Evolution of the Areado/MG seismic sequence - started in January, 2004.

Lucas V. Barros*; Daniel F. Caixeta; Cristiano N. Chimpliganond & Darlan P. Fontenele
Observatório Sismológico, Universidade de Brasília, Brazil, <obsis@unb.br>

This paper was prepared for presentation at the 9th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, 11-14 September 2005.

Abstract

A microearthquake seismic sequence, in course in the neighborhoods of the little Town of Areado, located in the southern part of Minas Gerais State is studied. This sequence started on January 21, with a 3.4 regional magnitude felt with a MMI V.

After that, a local seismograph network with up to six stations detected more than nine hundred microearthquakes, 458 of these located using data of at least three components stations.

A composite focal mechanism indicates a dextral transcurrent fault in NNE-SSW direction, in accordance with a hypocentral distribution of the microearthquakes.

Results of preliminary studies of that sequence were presented in the first Symposium of the Brazilian Geophysical Society (SBGf) occurred in São Paulo in September 2004. In these studies, it was presented the analysis results of the data generated by the seismic network from January 28 to May 28. This paper intends to update the results presented on 2004 SBGf Symposium, in a more conclusive way, showing seismicity and evolution from January 28, 2004 to May 28, 2005.

Introduction

The little town of Areado, located near the margins of Furnas Power Plant Reservoir, in the southern part of Minas Gerais State, is situated in a seismogenic area, which has been proven to be seismically active recently. In the past two years, two seismic sequences occurred, the first initiated in 16/03/2003 and the second in 21/01/2004, having main shocks of magnitude 3.4 m_b with MMI V (Modified Mercalli Intensity Scale) and 3.2 m_b with MMI IV, respectively. The first sequence was studied by both *Instituto Astronomico e Geofísico da Universidade de São Paulo* (IAG/USP) and *Observatório Sismológico da Universidade de Brasília* (SIS/UnB) networks and its results were published by Marza et al., 2003 and Fernandes et al., 2004.

The last sequence is still in progress and has been studied by SIS/UnB, which has been operating a local seismographic network with up to six triaxial stations (Figure 1 shows operational period of these stations). Its preliminary results were presented in the First Symposium of the Brazilian Geophysical Society (SBGf) occurred in São Paulo in September 2004 (Barros et al., 2004). These results comprised data collected from January 28, 2004, when a local seismographic network was being installed, to May 28, 2004. In this period, 372 microearthquakes were detected, 180 of these located with data of at least three 3-component stations.

These 180 events were distributed in two groups, the first containing 75 earthquakes, comprising those located with data of 4 and 5 stations and magnitude duration (m_D) greater or equal to zero. The second group, on the other hand, contained 24 events, which were selected with the same criteria of group 1, but with m_D = 0.2. The first group was used in determining v_p/v_s ratio, being v_p/v_s = 1,673 ? 0,006, and the second in determining the composite focal mechanism, resulting in a sinistral fault with the following parameters: strike = 184º, dip = 75º, and rake = -15º. This preliminary result cannot be considered correct, since it was not noticed that S3000EQ seismometer, manufactured by Sprenghneter, inverts the vertical component polarity and, in this case, the P-wave polarities should have been corrected before studying the focal mechanism.

The error mentioned above can be corrected, in the focal mechanism diagram, substituting compressions for dilatations and dilatations for compressions and, in this case, P (tension) and T (traction) axes are exchanged.

In this paper, it will be updated both results of single hypocentral location and composite focal mechanism, involving data generated from January 28, 2004 to March 31, 2005, therefore, 14 months of continuous operation of the Local Seismographic Network of Areado (LSNA). It will be presented as new results the joint hypocentral location and **b** value determination. All results obtained in the previous Paper will be used, and the focal mechanism will be corrected.

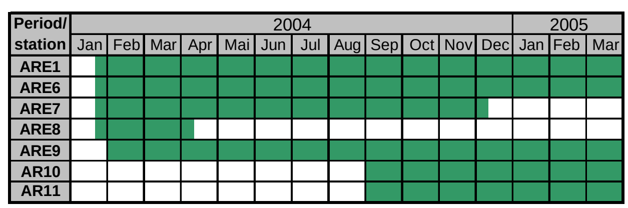

Figure 1 - Operational perform of the LSNA stations (green).

Method

The set of 901 events detected by LSNA in 14 months of continuous operation were classified in accordance with the number of recording stations, establishing 6 data sets (Table 1). Events from groups 1 and 2 were not located, although it was possible to do so, since epicenters can be determined using data of just one triaxial station (Haskov, 2001). However, as a matter of accuracy, we have preferred to locate the events using at least three 3-component stations, which guarantees a better azimuthal coverage of the stations and, therefore, better accuracy.

Table 1 summarizes Data Base characteristics of Areado/MG, showing the number of detected and located events, the gap (minimum, maximum and medium) in azimuthal coverage of the stations, as well as the root mean square of residual (minimum, maximum and medium).

Tabela 1 - Areado's Data Base

Nº of stations	detected events	Located events	azimuthal GAP (Degrees)			Resídual's RMS		
			MAX.	MIN.	MÉDIO	MAX.	MIN.	MÉDIO
1	285	-	-	-	-	-	-	-
2	158	-	-	-	-	-	-	-
3	153	153	337	127	180	0.06	0.01	0.019
4	267	267	279	96	150	0.11	0.00	0.021
5	34	34	242	96	140	0.23	0.01	0.044
6	04	04	194	95	140	0.02	0.02	0.022

Waveforms were analyzed in SEISAN environment (*The Earthquake Analysis Software*) (Haskov & Ottemöller, 1999), in which the Hypocenter Location Program HYPOCENTER (Klein, 1978) and the Focal Mechanism Program FOCMEC (Snoke et al., 1984; Arvidison, 1992) were used.

The Velocity model used was a single layer model (5,8 km/s) (Barros et al., 2004). V_p/V_s ratio used was the same obtained in the previous Paper (V_p/V_s = 1.673 ? 0.006).

Results

In 14 months, Aerado Local Seismograph Network detected 901 seismic events (Figure 2), being 458 located (with magnitude ranging from -1.0 to 1.8). From these 458 events, 153 were located using 3 stations, 267 using 4 stations, 34 with 5 and 4 with 6 stations.

Although these events had low magnitudes (47% with negative magnitude), it was possible to identify P and S phases in most of them (see Table 2), since the seismographs used have ample dynamic range (140dB) [It used Nanometrics ORION Datalogger and two types of seismometers: Guralp broadband CMG-40T (30s - 50Hz) (ARE10 Station) and Sprenghneter short period (1s) S3000EQ (1 - 100Hz) at the other stations]. All seismometers, excepting ARE11, were installed over rocky outcrop.

Magnitudes were calculated using the Blum formula (1993), m_D = 1.70 x logD - 1.02, where D is signal durations in seconds. Figure 3 shows magnitudes distribution for all 458 located events.

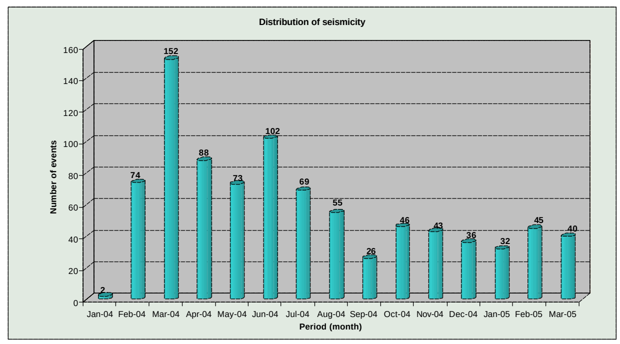

Figure 2 - Evolution of Areado's seismicity, without magnitude threshold, from 28/01/04 to 31/03/05.

Table 2 - Hypocentral location statistical Indicators.

Station	Set 1 = 153 events						Set 2 = 267 events					
	P RES.	RMS DEV	P Nº	S RES	RMS DEV	S Nº	P RES.	RMS DEV	P Nº	S RES	RMS DEV	S Nº
ARE1	-0.01	0.03	85	0.00	0.01	86	00	0.02	257	0.00	0.01	257
ARE6	-0.01	0.02	57	0.00	0.01	57	0.00	0.10	249	0.03	0.31	249
ARE7	0.00	0.02	124	0.00	0.01	127	-0.01	0.11	219	-0.02	0.19	219
ARE8	-	-	-	-	-	-	0.16	0.32	12	-0.15	0.34	12
ARE9	0.01	0.02	151	-0.01	0.01	152	0.00	0.05	266	-0.01	0.13	262
AR10	0.00	0.01	37	0.00	0.01	36	0.00	0.01	50	-0.01	0.02	49
Station	**Set 3 = 34 events**						**Set 4 = 4 events**					
	P RES.	**RMS DEV**	**P Nº**	**S RES**	**RMS DEV**	**S Nº**	**P RES.**	**RMS DEV**	**P Nº**	**S RES**	**RMS DEV**	**S Nº**
ARE1	-0.01	0.03	34	-0.01	0.02	33	-0.01	0.01	4	-0.02	0.00	4
ARE6	0.00	0.11	35	0.01	0.01	33	-0.02	0.00	4	0.00	0.01	4
ARE7	0.00	0.01	31	0.01	0.02	31	-0.02	0.01	4	-0.01	0.01	4
ARE8	-0.01	0.03	18	-0.01	0.03	18						
ARE9	0.00	0.03	34	-0.01	0.02	34	0.00	0.01	4	0.01	0.01	4
AR10	0.01	0.01	15	0.00	0.01	15	0.01	0.01	4	0.00	0.01	4
AR11	-0.01	0.00	4	0.05	0.01	4	0.05	0.01	4	0.04	0.02	4

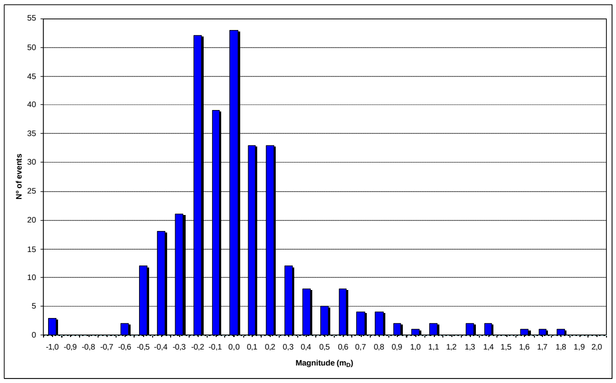

Figure 3 - Magnitudes (m_D) distribution of the 458 events located at Areado/MG related to aftershock activity.

Hypocentral Location

Single and joint hypocentral determination techniques were used. HYPOCENTER (Lienert, 1995) and VELEST (Kissling, 1995) Programs for single and joint hypocentral determinations, respectively.

a) Single location

Figure 4 shows epicenter distribution of 458 events, being five outside active Aerado fault, located using the HYPOCENTER program, applying a 5 km initial deep. Lower values were also tested, however the resulting hypocenters were not sensitive.

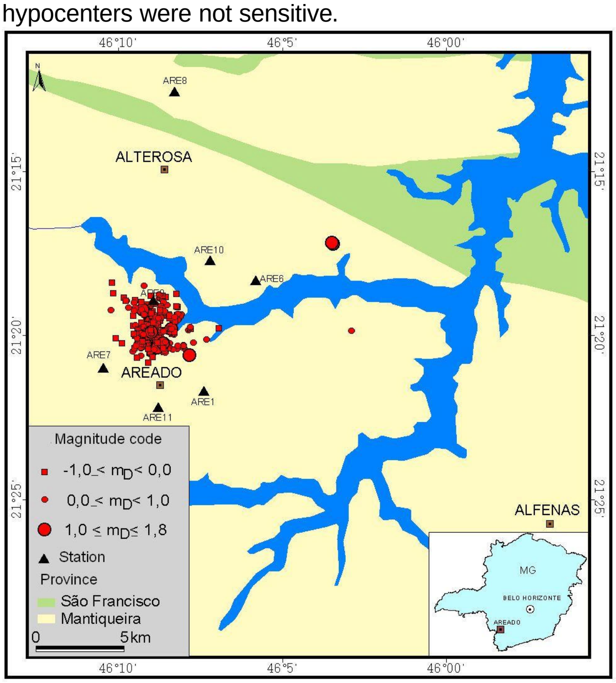

Figure 4 - Spatial distribution of the epicenters of all located events (HYPOCENTER Program) at Areado/MG. Seismographic stations are indicated by triangles, with their respective operation period indicated in Figure 1.

The locations of events in Figure 4 are a little scatter, especially for very low magnitude events. It can be due to error analysis or lateral discontinuities, not constrained by the single hypocentral location technique. This last case can be verified using a joint hypocentral determination program, where station corrections are incorporated in order to correct lateral discontinuities in the elastic properties of the rocks on seismic ray path from the source to each station.

b) Joint location

This technique, which is a generalization of the single location technique, includes station corrections for travel times with an additional parameter to be determined. In this case, instead of determining a hypocenter and an origin time to each event separately, these two parameters, as well as station corrections to all events set are determined simultaneously. That is why this technique is known as Joint Hipocentral Determination (JHD), which can be quite useful in defining fault geometry of aftershock seismic activity. VELEST (Kissling, 1995) was the program used in determining joint inversion.

Figure 5 shows the results obtained using VELEST program, which are not quite different when compared with results obtained using the single location program (Figure 4). Except when deeps are compared, which will be seen further.

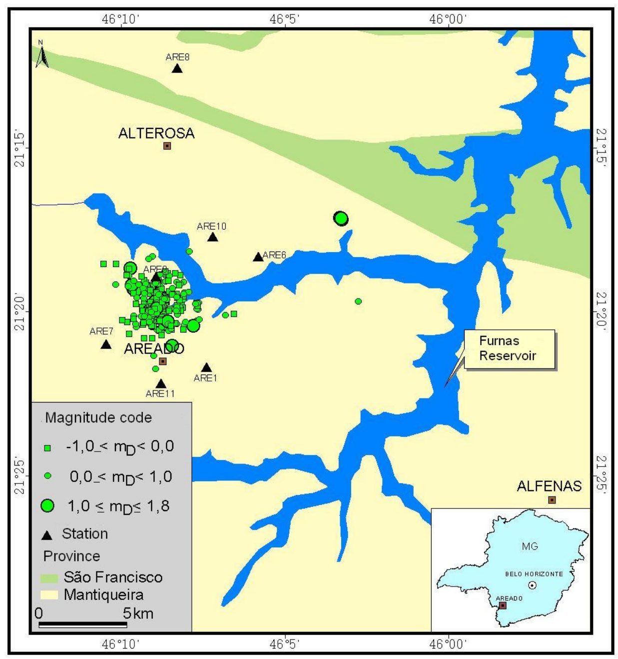

Figure 5 - Spatial distribution of the epicenters of all located events (VELEST Program) at Areado/MG. Seismographic stations are indicated by triangles, whit their respective operation period indicated in Figure 1.

b parameter Determination

Earthquake frequency distribution of a given magnitude range, in a particular seismogenic area, can be represented by Guttenberg & Ritcher (1944) relationship:

LogN = a – *b*M, where N is the number of earthquakes with magnitude = M; a and b = constant.

a value depends on the period of observation, region size to be considered, and level of seismic activity. **b** value, on the other hand, depends on the ratio between the number of small and large earthquakes. **b** parameter can be obtained empirically from the equation (Aki, 1965):

$$b = \frac{0{,}4343n}{\sum_{i=1}^{n} M_i - nM_{min},}$$

N = total number of earthquakes of the sample;

M_{min} = the lowest magnitude considered;

or linear regression (least squares method or similar). Normally, **b** varies between 0.5 and 1.5, mostly lying between 0.7 and 1.0.

Mogi (1962 and 1967) examined in laboratory the **b** parameter value, by standing brittle fracture of soft rocks, and concluded that **b** value is assumed to be related to the tectonic heterogeneity of the rock sample, and that it increases with the increase in heterogeneity. Therefore, shallow earthquakes, such as those induced by reservoirs; depend on the mechanical structure of Earth's crust.

Scholz (1968) reported that the *b* value depends on the percentage of the existing stress within the rock, related to the final breaking stress. Gupta (1962) reported that **b** values for induced earthquake sequences, for both pre and aftershocks, are comparable and greater than *b* values for local natural seismicity.

The plot in Figure 6 was obtained for all located earthquakes with positive magnitude, using the least squares method to adjust data to a straight line. The values obtained are: b = 1.32 ± 0.29, with coefficient determination = 0.9813.

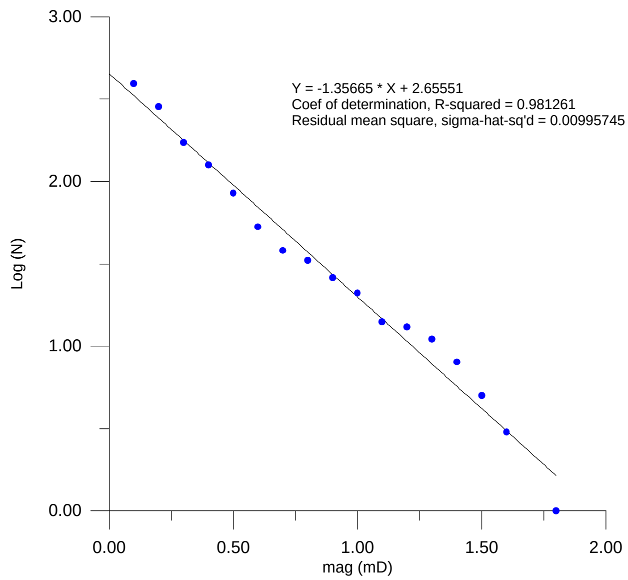

Figure 6 - Determination of b parameter.

Focal Mechanism

A different data selection was used in studying Focal Mechanism. Only earthquakes detected by four or more stations and with magnitudes greater or equal to $0.2m_D$ were used, establishing a group of 97 events and 241 polarities. Figures 7, 8, 9, and 10 show possible fault plane solutions when a search of 15, 10, 5, and 3 degrees with a FOCMEC program was used, respectively. Possible fault plane solutions are shown on the left corner of each Figure, in the following sequence: strike, dip, rake, and number of inconsistent polarities. Observing figures 4 and 5, it is possible to conclude that data presented in the focal mechanism diagrams are related to auxiliary planes.

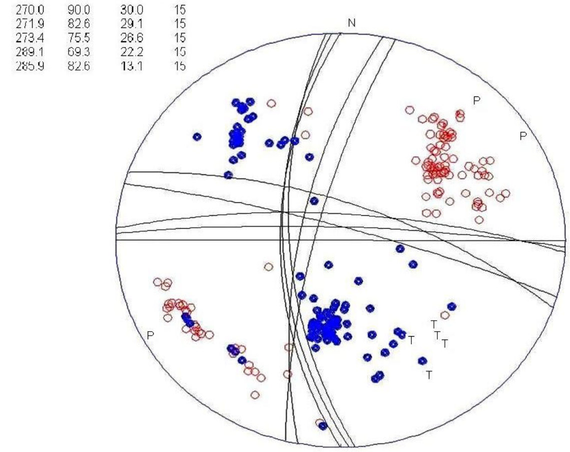

Figure 7 - Focal mechanism diagram, with 15 degrees search, five possible solutions with 15 inconsistent polarities in 241. Possible faults: dextral transcurrent, with a little variation of P and T axes position.

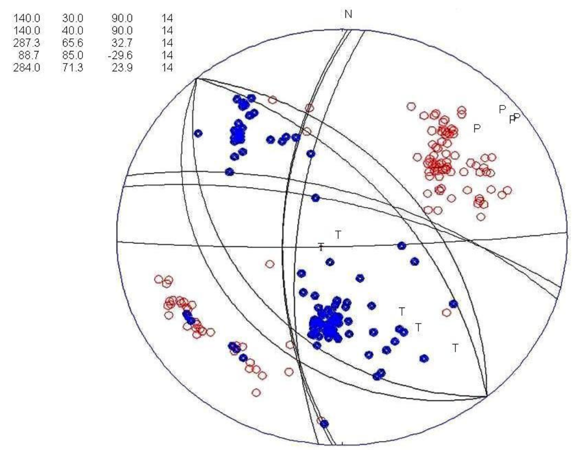

Figure 8 - Focal mechanism diagram, with 10 degrees search, five possible solutions with 14 inconsistent polarities in 241. Possible faults: dextral transcurrent and reverse, with 90 degrees of dip.

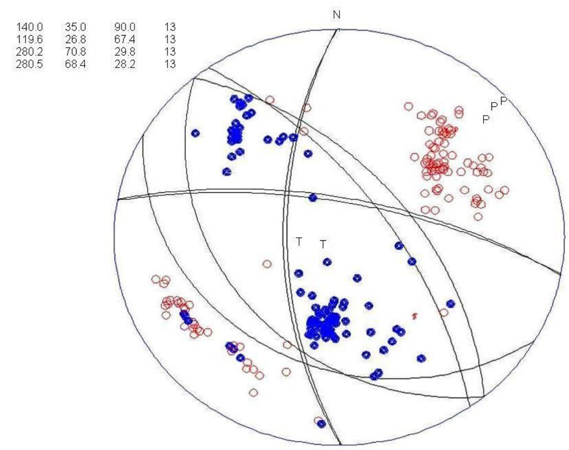

Figure 9 - Focal mechanism diagram, with 5 degrees search, four possible solutions with 13 inconsistent polarities in 241. Possible faults: dextral transcurrent and reverse.

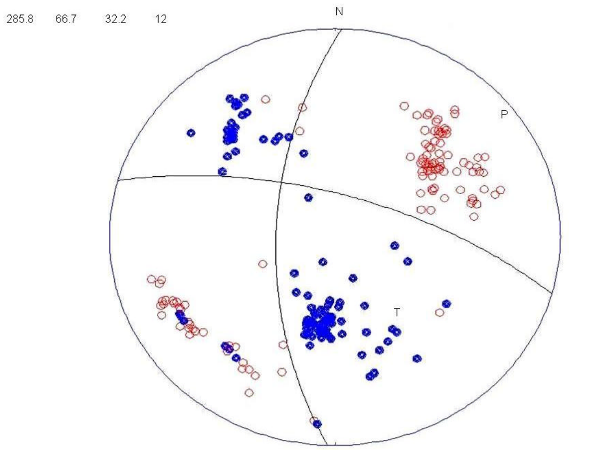

Figure 10 - Focal mechanism Diagram, with 3 degrees search, one possible solution with 12 inconsistent polarities in 241. Dextral transcurrent fault, dip in west direction and P axis (compression) in NE direction.

Discussion and Conclusions

The study of Areado seismic sequence with a 3-component local digital seismographic network, with up to six station, detected an active seismogenic area 2 km to the northern of Areado/MG, with shallow epicenters on the margins of and inside Furnas Reservoir.

Focal Mechanism study shows basically two types of faults: transcurrent dextral and pure reverse. The first seems to be more consistent, since it is a possible solution in all focal mechanism diagrams showed, and therefore, more stable. The lowest number of polarity inconsistencies are shown is this solution (12 error polarities in 241 = 5%), what is an acceptable value for composite focal mechanism study.

Observing Figures 11 (A), epicenter distribution (blue - single location and red - joint location), 11 (B) W-E section and 11(C) S-N section, we see a more visible NNE-SSW trend, consistent with the solution shown in Figure 10.

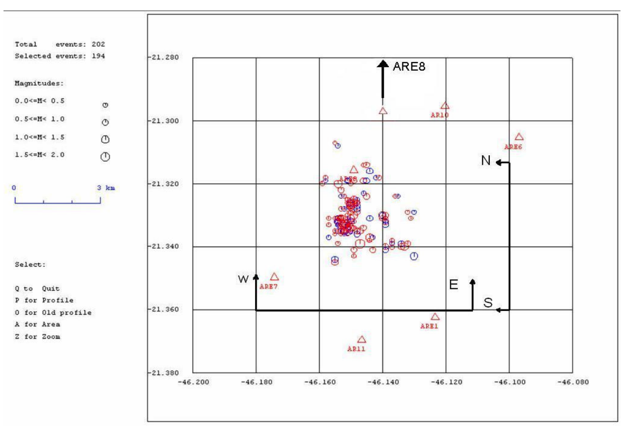

Figure 11A - Epicenter of the set of events (97) used in focal mechanism study (red VELEST and blue HYPOCENTER).

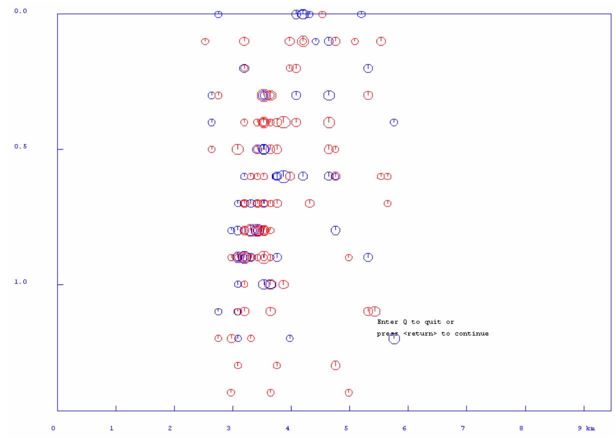

Figure 11B - W-E section.

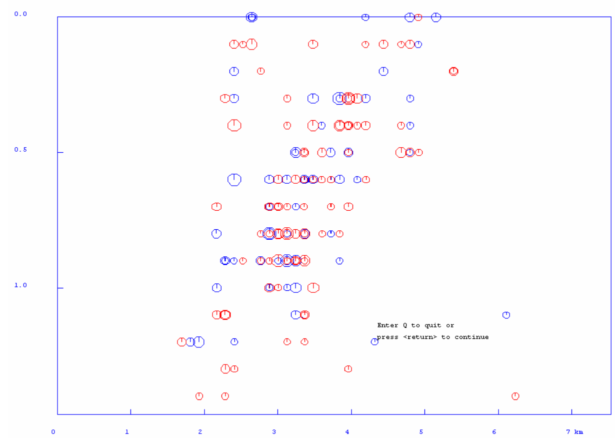

Figure 11C - S-N section.

Besides, for a reverse fault (possible in Figures 8 and 9) the P wave polarity of the 21/01/2004 main shock at FUR1 Station, should be negative. Although emerging in that event, the polarity seems to be positive. However, in the 16/03/2003 main shock, this polarity is clear and positive at FUR1 Station, and the equipment used was the same for both events. Furthermore, observing the seismic signature of both seismograms, great similarities can be observed, what leads to the conclusion that both events have the same source location, which shall be under the same stress regime.

From this Study we conclude that:

1) Hypocentral Locations of the Areado/MG earthquake are reasonably accurate (single and joint), although the single velocity model used may produce errors;

2) All earthquakes are shallow, with their deep ranging from 100 to 1500 meters (characteristics of induced earthquakes);

3) Joint and single hypocentral locations are quite similar due to little distances between the source and the stations. ARE8 Station, more distant, presents the greatest residual;

4) b parameter determined for the sequence (b = 1.36 ± 0.29) may have its value compatible with

b parameter of induced reservoir earthquakes. However, its standard deviation is high;

5) From all solutions found for the fault plane, the most reasonable shows a transcurrent fault (dextral) with inverse component, presenting the following parameters; NNE-SSW (182°) direction, dip = 61°W, and rake = 153°. The P and T axes have, respectively, following strike and dip: 52.7º and 38º, 145.7º and 38.7º;

6) Improvement in these results can be obtained whit the determination of a better velocity model from a geophysical experiment with controlled source.

Acknowledgments

We thank to Furnas Centrais Elétricas S/A by several years of cooperation, in special, to the Engeneers Emílio de J. P. Piantino, José Morvan F. Brasileiro, and the Technician Ricardo Ajej. We also thank Pedro F. de Andrade, Kate T. de Sousa, Edna L. da C. Camilo and Andreia F. C. Silva, by editing and revising the text.

References

AKI, K. (1965). Maximum likelihood estimate of b in the formula log N= a - bM and its confidence limits, Bull. Earthquake Res. Inst. Tokyo Univ. 43, p. 237-239.

ARVIDISON, R. (1992) FOCMEC - Programa para determinação de mecanismo focal composto.

BARROS, L. V.; CAIXETA, D. F. & FONTENELE, D. P. (2004). Seqüência Sísmica de Areado/MG, iniciada em janeiro de 2004: Resultados preliminares, 1º Simp. Reg. da SBGf, São Paulo/SP, 26-28 set/2004, 4pp.

BLUM M. L. B. (1993). Cálculo de magnitudes, estimativa do parâmetro b e considerações sobre a atividade sísmica de Areado, MG, outubro de 1993, Proc. III Int. Congr. Braz. Geop. Soc., Rio de Janeiro, 1, 694-699.

FERNANDES, C.; BERROCAL, J. & SCHRAMM, D., (2003). Ciclo de atividade sísmica em Areado/MG ocorrido em março de 2003. 8th Int. Congress of The Braz. Geoph. Soc., Rio de Janeiro/RJ.

GUPTA, H. K. (1992). Reservoir Incuced Earthquakes. Developments in Geotechnical Engineering. Amesterdam - London - New York - Tokyo: Elsevier Scientific Publishing Company, 64, p. 243-250.

GUTENBERG B. & RICHTER C.F. (1944). Frequency of Earthquakes in California, Bull. Seism. Soc. Am. 34:185-188.

HASKOV, J. (2001) Earthquake location. Institute of Solid Earth Physics. University of Berger, Norway.

HASKOV, J. & OTTEMÖLLER, L. (Eds), (1999), SEISAN: The Earthquake Analysis Software, V. 7.2: Inst. of Solid Earth Physics, Univ. of Bergen, Norway, 227pp.

KISSLING, E. (1995) Program and VELEST user's guide - Short introduction. Institute of Geophysics, ETH Zuerich and Swiss Seism. Service, ETH-Hoenggerberg. 26pp.

LIENERT, B. R. E. (1995). A computer program for locating earthquakes both locally and globally, Seismological Research Letters, 66, 26-36.

MARZA, V I; CHIMPLICANOND, C. N.; BARROS, L. V.; CAIXETA, D. F. & NAKAYOSHI, T. (2003) - Areado/MG March, 2003 Earthquake Sequence: reservoir Triggered or not? 8th Intern. Congr. Braz. Geop Soc. 14-18 Sep 2003, Rio de Janeiro/RJ 5pp.

MOGI, K. (1962). Study of elastic shocks caused by the fracture of heterogeneous materials and its relation to earthquake phenomena. Bull. Earthq. Res. Inst. Tokyo Univ. Ser. 7 (Geophys) 3, p. 129-195.

MOGI, K. (1967). Earthquake and fractures, Tectonophysics 5, p. 35-55.

SCHOLZ, C. (1968) The frequency-magnitude relation of microfracturing in and its relation to earthquakes, Bull. Seism. Soc. An. 58, p. 399-415.

SNOKE, J. A., MUNSEY, J. W., TEAGUE, A. G., & BOLLINGER, G. A. (1984). A program for focal mechanism determination by combined use of polarity and SV-P amplitude data. Earthq. Notes, 55, 3, p. 15.