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The intraplate Porto dos Gaúchos seismic zone in the Amazon craton — Brazil

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ABSTRACT

The largest earthquake observed in the stable continental interior of the South American plate occurred in Serra do Tombador, Mato Grosso state — Brazil, on January 31, 1955 with a magnitude of 6.2 m_b. Since then no other earthquake has been located near the 1955 epicentre. However, in Porto dos Gaúchos, 100 km northeast of Serra do Tombador, a recurrent seismicity has been observed since 1959. Both Serra do Tombador and Porto dos Gaúchos are located in the Phanerozoic Parecis basin. Two magnitude 5 earthquakes occurred in Porto dos Gaúchos, in 1998 and 2005, with intensities up to VI and V, respectively. These two main shocks were followed by aftershock sequences lasting more than three years each. Local seismic stations have been deployed by the Seismological Observatory of the University of Brasilia since 1998 to study the "Porto dos Gaúchos" seismic zone (PGSZ). A local seismic refraction survey was carried out with two explosions to help define the seismic velocity model. Both the 1998 and 2005 earthquake sequences occurred in the same WSW–ENE oriented fault zone with right-lateral strike-slip mechanisms. The epicentral zone is in the Parecis basin, near its northern border where there are buried grabens, generally trending WNW–ESE, such as the deep Mesoproterozoic Caiabis graben which lies partly beneath the Parecis basin. However, the epicentral distribution indicates that the 1998 and 2005 sequences are related to a N60°E fault which probably crosses the entire Caiabis graben. The 1955 earthquake, despite the uncertainty in its epicentre, does not seem to be directly related to any buried graben either. The seismicity in the Porto dos Gaúchos seismic zone, therefore, is not directly related to rifted crust. The probable direction of the maximum horizontal stress near Porto dos Gaúchos is roughly E–W, consistent with other focal mechanisms further south in the Pantanal basin and Paraguay, but seems to be different from the NW–SE direction observed further north in the Amazon basin. The recurrent seismicity observed in Porto dos Gaúchos, and the large 1955 earthquake nearby, make this area of the Parecis basin one of the most important seismic zones of Brazil.

1. Introduction

Brazilian seismicity is lower than in other mid-plate regions such as Eastern North America, India, and Australia, where magnitudes larger than 7 have been observed, such as in the New Madrid area, USA, (Johnston, 1989; Johnston and Kanter, 1990; Johnston, 1996a,b; Gangopadhyay and Talwani, 2003; Schulte and Mooney, 2005). Mid-plate earthquakes in Brazil have not exceeded magnitude 6.2 m_b but intensities up to VI or VII are not uncommon and make seismic risk evaluation an important issue in projects of critical facilities such as nuclear installations. Models to explain intraplate earthquakes were proposed, for example, by Sbar and Sykes (1973), Sykes (1978), Talwani (1989), Talwani and Rajendran (1991) and Kenner and Segal (2000). Intraplate earthquakes appear to result from ruptures in weakness zones or from stress concentration. The proposed models try to correlate intraplate earthquakes with geological features that could indicate zones of crustal weakness such as extended crust in aborted rifts or continental margins (Johnston, 1989; Johnston et al., 1994), or with structural inhomogeneities, which could concentrate stresses in the upper crust (e. g., Sykes, 1978; Talwani, 1989, 1999; Talwani and Rajendran, 1991; Kenner and Segal, 2000; Assumpção et al., 2004).

Schulte and Mooney (2005) compiled an intraplate earthquake catalogue (magnitude ≥4.5) for stable continental regions (SCRs), and compared the data with a global catalogue of rifts (Sengör and Natal'in, 2001). 27% of the earthquakes fell in interior rifts/taphrogens, 25% were in rifted continental margins, and 36% occurred in non-rifted crust (the remaining 12% were uncertain). These numbers are similar to those presented in previous studies (Johnston and Kanter, 1990; Johnston et al., 1994), who found that 56% of all SCR earthquakes are associated with extended crust (interior rift and rifted continental margins). However, according to Schulte and Mooney (2005), if we

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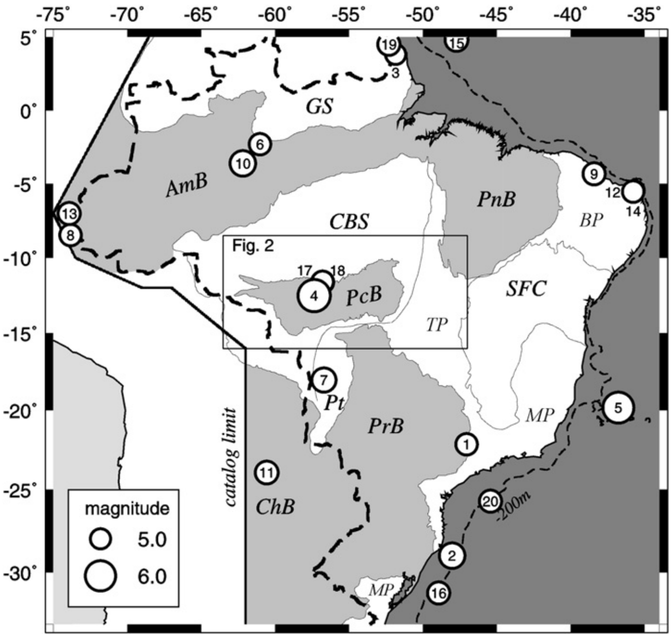

Fig. 1. Brazilian earthquakes with magnitudes ≥5.0 m_b since 1922, numbered as in Table 1. Circle sizes vary with the magnitudes. Lines show the main Brazilian geological provinces (Almeida et al., 2000): GS and CBS denote the Guyana and Central Brazil shields, respectively (which compose the Archean to Mesoproterozoic Amazon craton); Phanerozoic basins are: AmB Amazon Basin; ChB Chaco Basin; PnB Parnaiba Basin; PcB Parecis Basin; PrB Paraná Basin; Pt Pantanal Basin; SFC is the Archean to Mesoproterozoic São Francisco Craton. Neoproterozoic/Paleozoic foldbelts are: BP Borborema, TP Tocantins, and MP Mantiqueira Provinces. The dashed line offshore is the 200 m bathymetry. Thick dashed line is the Brazilian border. Epicentres from the catalogue of Berrocal et al. (1984), USGS bulletins and the references cited in Table 1.

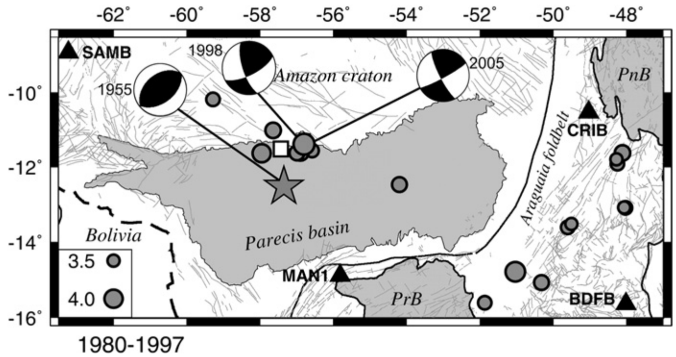

Fig. 2. Regional seismicity from 1980 to 1997 for magnitudes larger than 3.5 (circles). The source of epicentres is the catalogue of Berrocal et al. (1984) complemented with the Brazilian Seismic Bulletins published by the Brazilian J. of Geophysics. Epicentral uncertainties are a few tens of kilometers. The star denotes the large 1955 earthquake. The triangles are the permanent seismic stations in operation since the early 80s. The focal mechanism solutions shown in this figure, as well as in subsequent figures, are for the 1955 earthquake (Mendiguren and Richter, 1978), and the 1998 and 2005 sequences (this paper). Light gray areas are sedimentary basins; dark gray lines are geological lineaments (CPRM, 2001) and thick solid lines are the limits of the main geological provinces from Fig. 1. The square indicates the town of Porto dos Gaúchos. The SW–NE oriented lineaments south of station CRIB are called TransBrasiliano Lineaments.

consider continental interior earthquakes only and exclude continental margin events, it is observed that non-rifted crust has experienced more earthquake than rifted crust. So, on a global scale, the correlation of seismicity within SCRs and ancient rifts may have been over-estimated in the past. Schulte and Mooney's (2005) new catalogue increased the previous one in 58% and has more reliable data covering the period of 1994 to 2003. However, Schulte and Mooney's results agree with previous studies for earthquakes with magnitudes larger than 6.0: most of them are associated with extended crust (interior rift and rifted continental margins). The earthquakes in non-rifted crust occur mainly in Precambrian basement (Gangopadhyay and Talwani, 2003).

Fig. 1 and Table 1 show all known Brazilian intraplate earthquakes with magnitudes 5.0 m_b and above. Half of the epicentres (10 out of 20) lie close to the coast and the continental shelf and have been attributed to a combination of weakness zones (extended crust beneath the continental shelf) and amplification of the regional stresses due to local forces such as crustal inhomogeneities at the continent/ocean transition and flexural stresses (e.g., Johnston and Kanter, 1990; Assumpção, 1998a; Ferreira et al., 1998). Of the remaining epicentres in the continental interior, three are located in the centre north of the Parecis basin, including the large 1955 Serra do Tombador earthquake (event 4). The epicentral area of this earthquake was uninhabited in 1955, and the maximum epicentral intensity has been tentatively inferred as IX MM (Berrocal et al., 1984) or VIII MM (Johnston, 1989).

Table 1
Brazilian earthquakes with magnitudes ≥5.0 m_b since 1922.

Event number	Date	Origin time (UT)	Epicentre		Depth	Epicentral error (km)	Location	Magnitude	Source
	mm/dd/yyyy		Latitude	Longitude					
1	01/27/1922	06:50:40	−22.17°	−47.04°	N	40	Mogi Guaçu/SP	5.1	1
2	06/28/1939	11:32:22	−29.00°	−48.00°	N	90	Tubarão/SC	5.5	1
3	09/17/1949	–	03.83°	−51.84°	N	100	Oiapoque/AP	5.0	1
4	01/31/1955	02:03:07	−12.52°	−57.35°	N	30	Serra do Tombador/MT	6.2	2
5	28/02/1955	22:46:18	−19.84°	−36.75°	N	30	offshore Vitória/ES	6.1	2
6	12/13/1963	21:05:42	−02.30°	−61.01°	45	30	Manaus/AM	5.1	3
7	02/13/1964	08:21:46	−18.06°	−56.69°	5	30	NW of Mato Grosso do Sul	5.4	3
8	08/09/1967	07:14:08	−08.45°	−73.83°	42	30	Peru–Brazil/AC	5.1	8
9	11/20/1980	00:29:42	−04.30°	−38.40°	5	10	Pacajus/CE	5.2	4
10	08/05/1983	03:21:42	−03.59°	−62.17°	23	20	Codajás/AM	5.5	3, 4
11	04/12/1985	11:34:57	−23.94°	−60.55°	21	30	Paraguay	5.3	8
12	11/30/1986	02:19:50	−05.53°	−35.75°	5	10	João Câmara/RN	5.1	5
13	10/24/1987	21:23:40	−07.01°	−73.94°	N	30	Peru–Brazil	5.2	ISC
14	03/10/1989	01:11:21	−05.46°	−35.69°	5	10	João Câmara/RN	5.0	6
15	04/12/1989	04:09:29	04.80°	−47.72°	N	30	N. Atlantic shelf	5.3	ISC
16	02/12/1990	20:56:39	−31.19°	−48.92°	13	30	Cont. Shelf/RS	5.2	7
17	03/10/1998	23:32:44	−11.53°	−56.86°	3	5	Porto dos Gaúchos/MT	5.2	This study
18	03/23/2005	21:12:13	−11.60°	−56.77°	3	5	Porto dos Gaúchos/MT	5.0	This study
19	06/08/2006	16:29:13	04.66°	−51.90	N	20	French Guyana	5.1	USGS
20	04/23/2008	00:00:48	−25.74°	−45.42 °	17	20	Cont. Shelf/SP	5.2	USGS, USP

Sources: 1 — Berrocal et al. (1984); 2 — Relocated by Enghdal 2002; 3 — Assumpção and Suarez (1988); 4 — Assumpção et al. (1985); 5 — Ferreira et al. (1987); 6 — Takeya et al. (1989); 7 — Assumpção (1998a); 8 — Assumpção (1992). USP = University of São Paulo.

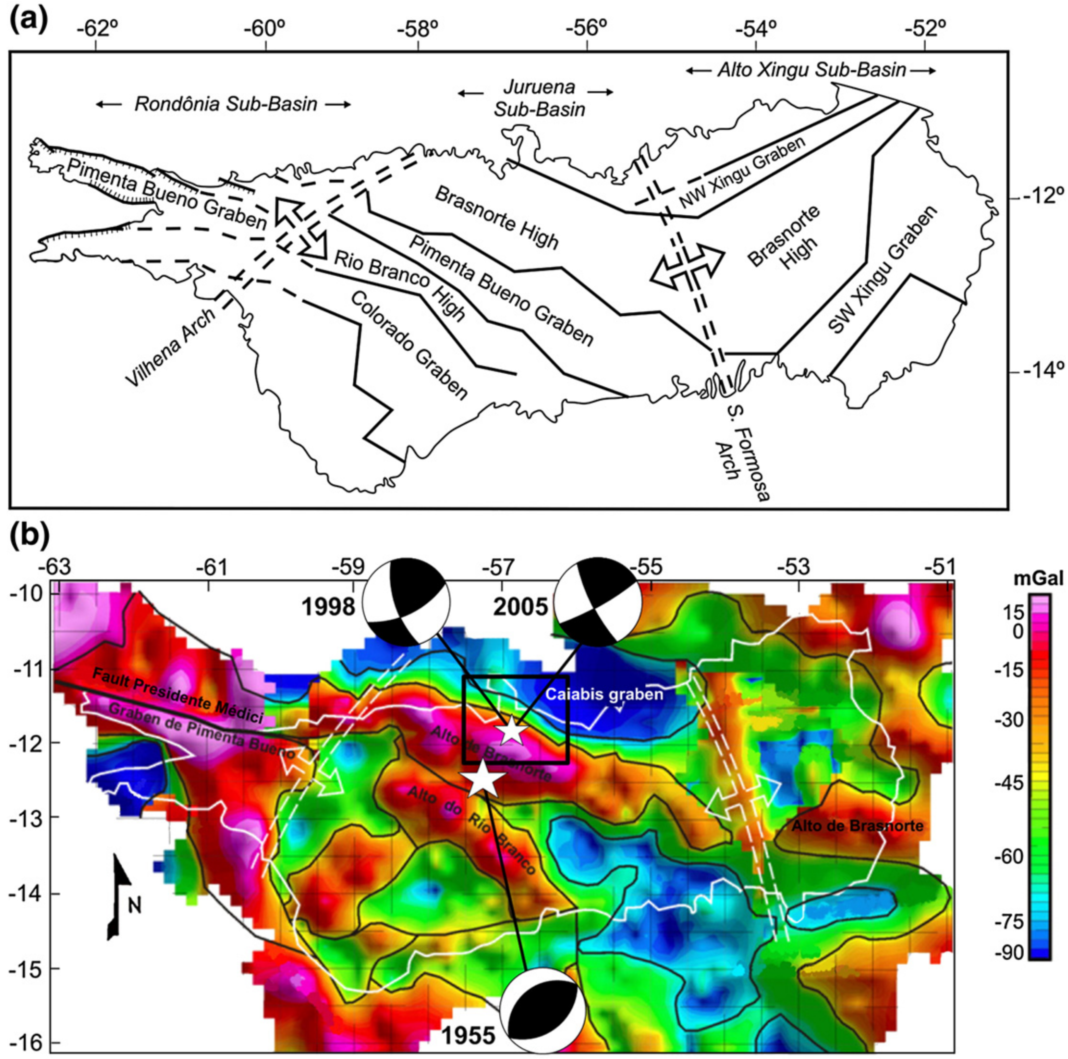

Fig. 3. a) Major structural units of the Parecis Basin (redrawn from Braga and Siqueira (1996) and Bahia et al. (2007). b) Bouguer gravity anomalies in the region of the Parecis basin. White solid line is the basin limit; dashed white lines indicate the two basement arcs. The low anomalies in the northern border indicate the ancient Caiabis graben of Mesoproterozoic origin. Focal mechanisms as in the previous figure. (Figure modified from Bahia et al., 2007). Black square is a reference for the study area.

Although no other earthquake has been located in the same epicentral area of the 1955 earthquake, a recurrent activity has been observed near Porto dos Gaúchos (Fig. 2), about 100 km NE of the 1955 epicentre. Fig. 2 shows the seismic activity in central Brazil recorded by the Brazilian stations from 1980 to 1997. A clear seismic zone can be identified near Porto dos Gaúchos with magnitudes up to 4.4 in that period. In fact, local events with intensities of V MM had been felt in Porto dos Gaúchos in 1959, two years after the initial settlement of the town.

In March 10, 1998, a 5.2 m_b event occurred near Porto dos Gaúchos with maximum intensity VI (MM). Three days later, the Seismological Observatory of the University of Brasilia (UnB) installed local stations in the region recording more than 2500 events until December 2002. In March 23, 2005, another shock of similar size (5.0 m_b and maximum intensity V MM) occurred in the same epicentral area. A new temporary local network was deployed by the University of Brasilia to study the new aftershock activity. In the following six months, more than 3300 events were detected.

This recurrent activity near Porto dos Gaúchos clearly defines one of the most important seismic zones in mid-plate South America which we have labeled “Porto dos Gaúchos Seismic Zone” (PGSZ). In this paper we investigate the potential relationship of this activity with the nearby Caiabis graben, a major feature of past extended crust. We address the problem of the isolated location of the 1955 Serra do Tombador earthquake. In Brazil, with generally low magnitude earthquakes and poor coverage by seismographic stations, only few events have allowed reliable determinations of focal mechanisms. Our studies of the two aftershock series in PGSZ, with well constrained focal mechanisms, will also contribute to increase the database upon which better inferences can be made about the state of stress in the middle of the South American plate. Intraplate stress pattern is a key feature for the understanding of the relative importance of the various forces driving the plates.

Here we investigate the seismic zone of Porto dos Gaúchos using two local networks deployed in the epicentral area of the 1998 and 2005 earthquake sequences.

2. Geological and geophysical setting

PGSZ is located near the northern border of the Parecis basin which overlies the Amazon craton, a region whose geology is complex and little known, because of access difficulties and the late identification of economic targets. Geological and geophysical studies in this area only progressed in the second half of the 80s mainly because of interest in oil prospecting (e.g., Siqueira, 1989; Siqueira and Teixeira, 1993). The study area, indicated by the square in Figs. 3 and 4, includes a

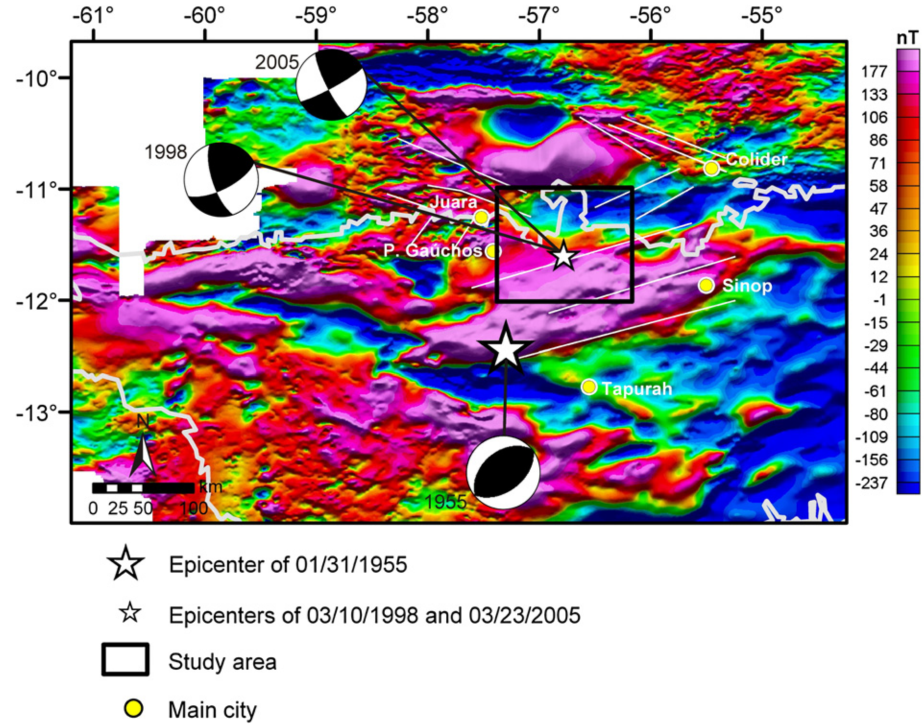

Fig. 4. Aeromagnetic anomalies (CPRM, 2004) in the central part of the Parecis basin (blank areas were not covered by this aeromagnetic survey). White lines are some of the major lineaments near Porto dos Gaúchos. Note WSW–ENE oriented short-wavelength lineaments roughly parallel with one of the nodal planes shown in focal mechanism diagram.

Precambrian basement (Amazon craton) and Phanerozoic terrains (Parecis basin). The area of the Amazon craton belongs to the Rio Negro-Juruena geochronologic province with 1.8 to 1.55 Ga (Tassinari et al., 2000), with an important feature, the Caiabis graben of Mesoproterozoic age (~1.36 Ga), according to Leite and Saes (2003).

The intracratonic Parecis basin began as a rift basin in Paleozoic times. The stratigraphic column of the Parecis basin includes Paleozoic, Mesozoic and Cenozoic units, distributed in three sub-basins separated by structural arcs (Fig. 3a). Two paleogeographic arcs cross the basin: Vilhena Arc in the West and Serra Formosa Arc in the East, separating the sub-basins (from West to East) of Rondônia (Paleozoic), Juruena (Mesozoic) and Xingu (Cenozoic) according to Siqueira and Teixeira (1993).

The gravimetric data of the Parecis basin (Fig. 3b) show a sequence of highs and lows associated by Siqueira (1989), Siqueira and Teixeira (1993) and Bahia et al. (2007) with a sequence of grabens and horsts, roughly oriented in the WNW–ESE direction. Bouguer anomaly lows define several grabens and depocentres, such as the deep Caiabis graben (Braga and Siqueira, 1996; Bahia et al., 2007) with Bouguer anomalies

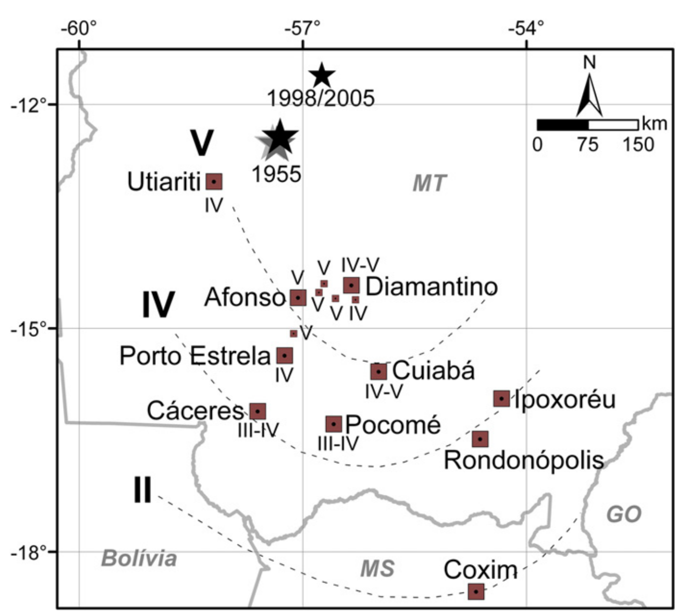

Fig. 5. Isoseismal map for 1955 Serra do Tombador earthquake (6.2 m_b) with macroseismic data collected in 1986. The stars are the three epicentres of the 1955 event (Table 2) and the 1998/2005 events. MT, MS and GO are states of Mato Grosso, Mato Grosso do Sul and Goiás, respectively.

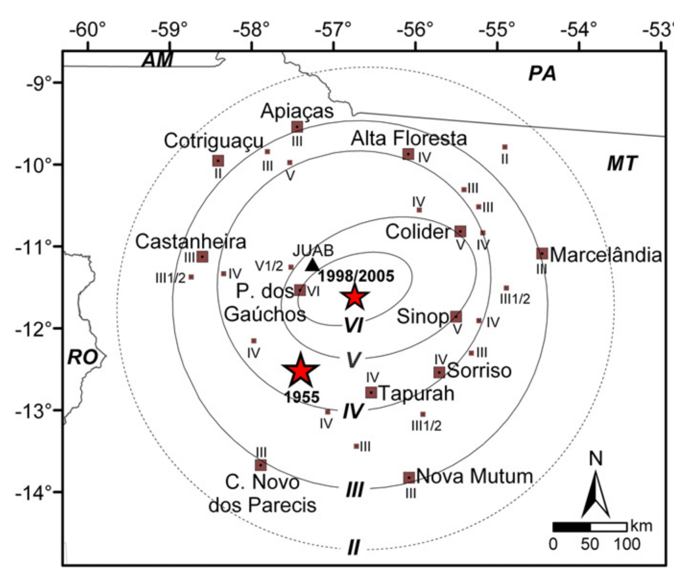

Fig. 6. Isoseismal map of the March 10, 1998 earthquake (5.2 m_b). The triangle indicates the location of JUAB station, the first local station to be installed, on March 13 of 1998. The two stars indicate the epicentre of 1998/2005 events and the epicentre of the large 1955 earthquake. RO, AM, PA and MT are the states of Rondônia, Amazonas, Pará and Mato Grosso, respectively,

Table 2
Source parameters of the January 31, 1955, Serra do Tombador earthquake. All depths fixed at normal depth.

#	Origin time	Latitude	Longitude	Magnitudes		Source, observations
	hh:mm:ss	(°)	(°)	m_b	Ms	
1	05:03:02	−12.50	−57.40	6.8	–	International Seismological Summary
2	05:03:07	−12.42	−57.30	6.2	5.5	Assumpção and Suarez (1998); m_b, Ms with stations PAS, OTT, PAL
3	05:03:06	−12.52	−57.35	–	–	Relocation by R.E. Engdhal (written comm., 2002)

lower than −80 mGal (Fig. 3b), the main negative gravity anomaly present in the interior of the Amazon craton (Siqueira, 1989). According to Siqueira (1989), Braga and Siqueira (1996), and Dardenne et al. (2006) these Bouguer anomalies are related to a thick sedimentation of up to 6000–7000 m in the Caiabis graben.

The main trend of the gravity anomalies near the PGSZ (black square in Fig. 3b) is oriented in the NW–SE direction related to the Brasnorte gravity high. However, the aeromagnetic anomalies (Fig. 4) show a series of ENE–WSW lineaments near the PGSZ which probably indicate major basement faultings during the geological evolution of this area.

3. Regional seismicity

Historical records are scarce as the region of Porto dos Gaúchos began to be inhabited only in 1957. In February 1959, according to an unpublished report (Colonizadora Nordeste Matogrossense Arinos, Report No. 54, April 10, 1959) "a strong tremor was felt in Gleba Arinos", currently Porto dos Gaúchos town (indicated by a square in Fig. 2). The effects described in that report indicate intensity V (MM), and the earthquake was followed by at least three aftershocks with intensities III–IV (MM).

Most of the regional stations shown in Fig. 2 were installed in the beginning of the 1980s. The permanent station in Brasilia was first installed in 1972 (initially the analog WWSSN station BDF, and later the digital BDFB), complementing the array station already operating in Brasilia since 1968. Stations SAMB and MAN1 (Fig. 2) were installed to monitor hydro-electric reservoirs in the early 80s (initially with analog equipment and later with digital recorders) and were very useful to detect regional seismicity in this part of the Amazon region. CRIB, a digital broadband station, was installed in the 90s. According to Assumpção (1998b) the threshold magnitude levels for earthquakes in central Brazil was near 6.0 m_b in 1950 (ISS Catalogue); 5.0 m_b in 1962 (beginning of the WWSSN network); 4.0 m_b in 1968 (installation of the array station in Brasilia) and 3.5 m_b since 1980 (installation of regional stations in the Amazon and central Brazil regions, such as those shown in Fig. 2). So the best assessment of the regional seismicity in Central Brazil is from 1980 when earthquakes with magnitudes above 3.5 should be complete.

Fig. 2 shows the regional seismicity in Central Brazil between 1980 and 1997, just before the large event of 1998. It is possible to see, basically, two areas of more expressive seismicity. In the East, a clear SW–NE oriented seismic zone can be seen stretching from the border of the Paraná basin (PrB) to the border of the Parnaíba basin (PnB). This seismic zone is roughly parallel to, but not coincident with, the Trans-Brasiliano Lineament, a series of faults of Neoproterozoic and lower Paleozoic age, coincident with high gravity anomalies along the Araguaia foldbelt (Assumpção et al., 1986; Fernandes et al., 1991).

The other concentration of epicentres around the town of Porto dos Gaúchos (Fig. 2) has been labeled the "Porto dos Gaúchos Seismic Zone" (PGSZ, including the 1955 earthquake). Since the increase of the Brazilian regional stations in the early 80s and before the main event of 1998, seven earthquakes have been detected in PGSZ, in 1981 (3.8 m_b),

Table 3
Source parameters of the March 10, 1998, earthquake.

Origin time	Latitude	Longitude	Depth[a]	Nsta	Magnitude	Source
hh:mm:ss			(km)		m_b	
23:32:44	−11.53	−56.86	5	36	5.0	UnB
23:32:43	−11.59	−56.86	0	23	4.8	IDC/CTBTO
23:32:44	−11.67	−57.00	10	122	5.2	NEIC/USGS
23:32:44	−11.75	−56.96	10	176	5.3	ISC

The epicentres are shown in Fig. 7. Nsta is number of recording stations.
[a] Depth fixed in all determinations.

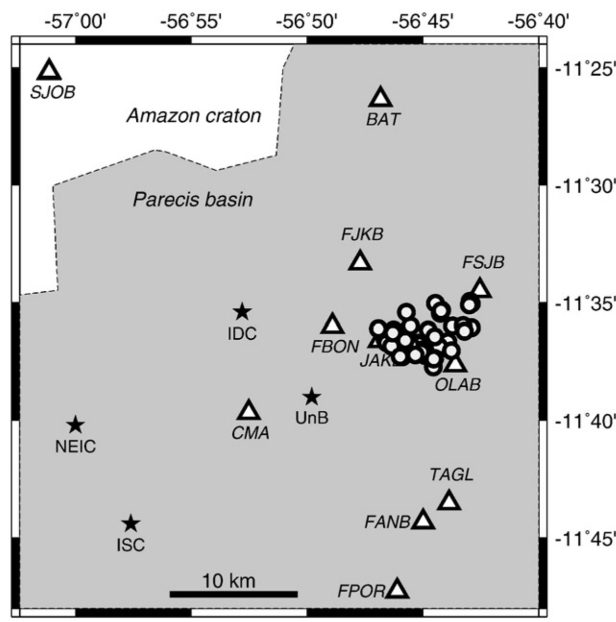

Fig. 7. Epicentres (gray circles) of the 60 best recorded events of the 1998–2002 sequence. Epicentral errors less than ±2 km. Solid stars indicate the epicentres of March 10 main shock as determined by IDC, ISC, NEIC and UnB. Open triangles are sites occupied by local temporary stations: station names ending with "B" denote broad-band (CMG-40T), all others codes mean short period (S3000EQ) stations. Not all stations operated simultaneously.

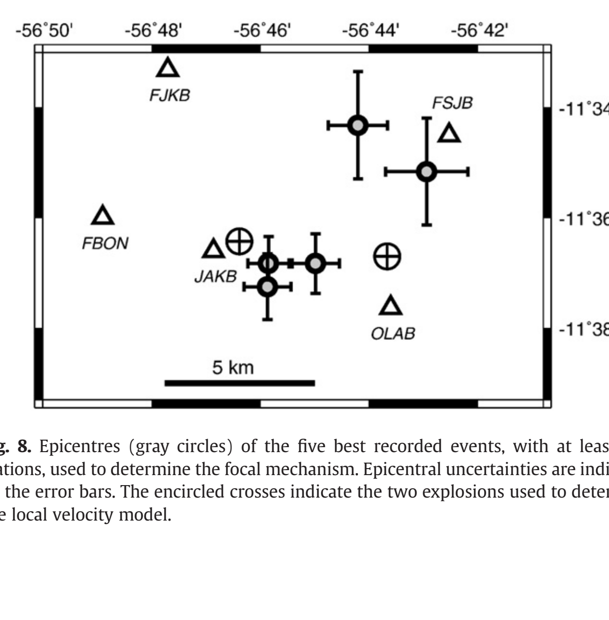

Fig. 8. Epicentres (gray circles) of the five best recorded events, with at least five stations, used to determine the focal mechanism. Epicentral uncertainties are indicated by the error bars. The encircled crosses indicate the two explosions used to determine the local velocity model.

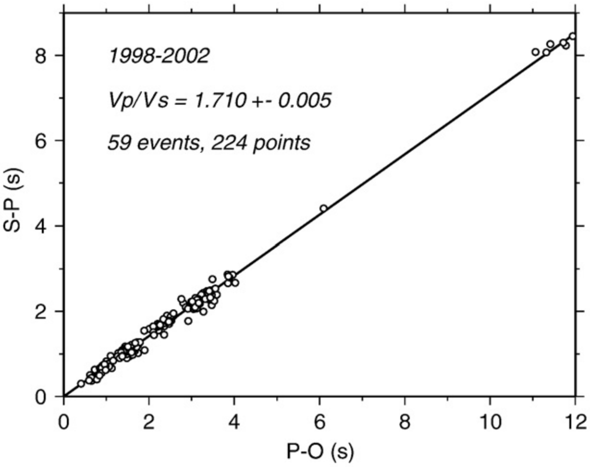

Fig. 9. Wadati diagram for 1998–2002 seismic sequence.

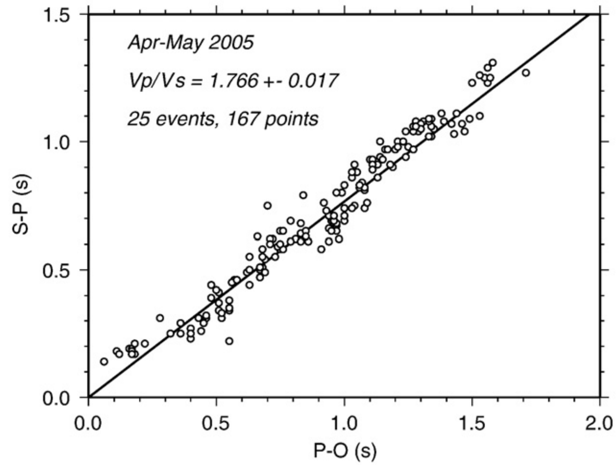

Fig. 10. Wadati diagram for 2005 seismic sequence.

1986 (3.6 m_b), 1987 (3.9 m_b and 3.5 m_b), 1988 (3.7 m_b, and 4.0 m_b), and in 1996 (4.2 m_b). The estimated epicentral errors range from 30 to 50 km.

4. Serra do Tombador earthquake of January 31, 1955

The 1955 Serra do Tombador earthquake occurred in an area completely uninhabited, with the closest village about 100 km to the south. A macroseismic survey was carried out by the University of Brasilia (UnB) in 1986, 31 years later, interviewing people in some towns and villages in the affected area, as shown in Fig. 5 (Carvalho, 1998). In Cuiabá, 375 km south of the epicentre, several people woke up (the event occurred at 02 AM local time) and a deflection of the barograph chart at the local meteorological station was recorded (Bombled, 1970). Magnitudes were estimated as 6.2 m_b and 5.5 M_s (Assumpção and Suarez, 1988).

Different epicentres have been calculated for the 1955 earthquake which was recorded by about 100 stations worldwide (Table 2). Besides the epicentre of the International Seismological Summary (ISS), Assumpção and Suarez (1988) calculated the epicentre using Herrin's tables, and R. Engdhal (written communication, 2002) relocated the event with 99 stations (87 with $\Delta > 28°$ and $\Delta_{min} = 11°$) using station corrections with the method of Engdahl et al. (1998). These three epicentres are about 20 km from each other as shown in Table 2 and Fig. 5. No depth phases (pP, sS) could be identified and so there is no estimate of focal depth.

The fault plane solution of the Serra do Tombador earthquake, studied by Mendiguren and Richter (1978) based on P and S wave polarities, showed a pure reverse faulting mechanism, with poorly constrained *P* axis roughly in the NW–SE direction (see focal mechanism in Figs. 2–4).

5. 1998 earthquake sequence

The main earthquake of March 10, 1998, was felt up to about 250 km away from the epicentre and had intensities up to VI MM (Fig. 6). It was recorded by regional and teleseismic stations with epicentre determined by three different international agencies (NEIC/USGS, ISC, and IDC — International Data Centre, Vienna) as well as the University of Brasília (UnB), as shown in Table 3 and Fig. 7. The UnB epicentre was calculated mainly with South American stations and all the Brazilian stations in the distance range 500–2000 km using a velocity model more appropriate for mid-plate South America (Kwitko and Assumpção, 1990). The correct location of the main event is the average epicentre of the aftershock series studied with local stations (Figs. 7 and 8). All epicentres of the main event calculated with distant stations are mislocated by 10 to 30 km towards the SW. This raises the question about the location of the large 1955 earthquake: Could it be mislocated about 100 km towards the SW, and its correct location be near Porto dos Gaúchos and not Serra do Tombador? This question deserves further investigation in the future, although an error of 30 km, at least, seems likely.

The magnitude 5.2 m_b was determined with 79 teleseismic measurements (ISC) and six regional measurements using the Brazilian regional magnitude scale, which is consistent with the teleseismic m_b scale (Assumpção, 1983). The area enclosed by the isoseismal IV MM (~140,000 km^2 in Fig. 6) corresponds to a macroseismic magnitude of 5.1, based on the empirical relationship between magnitude m_b and felt areas developed by Berrocal et al. (1984).

5.1. Aftershock activity

The aftershock activity was studied with a local network with up to seven simultaneous three-component stations (Barros et al., 2001). Both short-period (1–100 Hz frequency band) and broadband (30 s to

Table 4
1D velocity model, obtained with the two local explosions (Fig. 8), used for the hypocentral locations.

Vp (km/s)	Layer top (km)
3.88	0.00
5.98	0.30
6.20	2.00
6.78	15.0

Vp/Vs was 1.71 for the 1998 events, and 1.78 for the 2005 events.

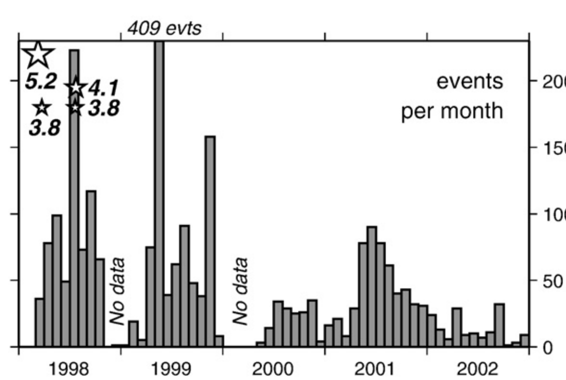

Fig. 11. Monthly distribution of the seismicity from March 1998 to December 2002. The gaps in seismicity are due to lack of seismic monitoring.

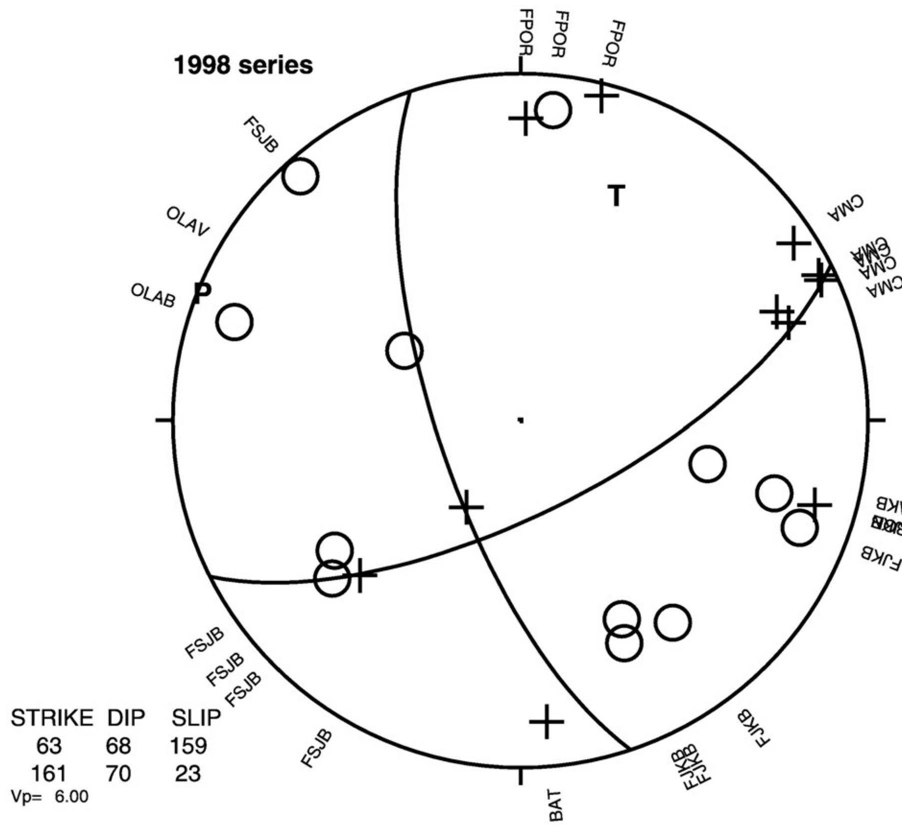

Fig. 12. Composite focal mechanism solution for 1998–2002 seismic sequence. Crosses and circles denote compressional and dilatational *P* arrivals, respectively.

50 Hz) seismometers were used. The first station (JUAB) was installed near the town of Juara, about 70 km from the epicentral area (Fig. 6). Access difficulties and the few available roads in this forest covered region prevented the installation of stations close to the epicentral area in the first field work. It took many months and several field trips for the stations to be installed within 10–20 km of the epicentres (Fig. 7). Most stations were installed on soft sediments. JUAB (Fig. 6) and SJOB (Fig. 7) were sited on granitic/gneissic bedrock. BAT (Fig. 7) and PDRB (Fig. 14a) occupied isolated granitic outcrops within the basin. The station distribution was not ideal because the area was almost completely covered by forest.

All collected data was inserted into a SEISAN database (Havskov and Ottemöller, 1999). Hypocentres were determined with the Hypocenter code (Lienert and Havskov, 1995). We used a 1D velocity model (Table 4) obtained with a shallow seismic refraction experiment carried out with two explosions, fired near the ends of the epicentral zone (Fig. 8) and recorded by up to eight stations of the local network (Barros and Caixeta, 2003; Barros and Rancan, 2004). The station corrections obtained with the explosions were used to improve the hypocentral locations. Vp/Vs ratios obtained by Wadati diagrams are shown in Figs. 9 and 10. The events of the 1998 sequence were located with a Vp/Vs = 1.71 (Fig. 9). A different Vp/Vs ratio of 1.78 was obtained with the 2005 deployment (Fig. 10) This difference in the Vp/Vs ratios is due to the different diameter of the seismic networks: the larger aperture of the 1998 network, with some stations located outside the Parecis Basin, samples a deeper part of the upper crust, whereas the smaller 2005 network actually gives a Vp/Vs more representative of the shallow sedimentary layers of the Parecis basin.

Fig. 11 shows the monthly distribution of all the 2500 events recorded from March 13, 1998, to December 2002, most of them (2200) detected by only one or two stations. Only 70 events were recorded by 4, 5, 6 or 7 stations. Fig. 7 shows the epicentral distribution of the 60 best located events with rms travel time residual <0.10 s; horizontal error (ERH) <2.0 km (most less than 0.5 km); vertical error (ERZ) <2.4 km, (most less than 1.0 km). The deepest events are located at a depth of about 6 km. 70% of the events have depths in the range 3–6 km. Despite some scattering, the epicentral distribution shows a trend roughly in the E–W or SW–NE direction. The estimated rupture area is about 6 km × 6 km.

5.2. Composite focal mechanism

A further quality selection from the previous data set (Fig. 8) was carried out to determine the focal mechanism. We selected events located with at least five stations (ERH<2.0 km and rms residual <0.05 s). This set of events presents 23 P-wave polarities. Fig. 12 shows the resulting composite focal mechanism solution, calculated with the FOCMEC code (Snoke et al., 1984) with only two polarity errors. The strikes of the two nodal planes are ENE–WSW and NNW–SSE and the

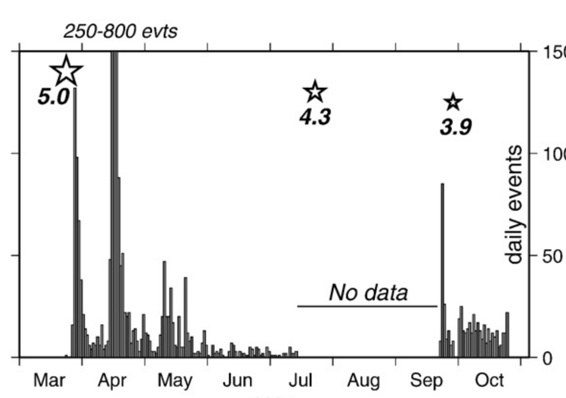

Fig. 13. Daily number of event for the 2005 seismic sequence. Stars indicate the largest events of the sequence with their magnitudes. Some days in April 2005 are off scale.

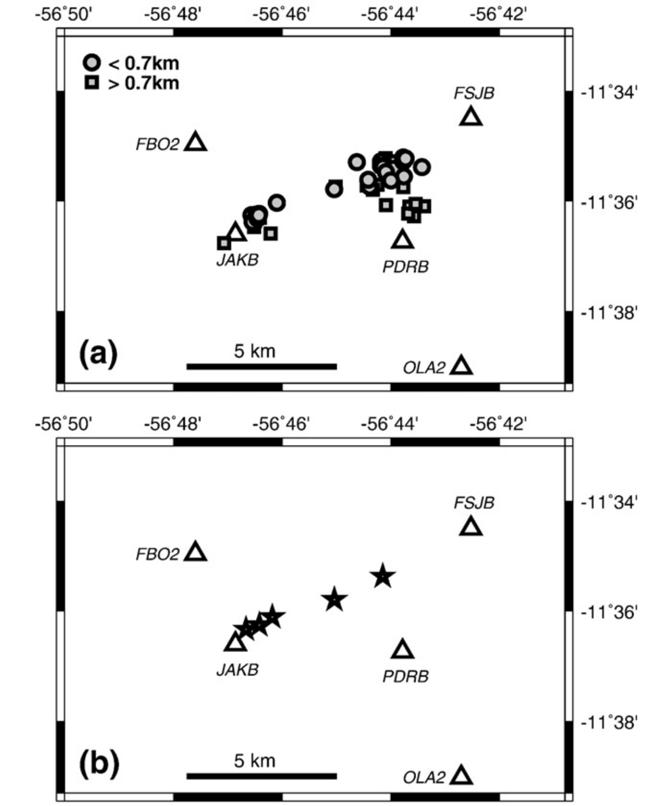

Fig. 14. (a) Epicentres (gray circles and squares) of the 44 best located events of the 2005 seismic sequence recorded by at least four stations. Circles and squares denote events shallower and deeper than 0.7 km, respectively. (b) Epicentres of the five best events, recorded by the same five stations, used to determine the 2005 focal mechanism. Open triangles are seismic stations.

azimuths and plunges of the *P* and *T* axes are 114°/0° and 24°/33°, respectively (Fig. 12). Despite the scatter in the epicentral distribution, only the ENE striking nodal plane (strike 63°, dip 68° and rake 159°) is consistent with the trend of the best hypocentres shown in Figs. 7 and 8.

6. 2005 earthquake sequence

The main shock of March 23, 2005, 5.0 m_b (NEIC) had the same epicentral location as the March 10, 1998 event, and was felt with intensities up to V MM, one unit less than the 1998 main shock. The temporal distribution of the 2005 seismic sequence is in Fig. 13. Three days (April 14–16) were especially active with almost 1600 recorded events, all of them with magnitudes lower than 2.7 m_b. Of all the 3300 detected events, only 44 were recorded by four or more stations, as shown in Fig. 14a.

For the 2005 sequence, the seismic stations could be installed closer to the known epicentral area (minimum station distance ranging from 4.0 km to 0.3 km, mostly between 2 and 3 km) and better locations were possible. For the 2005 sequence, a Vp/VS ratio of 1.78 was used (Fig. 10). The set of 44 events presents the following quality location parameters: ERH<0.5 km, ERZ<1.0 km and rms residual <0.05 s. This best recorded set of events (Fig. 14a) shows a clear alignment in the WSW–ENE direction with a trend of deeper events to the SSW. The deepest event is 3 km deep, and a trend of deeper events to the SW can be noted. The events also seem to be separated into two clusters, spaced about 2 km from each other.

6.1. Composite focal mechanism

For the fault plane solution we selected only the events detected by all five stations together, with rms <0.07 s, ERH<0.5 km and ERZ<1.0 km. Fig. 14b shows the five selected events. A clear epicentral alignment in the WSW–ENE direction defines the fault orientation. The composite fault plane solution, shown in Fig. 15, has strike 61°, dip 83° and rake 169°. The

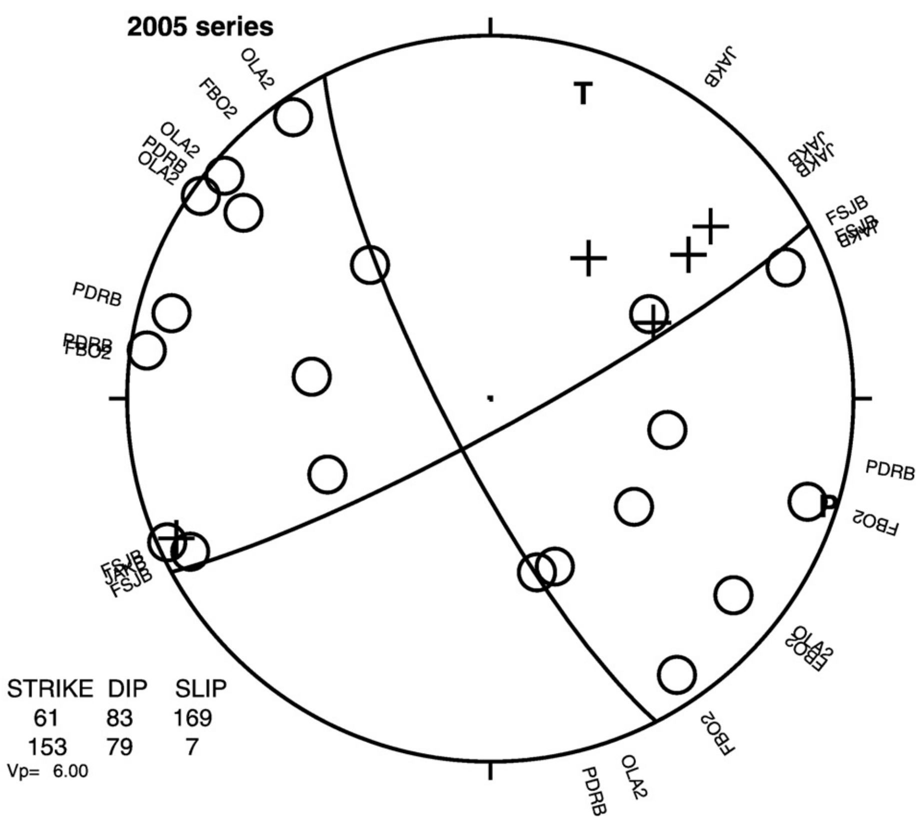

Fig. 15. Composite focal mechanism solution for the 2005 seismic sequence. Crosses and circles denote compressional and dilatational arrivals, respectively.

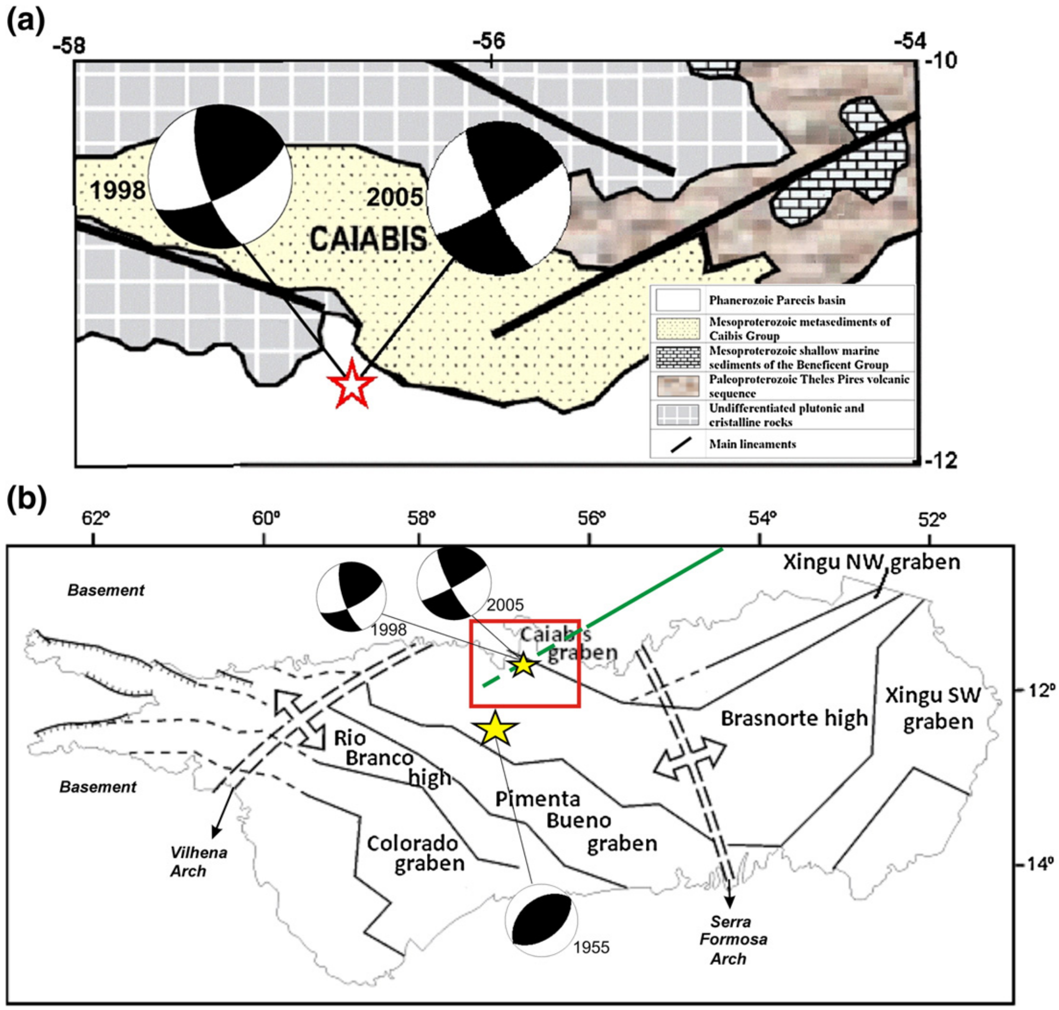

Fig. 16. (a) Simplified geological map of the Caiabis graben and surrounding areas (modified from Leite and Saes, 2003). Gray area = undifferentiated plutonic and crystalline rocks; brown area = Paleoproterozpic Teles Pires volcanic sequence; brick-stippled area = Mesoproterozoic shallow marine sediments of the Beneficente Group; yellow = Mesoproterozoic metasediments of the Caiabis Group; white area = Phanerozoic Parecis basin. Star is the 1998/2005 epicentre; focal mechanisms from Figs. 12 and 15. Note the WSW–ENE fault which bounds the deepest part of the graben and has the same orientation as the 1998/2005 fault plane. (b) Tectonic domains of the Parecis basin (modified from Bahia et al., 2007) with the sequence of WNW–ESE trending grabens and basement highs. The green solid line (N60°E) in the Caiabis graben is the WSW–ENE fault from Leite and Saes (2003) as shown in (a), extrapolated with dashed line towards the 1998/2005 epicentral area. The red square indicates the study area as in Figs. 3 and 4.

azimuths and plunges of the *P* and *T* axes are 107°/03° and 017°/13°, respectively. The fault area is estimated to be about 6 km × 3 km.

7. Discussion

Although a single faulting mechanism does not allow the determination of the tectonic stress directions, the most probable orientation of the maximum principal compression is about 30° from the fault plane. This means that in the Porto do Gaúchos region, the maximum horizontal stress (SHmax) is probably E–W oriented, which is consistent with the expected stress direction from the theoretical models of Coblentz and Richardson (1996) for the stress field in the South American plate. Further south, in the Pantanal and Chaco basins (near events 7 and 11 in Fig. 1), three other mid-plate earthquakes show *P* axes oriented roughly E–W, whereas in the Amazon basin SHmax tends to be rotated towards the NW–SE direction (Assumpção, 1998b; Assumpção, 1992; Assumpção and Suarez, 1988; Zoback and Richardson, 1996). The Porto dos Gaúchos Seismic Zone may be part of a large stress province, characterized by E–W oriented SHmax, which includes the Parecis, Pantanal and Chaco basins. However, more studies are necessary for a complete determination of the stress tensor in PGSZ.

Bouguer gravity anomalies of the Parecis basin show a very strong gradient just NE of the epicentral area of the 1998 and 2005 earthquakes (Fig. 3b). This gradient indicates the WNW–ESE border of the deep Mesoproterozoic Caiabis graben, an existing structure prior to the Paleozoic/Mesozoic sedimentation of the Parecis basin. Gravity modeling by Braga and Siqueira (1996), partly controlled by some drilling wells in the southern part of the Parecis basin, indicates that the Caiabis graben is composed of two parts, the deepest one reaching a depth of about 6–7 km, east of Porto dos Gaúchos seismic zone. However, despite being a major upper crustal structure, the WNW–ESE trending Caiabis graben does not seem to have a direct relationship with the 1998 and 2005 WSW–ENE faulting.

Although no direct correlation of the fault plane could be observed with the gravity features, a series of WSW–ENE short-wavelength lineaments can be observed in the aeromagnetic anomalies (Fig. 4), similar to the PGSZ fault orientation. Geological mapping of the Caiabis graben and surrounding area (Fig. 16a) by Leite and Saes (2003) shows a major WSW–ENE oriented fault reaching the middle of the Caiabis graben, parallel to the aeromagnetic lineaments seen in Fig. 4. This fault may have previously controlled the location of the deepest part of the Caiabis graben. This fault has exactly the same orientation as the fault planes of the 1998 and 2005 earthquake sequences and is perfectly aligned with the epicentral area. We propose that this WSW–ENE fault (Fig. 16a) crosses the entire Caiabis graben (as indicated by the dashed line in Fig. 16b) and its reactivation is the main cause of the Porto dos Gaúchos earthquakes of 1998 and 2005. However, detailed 3D information of the basement structure is not available beneath the Caiabis graben or PGSZ, so that further studies are necessary to confirm our hypothesis.

Although the focal mechanisms are consistent with the expected mid-plate regional stresses in South America, local sources of stress may also contribute to the observed seismicity. Lateral density variations in the upper crust, such as indicated by the Brasnorte basement high next to the deep Caiabis graben would produce local extensional stresses oriented NNE–SSW in the PGSZ, located in the basement high (Fig. 16b). This local effect would be consistent with the focal mechanisms and could also contribute to increase shear stresses in properly oriented faults.

The large 1955 earthquake also seems to be located in a basement high (Fig. 16b). The epicentre determined with about 100 teleseismic stations is probably misplaced by few tens of km to the SW (similar to the 1998 epicentre), which indicates that it is unlikely to be associated with the Pimenta Bueno graben in the middle of the Parecis basin (Fig. 16b). The focal mechanism, despite the large uncertainty in orientation of the fault planes, also confirms that a direct association with the WNW–ESE trending buried grabens in the Parecis basin is highly unlikely.

On the other hand, the model of intersecting structures, as proposed by Talwani (1999) and Gangopadhyay and Talwani (2003), could perhaps apply to the PGSZ if we consider the ENE–WSW seismogenic faults together with WNW–ESE structures of the buried grabens (Fig. 16b). Models of stress concentration, however, will require better constrained data for the deep structure of the Parecis basin.

8. Conclusions

The largest Brazilian earthquake of 1955 and the recurrent activity observed near the town of Porto dos Gaúchos since 1959 make this region one of the most important seismic zones in Brazil. The 1998 and 2005 focal mechanisms show right-lateral strike-slip motion in a fault oriented in the ENE–WSW direction. Both the epicentre and the fault-plane orientation indicate no direct relationship with buried grabens beneath the Parecis basin. Despite the uncertainties, the large 1955 earthquake does not seem to be related to any buried graben either. This means that the PGSZ is not related to a rifted continental crust. Given that the 1998 and 2005 earthquakes had moderate magnitudes, this result is not inconsistent with the statistics expected from the Schulte and Mooney's (2005) compilation.

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