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SEISMICITY PATTERNS AND FOCAL MECHANISMS IN SOUTHEASTERN BRAZIL

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The seismicity of SE Brazil is studied with a recent deployment of additional temporary digital and analog seismographic stations. Regional and local stations have allowed the determination of three new composite focal mechanisms for the earthquake series of Betim in 1992/93, Formiga in 1993, and the reservoir-induced events of Nova Ponte in 1995, all in Minas Gerais state. The focal mechanism data in the southern part of the São Francisco craton and adjacent Brasília fold belt indicate both normal and reverse faulting with a common E-W to NE-SW orientation of the maximum horizontal stress. Far from the continental margin, the focal mechanisms are consistent with theoretical estimates of stress directions from finite-element modelings of the forces driving the South American plate. Near the Serra do Mar coastal range, the stress pattern seems more complex. A selection of the earthquake catalog, using threshold magnitudes varying in time to yield a data set with spatially uniform coverage, indicates two main seismic areas: 1) the offshore continental shelf , and 2) the southern part of the Brasília fold belt and the São Francisco craton. The high topography areas of the Serra do Mar and Serra da Mantiqueira (in the Ribeira fold belt) and the Paraná basin are much less seismically active.

Key words: Seismicity; Crustal stresses; Southeastern Brazil.

SISMICIDADE E MECANISMOS FOCAIS NO SUDESTE DO BRASIL - *A sismicidade do SE do Brasil foi estudada com a operação adicional de estações digitais e analógicas temporárias. Estações locais e regionais permitiram a determinação de três novos mecanismos focais compostos para as séries de sismos de Betim 1992/93, Formiga 1993, e para os sismos induzidos pelo reservatório de Nova Ponte em 1995, todos em Minas Gerais. Os mecanismos focais na parte sul do cráton do São Francisco e na faixa de dobramentos Brasília indicam falhamentos inversos e normais, com uma direção comum para a tensão horizontal máxima entre E-W e NE-SW. Longe da margem continental, os mecanismos focais são consistentes com a direção teórica dos esforços determinada com modelamento por elementos finitos das forças tectônicas que atuam na placa sul-americana. Perto da Serra do Mar, o padrão de esforços parece mais complexo. Uma seleção do catálogo de sismos do Brasil, usando limites de detectabilidade diferentes para cada época para se obter uma cobertura geográficamente uniforme, revelou duas áreas sísmicas principais: 1) a plataforma continental, e 2) a parte sul da Faixa Brasília e Cráton do São Francisco. A área montanhosa das Serras do Mar e da Mantiqueira (na Faixa Ribeira), e a Bacia do Paraná são muito menos ativas sismicamente.*

Palavras-chave: *Sismicidade; Esforços crustais; Sudeste do Brasil.*

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INTRODUCTION

A review of seismicity studies in southeastern Brazil was given by Berrocal et al.(1996), who also presented a preliminary seismic hazard estimate (return periods for different magnitudes) for the region east of the Paraná basin, from the São Francisco craton to the continental shelf, assuming a uniform seismicity rate in the whole region. Seismic hazard estimates can be further improved if different seismogenic areas within the study region are recognized and taken into account. As a contribution to future studies of seismic hazard, we will first show that the seismicity in southeastern Brazil seems to be concentrated mainly in two different zones: the offshore continental shelf, and the southern part of Minas Gerais state, with the intracontinental Paraná basin and the Serra do Mar coastal ranges being relatively aseismic (Assumpção, 1992; 1993; Berrocal et al., 1996).

In Minas Gerais, small earthquakes are common both in the southern part of the São Francisco craton and the adjacent Brasília fold belt (Fig. 1). A recent deployment of a network of temporary digital 3-component stations in Minas Gerais, São Paulo and Rio de Janeiro states since late 1992 (Fig. 2) has enabled the recording of several small, regional events and the determination of some additional focal mechanisms. We will compare the stress data available for southern Minas Gerais with theoretical predictions based on the plate driving forces of the South American plate.

SEISMIC ZONING

To study the seismicity of SE Brazil, it is necessary to distinguish between two kinds of catalogs: the "whole data" catalog, and the "uniform coverage" catalog. The whole data catalog includes all reliable epicenters from the compilation of Berrocal et al. (1984) and the Brazilian Seismic Bulletins (Rev. Bras. Geofísica). This catalog includes both historical and instrumental data from 1861 to July/1996, shown in Fig. 1a. Its completeness is variable both in time and space. For example, events before 1900 only appear in the region approximately between the cities of São Paulo and Rio de Janeiro, where the population density was higher and accounts of earthquakes felt by the population were recorded in newspapers and books. In the late 1970's and early 1980's many seismographic stations were installed in reservoir

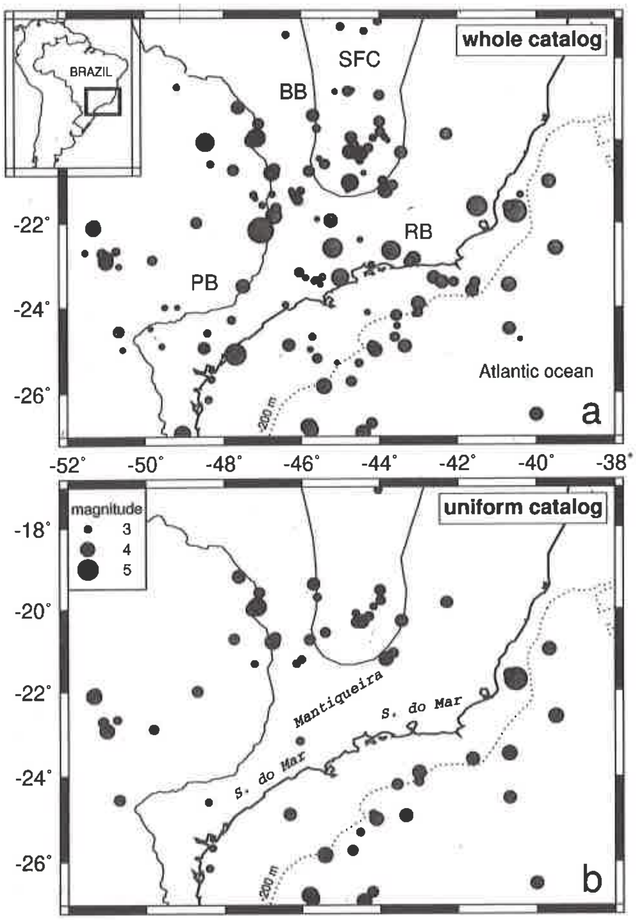


Figure 1 - Seismicity in SE Brazil. a) whole data catalog compiled from Berrocal et al.(1984) and the Brazilian Seismic Bulletins (Rev.Bras.Geof., 1983 to 1996, vols 1(2) to 14(1)). b) uniform coverage catalog with earthquakes selected according to magnitude and year with the thresholds of Tab. 1. Thin lines denote limits of the Paraná basin (PB) and the São Francisco craton (SFC); the Brasília belt (BB) and the coastal Ribeira belt (RB) are also indicated. The dotted line is the 200m bathimetry.

***Figura 1** - Sismicidade do SE do Brasil. a) catálogo com todos os dados compilados de Berrocal et al.(1984) e dos Boletins Sísmicos Brasileiros (Rev.Bras.Geof., 1983 a 1996, vols 1(2) a 14(1)). b) catálogo uniforme com epicentros selecionados de acordo com a magnitude e ano de ocorrência conforme a Tab. 1. As linhas finas indicam os limites da Bacia do Paraná (PB) e do cráton do São Francisco (SFC); a faixa de dobramentos Brasília (BB) e a faixa costeira de dobramentos Ribeira (RB) também estão indicadas. A linha pontilhada indica a batimetria de 200m.*

areas in Minas Gerais and São Paulo states, allowing events as small as magnitude 2.0 to be located in southern Minas or northeastern São Paulo. However, small events in the continental shelf, far from most of the seismographic stations, remained largely undetected.

To have a better representation of the geographical distribution of the seismicity, the "whole" catalog must be filtered to eliminate concentrations of events due to higher population density or large number of seismographic stations in some particular areas. The threshold magnitude (i.e., the minimum magnitude with a large probability of being detected in the whole southeastern region) varies with time. Tab. 1 (adapted from Assumpção, 1993) shows the threshold magnitudes used to produce the "uniform" catalog presented in the epicentral map of Fig. 1b. For example, events larger than magnitude 3.2 are only included in the uniform catalog if they occurred in 1980 or later, when there were enough seismic stations in SE Brazil to record any event of this size in the area of Fig. 1. A similar threshold (magnitude 3.1) was found for this region by Berrocal et al.(1996) for earthquakes after 1979. Since about 1990, with the installation of additional stations, specially digital 3-component stations in São Paulo and southern Minas Gerais, events down to magnitude 2.8 are believed to be completely detected in the southeastern region, as shown in Tab. 1.

year	threshold magnitude	observation
1940	6.0	world seismographic network;
1962	5.0	start of the World Wide Seismographic System network by the U.S. Geological Survey;
1968	4.5	start of the array station in Brasília;
1980	3.2	installation of several dam monitoring stations in SE Brazil;
1990	2.8	increase of regional stations in SE Brazil.

Table 1 - Threshold critera for selecting earthquakes for the uniform catalog.

***Tabela 1** - Critérios para os limites de seleção de sismos para o catálogo uniforme.*

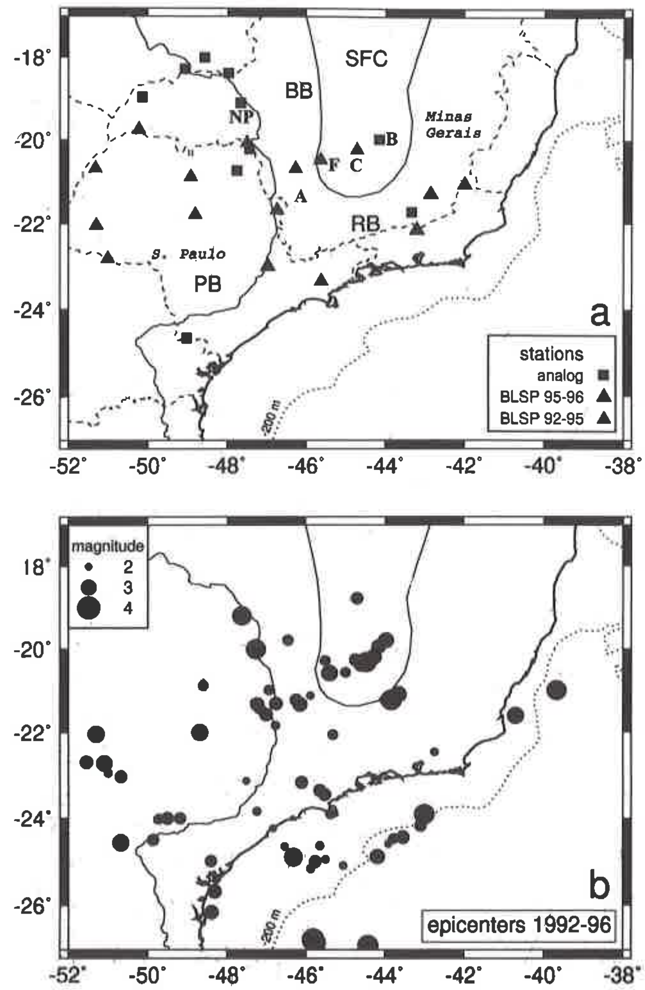


Figure 2 - a) Main seismic stations operated from 1992 to 1996. Squares denote vertical-component analog stations (mainly at dam sites), and triangles are digital 3-component broadband stations of the BLSP project (James et al., 1993). Dashed lines are state boundaries. Localities with detailed studies mentioned in this paper are indicated by A (Areado), B (Betim), C (Cajuru), F (Formiga), and NP (Nova Ponte). Other symbols as in Fig. 1. b) Epicenters in SE Brazil from 1992 to 1996 with magnitudes above 2. Note different magnitude scale compared with Fig. 1.

***Figura 2** - a) Principais estações sismográficas operadas entre 1992 e 1996. Quadrados são estações analógicas de componente vertical (principalmente em reservatórios), triângulos são estações digitais banda-larga de três componentes do projeto BLSP (James et al., 1993). Linhas tracejadas são limites de estado. Os locais de estudos detalhados mencionados neste trabalho estão indicados por A (Areado), B (Betim), C (Cajuru), F (Formiga), e NP (Nova Ponte). Outros símbolos como na Fig. 1.*

The "uniform" catalog (Fig. 1b) shows that earthquakes in SE Brazil tend to occur more frequently in two main seismic zones: 1) the offshore continental shelf, and 2) the southern part of the São Francisco craton with its adjacent Brasília fold belt. Fig. 1b clearly demonstrates the relative aseismicity of the Serra da Mantiqueira and Serra do Mar coastal ranges, in the Ribeira fold belt, as compared with the continental shelf and the southern part of the São Francisco craton and adjacent Brasília belt. The Paraná basin also seems to be relatively less seismic: the largest events in the basin (magnitudes ~3.5) have been induced by hydroelectric reservoirs or artesian wells (Berrocal et al., 1984; Mioto et al., 1991; Yamabe & Berrocal, 1991; Mioto & Ribotta, 1994; Assumpção et al., 1995; Yamabe & Hamza, 1996).

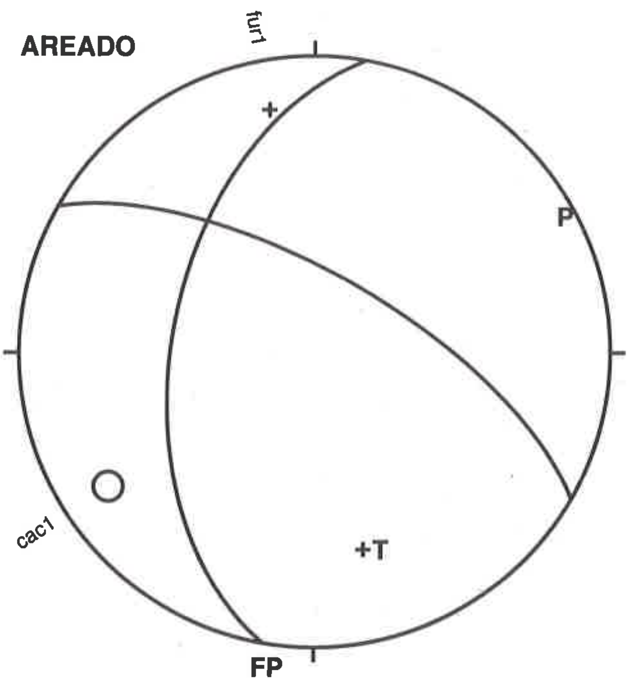


Figure 3 - Nodal plane solution of the Areado swarm, as determined with a local 5-station network (Blum, 1993). This solution is consistent with P-wave first motions of the largest events of the series, recorded at the regional stations Caconde (CAC1) and Furnas (FUR1). "FP" is the fault plane defined by the hypocentral distribution.

Figura 3 *- Solução de planos nodais da série de Areado determinada com uma rede local de cinco estações (Blum, 1993). Esta solução é consistente com as polaridades P dos maiores sismos da série registrados nas estações regionais Caconde (CAC1) e Furnas (FUR1). "FP" indica o plano de falha dado pela distribuição dos hipocentros.*

Seismicity maps using time-variable threshold magnitudes (e.g., Adams & Basham, 1991; Engdahl & Rinehart, 1991) are useful for recognizing areas with different seismicity rates and better defining seismogenic zones. On the other hand, for quantitative seismic hazard estimation, events not included in the "uniform" catalog must also be taken into account. For example, the Mogi-Guaçu, SP, magnitude 5 earthquake of 1922 (Assumpção et al., 1979; Berrocal et al., 1984), which is not included in the filtered catalog, also contributes to the seismic hazard. Extreme value statistics (such as used by Assumpção, 1983, and Berrocal et al., 1996) is one popular method to deal with partially complete catalogs. Maximum likelihood methods can also be used to estimate earthquake hazard using mixed catalogs with an incomplete historical part and more recent, complete instrumental records (e.g., Mârza et al., 1991).

Fig. 2 shows all located events with magnitudes above 2, from 1992 to 1996, and both the digital and the analog stations operating in the area in the same period. The digital stations are the broadband stations of the BLSP project (Brazilian Lithosphere Seismic Project, James et al., 1993). The other vertical-component analog stations are mainly those operated by the hydroelectric companies CEMIG, FURNAS and CESP to monitor their reservoirs. This figure helps confirm that the area of the Ribeira belt, near the coast, is less seismic than the southern part of the São Francisco craton and the continental shelf (note the different magnitude scales in Figs. 1b and 2b).

LOCAL STUDIES

In this section, more detailed studies of some recent earthquake swarms in Minas Gerais state (see localities in Fig. 2a) will be presented using data recorded by local, temporary stations as well as by some stations of the regional network shown in Fig. 2a.

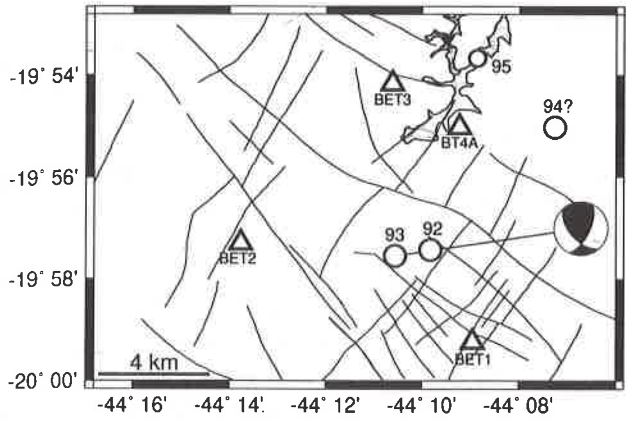


Figure 4 - Epicenters and local stations in Betim and Contagem, MG. The 1992 epicenter was determined with the three analog stations BET1, 2, 3; the 1993 epicenter with the local BT4A and the regional digital stations CDCB and FURB (Fig. 5). The 1994 epicenter is very uncertain and is based on macroseismic information, data from the local station BT4A and the regional station CDCB. The 1995 epicenters were determined with two digital 3-component stations (in BET1, and BET2) and the analog BT4A. Lines are geological faults mapped by "Assessoria do Meio Ambiente", Prefeitura de Betim, MG.

Figura 4 *- Epicentros e estações locais em Betim e Contagem, MG. O epicentro de 1992 foi determinado com as três estações analógicas BET1, 2, 3; o epicentro de 1993 com a estação local BT4A e as regionais CDCB e FURB (Fig. 5). O epicentro de 1994 é bastante incerto e é baseado em informações macrossísmicas e dados da estação local BT4A e da regional CDCB. O epicentro de 1995 foi determinado com duas estações digitais de 3 componentes (em BET1 e BET2) e a estação BT4A. As linhas são falhas geológicas mapeadas pela "Assessoria de Meio Ambiente" da prefeitura de Betim, MG.*

Areado, 1991-1996

A swarm of small earthquakes started in the town of Areado in September 1991 (see Fig. 2a for the location of Areado). The largest events reached magnitude $2.8m_R$ and intensities up to III or IV MM. A local 4-station network deployed in October 1991 recorded tens of events (Veloso, 1991; Blum, 1993), and showed that the activity was concentrated in an area less than about 1 km across. A well constrained nodal plane solution, with almost no inconsistent polarities, was obtained with the local stations indicating a predominantly reverse faulting mechanism. The two largest events of the Areado swarm were recorded at two other regional stations, 50 to 100 km away, with clear P-wave first motions consistent with the focal mechanism determined with the local stations, as shown in Fig. 3. The distribution of hypocenters favours the NW dipping plane to be the rupture plane (Blum, 1993). In August 1994 and May 1996, events from Areado recorded at Caconde still had P-wave first motion consistent with the early events.

Betim, 1992-1994

In June 1992, a series of small earthquakes started in the town of Betim, MG, many of them being felt by the population. Local stations were installed in the area from July 15 (analog, vertical-component seismographs), as shown in Fig. 4. The largest event (July 25, 1992) had a magnitude 2.8 and caused intensities up to V-VI MM. Several events were recorded by the local temporary stations as well as a few other regional stations. All events showed exactly the same P-wave polarity and P/S amplitude patterns at each of the three local stations, indicating that they all had the same hypocenter and focal mechanism. The activity decreased at the end of 1992 and early 1993, and only one local station remained operating. In August 1, and October 8, 1993, two other events (magnitudes 2.4 and 2.6) from Betim were recorded by a few regional digital stations (Fig. 5) with identical waveforms. Both instrumental data and macroseismic information indicated that the 1992 and 1993 epicenters were very close.

Focal mechanisms were determined by using S/P amplitude ratios in addition to P-wave first motions according to the method of Kisslinger (1980) and Kisslinger et al.(1982). We used the program FOCMEC (Snoke et al., 1984) which does a grid search of the nodal plane parameters to find the solution that best fits the observed log (amplitude-ratio). Initially, a solution for the 1992 events was determined by using the average SV/P amplitude ratios of the two best recorded events (August 17 and 29, 1992). The solution indicated strike-slip faulting with a reverse component, with E-W oriented P axis. The 1993 events had P and SH first motion directions at CDCB consistent with the 1992 solution. Assuming the 1993 events had the same mechanism as the 1992 series, we determined composite nodal plane solutions for both the 1992 and the 1993 events adding the SV/SH and the SH/P amplitude ratios at CDCB.

The results of the best fitting composite solution, which has a mean residual of the log (amplitude-ratio) of only 0.13, are shown in Fig. 6 and Tab. 2.

station	distance (km)	azimuth (°)	amplitude ratio	log (amplitude ratio) obser.	theor.	res.
BET1	3.5	157	SV/P	+0.45	+0.34	+0.11
BET2	7.2	274	SV/P	-0.42	-0.31	-0.11
BET3	6.3	346	SV/P	+1.06	+0.92	+0.14
CDCB	65.7	241	SH/P	+0.18	+0.35	-0.17
CDCB	65.7	241	SV/SH	-0.30	-0.17	-0.14

Table 2 - Amplitude ratios for the composite Betim 1992-1993 best nodal plane solution.

Strike = 138°, dip = 55°, slip = 35°.

Tabela 2 - *Razões de amplitude para a melhor solução de mecanismo composto.*
Strike = 138°, mergulho = 55°, obliquidade = 35°.

In April, 1994, two other events with magnitudes around 2.5 occurred in Betim. Both the waveforms at the digital stations CDCB and FURB (Fig. 5), and the macroseismic information (more widely felt in the neighbouring town of Contagem than in Betim) indicates that the 1994 epicenters were located to the NNE of the 1992/93 series. Fig. 4 shows a tentative epicenter for the 1994 events. From July to December 1995 two digital stations (BET1, 2) and one analog station (BT4A) operated in the area recording only three small events near the lake with magnitudes around 1 (Fig. 4), none of them felt by the local inhabitants.

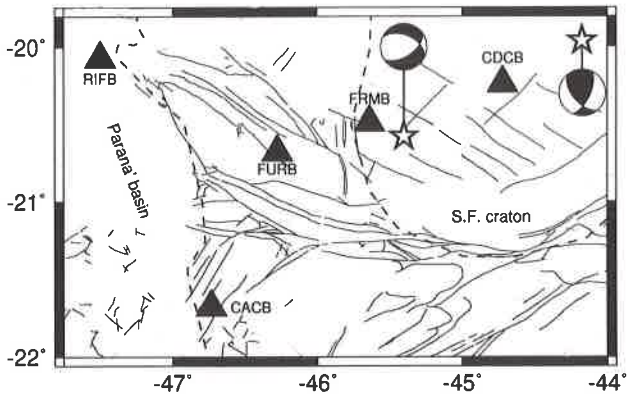


Figure 5 - Epicenters of the Betim (1992/93) and Formiga (1993), shown as stars, and digital stations of the BLSP net (triangles). Lines are geological faults (DNPM, 1978).

Figura 5 - *Epicentros dos eventos de Betim (1992/93) e Formiga (1993), indicados pelas estrelas, e estações digitais da rede BLSP (triângulos). As linhas são falhas geológicas (DNPM, 1978).*

Formiga 1993

Two earthquakes (3.1 and 2.9 m_R) occurred in the eastern edge of the São Francisco craton on March 09 and May 12, 1993, just south of the town of Formiga, MG (Fig. 5). The two earthquakes were felt up to about 25km distance with maximum intensities of IV MM. The

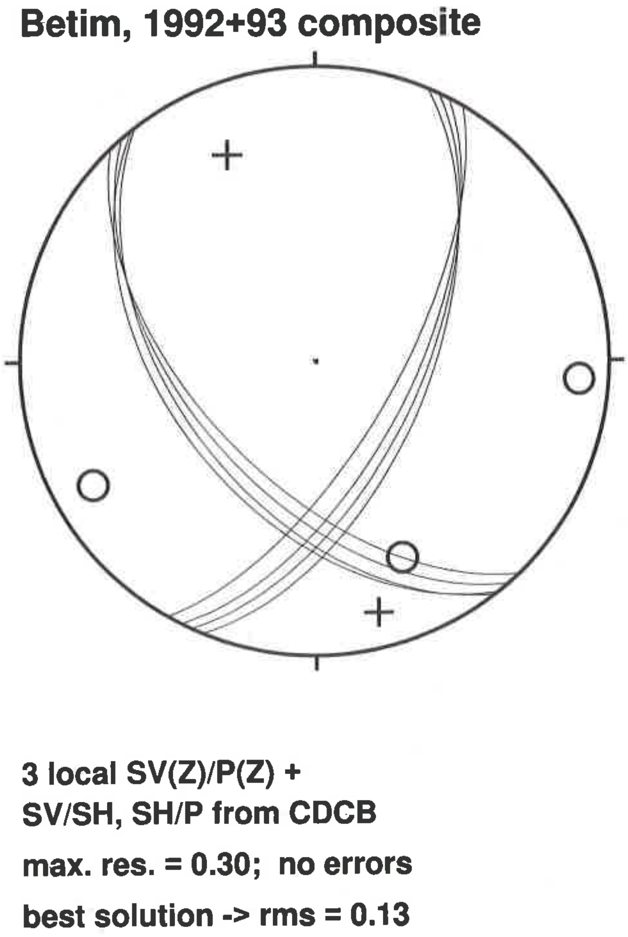


Figure 6 - Composite nodal plane solutions of the Betim 1992 and 1993 events, that satisfy all polarity data and have a residual in the log (amplitude-ratio) less than 0.3.

Figura 6 - *Solução de mecanismo composto dos sismos de Betim de 1992 e 1993 satisfazendo todas as polaridades e com um resíduo no log (razão de amplitudes) menor que 0,3.*

isoseismal maps were published in the Brazilian Seismic Bulletin # 16 (Rev.Bras. Geofís., 14(1), 1996). It is interesting to note that the felt area of the second event (May 12th) extended further to the north, despite having a slightly smaller magnitude.

Fig. 6 shows the Formiga epicenter and the digital stations. The waveforms of the P and S signals of the two events are very similar at the digital station CDCB, CACB and RIFB. Accurate location of the second event, relative to the first one, could be achieved by correlating the signals between the two events to pick the P and S arrival times. The signals were correlated with an accuracy of about 5 msec. The first event was taken as reference and its residuals were used for station corrections. With these station corrections, the second event had a rms residual of only 7 ms. The hypocenter of May 12 was located 180m ESE of the first event, and was 140m shallower. The standard errors of this relative location are 90m and 70m for the latitude and longitude, respectively, and 200m for the depth.

The relative location given above means that the two events were probably closer than about 300m, despite the differences in the felt areas. This apparent discrepancy could be attributed to the poor resolution of macroseismic information, specially when the events occurred at very different local times (6 AM and 9 PM). Also, the macroseismic surveys were carried out at different times (two months after, for the first event; one day after, for the second event). Maybe the felt area of the first event is slightly underestimated.

station	distance	azimuth	amplitude	log (amplitude ratio)			Qp
	(km)	(°)	ratio	obser.	theor.	res.	
FRMB	26.7	292	SH/P	+0.64	+0.82	-0.18	400
			SV/SH	+0.11	+0.06	+0.05	
CDCB	80.6	62	SH/P	+1.33	+1.24	+0.09	400
			SV/SH	-1.31	-0.97	-0.34	
FURB	92.0	263	SH/P	-0.08	-0.11	+0.03	800

Table 3 - Amplitude ratios for the Formiga 1993 best nodal plane solution. Strike = 292°, dip = 48°, slip = -48°.

Tabela 3 - *Razões de amplitude para a melhor solução de mecanismo focal para o sismo de Formiga de 1993. Strike = 292°, mergulho = 48°, obliquidade = -48°.*

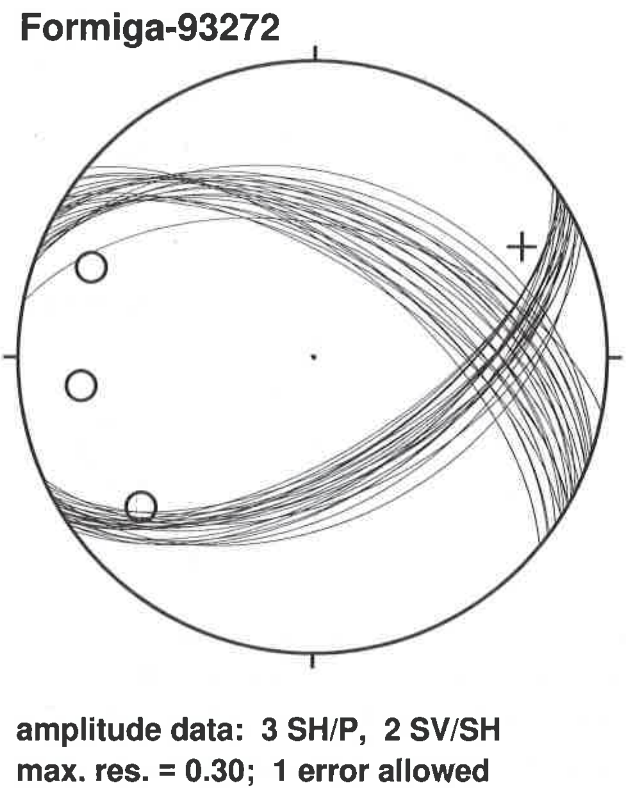


Figure 7 - Focal mechanism solutions of the Formiga event of September 29, 1993, with residuals less than 0.30 for the log(amplitude-ratio) in the stations FRMB, CDCB, and FURB. Only one residual higher than this limit was allowed.

Figura 7 - *Soluções de mecanismo focal para o evento de Formiga de 29/09/1993 com resíduos menores que 0,30 no log (razão de amplitudes) nas estações FRMB, CDCB, e FURB. Um único resíduo maior que este limite foi permitido.*

On September 29, 1993, a smaller event in Formiga (2.5 m_R) was recorded by other digital stations (FRMB, FURB, CDCB). It was not large enough to be well recorded at CACB and RIFB. At CDCB, however, the similarity of the waveform with that of the other events showed that the hypocenter was the same as in the previous two events.

The smaller distances to the stations FRMB (27km), CDCB (81km) and FURB (92km), allowed the determination of the focal mechanism by using P/SV/SH amplitude ratios. For stations FRMB and CDCB, besides P and SH polarities, SV/SH and SH/P amplitude ratios were used. For station FURB, 92 km away, only the SH/P amplitude ratio was used. At CACB, no amplitude information was used and only the dilatational P polarity helped constrain the nodal plane solution. Fig. 7 shows all possible solutions having a maximum residual of 0.30 in all but one station (i.e., one error was allowed in the five amplitude ratios used). Tab. 3 shows the resulting amplitude ratios for the best solution with a rms in the log (amplitude ratio) of 0.09 for the four stations that satisfied the 0.30 limit, and a rms of 0.23 with all five stations used. The solutions in Fig. 7 show a predominantly normal faulting event with NS oriented T axis.

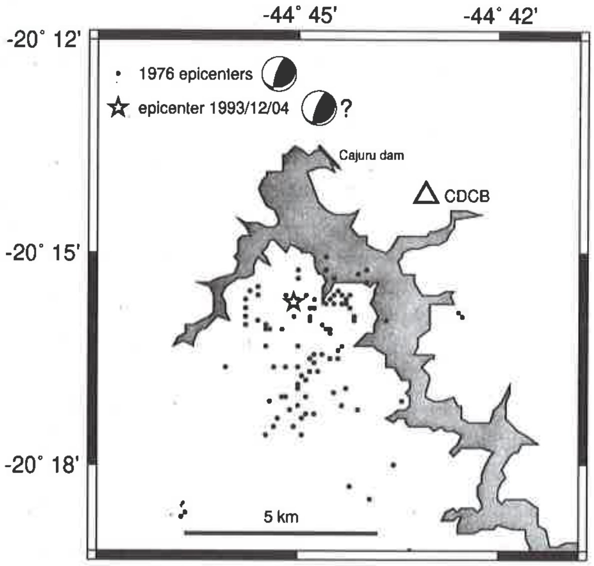


Figure 8 - Location of the December 4, 1993, event in the Cajuru Dam area determined by station CDCB in this paper, and earlier 1976 epicenters determined with a local network (Mendiguren & Richter, 1978; Viotti et al.,1997).

Figura 8 *- Epicentro do sismo de 04/12/1993 na área do reservatório de Cajuru determinado com a estação CDCB neste trabalho, e epicentros de 1976 estudados com uma rede local (Mendiguren & Richter, 1978; Viotti et al., 1997).*

Carmo do Cajuru, MG, December 04, 1993

A series of reservoir induced earthquakes have been observed near the Cajuru dam since 1970 with magnitudes up to 3.7 and intensities up to V-VI. Although the activity decreased sharply after 1978, some small earthquakes were still recorded by the local stations up to 1995 (Viotti et al., 1997). A composite focal mechanism, determined with a 7-station network deployed in the reservoir area during July/August 1976 (Mendiguren & Richter, 1978; Viotti et al., 1997), shows reverse faulting. This composite solution has several inconsistencies, indicating that focal mechanisms may vary somewhat across the seismic area which does not seem to be restricted to a single fault but is spread in a volume about 4km across (Viotti et al., 1997). However, a 2.5m_R event in December 4, 1993, recorded by the digital station CDCB installed in the reservoir area, had P- and SH-wave polarities as well as the P/SV/SH amplitude ratios consistent with the type of early composite solution of the 1976 studies. The epicenter, 4.5 km from the station, was also in the middle of the active area determined by the early studies (Fig. 8).

The small event of 1993 was felt near the station CDCB with intensity from III to IV MM. The data were recorded on scale in the low-gain channels of the digital station. The seismograms in Fig. 9 indicate that the maximum particle velocity was 0.2 mm/s. Fig. 9 also shows that the maximum accelerations were 18 and 16 mm/s^2 in the vertical and transverse components, respectively.

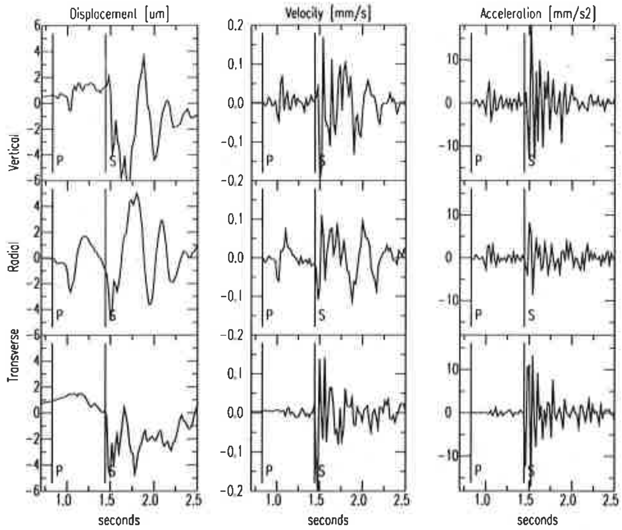
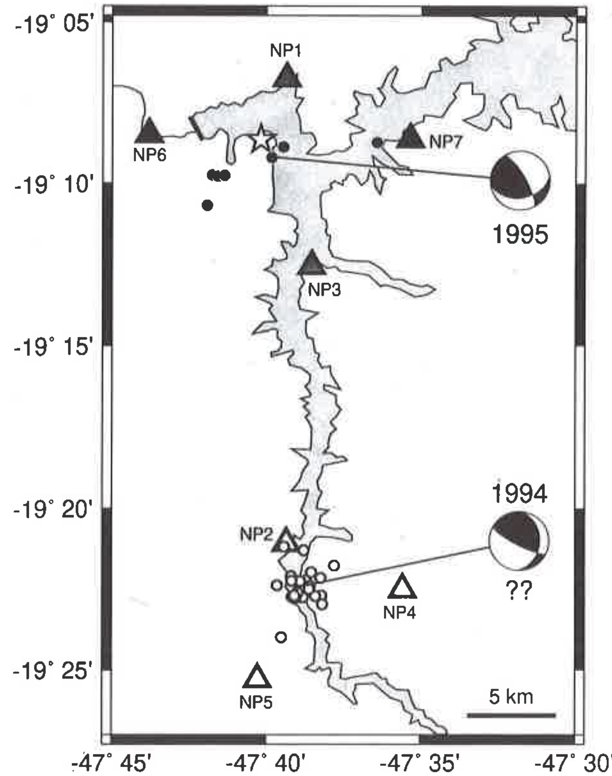


Figure 9 - Displacement (mm), velocity (mm/s) and acceleration (mm/s^2) of the December 4, 1993 event, 2,6 m_R, recorded by station CDCB at 4.5 km distance.

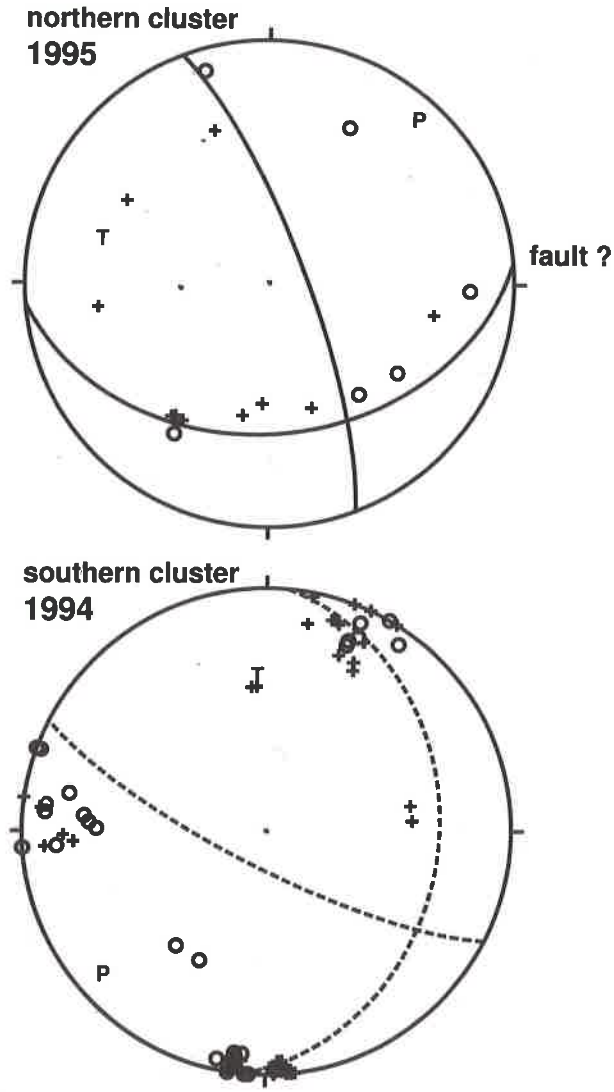
Figura 9 *- Deslocamento (mm), velocidade (mm/s) e aceleração (mm/s^2) do sismo de 04/12/1993, com magnitude 2,6 m_R, registrado pela estação CDCB a 4,5 km de distância.*

Nova Ponte, 1994-1995

The Nova Ponte reservoir started to be monitored with a single station in 1985, with no local events detected prior to the start of impoundment in October 1993. In 1994, five analog vertical-component stations (Fig. 10a) were



a)



b)

Figura 10 - a) Induced events in the Nova Ponte reservoir area. Open circles are all the best located events (April-June, 1994) recorded by stations NP1, 2, 3, 4, and 5, which operated in 1994 . Solid circles are the best located events (May-August, 1995) recorded by the 4-station telemetry network of 1995 (NP1, 3, 6, and 7); note the WSW-ENE epicentral trend. The star indicates the epicenter of the main event of April 21, 1995 with magnitude 3.5.

b) Composite focal mechanisms with the best located events shown in (a). Polarity data from station NP2 were not used in the 1994 mechanism due to large uncertainties in the azimuth.

Figure 10 *- a) Sismos induzidos no reservatório de Nova Ponte. Círculos abertos são os melhores eventos (Abril-Junho, 1994) registrados pelas estações NP1, 2, 3, 4, e 5 que operaram em 1994. Círculos fechados são os melhores eventos (Maio-Agosto, 1995) registrados pela rede telemétrica formada por NP1, 3, 6, e 7, que operou em 1995; note o alinhamento aproximado WSW-ENE dos epicentros. A estrela indica o epicentro do sismo principal de 21.04.1995 com magnitude 3,5.*

b) Mecanismos compostos com os eventos de (a). Os dados de polaridade de NP2 não foram usados devido à grande incerteza nos azimutes.

installed to study the seismicity induced by the filling of the reservoir (Veloso et al., 1994). The initial seismicity occurred mainly in a shallow part of the lake, 25 km south of the dam. The seismicity then migrated to another area closer to the dam. In 1995 the stations were moved northwards forming a telemetered network with central digital recording (Fig. 10a). The largest event so far occurred on April 21, 1995, with magnitude 3.5m_R, maximum intensity IV to V MM, and epicenter near the border of the lake, about 3 or 4 km east of the dam (Mârza et al., 1997), as shown in Fig. 10a. A first account of the seismicity history was given by Mârza et al.(1997). Here we present composite focal mechanisms using the analog stations of the 1994 deployment, and initial results of the 1995 telemetered network.

Fig. 10a shows the best located events with the first network during April-June 1994. The more distant stations NP1 and NP3 recorded generally consistent P-wave first motions: compressions at NP1 and dilations at NP3. This indicates that most events probably have a similar faulting mechanism and a composite solution could be attempted. The polarities at the near stations, however, are very variable. Because the seismograms were analog (smoked-paper recordings) the hypocenters had large errors and the composite focal mechanism (Fig. 10b, bottom diagram) is poorly constrained.

A selection of the best located events during May-August 1995 (Fig. 10a), recorded by the 4-station telemetered network, shows a seismic zone trending about WSW-ENE. The P-wave first motions for these events (Fig. 10b, top diagram) indicate reverse faulting with a component of strike-slip. This solution is consistent with the polarities of the main shock at the local stations and at a regional station (CAC1). One of the nodal planes has a strike similar to the epicentral trend. The P axes of the two focal mechanisms have a similar SW-NE orientation.

DISCUSSION

Fig. 11 shows all available focal mechanisms and stress directions in SE Brazil, and Tab. 4 shows the epicentral and focal mechanism information for the events in Minas Gerais discussed in this paper. The qualities of the focal mechanism solutions are based on the criteria of the World Stress Map project as used by Assumpção (1992). It should be remembered that the P and T axes of the focal mechanism solution are not necessarily the principal directions of the prevailing crustal stress. However, the orientation of the P axis of reverse-component and strike-slip faulting (and the B axis of normal faulting) events can be used as an approximate direction of the maximum horizontal stress (SH_{max}). Clearly, the average direction estimated with several focal mechanisms should be close to the actual SH_{max} direction.

In the southern part of the São Francisco craton and adjacent Brasília belt, both normal and reverse focal mechanisms can be observed (A, F, C, and B in Fig. 11). However, the direction of SH_{max} is relatively uniform ranging from E-W to NE-SW (with exception of the Cajuru mechanism which has lower quality (Tab. 4). The four estimates of SH_{max} (azimuths: 124°, 61°, 84°, 83°; Tab. 4) are not randomly oriented and pass the Rayleigh test, with

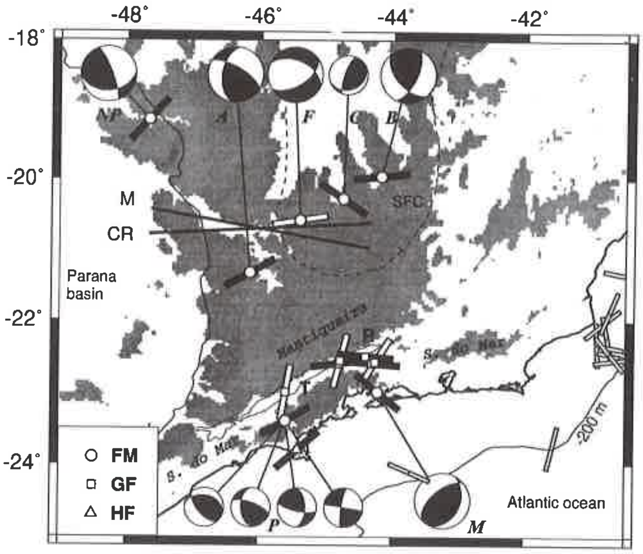


Figure 11 - Data of maximum horizontal stress orientations (SH_{max}) in SE Brazil. Bars with circles are SH_{max} estimated with focal mechanisms, bars with squares are from recent geological faults. Solid bars denote compressional or strike-slip faulting; open bars denote normal faulting. Thin bars in the continental shelf are SH_{max} orientations from breakouts (Lima et al., 1997). The solid bar with a triangle (near S.Sebastião Isl.) is SH_{max} determined from hydraulic faulting. Focal mechanisms are identified as NP = Nova Ponte; A = Areado; F = Formiga; C = Cajuru reservoir ; B = Betim; M = Monsuaba (Berrocal et al., 1993); P = Paraibuna reservoir (Mendiguren, 1980). The lines "M" and "CR" indicate the theoretical SH_{max} directions calculated by the finite-element models of Meijer (1995) and Coblentz & Richardson (1996). T and R are the Taubaté and Rezende basins in the Paraíba graben. The shading indicates topography higher than 800 m.

Figura 11 *- Dados de direção da compressão horizontal máxima (SH_{max}) no Sudeste do Brasil, obtidos com mecanismos focais (FM), estrias em falhas geológicas recentes (GF), e fraturamento hidráulico (HF). Barras cheias indicam falhamento inverso ou transcorrente; barras vazias indicam falhamento normal. Na plataforma continental as barras simples indicam SH_{max} obtidos de "breakouts". Mecanismos focais identificados por NP = Nova Ponte; A = Areado; F = Formiga; C = reservatório de Cajuru; B = Betim; M = Monsuaba (Berrocal et al., 1993); P = reservatório de Paraibuna (Mendiguren, 1980). As linhas "M" e "CR" mostram as direções de SH_{max} determinadas nos modelos de elementos finitos de Meijer (1995) e Coblentz & Richardson (1996). T e R são as bacias de Taubaté e Rezende no graben do Rio Paraíba do Sul. A região sombreada corresponde a altitudes maiores que 800 m.*

90% confidence limit, for the existence of a preferred orientation. This preferred, mean orientation is 81° ± 9°. This direction is similar to that predicted by the finite-element models of the tectonic forces acting in the South American plate (Meijer, 1995; Coblentz & Richardson, 1996). These theoretical models calculate the intraplate stresses resulting from boundary forces (such as Mid-Atlantic ridge-push, collision with the Nazca plate, and asthenospheric drag) as well as the effect of the spreading stresses at the continental margin due to the lateral density variations between continental and oceanic lithospheres. Both Meijer's (1995) and Coblentz & Richardson's (1996) models predict strike-slip stresses in Minas Gerais: roughly E-W compression and N-S tension. The mixture of both normal and reverse mechanisms is an indication that the crustal stresses are actually strike-slip, in agreement with the theoretical predictions. In other words, a strike-slip stress regime (E-W compression and N-S tension) will produce reverse-component or normal-component faulting depending on the orientation of the pre-existing earthquake fault. For this reason, we can say that the four focal mechanism solutions for the events in Minas Gerais (excluding the Nova Ponte mechanism) are compatible with the theoretical stresses calculated by finite-element models. The SH_{max} estimated with the Nova Ponte mechanism (42°) does not seem to belong to the same group of the other four events in the São Francisco craton and vicinity. This may be due to uncertainties in the focal mechanism or a slightly different direction for the crustal stresses near Nova Ponte.

Near the Serra do Mar coastal ranges the SHmax directions are more scattered which may be due to local topographical effects of the Serra do Mar coastal ranges and flexural stresses from the sediment load of the continental shelf. In-situ stress measurements by hydraulic fracturing, about 60-80m deep, near São Sebastião Island, Fig. 11, (C. Lima, Petrobrás, written communication) indicates NE-SW compressional stresses, consistent with the average SHmax orientation of the nearby dam-induced seismicity in the Paraibuna reservoir (Mendiguren, 1980). The stresses inferred from recent (mainly Pleistocene and Holocene) geological fault slip data in the Paraiba graben (Riccomini et al., 1989; Salvador & Riccomini, 1995) indicate rapid temporal changes of the stress patterns including E-W extension and compression. These rapid stress changes are not completely understood and may indicate changes in the topographical evolution of the Serra do Mar ranges, or changes in the in-plane stresses in the South American lithospheric plate.

Lima et al.(1997) showed that the theoretical models of Meijer (1995) and Coblentz & Richardson (1996) are a good first order approximation to the observed intracontinental stresses in Brazil, but fail to predict the stresses at the continental margins. Near the margins the observed SH_{max} direction tends to be parallel to the coast line. This was interpreted by Lima et al.(1997) as due to the additional effect of flexural stresses in the peripheral bulge (extension perpendicular to the coast, inducing SH_{max} parallel to the coastline) from sediment load in the continental shelf, which was not taken into account in the theoretical finite-element models. This conclusion is consistent with the data presented here which show a more uniform E-W oriented SH_{max} in the São Francisco craton

#	locality	date yyy mm dd	lat. (°S)	lon. (°W)	depth (km)	magnitude	focal mechanism strike	dip	slip	P axis az./pl.	T axis az./p;.	SH_{max}	WSM quality	reference
C	Cajuru	1976	-20.26	-44.75	1	<3.2	70	24	138	304/27	85/57	124	D	Viotti et al. (1996)
A	Arcado	1991 10	-21.33	-46.15	1.5	<2.0	190	50	151	61/11	162/46	61	B	Blum (1995)
F	Formiga	1993 09 29	-20.58	-45.40	0	2.5	292	48	-48	272/60	174/05	84	C	this paper
B	Betim	1992/93	-19.96	-44.18	3	<2.7	138	55	35	83/04	349/48	83	C	this paper
NP	N.Ponte	1995/05-08	-19.14	-47.67	3 ?	<2.0	85	38	20	42/24	285/45	42	C	this paper

Table 4 - Epicentral data and focal mechanism solutions. Event identification as in Fig. 11. P and T axes are given in azimuth and plunge. SH_{max} is the estimated direction of the maximum horizontal compression, and its quality was set according to the criteria of the World Stress Map project.

Tabela 4 *- Dados epicentrais e soluções de mecanismo focal. Identificação do evento como na Fig. 11. Os eixos P e T são dados em azimute e mergulho.* SH_{max} *é a direção estimada da maior compressão horizontal, e sua qualidade foi definida com os critérios do projeto "Mapa Mundial de Esforços".*

and Brasilia belt, and a more complex pattern in the Serra do Mar coastal ranges.

On the other hand, as shown in Fig.1b, the area near the coast, in both sides of the Paraiba graben, is much less seismic than the craton and Brasilia belt further inland. This seems paradoxical because abundant geological evidence of Pleistocene and Holocene faulting has been found in the aseismic Serra do Mar region (Riccomini et al., 1989; Salvador & Riccomini, 1995). This problem deserves further attention in the future, as no explanation can be presented yet.

CONCLUSION

Digital recordings of small events in southern Minas Gerais state has allowed the determination of additional focal mechanisms in the southern part of the São Francisco craton and adjacent Brasília fold belt. The combined use of polarity and S/P amplitude ratios allowed the determination of a normal faulting mechanism for the Formiga 1993 events, and a reverse faulting mechanism for the 1992/93 Betim series. Regional data from recent events in the Cajuru reservoir area and in Areado are compatible with previously published mechanisms based on local stations. For the 1995 Nova Ponte induced events, a preliminary mechanism shows predominantly reverse faulting with NE-SW P axis. The compiled stress data in SE Brazil shows that far from the continental margin, the observed focal mechanisms are compatible with the first order theoretical predictions of the force models in the South American plate calculated by Meijer (1995) and Coblentz & Richardson (1996).

In the Serra do Mar coastal ranges, near the continental margin, the observed data indicate a more complex pattern of stresses, probably due to local topographical effects and superposition of flexural stresses from the sediment load of the continental shelf.

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SISMICIDADE E MECANISMOS FOCAIS NO SUDESTE DO BRASIL

A sismicidade do SE do Brasil foi estudada com a operação adicional de estações digitais e analógicas temporárias. Foi feita uma seleção do catálogo de sismos do Brasil, usando limites de detectabilidade diferentes para cada época para se obter uma cobertura geográficamente uniforme, com os seguintes criterios: magnitude acima de 6 após 1940, acima de 5 após 1962, acima de 4,5 após 1968, acima de 3,2 após 1980, e acima de 2,8 após 1990. Este catálogo selecionado (determinado catálogo "uniforme") revelou duas áreas sísmicas principais: 1) a plataforma continental, e 2) a parte sul da Faixa Brasília e Cráton do São Francisco. A área montanhosa das Serras do Mar e da Mantiqueira (na Faixa Ribeira), e a Bacia do Paraná são muito menos ativas sismicamente. Três novos mecanismos focais em Minas Gerais foram determinados com estações locais e regionais. Para a série de sismos de Betim 1992/93 foram usadas as polaridades da onda P de três estações locais em 1992, e a razão de amplitudes S/P na estação digital CDCB em 1993. O mecanismo encontrado foi de um falhamento inverso com componente transcorrente. Os sismos de Formiga 1993 foram estudados com polaridades de P e SH, e razão de amplitudes S/P em três estações digitais do projeto BLSP. O mecanismo foi de falhamento normal com componente de transcorrência. Para os sismos induzidos pelo reservatório de Nova Ponte em 1995, foram usadas apenas polaridades da onda P de estações da rede telemétrica local, fornecendo um mecanismo inverso/transcorrente. Desta maneira, os seis mecanismos focais conhecidos na parte sul do cráton do São Francisco e na faixa de dobramentos Brasília indicam falhamentos inversos e normais, com uma direção comum para a tensão horizontal máxima entre E-W e NE-SW. Longe da margem continental, estes mecanismos focais são consistentes com a direção teórica dos esforços determinada com modelamento por elementos finitos das forças tectônicas que atuam na placa sul-americana. Perto da Serra do Mar, o padrão de esforços parece mais complexo. Dados de mecanismos de sismos, estudos de estrias em falhas Quaternárias, e uma determinação de tensão por fraturamento hidráulico indicam direções variadas para a tensão horizontal máxima, e também variações temporais. Esta variabilidade dos esforços perto da costa pode indicar maior influência de efeitos de topografia da escarpa da Serra do mar, assim como efeitos de flexura causados pela sedimentação na plataforma continental.

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