Areado, MG, March 2003 earthquake sequence: reservoir triggered or not?

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Abstract

The answer to the paper's enquiring title is affirmative. This positive assertion regarding the nature of the Areado March 2003 sequence is based on the following evidences (actually, prerequisites for triggered/induced earthquakes): (*i*) the mainshock's epicenter and its associated activity (that is, the aftershocks) lays in the proximity of the Furnas hydroelectric reservoir (the mainshock in less than 1 km distance from the lake); (*ii*) the activity is very shallow (less than 3 km depth); (*iii*) the *b*-value of the sequence is higher than the regional *b*-value, that is 1.54 *vs.* 1.06, considering a regional average of whole Pre-Cambrian Southeastern Brazil Seismotectonic Province (or even 0.94 considering the *b*-value for a smaller area of 100 km around the mainshock), a salient feature of reservoir triggered seismicity (*NB*: the difference is statistically significant at the 95% confidence level); (*iv*) the ratio between magnitude of the largest aftershock (M_1) and mainshock's magnitude (M_0), $M_1/M_0 = 0.833$, is matching the typical value for triggered earthquakes; (*v*) last but not least, there is a causal correlation between the timing of the sequence and the water-level fluctuation in the Furnas reservoir. To reach the above-mentioned evidences pointing out the reservoir triggered nature of the Areado 2003 sequence, we computed homogeneously the source parameters of the events and inferred some statistical properties of the sequence. Beside, we surveyed the macroseismic field (the felt area was 1,400 km^2), as well. In a nutshell, we now believe that the Furnas reservoir may be confidently grade as a case of reservoir triggered seismicity.

Introduction

On March 16, 2003, at 21h31m (UTC), or 18h31m (local time), the seismographs of the Seismological Observatory (SIS) of the University of Brasilia (UnB) operating in the N-W outskirts of Brasilia detected a regional seismic event (epicentral distance Δ = 660 km, backazimuth ≈ 160°, preliminary magnitude $m_R = 3.4$; actually in the coda of the main event it was noted another smaller one, an aftershock, rated to have a magnitude $m_R = 2.8$). During the next few hours the SIS received felt reports informing that at least two seismic events were felt in the area of the towns of Areado and Alterosa situated in southern part of the state of Minas Gerais, and in the S-W proximity of the Furnas hydroelectric reservoir. As the area of Areado experienced, previously, a salient seismic sequence during 1991-92 (Blum, 1993), the staff of SIS/UnB decided that it would be an opportunity to undertake a closer study of these recent occurrences. Hence, a team of SIS/UnB traveled to the area to install a temporary seismic network (jointly with a team of IAG/USP leaded by Prof. J. Berrocal) and to carry out a macroseismic survey. The data collected by this temporary field survey, supplemented with data from other seismographic stations operated by SIS in Minas Gerais, particularly for reservoir induced seismicity (RIS) monitoring, and other miscellaneous information are the input data for this study.

Geological, seismotectonical and engineering framework

From geological point of view the study area is situated at the contact between three main tectonic provinces, Tocantins Geological Province, (particularly the southern end of Brasilia Folding Belt), (central part of) Ribeira Folding Belt and (eastern part of) Paraná Basin (Schobbenhauss *et al.*, 1984). More exactly the area lays on the Varginha-Guaxupé complex, composed by gneisses, migmatites, metasedimentary rocks, milonitic rocks and some granitic intrusions (Blum, 1993). Berrocal *et al.* (1996) classified this larger area as the Pre-Cambrian Seismotectonic Province, embedded later in the Southeastern Brazil Seismotectonic Province by Berrocal *et al.,* (2001). From seismicity point of view, in Southeastern Brazil Seismotectonic Province the seismic activity is concentrated mainly in two areas: the offshore continental shelf and the southern part of the state of Minas Gerais, for this area the completeness threshold of the seismic catalogue is roughly 2.8 (m_R) since 1990 (*cf*. Assumpção *et al.* 1997). This seismotectonic province was recently the target of some earthquake hazard studies that assessed probabilities in the range of 10^{-5} to 10^{-3} for peak ground accelerations from 1 ms^{-2} to 1.5 ms^{-2} respectively in some selected site in this seismotectonic province (*viz.* Berrocal *et al.,* 2001). The SIS/UnB earthquake database contains 80-catalogued seismic events (Fig. 1) in a radius of 100 km around the epicenter of the Areado tremor of March 16, 2003. In this local data set (covering the temporal span 1839 to 2002) the largest events were: Jacuí (on 1996/10/18, m_R = 4.0, at a distance of 69 km from reference point), Poços de Caldas (1950/02/27, m_R = 3.9, 82 km) and Passos (1984/04/08, m_R = 3.8, 86 km). The available focal mechanisms studies for the Areado 1991-96 activity (Blum, 1993; Assumpção *et al.*, 1997) indicated a predominantly reverse faulting mechanism with well-constrained nodal planes and almost no inconsistent polarities, determined with local and regional data. The aftershock hypocentral distribution favors the NW dipping plane as the rupture surface

(Blum, 1993) and the SH_{max} strike inferred from focal mechanism compression axis P

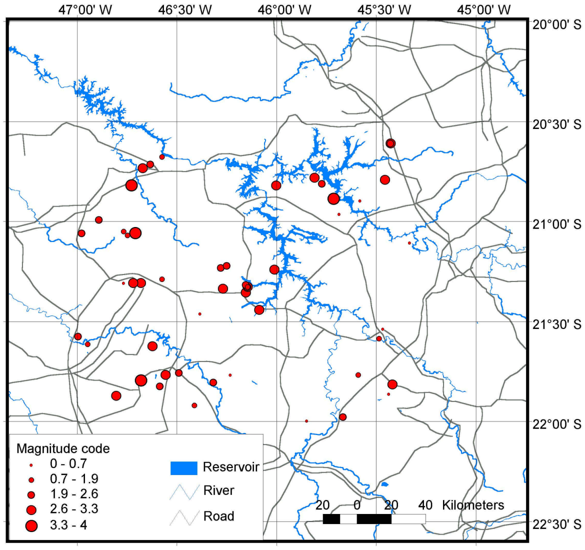

Figure 1. Seismicity in a radius of 100 km of Areado, MG, (80 events in the period from 1839 to 2002, no threshold magnitude used).

(61°, cf. Assumpção *et al.*, 1997) is in rather good agreement with theoretical SH_{max} direction for this region (Lima *et al.*, 1997). Last but not least, it should be noted that Areado active area is close to an important engineering work, the Furnas hydroelectric reservoir having a 23 km^3 water volume behind a 127 m dam height, impounded in 1963 (*viz.* CBGB, 1999). Moreover, the latest review survey (Assumpção *et al.,* 2002) on RIS in Brazil considered, owing to lack of weighty evidences, that this reservoir is (only) a doubtful case of RIS.

Instrumental deployment and data gathering

Although some activity from March 2003 Areado seismic was detected at regional distances, we deployed, in conjunction with IAG/USP some temporary field seismographs. SIS/UnB installed two 3-component seismometers (one broad-band sensor, Guralp CMG-40T, and a short-period Sprengnether S3000EQ) with continuous digital recording (Orion data loggers, sampling rate 100 Hz) supplemented by three seismographs from IAG/USP (one analog and two digital). The locations of these instruments moved during the survey in order to optimize the network layout, and the SIS's instruments recorded the activity during the period from 18 to 22 March, while those of IAG/USP operated during the period from 23 to 27 March. During the fieldwork it was distributed a Macroseismic Questionnaire, as well. The answers to this Questionnaire were used for portraying the macroseismic field of the mainshock.

Data processing, analysis and main results

In processing the seismic data for this work we extensively used the *SEISAN* analysis software package (Havskov & Ottemöller, 1999). First, we determined the main source parameters of the mainshock using all available data. The results are presented in Table 1. For hypocentral parameter computation we have used the

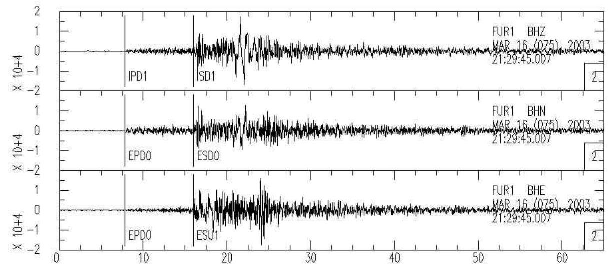

Figure 2. Waveforms of the mainshock recorded by the FUR1 seismographic station (Ä = 71.5 km, backazimuth = 169°). Note the well-developed L_g waves and the fact that, due to geographical position of the station in respect with the epicenter, the N-S component is quasi-coincident with the radial component.

standard regional velocity model, based on Herrin (1968) tables, a ratio v_P/v_S = 1.73, and data from closer stations (less than 200 km) in order to remove the misfit between the real medium and velocity model, which inflates with increasing distance. The hypocenter position is in good agreement with the aftershock grouping and the solution freely converged to a depth of 2.5 km, pointing out a very shallow event, fact that it is supported by the very efficient radiation of short period surface waves (L_g), *viz.* Fig. 2, a feature of very shallow seismic sources. For magnitude estimation we used the results based on the recordings of the reference station BAO (i.e., the CP point of the Brasilia Seismographic Array), we computed 3 kinds of magnitudes, as it follows: m_R = 3.4, m_{bLg} =3.8 and m_D =3.8 (magnitude scales defined by Assumpção, 1983; Nutlli, 1973; and Assumpção *et al.,* 1989, respectively). Eventually we adopted a value m_b = 3.6 (the average of the values of the first two categories of magnitude scales, that are more reliable). For the immediate aftershock (origin time 21h35m07s) following the same procedure, resulted a magnitude m_b = 3.0. The aftershock hypocentral parameters were inferred using a modified version of HYPOCENTER program of the *SEISAN.* This program works with arrival times of P and S phases and with back-azimuth (bearing) obtained from 3-component records. As for the time of getting ready this work we had available data from a few stations, considering the back-azimuth information helped much to constrain the solutions. For aftershock determinations we used data from the 3-component station AREP, SGRA, FVA and/or ARE1 (in variable configurations), and a local velocity model used for hypocentral determination at the Nova Ponte Reservoir, MG (Chimpliganond, 2002) and v_P/v_S = 1.66 (*cf.* Blum, 1993), the 2003 aftershock epicentral map is presented in Fig. 3. For the magnitude quantification of the aftershocks we used the formula devised by Blum (1993), based on signal duration (D, in seconds), specifically for Areado area: $m_D = 1.7\ log_{10}\ D - 1.02$. A list of all events with magnitude ≥ 0.5 is presented in Table 1, actually were determined hypocentral solutions for 85 aftershocks, down to a magnitude –0.5. As the *b*-coefficient of the frequency-magnitude distribution for earthquakes [alternatively known as the Gutenberg-Richter relationship: $log_{10}N = a - bM$, where N is the number of events, M is magnitude, *a* is related to activity rate and *b* is related to the relative number between small and large events; *cf.* Gutenberg & Richter, 1944, (the most commonly found values of *b* are near *b* = 1, but these values can vary as a function of space, time or seismic regime; e.g., Wyss, 1990)] is a very important statistical and physical parameter of the seismicity, we computed this parameter for the Areado 2003 sequence. To estimate *b*-value we used the maximum likelihood method (Aki, 1965), termed m.l.m.:

$$b = \frac{0.4343}{\frac{1}{n}\sum_{i=1}^{n} m_i - m_{min}}$$

were m_{min} is the minimum magnitude recorded completely. [NB: we applied the correction proposed by Utsu (1971) in order to remove the biasing effect of discrete magnitude bins, as well]. Using as a completeness threshold the value m_{min} = 0.5 it resulted that *b* = 1.54 (with σ_b = 0.308). The possible implications of this result will be discussed later. The result of the

Table 1. Some source parameters of available event, for a cutoff magnitude, m_D of 0.5.

#	Date	Origin Time (UTC)	Magnitude (m_D)
1	2003/03/16*)	21:29:41	3.8
2	2003/03/16	21:35:07	3.3
3	2003/03/19	01:08:29	0.8
4	2003/03/19	01:11:24	0.6
5	2003/03/19	03:15:08	0.6
6	2003/03/19	03:28:37	0.5
7	2003/03/19	05:49:00	0.5
8	2003/03/19	05:59:28	0.6
9	2003/03/19	07:16:16	0.5
10	2003/03/19	08:52:22	0.8
11	2003/03/19	16:07:44	1.0
12	2003/03/19	17:04:42	0.9
13	2003/03/20	00:01:13	0.8
14	2003/03/20	00:07:17	0.6
15	2003/03/20	00:32:58	0.5
16	2003/03/20	00:59:09	0.8
17	2003/03/20	01:08:02	0.5
18	2003/03/20	03:01:18	0.5
19	2003/03/20	10:31:04	0.9
20	2003/03/20	10:43:44	1.2
21	2003/03/20	12:12:04	1.2
22	2003/03/21	01:57:14	0.6
23	2003/03/21	03:26:57	0.6
24	2003/03/21	05:09:08	0.7
25	2003/03/21	07:14:42	1.8
26	2003/03/21	15:48:13	1.7
27	2003/03/21	15:50:42	0.8
28	2003/03/21	16:41:00	0.9
29	2003/03/22	02:52:35	0.7
30	2003/03/22	04:00:41	1.1
31	2003/03/22	04:04:03	0.5
32	2003/03/22	07:15:03	0.5
33	2003/03/22	10:11:36	0.8

*)Note: Mainshock: epicenter 21.312°S, 46.145°; depth 2.5 km.

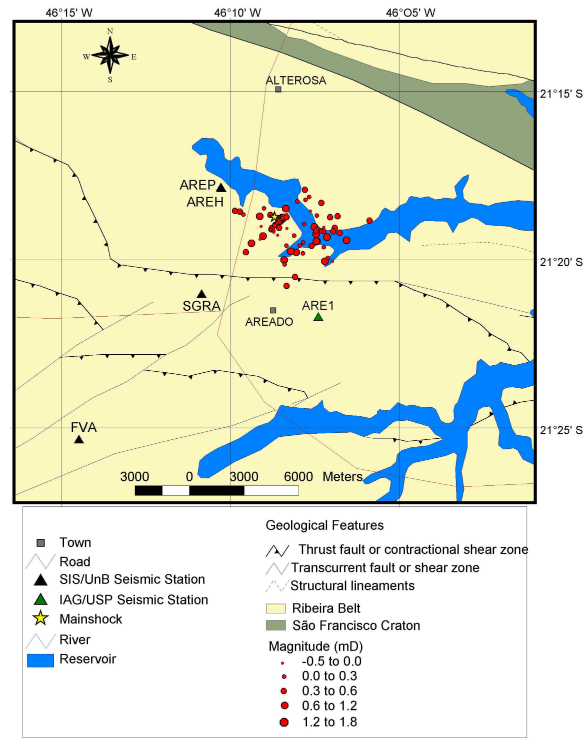

Figure 3. Epicentral distribution of the Areado, March 2003 earthquake sequence. There are shown the seismic station sites and the geology of the area, as well. There are plotted 88 events spanning the magnitude interval -0.5 to 1.8 and the time span March 19 (01h08m) to March 23 (10h11m).

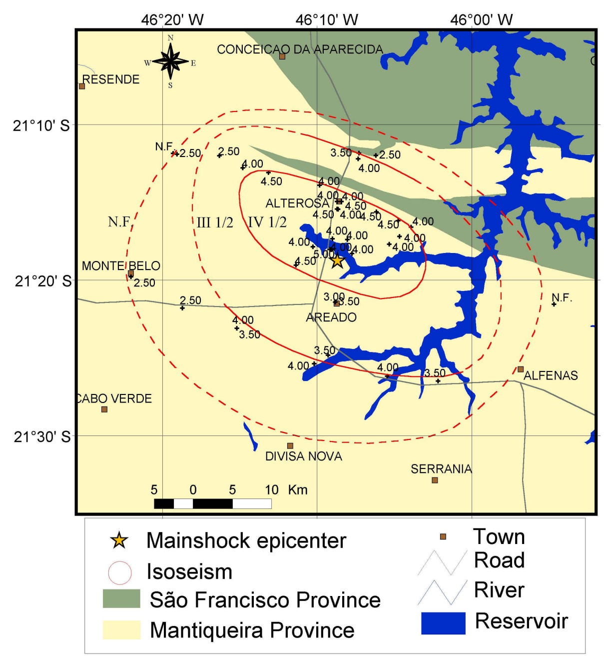

Figure 4. Macroseismic field of the March 16, 2003 Areado, MG, mainshock, m_b = 3.6, I_{max}= V (MM).

macroseismic survey through the evaluation of the answer to the seismic questionnaire is presented inFigure 4, where we may note a good consistency between the instrumental epicenter and peak (**I**$_{max}$ = V MM) macroseismic intensity. The felt area covers a surface of roughly 1,400 km^2, in roughly good agreement with the theoretical modeling of the macroseismic intensity attenuation in Brazil (e.g., Assumpção, 1985). Taking a closer look at Fig. 3, we may note that the aftershocks are distributed in two distinct alignments with NE –SW trend and in prolongation and surprising good agreement with two fault mapped on the same figure. We interpret that main rupture occurred on the northwestward fault and the southeastward one was (re)activated, interestingly that Blum (1993) epicenters appear to lay on this southeastward fault.

Interpretation and discussion

The occurrence of the Areado March 2003 earthquake sequence in the immediate vicinity of a large water reservoir raised again at once the question of its causal relationship with the reservoir. As it was referred to in a previous section, Assumpção et al. (2002) regarded the Furnas reservoir only as an inconclusive case of RIS due to lack of information and the fact that at the time of first activity reported the data were of macroseismic nature (Berrocal *et al.*, 1984). The intensity of the 1996 November 15 event, felt in the area of “Furnas – São Pedro da União - Timboré”, was **I**$_{max}$ = IV-V (MM) (*op. cit.*), and apparently it was accompanied by smaller quakes (*op. cit.*). Using the attenuation relationship of Assumpção (1995), tailored for the average case of an induced event [i.e., $m_R = 0.43\ \boldsymbol{I}_{max} + 1.28$] this intensity would correspond to a magnitude of $m_R = 3.2$. Since this first triggered occurrence at Furnas reservoir, no other events were rated as triggered/induced, although some happened in the area of influence of the reservoir after its impoundment, e.g., Alfenas (1982/09/11, m_R = 3.1; 1990/06/10, m_R = 3.0), Furnas (1982/11/24, m_R = 3.2), Areado (1991/09/17, m_R = 2.9; 1991/09/30, m_R = 3.0; 1991/09/30, m_R = 3.1), Formiga (1993/03/09, m_R = 3.1; 1993/05/12, m_R = 2.9), Guapé (1997/11/17, m_R = 3.7). The point is that the seismicity in the area of Furnas reservoir is in fact an intricate one, very probably a blend of natural and triggered seismicity. Blum (1993), in his study on the Areado October 1991 sequence, was elusive in classifying the nature of the 1991 sequence, although he called upon a great deal of RIS features, however we may argue that Areado 1991 sequence is not correlated with seasonal water lever variation, hence it would be reasonable to categorize Areado 1991 sequence as a doubtful case of RIS or even more likely as a natural one, as it is tacitly implied by the Assumpção *et al.,* (1997) work, fact now supported by the present paper, which shows that Areado October 1991 and March 2003 ruptured different faults (see the comment at the end of previous section). It is notorious that RIS is dissimilar from natural seismicity in respect with its physical process and these differences were inferred from RIS statistical features as opposed to natural ones (*e.g.,* Adams, 1974; Beacher & Keeney, 1982; Simpson, 1986; Gupta, 1992 etc). Next we will appraise how the Areado March 2003 sequence fulfills the prerequisites in order to be validated as a case of reservoir triggered seismicity. From the section dealing with the main results, it is straightforward that the proximity to reservoir criterion (this condition asks for distances less than 20-25 km) and the norm to be a very shallow hypocenter (*i.e.,* usually less than 3 km depth) are obeyed. Other prominent feature of triggered events is that their *b*-values should be higher than regional (natural) *b*-value of the area. Again, $b = 1.54$ ($ó_b = 0.301$) found for the 2003 sequence is higher than regional one (*cf.* Berrocal *et al.* 1996, 2001, $b = 1.06$ ($ó_b = 0.04$). Furthermore we computed (using the m.l.m, with $m_{min} = 2.4$) a *b*-value for the natural seismic background within 100 km of the 2003 mainshock and we got $b = 0.94$ ($ó_b = 0.127$), which once more meets the prerequisite for a higher *b*-value. A *F-statistic* (Fisher-Snedecor) test shows that the difference in *b*-values is significant for a better than 95% confidence level [if we consider the $b_{Are}/b_{Reg} = 1.638$ and $b_{Are}/b_{Bcg} = 1.453$, were b_{Are}, b_{Reg} and b_{Bcg} are the *b*-coefficients for Areado 2003 sequence, for regional (natural) and for background in a 100 km radius, respectively, then the $F_{crit.0.05\%}$ are 1.5910 and 1.4528, respectively, hence smaller than the two ratios of b-values, thus supporting the assertion that the *b*-slope for Areado 2003 is different, at a 95% confidence level, in respect with *b*-slopes for natural earthquakes]. Another trait discriminating natural and triggered sequences is the ratio M_1/M_0 between largest aftershock magnitude (M_1) and the mainshock magnitude (M_0), this ratio should be larger for triggered events comparing with natural ones (*e.g.,* Gupta, 1992). For Areado 2003 case we found $M_1/M_0 = 3.0/3.6 = 0.833$, while for natural sequences this ratio is small when *b*-value is high. Anew this prerequisite is accomplished. A last requirement considered here is the correlation between water-level variation (w.l.v.) and mainshock timing. From Fig. 5, showing the w.l.v. in Furnas reservoir and the earthquake occurrences we may infer that the 2003 sequence came about shortly after a significant long-term gradual decrease a faster rise during the last two seasons. This good correlation, between reservoir level fluctuation and the seismic activity, tells about a potential causal relationship between the water effect (pore pressure diffusion) and earthquake triggering.

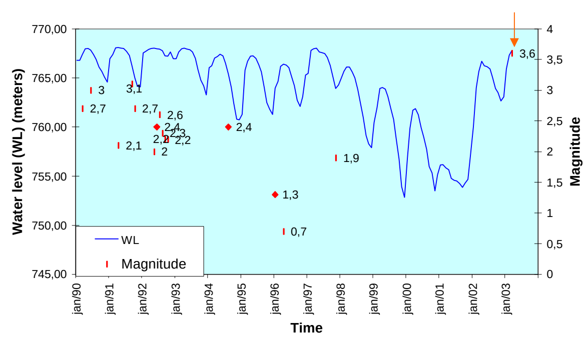

Figure 5. Water level fluctuation in Furnas (MG) reservoir during the period 1999-2003, the vertical arrow marks the time of the Areado March 2003 mainshock.

Conclusions

We find that our work brought up compelling evidences that the March 2003 Areado, MG, earthquake sequence may be confidently regarded as a (reservoir) triggered earthquake sequence, and in turn the Furnas reservoir may be positively deemed as an approved case of triggered/induced seismicity. Next in the logical reasoning line it raises the need to re-analyse the seismicity in the area of influence of Furnas reservoir in order to illuminate seismicity's composite structure, if any.

Acknowledgments

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References

Adams, R.D., 1974, Statistical studies of earthquakes associated with Lake Benmore, New Zealand, *Eng. Geology*, **8**, p.155-169.

Aki, K., 1965, Maximum likelihood estimate of b in the formula log N = a – bM and its confidence limits, *Bull. Earthq. Res. Inst.* **43**, p. 237-239.

Assumpção, M., 1983, A regional magnitude scale for Brazil, *Bull. Seism. Soc. Am.,* **73**, p.237-246.

Assumpção, M., 1985, Attenuação de intensidades macrossísmicos no Brasil e estimative de risco sísmico no sudeste, *Resumo do Trabalhos,* 1^0 Encontro Reg. De Geofísica, SBGf, Div. Reg. Sul, Sessão 4.A, p. 64.

Assumpção, M., Takeya, M., Ferreira, J.M., Costa, J.M. & Sophia, C.M., 1989, Cálculo de magnitudes e relação freqüência-magnitude dos sismos de João Câmara, RN, R*ev. Brás. Geofis.* **7**, p.107-116.

Assumpção, M., Barbosa, J.R., Berrocal, J., Bassini, A.M., Veloso, J.A.V., Marza, V.I., von Huelsen, M.G. & Ribotta, L.C., 1997, Seismicity patterns and focal mechanisms in Southeastern Brazil, *Brazilian J. Geophys.* **15**, 119-132.

Assumpção, M., Marza, V., Barros, L., Chimpliganond, C., Soares J.E., Carvalho J., Caixeta, D., Amorim A. & Cabral E., 2002, Reservoir-induced seismicity in Brazil, *Pure appl. Geophys.,* **159,** p.597-617.

Baecher, G.B. & Keeney, R.L., 1982, Statistical examination of reservoir-induced seismicity, *Bull. Seism. Soc. Am.,* **72**, p.553-569

Berrocal, J., Assumpção, M., Antezana, R., Dias Neto, C.M., Ortega, R., França, H. & Veloso, J.A.V., 1984, *Sismicidade do Brasil,* IAG/USP & CNEN, São Paulo, 320 pp. + 4 mapas.

Berrocal, J., Fernandes C., Bassini, A. & Barbosa J.R., 1996, Earthquake hazard assessment in Southern Brazil, *Geofísica Int.*, **35**, p.257-272.

Berrocal, J., Fernandes C., Diniz de Almeida, A.A. & Roehl, J.L.P., 2001, Avaliação de ameaça sísmica na região SE do Brasil através do método probabilístico, *Proc.* 7th Int. Cong. Brazilian Geophys. Soc., p.1264-1267 (in CD-ROM).

Blum, M. de L.B., 1993, Cálculo de magnitudes, estimativa do parâmetro ***b*** e considerações sobre a atividade sísmica de Areado, MG, outubro de 1991, *Proc.* 3rd Int. Cong. Brazilian Geophys. Soc., 7-11 November 1993, v. **1**, p.694-699.

CBGB, 1999, Registro Nacional de Barragens, Comitê Brasileiro de Grandes Barragens (in CD-ROM).

Chimpliganond, C.N., 2002, Caracterização da sismicidade induzida no Reservatório de Nova Ponte, MG, Brasil, *Dissertação de Mestrado*, Instituto de Geociências, Universidade de Brasília, 132 pp.

Gupta, H.K., 1992, *Reservoir-Induced Earthquakes*, Elsevier, Amsterdam, 364 pp.

Gutenberg, B. & Richter, C.F., 1944, Frequency of earthquakes in California: *Bull. Seism. Soc. Am.,* **34,** p.185-188.

Havskov, J. & Ottemöller, L., (Eds), 1999, *SEISAN: The Earthquake Analysis Software,* Version 7.0: Inst. Of Solid Earth Physics, University of Bergen, Norway, 227 pp.

Herrin, E., 1968, 1968 seismological tables for P phases, *Bull. Seism. Soc. Am.,* **58,** p.1193-1241.

Lima, C., Nascimento, E. & Assumpção, M., 1997, Stress orientations in Brazilian sedimentary basins from breakout analysis – Implications for force models in the South American plate: *Geophys. J. Int.,* **130, p.112-124.**

Nutlli, O.W., Seismic wave attenuation and magnitude relations for eastern North America: *J. Geophys. Res.,* **78**, p. 876-885.

Schobbenhaus, C., Campos, D.A., Derze, G.R., & Asmus, H.E., 1984, *Geológia do Brasil* – Texto explicativo do mapa geológico do Brasil e da área oceânica adjacente incluindo depósitos minerais, escala1:2.500.000: DNPM, Brasília, 501 pp.

Simpson, D.W., 1986, Triggered earthquakes, *Ann. Rev. Earth Planet. Sci.,* **14**, p.21-42.

Utsu, T., 1971, Aftershocks and earthquake statistics. III. *J. Faculty of Sci.,* Hokkaido University, Series VII, *Geophysics* **3**, p.379-441.

Wyss, M., 1990, Changes of mean magnitude of Parkfield seismicity: A part of the precursory process?: *Geophys. Res. Let.,* **17,** p. 2429-2432.