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Seismic activity triggered by water wells in the Paraná Basin, Brazil

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[1] Triggered seismicity is commonly associated with deep water reservoirs or injection wells where water is injected at high pressure into the reservoir rock. However, earth tremors related solely to the opening of groundwater wells are extremely rare. Here we present a clear case of seismicity induced by pore-pressure changes following the drilling of water wells that exploit a confined aquifer in the intracratonic Paraná Basin of southeastern Brazil. Since 2004, shallow seismic activity, with magnitudes up to 2.9 and intensities V MM, has been observed near deep wells (120–200 m) that were drilled in early 2003 near the town of Bebedouro. The wells were drilled for irrigation purposes, cross a sandstone layer about 60–80 m thick and extract water from a confined aquifer in fractured zones between basalt flow layers. Seismic activity, mainly event swarms, has occurred yearly since 2004, mostly during the rainy season when the wells are not pumped. During the dry season when the wells are pumped almost continuously, the activity is very low. A seismographic network, installed in March 2005, has located more than 2000 microearthquakes. The events are less than 1 km deep (mostly within the 0.5 km thick basalt layer) and cover an area roughly 1.5 km × 5 km across. The seismicity generally starts in a small area and expands to larger distances with an equivalent hydraulic diffusivity ranging from 0.06 to 0.6 m^2/s. Geophysical and geothermal logging of several wells in the area showed that water from the shallow sandstone aquifer enters the well at the top and usually forms waterfalls. The waterfalls flow down the sides of the wells and feed the confined, fractured aquifer in the basalt layer at the bottom. Two seismic areas are observed: the main area surrounds several wells that are pumped continuously during the dry season, and a second area near another well (about 10 km from the first area) that is not used for irrigation and not pumped regularly. The main area displays cyclic annual activity, but the second area does not. We explain the earthquake swarms as being triggered by pore pressure diffusion in the fractured basalt layer due to additional pressure from the newly connected surface aquifer. This reaches critically prestressed areas up to a few kilometers away from the wells. During periods of continuous pumping, the reduction of pore pressure in the confined aquifer stops the seismic activity. Our study suggests that this kind of activity may be more common than previously thought and implies that many other cases of small tremors associated with the drilling of water wells may have gone unnoticed.

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1. Introduction

[2] Seismicity triggered by the impoundment of large hydroelectric reservoirs and the high-pressure injection of fluids into deep wells is a common phenomenon that has been extensively studied [e.g., *Talwani and Acree*, 1984; *Simpson et al.*, 1988; *Gupta*, 1992; *Talwani et al.*, 2007]. Pre-existing near-critical stresses and diffusion of pore pressure in the porous or fractured rock mass play important roles in triggering the seismicity by reducing the effective stresses on seismogenic faults. Both observational and theoretical studies [e.g., *Roeloffs*, 1988] show that induced seismicity occurs by pore-pressure diffusion that is predominantly confined to a few critically stressed, permeable, saturated fractures or fault zones.

[3] Only a small percentage of reservoirs trigger seismicity. In the global compilations of *Gupta* [1992; 2002], a total of 95 cases of reservoir-triggered seismicity (RTS) were listed. The existence of tens of thousands of reservoirs worldwide, which have not caused any observable seis-

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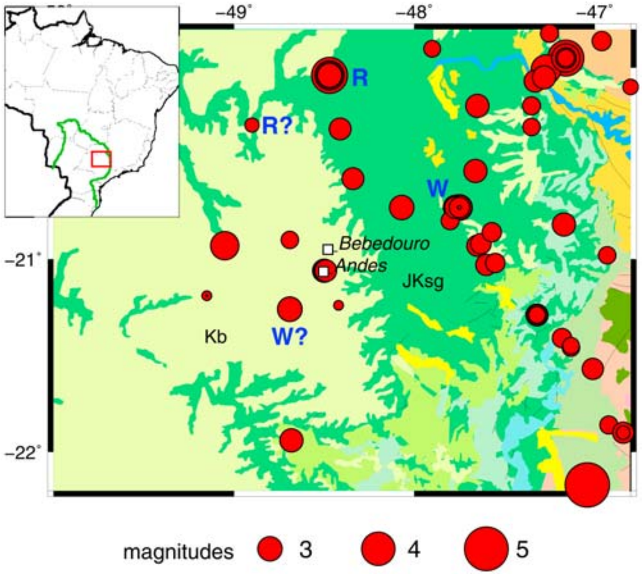

Figure 1. Regional geology and seismicity in the northeastern Paraná Basin. Light yellow (Kb) denotes Upper Cretaceous sandstones, and green (JKsg) denotes underlying Lower Cretaceous basalts. Red circles show the epicenters from the Brazilian catalog. R, reservoir triggered event; W, event triggered by water wells. The inset map of Brazil shows the border of the Paraná basin (green line) and the limit of Figure 1 (red rectangle).

micity, indicates that the probability of a reservoir causing seismicity is low. *Baecher and Keeney* [1982] estimated that reservoirs with a height >100 m have an approximately 10% probability of causing earthquakes, so special conditions, such as high pre-existing stresses, are necessary for the occurrence of RTS. Under special conditions (i.e., very large reservoirs, appropriate stress regimes and geological conditions), however, RTS hazard can exceed 50% [*Baecher and Keeney*, 1982].

[4] *Talwani et al.* [2007] showed that the characteristic hydraulic diffusivities associated with all cases of fluid-related seismicity (especially reservoir and injection-well-induced seismicity) are confined within a relatively small range between 0.1 and 10 m^2/s. In fault zones with near-critical stress conditions and the right permeability characteristics, very small pore-pressure changes can trigger seismicity. This occurred in the Açu reservoir [*Ferreira et al.*, 1995], where an annual water level variation of only about 3–5 m was enough to cause earthquakes with a delay of about 2 months. In Brazil, a total of 20 cases of RTS have been reported [*Assumpção et al.*, 2002; *Chimpliganond et al.*, 2007; *Ferreira et al.*, 2008], many of them near the northeastern border of the intracratonic Paraná Basin (Figure 1).

[5] Although seismicity related to water reservoirs and injection wells is relatively common, earthquakes triggered by the opening of water wells are extremely rare. Here we report a clear case of seismic activity that is related to changing patterns of groundwater flow in an area of the Paraná Basin where several deep wells were drilled to exploit a confined fractured aquifer. The northeastern part of the intracratonic Paraná Basin (Figure 1) in southeastern Brazil is characterized by a mid- to Upper Cretaceous sandstone layer overlying flood-basalt layers of the Lower Cretaceous Serra Geral formation, which is one of the world's largest igneous provinces. Intense groundwater exploitation occurs in this region, both in the unconfined shallow sandstone layer and in confined fractured aquifers between basalt flows. Our study area is in the São Paulo state, near the Andes Village in the municipality of Bebedouro

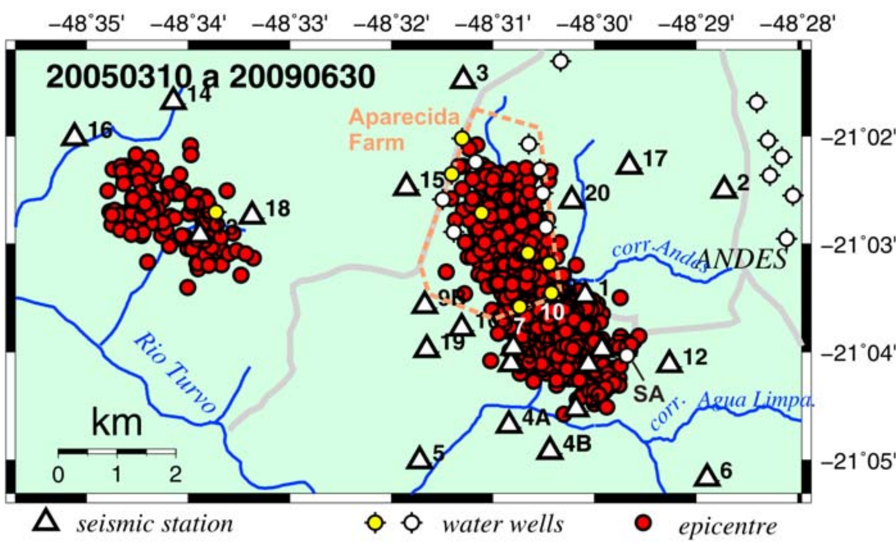

Figure 2. Epicenters (red circles) recorded by the seismic network in the Andes district from March 2005 to June 2009. Triangles represent seismic stations, and white and yellow circles are deep-water wells with outflow capacity less or larger than 60 m^3/h, respectively. Wells 7 and 10 have the largest outflow (190 and 158 m^3/h). The main activity in the right-hand side of the figure is in the Aparecida Farm, which started in 2004; the secondary activity on the left started in 2006 and is in the Pimentel Farm. The activity started about half a year after the drilling of one deep well. Shaded lines denote access roads. SA (near station 12) is the SantAna well shown in Figure 4b.

(Figures 1 and 2). No significant major seismic activity has been reported in the Andes district.

2. Seismicity Evolution and the Annual Cycle

[6] The surface sandstone layer in the Andes district is about 50 to 120 m thick. Shallow wells exploiting the sandstone aquifer are common, but they do not usually produce more than about 10 m^3/h of water. When larger water outflows are necessary, especially for farm irrigation purposes, deeper wells are drilled to reach confined fractured aquifers in the top 50 to 100 m of the basalt layer. These can produce up to 100 m^3/h (or even more in exceptional cases). Around March 2003, ten "deep" wells (i.e., drilled a few tens of meters into basaltic rocks below the sandstone layer) were drilled in the Aparecida Farm, mainly in its eastern and southern border. Four additional wells were drilled in February/March 2006 (Figure 2). The two wells furthest to the south (P7 and P10), which were drilled in 2003, have an extremely large outflow capacity of 190 m^3/h, and 158 m^3/h, respectively. In January 2004, about nine months after the first 10 wells were drilled, earth tremors were felt in the neighboring farm near station 1 (Figure 2). These tremors lasted until July 2004. From mid-August to mid-December 2004, the ten wells were almost continuously pumped (21 h/day) for irrigation during the dry season. No tremors were felt during this period. At the end of 2004, the seismic activity resumed. In February 2005, the number and intensity of the earthquakes increased, which prompted the local population to call for assistance. A local seismic network was installed in March 2005.

[7] Figure 2 shows the distribution of the seismic stations (a maximum of six to eight simultaneous stations were operated), the best-located epicenters from 2005 to 2008 and the deep-water wells in the area. A simple two-layer model (sandstone as the first layer and a basalt half-space) was used for the hypocentral determinations, using the standard HYPO71 code with a constant *P*- to *S*-velocity ratio of 1.80 that was obtained by analysis of the whole set of *P*- and *S*-wave arrival times. The best estimates for hypocentral depths range from 400 to 800 m, with uncertainties of about 100 m. We believe that the earthquakes occur in the competent and fractured basalt layer, between 100 and 600 m depth.

[8] Figure 3 summarizes the temporal evolution of the earthquakes the monthly rainfall, and the pumping periods of the deep wells in the Aparecida Farm. The temporal evolution was determined using macroseismic information in 2004 and early 2005, and data from the local seismic

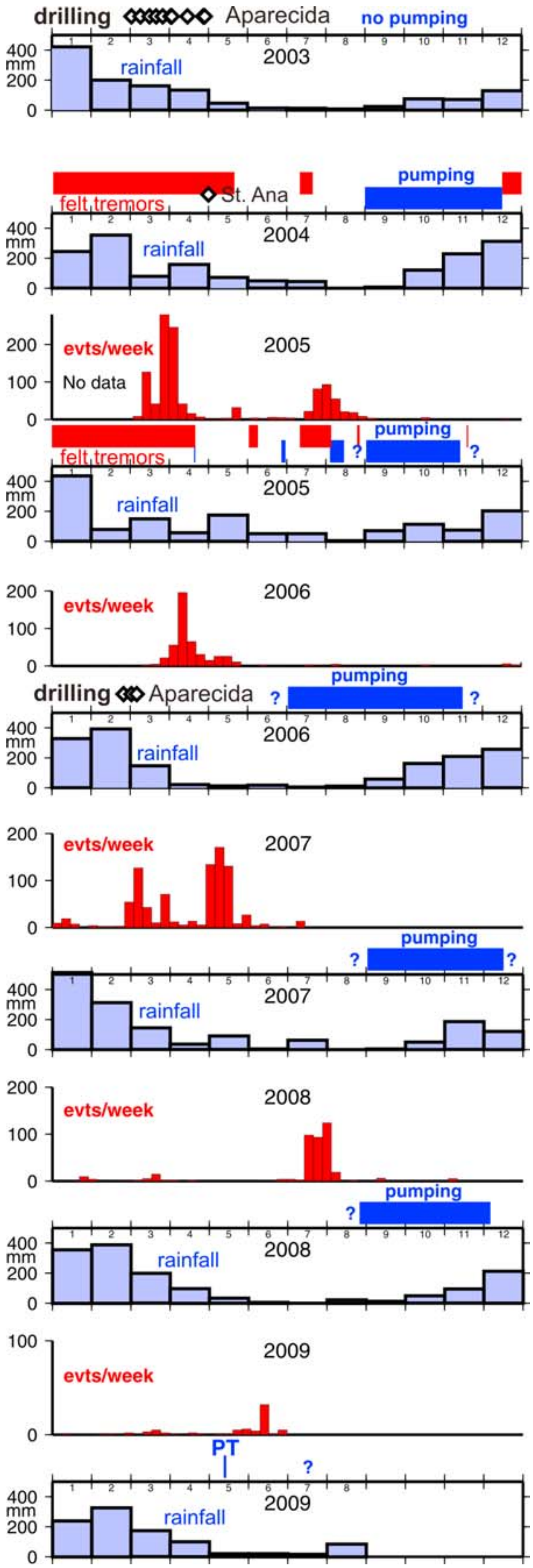

Figure 3. Annual evolution of the seismic activity (red), monthly rainfall (light blue histogram), drilling (open diamonds),and continuous pumping (dark blue bars) during the dry season. Red horizontal bars denote periods when earthquakes were felt before the deployment of the seismic network; red histograms show the number of earthquakes detected by the seismic network each week, with magnitudes ranging from ~0 to 2.9. Note the striking correlation of seismic activity with periods of no pumping. The drilling of the SantAna well in 2004 (near station 12, Figure 2) is also indicated, though this well is not continuously pumped for irrigation purposes. PT in 2009 denotes a pumping test in well P7.

network from March 2005. Seismic activity occurred in the first semester of every year since 2004. No significant activity has been detected during the dry season when all wells are pumped nearly continuously (i.e., 21 h/day). The largest events occurred in March and April 2005, reaching magnitudes 2.9 as well as intensities of V to VI MM and causing considerable panic in the local population.

3. The Effect of Drilling in Underground Aquifers

[9] The evidence points to close spatial and temporal associations between the drilling of water wells and the initiation of seismic activity. The most likely mechanism causing seismic activity is changes in subsurface fluid pressures. To obtain complementary information on differences in subsurface fluid flows, temperature logs were recorded in several wells of the Andes district around the Aparecida Farm. Geothermal methods can provide quantitative determination of subsurface fluid flows [e.g., *Ramey*, 1962; *Bredehoeft and Papadopulos*, 1965]. More recently, *Yamabe and Hamza* [1996] presented results of geothermal methods for identifying subsurface fluid flows associated with seismic activity in Nuporanga (Brazil), about 80 km from the present study area.

[10] The results shown in Figure 4a reveal the presence of near constant temperature zones in the depth interval of 40–125 m for all of the wells logged. In this interval, the temperature gradients are less than 1°C/km, which is much lower than the expected geothermal gradient of ~20–30°C/km [e.g., *Hamza et al.*, 1978; *Hurter and Pollack*, 1996; *Gomes and Hamza*, 2004]. The presence of such constant temperature zone indicates significant down flow of water through the interior parts of the wells. The alternative possibility of up flow is incompatible with the temperature distributions at deeper levels. At depths greater than 125 m, temperatures increase rapidly with depth with a rate much higher than normal geothermal gradients of 20–30°C/km. The presence of zones with such large temperature gradients indicates local cooling induced by down flow of water in the overlying zone. The combined existence of very low and very high gradient zones indicates that a permeable, unsaturated zone exists where the down flowing water leaves the well at a depth of

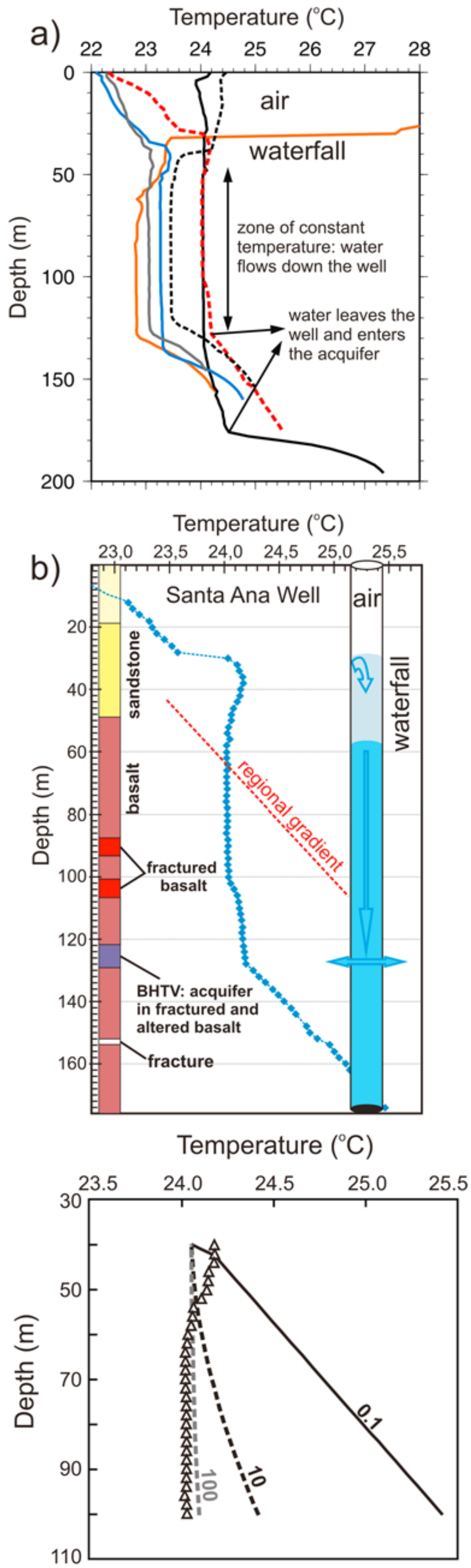

Figure 4. (a) Temperature logs from six deep wells, five in the Andes district (Figure 2, around the Aparecida Farm), and one in the neighboring municipality of Monte Azul Paulista. Waterfalls draining the surface aquifer and feeding the deeper fractured aquifer in the basalt layer are common to all the wells. The constant temperature depth interval denotes the descent of water from the original water level down to the aquifer level. (b) Temperature profile for SantAna well (well closest to station 12 in Figure 2) together with information from a borehole televiewer showing fractured and altered basalt at 120 m depth, which corresponds to the confined aquifer. The dashed line is the expected geothermal gradient if there were no water movement inside the well. (c) Results of temperature logs (triangles) in the upper part of the SantAna well and model curves for temperature distributions in the presence of in-hole fluid flow (continuous curves). The numbers on these curves are flow velocities in meters per hour. For details, see text.

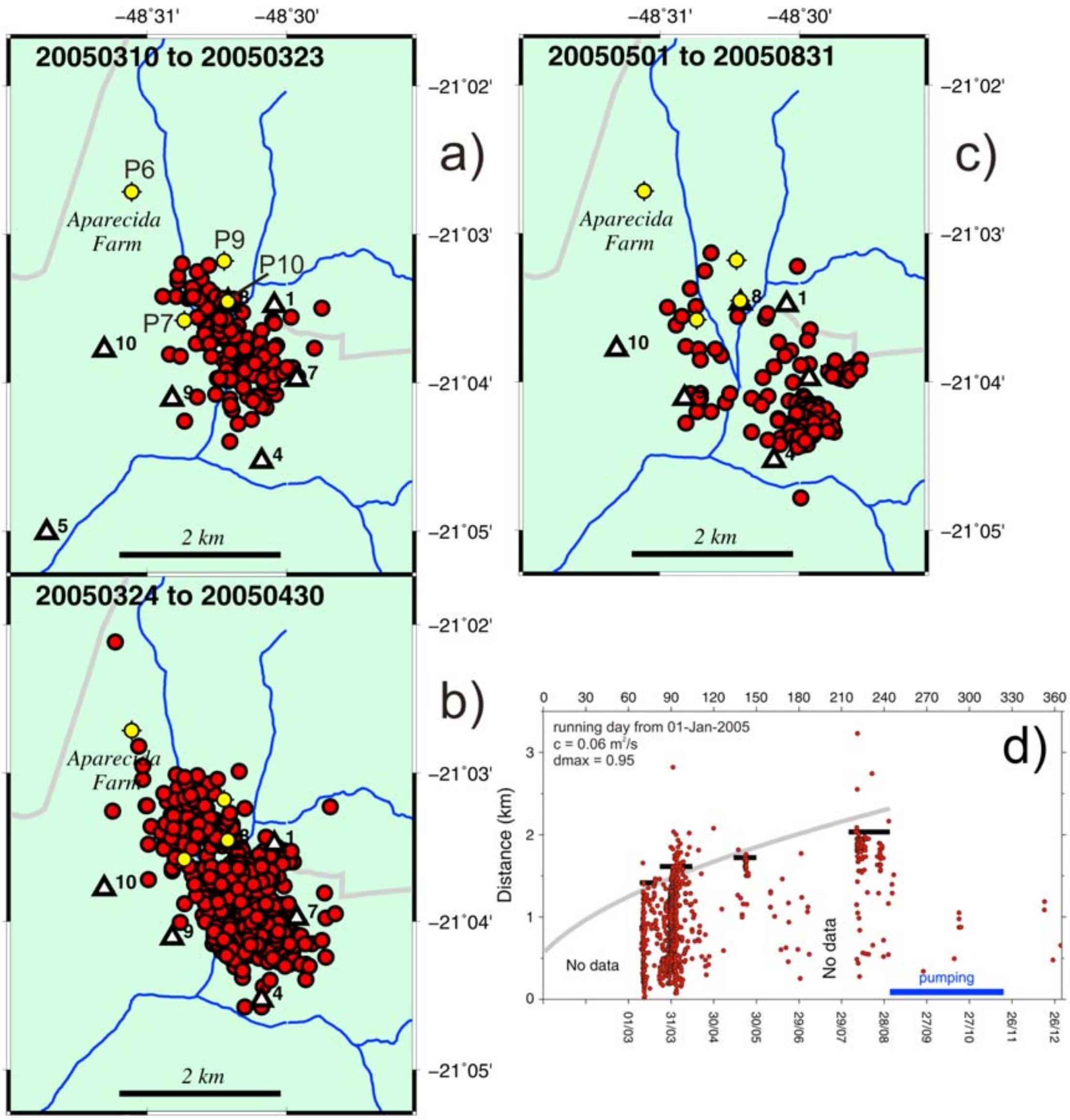

Figure 5. Epicenter migration during the 2005 seismic burst. (a,b,c) Epicenter distribution for three different periods: 1–23 March, 24 March 24–30 April, and May–August, respectively. Only the seismic stations (triangles) operating during the corresponding periods are shown. (d) Evolution of the epicentral distances from the midpoint between wells P7 and P10, during 2005; the horizontal bars indicate the area enclosing 95% of the events; the shaded curve shows the time-distance evolution for a diffusivity of c = 0.06 m^2/s assuming additional water pressure was added at the wells in mid-December 2004, soon after the end of the pumping period.

approximately 125 m. In other words, drilling new wells in this area often causes water to drain from the upper unconfined aquifer and contributes to an increase of fluid pressure in the confined bottom aquifer.

[11] There is additional evidence apart from temperature logs supporting the scheme of subsurface fluid flow. First, the occurrence of waterfalls inside wells is a very common feature in the Andes district. The presence of in-hole waterfalls is often easily verified by the characteristic sound near the well "mouth." In one of the wells (Figure 4b), a borehole televiewer (BHTV) showed various sections of altered/fractured basaltic rocks. The largest altered section, at 120 m, coincides with a kink in the temperature profile and marks the depth of the confined aquifer (altered or fractured section between two intact basalt sections).

[12] An estimate of the magnitude of water flow necessary to maintain unusual temperature distributions in the wells can be obtained from relevant heat transfer relations for fluid flow in cylindrical geometry. We make use of the solution, proposed initially by *Ramey* [1962], where the temperature variation (T) with depth (z) in flowing wells is given by

$$T(z,t) = T_0 + \Gamma z - \Gamma A + \left[T_f(t) + \Gamma A - T_0\right] e^{-z/A}, \qquad (1)$$

where T_0 is the surface temperature, Γ is the geothermal gradient, and $T_f(t)$ is the temperature of fluid entering the

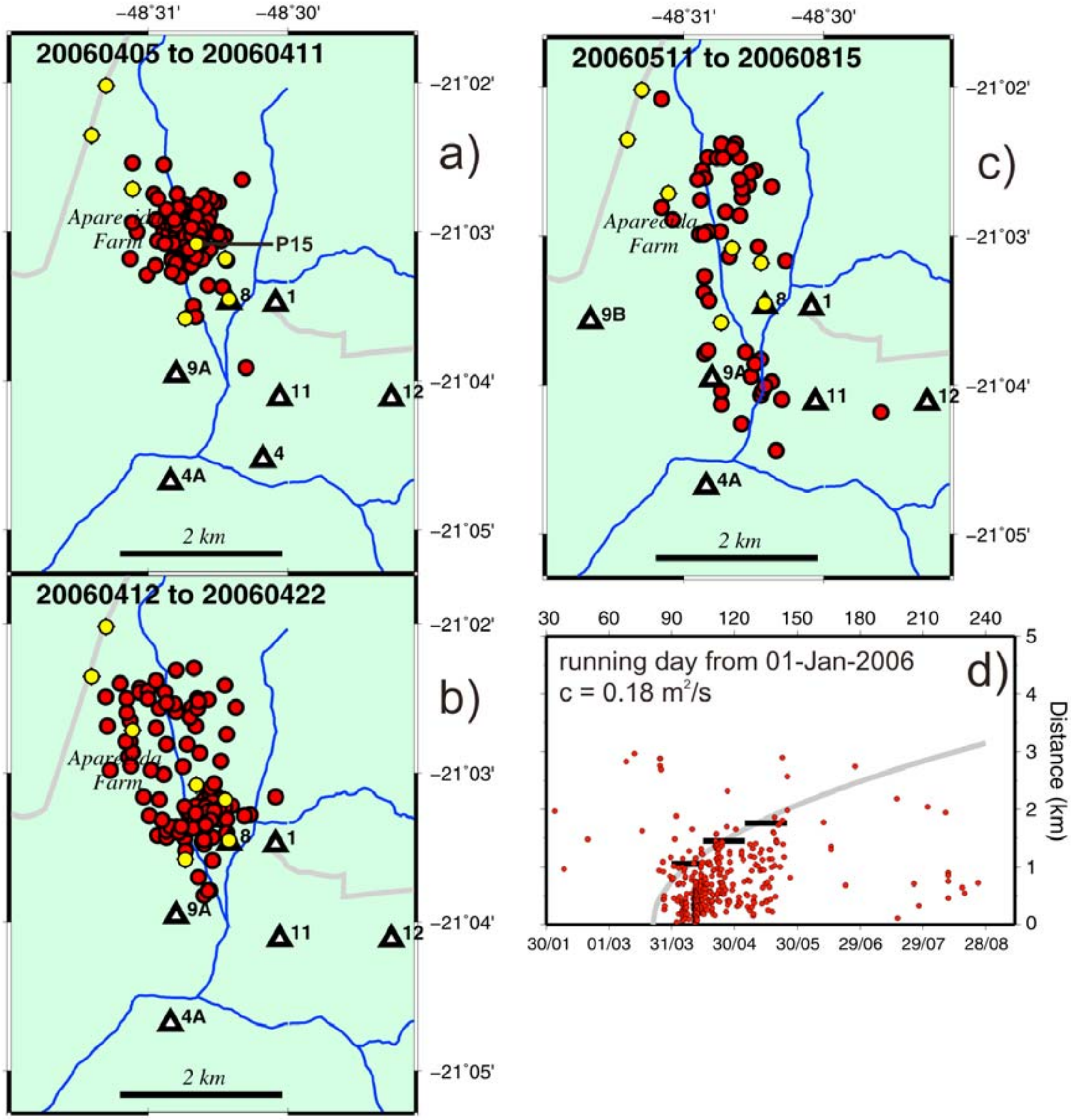

Figure 6. Epicenter migration during the 2006 seismic burst. (a,b,c) Epicenter distribution for three different periods in 2006. Note additional wells drilled in early 2006 (including P15). (d) Evolution of the epicentral distances from well P15 with a diffusivity curve with $c = 0.18$ m^2/s. Other symbols as in Figure 5.

well. In equation (1), A is a parameter related to advective heat transport for in-hole flows, given by

$$A \approx \frac{r_1^2 v\rho\, c\, f\,(t)}{2\lambda}, \qquad (2)$$

where r_1 is the radius of the well, v is the velocity of fluid flow, ρ is the density of fluid, c is its specific heat, $f(t)$ is a time function related to the period elapsed since the fluid flow was initiated, and λ is the thermal conductivity of the wall rocks. Comparisons of the measured temperatures with model values calculated using equations (1) and (2) may be made by setting reasonable limits for velocities of in-hole fluid flow.

[13] For example, Figure 4c shows the results of temperature log data for the depth range of 40 to 120 m in the well Santa Ana and model curves calculated using equations (1) and (2) for different flow velocities. It is fairly simple to see that flow velocities in excess of 100 m/h are needed to maintain constant temperatures at depths between 40 and 120 m. For reasonable values of the parameters in equations (1) and (2), the corresponding minimum value for the in-hole flow rate is about 2 m^3/h. For such high values of flow velocities, however, this method has poor resolution (Figure 4c).

[14] We can roughly estimate the increase in water pressure in the confined aquifer (due to the in-hole flow from above) using the well characteristics in the area. For a confined large aquifer, the decrease in water level, S_d (meters), is directly proportional to the pumped outflow Q (cubic meters per hour). The specific outflow (i.e., the ratio of water outflow to water level decrease), measured during pumping tests of all the wells, ranges from $Q/S_d = 0.2$ to 5 m^2/h. The

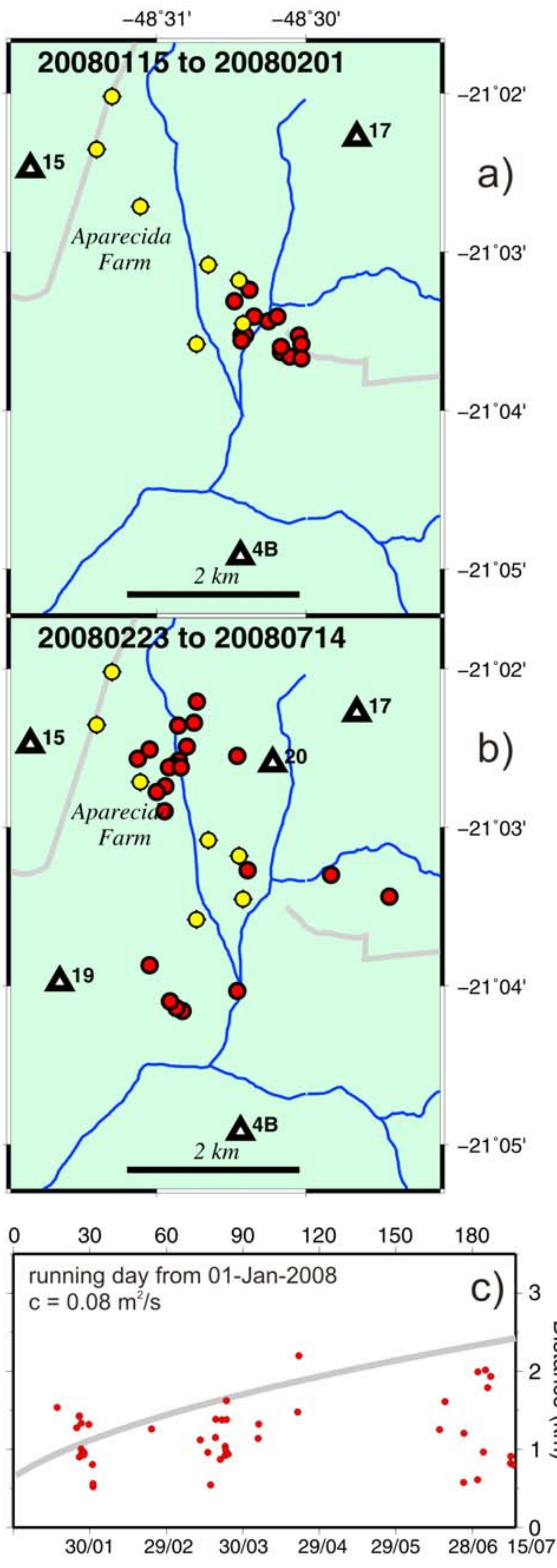

Figure 7. Epicenter migration from January to mid-July 2008. (a,b) Epicenter distribution for two different periods in 2008: 15 January-1 February and 23 February-14 July. (c) Evolution of the epicentral distance from the midpoint between wells P7 and P10; the shaded curve shows the time-distance evolution for a diffusivity of 0.08 m^2/s assuming additional water pressure was added at the wells in mid-December 2007, soon after the end of the pumping period in the previous year.

shallow wells in the region exploit only the upper aquifer and have outflows in the range 5 to 15 m^3/h. Assuming the waterfalls in the wells have a downwards flow, Q_w, of about 2 m^3/h (as given by the geothermal analysis above, which is about 1/5 the average operating pumped outflow), the resulting water level rise, S_u, is given by

$$S_u = Q_w.(S_d/Q) = 0.4 \text{ to } 10 \text{ m}.$$

[15] Despite the uncertainties in some of the model parameters, it is reasonable to expect an increase of pressure in the bottom aquifer on the order of one meter of water column.

4. Expanding Seismic Area and Hydraulic Diffusivities

[16] Almost every year, the seismic activity begins in a small area and expands to larger distances. When seismic monitoring began in March 2005, the activity was concentrated near the two wells P7 and P10 (Figure 5a). In April, the events were scattered throughout a larger area both to the south and to the north. In August, most of the activity occurred far from P7 and P10, and very few events occurred near the area of initial activity in March. The temporal evolution of the "seismic front" (i.e., the maximum epicentral distances) is compatible with fluid diffusion in fractured media, exhibiting rapid expansion in the beginning that slows down with time. When continuous pumping stops at the end of the dry season, water from the top aquifer starts to flow down the wells. This increases the pore pressure in the confined fractured aquifer in the basalt layer and the migration of the pore-pressure front triggers seismicity.

[17] For a one-dimensional case, such as beneath a large water reservoir at the surface, the time t taken for surface pressure to diffuse to a depth z is given by $t = z^2/4c$, where c is the hydraulic diffusivity of a porous medium [e.g., *Wang*, 2000]. *Kessels and Kück* [1995] showed that for fluid injection in a borehole, considered as a linear source, the time t for the maximum pressure to diffuse along a fracture a distance r from the borehole is also given by $t = r^2/4c$ [*Talwani et al.*, 2007].

[18] Here, we assume that the extra pressure in the bottom aquifer also propagates away from the water well as a pressure front and follows a similar law, raising the pore pressure and triggering earthquakes over time t:

$$t = d^2/4c, \tag{3}$$

where the distance d of the pressure/earthquake front was measured as the distance enclosing 95% of the epicenters.

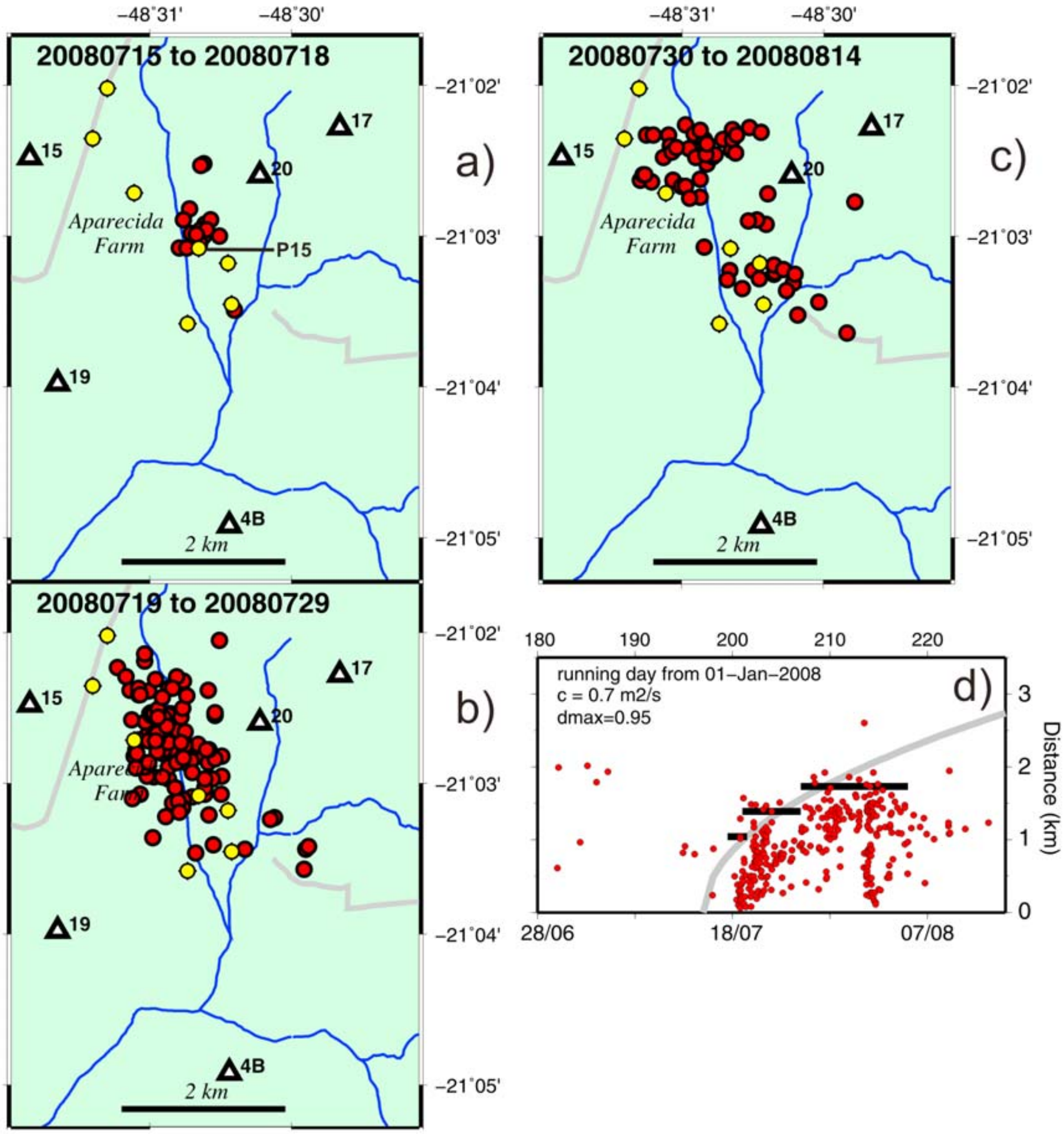

Figure 8. Epicenter migration during the July 2008 seismic burst. (a–c) Epicenter distribution for three different periods in July–August 2008. (d) Evolution of the epicentral distances from well P15; the shaded curve corresponds to a diffusivity of 0.7 m^2/s; horizontal bars enclose 95% of the distances for three different periods during 2008.

[19] We can estimate the hydraulic diffusivity controlling the 2005 seismic migration (Figures 5a through 5c) assuming that (1) an increase in pore pressure in the fractured aquifer started in mid-December 2004 when the continuous pumping was stopped and water from the surface aquifer started to flow down the wells again, and (2) wells P7 and P10 (those with the largest outflow capacity) are the wells with the most efficient connection to the fractured aquifer. We measured the distance of the seismic front from the midpoint between wells P7 and P10, defined as the distance enclosing 95% of the epicenters, during four periods of higher seismicity (Figure 5d). These four data points, together with the origin time, were fitted to equation (3) and indicate a front migration consistent with a hydraulic diffusivity of 0.06 m^2/s.

[20] Four new wells were drilled in February and March 2006, three in the northern part of the Aparecida Farm (P12 to P14), and one in the middle (P15). Two of these wells have outflows larger than 100 m^3/h (such as P15 in Figure 6a). Roughly one month after drilling, a seismic burst began in the middle of the farm. Because several different wells now contribute to an increase of the pore pressure in the basalt aquifer, it is more difficult to model the point of origin of the additional increase in pore pressure. However, the April 2006 seismic burst started very close to well P15, which was drilled about a month earlier. Assuming the seismogenic increase in pore pressure initiated at P15 with the first local events occurring at the end of March 2006, the increase of the seismic front in 2006 corresponds to a hydraulic diffusivity of 0.22 m^2/s (Figure 6d).

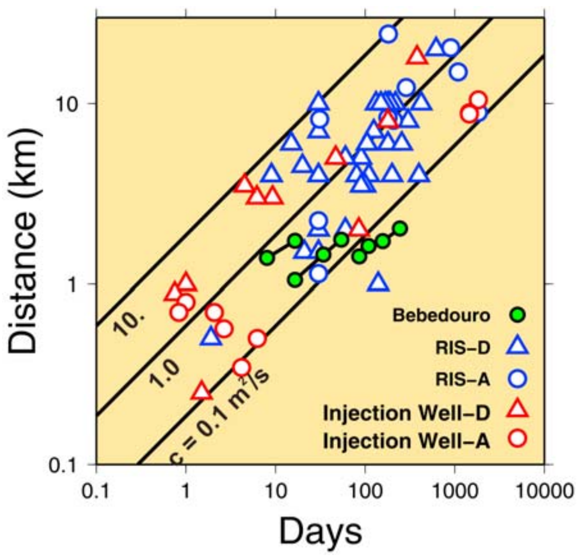

Figure 9. Diffusivities of fluid induced earthquakes related to reservoir induced seismicity (RIS) and injection wells, compiled by *Talwani et al.* [2007], and the three Bebedouro sequences of 2005, 2006, and July 2008. Triangles (-D) and circles (-A) are diffusivities calculated by time delay and seismic area growth, respectively.

[21] In 2008, the seismic activity resumed with a lower rate compared to previous years (Figures 3 and 7). Although an expanding front was not as clearly observed during 2008 as in 2005 and 2006, a general trend of increased epicentral distances from P10 for January to mid-July 2008 can be seen in Figure 7. On July 15, a strong burst of activity started near P15, the same well that experienced activity in 2006, and the seismic front expanded with a diffusivity of about 0.7 m^2/s (Figure 8).

[22] The hydraulic diffusivities estimated here (0.06–0.6 m^2/s) fall within the typical range of all cases of seismicity triggered by reservoirs and injection wells, as compiled by *Talwani et al.* [2007] and shown in Figure 9. Hydraulic properties of fractured media can be very complex, and it would be difficult to quantitatively model the interaction of several wells in the same area. In addition, it has not been possible to make detailed investigations of the wells in the Aparecida Farm. Nevertheless, the repeated pattern of seismic area growth, with rates similar to fluid-related seismicity, clearly shows that the earthquakes in the Aparecida Farm are caused by pore-pressure perturbations in the fractured basalt layer.

5. Conceptual Model for Well-Induced Seismicity

5.1. Aparecida Farm

[23] We explain the observed seismicity and annual cycles in the Aparecida Farm by increased pore pressure in seismogenic fractures within the basalt layer. The area in the Andes district was probably critically stressed already. The opening ten wells in 2003 allowed a gradual increase in pore pressure in the confined aquifer. This was caused by waterfalls from the surface aquifer during the first nine months. The increase in pore pressure caused a decrease in the effective normal stresses in seismogenic fractures. In the beginning of 2004, effective stresses finally reached critical conditions and seismicity began. During pumping periods, the pore pressure in the bottom aquifer is reduced, and friction predominates in the seismogenic fractures, which acts to shut down the seismicity. The rate of pore pressure increase is probably modulated by rainfall, through larger flow from the waterfalls down the wells, though this may have a delayed effect. This can be seen, perhaps, in 2005 and 2006 with the peaks in seismic activity following peaks in rainfall with an ~2 month delay.

[24] The amount of pore-pressure increase is small, probably only a few meters of the water column. For critically stressed conditions, however, very small changes in pore pressure can trigger seismicity. This was observed in the Açu reservoir of northeastern Brazil, where an annual increase of about 3 m in the water level triggered seismicity a couple of months later. Several cases of rain-induced seismicity have also been observed, and modeling of poroelastic properties of the rock mass indicates that a pore pressure of less than 0.05 MPa (5 m of water column) is enough to trigger earthquakes [e.g., *Saar and Manga*, 2003, 2004; *Costain*, 2008]. Even much smaller hydrologically induced stress perturbations (about 0.002 MPa) have been suggested to help trigger earthquakes in the San Andreas fault [*Christiansen et al.*, 2007].

5.2. Pimentel Farm

[25] A secondary seismic area began in August 2006 in the Pimentel Farm (Figure 2), about 10 km to the west of the Aparecida Farm. The largest events were strong enough to cause intensities IV MM and significant concern from the local people. A deep well had been drilled in the Pimentel Farm at the end of 2005 or beginning of 2006. This well is not pumped continuously for irrigation during the dry season, and thus a clear annual cycle is not observed in the seismicity evolution (Figure 10).

6. Discussion and Conclusion

[26] We report a clear case of earthquake activity triggered by the perturbation of pore pressures in a confined fractured aquifer caused by the drilling of water wells. Earthquakes induced by water injected at high pressures into deep disposal wells are relatively common (see list in *Talwani et al.* [2007]). The seismic activity in the Aparecida Farm can be considered as a special case of injection wells, with rainwater naturally injected under very low pressures through waterfalls from surface aquifers.

[27] Underground water in the Paraná Basin is extensively exploited and hundreds of new, deep wells are drilled every year in the northeastern part of the basin, as shown in Figure 1. However, only one other clear case of well-water triggered activity had been previously reported [*Yamabe and Hamza*, 1996]. This case occurred in Nuporanga, a town just 80 km to the east of Bebedouro (Figure 1), where water from fractured aquifers in the basalt layer is also commonly exploited. Similar to the Andes district, shallow water flowing down the well and feeding a deeper aquifer was observed in Nuporanga, along with a decrease in activity during pumping periods.

[28] Two other suspected cases of well-water-induced activity have been reported in the Paraná Basin. In 1959, Fernando Prestes, a town about 50 km southwest of Bebedouro (Figure 1), reported earth tremors following the dril-

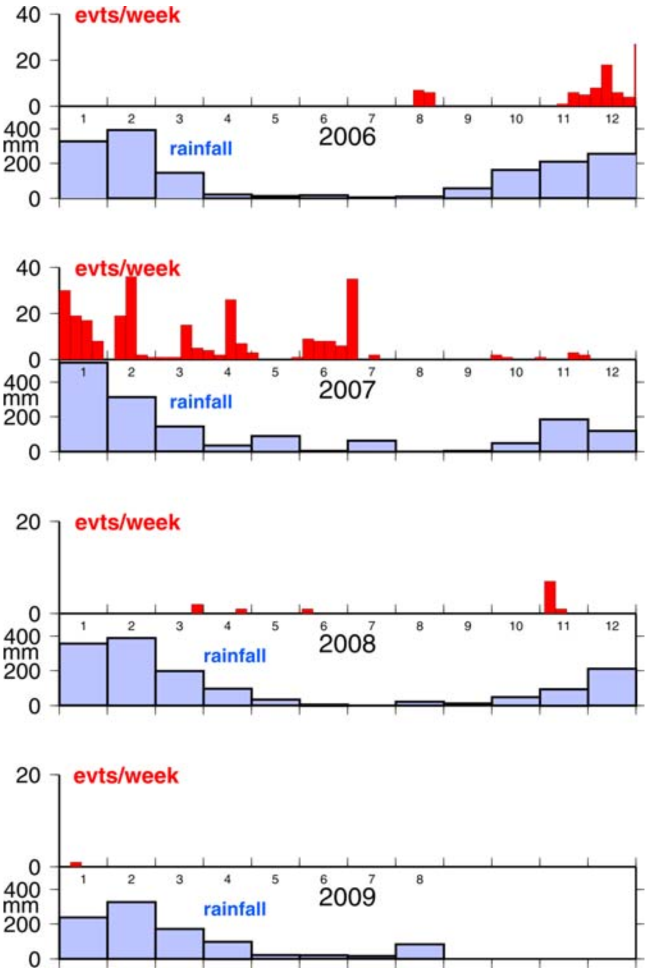

Figure 10. Annual evolution of seismic activity for the secondary seismic area (Pimentel Farm). Red histograms show the weekly numbers of events and the light blue histogram shows monthly rainfall. A deep well was drilled in the Pimentel Farm in early 2006; no continuous pumping is carried out.

ling of a deep well with characteristics similar to the Andes wells [*Berrocal et al.*, 1984]. No detailed study was possible at the time. *Yamabe and Berrocal* [1991] also reported earthquakes a few years after the drilling of a very deep well in Presidente Prudente (in the middle of the Paraná Basin), an area with no record of previous natural seismicity. None of these previous cases were studied in detail with a dense seismographic network, as in Bebedouro.

[29] Even though hundreds of new, deep wells are drilled every year in the Paraná Basin, seismic activity triggered by the opening of these water well, such as that seen in the Aparecida Farm, seems to be a rare phenomenon. However, the activity observed in the other area (Pimentel Farm) would have gone unnoticed if a study was not already being conducted in the nearby Aparecida Farm. *Assumpção et al.* [2008] reported several other cases of earth tremors being felt close to recently drilled, deep wells in the neighboring municipality of Monte Azul Paulista, about 30 km west of Bebedouro. Again, these cases would have gone unreported and were only brought to our attention because of the ongoing study in the Andes district of Bebedouro. This implies that seismic activity caused by drilling water wells may not be as rare as previously thought, and more attention should be given to this phenomenon by drillers and groundwater users.

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