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SEISMIC ACTIVITY IN SENADOR SÁ-CE, BRAZIL, 1997–1998

George Sand França[1], Joaquim Mendes Ferreira[2] and Mario Koechi Takeya[3]

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ABSTRACT. The Tucunduba Dam is about 290 km West of Fortaleza, in Ceará state. The seismic monitoring of the area, with a local network, began on June 11, 1997, soon after the occurrence of an event with magnitude $3.2m_b$ on June 09, 1997. The monitoring was done with one analog station (used for magnitude measurement and statistical control of the activity) and seven digital stations. The digital three-component stations were operated from June to November 1997. In this work, the data collected during digital monitoring was analyzed to determine hypocenters and focal mechanism. To determine the hypocenters, we used a half-space model, whose parameters were 5.95 km/s, for P-wave velocities, and 1.69 for the ratio between P and S-wave velocities. The active zone was nearly 1 km long, with depth between 4.5 and 5.2 km. With 16 events recorded in the same six stations, we determined the direction of the fault plane (NE-SW). The fault mechanism is strike-slip with a small normal component. The dip was estimated to be $65°$SE using composite focal mechanisms and $80°$SE from the P/S amplitudes ratios. Preliminary estimates of maximum horizontal compressive stress, from the P-axis direction, were in agreement with Ferreira *et al.*(1998). The small difference is probably due to influence of the sedimentary basin on the regional stress. The active area is in accordance with seismicity described by Assumpção (1998).

Keywords: seismicity, focal mechanism, intraplate stress.

RESUMO. O Açude Tucunduba está localizado no município de Senador Sá, a aproximadamente 290 km a oeste de Fortaleza – CE. O monitoramento sísmico da região foi realizado com uma rede sismográfica local e teve início em 11 de junho de 1997, logo após a ocorrência de um evento com magnitude $3,2m_b$, no dia 09 de junho de 1997. A rede era composta de uma estação analógica (utilizada na determinação da magnitude e no controle estatístico da atividade) e sete estações digitais. As estações digitais, com três componentes cada, operaram no período de junho a novembro de 1997. Neste trabalho foram analisados os dados coletados pelas estações digitais objetivando a determinação de hipocentros e mecanismos focais. Para determinação hipocentral, usamos um modelo de semi-espaço, de parâmetros iguais a 5,95 km/s, para a velocidade da onda P, e 1,69, para a razão entre as velocidades das ondas P e S. A zona ativa era de aproximadamente 1 km de extensão e a profundidade variando de 4,5 a 5,2 km. Com um conjunto de 16 sismos, registrados na mesmas seis estações, foi determinado um plano de falha (NE-SW) com um mecanismo focal transcorrente e uma pequena componente normal. O mergulho foi estimado para está entre $65°$SE, usando o mecanismo focal composto e $80°$SE, através da razão das amplitudes P/S. Estimativas preliminares do esforço máximo compressivo horizontal, a partir da direção do eixo-P, estão de acordo com Ferreira et al. (1998). A pequena diferença pode ser devido à influência da bacia sedimentar no esforço regional. O comportamento da atividade está de acordo com a sismicidade descrita por Assumpção (1998).

Palavras-chave: sismicidade, mecanismo focal, esforço intraplaca.

Laboratório Sismológico, Departamento de Física Teórica e Experimental, Universidade Federal do Rio Grande do Norte, Campus Universitário, 59072-970 Natal, RN, Brazil – Fax: (84) 3215-3791

[1]E-mail: george@dfte.ufrn.br; Tel: (84) 3215-3793 ramal 202

[2]E-mail: joaquim@dfte.ufrn.br; Tel: (84) 3215-3796

[3]E-mail: takeya@dfte.ufrn.br; Tel: (84) 3215-3800

INTRODUCTION

The Northwest of Ceará is an area of seismic activity known since the XIX century (Ferreira & Assumpção, 1983; Berrocal *et al.*, 1984; Ferreira *et al.*, 1998). On June 09, 1997, an event with magnitude $3.2\, m_b$ (Intensity III-IV MM) occurred in the district of Serrota, Senador Sá-CE, scaring the local population. The growth of the seismic activity in Serrota, especially in the Tucunduba Reservoir, led the Universidade Federal do Rio Grande do Norte (UFRN) to study the seismic activity, in order to determine the hypocenter and displacement mechanism with high precision and to try to understand the local seismicity.

For this study, an analog station and a digital network with seven stations were installed (Figure 1). The analog station operated from June 11, 1997 to August 14, 1998 and the digital network from June 18 to November 05, 1997. The analog station was used in the statistics of the earthquakes as well as to obtain the magnitude from the duration ($m_D = 1.64 \log D - 0.97$), using the same parameters as Blum & Assumpção (1990), since the analog station operated in the same conditions.

LOCAL GEOLOGY

The seismic area is part of the Borborema province which is divided in to five tectonic domains (Brito Neves *et al.*, 2000). The Northwest of Ceará is formed by two of these domains; the Medium Coreaú Domain (MCO) and the Ceará Central Domain (CC)(Figure 2a).

The CC domain consists of gneissic basement formed during the Transamazonian collage and contains a series of middle Neoproterozoic supracrustal sequences or remanent of folds belts and expressive Brasiliano plutonism.

The dam is located at the boundary of the MCO domain, more precisily on the Tucunduba horst (Figure 2b). The MCO domain is bounded by the cenozoic sedimentary cover, CC domain and Parnaíba basin. The domain is characterized by a series of grabens and horsts lying along SW-NE (Torquato & Nogueira Neto, 1996) whose boundary faults in the same direction (Transbrasiliano Lineament or Sobral-Pedro II Shear zone) and consists of basement high-grade methamorphic rocks and pelitic-carbonate (2.5 Ga) fold belts(Figure 2b). Figure 1 shows two faults that cross the dam, those faults were mapped by DNPM (1971).

SEISMIC ACTIVITY

The seismic activity in the Northwest of Ceará is known since last century (Ferreira & Assumpção, 1983), as shown in Table 1. After two events with magnitude 3.9 and 4.1 m_b in Groaíras in 1988, the Universidade Federal do Rio Grande do Norte installed a network of stations in order to study the activity of Groaíras. This network also allowed the study of other close areas that consequently had been also studied (Ferreira *et al.* 1998). Table 1 and Figure 2 show the main events that occurred in the Northwest of the Ceará.

A large event in the Tucunduba Dam, with magnitude $3.2m_b$, occurred on June 9, 1997 and was felt mainly in Serrota, a small village in Senador Sá, by the margins of the dam (Figure), where roofs and windows were shaken, school materials fell off desks and, the inhabitants were frigtened (França, 1999). Subsequently, on June 11, 1997, an analog seismograph station, using an MEQ-800 with smoked paper recorder (SN1A), was installed. A local network with seven digital short period portable stations were also installed, on June 18, 1997. Except for station SN03, all the stations were installed in granitic/gneissic bedrocks of the crystalline basement, allowing low noise and clear P and S wave arrivals. The digital station clocks were corrected every hour using GPS and P-wave readings had an accuracy to $\pm 0.001s$.

Station SN1A operated from June 11, 1997 to August 14, 1998, recording a total of 2217 events (Figure 3), and the largest magnitude was m_b = 3.0 on December 12, 1997.

Determination of Hypocenters

Hypocenters were determined using the program HYPO71 (Lee & Lahr, 1975). Half-space velocity models have produced results with considerable accuracy when applied to several areas of Brazilian Northeast (Ferreira *et al.*, 1987; 1995; 1998; Takeya *et al.*, 1989; Nascimento, 1997). This half-space model was adopted, since the seismic area is in the precambrian basement composed of consolidated rocks and low attenuation, generating clear P and S waves arrivals in the seismographs (Figure 4).

Various tests were made to find the best P velocity (v_P) and (v_P/v_S) ratio. We varied the P wave velocity between 5.4 and 6.45 km/s and the v_P/v_S ratio between 1.60 and 1.74. The velocity model with the lowest root mean square (rms) time residual had v_P/v_S = 1.69 and v_P = 5.95 km/s. The value for v_P is acceptable, since in different parts of the world, v_P in granitic/gneissic upper crustal rocks varies from 5.8 to 6.4 km/s (Christensen, 1982; Christensen & Mooney, 1995). For this model, all 160 selected events (recorded by at the least four stations) had an rms residual less than 0.03 sec and horizontal errors less than 0.5 km and are shown in Fig. 1. Most of the events have rms $\leq$ 0.01 s, erh $\leq$ 0.1 km and erz $\leq$ 0.1 km. These values are low because of choice of deployment site (mainly bedrock), near the epicentral area and a high sampling rate (500 samples per second).

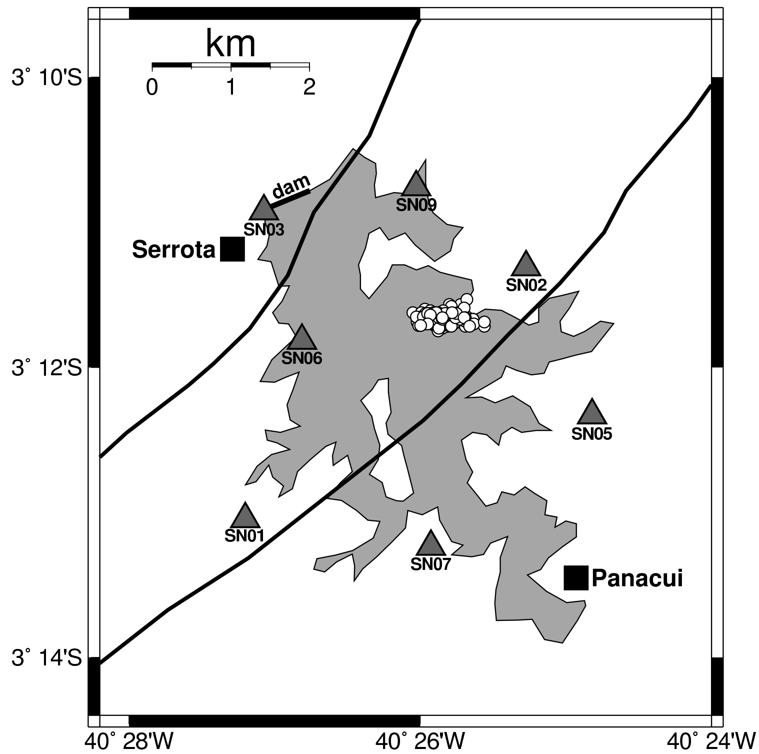

Figure 1 – Map of the locations of the seismographic stations. The triangles represent the seismographic stations. At SN01 an analogical (SN1A) and a digital station were deployed. The squares represent the small villages; lines crossing the dam are faults (DNPM, 1973). Cicles are epicenters recorded by local network. The 160 selected events (circles), recorded by at least four stations (rms $\leq$ 0.02 s, erh $\leq$ 0.02 km, erz $\leq$ 0.2 km).

Figura 1 – *Mapa das estações sismográficas. O triângulo representa a estação sismográfica. A estação analógica (SN1A) foi instalada na mesma localização de SN01. Os quadrados indicam as localidades maiores próximas ao açude e as linhas que interceptam o açude indicam falhas mapeadas (DNPM, 1973). Círculos são os epicentros registrados pela rede local. Os 160 eventos selecionados (círculos), registrados em pelo menos em 4 estações (rms $\leq$ 0,02 s, erh $\leq$ 0,02 km, erz $\leq$ 0,2 km).*

As can be seen, all events occurred inside the lake, in a zone about 1 km long with depths between 4.5 and 5.2 km, approximately an cluster with probable direction E-W. The Tucunduba dam, constructed in 1919[1], has the maximum height of 17.6 m and a depth of 10 m. According to Baecher and Keeney (1982), the probability of induced seismic activity at this hight is very low, less than 10%. Moreover, there is no information about the change in the water level before or the seismic activity during and after impoundment. Thus, the induced seismicity was ruled out.

FAULT PLANE

To estimate the fault plane, we used the 16 best-located events recorded at the same six stations (Table 2, Figure 5). The hypocenters were distributed along a 0.3 km length, with depth varying from 4.68 to 4.87 km (Figure 6).

Using these data, we determined, using least squares, the direction and the dip of the fault plane. The azimuth was $60° \pm 10°$ and the dip $88° \pm 11°$. Projections of the hypocenters parallel and perpendicular to the fault plane are shown in the Figure 6. The vertical and horizontal maximum errors observed for this set of data were 0.1 km, while the range of the active zone was of 0.3 km and the variation in depth was of 0.2 km. In these conditions, the hypocentral distribution can provide only a rough estimate of the fault plane orientation.

FOCAL MECHANISMS

Composite focal mechanisms were determined using clear P wave first motions with aid of the FPFIT program (Reasenberg & Oppenheimer, 1985). The FPFIT program does a grid search to find the solution that minimizes a weighted sum of discrepancies in the polarities, considering both the estimated variance of the data and the theoretical P wave radiation amplitude (Reasenberg &

[1] http://www.cbdb.org.br/barragem.htm

Table 1 – The main events ever recorded in the Northwest of the Ceará with magnitude $\geq 3.0\ m_b$ and intensity $\geq IV$ MM (MM - Modified Mercalli, RBGf - Boletim Sísmico da Revista Brasileira de Geofísica, IAG - Instituto de Astronomia, Geofísica e Ciências Atmosféricas).

Tabela 1 – *Os principais eventos registrados no Noroeste do Ceará com magnitude* $\geq 3.0 m_b$ *e intensidade* $\geq IV$ *MM (MM - Mercalli Modificada, RBGf - Boletim Sísmico da Revista Brasileira de Geofísica, IAG - Instituto de Astronomia, Geofísica e Ciências Atmosféricas).*

Local	Date	Mag (m_b)	Int. (MM)	Reference
Granja	1942	3.0	IV	Ferreira & Assumpção, 1983
S.L. do Curu	15/12/1974	3.3	VII	Ferreira & Assumpção, 1983
Itapajé	25/02/1987	3.0	IV	RBGf
Groaíras	01/04/1988	4.1	V-VI	RBGf
Groaíras	01/04/1988	3.9	-	RBGf
Frecheirinha	27/12/1989	3.2	IV-V	RBGf
Irauçuba	19/04/1991	4,8	VI-VII	RBGf
Groaíras	10/05/1995	3.4	-	RBGf
Frecheirinha	22/04/1997	3.2	-	UFRN/IAG
Senador Sá	09/06/1997	3.2	-	UFRN/IAG
Senador Sá	12/12/1997	3.0	-	UFRN/IAG

Table 2 – Events recorded by at least the six stations. H-origin is the true origin, m_D is the duration magnitude using the same parameters as Blum & Assumpção (1990) ($m_D = 1.64 + logD - 0.97$).

Tabela 2 – *Eventos registrados nas mesmas seis estações. H-origin é a hora de origem,* m_D *é a magnitude de duração usando os mesmos parâmetros de Blum & Assumpção (1990)* ($m_D = 1,64 + logD - 0.97$).

Event	Date	H-origin		lat S	long W	depth	m_D
		hhmm	ss.ss			km	
1	970904	2052	47.87	3-11.63	40-25.79	4.87	1.5
2	970905	0113	50.93	3-11.64	40-25.81	4.81	1.0
3	970905	0114	02.56	3-11.63	40-25.78	4.80	1.0
4	970909	0427	55.67	3-11.70	40-25.88	4.78	1.5
5	970911	2146	59.60	3-11.66	40-25.88	4.70	< 1.0
6	970912	0517	31.43	3-11.66	40-25.87	4.74	< 1.0
7	970912	0517	59.47	3-11.64	40-25.84	4.79	< 1.0
8	970912	0518	09.73	3-11.66	40-25.86	4.70	< 1.0
9	970912	0519	30.63	3-11.68	40-25.88	4.70	< 1.0
10	970912	0519	40.12	3-11.67	40-25.81	4.78	< 1.0
11	970912	0519	55.12	3-11.69	40-25.86	4.71	< 1.0
12	970912	0523	55.15	3-11.68	40-25.87	4.68	2.2
13	970912	0536	47.90	3-11.64	40-25.81	4.76	1.5
14	970912	0548	26.82	3-11.65	40-25.80	4.74	1.5
15	970912	0551	04.71	3-11.65	40-25.84	4.79	2.3
16	970912	0843	28.86	3-11.68	40-25.85	4.73	< 1.0

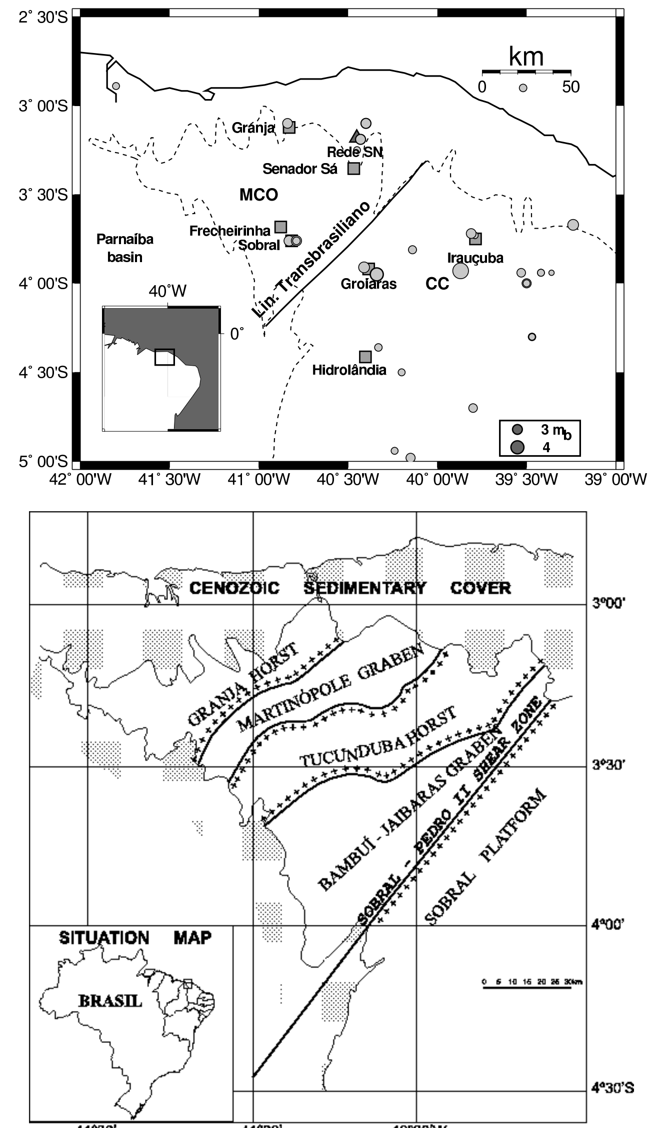

Figure 2 – Simplified maps of NW Ceará; a. Map showing the two main domains in NW Ceará. The Medium Coreaú Domain = MCO, the Ceará Central Domain = CC and Transbrasiliano lineament. The dashed line is the limit of the sedimentary basins. Cicles are epicenters recorded by the UFRN network. Triangles indicate seismic stations. b. Figure showing the location of the Bambui-Jaibaras, and Martinópole grabens separated by the Tucunduba horst (Figure taken from Sial *et al.*, 2000 – p. 550, Fig. 9).

Figura 2 – *Mapa simplificado do NW do Ceará, Brasil; a. Mapa mostra dois domínios principais no NW do Ceará. O domínio do Médio Coreaú = MCO , o domínio do Ceará Central = CC e o Lineamento Transbrasiliano. Linha tracejada é o limite da bacia sedimentar. Círculos são epicentros registrados pela rede da UFRN. Triângulo indica estação sísmica. b. Figura mostra a localização dos grabens Bambui-Jaibaras e Martinópole separados pelo horst Tucunduba (Figura cedida por Sial et al., 2000 - p. 550, Fig. 9).*

Oppenheimer, 1985). In order to improve our estimates, we used the information contained in the amplitude ratios of P and S waves (SV/SH, SV/P and SH/P ratios) to restrain the number of possible nodal-plane solutions (e.g. Kisslinger 1980; Kisslinger et al. 1982). This estimate is for individual events where we used the code focmec, developed by Snoke et al. (1984).

Firstly, with the 16 events (Table 2) and we used the best fit plane previous section as a reference in determining the composite focal mechanism solution ($60°$), withing the range $\pm 30°$. In this case of event 1 (Table 1) we included a positive P reading from a short period station in Sobral-CE, 85 km from the epicenter. The resulting composite focal mechanism, using FPFIT, is shown in

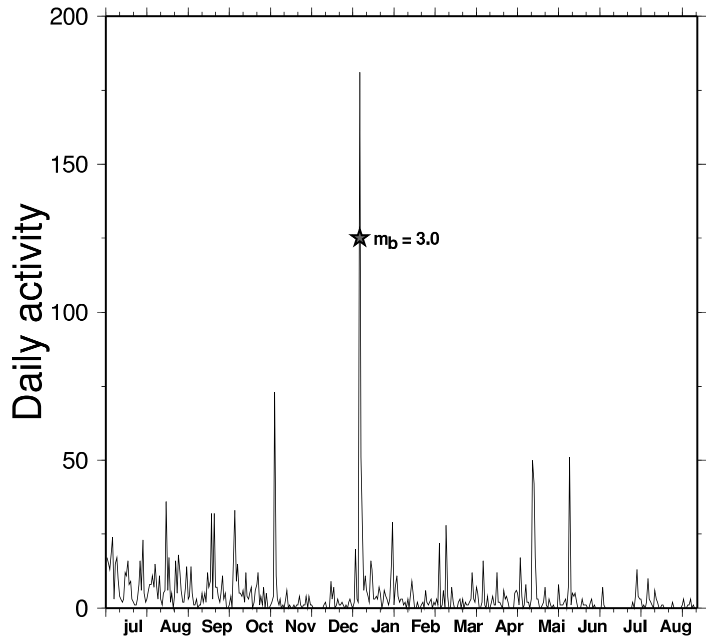

Figure 3 – Tucunduba activity. Number of daily events recorded by SN1A station from June 11, 1997 to August 14, 1998.

Figura 3 – *Atividade de Tucunduba. Número de sismos registrados por dia pela estação SN1A, no período de 11 de junho de 1997 a 14 de agosto de 1998.*

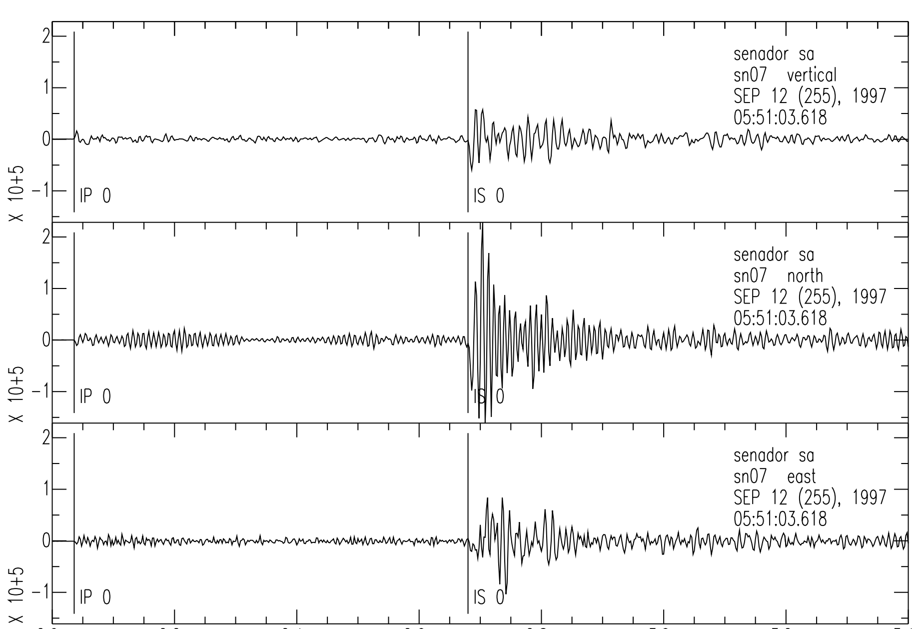

Figure 4 – Seismogram recorded at SN07 station with clear P and S arrivals in the vertical component. Event n° 15 (table 2) with magnitude 2.3 m_b.

Figura 4 – *Sismograma registrado pela estação SN07 com polaridade da chegadas da P e S (componente vertical). Evento número 15 (tabela 2) com magnitude 2.3* m_b.

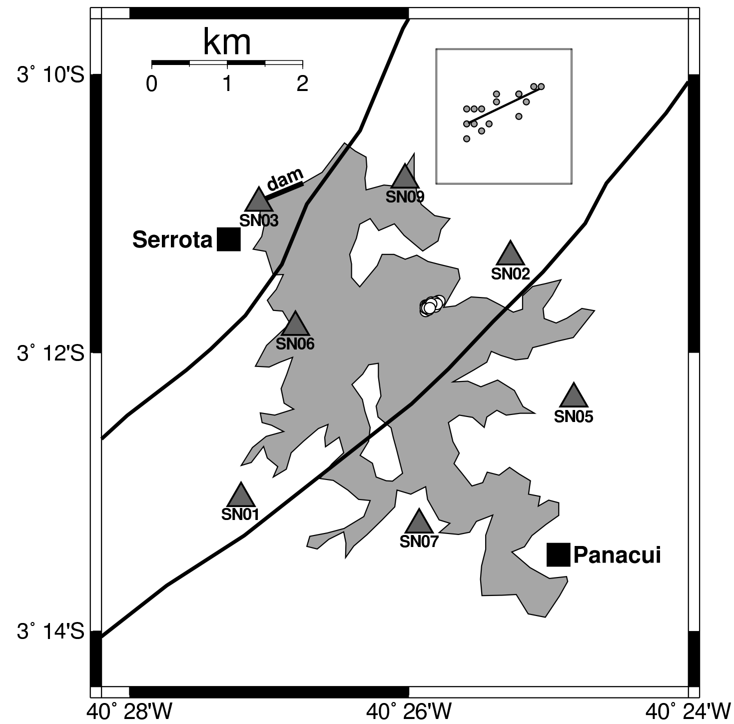

Figure 5 – Map of epicenters with 16 selected events (circles), recorded by at least six stations. Triangles indicate seismic stations. Squares represent a closer look of the epicenters.

Figura 5 – *Mapa epicentral dos 16 eventos selecionados (círculos), registrados nas mesmas seis estações. Triângulo indica estação sísmica. Quadrado representa uma ampliação dos epicentros.*

Table 3 and Figure 8. The solution of the focal mechanism is approximately a NE-SW fault, with strike-slip dextral movement with normal component. The fault plane was chosen by taking into account the hypocentral distribution (Figure 5). The composite focal mechanism solution is a strike-slip type, which is predominant in the northeast of Brazil (Assumpção *et al.*, 1985; 1989; Ferreira *et al.,* 1995; 1998). The direction of the P axis ($278°$), obtained using FPFIT, differs by $6°$ from the maximum horizontal compressive stress (SH_{max}), obtained by Ferreira *et al.* (1998) in the NE Ceará region.

Secondly, for individual focal mechanism, we used selected six events from Table 2 (Table 4), using as our selection criterion the largest number of clear polarities of the S wave. The results obtained through FOCMEC are in Table 4, limiting the range of orientation (between $60°$ and $90°$) and dip (between $0°$ and $30°$) of the B (null axis), A and N (corresponding to Herrmann's X and Y axes) axes, with a step of $2°$. The solutions that satisfy the polarity data and that fit the amplitude ratios within a given maximum residual in terms of log (amplitude ratio). The results showed a strike-slip mechanism. The average strike for all events was $65° \pm 19°$. The average dip was $80° \pm 9°$. These average values were close the values obtained by fitting of the fault plane by least squares and composite focal mechanisms (FPFIT).

To estimate S_{Hmax} using the individual focal mechanism, we averaged of the P-axes directions, since all events are strike-slip. The obtained value was $265°$, near the values obtained by FPFIT ($278°$) for the direction of the P axis it differ by about $20°$ from the value of S_{Hmax} for northwestest Ceará ($293°$) obtained by Ferreira *et al.* (1998).

DISCUSSION

A network composed of seven portable digital stations, almost all installed in granitic/gneissic bedrocks of the crystalline basement, was used to monitor the seismic activity in the Tucunduba Dam. It was possible to obtain records of good quality, with clear P and S waves. In addition, the network configuration used two stations that were installed close to the epicentral area. Thus, it was possible to determine the hypocenters with high accuracy.

The active zone was small, less than 1 km long with a depth varying from 4.5 to 5.2 km, considering all events analyzed. It was

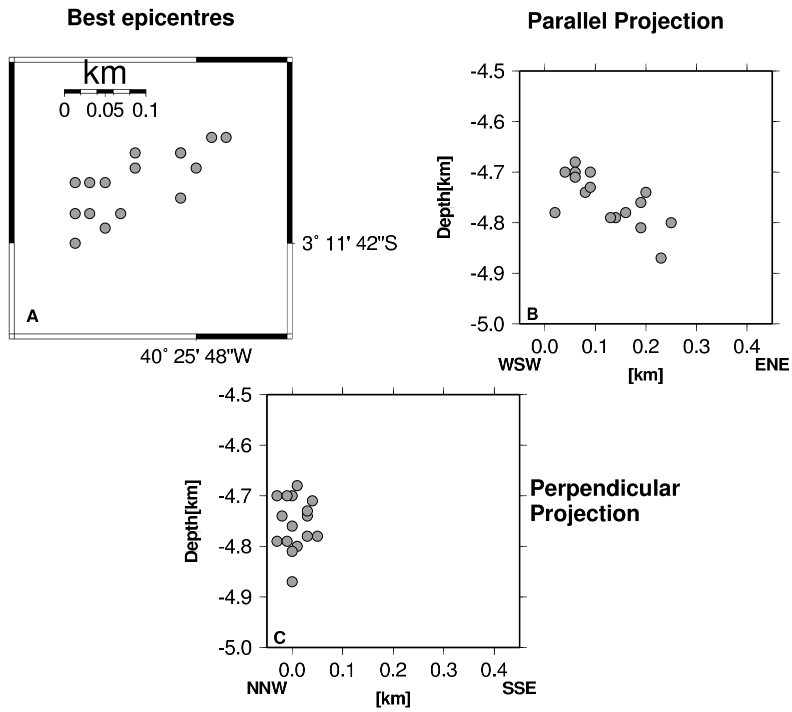

Figure 6 – A) Detailed map of epicenters in Figure 5. B and C) Projections of the hypocenters on the vertical plane across the probable fault plane (Parallel and Perpendicular), respectively.

Figura 6 – *A) Mapa detalhado dos epicentros na Figura 5. B e C) Projeções dos hipocentros no plano vertical ao longo do provável plano de falha (Paralelo e Perpendicular, respectivamente).*

Table 3 – Result of the composite focal mechanism using FPFIT program (Reasemberg & Oppenheimer, 1985).

Tabela 3 – *Resultado do mecanismo focal composto usando o programa FPFIT (Reasemberg & Oppenheimer,1985).*

Azimuth	Dip	Rake	P-Az/plunge		T-Az/plunge	
$60° \pm 11°$	$65° \pm 5°$	$-174° \pm 4°$	$278°$	$27°$	$15°$	$14°$

inside the Tucunduba Reservoir.

A set of 16 events recorded by the same six stations was selected to define a fault plane, yielding values of $60°$ for the azimuth and $88°$ for the dip.

The focal mechanism solution shows a dextral NE-SW strike-slip fault with normal component. This solution is consistent with a succession of horsts and grabens in the MCO domain (direction NE-SW), with the same direction as the main faults in the northwest of Ceará. The fault plane was chosen by taking into account the hypocentral distribution (Figure 6). The direction of the P axes ($278°$), obtained by composite focal mechanism, differs by $15°$ from the direction of the horizontal maximum stress (S_{Hmax}), obtained by Ferreira *et al.* (1998). In the determination of individual focal mechanisms, there are three or four stations with the same polarities, which may indicate that mechanisms do not change much. Thus the strike-slip mechanism is fully in accord with previous results. The average direction of the individual planes are $65°$ for the azimuth and $80°$ for the dip, which are close to the values obtained by the composite mechanism and least squares plane fitting. As the direction of horizontal maximum stress (S_{Hmax}) was $265°$, it differs $1°$ from the best estimated by Ferreira *et al.* (1998).

The seismic activity is located in the border of the basin, a common characteristic of the seismicity of the Northeast (Assumpção, 1998; Ferreira *et al.*, 1998). The estimated focal mechanism (strike-slip type) is the most common in the Northeast of

Table 4 – Results of focal mechanism – FOCMEC. All solutions show strike-slip mechanism with focal mechanism event numbers corresponde to Table 2.

Tabela 4 – *Resultado do mecanismo focal – FOCMEC. Todas soluções mostram mecanismos transcorrente onde o número do mecanismo focal corresponde aos eventos na Tabela 2.*

Ev. n°	Az.	Dip	Rake	Az./plunge P-axis	Az./plunge T-axis	Log(Am. ratio) res. average
1	44°	68°	-166°	85°/25°	178°/06°	0.10
3	44°	89°	170°	89°/07°	178°/07°	0.15
10	78°	85°	174°	123°/00°	212°/08°	0.04
13	82°	87°	-24°	36°/16°	130°/14°	0.17
14	89°	84°	-10°	45°/12°	135°/03°	0.11
15	51°	72°	-172°	93°/33°	180°/11°	0.06

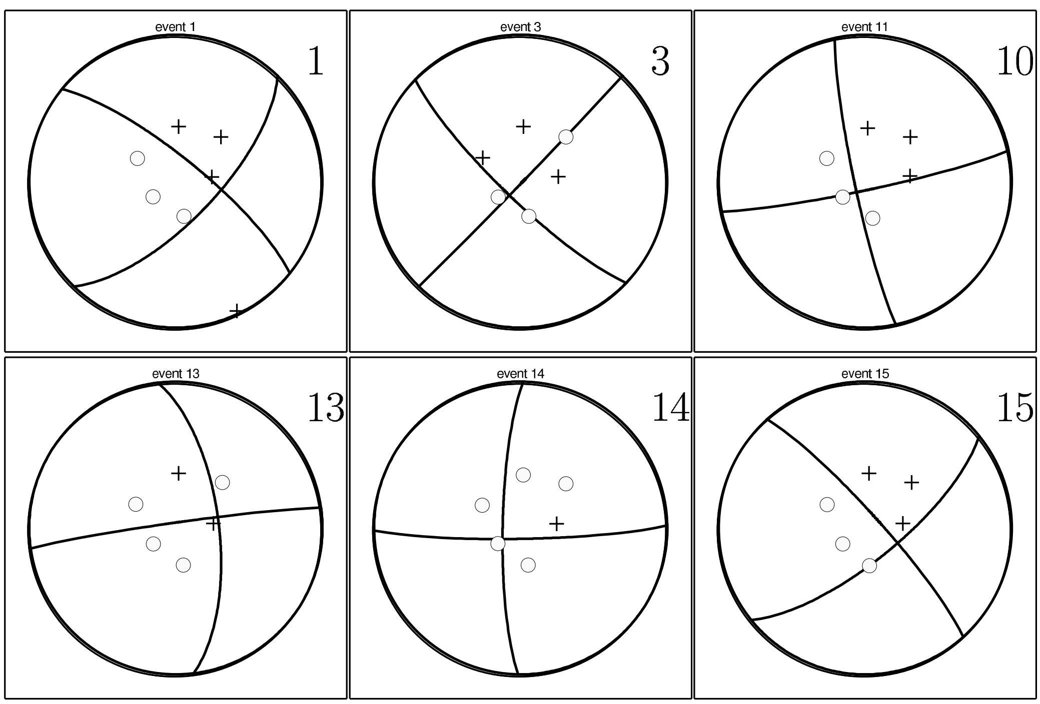

Figure 7 – Focal mechanisms using FOCMEC and half-space model; + = up and ○ = down; Numbers refer to table 2.

Figura 7 – *Mecanismos focais usando FOCMEC, com modelo de semi-espaço; + = up e ○ = down.*

Brazil (Assumpção *et al.*, 1985; 1989; Ferreira *et al.*, 1995; 1998). The S_{Hmax} estimated has a small difference. Probably, that difference is because Ferreira *et al.*, (1998) used events to the South of the active area and that the line of the coast suffers more flexural effect than area to the South.

The events at Senador Sá are consistent with the stress regime determined by Ferreira *et al.* (1998) in NW Ceará (EW compression, NS extension) and can be used to extend the stress province towards the coastline.

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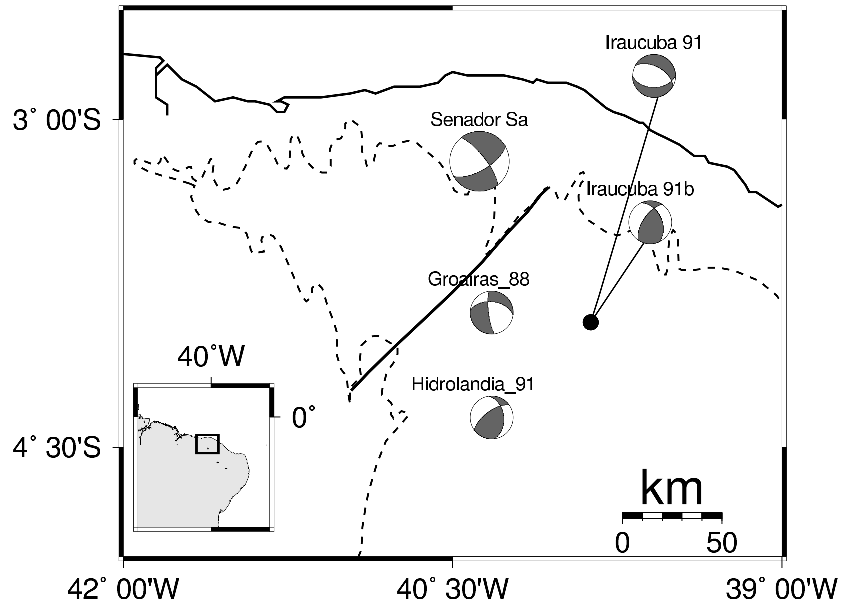

Figure 8 – Composite Focal Mechanism for the 16 events of Senador Sá (Table 1). Lower hemisphere, equal-area projections. Black and white quadrants Circles denote compressive and extensive first motions, respectively. Others mechanisms from Ferreira *et al.* (1998).

Figura 8 – *Mecanismo focal composto para 16 eventos de Senador Sá (Tabela 1). Hemisfério inferior, projeção de "equal-area". Quadrantes preto e branco (nos círculos) representam primeiro movimento compressivo e extensivo, respectivamente. Outros mecanismos foram obtidos por Ferreira et al. (1998).*

providing us Figure b. Maps were plotted using GMT (Wessel & Smith, 1991) and seismograms were analysed with SAC (Goldstein *et al.,* 2001). GSF is supported by CNPq (309975/2003-4).

REFERENCES

ASSUMPÇÃO M. 1998. Seismicity and Stress in the Brazilian Passive Margin. Bull. Seism. Soc. Am., 88(1): 160–169.

ASSUMPÇÃO M, SUÁREZ G & VELOSO JA. 1985. Fault plane solutions of intraplate earthquakes in Brazil: some constrains on the regional stress field. Tecnophysics, 113: 283–293.

ASSUMPÇÃO M, FERREIRA JM, CARVALHO JM, BLUM ML, MENEZES EA, FONTENELE D & AIRES A. 1989. Seismic activity in Palhano, CE, October 1988, preliminary results. Rev. Bras. Geofís., 134: 11–17.

BAECHER GB & KEENEY RL. 1982. Statistical Examination of Reservoir-induced Seismicity. Bull. Seismol. Soc. Am., 72: 553–569.

BERROCAL J, ASSUMPÇÃO M, ANTEZANA R, DIAS NETO CM, ORTEGA R, FRANÇA H & VELOSO JAV. 1984. Sismicidade do Brasil. Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, 320 pp. (in Portuguese).

BLUM ML & ASSUMPÇÃO M. 1990. Estimativa do parâmetro b dos sismos de Palhano, CE, de outubro de 1988. XXXVI Congr. Brasileiro de Geologia, Natal, RN. Anais, 5: 2160–2163 (in Portuguese).

BOLETIM SÍSMICO. published monthly in Rev. Bras. Geof.

BRITO NEVES BB, DO SANTOS EJ & VAN SCHMUS WR. 2000. Tectonic history of the Borborema Province, Northeastern Brazil. In Cordani U, Milani EJ, Thomaz Filho A & Campos DA, eds., Tectonic evolution of South America 31st International Geological Congress, Rio de Janeiro, Brazil, p. 151–182.

CHRISTENSEN NI. 1982. Seismic velocities, in: Charmichael RS (Ed.), Handbook of Physical Properties of Rocks, Vol II CRC Press, Boca Raton, FL, p. 2–228.

CHRISTENSEN NI & MOONEY WD. 1995. Seismic velocity structure and composition of the continental crust: a global view. J. Geophys. Res., 100: 9761–9788.

DNPM. 1973. Projeto Jaibaras. 1:100.000.

FERREIRA JM & ASSUMPÇÃO M. 1983. Sismicidade do Nordeste do Brasil. Rev. Bras. Geofís., 1: 67–88 (in Portuguese).

FERREIRA JM, TAKEYA MK, COSTA JM, MORREIRA JAM, ASSUMPÇÃO M, VELOSO JAV & PEARCE RG. 1987. A continuing intraplate earthquake sequence near João Câmara – Northeastern Brazil – preliminary results. Geophys. Res. Lett., 14: 1402–1405.

FERREIRA JM, OLIVEIRA RT, ASSUMPÇÃO M, MORREIRA JAM, PEARCE RG & TAKEYA MK. 1995. Correlation of sismicity and water level in the Açu reservoir – an example from Northeast Brazil. Bull. Seism. Soc. Am., 85: 1483–1489.

FERREIRA JM, OLIVEIRA RT, TAKEYA MK & ASSUMPÇÃO M. 1998. Superposition of local and regional stresses in northeast Brazil : evidence from focal mechanisms around the potiguar marginal basin. Geophys. J. Int., 134: 341–355.

FRANÇA GS. 1999. Estudo sísmico no Açude Tucunduba, Senador Sá. CE. Dissertação de Mestrado PPGG/UFRN, 85 p. (in Portuguese).

GOLDSTEIN P, DODGE D & FIRPO M. 2001. SAC2000: Signal processing and analysis tools for seismologists and engineers, UCRL-JC-135963, Invited contribution to the IASPEI, International Handbook of Earthquake and Engineering Seismology.

KISSLINGER C. 1980. Evolution of S to P amplitude ratios for determining focal mechanisms from regional network observations. Bull. Seism. Soc. of Am. 70: 999–1014.

KISSLINGER C, BOWMAN JR & KOCH K. 1982. Determination of focal mechanism from SV/P amplitude ratios at small distances. Phys. Earth and Planet. Int., 30: 172–176.

LEE WHK & LAHR JC. 1975. HYPO71(revised): a computer program for determing hypocenter, magnitude, and first motion pattern of local earthquakes. U.S. Geol. Surv. Open File Rep., 75–311, 114pp.

NASCIMENTO AF. 1997. Estudo da sismicidade induzida pelo reservatório da barragem do Assu (RN) Dissertação de Mestrado PPGG/UFRN, 68 p. (in Portuguese).

REASENBERG P & OPPENHEIMER D. 1985. FPFIT, FPPLOT and FPPAGE: Fortran computer programs for calculating and displaying earthquake fault-plane solutions. U. S. Geol. Surv. Open File Rep., 85–739, 109p.

SIAL AN, FERREIRA VP, DE ALMEIDA AR *et al.* 2000. Carbon isotope fluctuations in Precambrian carbonate sequences of several localities in Brazil. An. Acad. Bras. Ciênc., 72(4): 539–558.

SNOKE JA, MUNSEY JW, TEAGUE AG & BOLLINGER GA. 1984. A program for focal mechanism determination by combined use of polarity and SV-P amplitude ratio data. Earthquake Notes, 55(3): 15.

TAKEYA M, FERREIRA JM, PEARCE RG, ASSUMPÇÃO M, COSTA JM & SOPHIA CM. 1989. The 1986-1988 intraplate earthquake sequence near João Câmara, northeast Brazil-evolution of seismicity. Tectonophysics, 167: 117–131.

TORQUATO JR & NOGUEIRA NETO JA. 1996. Histografia da região de dobramentos do médio coreaú. Rev. Bras. de Geociências, 24(4): 303–314 (in Portuguese).

WESSEL P & SMITH WHF. 1991. Free software helps maps and displays data: Eos Trans. AGU, 72: V441 445–446.

NOTES ABOUT THE AUTHORS

George Sand Leão Araújo de França. Doctor in Geophysics at University of São Paulo (2003); worked at Seismological Observatory of University of Brasília (2003), and at the Department of Physics in the Federal University of Rio Grande do Norte (2004-present). Main interests: intraplate seismicity, local and reservoir induced seismicity, crustal and upper mantle structure.

Joaquim Mendes Ferreira. Doctor in Geophysics at University of São Paulo (1997); worked at Department of Physics of UFRN since 1976 and with Seismology since 1979. Main interests: intraplate seismicity, local and reservoir induced seismicity, seismic risk assessment.

Mario Takeya. PhD in Geophysics at Edinburgh University (1992). Presently working at Departament of Physics in the Federal University do Rio Grande do Norte. Main interests: intraplate seismicity, local and resevoir induced seismicity.