Relocation of Hypocenters of the Induced Activity in Bebedouro, Paraná Basin, Brazil

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Abstract

Shallow seismic activity with magnitudes up to 2.9 and intensities V MM has been observed in the Bebedouro rural area, Northeast of São Paulo State, Brazil, since 2004, near to deep wells (120–200 m) that were drilled in early 2003. 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.

The activity occurs as swarms of events mostly during the rainy season when the wells are not pumped. The spatio-temporal evolution of the seismicity shows it was triggered by the drilling and operation of the water wells.

We used results of other geophysical surveys (shallow seismic refraction and high-frequency receiver functions) to define more accurate velocity models for the hypocentral location.

Introduction

Shallow seismic activity with magnitudes up to 2.9 and intensities V MM has been observed in a village called Andes, in the Bebedouro rural area, since 2004. During the high activity periods, more than 100 to 200 events were recorded daily, dozens of which being felt by the people in the epicentral area.

In general the houses shake and the scared people run away from them. The largest earthquakes are felt up to 5 or 10 km away and most of the epicenters are located near some deep wells (120-200m deep) drilled in early 2003 to extract water from a basalt fractured aquifer (Assumpção et al., 2007).

Since January 2004 the activity occurs as swarms of high seismic activity, lasting for several months, alternating with periods of very low activity during the dry season. The wells, drilled for irrigation purposes, cross a sandstone layer about 60-80m thick and extract water from a confined aquifer located in fractured zones between basalt flow layers (Cretaceous Serra Geral Formation of the intracratonic Paraná Basin). The basalt pack in this region is about ~500m thick.

The main purpose of this investigation is to improve the location of the micro earthquakes, using both P and S arrival time data and S-P differences, as part of a detailed study of the induced seismicity caused by the drilling of water wells.

We tested different absolute locations algorithms as well as joint and relative location techniques for the relocation of hypocenters of earthquakes recorded by different station distributions.

A comparison between different methods will be shown and the resulting implications for the interpretation of the induced mechanism.

Methodology

In this study, we use more than 3000 micro earthquakes collected by a seismographic network, since March 2005 (Assumpcao et al., 2010), network which is operated by the laboratory of seismology of the IAG/USP (Fig1. Micro earthquake).

The preliminary estimate of origin times and hypocentral coordinates is obtained by HYPO71. This is a computer program for determining hypocenter of local earthquakes written by Lee et al. [1972].

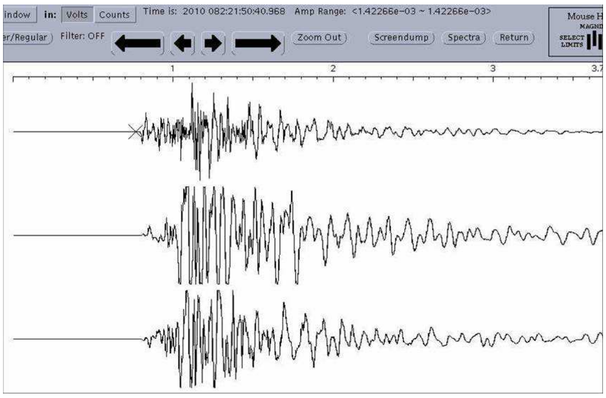

Fig 1: 23-03-2010, 21:50UT. (Mb≈0.6)
Microearthquake recorded in the study area BEB22.

The hypocenter location was performed using the HYPOCENTER 3.2 earthquake location program (Lienert et al., 1995). This program has the capabilities to locate earthquakes locally, regionally and globally. The program was adapted to use 3 decimal places in the arrival times.

The arrival time residuals are minimized to get a set of location parameters, using both P and S arrival time data and S-P differences (Bulut, F., et al., 2007), with a least-square method, that works behind this program. The procedure is repeated through an iterative process till an acceptable error criterion is met, the final adjusted parameters are then accepted as the best possible estimate of the source location.

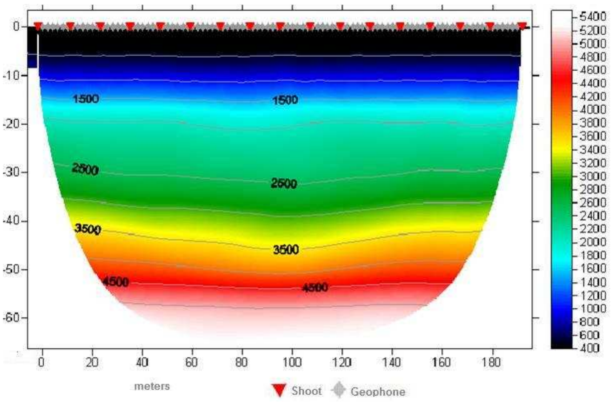

Fig 2: Seismic tomographic - BEB4A
Three layers are identified soil, sand and basalt

The initial P-wave velocity structure was modeled on the basis of a refraction profiling survey carried out between January and February of 2008, using the smooth inversion tomographic method (Fig. 2) and reciprocal method of the Rayfract software, these tools are based on physically meaningful modeling of seismic first break energy refraction, transmission and diffraction. P-wave propagation is modeled with wave paths (also known as Fresnel volumes) instead of conventional rays. Although with the refraction profiling survey were identified three refractors layers: Soil about 10 m thick, a surface sandstone layer about 50 to 120 m thick, and the top of the Basalt.

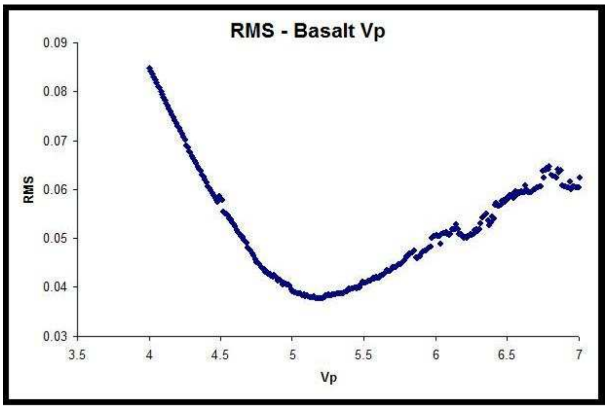

Fig 3: Vp determination by residual analysis (RMS) in the basalt layer.

Using the initial P-wave velocity and analyzing the shallow travel time residuals was adopted the final 1D velocity structure for the S-wave for the soil, sand and basalt layers. (Fig. 6)

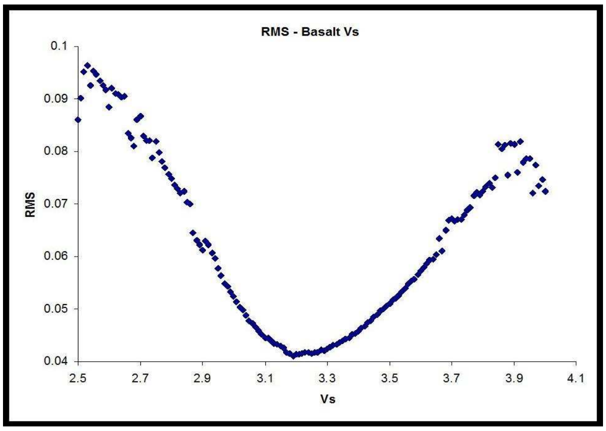

Fig 4: Vs determination by residual analysis (RMS) in the basalt layer.

A subset of 17 micro earthquakes well registered (Hypocenters are determined using at least four stations with a minimum of eight P and S readings) and the initial velocity structure, were employed to accurately calculate final 1-D velocity model using a grid search method (Figure 5). This is based on the calculation of the root mean square (rms) travel time residual, three-dimensional grid points for Vp and Vs, allow the determination by residual analysis (P-wave, S-wave and RMS) of a reasonable layering of the velocity model of P-wave and S-wave.

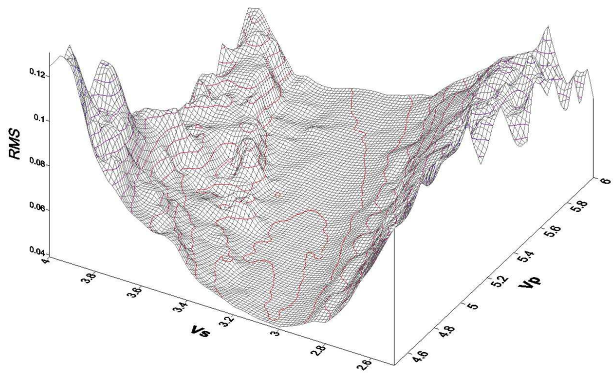

Fig 5: Vp-Vs grid search, determination by residual analysis (RMS) in the basalt layer.

Results

Hypocenter determination of the almost 3000 micro earthquakes was achieved by fitting the arrival time readings to the calculated ones based on a local 1-D velocity model that depicted its improvement on absolute locations.

The final 1D model was constrained by shallow seismics for the shallow layer and grid search for the basalt layer (Fig.7). This model shows that most well located hypocenter are in the top part at the basalt layer, more consistent with the induced nature of the seismicity.

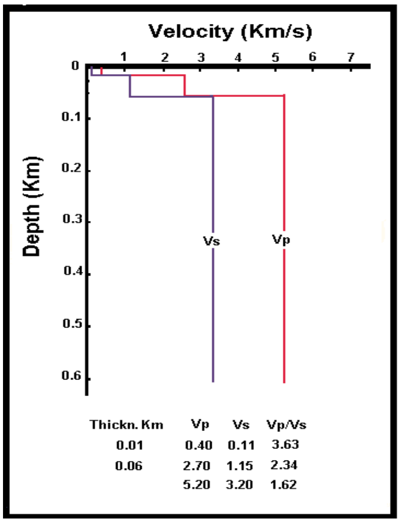

Fig 6: 1D velocity structure adopted for the present analysis, the model is derived on the basis of a refraction model and shallow travel time residuals.

Here we assume that appropriate layering of the local crust can be defined for which the most reliable hypocenters are obtained, in terms of not only average RMS error but also location uncertainty and determined the depths of interfaces for which all models converge.

The adopted model has a velocity profile changing with depth. The epicentral distribution of the relocated deeper events in most 0.3 – 0.6 km shows scattered distribution in the NW direction cover an area roughly 1.5 km x 5 km across (Fig. 11).

This methodology improves spatial resolution and allows identifying small-scale structures, especially in the depth distribution of the hypocenters, that otherwise remain hidden in the cluster. Hand-picked arrival times give a first-order estimate of relative travel times, and accuracy of the hypocenter location is significantly increased.

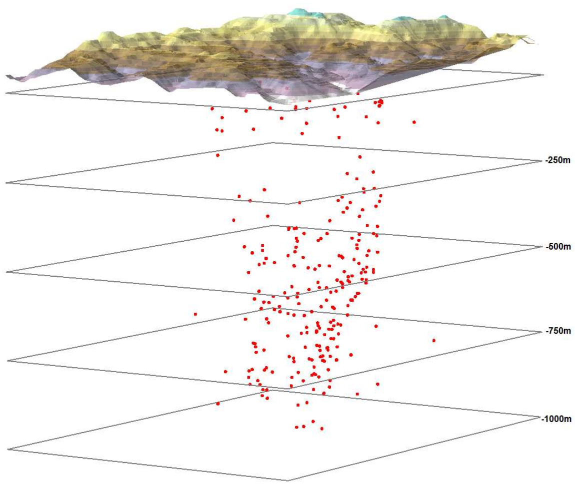

Fig 7: Hypocenters distribution determined initially with Hypo71, rms ≤ 0.05 and No ≥ 8 (No of phases)

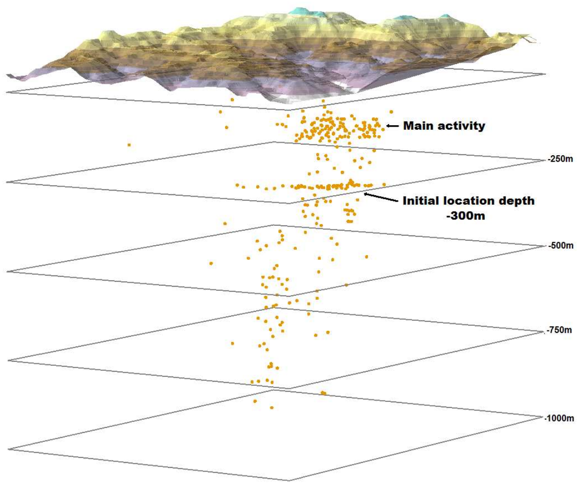

Fig 8: Relocated distribution of hypocenters determined with Hypocenter3.2, rms ≤ 0.05 and No ≥ 8

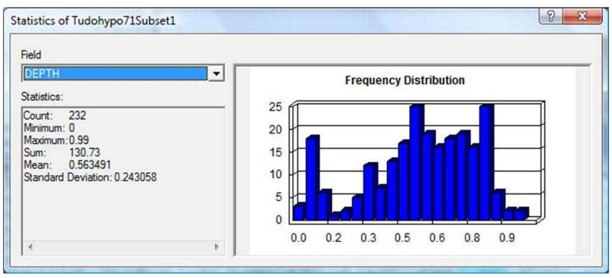

Fig 9: Histogram of the distribution of microearthquake depth obtained using HYPO71 and previous model with most events between 500 and 600m.

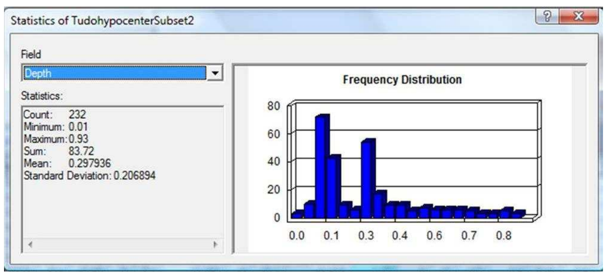

Fig 10: Histogram of the distribution of microearthquakes depth, obtained using HYPOCENTER showing concentration near to 100m depth, this mean that the events are inside the basalt layer.

Discussion and Conclusions

The seismicity in the study area varies spatially and temporarily among a seismic cluster in a relatively small region associated with drilling of water wells exploiting a confined fractured aquifer, this suggested that temporal changes of parameters like pore pressure diffusion in the fractured basalt layer might have occurred, induced by the new wells that allowed the communication between upper aquifer and the fractured zones in the basalt, which increased pore pressure in the fracture aquifer medium and facilitated the seismic activity.

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 x 5 km across. More accurate depths are necessary to better understand the process of migration of epicenters away from the wells, clearly observed every year since 2005 with a “seismic diffusivity” of about 0.3 to 0.6 m2/s.

Previous cases of earthquakes induced by water-well drillings were observed in Nuporanga, (Yamabe & Hamza, 1996) and in Presidente Prudente (Yamabe, 1999), respectively Northeast and Central North of Paraná Basin. In both cases the seismic events occurred inside a basalt layer of the same Serra Geral Formation. The present case indicates that the probability of deep wells triggering earthquakes can be much larger than previously thought.

Considering that porosity and permeability in a fissured aquifer depend on distribution, opening and size of the basalt fissures (Feitosa e Manoel F°, 2000), it is possible to infer that tubular wells with such high water flow are indicative of the high concentration of basalt fractures or fault permeability in the epicentral area (Assumpção et al., 2007).

Acknowledgements

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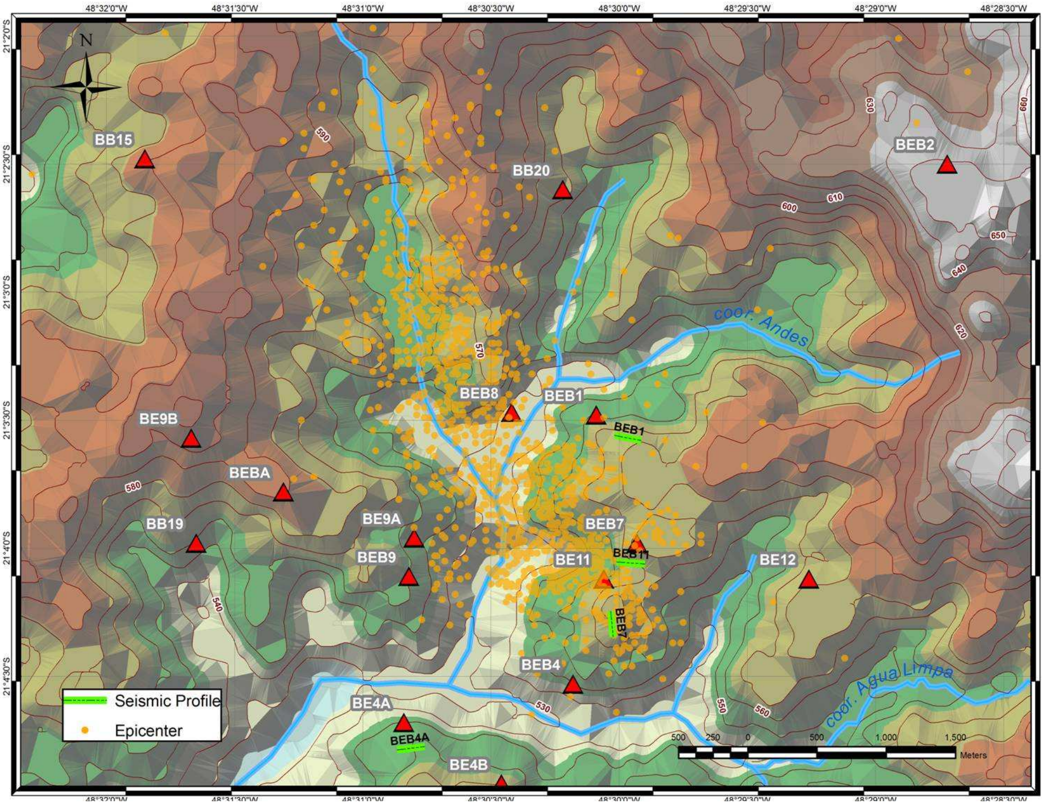

Fig 11: Map of the study area