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Focal mechanism to Furnas reservoir induced seismicity detected in Areado-MG in 2003-2004

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Abstract

A fault plane solution to Furnas reservoir triggered seismicity occurred in Areado is presented. This seismogenic area has been proven to be seismically active some times in the past, especially in the last three years when two seismic sequences were detected there.
In recent survey carried out for the last sequence, from January/2004 to December/2005, more than a thousand and half of micro earthquake were detected, almost a half of them being located. The spatial distribution of the epicenters establishes a NNW - SSE trend in accordance with focal mechanism solution, such result indicated a pure reverse faulting regime with SHmax roughly in E-W direction.
Beside the seismicity, this work intends to present the results of a well constrained focal mechanism determination gotten from a very particular set of data selected from 1524 micro earthquakes detected in the period of two years. It will be addressed to the main reasons that lead us to conclude that Areado seismicity is the more delayed case of reservoir triggered seismicity in Brazil.

Introduction

The first seismic activity felt by Areado's population occurred in January 1991, 27 years after the first impoundment of Furnas reservoir. In October of 1991, after 2.8 magnitude on September 17, felt in Areado town with a MM intensity IV, a local seismic network was deployed (Veloso, et al., 1991 and Blum, 1993). In 1994, 1996 and 1997 isolated events were detected in Areado (Assumpção at al., 1997 and Fernandes et al., 2003). However, in March 2003 and January 2004, two main events were registered with magnitudes 3.4m_b (MM V) and 3.2m_b (MM IV), respectively. These last two events were followed by aftershock activity and studied with local seismographic network (Marza et al., 2003; Fernandes et al., 2003 & 2005 and Barros et al., 2004 & 2005). The first activity remained alive for few months, but the second one still yet in course until now (June, 2006).
To study the last sequence it was deployed a seismic network with up to six three components stations that detected 1524 micro earthquakes from January 2004 to December 2005, almost a half of them being located with data gathered by at least three stations. All hypocenters are shallow, with deeps ranging from zero to 1,5 km, and located on the margins and inside a Furnas Reservoir branch. The spatial distribution of the epicenters establishes a trend in NNW-SSE direction dipping to SW, in good accordance with the focal mechanism solution, such results indicated a pure reverse faulting (strike = 145°, dip = 20° and rake = 90°), the maximum horizontal compression axe has an strike of 55°.

Area of study and historical seismicity

The Furnas reservoir Power Plant is situated in the southeast of Brazil, in the extreme south of Minas Gerais state, in the contact between three main geological provinces: the south of São Francisco Craton, the Brasilia Folding Belt and the coastal Ribeira folding Belt. More exactly, the area of study lies on the Varginha-Guaxupe complex, composed by gneisses, migmatites, metasedimentar rocks, milonitics rock and some granite intrusions (Blum, 1993). Areado is located on Mantiqueira province, close to the south of the Sao Francisco Province, mainly crossed by shear faults or by contractional shear zone, oriented mainly in E-W direction (Figure 1).
The Furnas reservoir, according to the CBGB (Comite Brasileiro de Grandes Barragens), is classified as a large dam, with a volume of 23 km^3, area of 1,440 km^2, depth of 127 m and maximum extension of 220 km. The first impoundment of the reservoir started in 1963, but the seismic monitoring begins only in 1981 (FUR1 station in Figure 1, 75 km far from the Areado seismogenic zone), 19 years later, with a uniaxial analog short period station, which was replaced by a digital short period three components station in 2001.
According to Assumpção et al. (1997), the southern part of Minas Gerais State, together with the offshore continental shelf concentrates mainly the seismicity of the southeast of Brazil. So, the Furnas Reservoir is located in an area of relatively high seismicity.
The first seismic event documented around Furnas Reservoir occurred in São Pedro da União, six months after the impoundment of the reservoir (Berrocal et al. 1984). However, there is only microsseismic information for this event. After that, another event was registered in Cabo Verde (in 1967). Nevertheless, the epicenters in both cases were located a bit far from the reservoir margins; therefore they could not be associated to triggered seismicity.
In Alfenas, from 1981 to 1990, seven events were detected with magnitude ranging from 2.1 to 2.9. According to Fernandes et al. (2003), these events could not be associated with the reservoir, since the frequency of occurrence is not common for triggered reservoir

seismicity. They were located by regional stations, 20 km in southeastern of Areado (Figure 1). However, the biggest event ever detected in Alfenas (3.1m_R) occurred in September 9 of 1991. In spit of located close to a branch of Furnas Reservoir it was not possible to associate any swarms of quakes to these events, they happened in isolated form. But, in another hand, the events were located inside the lake and the closer station (FUR1), located about of 100 km away from, such capability of detection should have a threshold magnitude around of 2,0.

The most well studied events (five occurred between March of 1993 and July of 1995 and magnitudes ranging from 1.8 to 3.1) with epicenters around Furnas reservoir occurred in Formiga, or more precisely 10 km in the south of the town of Formiga, located in the eastern edge of the Sao Francisco craton. Assumpção et al., (1997) determined focal mechanism solution for the events of 1993 (three, with magnitudes of 2.5, 2.9 and 3.1) using amplitude ratio in three regional broad-band stations. They founded a predominantly normal faulting with N-S oriented T axis.

However, the most expressive seismicity around Furnas reservoir is concentrated in the Areado seismic zone; from all events plotted in Figure 1 (seventy at all), a half of them were located in Areado, and it should be noticed that the most important events of Areado happened mainly in height water level of Furnas reservoir. There is a clear correlation between these events occurrence and picks of the reservoir impoundment.

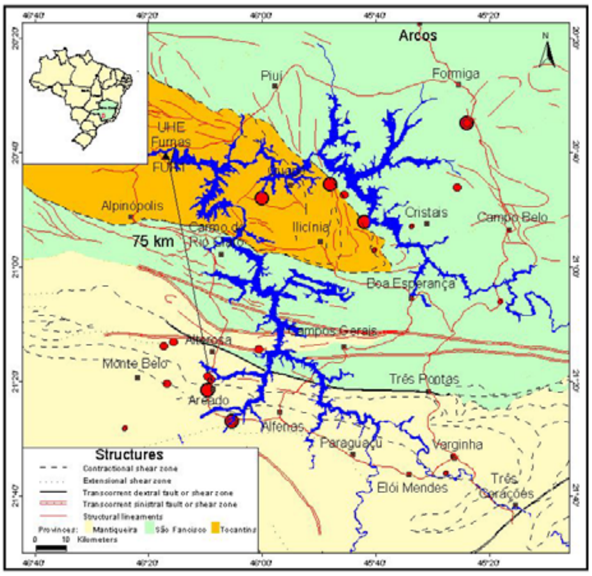

Figure 1 - Geological setting and seismicity around Furnas Reservoir since 1965. Magnitudes are proportional to the circle size. The FUR1 station, indicated as triangle close to the Furnas dam, is located 75 km away from Areado seismic zone.

Areado seismic sequence of 2004-2005

This sequence was studied with a local seismographic network (with up to six stations) that operated from January 28 of 2004 to December of 2005. The stations location can be seen in Figure 2. All stations are three components digital short period, except for the ARE10 station, which is a broad-band type.

Analysis method

The data collected was recorded in two different sets of seismographic: 1) A short period three components S3000EQ Sprengnether seismometer, coupled to a data logger mark Orion, factored by Nanometrics, operating in the frequency band of 1Hz to 100Hz; 2) A broad-band three components CMG-40T Guralp seismometer, coupled to the same datalogger, as above, operating in the frequency band of 30 s to 100Hz. In both cases the sample rate was 100Hz.

Before processing, the data was prepared in order to insert in SEISAN data base (*The Earthquake Analysis Software*) (Haskov & Ottemöller, 1999) in such environment the waveforms were analyzed, using different programs, such as: programs for Hypocenter Locations, HYPOCENTER (Klein, 1978) and VELEST (kissiling, 1995), Focal Mechanism determination, FOCMEC (Snoke et al., 1984; Arvidison, 1992), wave form analysis, SAC - Seismic Analysis Code (Taplay, 1991) and Mulplt (Haskov & Ottemöller, 1999), etc

Data Base Selection

A set of 1524 micro events (magnitudes ranging from menus1,0 to 1,8) detected by *Areado's Local Seismographic Network (ALSN*) in two years of continuous operation were classified in accordance with the number of recording stations, establishing 6 data sets, according to the number of stations that detected the same event (Set1 composed by that events detected by only one station=337; set 2 detected by only two station = 448 events (and so on); set 3 =301 events; set 4 = 284; set 5 = 45 events and set 6 = 4 events). Events of sets 1 and 2 were not located, although it was possible to do so, since epicenters can be determined using data of just one triaxial station (Haskov, 2001). However, as a matter of accuracy, it was dicided to locate the events using at least three 3-component stations, which guarantees a better azimuthal coverage and, therefore, better accuracy in hypocenter locations.

Velocity Model

The ratio between P-wave and S-wave velocities (Vp/Vs) was determined using Wadati diagram with a set of 30 events detected by at least five 3C stations and duration magnitude above 0,2. It was found

vp/vs = 1.6782 ± 0.003. The velocity model was determined experimentally through the minimum RMS (Root Mean Square) criteria of the travel time's residual. The best single layer velocity model founded was: vp= 5.8 km/s (Barros, et al., 2004).

Hypocentral location

Single and joint hypocentral determination techniques were applied, using HYPOCENTER (Lienert, 1995) and VELEST (Kissling, 1995) locations Programs, respectively. The location results are more or less the same. The Figure 2 shows the epicentral distribution (joint location) of 634 events, being five outside active Aerado`s fault. Triangles denote seismic station.

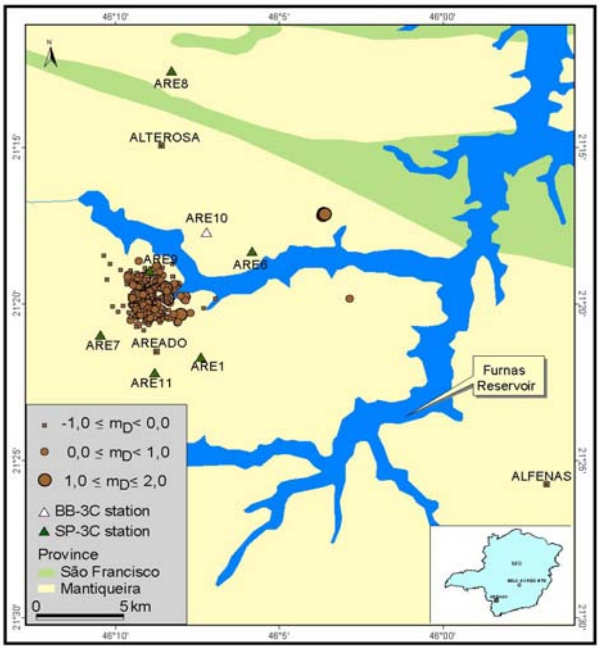

Figure 2 – Map of epicentral distribution (joint location) of the Areado earthquakes. The seismographic stations are indicated by triangles.

Focal Mechanism Determination

The aim of the focal mechanism studies is to determine the fault orientation (strike and dip angles) and the sense of its movement (slip vector), as well as the direction of the compression (P) and dilatation (T) axes. These parameters are strongly dependent on the hypocenter location accuracy, especially in the case of local studies, when a station can be located very close to a nodal plane. Short location errors can put the epicenter in other side of the fault, due to short variation in the ray incident angle; and so causing misunderstands in the distribution of polarities.

Other aspect that one should be take in account, when determining fault plane solution is to avoid mistakes when reading P polarity due to the presence of some onset P-wave precursors spurious introduced by the violation of the Nyquist theorem (Scherbaum, 1998). Which should be avoid by applying FIR filtering in order to remove alias effect before analyze data.

Taking this constraint in mind it was made a selection of only four events detected by the same six stations,, observing the firs signal arrivals simultaneously in the three components of the ground movement, in order to be secure in the polarity readings. In Figure 3 it is presented the spatial distribution of the four epicenters (a) and a view of hypocenters distribution in SW-NE direction in (b).

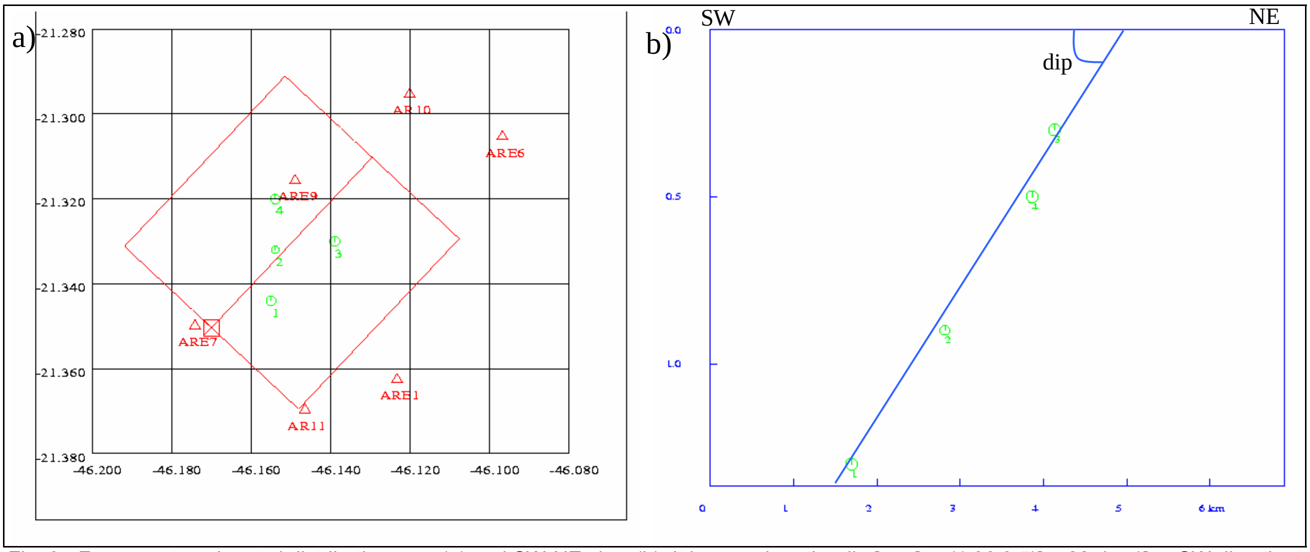

Fig. 3 - Four events epicentral distribution map (a) and SW-NE view (b). It is very clear the dip [arc [tan(1.36;3.5)] = 22 deg.)] to SW direction

As we can se easily, there is a clear dip (arc[tan(1,36/3,5)] = 21,26°) to the SW direction. This result is consistent with the dip founded in the focal mechanism solution, as can be seen later.

It was made individual focal mechanism for each event in order to see the consistence between the individual solutions and composite focal mechanism solution of all set. As we can see in Figure 4 (a, b, c and d), focal mechanism solutions for events 1, 2, 3 and 4, respectively, all individual mechanism is consistent with the composite focal mechanism solution presented in Figure 5. In such solution there is a unique inconsistence polarity in station ARE9 for the event 3, the shallowest.

Otherwise, it should be noted that hypocenter very close to the surface, as is the case of event 3, where the rocks are not solid, composed by loose sediments (normally offering little resistance), there is no need for a fault rupture to break along the exact same surface.

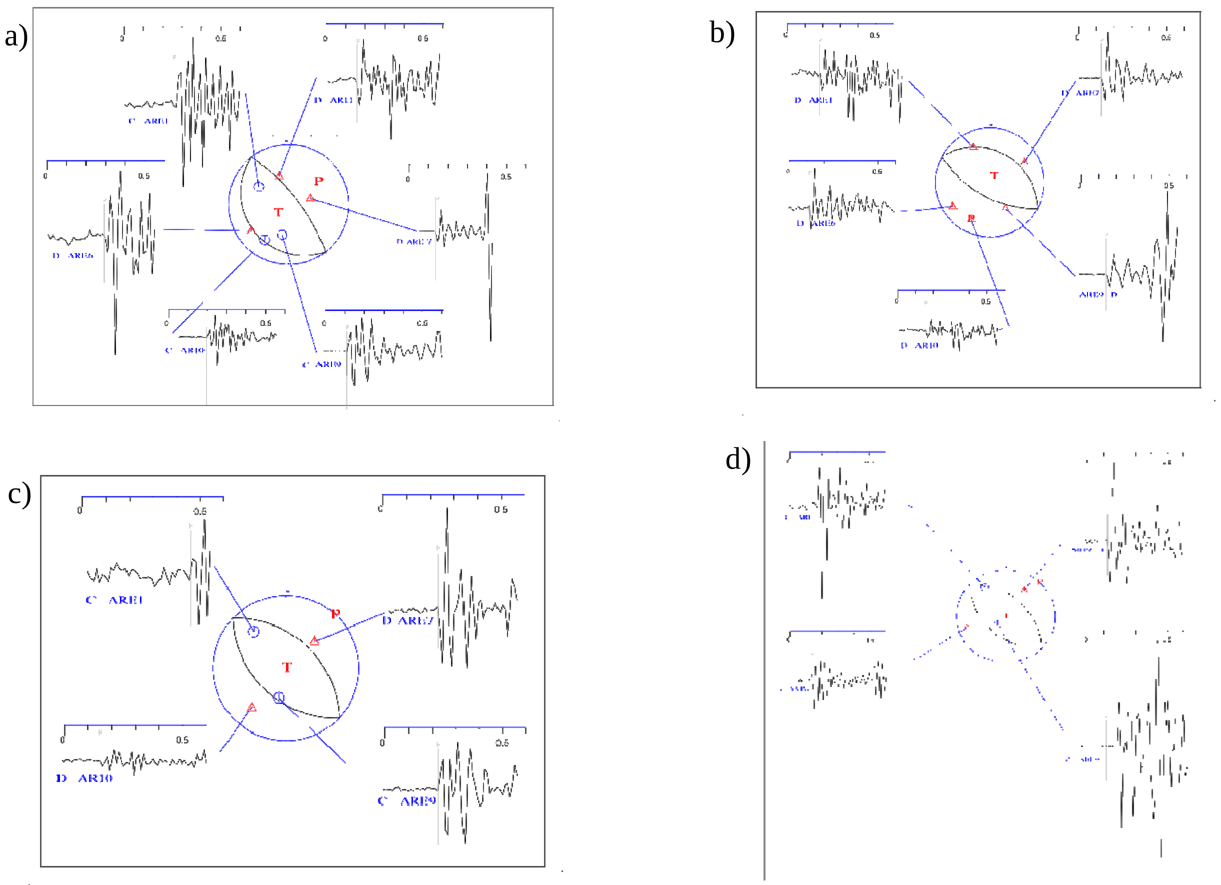

Fig 4 - individual focal mechanism solution for the set of four event a) event 1: b) event 2: c) event 3 and d) event 4.

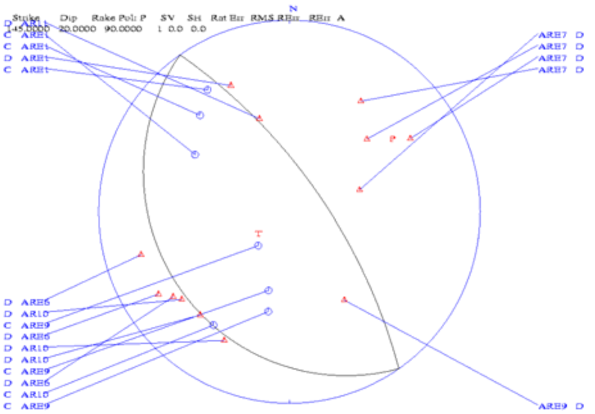

Fig 5 - Composite focal mechanism solution for a set of four events. Projection in the inferior hemisphere as above. Triangle denotes dilatation (D) and circle compression (C). There is a unique inconsistence polarity in station ARE9.

As the ARE9 station is very close to the fault plane, little horizontal error in the event 3 epicenter may moves it to other side of the fault trace, resulting in a opposite polarity, in the case dilatation one (D), in opposition to that ones observed for the events 1, 2 and 4 (Compression - C). All individual solution presents an inverse faulting, dipping to the southwestern direction, as is the case of final solution, presented in Figure 5.

According to the composite focal mechanism solution (Figure 5) the 2004-2005 Areado micro earthquakes seismic sequence were due a pure reverse faulting with the following parameters: strike = 145º; dip = 20º forward SW and rake = 90º. The P and T axes have following strike and dip 55 and 25, 235 and 65, respectively.

Discussion

The Furnas reservoir power plant, located in the southern portion of Minas Gerais state is located in an area of relatively height seismicity (Assumpção et al., 1997). But, all the seismicity observed around the reservoir occurred mainly after its first impoundment, in 1963 (Figure 1).

The study of Areado 2004-2005 seismic sequence with a 3-component local digital seismographic network, with up to six stations, detected an active seismogenic area 2 km to the northern of Areado/MG town, with shallow epicenters located on the margins of and inside Furnas Reservoir. This seismogenic area are not quit different that one identified in previous studies (Blum, 1993, Assumpção et al., 1997; Fernandes et al. 2003 & 2004; Marza et al., 2003 and Barros et al., 2003 & 2004) related to the 1991-1992, 2003 and 2004-2005 seismic sequences.

A well constrained nodal plane solution presents for Areado seismogenic area a pure reverse faulting as more stable solution, since it is a possible solution in all focal mechanism diagrams attempted, and therefore, more stable.

The fault dip founded (20°) is very consistent with that one observed in Figure 3.b), but the strike (145°) could not be seen in Figure 2, because in that Figure it were plotted all events located (634), and the epicentral distribution presents a little scatter due to location inaccuracy, since a half of events located was detected with data of three station with a gap ranging between 341° and 126°. But one should be attempted to conclude that there is a clear trend in N-S or NNE-SSW directions. However, this conclusion is not confident because there is no precise hypocenter location due to, especially, data quality.

In Figure 3.a), despite of a good accuracy in hypocentral location, there are not enough events in order to draw a confident line representing the fault trace on the surface plane. So, it was prepared a new set of events composed by events detected by at least five stations and magnitude above 0.2. This selection comprises 30 events and its epicentral distribution is displayed in Figure 6, enclosed by the rectangle such main sides are aliened with sequences of events, establishing a fault trend in a NNW-SSE direction, in accordance with the fault strike determined in composite focal mechanism.

The founded azimuth of compression axe (P) of 55°, a good approximation of the maximum horizontal stress (SHmax.), is in good agreement with previous studies of modeling the driving and resistive forces actuating in the South America plate (Assumpção, 1992; Mejer & Wortel, 1992; Richardson & Coblentz, 1996).

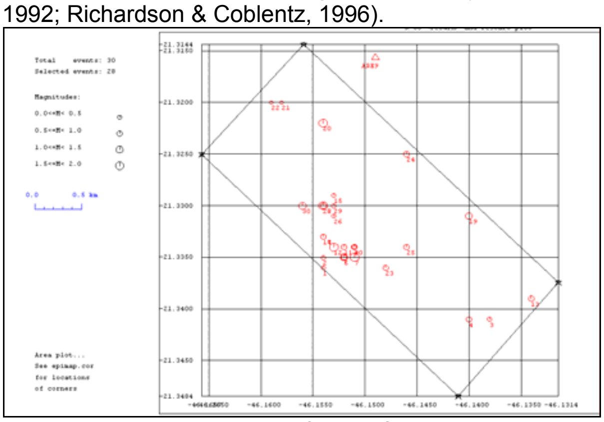

Figure 6 Epicentral distribution of a set of 30 events detected by at least five 3C stations and magnitudes ≥ 0.2 m_D.

It seems to be very straightforward to conclude that the Areado seismicity is triggered by Furnas reservoir, because it were founded strong prerequisites to point out that: i) A clear cause and effect relation between seasonal water level fluctuation and seismicity; ii) Epicenters close or inside the reservoir; iii) Focal depth very shallow, between zero and 1.5km; iv) b value parameter high enough to be compatible with the value of triggered sequences; v) All the seismicity in Areado has occurred in swarms, common in cases of triggered seismicity and vi) No seismicity detected before the existence of the Reservoir. So, it can be concluded that Areado is a case of delayed triggered seismicity; the quakes appeared only 27 years after the first impoundment of the reservoir.

The Areado seismicity should be due to a preexistent fault reactivated by Furnas reservoir, mainly caused by increase in pore pressure by slow diffusion of the reservoir water in 27 years, that it was the elapsed time between the first impoundment of the reservoir, in 1963, and the first seismic event detected in Areado, in 1991. This is the more delayed case of SIR in Brazil, followed by Carmo do Cajuru reservoir that takes 17 years (Assumpção et al., 2002).

Reservoir loading has little influence in a regime of inverse faulting and some times actuates in opposite direction, moving the Mohr circle away from the rupture envelope (Figure 7). So, it should be admitted that the main cause of the Areado seismicity is due to E-W regional tectonic stress added to local effects specially related to the high topography in the area of Areado, almost above 1000 m. This topographical influence is responsible for the rotation in 10 ° on SHmax main stress to SE direction.

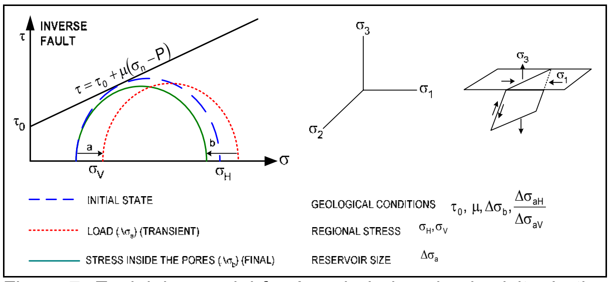

Figure 7- Explaining model for Areado Induced seismicity. In the inverse faulting regime, as is the case of Areado, the reservoir loading tends to move the Mohr circle away from the rupture envelope, as it shown with the dash read line. The pore pressure actuates in opposite side, moving the Mohr circle in the direction of the rupture envelop (green line), that is the dominant effect case in Areado. In center is shown the directions of the principal axes the maximum horizontal compression is coincident with σ_1. H and V denote tensions horizontal and vertical, respectively, a and b refers to the effects of loading and pore pressure s, respectively. Modified from Snow, (1972).

.Conclusions

From this Study we conclude that:

1) Hypocentral locations of the Areado/MG micro earthquakes are reasonably accurate (single and joint), although the single velocity model, despite reasonable, may produces errors, as it can be seen in the little dispersion Wadati diagram data points, showed in the Figure 07;
2) All earthquakes hypocenters are located in the margins or inside a branch of Furnas reservoir which are shallow, with their deep ranging from zero to 2.0 km (characteristics of induced earthquakes);
3) Joint and single hypocentral locations are quite similar due to little distances between the source and the stations and so the low heterogeneity of the rocks elastics properties inside the ALSN;
4) b parameter determined for the sequence (b = 1.36 ± 0.29) may has its value compatible which b parameter of induced reservoir earthquakes. However, its standard deviation is a little bit high, due to the low amount of data used;

5) From all solutions founded for the fault plane, the most reasonable shows a pure reverse faulting, in the NNW-SSE (145°) direction, dip = 20°SW, and rake = 90°. The P and T axes have, respectively, the following strike and dip: 55º and 25º, 235º and 65º. The direction of the maximum compression exe (T), a god approximation of the maximum horizontal stress (SHmax), is in agreement with theoretical models of the driving forces actuating in South American plate;
6) Few Improvement in these results can be obtained whit the determination of a better velocity model from a geophysical experiment with controlled source, possible in the future;
7) It should be noted a very strong correlation between the reservoir water level fluctuation and Areado seismicity; all the Areado main shocks occurred in higher reservoir water level, as well as the number of after shocks for 2004-2005 seismic sequence accompanying the reservoir fluctuations. Keeping these observations in mind we can conclude that Areado seismicity is one case of delayed triggered seismicity, the first events observed only 27 years after the firs impoundment of the reservoir.
8) The Areado well constrained focal mechanism solution may gives a great contribution to future studies of tectonics stress modeling related to the orientation of the resistive and driving forces actuating in the South America Plate;
9. The Areado seismicity should be due to a preexistent fault or system of faults reactivated by Furnas reservoir, mainly caused by increase in pore pressure by slow diffusion of the reservoir water. The differences in fault location and focal mechanism solution in the three different studies carry out in Areado should be related with the data quality used in each case.

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