Geofísica Internacional (1996), Vol. 35, Num. 3, pp. 257-272

Earthquake hazard assessment in Southeastern Brazil

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RESUMEN

La región sudeste del Brasil contiene algunas de las ciudades más importantes y los principales centros industriales del país. En los últimos 200 años se produjeron cuatro sismos mayores de m_b 5.0, uno de los cuales fue de m_b 6.3. El parámetro b se calcula en 1.10± 0.33. Se calculan intervalos de recurrencia de varios siglos para sismos de magnitud superior a 5.

PALABRAS CLAVE: Brasil, sismicidad intraplaca, intervalos de recurrencia.

ABSTRACT

Southeastern Brazil is subject to the low level of seismic activity typical of intra-plate regions. One large-magnitude earthquake (m_b=6.3) and three more with m_b magnitude above 5.0 have occurred in this region during the last 200 years. Just over a dozen earthquakes with m_b magnitude between 4.0 and 5.0 are known. Instrumental data are available since the 1970's when the South American Array Station was installed in Brasilia. Several other short period vertical stations have now been installed within the region. The frequency/magnitude relation from m_b>3.0 is given by

$$\text{Log}^{*}(N)=3.09\ (\pm0.12)-1.06(\pm0.10)m_b\ .$$

The b value with the maximum likelihood method is 1.10(±0.33), in close agreement with the value presented above. Using the extreme value method, it is possible to determine other recurrence curves and to estimate the seismic risk in the region. Recurrence intervals agree with observed values of magnitude $m_b \leq 5.0$. For larger magnitude events, the catalog is too small to make valid comparisons. The recurrence intervals for m_b magnitude 5.1, 5.5 and 6.3 events are 200, 600 and 4,000 years respectively.

KEY WORDS: Brazil, intraplate seismicity, recurrence times.

INTRODUCTION

This work presents earthquake hazard assessment for the Southeastern region of Brazil, based on a seismic catalog compiled at the Astronomical and Geophysical Institute of São Paulo University (IAG/USP). The results can be applied to the planning and construction of large engineering facilities within that region.

The region is located between the parallels 15°S-32°S and the meridians 35°W-52°W. It contains the most highly developed area of Brazil, and the largest populated and industrial centers of the country-São Paulo, Rio de Janeiro, and Belo Horizonte. Important engineering works, hydroelectric dams, and the Angra dos Reis nuclear power plant are also in this area.

Due to the relatively low level of seismic activity in most of Brazil and to the fact that no single catastrophic earthquake has occurred during historical times, the study of seismology in this country began only in the 1970's. Prior to construction of the Angra dos Reis nuclear plant in 1972, no seismic hazard studies had been performed in Brazil. Nevertheless, seismic activity in Brazil has been cataloged since historical times (Capanema 1859; Braner 1912, 1920; Silveira 1906, 1920, 1924; Sampaio 1916, 1919, 1920; and others). More recent compilations at a national level are due to Haberlehner (1978), Sadowski *et al.* (1978), and Berrocal *et al.* (1984). A seismic bulletin is published on a regular basis in the *Revista Brasileira de Geofísica.*

GEOLOGY

The region considered in this study is located in east-central South America, in an intraplate region where present-day tectonic processes are minimal compared to those along the borders of the South American tectonic plate.

The SE region of Brazil is composed of rocks of the Atlantic Shield and of the Phanerozoic Paraná Basin (Almeida and Hasui, 1984). The Archeozoic and Proterozoic basement rocks in that region were affected by the Transamazonic (~2.000 Ma) and Brasiliano (450-700 Ma) thermotectonic events (Schobbenhaus *et al.*, 1984), as shown in Figure 1. These thermotectonic events are the tectonic cycles that involve metamorphic, folding and plutonic processes, sedimentation, volcanism, and other tectonic manifestations.

According to Hasui *et al.* (1982), the South American Platform became consolidated after the Brasiliano event and remained in orthoplatformal conditions up to the Upper Jurassic. During that period, the Paraná Basin was developed, under the regime of a more stable tectonism. After the Upper Jurassic, new instability conditions appeared in most of the Brazilian territory and in the present continental margin, associated with the opening of the Atlantic Ocean. During the Mesozoic and Tertiary ages, the region of study experienced reactivation of the Paraná Basin area, the development of the Santos Basin, and displacements in the remaining continental areas.

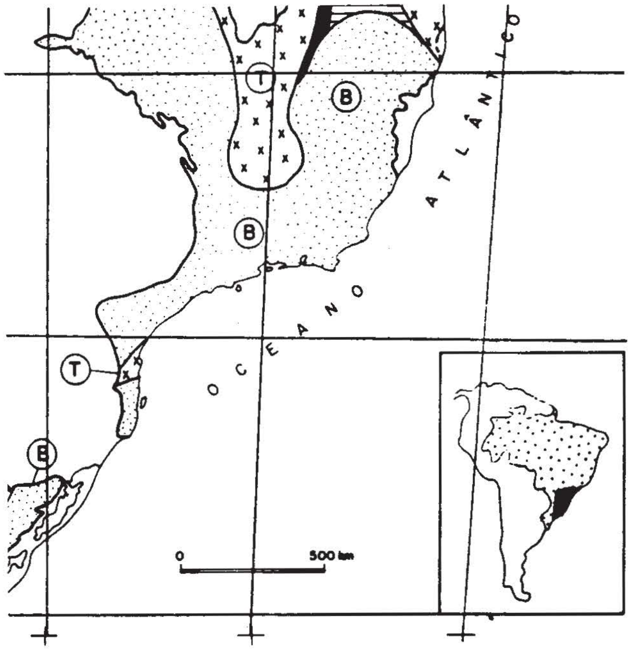


Fig. 1. Thermotectonic events, corresponding to tectonic cycles that have affected the region of study: (B), Brasiliano (470-700 Ma); (T), Transamozonic (~2000 Ma). Figure is taken from Schobbenhaus *et al.* (1984).

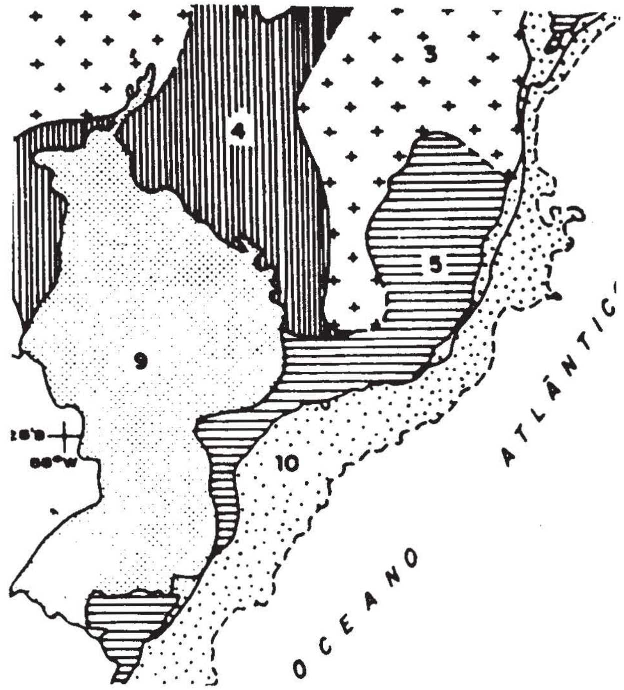


Fig. 2. Tectonic Provinces present in the region: (3) São Francisco Province; (4) Tocantins Province; (9) Paraná Province; (5) Mantiqueira Province and (10) Continental Margin Province. Figure is taken from Schobbenhaus *et al.* (1984).

Intense magmatic activity was associated with the Mesozoic and Tertiary tectonic activity (Hasui *et al.*, 1982), represented by basic sill flows; basic, ultrabasic and alkaline dikes; and alkaline massive intrusions. The São Paulo, Taubaté, Resende, Volta Redonda, Guanabara and Santos basins developed during active morphogenesis, as did the Serra dos Orgãos, Serra da Mantiqueira, Serra do Mar, and other mountain ranges, and the Caldas, Senador Amaral, and other plateaus.

The general structural framework outside the Paraná Basin area, but inside the region of study, is formed by large blocks down-dropped in the Santos Basin direction and tilting to the continental side (Hasui *et al.*, 1982). Uplifted zones and lowered blocks dominate the regional structure, indicating that larger active processes during the end of the Brasiliano cycle have influenced the modern tectonic picture. The Waldenian Reactivation, associated to the opening of the Atlantic Ocean, suggests a more intense tectonism in the Continental Margin than in the rest of the region.

The present tectonic regime involves discreet accommodation of the blocks that were intensely deformed during the Tertiary (Hasui *et al.*, 1982). This accommodation is not generalized but concentrates in areas of major influence, as illustrated by the geomorphologic and seismicity data.

The tectonic provinces in the region, according to Hasui *et al.* (1982), are the São Francisco, Tocantins, Mantiqueira, Paraná and Continental Margin provinces (see Figure 2). These provinces are characterized by sedimentary, metamorphic, magmatic, and tectonic processes that dominate the regional geotectonic framework.

The fault systems of regional size are the more conspicuous tectonic features in the region of study, as seen in Figure 3. These faults were formed at the end of the Brasiliano thermotectonic event as most of them affected Late Proterozoic units through folding and metamorphism (Almeida and Hasui, 1984). Some of these faults were reactivated during the Tertiary. The transcurrent faults are not uniformly distributed. They form subparallel and oblique discontinuities, grouped in shear zones, along the regional blocks, as shown in Figure 3. Several normal faults are smaller in size than the transcurrent faults, mainly in the Serra do Mar and Serra da Mantiqueira. Most normal faults are related to the Mesozoic-Cenozoic tectonic deformation. Some of these normal faults, younger than the transcurrent faults in that region, have affected the Pliocene and Pleistocene sediments of the continental traphogenic basins. According to Hasui *et al.* (1982), the alluvial and marine Holocene deposits have not been affected by faults up to present times.

The Paraná Basin was developed as a geosyncline between Early Devonian and Late Jurassic. Tectonic and magmatic processes have transformed the basin into an anticline. Those processes consisted, according to Almeida *et al.* (1981), of extensional faulting and fracturing with extrusion of large volumes of basaltic magma, forming thick layers and many dikes and sills. Bent layers, flexures and other tectonic structures also originated during this time.

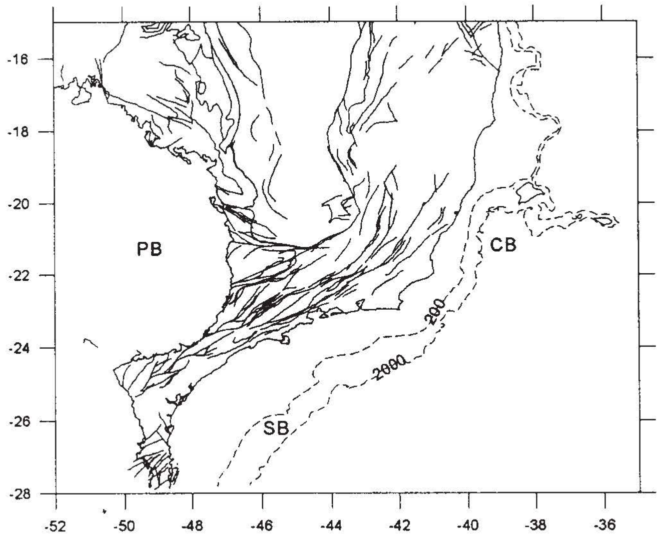


Fig. 3. Main Paleozoic and Proterozoic tectonic faults in the region of study. The 200 m and 2,000 m isobaths, and the Paraná (PB), Santos (SB) and Campos (CB) basins are shown in this map.

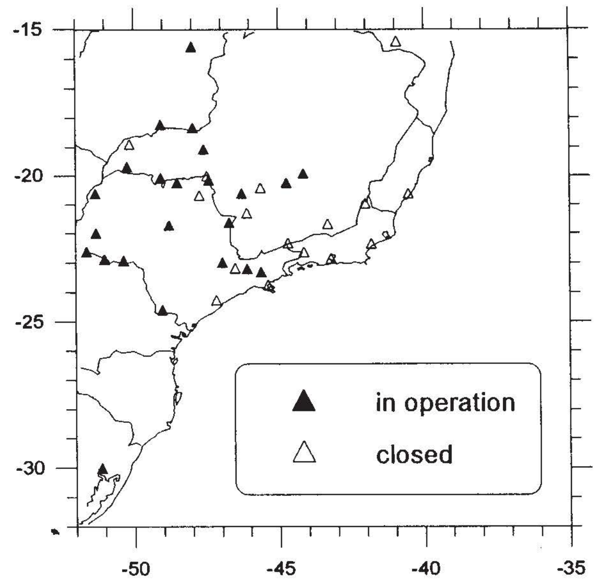


Fig. 4. Regional seismograph network in and around the SE region of Brazil, showing the stations that have operated since the 1970s.

The main structural features associated with the Paraná Basin are: the Ponta Grossa Arc, the Tiete and Guapiara lineaments and the Goiana Flexure.

Another major structural discontinuity is the Cabo Frio (RJ)-Poço de Caldas (MG) lineament, as suggested by Dias Neto (1986). This feature was based on the distribution of alkaline intrusions; on the presence of the Resende, Volta Redonda and Itaborai Cenozoic basins, between those intrusions; and on the Paraiba do Sul depression that developed predominantly on the southern side of that discontinuity. The alkaline magmatism in this lineament represents the most recent magmatic activity in the SE Brazilian region (~50 Ma).

The most important structural features in the oceanic portion are the depressions and highs, such as the Santos Basin axis, the Cabo Frio High and the high that separates the Santos Basin and the São Paulo Plateau. The development of these structures is influenced, according to Hasui *et al.* (1982), by normal faults present in the continental side of the basin, where the blocks of the oceanic side dropped down in relation to the blocks on the continental side, with slips of the order of 3,000 m. Other important tectonic features in the oceanic portion are the Victoria-Trindade High, and the Rio de Janeiro, Florianópolis and Porto Alegre lineaments.

SEISMOLOGICAL ASPECTS

Seismological data for this study were extracted from the catalog compiled by Berrocal *et al.* (1984) and from the *Boletim Sísmico Brasileiro* that is published in a regular basis in the *Revista Brasileira de Geofísica.* The data used in this work cover the interval 1767 - 1992 (April). Table 1 lists the most important events, with $m_b \geq 3.5$.

The epicenters of the more recent earthquakes, especially since the late 1970s, were calculated by using instrumental readings from the seismographic network operating in the SE Brazilian region (see Figure 4). We used the HYPO71 program (Lee and Lahr, 1975), assuming the Herrin (1968) tables. In some cases of earthquakes widely felt by the population, it was possible to determine the macroseismic epicenter with better precision (within a few km) than by using instrumental data where the instrumental determination error was of the order of tens of kilometers, especially older events or those with their epicenters lying outside the regional network. Epicenters offshore have larger determination errors.

The magnitudes were calculated by using the following equation (Assumpção, 1983):

$$m_R = \log V + 2.3 \log \Delta - 2.28 \quad , \qquad (1)$$

where

m_R is the regional magnitude,
$V = 2\pi A/T$ (A is maximum ground amplitude in micrometers and T the period in seconds).
Δ is the epicentral distance between 200 and 2,000 km.

Magnitude values for some of the more recent earthquakes have been revised in this work. Some magnitudes, especially in the case of historical events, were based on the following intensity/magnitude relations shown in Figure 5:

$$m_b = 0.64 I_0 - 0.11 \qquad (2.a)$$

for very shallow earthquakes with focal depths of the order of 1 or 2 km (Figure 5a), and

$$m_b = 0.63 I_0 + 1.12 \qquad (2b)$$

Table 1

Main earthquakes (m_b≥3.5) occurred in the region during the interval 1767-1992 (April).

DATE	LOCAL TIME	LAT.	LONG.	ERROR km	LOCALITY	ST	I_0 MM	AREA 10^3 km^2	MAG m_b	REMARKS
1767 08 01	20	-20.31	-40.33		VITORIA	ES	V		4.2	EPI.NO ALTO VII-TRIDADE?
1789 05 09		-25.01	-47.94		CANANEIA	SP	V-VI		4.6	
1861 07 31	01	-22.60	-45.20	50	LORENA	SP	V	52.0	4.4	
1863 04 08	23 45	-21.93	-45.25	20	CAMPANHA	MG	IV	1.5	3.6	
1874 10 30	09 30	-23.50	-47.50	10	SOROCABA	SP	V	1.7	3.6	
1886 05 09	15 15	-22.66	-43.69	20	S.PEDRO-S.PAULO.	RJ	V	23.0	4.3	AREA IV = 4700 KM2
1898 02 25	01	-26.93	-49.06		BLUMENAU	SC		5.4	3.9	
1917 05 05	04 50	-21.60	-41.50	50	CAMPOS	RJ	V	70.0	4.5	
1920 01 31	08 10	-21.03	-44.75	10	BOM SUCESSO	MG	VI	9.5	4.0	
1922 01 27	03 50 40	-22.17	-47.04	40	PINHAL	SP	VI	250.0	5.1	
1935 10 21	07 40	-21.03	-44.75	10	BOM SUCESSO	MG	V-VI	2.8	3.7	
1939 06 28	08 32 22	-29.00	-48.00	90	TUBARAO	SC	VI	1100. 0	5.5	(ISS, IAG) I.E.I.= VII
1946 07 18	04 15	-25.10	-47.70	30	CANANEIA	SP	IV-V	60.0	4.5	AREA IV = 25000 KM2
1947 02 19	01	-20.72	-46.61		PASSOS	MG	V		4.2	
1950 02 27	08 58	-21.82	-46.71	20	P. DE CALDAS	MG	V	6.0	3.9	
1955 02 28	22 46 18	-19.84	-36.75	30	FTE.VITORIA	ES			6.3	(ISS) VITORIA V MM RELOCAL. I.E.I.= VIII-IX M(ROTHE)=6; MB(PAS)=6.5
1967 03 22	21 12 15	-23.30	-45.00	20	CUNHA	SP	VI-VII	30.0	4.1	
1967 08 05	06 56 10	-22.85	-43.12	10	SAO GONCALO	RJ	V-VI	2.7	3.6	
1971 08 08	10 32 39	-20.28	-44.75		C.DO CAJURU	MG	V-VI		3.5	RIS
1972 01 23	00 03 51	-20.28	-44.75	5	C. DO CAJURU	MG	VI	3.2	3.7	RIS
1972 10 24	12 36 36	-21.72	-40.53	30	CAMPOS	RJ	V	210.0	4.8	(ISC, IAG) RELOCAL. H=15 I.E.I. = VI M M
1974 02 03	17 20 23	-29.50	-42.54	30	MARGEN CONT.	SC			4.4	(ISC)
1974 02 24	00 19 40	-20.04	-48.47	10	CONC.ALAGOAS	MG	VI-VII	7.0	4.2	
1974 04 11		-16.42	-41.64	5	TUPARECE	MG	VI-VII	2.8	3.7	
1975 03 30	14 06 00	-23.40	-42.40	30	PLAT. CONT.	RJ			3.5	(IAG)
1976 01 05	10 06 58	-15.35	-50.46	15	ITAPIRAPUAN	GO	V-VI	13.0	3.7	(ESB: BDF-3.2+.5
1977 06 19	00 03 30	-23.30	-42.60	30	PLAT. CONT.	RJ			3.5	
1977 11 20	11 46 35	-15.80	-43.50	30	JANAUBA	MG			3.7	
1979 03 27	09 54 45	-22.84	-51.01	5	PRIM.DE MAIO	PR	V-VI	1.3	3.7	RIS
1979 08 22	20 01 40	-16.26	-49.95	10	RUBIATABA	GO	IV	5.0	3.5	(ESB) AREA IV MM
1980 04 23	13 11 30	-26.50	-40.00	100	OC.ATLANTICO	SC			3.5	(IAG, ESB)
1981 05 07	00 44 55	-22.60	-39.50	50	PLAT. CONT.	RJ			3.7	(ESB)
1982 03 12	14 14 43	-23.60	-41.63	30	PLATAFORMA	RJ			3.5	(ESB, IAG)
1982 09 17	09 28 41	-25.84	-45.42	40	PLATAFORMA	SP			3.8	(ESB, IAG)
1984 02 22	05 00 26	-23.47	-40.70	50	PLAT. CONT.	RJ			3.7	(ESB, IAG)
1984 02 22	05 00 26	-23.47	-40.70	50	PLAT. CONT.	RJ			3.7	(ESB, IAG)
1984 04 08	17 56 00	-20.80	-46.76	10	PASSOS	MG	IV	6.2	3.8	(ESB,IAG)
1984 05 25	05 36 34	-24.92	-43.35	50	PLAT. CONT.	RJ			3.5	(ESB, IAG)
1986 01 14	17 14 26	-15.08	-50.32	20	ARAGUAPAZ	GO	IV	14.0	3.7	(ESB, IAG)
1987 07 29	04 18 28	-27.60	-43.50	100	ATLANTICO				3.7	(IAG, IPT)
1987 08 27	10 01 22	-25.00	-44.10	50	PLAT. CONTIN	SP			3.6	(IAG, ON, IPT)
1988 04 05	00 00 51	-22.10	-51.34	20	P. PRUDENTE	SP		5.0	3.8	(ESB, IAG)
1989 01 07	08 36 39	-22.93	-51.01	2	IBIACI	PR	VI	0.8	3.7	(IPT,IAG,UnB,ON)
1990 01 19	19 05 15	-19.95	-47.16	10	SACRAMENTO	MG	V-VI	5.0	3.9	(IPT,UnB,IAG,ON,UNESP)
1990 02 12	20 56 39	-31.19	-48.92	30	MARGEM CONT.	RS			5.5	H=030(GS mb=5,5,IAG,UnB, IPT,UNESP)P.Alegre(IIMM)
1992 01 28	13 05 39	-20.98	-39.70	30	MARGEM CONT.	ES			3.6	(IAG,IPT,UnB)
1992 02 01	14 24 30	-26.91	-44.42	30	MARGEM CONT.	SC			3.7	(IAG, IPT)
1992 03 02	03 06 37	-19.95	-47.16	10	SACRAMENTO	MG	IV		3.6	(IAG,UnB,IPT,UNESP)
1992 04 24	00 09 30	-26.85	-45.76	10	MARGEM CONT.	SC			4.0	(UnB,IPT,IAG,UNESP)
1992 04 24	00 31 31	-26.77	-45.81	10	MARGEM CONT.	SC			4.2	(UnB,IPT,IAG,UNESP)

for shallow crustal earthquakes with focal depths larger than 2 km (Figure 5b), where I_0 is the maximum epicentral MM intensity.

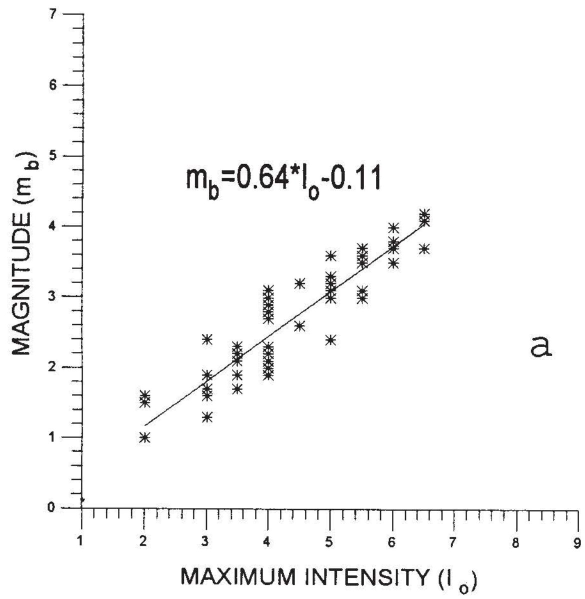
The magnitude of some earthquakes has been inferred by using the total felt area (A_f in km^2) and the following relation (Berrocal *et al.*, 1984):

$$m_b = 1.63 + 0.60 \log A_f \quad (3)$$

or by using signal duration for recent local earthquakes recorded instrumentally, as explained in Berrocal *et al.* (1993).

Figure 6 is a seismotectonic map of the portion of the studied region that includes the most important tectonic features and all reliable seismological data compiled in the catalog.

The largest earthquake in that region occurred on February 28, 1955. It was an m_b 6.3 event with epicenter around 400 km offshore. It was felt onshore with a maximum intensity V MM. This earthquake was felt in small towns, especially in the state of Espírito Santo (Figure 7). The epicentral intensity was estimated as VIII-IX MM by Berrocal *et al.* (1984), by using macroseismic data.



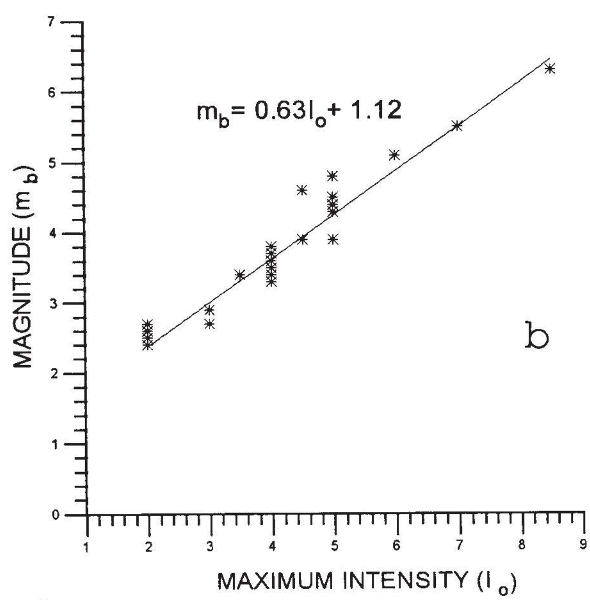


Fig. 5. Intensity/magnitude relations for earthquakes that have occurred in the region: (a) for very shallow events with depths less than 2 km and (b) for shallow crustal earthquakes with depths deeper than 2 km.

The next largest earthquake in the region occurred on June 28, 1939. This event, with magnitude m_b 5.5, also occurred under the Continental Margin, but only about 50 km offshore. This event near the epicenter had intensity VI MM, and was felt in many towns of Southeastern and Southern Brazil, up to distances of around 600 km, covering an area of the order of 1.1×10^6 km^2 (Figure 8). Berrocal *et al.* (1984) estimated a maximum epicentral intensity of VII MM for this earthquake.

Another m_b 5.5 earthquake occurred on February 12, 1990, approximately 200 km to the south of the previous one, also under the Continental Margin off Río Grande do Sul State (see Figure 8 for location). The epicenter, well located with data from more than 90 stations from the international and regional networks, was about 160 km offshore, on the edge of the Continental Platform. Unlike the June 1939 event it was not felt in the small seaside towns. It was felt slightly by persons on the upper floors of some tall buildings of Porto Alegre, located 360 km from the epicenter. This suggests a very shallow focal depth for this event, less than the reported 29 km and shallower than the June 1939 earthquake that was felt with intensity V MM up to distances of 200 km.

This February 1990 event could correspond to a huge landslide that collapsed a slope of almost 3,000 m, considering the occurrence of large mass movements during recent geological times where its epicenter was located. A high-gain seismograph station installed in 1991 in Porto Alegre, capable of recording earthquakes with $m_b \geq 3.0$ at regional distances of the order of 500 km, has not recorded any aftershocks in the epicentral region of the February 1990 event. An m_b 5.1 earthquake which occurred on 26 June 1988, east of the Rio de la Plata, had similar characteristics as the February 1990 event.

Next comes the earthquake of Pinhal-SP on January 27, 1922, near the border of São Paulo and Minas Gerais states. This magnitude m_b 5.1 earthquake produced a maximum felt intensity of VI MM in the epicentral zone. It affected many towns of the São Paulo, Minas Gerais and Rio de Janeiro states, over an area of over 250×10^3 km^2 (Figure 9).

There are some important earthquakes with magnitude under m_b 5.0. First there is an m_b 4.8 earthquake on October 24, 1972, in the Continental Platform, around 50 km off the border between Espírito Santo and Río de Janeiro states. It had a maximum observed intensity of up to V MM (VI MM of inferred epicentral intensity) in several important towns (Victoria, Campos and Río de Janeiro) and in some small towns both north and south of the states boundary (Figure 10). The relocated hypocenter yields a focal depth of 15 km, and the same epicenter as provided by NEIS/USGS. Two earthquakes occurred in Cananeia-SP, one on May 09, 1789, and the other on July 18, 1946, with V-VI and IV-V MM intensities and inferred magnitudes of m_b 4.6 (calculated with equation 2b) and 4.5 (calculated with equation 3 and $A_f=60 \times 10^3$ km^2). Other earthquakes occurred in Lorena-SP on July 31, 1861, with m_b 4.4, and in Campos-RJ on May 05, 1917, with m_b 4.5, both felt with V MM intensity.

Another important earthquake occurred on March 22, 1967, in Cunha-SP. Despite its relatively modest magnitude (m_b 4.1) it had a relatively significant VI-VII MM felt intensity. This earthquake was felt by passengers in moving vehicles in two different places, corresponding to the highest intensity felt in the whole region. The area of this earthquake is shown in Figure 11.

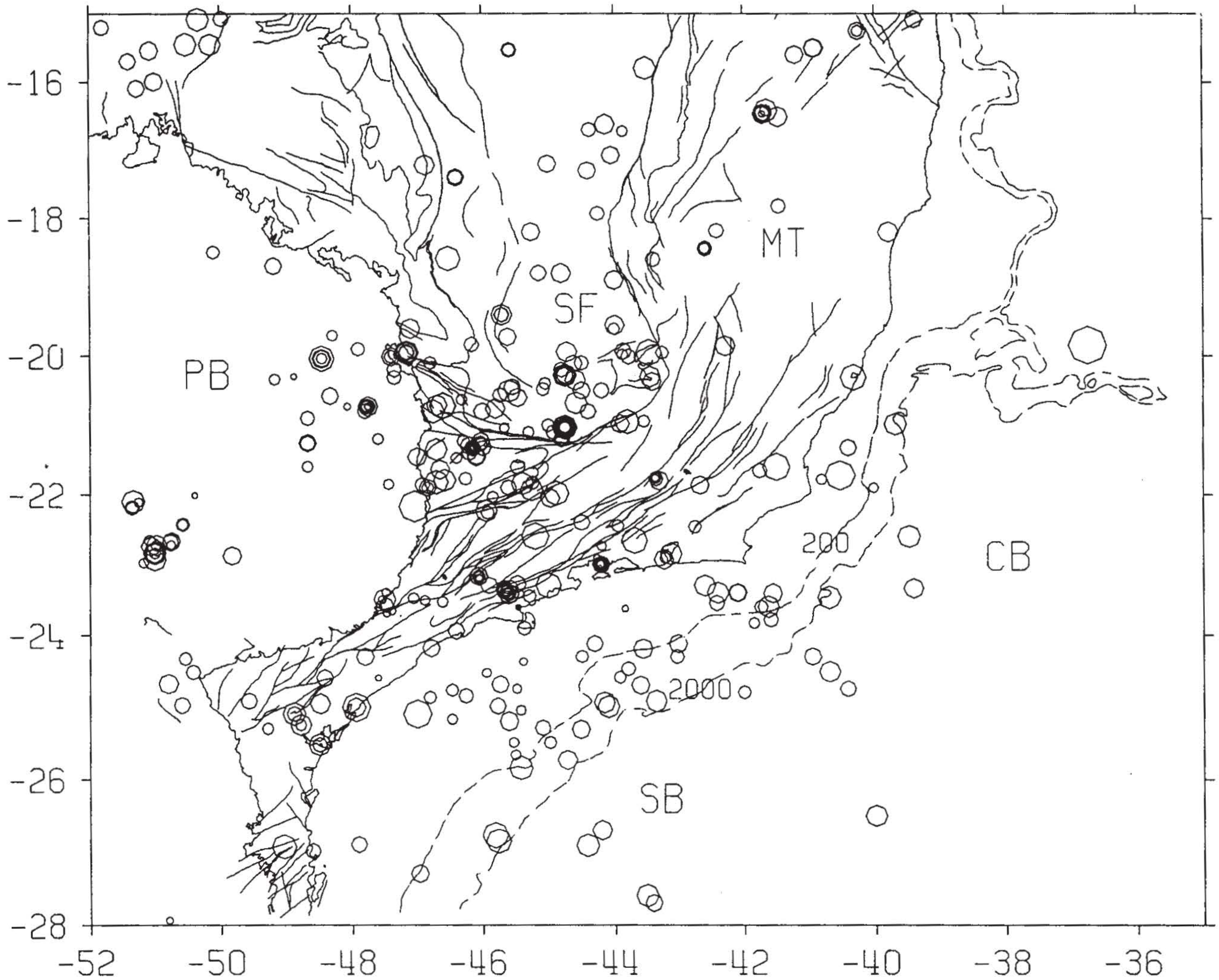


Fig. 6. Seismotectonic map of the region showing the main tectonic features and more reliable seismic epicenters. The size of the octagons correspond to magnitudes from m_b 1.0 to 6.3. The discontinuous lines correspond to the 200 m and 2,000 m isobaths. Also shown the Paraná Basin (PB), São Francisco (SF) and Mantiqueira (MT) Tectonic Provinces, and the Continental Margin Province represented by the Santos (SB) and Campos (CB) basins.

Table 1 lists some other events with intensities equal to or higher than VI MM but with relatively small magnitudes (around m_b 4.0). They were induced by hydoelectric reservoirs. The largest of these earthquakes, m_b 4.2 and intensity VI-VII MM, occurred on February 24, 1974, in Conceição das Alagoas-MG, induced by the impoundment of the Volta Grande and Porto Colombia reservoirs.

The earthquake in Cunha-SP and the induced event felt in Conceição das Alagoas-MG probably had very shallow focal depths, because of the high intensity produced by these modest magnitude earthquakes. Similarly, the tremors that occurred in August 1972 and April 1974 in Tuparece-MG, were probably shallow and effected a very small area of a few kilometers of radius.

The Southeastern region of Brazil is subject to quite low levels of seismic activity, typical of stable intraplate regions. The catalog compiled by Berrocal *et al.* (1984), with data since 1560, and the Brazilian Seismic Bulletins, with data up to 1992, show that during the last 430 years, only one earthquake with magnitude m_b larger than 6.0 and three earthquakes with m_b between 5.0 and 6.0 (two if the February 1990 event was a landslide) have occurred in southeast Brazil. During the last 220 years only fourteen earthquakes with magnitude m_b between 4.0 and 5.0 have occurred in this region, four before 1900, eight in the time interval 1900-1974, and two in April 1992.

Several seismic swarms have affected the region. Three swarms occurred in Bom Sucesso-MG during 1900-1902, 1919-1920, and 1934. Two swarms occurred in Monsuaba-RJ at the end of 1988 and beginning of 1989. Another swarm occurred in Areado-MG from 1991 to 1992. These seismic swarms are characterized by small magnitude (m_b <3.0) microtremors.

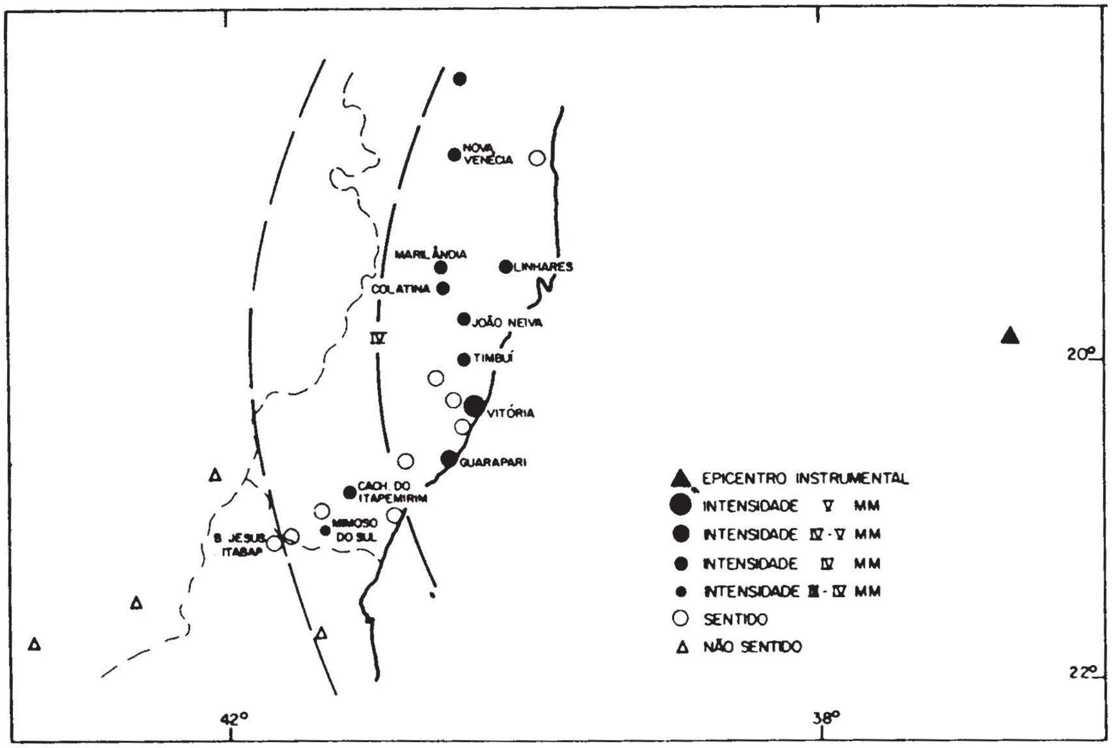


Fig. 7. Macroseismic data for the earthquake of February 28, 1955. Figure is taken from Berrocal *et al.*, (1984).

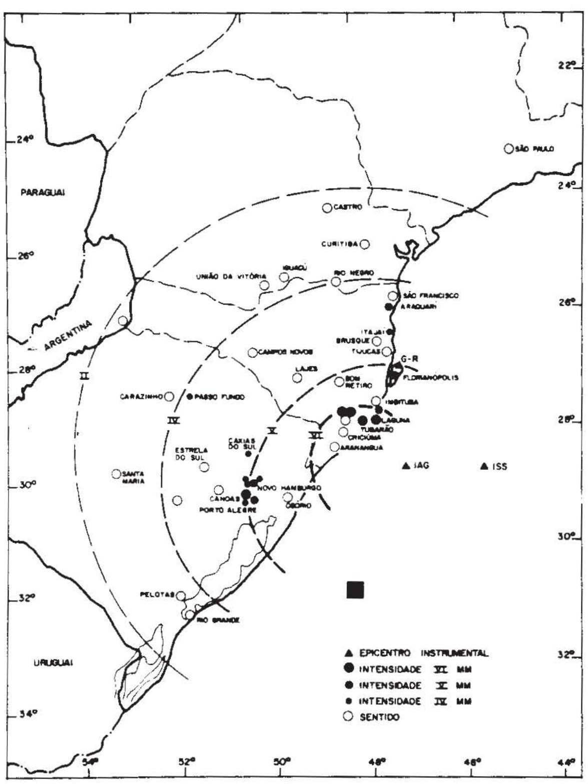


Fig. 8. Macroseismic data for the earthquake of June 28, 1939. The square symbol is showing the February 12, 1990 earthquake epicenter. Figure is taken from Berrocal *et al.*, (1984).

Increase of seismicity level in areas where induced seismicity occurred in the 1970's, has been observed in the Paraibuna-Paraitinga (SP) and Capivara (SP/PR) hydroelectric reservoir areas, where seismic activity occurs up to the present.

SEISMOTECTONIC PROVINCES

Regional seismotectonic interpretations for the Brazilian territory have been proposed by Heberlehner (1978), Sadowski *et al.* (1978), Hasui *et al.* (1982), Mioto (1984, 1993), Berrocal *et al.* (1984) and Dias Neto (1986). However, knowledge of the seismicity in the Brazilian territory, including the southeastern region, is still insufficient to permit the correlation of seismic activity with known tectonic features.

Instrumental recording of seismic activity in Brazil started in the 1960's, first with the Natal station installed in NE Brazil in 1964 and next with the temporary South American Array System (SAAS) installed near Brasilia in 1966. The permanent SAAS (BAO station) was installed in 1972. The first seismographic station in Brazil was RDJ, installed in 1906 near Rio de Janeiro. It contributed little to the knowledge of the seismicity in the southeastern region due to its long period seismographs and low amplification. Prior to the installation of the regional seismic network, the seismicity data consist of macroseismic information mainly in the more populated regions along the coast.

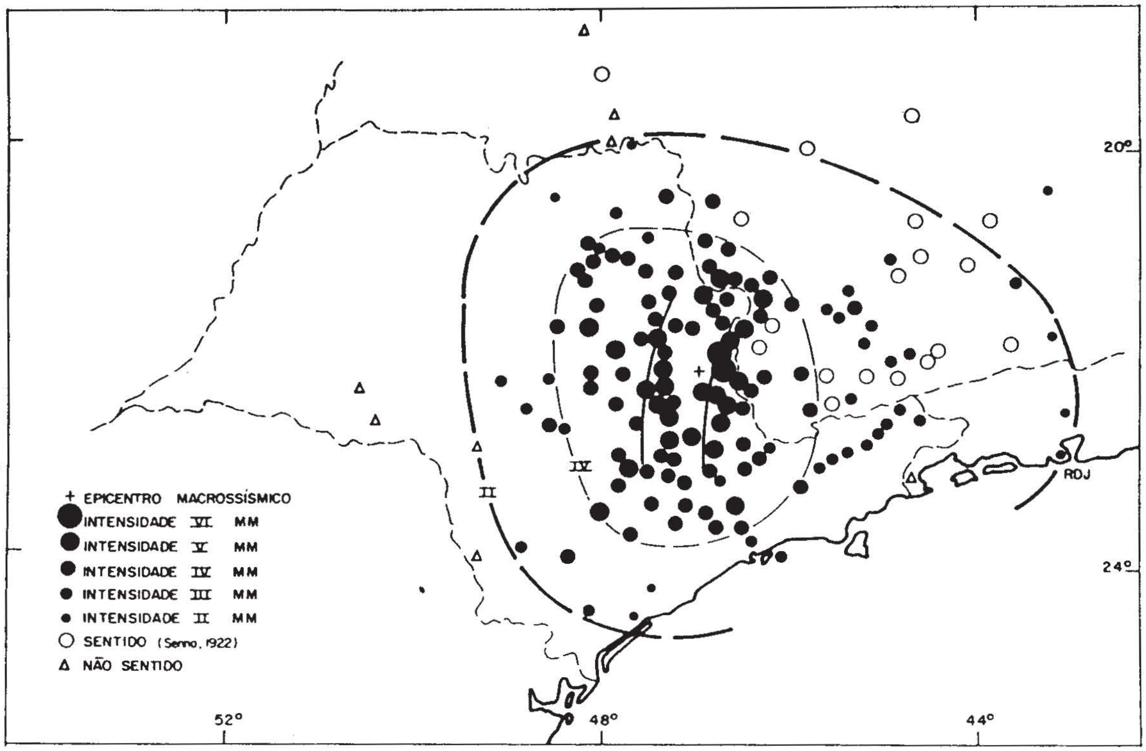


Fig. 9. Macroseismic data for the earthquake of January 27, 1922. Figure is taken from Berrocal *et al.*, (1984).

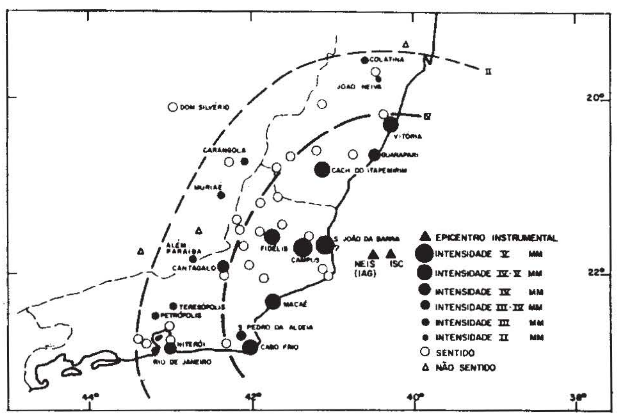


Fig. 10. Macroseismic data for the earthquake of October 24, 1972. Figure is taken from Berrocal *et al.*, (1984).

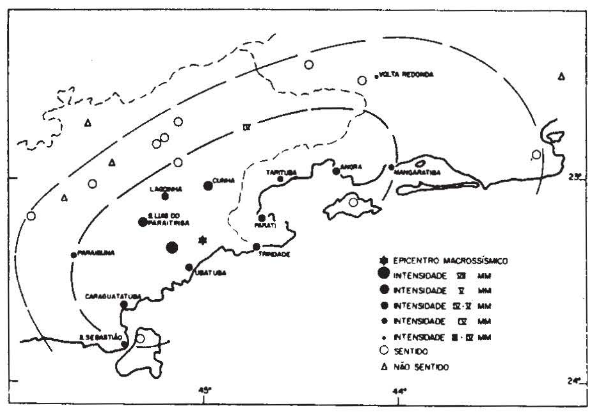


Fig. 11. Macroseismic information for the earthquake of March 22, 1967. Figure is taken from Berrocal *et al.*, (1984).

The seismographic network in the southeastern region (Figure 4) is well situated to constrain the location of seismic activity in this region. However, timing problems in several stations prevent precise epicentral location in most cases. The quality of the recorded data is poor and a structural model for this region is lacking. In a few cases, local temporary networks allowed precise hypocentral determinations, for example for the seismic swarm in Monsuaba-RJ (Berrocal *et al.*, 1993).

The seismotectonic map in Figure 6 illustrates the following features.

(1) Seismic activity is concentrated mainly in the southern portions of the Mantiqueira and São Francisco Tectonic Provinces and in the Santos and Campos basins (see also Figure 2).

(2) Correlations between epicenters and the main tectonic features are not clear. There are weak concordances with the NW-SE trending lineament suggested by Dias Neto (1986) and a SW-NE concentration of epicenters in the Santos Basin. Some events are located in the deepest portion of the continental margin, away from the coast, suggesting a possible offshore extension of structures mapped onshore.

(3) Seismicity in the inner portion of the Paraná Basin represents almost exclusively earthquakes induced by hydroelectric reservoirs or by deep wells for water supply.

Composite focal mechanism solutions of earthquakes induced by the Paraibuna-Paraitinga reservoir (Mendiguren, 1979), suggest that this activity occurred close to the Cubatão fault, but the induced earthquakes occurred along NS and EW planes and not along the SW-NE trend of that fault. Similar focal mechanism solutions were obtained by Berrocal *et al.* (1993) for the Monsuaba-RJ earthquakes.

We conclude that, even at present the data are insufficient to define seismogenic zones or seismotectonic provinces that could be used with confidence to determine seismicity parameters for hazard assessment in this region. Given the diffused spatial distribution of seismic activity, we propose to divide the whole region into two seismotectonic provinces: (a) the Paraná Basin Seismotectonic Province, represented mainly by induced seismic activity, and (b) the Pre-Cambrian Basement Seismotectonic Province, where most of the seismic activity within the region has occurred.

SEISMICITY PARAMETERS

The temporal distribution of the data presented in Figure 12a shows the evolution of data compilation in the southeastern region over the 220 years covered by the catalog. The lack of data, especially of small magnitude (m_b<3.0) events, is clear during most of the last two centuries, in contrast with the increasing number of events during the last 20 years. This is illustrated in Figure 12b, for 1960 to 1993. The catalog is fairly complete for lower magnitudes since the second half of the 1970's, when instrumental epicentral determinations started to be performed by using the seismographic network (Figure 4).

Seismicity parameters for the region of study can only be estimated for the time interval covered by instrumental data.

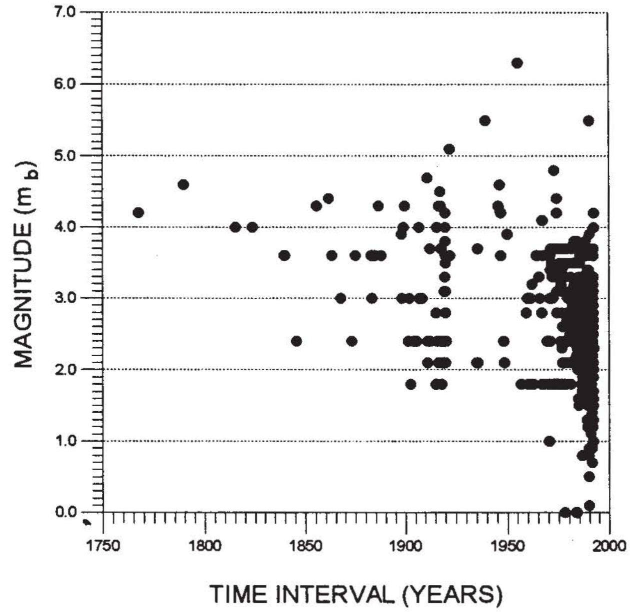
Frequency/Magnitude Relations

We used the frequency/magnitude relation proposed originally by Gutenberg and Richter (1954):

$$\log N = a - bM \quad (4)$$

where N is the number of earthquakes that occur in a given region in a unit time interval with magnitude M and the parameters a and b are constants to be determined by using the least squares' method.

The values of N for the Pre-Cambrian Basement Seismotectonic Province are presented in Table 2. They were obtained by dividing the total number of earthquakes of a given magnitude (from m_b 1.0 to 4.2 in increments of 0.1 m_b) by 13.3 the number of years between January 1979 and April 1992. Those values of N were smoothed with a Hanning window (Båth, 1981), where for instance $N_2 = (N_1+2N_2+N_3)/4$ is the corrected value for N_2. The corrected values for N are shown in Table 2.



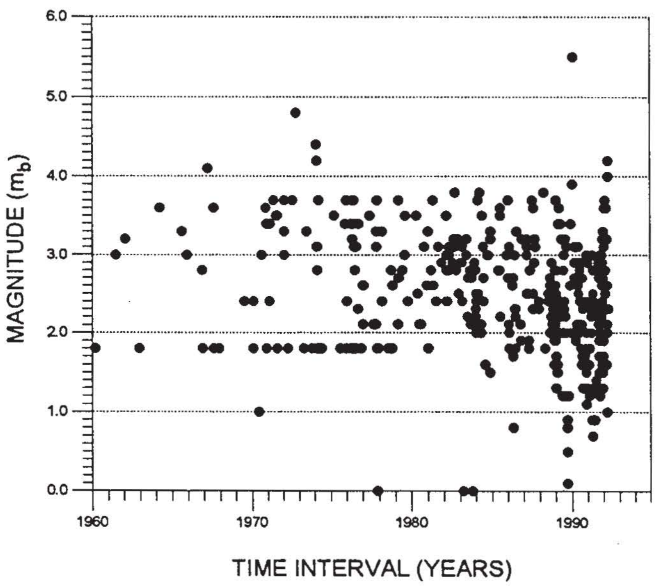


Fig. 12. Temporary distribution of seismic activity in the region, a) during the entire observing interval and b) in the interval from 1960 to 1993.

The logarithm of the corrected values of N is plotted in Figure 13 as a function of m_b. This figure illustrates the magnitude detectability threshold of the regional seismographic network used in this study, which is about m_b 3.1. This means that the network has recorded all earthquakes with $m_b \geq 3.1$ in the Pre-Cambrian Basement Seismotectonic Province, and that the number of reported earthquakes with m_b<3.1 is incomplete.

Table 2

Number of earthquakes with specific magnitude m_b which occurred in the Pre-Cambrian Basement seismotectonic province in the interval 1979-1992 (April).

m_b	N(orig)	ΣN(orig)	N(cor)	ΣN(cor)	N/ano	ΣN/ano
1.0	2	206	2.50	206.00	0.1875	15.4539
1.1	3	204	3.00	203.50	0.2251	15.2663
1.2	4	201	4.25	200.50	0.3188	15.0413
1.3	6	197	4.25	196.25	0.3188	14.7224
1.4	1	191	3.25	192.00	0.2438	14.4036
1.5	5	190	5.25	188.75	0.3938	14.1598
1.6	10	185	8.50	183.50	0.6377	13.7659
1.7	9	175	8.25	175.00	0.6189	13.1283
1.8	5	166	7.50	166.75	0.5626	12.5094
1.9	11	161	9.75	159.25	0.7314	11.9467
2.0	12	150	11.75	149.50	0.8815	11.2153
2.1	12	138	11.50	137.75	0.8627	10.3338
2.2	10	126	11.50	126.25	0.8627	9.4711
2.3	14	116	12.50	114.75	0.9377	8.6084
2.4	12	102	12.50	102.25	0.9377	7.6707
2.5	12	90	11.75	89.75	0.8815	6.7329
2.6	11	78	10.75	78.00	0.8065	5.8515
2.7	9	67	10.25	67.25	0.7689	5.0450
2.8	12	58	9.50	57.00	0.7127	4.2761
2.9	5	46	6.50	47.50	0.4876	3.5634
3.0	4	41	5.00	41.00	0.3751	3.0758
3.1	7	37	5.75	36.00	0.4314	2.7007
3.2	5	30	5.50	30.25	0.4126	2.2693
3.3	5	25	5.00	24.75	0.3751	1.8567
3.4	5	20	5.00	19.75	0.3751	1.4816
3.5	5	15	4.25	14.75	0.3188	1.1065
3.6	2	10	2.75	10.50	0.2063	0.7877
3.7	2	8	2.25	7.75	0.1688	0.5814
3.8	3	6	2.25	5.50	0.1688	0.4126
3.9	1	3	1.50	3.25	0.1125	0.2438
4.0	1	2	0.75	1.75	0.0563	0.1313
4.1	0	1	0.50	1.00	0.0375	0.0750
4.2	1	1	0.50	0.50	0.0375	0.0375

The following frequency/magnitude relation was obtained by using the corrected values of N for $m_b \geq 3.1$:

$$\log N = 3.09\ (\pm 0.12) - 1.06\ (\pm 0.10)\ m_b\ , \qquad (5)$$

shown as the lower line in Figure 13.

Another way of estimating the frequency/magnitude relation is by using the cumulative number of N(ΣN) that includes all events with magnitudes equal or higher than a given magnitude (Table 2 and Figure 13). In this case, as recommended by Båth (1981), the following relation is used to estimate the distribution:

$$\log \Sigma N = a - bM + \log \frac{1 - 10^{-b\delta M} \cdot 10^{-(a-bM)}}{1 - 10^{-b\delta M}} \qquad (6)$$

where a and b are the parameters of (4), M is the magnitude and δM is the magnitude increment (in this paper, 0.1 m_b).

The distribution of logΣN is not linear, as seen in Figure 13. It can be fitted by using relation (6) or through a series of straight lines adjusted for small intervals. The distribution of ΣN for the magnitude interval between m_b 3.1 and m_b4.2 was approximated by using the least squares' method:

$$\log \Sigma N = 5.73(\pm 0.13) - 1.65(\pm 0.11) m_b\ . \qquad (7)$$

The recurrence intervals for single or cumulative values of magnitude can be obtained from equations (5) and (7), respectively. The results are shown in Figure 14, together with other recurrence curves to be explained in the following.

The Maximum Likelihood Method

The b parameter of equation (4) can also be determined by using the maximum likelihood method (Aki, 1965):

Table 3

Extreme value data for the Pre-Cambrian Basement Seismotectonic Province in the time interval 1972-1992.

	m_b	G(M)	lnG(M)	-lnG(M)	ln(logG(M))
1	3.0	0.0455	-3.0910	3.0910	1.1285
2	3.0	0.0909	-2.3979	2.3979	0.8746
3	3.1	0.1364	-1.9924	1.9924	0.6894
4	3.1	0.1818	-1.7047	1.7047	0.5334
5	3.2	0.2273	-1.4816	1.4816	0.3931
6	3.3	0.2727	-1.2993	1.2993	0.2618
7	3.3	0.3182	-1.1451	1.1451	0.1355
8	3.4	0.3636	-1.0116	1.0116	0.0115
9	3.4	0.4091	-0.8938	0.8938	-0.1123
10	3.5	0.4545	-0.7885	0.7885	-0.2377
11	3.5	0.5000	-0.6931	0.6931	-0.3665
12	3.5	0.5455	-0.6061	0.6061	-0.5007
13	3.5	0.5909	-0.5261	0.5261	-0.6423
14	3.6	0.6364	-0.4520	0.4520	-0.7941
15	3.6	0.6818	-0.3830	0.3830	-0.9597
16	3.7	0.7273	-0.3185	0.3185	-1.1443
17	3.8	0.7727	-0.2578	0.2578	-1.3555
18	3.9	0.8182	-0.2007	0.2007	-1.6061
19	4.2	0.8636	-0.1466	0.1466	-1.9200
20	4.4	0.9091	-0.0953	0.0953	-2.3506
21	4.8	0.9545	-0.0465	0.0465	-3.0679

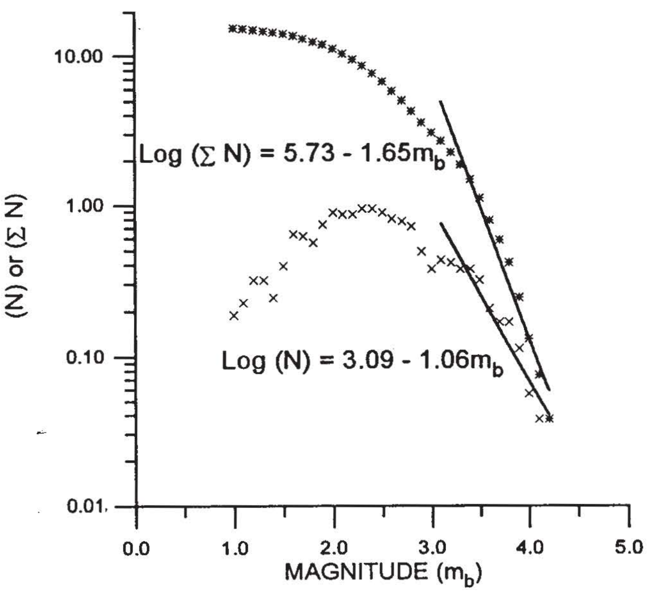


Fig. 13. Single (N) and cumulative (ΣN) frequency/magnitude annual distribution for the Pre-Cambrian Basement Seismotectonic Province, during the period between 1979 and 1993.

$$b = \frac{\log e}{\overline{M} - M_1} \qquad (8)$$

where $\overline{M}$ is the mean magnitude equal to or higher than the threshold of detectability M_1, which was determined using the single frequency/magnitude relation:

$$\overline{M} = \frac{\Sigma(Nm_b)_i}{\Sigma N_i} \qquad (9)$$

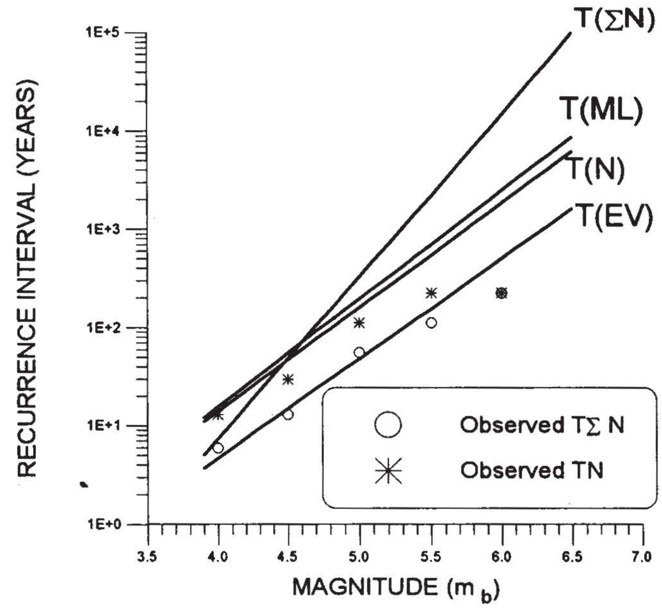


Fig. 14. Recurrence curves and observed values for the Pre-Cambrian Basement Seismotectonic Province. The curves based on single magnitude values distribution were obtained through the single frequency/magnitude T(N) and maximum likelihood T(ML) methods. The recurrence curves of cumulative magnitudes were calculated with the extreme values T(EV) and cumulative frequency/magnitude T(ΣN) methods. Note the real single and cumulative observed magnitude values of earthquakes occurred in the region.

where i varies from 1 (corresponding to the first m_b value larger than M_1) through n (corresponding to the largest m_b value in the catalog).

By using the corrected values of N in Table 2, we find $M_1 = 3.1$ and $\Sigma N_i = 2.27$. Equation (9) yields a value of $\overline{M} = 3.50$. With these values, the result of equation (8) is $b = 1.10$, with a variance $\sigma = \pm 0.33$ (where $\sigma = b/\sqrt{n}$).

Parameter a can be calculated by using the following relation obtained from equation (4):

$$a = \log \Sigma N + \log(\Sigma 10^{bM_i}) \qquad (10)$$

where ΣN corresponds to $m_b > M_1$ (2.2693 as indicated in Table 2), $b = 1.10$ and M_i are the values of m_b larger than 3.1 in Table 2. Using these values, equation (10) yields $a = 3.21$. In conclusion,

$$\log N = 3.21 - 1.10\, m_b \ . \qquad (11)$$

This is equation (5), as obtained by using the maximum likelihood method. The recurrence curve computed with equation (11) is shown in Figure 14.

The Extreme Value Method

The complete set of earthquake data is often not available. By dividing the time scale in equal intervals and considering the maximum value for each interval, called "extreme value", we may find a sequence of regular points whose proprieties have been discussed widely by Gumbel (1958, in Lomnitz, 1974). Four mathematical distributions of extreme values were discussed by Gumbel, of which the first one, known as Type I, is

$$G(M)=\exp(-\alpha e^{-\beta m}) \qquad (12)$$

where M is the magnitude of the extreme values and α and β are constants to be estimated.

The Southeastern Brazil seismicity catalog was used to solve equation (12). For the more recent data starting in 1972, the events with maximum magnitude each year from 1972 to 1992 (April) (almost 21 consecutive years) were selected and ordered in a decreasing sequence as shown in Table 3.

The G(M) values were calculated by using the following relation:

$$G(M_j)=j/(n+1) \qquad (13)$$

where j = 1,2,...n, and n is the number of years being considered (21 in our case). The values of $G(M_j)$ are presented in Table 3.

The values for α and β are estimated by least squares as follows:

$$\ln[-\ln G(M)]=\ln\alpha-\beta M \ . \qquad (14)$$

The values of -lnG(M) and of ln[-lnG(M)] are also shown in Table 3. The following results were obtained:

$\ln \alpha = 7.81 (\pm 0.21)$
$\alpha = 2{,}462.643$
$\beta = 2.33981.$

After determining α and β several other parameters useful for seismic hazard assessment can be determined (Lomnitz, 1974). Some of those parameters are:

(a) Yearly cumulative number of earthquakes (ΣN), with $m_b \geq 0$, corresponding to the value of α = 2,462 events.

(b) Cumulative number of earthquakes (ΣN), with magnitude equal or larger than M_1 (detectability threshold, m_b =3.1), in a given number of years D:
$\Sigma N_{(M1)}=D\alpha\exp(-\beta M_1)$
If D=1 year, $\Sigma N_{(M_1)}$=1.74 earthquakes with $m_b \geq 3.1$
If D=10 years, $\Sigma N_{(M_1)}$=17.4 earthquakes with $m_b \geq 3.1$
If D=100 years, $\Sigma N_{(M_1)}$=174 earthquakes with $m_b \geq 3.1$.

(c) Mean magnitude ($\overline{M}$) of earthquakes that occur in the region:

$$\overline{M}=M_1+\beta^{-1}=3.53 \ .$$

This is similar to the value of $\overline{M}$ calculated by the maximum likelihood method.

(d) Maximum Modal (MM) or maximum value observed more frequently and with the largest probability of occurrence:

$$MM=(\ln \alpha)/\beta =3.34 \ .$$

(e) Mean recurrence interval (T), the inverse value of the yearly number of earthquakes with magnitude larger than M:

$$T_M=1/\Sigma N_M=\exp(\beta M)/\alpha \ .$$

The following recurrence intervals were obtained for the listed cumulative magnitude values:

$M(m_b)$	T_M(years)
≥ 4.0	4.7
≥ 4.5	15.2
≥ 5.0	48.9
≥ 5.5	157.6
≥ 6.0	507.7
≥ 6.5	1653.6

The recurrence curve calculated for m_b between 3.9 and 6.5, is shown in Figure 14 together with the other recurrence curves calculated with the methods described above.

Analysis of the Recurrence Curves

The frequency/magnitude relations represented by equations (5) and (11), for single distribution N, and (7) for cumulative distribution (ΣN), were extrapolated to higher values of magnitude and inverted to obtain the recurrence intervals for magnitude m_b values between 3.9 and 6.5 (Figure 14). Also the recurrence intervals obtained from the extreme values' method corresponding to cumulative distribution of m_b, for magnitudes 3.9 to 6.5 are plotted in Figure 14.

The recurrence curves corresponding to the single frequency/magnitude distribution (T(N)) and for the maximum likelihood method (T(ML)) are identical. On the other hand, the recurrence curves corresponding to the cumulative frequency/magnitude distribution (T(ΣN)) and to the extreme values' method (T(EV)) show results that are completely different.

The curve for T(ΣN) is valid only up to m_b 4.2, the largest magnitude in the catalog during the time interval in this study. The fit of the cumulative data was done using a linear regression instead of an exponential format as recommended by Båth (1981), so the gradient of the curve corresponds to a larger value of b (1.65), and the recurrence values rapidly become larger than the values of the single regression recurrence curve T(N), which is not correct. On the other hand, the recurrence curve T(EV) has almost the same gradient as the curves T(N) and T(ML), but with smaller recurrence interval values, which makes sense when such a curve is considered to represent the cumulative number of earthquakes.

The observed recurrence intervals, calculated with the data presented in Figure 12a, are also shown in Figure 14. The observed recurrence intervals (Table 4) consider the number of events with magnitude $m_b \pm 0.1$, in the case of single values of magnitude, or the number of earthquakes with magnitude $\geq(m_b-0.1)$, for the cumulative values of magnitude, to compensate for uncertainties in the calculation of the observed magnitude values. For earthquakes with magnitude $m_b<5.0$, we assumed a catalog completeness interval of 92 years (1990-1992) and for events with magnitude $m_b \geq 5.0$, the assumed interval was 225 years (1767-1992), as shown in Table 4.

Table 4

Observed recurrence intervals in the Pre-Cambrian Basement Seismotectonic Province

m_b	simple m_b			acumulative m_b		
	Interval	N	T	Interval	ΣN	T
4.0	92	7	13	92	14	6
4.5	92	3	30	92	7	13
5.0	225	2	112	225	4	56
5.5	225	1	>225	225	2	112
6.0	225	1	>225	225	1	>225

The observed recurrence intervals for single values of magnitude agree relatively well with the curves T(N) and T(ML) up to m_b=5.0. For larger values of m_b the observed recurrence intervals are increasingly smaller, which could be due to assuming a time interval (225 years) too small for events with magnitude larger than 5.0, or to the fact that the extrapolation of the curves T(N) and T(ML) results in artificially large estimated values of recurrence intervals for the largest magnitude events.

The recurrence curve obtained by using the extreme values' results (T(EV)) has a gradient similar to the single distribution recurrence curves and agrees fairly well with the observed values of cumulative number of events, up to $m_b \geq 5.5$. For larger values the predicted recurrence interval is higher than the observed one. Perhaps the observed period of 225 years is too short for events with magnitude larger than 5.5, which seems reasonable.

From Figure 14 and Table 4, it is concluded that the recurrence intervals predicted with the curves T(N) and T(ML) are consistent with the observed values in the Pre-Cambrian Basement Seismotectonic Province up to magnitude m_b=5.0. For larger magnitudes the predicted recurrence intervals are larger than the observed ones, due to the relatively small interval of observation (225 years) considered in the catalog. In the same way, the recurrence intervals for cumulative magnitude values predicted with the curve T(EV) is consistent with the observed data up to $m_b \geq 5.5$, and for larger magnitude earthquakes, the predicted value is larger than the observed one, again due to the short length of the catalog. Based on these results, we suggest the following predicted and observed recurrence intervals (in years) for known earthquakes:

Earthquake/m_b	Single Distribution		Cumulat. Distribution	
	T(N)	Obs. Int.	T(EV)	Obs. Int.
Cunha 1967/4.1	17	15	6	6
C. Marg. 1972/4.8	100	80	30	28
Pinhal 1921/5.1	200	>112	60	50
C. Marg. 1939/5.5	600	>225	180	112
Alto V-T. 1955/6.3	4,000	>225	1000	>225

Thus an earthquake similar to the 1967 Cunha event should occur about every 17 years, and an earthquake with magnitude equal to or greater than m_b 4.1 may be expected every 6 years in the Pre-Cambrian Basement Seismotectonic Province. Similarly, an event of the size of the 1921 Pinhal event may occur once every 200 years, but events with magnitude equal to or larger than m_b 5.1 may occur about every 60 years.

Seismic Risk Evaluation

The seismic risk (R), corresponding to the probability of occurrence of an earthquake of a given magnitude ($M \geq m_b$) in a time interval (D) is given, according to Lomnitz (1974), by:

$$R_D(M)=1-\exp(-\alpha D e^{-\beta M}) \quad (15)$$

where α and β are the parameters determined using the extreme values' method.

Table 5 and Figure 15 present the values for seismic risk in the Pre-Cambrian Basement Seismotectonic Province, calculated using relation (15), for cumulative magnitude values in the range of m_b from 4.0 to 6.0, and for time intervals from 1 to 100 years. An m_b 4.0 earthquake, for instance, has a probability of 19% of occurring in one year interval, but almost 90% in an interval of ten years and nearly 100% in time intervals larger than 25 years. On the other hand, an event with m_b 6.3 has a probability of less than 10% of occurring in a time interval of 100 years.

DISCUSSION AND CONCLUSIONS

The southeastern region of Brazil has a low level seismic activity typical of intra-plate regions, as is the case for most of the Brazilian territory. Only one earthquake with magnitude m_b>6.0 occurred in this region during the last 200+ years covered by the catalog used in this work. No more than three events with m_b>5.0 and 14 with m_b between 4.0 and 5.0 have been catalogued in that time interval.

Instrumental data is available beginning in the 1970's. The epicentral parameters determined with the regional seismographic network have relatively large errors due to the poor time control of most stations, and to the lack of an appropriate crustal structure model in the region. Consequently, it is not possible to correlate epicenters with tectonic features. Therefore, it is not possible to define seismogenic zones or seismotectonic provinces to be

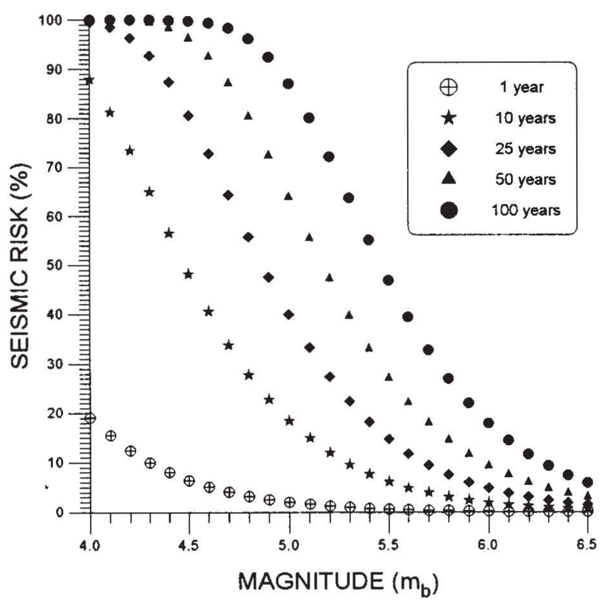


Fig. 15. Seismic risk in the Pre-Cambrian Basement Seismotectonic Province for cumulative magnitude values and time intervals from 1 to 100 years. The risk is given as the probability (in percentage) of occurrence of events of equal to or larger than a given magnitude (m_b), during one of the time intervals shown with different symbols.

Table 5

Seismic risk in the Pre-Cambrian Basement Seismotectonic Province for accumulative magnitud values. The risk is given as the probability (in percentage) of occurrence of events of equal to or larger than a given magnitude (m_b), during one of the following time intervals: 1,10,25,50 or 100 years.

m_b	1	10	25	50	100
4.0	19.119	88.020	99.503	99.998	100.000
4.1	15.458	81.349	98.498	99.977	100.000
4.2	12.444	73.524	96.393	99.870	100.000
4.3	9.983	65.065	92.786	99.480	99.997
4.4	7.986	56.494	87.516	98.441	99.976
4.5	6.374	48.245	80.730	96.287	99.862
4.6	5.079	40.621	72.831	92.618	99.455
4.7	4.041	33.800	64.343	87.286	98.384
4.8	3.212	27.851	55.785	80.450	96.178
4.9	2.550	22.766	47.578	72.519	92.448
5.0	2.024	18.490	40.017	64.020	87.054
5.1	1.605	14.938	33.267	55.467	80.169
5.2	1.272	12.018	27.392	47.280	72.207
5.3	1.008	9.636	22.378	39.748	63.696
5.4	0.799	7.706	18.165	33.031	55.151
5.5	0.633	6.149	14.670	27.188	46.984
5.6	0.501	4.898	11.799	22.205	39.480
5.7	0.397	3.896	9.458	18.021	32.795
5.8	0.314	3.096	7.562	14.551	26.985
5.9	0.249	2.458	6.033	11.702	22.034
6.0	0.197	1.950	4.805	9.379	17.879
6.1	0.156	1.547	3.822	7.498	14.434
6.2	0.123	1.226	3.037	5.982	11.605
6.3	0.098	0.971	2.411	4.764	9.301
6.4	0.077	0.770	1.913	3.789	7.435
6.5	0.061	0.610	1.517	3.011	5.931

used in the assessment of seismic hazard. The region was divided into two seismotectonic provinces: the Paraná Basin, a stable province subjected to induced earthquakes, and the Pre-Cambrian Basement province, where most seismic activity occurs.

Temporal distribution of reliable data allows the calculation of recurrence relations using the methods of frequency/magnitude and maximum likelihood for single values of magnitude, and the extreme values' method for cumulative values of magnitude. The observed data agree fairly well with the recurrence curves up to magnitude m_b<5.0. For larger values of magnitude the observed recurrence intervals are increasingly smaller than the predicted ones, probable due to the relatively small time interval (225 years) considered in the catalog. The extreme values' method allows the calculation of an estimate of the seismic risk in the region for events of magnitude equal or larger than a given value in the range from m_b 4.0 to 6.5, and over time intervals from 1 to 100 years.

These results, based on instrumental data, represent the characteristics of the seismicity in the Pre-Cambrian Basement Seismotectonic Province, and can be useful in the selection of a design earthquake in this province. Definition of a design earthquake, for sites of interest inside the Paraná Basin Seismotectonic Province, should consider the Pre-Cambrian Basement Seismotectonic Province as the seismogenic province.

Seismic attenuation for the region may be estimated in two ways: (1) assuming the attenuation function defined by Campbell (1982) for Central and Eastern United States,

$$I_{MM}=2m_b-0.3-0.0011\Delta-1.17(\ln\Delta)$$

where Δ is the epicentral distance in km, or (2) from the isoseismal maps of important earthquakes that have occurred in the region. For the second approach it is necessary to consider the probable focal depth of the design earthquake: if it is very shallow, like the 1972 Cunha's earthquake, the attenuation rate can be of the order of 1 unit of MM intensity per 18 km. If the earthquake occurs at mid crustal depths, as for the 1922 Pinhal event, the attenuation rate may be of the order of 1 unit of MM intensity each 80 km.

The lack of accelerograms makes the estimation of the peak ground acceleration at a given site of interest inside the region difficult. We suggest the following empirical relation developed for the central and eastern regions of United States (Campbell, 1982):

$$\ln(a_h)=1.05-0.158m_b+0.63\ I_{MM}$$

where I_{MM} is the expected intensity at the site of interest and a_h is the horizontal acceleration given in cm/s^2. The peak acceleration obtained in this way, may then be correlated with a selected response spectrum to calculate the seismic ground motion in a site of interest.

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