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Reservoir-induced Seismicity in Brazil

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Abstract—A compilation of 16 cases of reservoir-induced seismicity in Brazil is presented with maximum magnitudes ranging from 1.6 M_L to 4.2 m_b. The compilation includes: location of the main epicentral area with respect to the reservoir (inside the lake, at the margin, or outside), predominant geology, and the temporal distribution of the main phase(s) of activity (initial or delayed in relation to impoundment). Data on the regional stress field for some reservoirs is also included. Four recent cases are discussed in more detail: Tucuruí, Nova Ponte, Miranda, and Serra da Mesa. A comparison with all other reservoirs deeper than 30 m and 50 m suggests that the hazard for induced-seismicity varies within Brazil: the NE part of the intracratonic Paraná basin has higher hazard as compared with the southern part of the same basin. No correlation of the induced hazard with variations in natural seismicity can be observed.

Key words: ■

Introduction

In the late 1960s and early 1970s, after the confirmation that impoundment of large reservoirs worldwide could cause moderate-sized earthquakes (magnitudes $6.5 > m_b > 5$) with damaging potential, studies of reservoir-induced seismicity attained great scientific and practical interest. It was soon realized that aseismic areas do not necessarily have lower potential for inducing earthquakes. In Brazil, studies of reservoir-induced seismicity (RIS) started around 1972 when an event of magnitude 3.7 caused intensity VI MM in a small reservoir (only 20 m deep) in the state of Minas Gerais. Gupta (1992) described nine cases of RIS in Brazil, and Gomide (1999) analyzed 15 cases. Here we present an updated summary of 16 cases of RIS in Brazil, with magnitudes reaching 4.2 m_b (Tables 1 and 2), in a contribution to future statistical studies of the correlation with reservoir size, geology, tectonic stress field

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and impoundment history, such as done for example by Baecher and Keeney (1982) and Feng *et al.* (1995).

Besides depth and volume of the reservoir, other factors such as geology and stress regime have been investigated as possible parameters facilitating RIS hazard estimation. Castle *et al.* (1980) had suggested that both normal and strike-slip stresses have higher RIS hazard than compressional regimes. On the other hand, Knuepfer *et al.* (1979) and Baecher and Keeney (1982) proposed that strike-slip stress regime have slightly higher RIS hazard than compressional or tensional stresses. They also showed that regions of sedimentary geology are about twice more prone to RIS than igneous or metamorphic regions. The present updated summary of Brazilian cases may contribute to the future resolution of such discrepancies and improve estimates of RIS hazard levels.

General Features of Reservoir-induced Seismicity

The studies and observations of RIS worldwide in the last three decades have shown that:

(a) Only a small percentage of reservoirs induce seismicity. In a recent worldwide compilation, Gupta (1992) lists 68 accepted cases, including certain cases considered doubtful by other authors (such as Castle *et al.*, 1980). The existence of tens of thousands of reservoirs worldwide, which have caused no observable seismicity, indicate that the probability of a reservoir-inducing seismicity is low, and very special conditions are necessary for the occurrence of RIS. Baecher and Keeney (1982) estimate that reservoirs with height >100 feet have a probability around 10% of causing RIS (using only RIS larger than about 3 m_b) . In Brazil, of 17 reservoirs deeper than 90 m only two caused induced seismicity with m_b 3, which is consistent with Baecher and Keeney's estimate. Under special conditions, however, (very large reservoirs, appropriate stress regime and geological conditions) RIS hazard can exceed 50% (Baecher and Keeney, 1982); i.e., more than half of the reservoirs will have RIS.

(b) It has long been recognized that the effect of the reservoir in the tectonic stress field (i.e., the weight of the water and the pore pressure at depths) is small compared to the stresses released by some of the largest induced earthquakes. This implies that reservoir induced seismicity can only occur if the area is already under near-critical tectonic stresses. In fact some authors prefer the term "triggered" seismicity, instead of "induced", to better convey the fact that high near-critical stresses are usually necessary for the occurrence of the earthquake activity (see Talwani, 2000, for a discussion on this subject).

(c) Low levels of natural seismicity do not necessarily imply less hazard of induced seismicity. The identification of several cases of RIS in aseismic regions (e.g., Simpson, 1976; Castle *et al.*, 1980; Gupta, 1992) shows that little correlation exists between natural seismicity and the likelihood that a reservoir will induce seismicity. More studies of this aspect are necessary because the known number of RIS may be underestimated in seismic regions where identification is more difficult (see for instance the debate related to the Oroville reservoir in California, as reported by GUPTA, 1992). In this paper we briefly show that RIS hazard within Brazil does not seem to correlate with variations of the regional level of intraplate seismicity.

(d) It is generally agreed that the maximum possible induced earthquake cannot exceed the maximum possible natural earthquake in the region (e.g., GUPTA, 1992). This is consistent with all reported empirical evidence to date, and also with the concept that near-critical pre-existing stresses are necessary for the occurrence of RIS. In Brazil the maximum induced magnitude was 4.2 m_b, in the SE seismic province, a region where natural earthquakes up to 5.1 m_b have been observed (BERROCAL *et al.*, 1983, 1984).

The mechanisms by which earthquakes are induced have been extensively studied (e.g., TALWANI and ACREE, 1984/85; SIMPSON *et al.*, 1988; SIMPSON and NARASIMHAN, 1990; TALWANI, 1997). The main aspects involve the perturbation of stresses and pore pressures at depths caused by the weight of the reservoir, and the diffusion of additional weight-induced pore pressures to hypocentral depths from the reservoir at the surface. Both theoretical (e.g., BELL and NUR, 1978; SIMPSON, 1986; ROELOFFS, 1988) and observational studies (e.g., HEALEY *et al.*, 1968; ZOBACK and HICKMAN, 1982) have shown that the controlling factors in these processes are the pre-existing tectonic stresses and pore pressures, the permeability of the rock masses and fracture systems, the strength of fault systems, and the relative orientation between the tectonic stresses and potential fault systems.

Because of the inhomogeneous properties of the rocks beneath a reservoir (such as permeability and fracture systems, as well as the local stress field) the induced seismicity can show complex temporal and spatial patterns in response to the impoundment history. For example, migration of activity from one area of the reservoir to another can be periodically observed, such as in the Açu reservoir, in NE Brazil (FERREIRA *et al.*, 1995).

Proposals to classify the patterns of induced activity into two main components have been presented by SIMPSON *et al.* (1988) and TALWANI (1995, 1997). The two categories of SIMPSON *et al.* (1998) are "*rapid*" (when activity begins immediately following first filling, or major changes in water level, and dies out after a few years) and "*delayed*" (when the predominant seismicity, including the largest event, occurs several years after impoundment, i.e., after a number of annual cycles in the water fluctuation). TALWANI (1995, 1997) defines the two categories as "*initial*" (associated with initial impoundment or large lake level fluctuation; usually seismicity is widespread in the periphery of the lake) and "*protracted*" (after the effect of the initial seismicity has diminished; it persists for many years without significant decrease in frequency and magnitude; epicenters can be beneath the lake or in the surrounding areas). Although some reservoirs show only an initial (or rapid)

Table 1

Reservoir characteristics

#	Dam name (state)	Dam height (m)	Maximum water depth (m)	Reservoir volume (km^3)	Start of impoundment	Predominant geology	Regional stress; SH_{max} direction (reference)
1	Porto Colômbia & Volta Grande (MG/SP)	40 & 45	35 & 37	1.46 & 2.30	1973 April & 1973 September	Basalt	
2	Nova Ponte (MG)	142	132	12.8	1993 October	Basalt/gneiss	Compression; NNE-SSW? (b)
3	Cajuru (MG)	23	20	0.20	1954	Granite-gneiss	Strike-slip; E-W (b, c)
4	Capivara (PR/SP)	60	55	10.5	1976 January	basalt	
5	Tucuruí (PA)	106	90	45.8	1984 September	Metamorphic	
6	Balbina (AM)	42	35	17.5	1987 October	Sediments/ granite-gneiss	Possibly compression; NNW-SSE? (a, f)
7	Miranda (MG)	85	82	1.14	1997 August	Basalt/gneiss	Compression; NNE-SSW? (b)
8	Paraibuna-Paratinga (SP)	98 & 104	90	4.74	1974 & 1976	Granite-gneiss	strike-slip; NE-SW (g)
9	Jaguari (SP)	67	53	1.5	1969 December	Granite-gneiss	
10	Capivari-Cachoeira (PR)	61	58	0.18	1970 July	Gneiss	
11	Açu (RN)	31	31	2.4	1985	Granite-gneiss	Strike-slip; E-W (d, e)
12	Serra da Mesa (GO)	150	146	54.4	1996 October	Granite	Compression; NNW-SSE (a)
13	Marimbondo (MG/SP)	90	86?	6.15	1975	Basalt	
14	Sobradinho (BA)	43?	40	34.1	1977	Granite-gneiss/schist	
15	Emborcação (MG/GO)	158	154	17.5	1981 August	Gneiss	
16	Xingó (SE/AL)	140	110?	3.8	1994 June	Metamorphic	
				Doubtful cases			
17	Peti (MG)	43	42	0.042	1946	Gneiss	
18	Furnas (MG)	127	106	23	1963	Quartzite	Strike-slip; E-W (a)
19	Três Marias (MG)	70	60?	21	1962	Sediment	

References: (a) ASSUMPÇÃO (1992). (b) ASSUMPÇÃO *et al.* (1997). (c) ASSUMPÇÃO (1998b). (d) FERREIRA *et al.* (1995). (e) FERREIRA *et al.* (1998). (f) LIMA *et al.* (1997). (g) MENDIGUREN (1980).

response, many reservoirs exhibit a mixed behavior, with a later phase of activity following the initial response.

Despite the progress attained in explaining the mechanisms of RIS, it is not possible to predict the occurrence of induced seismicity of a future reservoir, because of the practical difficulties in accurately mapping, in a large volume of rock beneath the reservoir, key parameters such as *in situ* stresses, permeability of the rock masses and geometry of fracture systems. From a practical point of view, statistical studies of previous cases (e.g., CASTLE *et al.*, 1980; BAECHER and KEENEY, 1982; FENG *et al.*, 1995) can be useful for hazard evaluation of future reservoirs. In this respect, more complete compilations of past cases of RIS worldwide, including their temporal/spatial behavior, should contribute to better hazard evaluation of future reservoirs.

Reservoirs with Induced Activity in Brazil

Tables 1 and 2 list all cases of Brazilian reservoirs where induced activity has been reported. Besides the 16 confirmed cases, three other reservoirs with doubtful seismicity have been included for the sake of completeness. Table 1 supplies information concerning the reservoir size, main rock type in the reservoir area, and stress regime when available. Table 2 lists the main characteristics of the activity; the quality of the earthquake information varies considerably, depending on the number of seismic stations used in the studies. Locations of the reservoirs are shown in Figure 5, to be discussed later.

The magnitude adopted in this paper is the teleseismic m_b. For events recorded in the range of 200 to 1500 km by Brazilian stations, a regional scale (m_R) is used which is equivalent to the teleseismic m_b ranging form 3.8 to 5.5 (ASSUMPÇÃO, 1983). The regional magnitude m_R reproduces the teleseismic m_b with a standard error of about 0.2 units (ASSUMPÇÃO, 1983, 1998a). In reservoirs where the events are very small, local magnitudes (M_L) or duration magnitudes (m_D) are used and tied to the regional m_R when possible. The uncertainties of the duration magnitudes are about 0.3 units.

The largest induced earthquake in Brazil was m_b 4.2, associated with two close-by reservoirs, Porto Colômbia and Volta Grande, which started filling in April and September 1973, respectively. Small events started to be felt by the local population near Porto Colômbia reservoir in November 1973. The largest event occurred in February 1974 with MM intensities VI–VII, causing damage to some peasant houses. Although no seismic station was installed near the reservoir, macroseismic information from the local population showed that the activity had died out by mid-1974, about one year after impoundment of the second reservoir (KNUEPFER *et al.*, 1979; BERROCAL *et al.*, 1984).

The temporal/spatial behavior of the seismicity in each reservoir is included in Table 2. We use the category "*initial*" for the cases where the main burst of activity followed impoundment in less than a year or so, with the largest event occurring

Table 2

Characteristics of the induced seismicity

#	Dam name (state)	Seismicity type	Largest events					Comments	Refs.
			Date	Magnit. (m_b)	I_o (MM)	ΔT (years)	Location		
1	Porto Colômbia & Volta Grande (MG/SP)	Initial	1974.02.24	4.2	VI–VII	~1	Margin?	Largest induced event in Brazil, no local stations	Be84, Kn79, Gu92
2	Nova Ponte (MG)	Initial,	1995.04.21	3.5	IV–V	1.5	Margin	Local telemetered network	As97, Ma99,
		Delayed	1998.05.22	4.0	VI	4.5	Outside	after new maximum water level	this paper
3	Cajuru (MG)	Delayed	1971.08.08	3.5	V–VI	17	Outside?	Local stations since 1975;	Be84, Vi97,
			1972.01.23	3.7	VI	18	Outside?	correlation with water level	Gu92
			1976.05.23	3.2	–	22	Outside	during 1978–1985	
4	Capivara (PR/SP)	Initial,	1976.01.25	<3	V–VI	0.1	Margin	No local stations during filling;	Mi9l, Gu92
		Delayed	1979.03.27	3.7	V–VI	~3	Margin	stations from 1978–1997;	As95
			1989.01.07	3.7	VI	13	Margin		
5	Tucuruí (PA)	Initial,	1985.11.02	3.2	–	~1	Inside	Local network	Ve92,
			1987.04.01	3.3	–	~2.5	Margin?		this paper
		Delayed	1998.03.02	3.6	IV–V	14	Inside	after large water changes?	
6	Balbina (AM)	Initial	1990.03.25	3.4	–	2.5	Outside	Local network	Ve91
7	Miranda (MG)	Initial	1998.04.07	2.4	felt	0.8	Margin?	Local stations,	this paper
		Delayed	2000.05.06	3.3	V–VI	2.7	Margin	macroseismic	
8	Paraibuna-Paraitinga (SP)	Initial	1977.11.16	3.0	IV	~1	Inside	Local stations since 1977	Ri89
9	Jaguari (SP)	Delayed	1985.12.17	3.0	V–VI	16	Margin	No felt events in the first years	MR95
10	Capivari-Cachoeira (PR)	Initial	1971.05.21	<3	VI	~1	–	macroseismic information	Be84, Gu92
11	Açu (RN)	Delayed	1994.08.26	3.0	IV?	9.5	Inside/ Margin	No felt events in the first years	Fe95
12	Serra da Mesa (GO)	Initial	1999.06.13	2.2	–	~3?	Margin	Local telemetered network	this paper
13	Marimbondo (MG/SP)	Initial	1978.07.25	2.0 M_L	not felt.	~3	Margin	Local station	Gu92
14	Sobradinho (BA)	Initial	1979.07.05	1.9 M_L	not felt.	~2	Inside	Local network	Gu92
15	Emborcação (MG/GO)	Initial	1982.05.20	1.6 M_L	not felt.	~1	Inside	Local network	VA86
16	Xingó (SE/AL)	Initial	1994.07.20	1.7	III–IV	~0.1	Margin	Local network	Be00
					Doubtful cases				
17	Peti (MG)	Initial?	1948.11.10	n.a.	IV	~2	–	Macroseismic information	Ve92b

18	Furnas (MG)	Initial?	1966.11.15	n.a.	IV–V	3.5	–	Macroseismic information	Be84
19	Três Marias (MG)	Delayed?	1969	n.a.	felt	~7	–	Macroseismic information	Ve92b

ΔT = time interval (years) since beginning of impoundment.

References: As95) Assumpção *et al.* (1995). As97) Assumpção *et al.* (1997). Be00) J. Berrocal (pers. comm). Be84) Berrocal *et al.* (1984). Fe95) Ferreira *et al.* (1995). Gu92) Gupta (1992). Kn79) Knuepfer *et al.* (1979). Ma99) Marza *et al.* (1999a,b). Me80) Mendiguren (1980). MR95) Mioto and Ribotta (1995). Mi91) Mioto *et al.* (1991). Ri89) Ribotta (1989). VA86) Veloso and Assumpção (1986). Ve91) Veloso *et al.* (1991). Ve92a) Veloso (1992a). Ve92b) Veloso (1992b). (Vi97) Viotti *et al.* (1997).

within about two years or so. Our "initial" activity includes rapid response due to reservoir loading as well as diffusion to short distances and shallow depths. Most reservoirs seem to manifest only an initial response. Other reservoirs display a later seismicity well after the initial response. Some reservoirs show a pronounced decrease in the initial activity and a strong reactivation delayed by several years (such as Capivara and Tucuruí). In other reservoirs, the later activity seems to spread for decades with very slow decrease rate, sometimes correlating with water level fluctuations, which could be classified perhaps as "protracted" behavior (such as Cajuru, Paraibuna and Açu). However, for the sake of simplicity, we have used the term "*delayed*" for any significant activity (including the largest event, or others of similar magnitude) that occurred several years after impoundment.

In some reservoirs, earthquakes occurring several years after impoundment have been attributed to previous short-term changes in the water level. In Nurek and Aswan, for example, abrupt changes in water level over a few days impacted the rate of seismicity (SIMPSON and NEGMATULLAEV, 1981; SIMPSON *et al.*, 1990). At Koyna reservoir, earthquakes larger than 5 m_b seem to occur whenever the water level exceeds the previous maximum (TALWANI, 2000). In such cases, the inducing mechanism can include some elastic effect from the recent change in water load, typical of "rapid" or "initial" activity. We present below evidence of three cases in Brazil in which a large, delayed earthquake could be associated with recent water level changes. However, because most Brazilian reservoirs have not been thoroughly studied, we will maintain the classification of "delayed" activity even for the cases in which a short-term contribution from the water level change is possible.

In some cases the initial activity is not well known because instrumental monitoring started well after filling of the lake. Several reservoirs have shown both initial and delayed activity, such as Capivara and Tucuruí. It should be borne in mind, also, that activity is still continuing in many reservoirs, consequently this classification may change as the activity evolves. For instance, Miranda reservoir, impounded in 1997, showed a clear initial activity which rapidly decreased in the following years; only one or two seismographic stations were kept in operation to reduce costs. In May 2000 an event with m_R 3.3 occurred, causing MM intensities V–VI, the largest induced earthquake to date.

One of the best examples of delayed seismicity is the Cajuru reservoir. With a dam only 23 m tall, it was impounded in 1954. Small earthquakes started to be felt by the local population in 1970 with the largest event (3.7 m_R) in 1972 generating MM intensities VI. Instrumental monitoring started in 1975 and seismicity was still being recorded 20 years later in 1995 (VIOTTI *et al.*, 1997) with occasional events ranging from 2.5 to 3.0 m_R being felt by the local population (ASSUMPÇÃO *et al.*, 1997). Although no instrumental monitoring had been used in the first decade, no events were felt during this period. Valid evidence of a correlation between water level and the number of events seems to exist for the period 1978–1985 (VIOTTI *et al.*, 1997) which confirms the induced nature of the activity.

Paraibuna/Paraitinga reservoir caused induced seismicity soon after filling in 1976; the largest event, 3.0 m_R, occurred in November 1977 about one year later (MENDIGUREN, 1980; RIBOTTA, 1989). Twenty years later small events are still recorded by the local network and occassionally felt by the local population (L.C. Ribotta, personal communication). Paraibuna/Paraitinga has been classified as having only initial seismicity because the later activity, although being almost in steady-state for many years, did not show events with magnitudes comparable to the initial phase.

Recent Cases of RIS

We now briefly describe the main features of some cases of recent activity in Brazilian reservoirs, not published before.

Tucuruí (# 5 in Tables 1, 2)

Pre-impoundment monitoring for five years with a single station (*TUC1*) detected no local events. Initial seismicity occurred soon after impoundment of the reservoir in 1984 (Fig. 1a). A network of up to four analog stations showed that this initial seismicity was concentrated beneath the reservoir, south of the dam (Fig. 1b); the largest event in this initial period registered magnitude 3.2 m_R. A second burst of seismicity followed the next year with some epicenters west of the dam and magnitudes reaching 3.3 m_R. Hypocentral depths are not reliably determined: the local data give depths in the range of 0 to 6 km with large uncertainties. Despite the large epicentral uncertainties (about $\pm$ 3 to 5 km) a general SW-NE trend can be recognized for this initial activity (Fig. 1b). In the reservoir area, a NS trending belt of metamorphic rocks, including a thrust fault, separates mainly Phanerozoic sedimentary rocks east of the lake (Barreiras sandstones) from Precambrian granitic/gneissic rocks on the west (Fig. 1; ELETRONORTE, 1977). Some NW-SE oriented faults were tentatively recognized on the western part of the lake (ELETRONORTE, 1977). However, as noted by VELOSO (1992a), no major tectonic feature can be correlated with the SW-NE trend of the epicentral distribution.

Seismicity decreased considerably the following years and the network was deactivated because of high operational costs. The largest event as yet occurred in March 1998 reaching a magnitude 3.6 m_b and epicenter near the deepest part of the lake (Fig. 1b). Only one analog local station was operating at the time, nonetheless the event was well recorded by the pIDC (prototype International Data Centre) which recorded an epicenter consistent with the average *S-P* interval of the aftershocks detected by the local station *TUC2* (*S-P* = 2.9 $\pm$ 0.1). This largest event caused MM intensity of about IV–V near the dam, which is not inconsistent with the pIDC epicenter. No reliable information is available on the focal depth of this event.

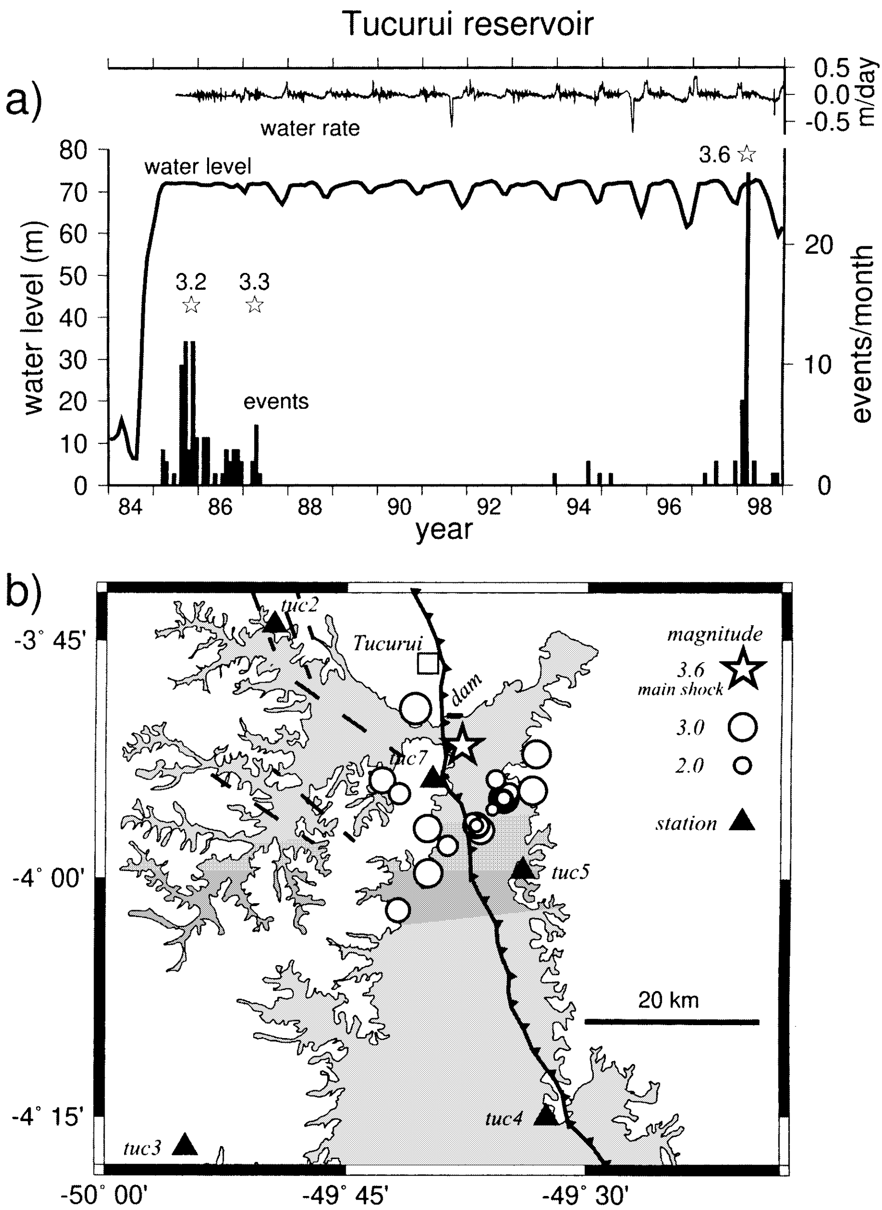

Figure 1

Seismicity in Tucuruí reservoir (#5 in Tables 1 and 2), state of Pará. (a) Temporal evolution: number of monthly events (histogram), monthly averaged water level (thick line), and rate of water level change (top trace); the stars denote the largest magnitudes. (b) Epicentral distribution: triangles denote seismographic stations, circles denote epicenters (errors in the range ± 3 to 5 km) with duration magnitudes above 1.6; the star is the main shock of March 1998 with magnitude 3.6 m_b. N-S oriented dented line is a reverse fault; dashed lines west of the dam are inferred faults of unknown type.

Tucuruí reservoir shows two main cycles of activity: one initial activity following impoundment and another phase in 1997–1998. It is possible that this last phase could have been caused by the large water variations in preceding years: a drop of ~10 m in 1996 and an abrupt increase in early 1997 (Fig. 1a). In mid-1997 the water reached its highest level of 72.5 m. In Tucuruí the water level is measured daily with centimeter accuracy. Figure 1a (top part) shows the rate of water level change in meters/day. No anomalously large short-term variation can be clearly related to the 1998 event. Also, the maximum water level in 1997 (72.5 m) does not seem to be significantly different from previous peaks of 72.4 m reached in 1990, 1992 and 1996. Therefore, because of the weak evidence for a causal relationship between the 1998 event and water level variations in the preceding years, we have preferred to classify the 1998 earthquake as delayed activity (Table 2). Unfortunately, no focal mechanisms are available for the Tucuruí events and hypocenters are not accurate enough to better understand the mechanism of induction.

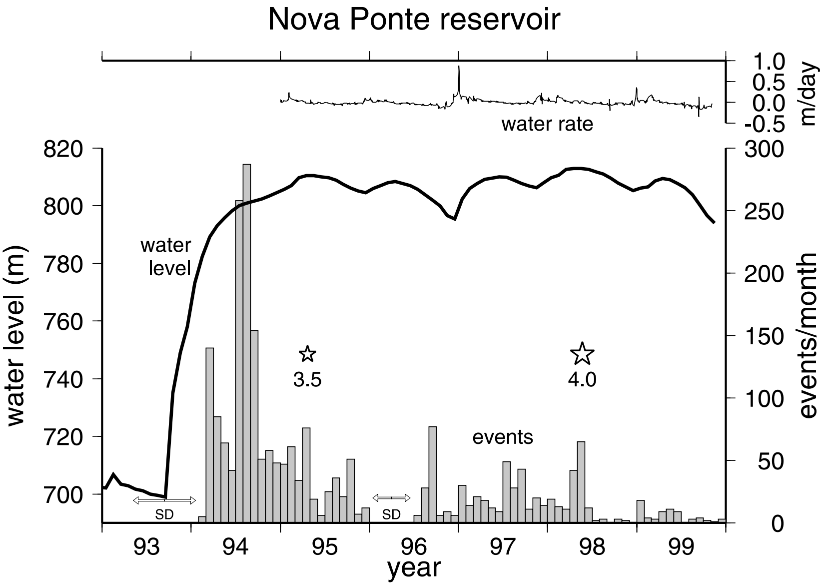

Figure 2

Seismicity in Nova Ponte reservoir (#2 in Tables 1 and 2), state of Minas Gerais. (a) Temporal evolution: number of monthly events (histogram), monthly averaged water level (thick line) referred to mean sea level, and rate of water level change (top trace); the stars denote the two largest events. The number and location of seismographic stations varied during the monitoring and may have affected the detection threshold; SD indicate the two periods without data when the stations were down. (b) Epicentral map for the period 1994 to 1999: circles are small events (magnitudes in the range 0.5 to 3) showing the two main areas of activity: the area in the south showed only initial seismicity which died out more rapidly than the main area near the lake; epicentral errors range from 0.3 to 1.5 km. The stars denote the epicenters of the two main events: the smaller star near the lake is the 3.5 m_b event of 1995, and the larger star further to the south is the 4.0 m_b event of 1998.

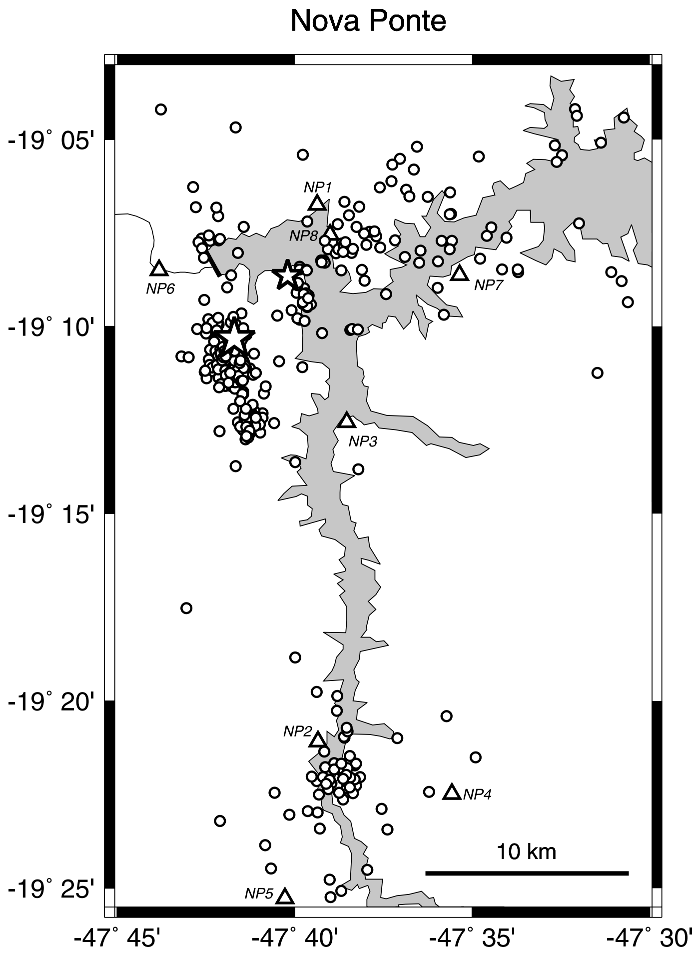

Figure 2b

Nova Ponte (# 2 in Tables 1, 2)

Pre-impoundment monitoring of the Nova Ponte reservoir was carried out with one station (*NP1*) for eight years. Unfortunately, this local station *NP1* experienced operational problems and malfunctioned during impoundment which started in October 1993 (Fig. 2a). Events started to be felt by the the local population in January 1994. Five analog stations were deployed in February/March 1994, revealing seismic activity in two well separated areas: one small area about 25 km south of the dam in a narrow branch of the lake, and another, larger area at the margins of the deepest part of the reservoir (Fig. 2b). A four-station vertical-component telemetered network was installed in 1995 and more stations have since been added to the network. The number and efficiency of the seismic stations have been rather variable, so the number of monthly events shown in Figure 2a may be affected by uneven coverage.

Despite the uneven detectability of the network, a clear initial phase can be seen in Figure 2a with the largest event (3.5 m_R) occurring near the lake when the water level was about to reach its first maximum of 810.6 m, about 1.5 years after the start of impoundment. The initial activity far from the dam decreased rapidly in the first few years and attained a maximum magnitude of only about 2.0 m_D (VELOSO *et al.*, 1994). The activity near the dam has continued with a maximum magnitude of 4.0 m_b (MM intensities up to VI) occurring in May 1998, more than four years after impoundment. Compared with the initial activity, the main event of 1998 occurred further from the lake margin, which is probably due to the delayed response from pore pressure diffusion. GOMIDE (1999) used the increase of the active area near the lake to estimate the seismic hydraulic diffusivity (k_s) at Nova Ponte as 1.5 m^2/s, which is in the mid-point range (0.1 to 10 m^2/s) observed at other reservoirs (TALWANI and ACREE, 1984/85). Also, it is interesting to note that, although no abrupt change in the water level can be observed shortly before the main shock of May 1998 (top trace in Fig. 2a), it occurred three months after the water level had exceeded the previous maximum of 1995, and about 10 days after a new maximum of 813.1 m had been reached.

The 1998 main event in Nova Ponte (the second largest induced earthquake in Brazil; Table 2) seems to have occurred after two days of immediate foreshocks which were preceded by a quiescent period of 12 days, according to MÂRZA *et al.* (1999a).

Composite focal mechanisms have been presented for the Nova Ponte southern cluster (VELOSO *et al.*, 1994) and the northern cluster (ASSUMPÇÃO *et al.*, 1997), indicating predominance of reverse faulting and roughly NE-SW oriented *P* axes. Unfortunately, accuracy of hypocentral depths has been inadequate to define fault planes in the Nova Ponte area.

Miranda (# 11 in Tables 1, 2)

Seismic activity was observed at Miranda immediately following impoundment of the reservoir, started in August 1997, in a clear case of initial response (Fig. 3a). Although no local station had operated near Miranda dam, the network monitoring the Nova Ponte reservoir since 1992, about 30 to 50 km away, had detected no event near Miranda during its pre-impoundment period. One local station was installed during impoundment (*MIR1*) followed by other stations later. The largest event in the initial months sustained a magnitude 2.1 m_D. During 1998 the activity decreased with occasional small reactivations periods; the largest magnitude during the initial phase was 2.4 m_D. In 1999 and early 2000 the activity decreased considerably, and most stations were deactivated to reduce costs.

On May 06, 2000 a delayed large event occurred with magnitude 3.3 m_R and MM intensities V–VI. Unfortunately, the only two local stations were down and the records from the nearest stations (Nova Ponte reservoir, ~50 km away) do not allow an accurate epicentral determination for this main shock. In Figure 3b we show the macroseismic epicenter defined by a country house damaged with several wall cracks. Four portable local stations were deployed a few days after the event, but no aftershocks were detected, indicating that the Miranda main shock of 2000 occurred as an isolated single event. Figure 3a shows that the earthquake occurred during a *decrease* of the water level.

Epicentral accuracy is highly variable due to changing station configuration and equipment problems. In Figure 3b we show only the best epicenters, determined by at least three stations with both P and S arrivals read by cross-correlation of the waveforms. Although the absolute epicentral errors can reach up to 1 km, the *relative* location errors are very small, usually less than 0.1 or 0.2 km. This allowed the identification of at least three clusters of epicenters aligned in the SW-NE direction. The cluster nearest the dam aligns rather well with a SW-NE branch of the lake which probably defines a geological fault. Although no geological faults have been mapped yet in the Miranda area, a more regional mapping reflects a predominance of SW-NE oriented faults about 30 km NW of the dam (CEMIG, 1995).

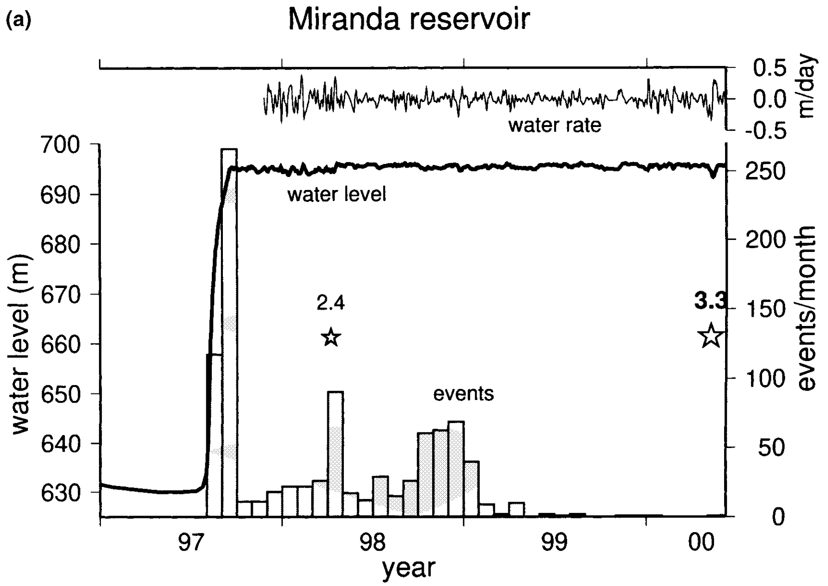

Figure 3
Seismicity in Miranda reservoir (#7 in Tables 1 and 2), state of Minas Gerais. (a) Temporal evolution: number of monthly events (histogram), daily water level (thick line), and rate of water level change (top trace); stars denote the largest event of the initial phase and the delayed, main event of May 2000 with magnitude 3.3 m_b. (b) Geology and epicenters: circles are well determined epicenters with three or more stations (relative locations accurate to within ± 0.2 km); note the three SW-NE oriented clusters; magnitudes in the range 1.0 to 2.4 m_D; the smaller star shows the largest event of April 1998 (2.4 m_D) in the initial phase; the larger star shows the macroseismic epicenter of the delayed, magnitude 3.3 m_R event of May 2000.

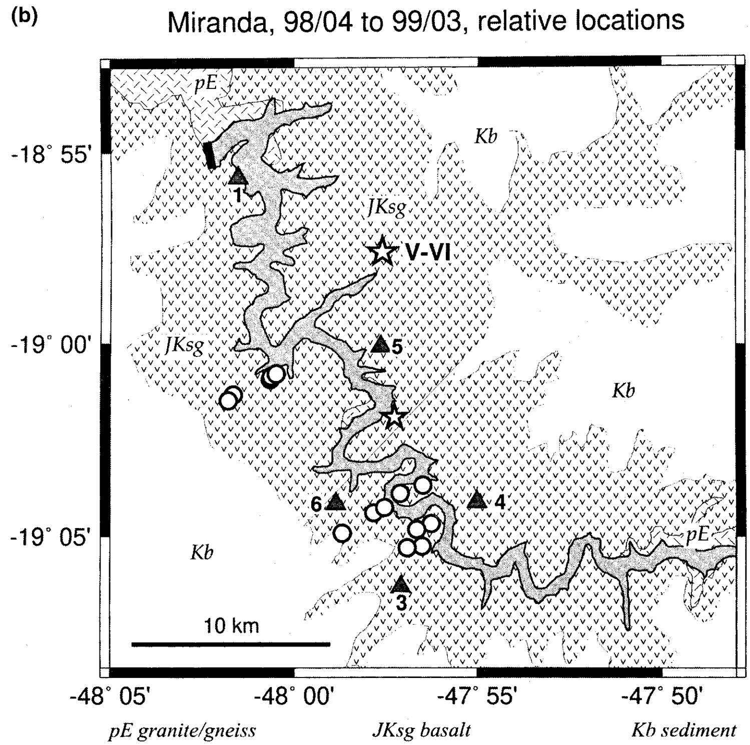

Figure 3b

The geology beneath the Miranda reservoir is characterized by Mesozoic flood basalts (Serra Geral Formation), no more than a few hundred meters thick, overlying Proterozoic gneisses. The seismic activity has occurred far from the deepest part of the reservoir, mainly on its margins, probably in SW-NE oriented fractures reactivated by the lake impoundment. The epicenters are all in basalt areas; the focal depths are usually around 1 km, however the accuracy is imprecise to define whether the activity is occurring in the basalt layers or in the basement. It is possible that fractures in the basalt provide conduits for pore pressure to diffuse to deeper levels, as suggested for Bhatsa, Koyna and Warna reservoirs in the Deccan traps of India (GUPTA, 1992; TALWANI, 2000; P. Talwani, personal communication).

Preliminary focal mechanisms indicate predominance of reverse faulting with nodal planes consistent with the SW-NE epicentral alignment. The focal mechanisms in the nearby Nova Ponte reservoir, together with preliminary mechanisms in Miranda, are consistent with regional compressional stresses roughly oriented NNE-SSW. In a compressional environment, the initial seismicity occurring immediately upon lake impoundment (Fig. 3a), with epicenters in the margins of the lake, suggests an inducing mechanism of elastic response to the water load for the initial phase, also called "rapid" response. The delayed activity, especially the main shock of May 2000, is probably due to the long-term effect of pore-pressure diffusion coupled, perhaps, with additional short-term elastic effects from a rapid decrease in the water level. Further studies, especially focal mechanism determinations, are necessary to better understand the occurrence of the main event of May 2000.

Serra da Mesa (# 12 in Tables 1, 2)

Filling of the reservoir started in October 1996. About one year later small local events (maximum magnitude 2.2 m_b) started to be recorded by the local four-station vertical-component telemetered network (Fig. 4). The activity is very sparse although the epicenters seem to occur preferentially in the margins of the lake.

The local events were too small to allow determination of focal mechanisms. However local stress measurements by hydraulic fracturing near the Serra da Mesa dam (CAPRONI and ARMELIN, 1990; ASSUMPÇÃO, 1992) indicate NW-SE oriented compressional stresses which would be consistent with the epicenters being preferentially at the margins of the lake (e.g., BELL and NUR, 1978).

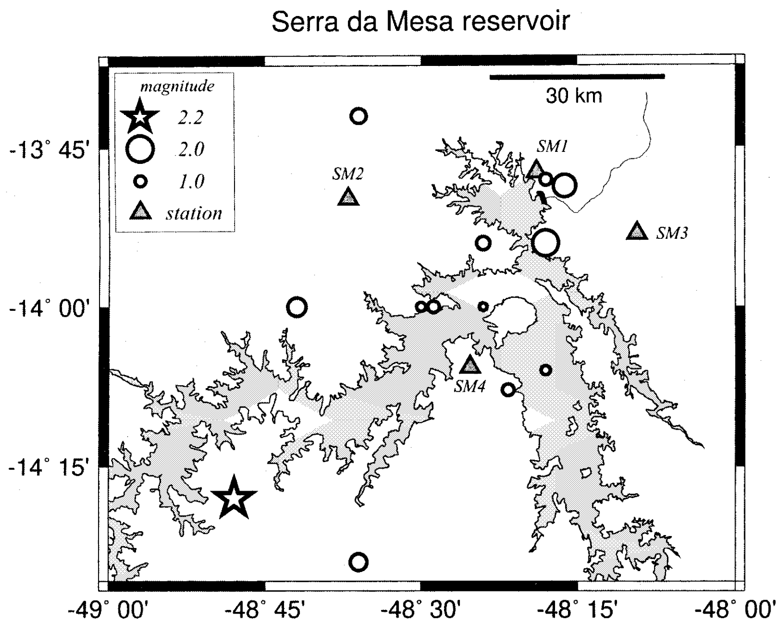

Figure 4
Seismicity in Serra da Mesa reservoir (#12 in Tables 1 and 2), state of Goiás. Epicentral errors are about ± 10 km. The star is the largest event with 2.2 m_R. Triangles are seismographic stations.

Discussion and Conclusions

Figure 5 shows the locations of all 16 confirmed cases of RIS in Brazil (Tables 1 and 2) compared with the background level of natural seismicity and the location of all other reservoirs deeper than 30 m (taken from CBGB, 1999). In Figure 5a, the size of the closed circle denotes the magnitude of the largest reservoir-induced event (note the different scale for magnitudes of the natural events). The background seismicity is not the complete catalog, but has been filtered, according the following time-varying completeness thresholds: $m_b > 6.0$ after 1940, $m_b > 5.0$ after 1961, $m_b > 4.1$ after 1967, and $m_b > 3.2$ after 1980 (similar to the values used by ASSUMPÇÃO *et al.*, 1997). This filtered catalog better represents the spatial variations in natural seismicity levels in the continental area of Brazil.

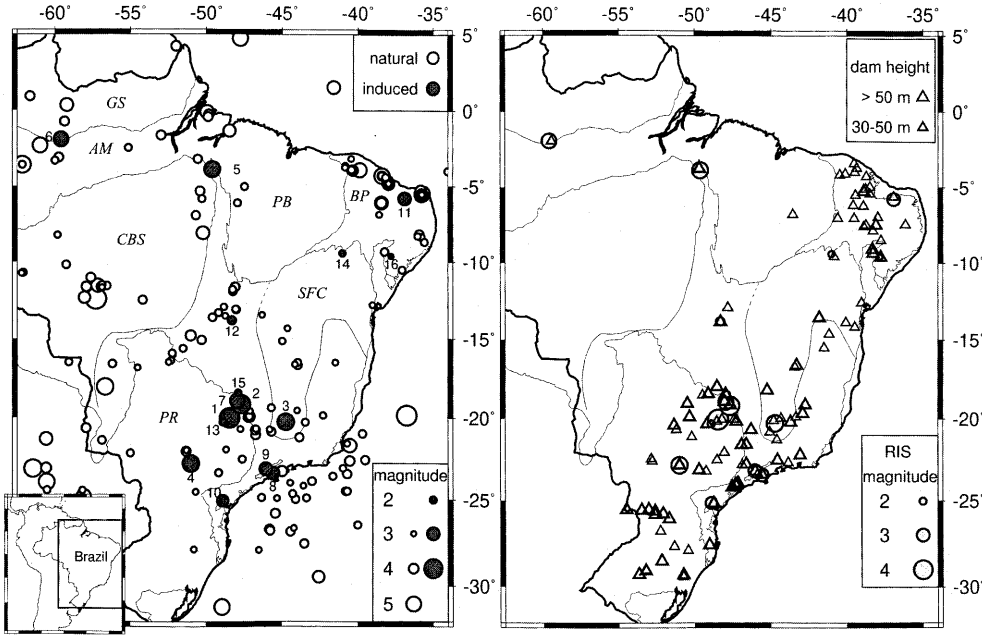

Figure 5

Location of the reservoirs with induced seismicity. Thin lines refer to the main geological provinces in Brazil. (a) Comparison with natural seismicity: note the different scales for the maximum induced event (closed circles) and for the natural seismicity (smaller open circles); numbers refer to Tables 1 and 2. AM = Amazon basin, BP = Borborema Province; CBS = Central Brazil shield, GS = Guyana shield, PB = Parnaíba basin, PR = Paraná basin, SFC = São Francisco craton, other unnamed areas are Upper Proterozoic fold belts and coastal marginal basin. (b) Comparison with other reservoirs where RIS has not been reported (triangles); smaller and larger triangles refer to reservoirs with depths ranging from 30 to 50 m, and larger than 50 m, respectively.

The distribution of dams in Figure 5b may give a rough idea of the RIS hazard in Brazil. In the central and northern parts of Brazil, very few reservoirs have been built and thus no conclusions can be drawn yet. We will then only discuss the data for the eastern part of the country. Although more detailed analyses are still necessary, some interesting observations can be made.

In the Borborema province (NE corner of Brazil, north of 8°S, and east of the Parnaíba basin) where natural seismicity is relatively high (Fig. 5a) only one reservoir has caused induced seismicity (Açu, # 11, 31 m deep) among approximately 20 others of similar height. Although only Açu was instrumentally monitored, many events were felt by the local population near its margins. No other reservoir in the Borborema province has had any confirmed reports of macroseismic effects. Although the majority of dams in that region are lower than 50 m, there is no indication that the higher natural seismicity makes NE Brazil more hazardous to RIS, compared with other regions of the country.

In the southern part of the Paraná basin (south of 25°S) no activity has been reported in 13 reservoirs, most of them deeper than 50 m (Fig. 5b). In this part of the country, only about five dams have been instrumentally monitored (only those finished after 1980), none of which showed any seismicity (i.e., either no events or magnitudes less than about 1). This area also has extremely low natural intraplate seismicity (Fig. 5a).

A concentration of six RIS cases, three of them with magnitudes around 4 m_b, can be observed in the northeastern part of the Paraná basin; an area with about 24 reservoirs, half of them deeper than 50 m (Fig. 5b). The natural seismicity of the NE part of the Paraná basin seems to be lower than other seismic areas in Brazil (Fig. 5a). The natural seismicity seems to occur near the NE margin of the Paraná basin, somewhat offset from the induced seismicity. In the NE part of the Paraná basin, besides the concentration of RIS cases, three cases of seismicity induced by artesian wells have been observed (BERROCAL *et al.*, 1984; YAMABE and HAMZA, 1996). No explanation for this apparently higher induced hazard has been found yet.

Despite the small number of cases, it seems that RIS hazard in Brazil is not uniform: some areas seem to be more prone to induced seismicity (such as the NE part of the Paraná basin) while the RIS hazard in other areas are much lower (such as the southern part of the Paraná basin). No correlation between RIS hazard and the level of natural seismicity can be observed with the present data.

Considerable emphasis has been given in recent decades to RIS in deep (more than ~100 m) reservoirs. Although deep reservoirs clearly have a decidedly higher potential for causing induced seismicity. Tables 1 and 2 show that shallower reservoirs can also cause seismicity with significant engineering and social concern (MM intensities up to VI) and that the 100 m figure should not be used to reduce studies of RIS in smaller reservoirs.

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