Presented at "Short Course V on Conceptual Modelling of Geothermal Systems",
organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, February 24 - March 2, 2013.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

MICRO SEISMIC MONITORING DURING PRODUCTION UTILIZATION AND CASE EXAMPLES FOR MEXICO

Efrén Cruz-Noé, Cecilia Lorenzo-Pulido, Jorge Soto-Peredo and Saúl Pulido-Arreola
Comisión Federal de Electricidad (CFE)
Alejandro Volta 655, Morelia, 58290, Mich.
MEXICO
efren.cruz@cfe.gob.mx

ABSTRACT

Seismic networks in the geothermal fields of México have operated since the 1990's. This paper reports the results and applications of the micro seismicity recordings in Los Azufres, Los Humeros and Las Tres Virgenes Geothermal fields in México. The information generated in those fields is useful since micro seismicity is a support tool for defining drill targets of production and injection wells, as well as to identify fluid movement in the subsurface, which can be related to permeable zones. It has been shown that seismic activity within the Mexican geothermal fields, associated with the production and injection strategy, does not exceed the 3.5 degree magnitude, so no major events associated with the operation of the reservoir are produced, that may constitute a risk to people or infrastructure.

1. INTRODUCTION

Geothermal energy in Mexico is almost entirely used to produce electricity, since its direct uses are still under development and currently remain restricted to bathing and swimming. The net installed geothermal-electric capacity in Mexico as of December 2010 is 958 megawatts (MW). This capacity is currently operating in four geothermal fields: Cerro Prieto (720 MW), Los Azufres (188 MW), Los Humeros (40 MW) and Las Tres Vírgenes (10 MW). However, the running capacity is less than that, because of production decline mainly at Cerro Prieto geothermal field, one of the largest geothermal fields in the world. All of the geothermal fields and power plants are owned and operated by the governmental agency CFE (Comisión Federal de Electricidad). Electric uses of geothermal are planned, developed and operated by the Gerencia de Proyectos Geotermoeléctricos – the geothermal division of the CFE, (Flores-Armenta, 2012). In 2012, 221 production and 29 injection wells were operating in Mexico at the geothermal fields of Cerro Prieto, Los Azufres, Los Humeros and Las Tres Vírgenes. (Gerencia de Proyectos Geotermoeléctricos, GPG, 2012).

During the operation of a geothermal reservoir, stress changes occur which can be generated for several reasons; sudden release of energy in the ground, by the collapse of a geological structure, reactivation of geological structures, by exploitation of the geothermal resource and re-injection; these changes can be measured using the technique of microseismicity.

The use of geothermal microseismicity is significant since it is a powerful tool when combined with other subsurface measurements, resulting in an increase of the knowledge of the reservoir, useful for decisions making, when the exploitation strategy and the reservoir response is linked; in this way it can be observed that zones with high seismicity can be related to high permeability zones, those zones are very important in the development and profitability of the projects.

This article documents the use of this tool and it is illustrated with case studies of geothermal fields in Mexico.

2. UTILIZATION OF MICRO SEISMIC MONITORING

Monitoring of passive micro seismic activity among the geothermal fields in Mexico, aims to identify active faults, fractured or permeable zones, and the relationship that can be inferred with geothermal water injection and / or extraction of geothermal fluid in the subsurface, which may be related to the geothermal reservoir. These zones can manifest themselves due to the occurrence of very small seismic events, called microseisms, which originate due to the geothermal fluid movement or the reactivation of existing fault systems.

Seismic monitoring confirms the changes in the local stress and the presence of activity in areas where seismic activity had not been observed. Micro seismicity normally occurs in a place even before the operation of a geothermal field, but it might increases during the operation of the same due to numerous reasons.

Additionally the micro seismicity is a support tool for setting the objectives for production and injection new wells, joint to the resistivity and geology studies, as well as geoelectric gradients associated with structural systems matching the hypocentral location of seismicity. Also, having a comprehensive catalog of micro-earthquakes, it is possible to calculate the b-value, which is used to delineate indirectly the presence of magma beneath the reservoir (high b-values) or the lack of magma at the subsurface (small b-values).

Study cases for Los Azufres, Los Humeros and Las Tres Virgenes geothermal fields will be discussed as follow.

2.1 Los Azufres Geothermal Field

Los Azufres is the second geothermal field operating in Mexico. It is located in the central part of the country, 250 km away from Mexico City, and lies within the physiographic province of the Mexican Volcanic Belt in a pine-forest at 2,800 masl. The first power units were commissioned in 1982, and presently there are 14 power units in operation: one condensing of 50 MW, four condensing of 25 MW each, seven 5-MW back-pressure and two 1.5-MW binary cycles. The total installed capacity is 188 MW. (Flores-Armenta, 2012).

Three structural systems are identified in the whole field. The oldest of them is the NW-SE system, the NE-SW is intermediate in age, and the most recent is the E-W. Most of production wells are associated to this later and to its intersection with the others. (Pérez-Esquivias, 2001).

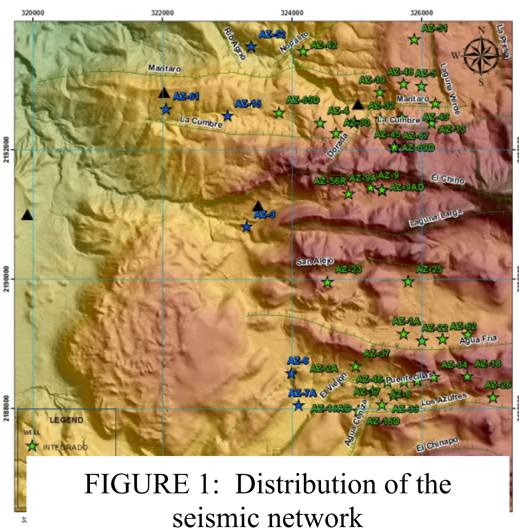


FIGURE 1: Distribution of the seismic network

The seismic network in this area consists of five seismic stations which are distributed optimally in coverage to record as many earthquakes that occur on the field (Figure 1).

These stations have digital seismographs, triaxial and broadband CMG-6TD Güralp, owned by the Universidad Nacional Autónoma de México (UNAM). The equipment continuously records 100 samples per second per channel, in a solid state memory with capacity of 2 GB. The equipment has GPS, for timing control.

To locate the seismic network detected, the Hypocenter program was used (Lienert, et al., 1986). The velocity model used in this study is presented below (Table 1):

TABLE 1: Velocity model

P Wave Velocity (km/seg).	Depth (km).
3.5	0.0
4.0	1.0
6.0	3.0
6.5	15.0

To illustrate the usefulness of the data obtained from the seismic monitoring, the period from November 2011 to October 2012 was selected. There were located 121 seisms of tectonic type with three or more seismic stations in the vicinity of the Azufres Geothermal Field. The seisms, which magnitudes vary between 0.3 and 1.7 degrees, are located primarily in the western sector of the seismic network. The depths of the hypocenters are generally less than 3 km (the average depth of the hypocenters at the geothermal reservoir is 2.4 km), although seisms a little further away from the reservoir have been detected, with depths of 11 km beneath the surface. Between the seismic activity reported, we observed two swarms of earthquakes in the vicinity of injection wells AZ-15 and AZ-61; on January. 14th with 16 seismic events, on May 25th with 15 seismic events; those seismic swarms, define an alignment or a tendency NW-SE and NS (Figure 2). While these possible fractured zones have not been mapped through the geological area surface, the seismic alignment NW-SE correlates well with a geoelectric gradient with the same direction, which indicates a possible major active structural system (Figure 3), since as mentioned earlier, it might represent a fractured area, with permeability and possible high temperature, so it is considered a potential area for new locations of wells.

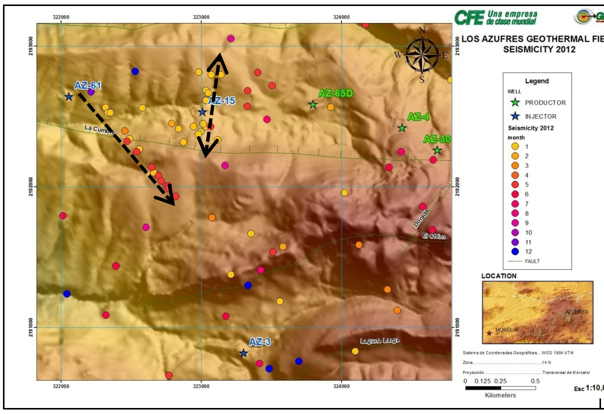


FIGURE 2: Los Azufres Geothermal Field Seismicity 2012

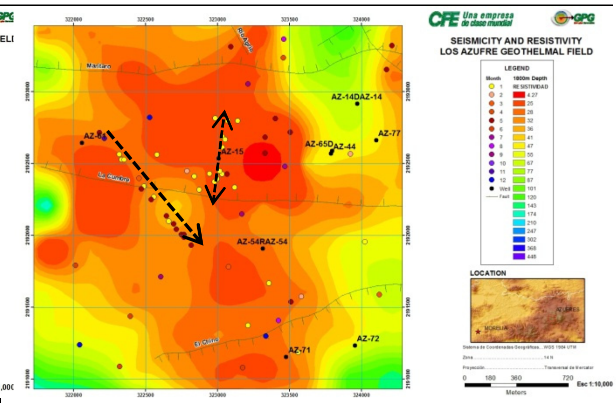


FIGURE 3: Los Azufres Geothermal Field Seismicity vs Electromagnetics

Another analysis of importance that begins to be used in this field, is the calculation of the B value, which is the value of the line's slope that best fits the linear part of the logarithm of the cumulative number of events and the magnitude into a region, according to Gutenberg and Richter relationships. High b-values are associated with the presence of magma, while the absence of high B-value, suggest a lack of magma, (C. Valdez-Gonzalez, 2012). Other factors that produce high b-values are the presence of hot fluids in geothermal systems or highly fractured systems, acquired by past eruptions. With this recorded seismicity at Los Azufres, the b-value calculation was performed and plotted in a three dimensions figure (Figure 4). This chart shows that there are high b-values in the South and Southwest location of the "El Chino" seismic station, and that at depth, the maximum b-value occurs approximately among 2 to 4 km below the surface. The high-B values calculated with this technique also corresponds to the higher temperature isotherms in Los Azufres, so this methodology is also useful to identify sites with higher temperature or heat ascent zones, to locate new production areas and could also identify the approximate location of the heat source of the system

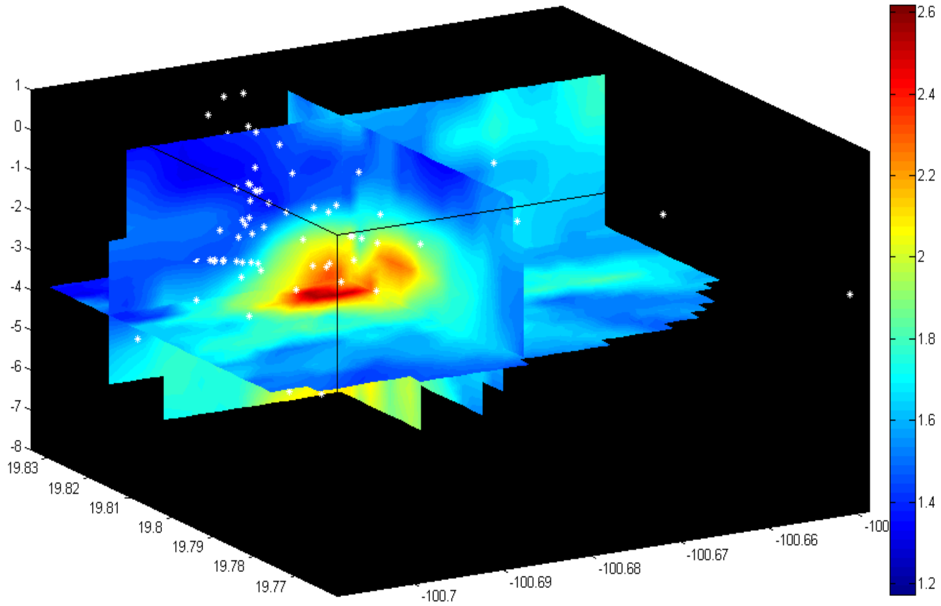


FIGURE 4: B value at Los Azufres Geothermal Field

An important part of the geothermal exploration activities, is the location of new geothermal wells, with the objective of increasing the production of steam, which means greater power generation. In this sense the micro seismic technique has shown to be of great support in locating new wells for production and injection if used in conjunction with detailed geological, gravity and electromagnetic studies. This is exemplified below with the location proposal of well AZ-77.

This well is located in the northern part of the geothermal field, with a target at depth of crossing the structural geological systems NW-SE 800 to 2000 m, NE-SW from 1100 to 1700 m, 1500 to EW 2000 m depth (La Cumbre Fault).

Figure 5 shows the NE 62 ° SW section, which shows that the seismicity occurring in the NW-SE geoelectric gradient with a fallen to the NE from 800 m and deeper, in the vicinity of the proposed well AZ-77; this gradient represents the structural system of La Cumbre fault and the seismicity indicates that it is an active fault.

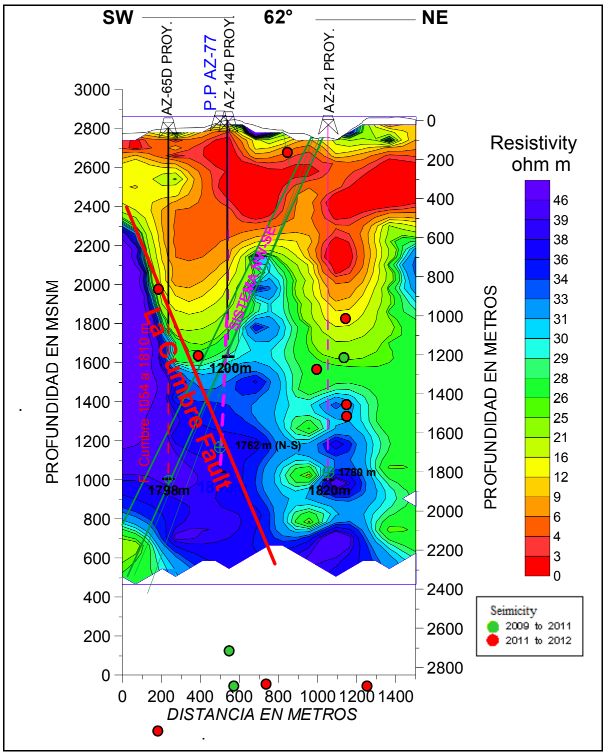


FIGURE 5: SW-NE Section Well AZ-77

The structures determined by the occurrence of spatial geoelectric gradients and seismic events recorded, corresponding to the SW part of the section as the Structural System "La Cumbre" which dips to the NE. These changes of gradient and the tendency that hypocenters show are associated to the present structure, being this the target for the production well AZ-77.

2.2 Los Humeros Geothermal Field

The geothermal field of Los Humeros-Puebla, is located in the eastern portion of Puebla, on the border with the state of Veracruz at 19.2 km northwest of the city of Perote, Veracruz, is part of the Transmexican Neovolcanic Axis. It should be mentioned that the complex superficial geology, product of the various geologic events that created the Caldera of Los Humeros, and the ones after its formation, resulted in some areas of geothermal interest with insufficient evidence surfacing in surface structures, except some exceptions. Microseismic monitoring, and lifting electromagnetic studies, are the support of indirect methods for the exploration stage, which helps to identify faults and fracture systems that lack of structural features visible on the surface. Furthermore, in the operational phase, they are used in the development of geothermal conceptual models and in the proposal of production and injection wells.

The Seismological Network of the geothermal field was installed in December 1997 and it is in operation to this day, being property of CFE. The main objective of the network is to monitor seismic geothermal reservoir, and to know the present seismic zones, which can identify the relationship that this activity present with the injection, and extraction of geothermal fluid, and the relationship with the presence of active structural geological systems (faults, fractures, etc.) and geothermal fluid conductors. From December 1997 to December 2004, the network was instrumented with high sensitivity equipment consisting of 6 remote stations (Figure 6) with three data channels each (components Z, NS and EW). These 18 data channels are transmitted to a central station via a relay station, for processing and recording, using the digital data transmission.

The six field telemetric stations consisted of:

- Three short-period seismometers Ranger SS-1 (1 second).
- A digital recorder Altus Kinemetrics K2, which is configured to shot STA / LTA, its event files are stored on its hard drive.
- A FreeWave Spread Spectrum Transceiver (DGR-115H).
- The house, tower and gate for protection.
- GPS Antenna Yagi TY-900.
- Solar panels, gel batteries and connector pins. From January 2008, to this date, a change of seismic instrumentation was made, on the six field stations which consist of:
- Three components X, Y, Z; oriented orthogonally.
- Broadband triaxial seismometer Analog, USB internal memory of 16 GB.
- Radio-Modem spread spectrum.
- GPS antenna.
- Solar panels, gel batteries and connector pins.

The change in the design of the seismic network was conducted to gain more control because migration of the recorded events was detected and also in order to continue recording the natural and local seismicity induced by the injection and exploitation of the geothermal field (Figures 6 and 7). In the geothermal field of Los Humeros the magnitudes of the local seismic events are between 1.1 to 2.9, with the presence of two tectonic events of magnitudes 4.2 and 3.6.

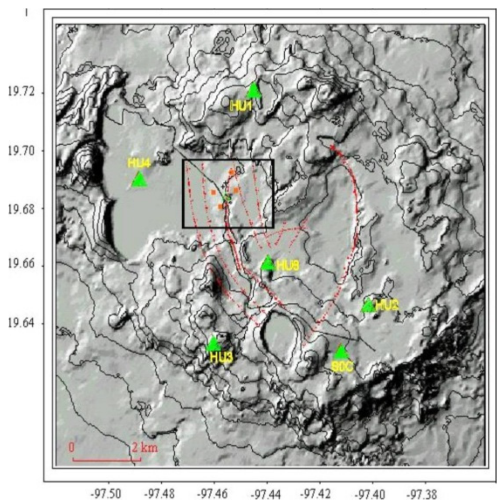


FIGURE 6: Design seismic network 1997 to 2004

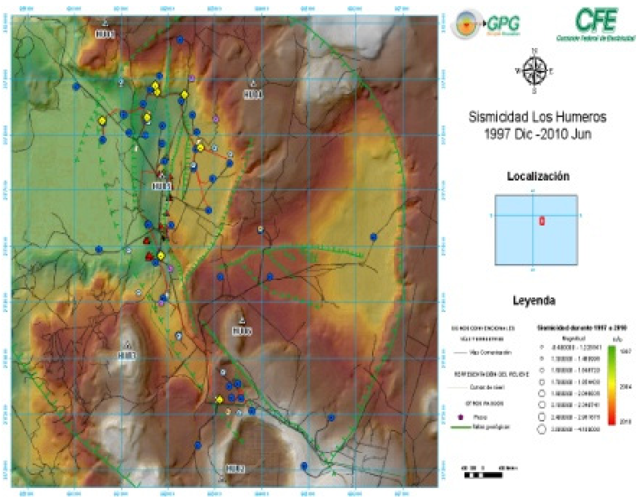
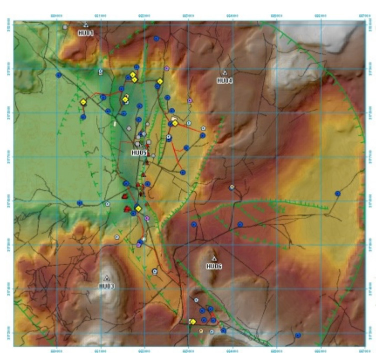
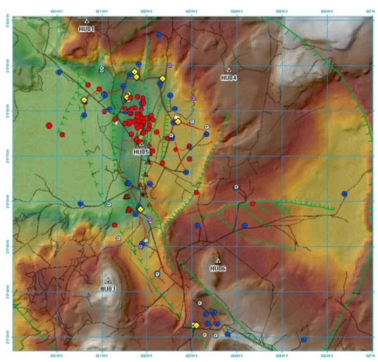


FIGURE 7: Design seismic network 2005 to date

From December 1997 to January 1999, seismic activity was concentrated mainly in the northern part of the geothermal field; i.e. around H29D and H38 injection wells reaching depths of about 4 km (Figures 8 and 9), but from February 1999 the seismicity started to be detected towards the south zone of the field (Figure 10).





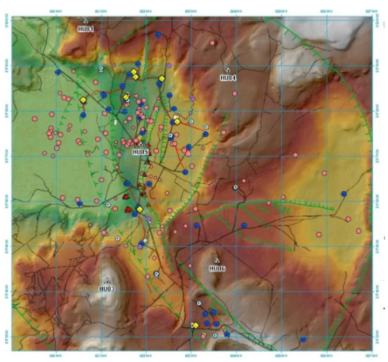


FIGURE 8: Activity December 1997 FIGURE 9: Activity year 1998 FIGURE 10: Activity year 1999

In general, these microseismics were distributed along the fault of Los Humeros, just south of this fault, an earthquake of moderate magnitude (Md = 3.6) and shallow depth (2 km) occured on January 21th, 2002.

The analysis of the information showed an activation of the northern part of Los Humeros fault, which finalized with the January earthquake. Soon after, a moderate and progressive increase in wellhead pressure and steam production was observed in some of the wells related to that geological structure. Figures 11 and 12 showed the normalized production of well H-09 versus the seismic activity, being notable a change in the normalized production slope, showing an improvement in wellhead conditions without any change in the orifice plate.

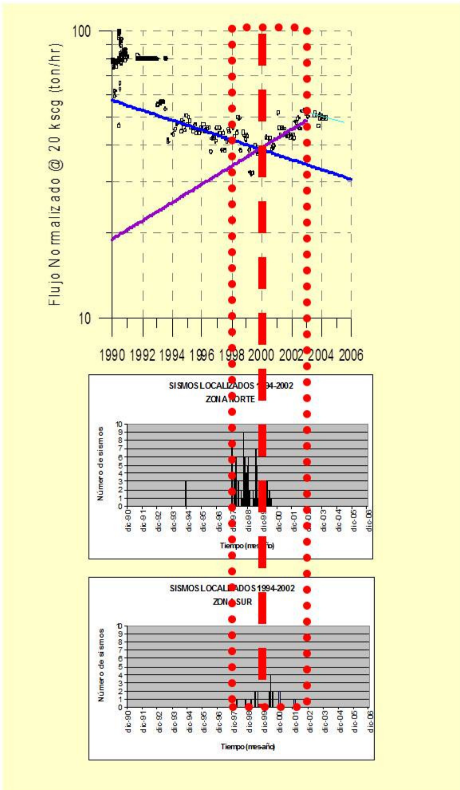


FIGURE 11: Normalized production of well H-09 versus Number of seismic events

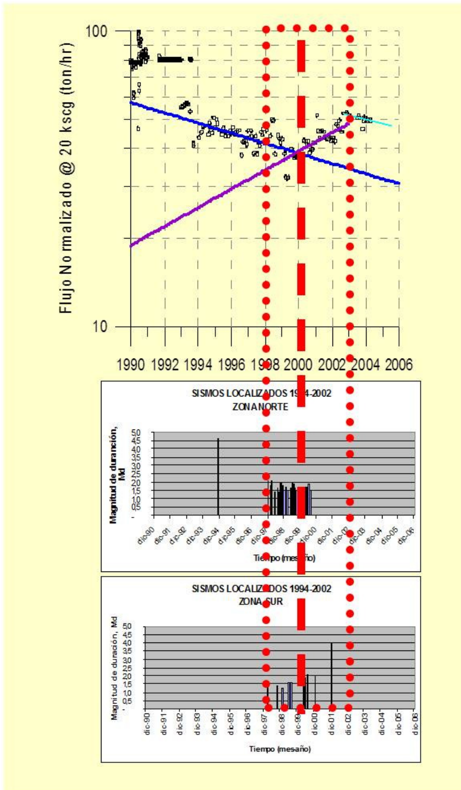


FIGURE 12: Normalized production of well H-09 versus Magnitude of the seismic events

Figure 13 shows the correlation of the present production in the geothermal field between 1990 and 2005, with respect to the number of seismic events recorded in the Northern and Southern part of the field, which highlights an increase in the normalized production after the seismic event of January 21th, 2002, this same correlation was performed in Figure 12, considering for this the magnitudes of all seismic events recorded in this period, with emphasis on the maximum magnitude of 3.6 registered on January 2002.

The monitoring of the registered seismic activity recorded from December 1997 to June 2010, has allowed to identify the presence of different sources of energy release which are:

- Seismicity induced by injection of geothermal water.
- Seismicity induced by extracting geothermal fluid.
- Seismicity by the presence of active geological faults, and fault reactivation.

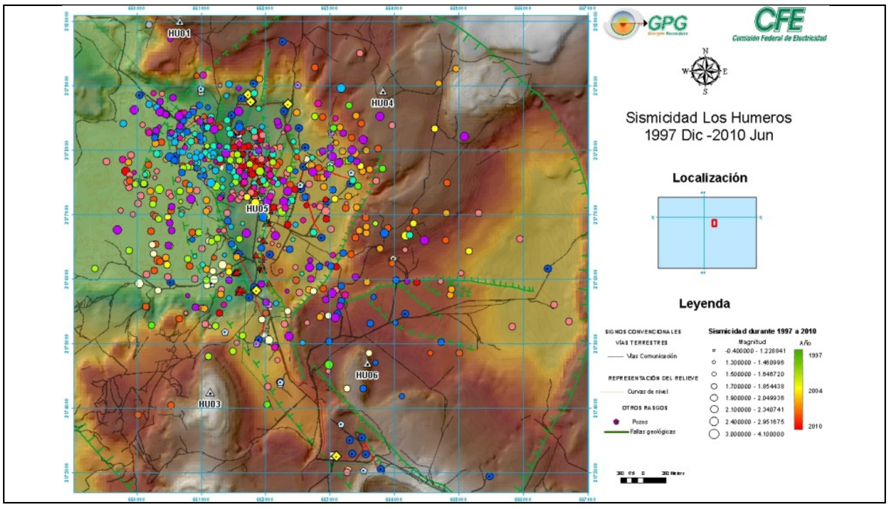


FIGURE 13: Seismic activity registered from the year 2000 to June 2010

Similar to what was presented to The Azufres, an important part of the geothermal exploration activities, is the location of new geothermal wells, and the case of Los Humeros is no exception. Following, it will be exemplified with the H-43 production well.

In 2007, a multidisciplinary work was conducted to locate a new production well (H-43), in the northern part of the geothermal field, with the target of crossing the Structural System "La Antigua" at depth.

Figure 14 shows the W-E section, where as part of the analysis, the resistivity profile was plotted and the hypocenters recorded the period from 1998 to 2008, which were identified between 1100 m and 4400 m depth in the vicinity of the proposed H-43 well. The geoelectric response identified three main resistive packages:

1. Unit U1 is presented which is the outermost layer with an average thickness of 200 m in the W section and a thickness of 100 m in part E. In general Unit 1 has a resistivity ranging from 63 to 100 Ohm-m corresponding to pumice material, basalt and andesite.
2. U2 Unit has thicknesses of approximately 500 m to 1000 m in Part E of this section, in general the U2 unit comes with a resistivity of 0-35 Ohm-m, corresponding to the compositional lithology tuff lithic, ignimbrite and andesite.
3. The U3 Unit presents greater thicknesses of 1200 m on the W and E of this section, in general the U3 Unit has a resistivity of 47-100 ohm-m, which materials are glassy tuff and hornblende andesites.

The structures determined by spatial occurrence of the geoelectric gradients and seismic events recorded, corresponded to the structural system "La Antigua" which dips to E. Derived from the presence of high deep seismic activity, it was decided to drill a vertical well reaching 2200 m depth, resulting in a production two times better than the average of the field.

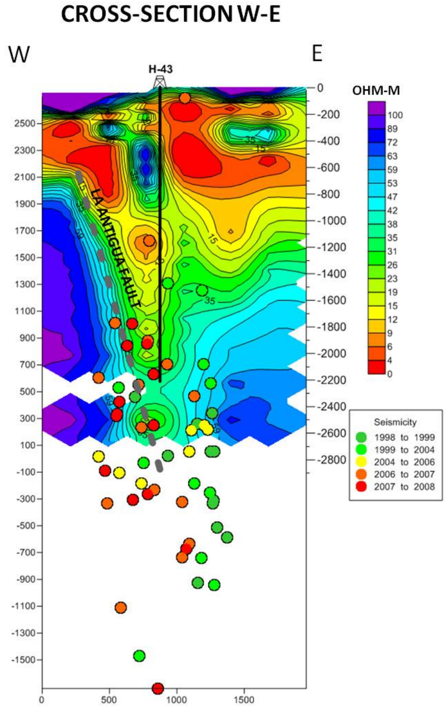


FIGURE 14: W-E Section Well H-43

2.3 Las Tres Vírgenes Geothermal Field

Las Tres Vírgenes is located in the middle of the Baja California peninsula, at the north of the state of Baja California Sur and inside the buffer zone of the El Vizcaíno Biosphere Reserve. Las Tres Vírgenes is inside a Quaternary volcanic complex composed of three N-S aligned volcanoes, from which the name of the field comes from. The geothermal fluids are hosted by intrusive rocks and the heat source of the system is related to the magma chamber of the La Virgen volcano, the youngest and most southern of the volcanic complex. There are only two condensing 5-MW power units in operation that were officially commissioned in 2002. (Flores-Armenta, 2012).

In this geothermal field there are identified four structural systems, two of them are the ones with the most geothermal importance. The first structural system has a direction NW-SE, it is one of the most important and it is represented by the faults "La Vírgen", "El Azufre", "Las Víboras", "El Volcán", "El Viejo (1)", "El Viejo (2)" and "El Partido". The second structural system in importance is the N-S; it is formed by the faults "El Colapso", "El Cimarrón" and another one yet unnamed. Both systems are active and are considered to move hydrothermal fluids with high temperature. The intersection of the faults "El Volcán" and "El Viejo (2)" with the N-S system are considered to allow much better permeability and therefore production. The third structural system has a NE-SW direction and is represented by the fault "La Puerta". At present, this fault is not active, since it does not show hydrothermal activity through fractures or faults. The fourth structural system has an E - W direction. It is the least studied, because it has little presence, thus, minor geothermal importance within the study area. It is possible that the E - W system, does not have much penetration (Gómez-López et al. 2010).

The study of seismicity in this geothermal field and surrounding areas began in 1992 with some interruptions until 2007. The earlier and recent studies (Macias, 1997) and (Lermo et al. 2009), consider this region as an area of high regional seismicity.

Until 2008 in the geothermal field of Las Tres Virgenes, BCS, seismological instrumentation consisted of five Kinemetrics K2 accelerographs autonomous, however these equipment's started to have problems in their different electronic cards due to the obsolesce of the equipment (more than 10 years).

As the year of 2008 it was decided to use for temporary monitoring, other seismographs new high dynamic range and higher capacity storage (one month), able to continuously keep records of the three components of motion (NS, EW and Z) with 100 samples per second.

The spatial distribution of the new seismic network, central station and relay station is shown in Figure 17, like the distribution of seismic stations can now be seen that the coverage seismic network is good for monitoring seismogenic areas of geothermal interest, and to have good locations of earthquakes with respect to the current coverage.

During the period April 2009 to November 2010, 1920 local earthquakes were identified, of which only 331 were able to estimate their hypocentral parameters, due to its small magnitude size, which in most cases can be identified only in the diagnostic station; for all of the others it is difficult to determine the arrival of body waves, since they can be confused with the natural noise of the station (Figure 15).

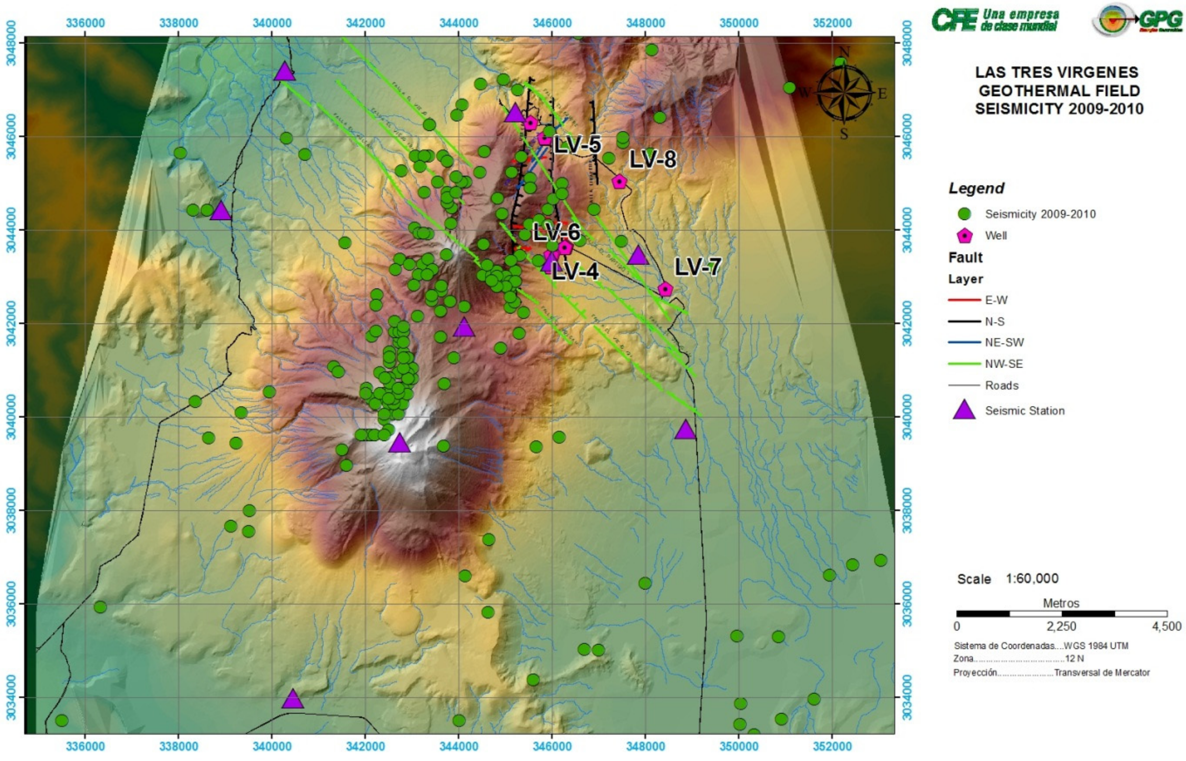


FIGURE 15: Las Tres Virgenes Geothermal Field Seismicity 2009-2010

It was interesting to note that while drilling the producer well LV-6 (from June 25th to December 18th, 2009); it was observed a sudden increase of local earthquakes, which also correlate with the acid job in the well on December of that year.

After this increased of seismic activity, further changes occur precisely when the production evaluation of the well started, beginning with a 3.5 inch orifice plate when the sudden aperture of the valve increased the number of local earthquakes which in this case, could count 32 earthquakes in just one hour, at 03:00 am (GMT hour) on March 9, 2009. This same behavior is repeated on June 15, when they changed from 3.5 to 4.0 inches. Subsequently, a raise in the local seismicity in the months of July, August and September, which can be associated with a change in the injection well LV-8, when going from 200 to 260 t/h. Given their maximum values on the early days of august, precisely when the largest earthquake of the period was detected (Mc = 3.2), this earthquake occurs on August 13 at 14:27, located near the injection well LV-5, at a depth of 3.1 km. (Figure 16).

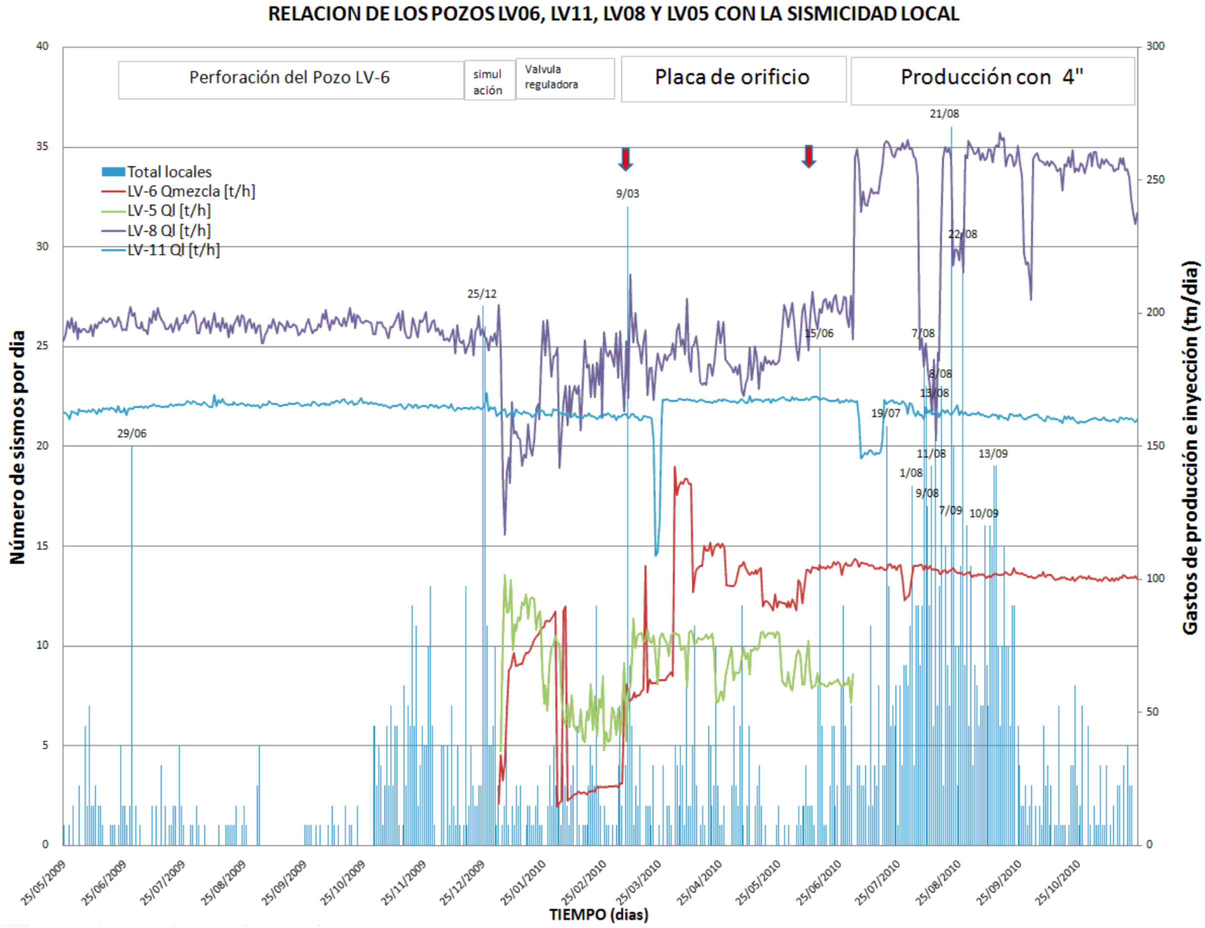


FIGURE 16: The graph shows the relationship during drilling, acidification and production of well LV-6, as well as the injection, versus local seismicity

Finally it should be noted that this seismicity is occurring in the Fault systems of "La Virgen", "El Volcán" (La Cuesta) and the faults "El Viejo" 1 and 2, which represent the structural systems of most interest for the location of new wells.

On the other hand, the seismicity in this geothermal field allowed raising an interesting hypothesis during the update of the Conceptual geothermal model of Tres Vírgenes (Soto-Peredo, et. al, 2010 and 2012), in reference to the location of the magma chamber of this site.

Macías et al, in 2011 suggested the location of the magmatic system at depths between 7 and 9 km below the crater, after analyzing the composition of the edges of plagioclase and amphibole minerals.

By observing the spatial distribution of seismicity in the vicinity of the volcanic complex, it seems clear that there is a seismic gap below the 5500 mbsl, (Figure 17). In addition, the rounded form in that the events line up to the mentioned depth might suggest to be a laccolith with an extension of approximately 13 km in direction N37°E. This magmatic chamber of the volcanic complex of Tres Vírgenes would possibly be associated with the heat source of the geothermal system nowadays in exploitation.

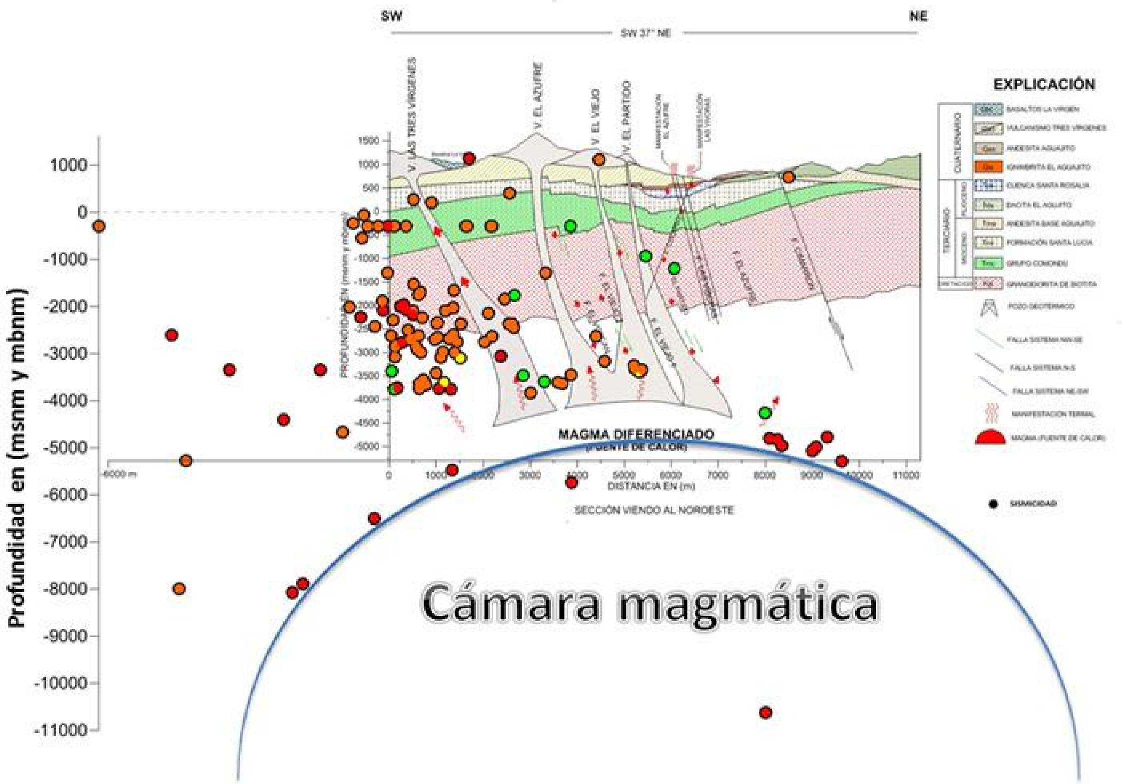


FIGURE 17: The section showing in color the original profile of 2010 as a spatial reference, the coloured circles are the hypocenters

3. CONCLUSIONS

The micro seismicity along with the electromagnetic method, are an important tools to identify fluid movement and to record subsurface activity of the geological faults. It provides information to support new production and injection wells, and especially in geothermal areas where no surface structural features are evident.

Micro seismicity catalogs can be exploited to determine the value of B, which may indicates us high temperature zones.

The energy release recorded in the seismic activity can be related to changes in production-injection strategies and also to the presence of active geological systems.

Changes in the micro seismic activity can also be measured while drilling, stimulation jobs and testing of producer wells.

The micro seismicity also reflects movements and breaks in the basement, identified as faults and fracture zones, which are favorable for geothermal fluid flow, as observed in seismic monitoring in the geothermal field of Los Humeros on the period from 1994 to 2005, where there were increases in production in several geothermal wells after an earthquake of 3.6 magnitude that reactivate the northern sector of the Los Humeros fault.

It is important to point out that the seismic activity within geothermal fields does not exceed the 3.5 magnitude, despite being in tectonically active areas, and there is no major event associated with the operation that could be considered a risk to population or infrastructure.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Deputy Director, Lúdvík S. Georgsson of the United Nations University-Geothermal Training Program for providing the opportunity for writing this paper. Also, I want to specially thank M.C. Magaly Flores Armenta for comments and improving the manuscript. Finally, I want to thank to my wife for giving me support and that extra time to spend on this paper.

REFERENCES

Barry R. Lienert, E. Berg and L. Neil Frazer: *HYPOCENTER: An earthquake location method using centered, scaled, and adaptively damped least squares.*

Flores-Armenta, M., 2012: *Geothermal Activity and Development in Mexico – Keeping the production going.*

Gerencia de Proyectos Geotermoeléctricos, 2012: *Consolidated control board of GPG.*

Gómez-Lopez J., Pulido-Arreola, S.,Soto-Peredo, J., Sandoval-Medina, F., 2010: *Las Tres Virgenes geothermal model updated.*

Jaimes-Maldonado, J., Gutiérrez-Negrín, L., and Diez-León, H., 2012: *life cycle of geothermal wells-experience in México.*

Lermo-Samaniego, J., Cruz-Noe, E., Hernández-Lagunas, P., Nuñez, F., Urban, E., and Espitia, G., 2009: *Passive seismic survey in Las Tres Virgenes, BCS.*

Lorenzo-Pulido, C. S*eismic activity during acceptance tests injection wells H-38 and H-29D during the period from 13 to 16 February 2007.*

Macías, M., 1997. *Analysis of seismic data in Las Tres Virgenes Geothermal Field, BCS.*

Pérez-Esquivias, H., 2001: *Current conceptual model of the Los Azufres, Mexico, geothermal field.*

Soto-Peredo, J. Pulido-Arreola,S., Estrada-Rios, M.,Sagado, Jimenez, E., Sanchez-Luviano, M., 2011: *Multidisciplinary approach to the drilling of four wells, Los Humeros geothermal field.*

Valdéz-González, C., 2012: *Estudio de sismica pasíva. período 2012 en el campo geotérmico Los Azufres.*