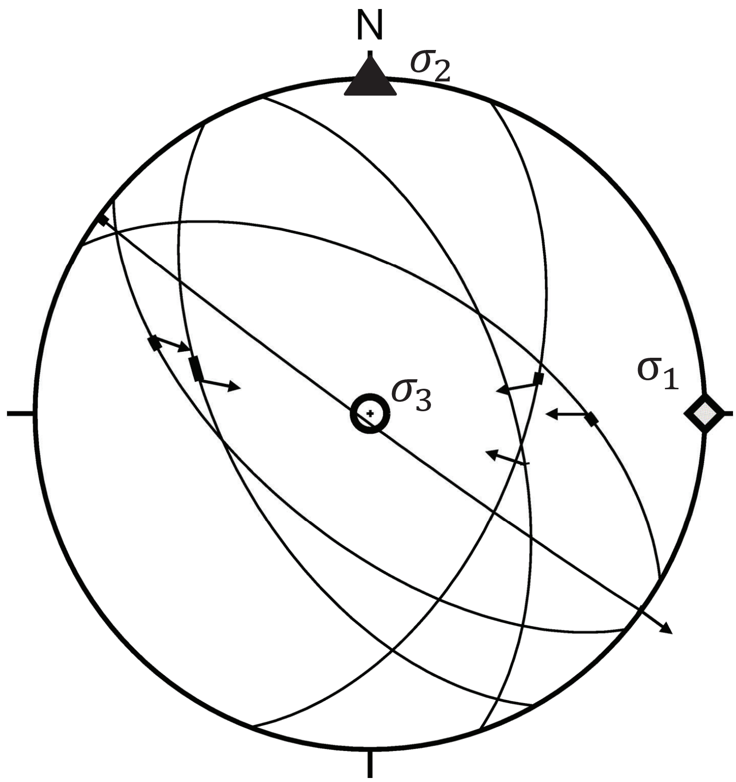

Figure 8 - Stress tensor inversion of the two Pantanal events and four Chaco Basin events. Maximum principal compression (σ_1) is illustrated by the diamond, the circle is the minimum compression (σ_3) and the intermediate compression (σ_2) is represented by the triangle. The arrows are the observed rake and the thick line near the arrows represents the difference between the observed and calculated rake. Inversion shows compressional stress with E–W oriented (σ_1).

sub-horizontal P-axis oriented approximately NE-SW (Fig. 7). This type of mechanism is similar to the 1964 earthquake, which had a P-axis oriented NE-SW. This is similar to the 5 km depth and focal mechanism of the 1964 event obtained with waveform modelling by Assumpção and Suárez (1988).

Fig. 7 shows a compilation of focal mechanisms for intraplate earthquakes in South America (Assumpção et al. in press). The bars indicate the approximate orientation of SHmax (maximum horizontal compression) from the earthquakes while the faulting mechanism is represented by the colors. The orientation of the bars shows that both earthquakes in the Pantanal Basin and in the four in Chaco Basin have very similar stress directions (highlighted in Fig. 7 by a box).

Fig. 8 shows a stress tensor inversion for these four events indicating that they could result from a uniform compressional stress field with oriented E-W and vertical . This analysis suggests that the Pantanal region is currently under neotectonic compression oriented approximately E–W. Despite the present subsidence, the neotectonic stresses in the upper crust are compressional. Extensional stresses observed in the Pantanal Basin in its initial stages were attributed to flexural stress from the Andean forebulge (Ussami et al. 1999) but any current E-W extension from Andean flexural effects (with N-S axis) is inconsistent with the observed

E-W compression from focal mechanisms. This issue deserves further studies in the future.

It has been suggested that the seismicity in the Pantanal Basin could be associated with the TBL. However, the focal mechanism of the Coxim event has no nodal plane that could be directly associated with SW-NE trend of the main TBL system. In addition, the 1964 focal mechanism has no SW-NE oriented nodal plane either (Assumpção and Suárez 1988). A roughly parallel to the TBL trend (Fig. 8) also indicates that a direct link of the TBL with the seismicity in the Pantanal Basin is improbable.

A definitive explanation for the seismicity of the Pantanal Basin is not yet possible. Mechanism such as stress concentration due to lithospheric thinning or flexure have been proposed (Assumpção et al. 2014) but more studies are necessary.

CONCLUSIONS

The Coxim event had magnitudes: m_b 4.8 (ISC), m_R 4.8, M_s 4.8 and M_w 4.3 with intensities up to MM V (Figs. 2 and 3), with minor damage to some houses and breaking objects in the epicentral area. The focal depth was approximately 6 km, therefore, within basement rocks, at least 5 km below the Pantanal basin.

First-motion polarities provided two nodal planes with orientation of (strike/dip/rake) of 300°/55°/45° and 180°/55°/35°, i.e., reverse faulting with a component of lateral movement, and P-axis approximately NE-SW. This mechanism is consistent with regional waveform modelling.

The stress inversion from two events in the Brazilian Pantanal and four in the Chaco Basin shows that the stress regime has changed along previous normal faults originated in the initial stages of basin formation, which are now subjected to E–W compressive stress. The orientation of the nodal planes (Fig. 4) and the estimated σ_1 (Fig. 8) do not support a direct link of the Pantanal seismicity with the TBL main trend.

The causes of intraplate seismicity and its relation with geology are always difficult to explain. Lithospheric weakness and/or local stress concentration are the most common reasons used to explain the intraplate seismicity, but these models can only be tested in areas where there are good geological and geophysical data coverage. It is expected that more detailed studies of seismicity in the Pantanal with recently installed stations, as Aquidauna (AQDB), Chapadão do Sul (C2SB) and Sonora (PP1B), will allow a better delineation of the active stress regime in the basin and its surroundings.

ACKNOWLEDGMENTS

We thank research grants from Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) (2007/55987-3, 2011/20165-9), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (A.C. Paranhos Filho - 305300/2012-1; G.S.L.A. França - 303529/2010-5, M.L. Assine - 305108/2009-3 and M. Assumpção - 309724/2009-0), Propp/UFMS (2011/0276), BPRAM/CPAq-UFMS and Fundação de Apoio ao Desenvolvimento do Ensino, Ciência e Tecnologia do Estado de Mato Grosso do Sul (FUNDECT) (23/200.728/2012). The authors would like to thank the anonymous reviewers.

REFERENCES

ASSINE ML. 2003. Sedimentação na Bacia do Pantanal Mato-Grossense, Centro-Oeste do Brasil. Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas. (Tese de Livre-Docência), 106 p.

ASSINE ML AND SOARES PC. 2004. Quaternary of the Pantanal, west-central Brazil. Quater Int 114: 23-34.

ASSUMPÇÃO M. 1983. A regional magnitude scale for Brazil. Bull Seismol Soc Am 73(1): 237-246.

ASSUMPÇÃO M, DIAS F, ZEVALLOS I AND NALIBOFF J. IN PRESS. Intraplate Stress in South America from Earthquake Focal Mechanism. J S Am Earth Sci. http://dx.doi.org/10.1016/j.jsames.2016.07.005.

ASSUMPÇÃO M, DIAS NETO CM, BERROCAL J, ARTEZAMA R, FRANÇA H AND ORTEGA R. 1980.

Sismicidade do sudeste do Brasil. In: Congr. Brás. Geol., 31. Anais. Camboriá, SBG, p. 1075-1092.

ASSUMPÇÃO M ET AL. 2014. Intraplate Seismicity in Brazil. In Intraplate Earthquakes, chapter 3, ed., P. Talwani, Cambridge U.P.

ASSUMPÇÃO M AND SACEK V. 2013. Intra-plate seismicity and flexural stresses in central Brazil. Geophys Res Lett 40: 487-491.

ASSUMPÇÃO M AND SUÁREZ G. 1988. Source mechanisms of moderate size earthquakes and stress orientation in mid-plate South America. Geophys J 92: 253-267.

BARROS LV, ASSUMPÇÃO M, CHIMPLIGANOND CN, CARVALHO JM, HUELSEN MGV, CAIXETA DF, FRANÇA GS, ALBUQUERQUE DF, FERREIRA VM AND FONTENELE DP. 2015. The Mara Rosa 2010 GT-5 earthquake and its possible relationship with the continental-scale Transbrasiliano lineament. J S Am Earth Sci 60: 1-9.

BERROCAL J, ASSUMPÇÃO M, ANTEZANA R, DIAS NETO C, ORTEGA R, FRANÇA H AND VELOSO JA. 1984. Sismicidade do Brasil. Published by IAG/USP and Comissão Nacional de Energia Nuclear, Brazil, 320 p.

BORMANN P, WENDT S AND DIGIACOMO D. 2013. Seismic Sources and Source Parameters. In: Bormann P (Ed), New Manual of Seismological Observatory Practice 2 (NMSOP2), Potsdam: Deutsches Geo Forschungs Zentrum GFZ, p. 1-259.

BRANNER JC. 1912. Earthquakes in Brazil. Bull Seism Soc Am 2(2): 105-117.

CATTO AJ. 1975. Análise geológica e geofísica da Bacia do Pantanal Matogrossense. Rel Int Petrobras, 23 p.

CURTO JB, VIDOTTI RM, FUCK RA, BLAKELY RJ, ALVARENGA CJS AND DANTAS EL. 2014. The tectonic evolution of the Transbrasiliano Lineament in northern Paraná Basin, Brazil, as inferred from aeromagnetic data. J Geophys Res 119: 1544-1562.

DIAS F, ZAHRADNÍK J AND ASSUMPÇÃO M. IN PRESS. Path-specific, dispersion-based velocity models and moment tensors of moderate events recorded at few distant stations: Examples from Brazil and Greece, J S Am Earth Sci. http://dx.doi.org/10.1016/j.jsames.2016.07.004.

FACINCANI EM. 2007. Geomorfologia e Geologia do Cenozóico do Médio Vale do Rio Aquidauana, Borda Sudeste da Bacia do Pantanal, MS. Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista - UNESP, Rio Claro, Relatório de Pós-Doutorado, 100 p.

FACINCANI EM, ASSUMPÇÃO MS, ASSINE ML AND FRANÇA GLSA. 2011. Sismicidade da Bacia do Pantanal Mato-Grossense. XIII Simpósio Nacional de Estudos Tectônicos (XIII SNET). Campinas, SP.

FOJTÍKOVÁ L AND ZAHRADNÍK J. 2014. A new strategy for weak events in sparse networks: the first-motion polarity solutions constrained by single-station waveform inversion. Seis Res Letters Nov 85(6): 1265-1274.

HASUI Y. 1990. Neotectônica aspectos fundamentais da tectônica ressurgente no Brasil. In: Workshop sobre a Tectônica e Sedimentação Cenozoica Continental no Sudeste Brasileiro. Anais. Belo Horizonte: SBG-MG, p. 1-31 (Boletim 11).

MAZZOTTI S. 2007. Geodynamic models for North America intraplate earthquakes. In: Stein S and Mazzotti S (Eds), Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425: 17-33.

MYERS SC, BEGNAUD ML AND BALLARD S. 2011. Extending Regional Seismic Travel Time (RSTT) Tomography to New Regions, in Proceedings of the 2011 Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies, LA-UR-11-04823, p. 342-351.

RICCOMINI C AND ASSUMPÇÃO MS. 1999. Quaternary tectonics in Brazil. Episodes 22(3): 221-225.

SCHOBBENHAUS C, RIBEIRO CL, OLIVA LA, TAKANOHASHI JT, LINDENMAYER ZG, VASCONCELOS JB AND ORLANDI V. 1975. Folha Goiás (SD-22). In: Carta Geológica do Brasil ao Milionésimo, Brasília: DNPM, 113 p.

SOARES PC, RABELO L AND ASSINE ML. 1998. The Pantanal Basin: recent tectonics, relationship to the Transbrasiliano Lineament. In: INPE, 9º Simpósio Brasileiro Sensoriamento Remoto. Santos, CD ROM, 11 p.

SOKOS E AND ZAHRADNÍK J. 2008. ISOLA: a Fortran code and a MATLAB GUI to perform multiplepoint source inversion of seismic data. Comput Geosci 34(8): 967-977.

SOKOS E AND ZAHRADNÍK J. 2013. Evaluating Centroid-Moment-Tensor Uncertainty in the New Version of ISOLA Software, Seis Res Letters, July/August 2013 84: 656-665.

SYKES L. 1978. Intraplate seismicity, reactivation of pre-existing zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation. Rev Geophys Space Phys 16: 621-688.

TALWANI P AND RAJENDRAN K. 1991. Some seismological and geometric features of intraplate earthquakes. Tectonophysics 186: 19-41.

USSAMI N, SHIRAIWA S AND DOMINGUEZ JML. 1999. Basement reactivation in a sub-Andean foreland flexural bulge: The Pantanal wetland, SW Brazil. Tectonics 18: 25-39.

WEYLER G. 1962. Relatório final dos poços perfurados no Pantanal Matogrossense - Projeto Pantanal. Petrobras, Ponta Grossa, Brasil, p. 27.