Seismicity of Ijaci, south of Minas Gerais state, near the FUNIL UHE reservoir and mineral extraction areas.

Lucas Vieira Barros[1], Diogo F. Albuquerque[1], Vinícius M. Ferreira[1], Mônica G. Von Huelsen[1], Victor F. Mourão[1], Darlan P. Fontenele[1], Francimilton S. da Silva[1], Jefferson F. Soares[2] and Walisson de Sousa Soares[2]. (1) Observatório Sismológico - Universidade de Brasília; (2) Consórcio FUNIL.

This paper was prepared for presentation during the 13th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 26-29, 2013.

Abstract

On August 14th, 2011, the FUN1 seismic station, installed in the FUNIL UHE reservoir area, detected an earthquake of 3.2 magnitude on the Richter scale. The earthquake was felt more strongly in the town of Ijaci, located on the left margin of the FUNIL reservoir, in the south of Minas Gerais State. On October 5th, November 13th and November 23th, 2011, Ijaci residents were again shaken by new seismic occurrences. As a result, in December of 2011, the Seismological Observatory (SIS) at the University of Brasilia (UNB), in partnership with the Funil Consortium, deployed a local seismograph network, with six stations to better study this seismicity. The network operated until May 23th, 2012, during a period in which more than 1000 seismic events (natural and artificial) were detected, of which 500 were located, but only about 70 with reasonable accuracy. The events were located very close to the lake and the quarries in the region, in an area where there was no known previous seismicity. However, about 30 km NE of Ijaci, in Bom Sucesso, there is an area of known seismic activity. This work is a synthesis of two special reports issued at the request of the Public Ministry of Minas Gerais, which received a complaint from Ijaci City Hall on the effects, in homes, of detonations near the town of Ijaci, in southern Minas Gerais.

Introduction

Funil Dam dams waters from the Rio Grande River, forming a lake with 35 km^2 of flooded area and a volume of 0.258 Km^3. It has a maximum height of 40 m, with an extension of 30 km, reaching the municipalities of Lavras, Perdões, Ijaci, Bom Sucesso, Ibituruna, and Itumirim. The lake was formed in November of 2002 and since then operates with three turbines, each generating output energy of 60 MW. The FUN1 station, which monitors the seismicity of the Funil Reservoir, came into operation on December 21, 2010 with local recording, and from August 26, 2011, its data were sent to Brasilia in real time.

Local events began to be detected as soon as the station went into operation. On August 14, 2011, the FUN1 station detected, at 13h50m (local time), an earthquake of 3.2 magnitude on the Richter scale, felt with intensity IV (MM) in the town of Ijaci, located on the left margins of the Funil Reservoir. The second strongest earthquake, with a magnitude of 2.8, also felt by the local population, was recorded by FUN1 station on October 05, 2011, at 15h09m (local time). Two other events of equal magnitude were recorded by FUN1 station on November 13 and 23 at 07h39m and 07h09m, respectively. This was also felt by the population of Ijaci. These events led to the installation of a local seismic network to monitor this seismicity. The network has been deployed and operated by SIS - UNB, in partnership with the Funil Consortium. The map of Figure 1 shows the stations spatial distribution, six temporary and one permanent station (FUN1) as well as the locations of blasting points, which are systematic detonations sometimes made without scheduling information and when this is done, it is done inaccurately. This hampers the discrimination of tectonic events from artificial events, considering the similarity between the waveforms of certain bursts with those generated by natural events, as well as the proximity of the epicenters of both types of events.

Presented in this study are the epicenter location of the 08/14/2011 Ijaci earthquake and the preliminary results of the analysis and interpretation of more than one thousand local events (natural and artificial). These were detected by the Funil Local Seismic Network between August 14 of 2011 to May 25 of 2012 of which about 500 were located, and most only with data from the FUN1station.

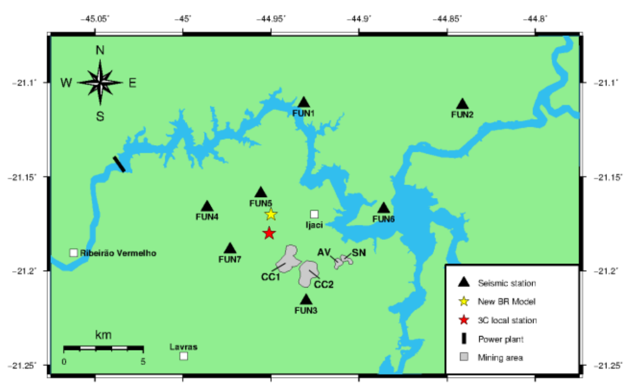

Figure 1: *Map of Funil Reservoir with the locations of the local network seismographic stations (black triangles), the region's mining and epicenter location of the Ijaci/MG event, of October 14, 2011, determined with data from the 12 stations in Figure 2 (yellow star), using the NewBr velocity model (Assumpção at al, 2010) and with data only from the FUN1 station (red star), using a local model.*

Seismic network and seismic data acquired

The Funil Seismograph Network (Figure 1) was installed between 21 - 24 of December, 2011 (Stations Fun2, 3, 4 and 6). The FUN7 station was installed on January 19 of 2012 and FUN1 station on December 21, 2010. With the exception of FUN2 station, which was installed above sediments, all the others were installed on rocky outcrop. The brand of the instruments is GURALP in band range of 30s to 100Hz and data were sampled at a rate of 100 sps. The network was uninstalled on May 25, 2012, leaving only the FUN1 station. During this period, more than 1000 events were detected and about 500 were located, according to Table 1.

Table 1: *Monthly temporal evolution of the seismicity (natural and artificial) observed near the town of Ijaci/MG, from August 14, 2011 to May 25, 2012.*

Month	Events detected	Located (blasts)	Located (natural)	Located (total)
Aug/2011	21	8	12	20
Sep/2011	83	9	42	51
Oct/2011	110	8	48	56
Nov/2011	178	16	41	57
Dec/2011	182	13	18	31
Jan/2012	135	22	21	43
Feb/2012	89	61	29	90
Mar/2012	95	42	22	137
Apr/2012	77	41	31	72
May/2012	57	37	20	51
Total	**1027**	**257**	**20**	**57**

Ijaci main event

The main event in Ijaci on August 14, 2011 was recorded by 12 stations (Figure 2), four from UNB (blue triangles), four from the Institute of Astronomy, Geophysics and Atmospheric Sciences (IAG), University of São Paulo (USP) (red triangles) and four from the National Observatory (ON) (black triangles). The hypocenter, determined using the NewBr model by Assumpção et al.(2010) and the program LocSat (Miljanovic, 2007), was the following: Origin Time (OT) = 16h50m10.66s (UTC), Latitude = 21:07.39°S, Longitude = 44:59.67°W and depth (H) = 0.0 km. The event seismograms in the vertical components of the twelve stations are shown in Figure 3.

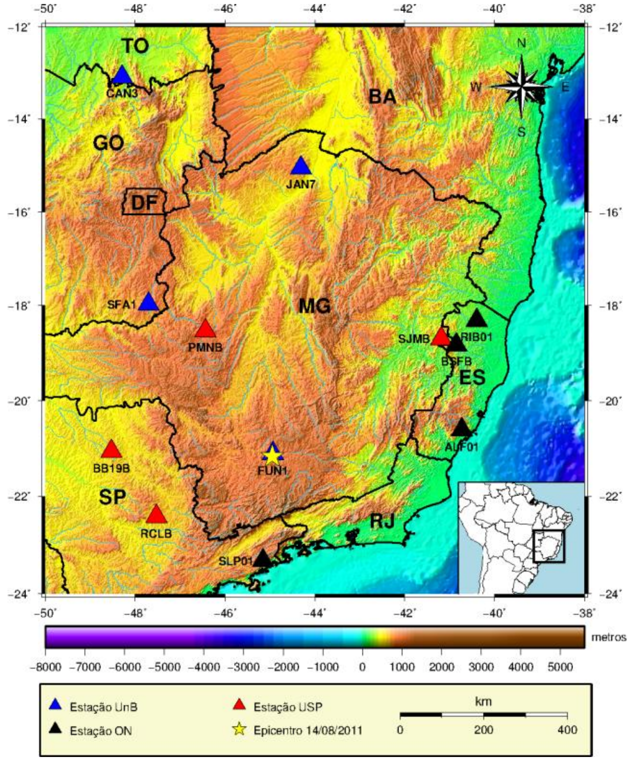

Figure 2: *Map with the location of seismograph stations (triangles), whose data were used in determining the Ijaci hypocenter earthquake on August 14th, 2011, at 16h50m10.66s (UTC). Note that the FUN1 station is located beneath the star (red) indicating the epicenter of the event. The ON stations (coastal) are indicated by black triangles, the USP stations by red triangles and the UNB stations by blue triangles.*

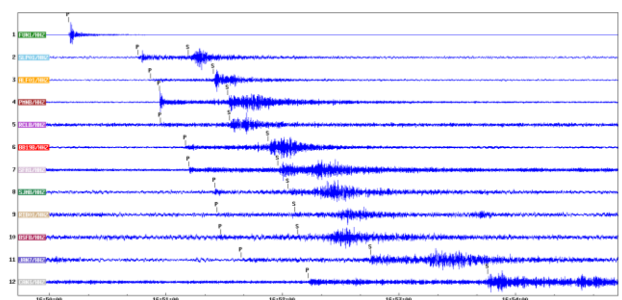

Figure 3: *Seismogram of Ijaci main event of August 14 of 2011 (vertical components) in the twelve stations of Figure 2.* Also shown are the markings of the P and S phases in order of increasing arrivals.

Location of the Ijaci event, FUN1 station

The event was located using data only from the FUN1 station considering the proximity of the Ijaci epicenter event to the FUN1 station and the long distances in relation to the other stations. The ratio of the amplitudes of ground movement in the north-south and east-west was used to determine the event's back azimuth (Fig. 4) and the differences in times propagation of P and S phases (tS-tP) to determine epicenter distance (Figure 5).

In this case, the depth was fixed on the surface. It The program locator, Hypocenter (Lienert, 1994), was used, running on a Seisan (Earthquake Analysis Software) environment (Havskov Ottomöller, 2009). Figure 4 shows the 2D particle motion in the directions - from right to left - horizontal (north-south) x vertical (Z), horizontal (east-west) x vertical (z) and in the horizontal plane.

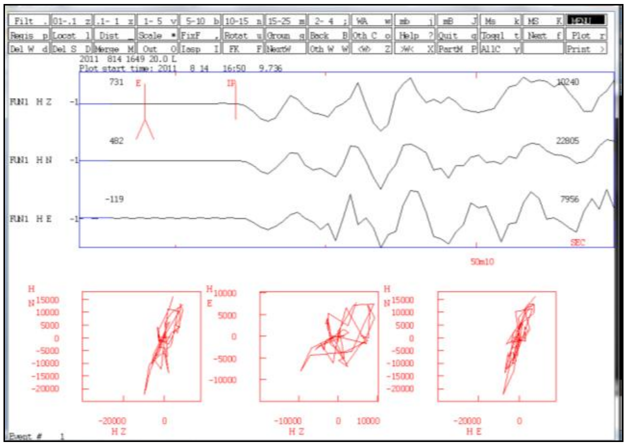

Figure 4: *Seismogram of Ijaci event of August 14, 2011 in the vertical, norte-south and east-west directions (three above traces) and particle motion in the north-south x vertical, east-west x vertical and horizontal (north-south x east-west) directions. Observe that the event-back azimuth in the lower right figure is approximately igual to 195 degrees.*

A semi-space with P-wave velocity (V_P) = 6.0 km/s and a ratio V_P/V_S = 1.72 velocity model was used. This model produced the best result in terms of lower RMS value of the residual.

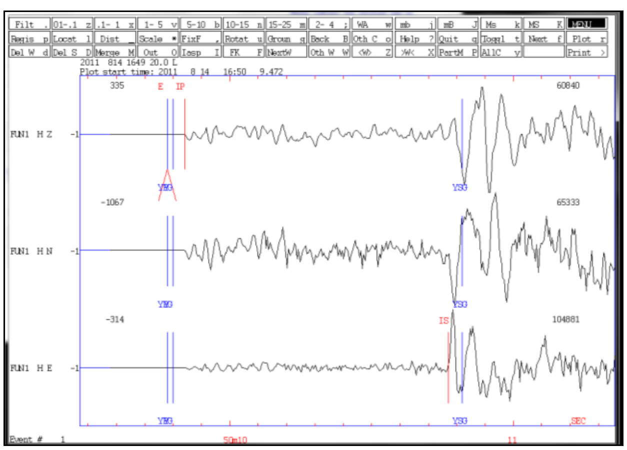

Figure 5: *Record of waveform event of August 14, 2011, indicating the reading of P (on the vertical) and S (horizontal east-west) phases. Note that the maximum amplitude (104,881 digital counts) of S-phase is in the east-west-component, which was to be expected considering the epicentral location of the event in Figure 6, almost to the south of FUN1. Therefore, the direction of particle vibration to S-waves, perpendicular to the direction of wave propagation, in this case the north-south component, rotated 15 degrees in a clockwise direction.*

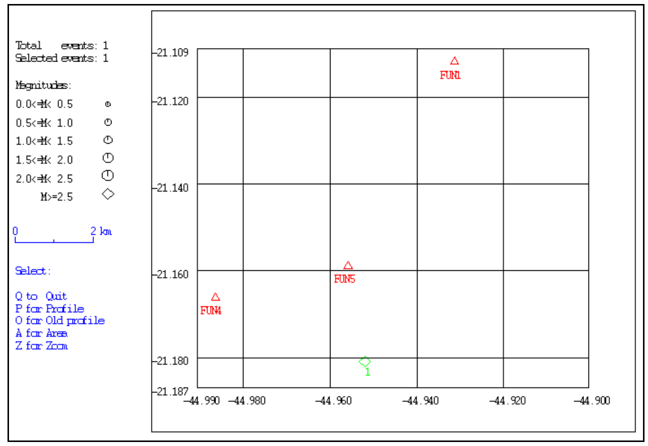

Figure 6: *Map of epicenter location of August 14, 2011 event using an Vp/Vs of 1.72, and VP of 6,0 km/s and a depth fixed at 1 km. Epicenter in 21.182º S and 44.952ºW.*

The resulting seismogram obtained from the rotation of the horizontal components north-south and east-west in the radial and tangential directions is shown in Figure 7. As noted, S-wave amplitude improved in the tangential component, increasing from 104,881 digital counts (in the east-west component) to 113,312 digital counts in the tangential component. This demonstrates the consistency of the epicenter location shown in Figure 6.

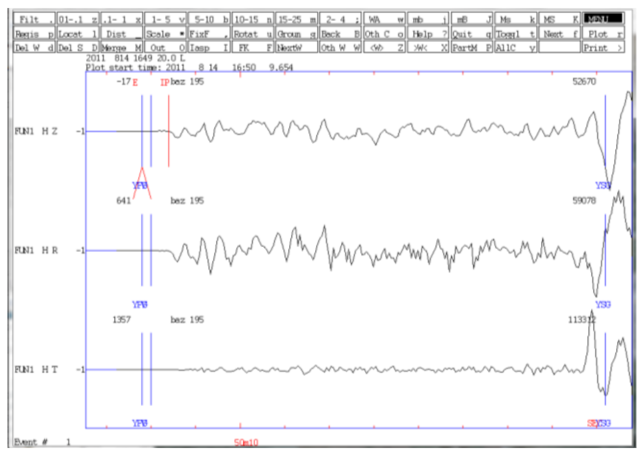

Figura 7: *Seismogram of the Ijaci event on 14/08/2011, with horizontal components north-south and east-west directions rotated to radial (HR trace, center) and tangential (HT trace, bottom). The back azimuth is 195 degrees, so the horizontal components rotated 15 degrees clockwise. Note the clarity of the S phase in the tangential component.*

Based on the above method locations were determined for the four major Ijaci events, which occurred on 08/14, 10/05, 11/13 and 11/23 of 2011. However, all of them were registered only by the FUN1 station because they occurred before the installation of the local seismic network. The events were located individually (Hypocenter, Lienert, 1994) and together (VELEST, Kissling, 1995). However, the results are more or less the same as can be seen in Table 2.

Table 2: *Seismic parameters of the four main Ijaci events located in singular (Hypocenter) and joint (Velest program) way using only FUN1 station data. All the depths were fixed at 1,0 km.*

Event loc.	Date yyyymmdd	Time (UTC)	Loc.	Mag.
1 Sing.	2011 08 14	165008.48	21.182S 44.952W	3.2
1 Joint.	2011 08 14	165008.04	21.1817S 44.952W	3.2
2 Sing.	2011 10 05	180930.83	21.198S 44.952W	2.6
2 Joint.	2011 10 05	180930.37	21.1975S 44.9516W	2.6
3.Sing.	2011 11 13	073926.69	21.201S 44.945W	2.6
3.Joint.	2011 11 13	073926.22	21.2008S 44.9454W	2.6
4 Sing	2011 11 23	070915.79	21.200S 44.949W	2.6
4 Joint	2011 11 23	070915.32	21.1974S 44.9485W	2.6

Analysis of the seismic activity detected by the local network

We analyzed data acquired between August 14th, 2011, the day of the Ijaci main event, and May 25, 2012, when the network was dismounted, leaving only FUN1 station. During this period, 1020 events were detected of which approximately 500 were located (241 artificial events - explosions and 276 natural events). Presented in Annex 1 of Special Report nº 2 is the classification for the nature of such events, detailing whether they were artificial (explosions) or natural. In the case that it was an explosion, the report details whether or not it appears on a list of scheduled detonations/explosions supplied by the quarries and if the time given is the same time the recording was made. The majority of events were located with data from a single station, especially FUN1 station (Table 3).The main quarries in the region are shown in Figure 1 and 8. They are: Camargo Correia North (CC2), Camargo Correia South (CC1), Alvarenga (AV) and Mina Santa Helena (SN). It is difficult to analyze the data since some explosion records are much like the records of natural earthquakes and therefore discrimination is very difficult and time consuming. Table 3 shows the number of events localized and the number of stations used.

Table 3: *List of events located by number of stations.*

Events located by number of stations	Explosions	Natural	Total
Events located by 1 or more stations	241	276	517
Events located by 2 or more stations	144	87	251
Events located by 3 or more stations	106	50	156
Events located by 4 or more stations	77	27	104
Events located by 5 or 6 stations	28	7	35

Reliability in the epicenter locations

The accuracy of locating the epicenter, among other factors, depends on the number of recording stations, distances between stations to the epicenter and on the value of the gap in the azimuthal coverage of stations. Events detected by many nearby stations and epicenters located in an area circumscribed by the seismic stations of a network usually have more accurate locations. Despite having located a relatively large number of events, both natural and artificial, in this work we will restrict the cases where accuracy in the epicenter locations is on the order of 1-2 km. So, we have to impose appropriate constraints in order to get such event precision. Thus, the epicenters of natural and artificial events have been plotted as follows.

Location of natural events

We selected thirty (30) natural events detected by three or more stations, with a maximum gap coverage in an azimuth of 250º stations. Figure 8 shows the epicenters of thirty (30) natural earthquakes (red circles). Events 1, 2, 3 and 4, indicated by blue circles, are the four main Ijaci events shown in Table 2.

Locating artificial events

The selection of artificial events was more restrictive and considered only events detected by 4 or more stations and a maximum azimuthal gap of 280º. Thus, we selected 39 (thirty-nine) events whose epicenters are plotted with yellow circles in Figure 8.

Discussion and conclusions

Seismic activity, natural and artificial, observed near the city of Ijaci/MG was studied with a local seismic network of seven stations, although the period was too short for when all seven stations operated simultaneously. No event was detected by all seven stations together. The maximum number is six stations.

Natural earthquakes are happening very close to the quarry and Funil reservoir, even within the lake, as shown in Figure 8.

The dispersion at the locations of the artificial events is related to the precision in the locations' epicenters, since it is expected that the detonation points are those which can be seen in the image of Figure 8. We do not know if there are other points of mineral extraction different from what can be seen in the image.

As can be seen in Special Report No. 1, historically there has not been seismicity in this area. There are however, three new events in the area, namely:

1st. The Funil reservoir;
2nd. The quarries and;
3rd. The lowering of the water table level in the Camargo Correia quarry.

Arguably, all of these factors can trigger seismicity together or separate. However, we cannot say which one or ones are contributing to the observed tectonic earthquakes in the area. Moreover, events of these magnitudes can happen anywhere, even in areas where no historical seismicity had been observed.

Available data will be further analyzed in order to determine the type of faulting causing the natural and/or triggered events. To this end, a focal mechanism study will be made to understand the type of geological fault along which these events are happening. To achieve this, we need information from the quarries about conducting or not conducting detonations that were recorded which may not have been properly reported or not reported at all. In the focal mechanism study we cannot confuse artificial events with natural events.

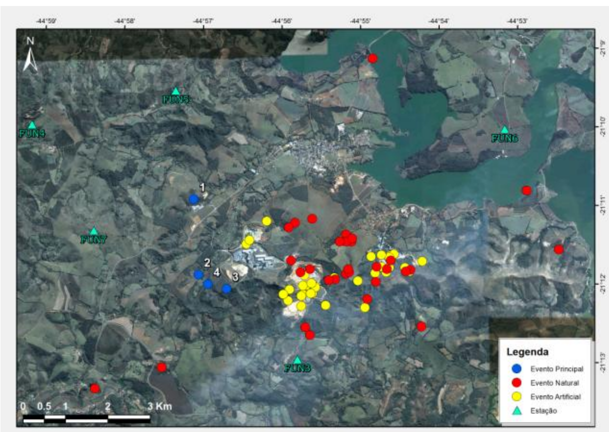

Figure 8: Distribution of epicenters of natural (red circles) and artificial (yellow circles) events detected selected according to the text. The four blue circles indicate the epicenters of major natural Ijaci events. Event 1 (08/14), event 2 (10/05), event 3 (11/13) and event 4 (11/23) were located with the FUN1 station.

Acknowledgements

The authors thank the engineer Gilson Machado da Luz from Eletronorte Company who kindly loaned instruments for two seismographic stations, without which this work would not have been possible. We would also like to thank the Consortium FUNIL for having invested in the deployment of the seismographic network.

References

Barros, L.V., 2011. Relatório Especial Nº 1, Observatório Sismológico da Universidade de Brasília, 31 de janeiro de 2012, 22pp.

Barros, L.V., 2012. Relatório Especial Nº 2, Observatório Sismológico da Universidade de Brasília, 31 de janeiro de 2013, 42pp.

Assumpção, M., Ardito, J. e Barbosa, J.R., 2010. An improved velocity model for regional epicentre determination in Brazil. IV Simpósio Brasileiro de Geofísica, Brasília, 13-16 de novembro de 2010.

Berrocal, J., Assumpção, M., Antezana, R., Dias Neto, C., Ortega, R., França, H., Veloso, J.A., 1984. Sismicidade do Brasil. Published by IAG/USP and Comissão Nacional de Energia Nuclear, Brazil, 320p.

Havskov, J. & Ottemöller, L. (Eds.). SEISAN: The Earthquake Analysis Software, Version 8.1. Inst. of Solid Earth Physics, University of Bergen, Norway, 2008. 227 p.

Kissling, E., 1995. Program and VELEST user's guide - Short introduction. Institute of Geophysics, ETH Zuerich & Swiss Seismological Service, ETH-Hoenggerberg. 26 p.

Lienert, B. R. Hypocenter 3.2: A computer Program for Locating Earthquakes Locally, regionally and globally. Ha waii Institute of Geop. & Planetology, Corea, 1994.

Miljanovic, V. "Geotool – Software User Tutorial, CTBTO/IMS/IDC 1.0 13.07.2007. Vera Miljanovic Software User Tutorial <GT_tutorial_ver01.pdf>.