LOCAL SEISMICITY IN THE EXPLOITATION OF LOS HUMEROS GEOTHERMAL FIELD, MEXICO

Edgar Urban1,2 and Javier F. Lermo1

1. Institute of Engineering, Universidad Nacional Autónoma de México (UNAM)
2. Universidad Nacional Autónoma de México
E-mail: eurbanr@iingen.unam.mx

ABSTRACT

During the last decade of seismic monitoring in Los Humeros Geothermal Field in Mexico, a large number of events have been observed around the exploitation area in the north side of the field, an area of high pressure and temperature, which concentrate the leading rate of production and injection in the field. A major earthquake in 2002 (Mw=3.2) were followed with a considerably increased in production, due to high permeability paths towards the vicinity of the wells, also a proportional relationship between the increase of injection and the number of events observed in the local seismic network, related to local induced stresses and directions changes.

A study is conducted to determined fractured zones, interpolating the hypocenters and magnitude of the earthquakes with a Kriging Algorithm, it’s possible to associate an area of high energy, this area is been observed at the center of the most productive wells and 250 meters from mayor faults, this zone is also correlated with seismic anisotropy observed in the nearest seismic stations, focal mechanism and reservoir temperature, confirming stress changes due to fluid injection/extraction, and possible fracture propagation.

The temperature interval of 310 to 395 ºC presents a large number of micro-earthquakes associated, also large activity in the productive permeable horizons identifies in the reservoir.

INTRODUCTION

For several years the Institute of Engineering at UNAM has establish an agreement with the Comisión Federal de Electricidad (CFE, by its acronym in Spanish), for monitoring the seismic activity in the Geothermal of Mexico and several studies have been carried out for develop a bigger understanding of the reservoir and the activity observed.

The study and monitoring of microseismicity at geothermal fields has been carried out in several places in the world (Lermo et al., 2007, 2008, 2009; Valdés, 2004; Rutledge et al., 2002; Phillips et al., 2002; Segall, 1989; Eberhart-Phillips et al., 1984; Ponce and Rodriguez, 1977, etc.) these studies have proposed models of performance and characterization based on the analysis of microseismicity.

Los Humeros Geothermal Field is the third largest in Mexico, after the fields Cerro Prieto and Los Azufres, is located in the state of Puebla near the border of Veracruz (Fig. 1). In 1968, CFE made the first geological, geochemical and geophysical studies. In the year 1982 the first well was drilled deeper in order to confirm the results of previous exploration. In 1990 began the commercial exploitation of the reservoir with the installation of the first 5 MWe unit.
wells (H-29 and H-38) located in the north central part of the field, pumping an average of 90 to 100 t/h.

In previous studies we observe a large accumulation of earthquakes near the exploitation area. Los Humeros Geothermal Field, gather the largest number of earthquake associated to injection and production in Mexico, in several times of injection/extraction history the statistics showed a proportional increase and decrease followed by a large number of earthquakes confirming stress changes and in some particular regions a direction change. In the process of understanding the reservoir finding permeability zones represent a vital parameter in the economical and rentability development, and may establish the future success of the field.

Geology
According to geological studies from Arellano et al., (2000) and Cedillo (1997), geophysical seismic reflection (COMESA, 1998) and gravimetric studies (Campos-Enríquez and Arredondo-Fragoso, 1992) Los Humeros Field is a caldera whose stratigraphy conforms nine dominant layers (Table 1). Geochemical studies (Barragán et al., 1988), studies of log wells and core analysis (Arellano et al., 1998) show the presence of two basins at different depths, the shallower at 1.5 km with 280°C temperature and the deeper to 330°C. The shallower basin is Dominant Liquid and the deeper is Dominant Steam (Arellano et al., 2000).

Table 1: Subsurface geology (lithological units) of the Los Humeros. (Modified from Cedillo, 1997).

<table>
<thead>
<tr>
<th>U</th>
<th>Description</th>
<th>Permeability</th>
<th>Hydrogeology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pumice, olivine basalt &amp; andesites</td>
<td>High</td>
<td>Surface water &amp; hot &amp; cold</td>
</tr>
<tr>
<td>2</td>
<td>Lithics tuffs &amp; Zaragoza Ignimbrite</td>
<td>Medium</td>
<td>Possible aquifer</td>
</tr>
<tr>
<td>3</td>
<td>Xáltipan Ignimbrite</td>
<td>Low to null</td>
<td>Aquiclude</td>
</tr>
<tr>
<td>4</td>
<td>Andesites &amp; ignimbrites interleave</td>
<td>Low to null</td>
<td>Aquiclude</td>
</tr>
<tr>
<td>5</td>
<td>Augite Andesites</td>
<td>Medium</td>
<td>Superior Geothermal Reservoir</td>
</tr>
<tr>
<td>6</td>
<td>Humeros Vitreous Tuff</td>
<td>Low</td>
<td>Aquiclude</td>
</tr>
<tr>
<td>7</td>
<td>Hornblende Andesite</td>
<td>Medium</td>
<td>Lower Geothermal Reservoir</td>
</tr>
<tr>
<td>8</td>
<td>Basalts</td>
<td>Medium</td>
<td>Lower Geothermal Reservoir</td>
</tr>
<tr>
<td>9</td>
<td>Limestones, marbles &amp; intrusives (local basement)</td>
<td>Low</td>
<td>Aquiclude</td>
</tr>
</tbody>
</table>

In Los Humeros Field were detected two faults systems (Seismocontrol, 2005). The first consists on Malpais, La Antigua, Maztaloya, La Nueva, Iman and La Cuesta faults, they tend in NW-SE direction, the latter two are observed on the surface and the rest were inferred by geological and geophysical methods. The second faults system is oriented in NE-SW direction: Pamela, Parajes and Morelia faults (Lorenzo, 2002), while Las Papas and Las Viboras faults are oriented approximately E-W direction (Fig. 2).

Reservoir
To infer the distributions pressure and temperature, Arellano et al. 2000, developed two models in one and two dimensions of the reservoir in its initial state, analyzing considerable amount of information grant from 42 drilled wells in the field. The models reveal existence of at least two deposits, located in the most permeable zone formations of augite andesite and hornblende andesite. The first reservoir or superior reservoir is located below the 850 to 1800 MBSL; the pressure profile of this deposit corresponds to a water column boiling approximately 300 and 330 °C. The second bigger and a predominantly liquid field is located between 2000 and 2700 MBSL, with the available data is to be considered a low fluid saturation reservoir, for that feed wells in this area.
were estimated with a temperature between 300 and 400 ° C.

**Local Seismic Analysis**
The seismic monitoring in Los Humeros field started with the earthquake of November 25, 1994 (Md = 4.6), which caused considerable damage to his infrastructure (Lermo et al., 1999). In December 1997, CFE installed a Permanent Telemetric Seismic Network (RSTP, by its acronym in Spanish), composed of six digital triaxial seismographs (S01, S02, S03, S04, S05 and S06).

In the previous study we selected a total of 237 local earthquakes distribute along the field from December 1997 to October 2008; for this study we consider events only in the north area of Los Humeros Field, a smaller area restricted to the primary exploitation area. A total of 146 seismic events from 1997 to 2008 were selected from two different established seismic networks.

The location of seismic events was performed with the subroutine hypocenter, from the program SEISAN version 8.0 (Havskov and Ottemoller, 2003). This program uses as input data: station name, geographical coordinates (latitude and longitude), altitude, reading times of the P wave (Tp) and S waves (Ts) arrivals, duration of the earthquake, velocity ratio (Vp / Vs), velocity model (Table 2) and an equation for calculating the duration magnitude.

In this study, the time readings of arrival were performed with an accuracy of 0.01 s for P wave and 0.05 s for S wave. The ratio Vp / Vs = 1.76 used for localization was obtained by Wadatti curve constructed from the arrival times of P and S waves (Antayhua, 2007). The velocity model corresponds to that proposed by Lermo et al., (2001) ant the seismic reflection profile by COMESA (1998). The P wave velocity (Vp) and the equivalent depth of nine strata of Los Humeros Field were obtained following the methodology described by Dix (1995). The equation used to calculate the duration magnitude of Los Humeros Geothermal Field events, is proposed by Antayhua (2007) in equation (1).

\[
Md = -0.1285 + 1.6283 \log_{10} (T) + 0.0487 (D)
\]

Where: Md is the duration magnitude in degrees corrected from the equation proposed by Lee et al. (1975), T is the total duration of the seismic event in seconds and D is the epicentral distance in kilometers.

**Table 2:** Velocity model in Los Humeros Geothermal Field (Hurtado, 2001.)

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Vp (km/s)</th>
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<tbody>
<tr>
<td>0</td>
<td>1.24</td>
</tr>
<tr>
<td>0.24</td>
<td>1.94</td>
</tr>
<tr>
<td>0.65</td>
<td>2.85</td>
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<tr>
<td>1.25</td>
<td>3.54</td>
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<tr>
<td>1.79</td>
<td>3.69</td>
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<tr>
<td>1.93</td>
<td>3.9</td>
</tr>
<tr>
<td>2.13</td>
<td>4.14</td>
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<tr>
<td>2.37</td>
<td>5.18</td>
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<tr>
<td>30</td>
<td>6</td>
</tr>
</tbody>
</table>

**Spatial Distribution in surface and depth**
It’s been observed previous activity in the surrounding of the principal geological structures from a total of 237, around 15 percent distributed over the traces of La Cuesta, Los Humeros, Loma Blanca (reactivation) and Las Papas faults, activity close related to the main area of production, which offers conditions favorable to flow with permeable surroundings.

There are two significant permeable zones in Los Humeros Geothermal Field, in each of these zones a large seismic activity has been observed, in the augite andesite permeable horizon and in the second mayor permeable horizon hornblende andesite, the first located in an interval of 1000 to 2000 meters deep presents 121 earthquakes which represents 82% of the total 147 delimited for this study, close to the exploitation area. The second permeable horizon around the interval of 2000 to 2700 meters (deeper...
area, Fig. 4) conglomerate 40 events, spread below the wells perforated interval, the most important production zone are also related with 28 events deeper near to La Antigua Fault in the limestone area.

Figure 4: Seismic section E-W, seismicity (red spheres), projection of faults: Los Humeros (orange polygon), La Cuesta (green polygon), Antigua (gray polygon), and Las Papas (red polygon). Injection wells (blue lines) and producers (orange lines).

**Ellipses of error**

Hypocentral location errors (latitude, longitude and depth) are less than 3 km. for the earthquakes located with 4, events selected for this particular zone in the north side of the field, for a better view, the ellipses of error have been determined with the subroutine “epimap” include in the program SEISAN.

In Fig. 5 and 6 it’s presented the ellipses errors in the entire field, top and side view respectively.

Figure 5: Top View showing error ellipses in the determination of hypocenters (green ellipses)

Figure 6: E-W view showing error ellipses in the determination of hypocenters (green ellipses) side view EW, for the period December 1997 to October 2007.
Focal Mechanism
To construct focal mechanisms, we used another of subroutines include in the program SEISAN called "focmec".

Figure 7: Location of representing simple focal mechanisms in the study zone, obtained from the polarity of the P wave and seismic stations registered on 5 stations.

Figure 7 shows three focal mechanisms estimated for the last observation period (November 2007 to October 2008), their solutions correspond to a oblique, normal and normal with strike-slip faults, associated to Los Humeros and Morelia faults respectively.; it’s suggested for a more accurate solution and coupling with the model, gather the most of signals observed in the seismic network, which can only be obtained with a greater number of stations, therefore a larger number of polarities in the parameters of this solution, improving the delimitation of fault planes.

Seismic Anisotropy
The surroundings of the injection and production area, showed large accumulation of events, this is a notorious indicator of a stress complex environment. Rodriguez, et al., 2012, investigate the seismic anisotropic in Los Humeros Geothermal Field, observing change in local stress directions in the area of exploitation compared to in situ stresses along the field and region, the studies show two dominant stress directions in this zone of study, one between production well H-17D and H-32 and another south of the injection wells observed at HU 2 Station, the SW directions aligns with the presence of mayor earthquakes and these wells, with the assumption that this area encounter constant and large exploitation activities, is perceive the ruling flowing patters are analogous (Fig. 8).

Exploitation
Injection
In order to optimize the hypocentral location for these specific zone, we selected the seismic events that followed specific characteristics, especially those seismic events located in the north side with phases P and S waves are easily identifiable and showed a close arrive to diagnose station S05 and S06: duration magnitude [1-3.5 Md], detected in at least five stations, with location errors less than 2 km of surface and depth, Root Mean Square (RMS) less than 0.5 (Antayhua, 2007).

The studies carried out by Romero (2009), in Los Humeros Geothermal Field point out that according to the enthalpy values measured at the bottom of the wells, the production has not been affected by the injection. Antayhua (2007), studied the influence of the injection into the stress state of the field, making a statistical analysis of the number of earthquakes and relating the tons of brine injected, in a continuous and discontinuous statistical data (open and closure of wells), she was able to observe a proportional increase in the number of earthquakes to the rate of injection wells (H29-H38), and there is a proportional increase and decrease in the rate of the hole injection (Fig. 9), as we observed in previous studies the percentage of seismic events in the injection area is of 55 percent.
**Production**

Regarding the relationship between production and the number of earthquakes, has not been defined the amount of influence of this operation in Los Humeros Field. Antayhua (2007), compiled for nearly 8 years the earthquakes recorded at monitoring stations closest to the wells, correlated rates of production and the number of earthquakes, in a period from 1997 to June 2005; six wells produced without interruption (P7, P8, P9, P11, P19 and P20) and steam rate remained while 6 producing wells operated intermittently (P17, P30, P32, P33, P36 and P39), P33 and P36 wells were shut down completely for failing to meet the minimum production rate, but about 8 wells located in the northern part of the geothermal field (P1, P9, P12, P15, P16, P31, P35 and P37) showed an increase in production, the most augment was observed in P1 well (pink line, Fig. 10), which had an increase of almost 40%.

After the occurrence of January 21, 2002 earthquake (Fig. 10 and 11, Mw = 3.2), with the seismic anisotropy correlation, we are able to observed the hypocenter align with production interval and was probably the indicator of permeability paths, which allow a large flow of fluids through; therefore the production of steam in the field increased notoriously, despite the interruption of some important production wells.

**Interpolation Application in Seismic Data**

In order to reduce Modeling Spatial Uncertainty (Fig. 12), and improve the accurate of this study, a spatial analysis is performed for interpolating seismic hypocenters and duration magnitude, using a Geography Information System GIS program called ESRI ArcGIS. Interpolation is a procedure used to predict the values of cells at locations that lack sampled points. It is based on the principle of spatial autocorrelation or spatial dependence, which measures degree of relationship/dependence between near and distant objects.
There are two categories of interpolation techniques: deterministic and geostatistical. Deterministic interpolation techniques create surfaces based on measured points or mathematical formulas. Methods such as Inverse Distance Weight (IDW) are based on the extent of similarity of cells while methods such as Trend fit a smooth surface defined by a mathematical function. Geostatistical interpolation techniques such as Kriging are based on statistics and are used for more advanced prediction surface modeling that also includes some measure of the certainty or accuracy of predictions, permitting to estimate unknown values at specific points in space by using data values from known locations. The intrinsic characteristics of this method, developed during the 1960s and 1970s, have long been acknowledged as a good spatial interpolator. Among the most important features of this method are (1) the unbiased estimate of results, (2) the minimum estimation error, and (3) uncertainty evaluation of interpolated data points.

The main assumption, when using Kriging, is that data analyzed are samples of a regionalized variable. The properties of this kind of variable lie in the range between true spatial randomness and fully deterministic behavior. Determinism is not complete and depends on the spatial distance between points; the closer they are, the stronger is their relation. At greater distances determinism is lost, and spatial autocorrelation of data vanishes. The semivariogram is the analytical tool used to evaluate and quantify the degree of spatial autocorrelation; its results constitute the basis of the Kriging interpolation, Kriging is the most used interpolation algorithm in the field of earth sciences, and general, in any situation where spatial data must be interpolated (De Rubeis V. et al., 2005).

In this study the interpolation method that offers a better adjustment was Kriging. Natural Neighbor and Spline also present a similar approach but Kriging showed more stable representation of values; therefore a more refine result, the Kriging Algorithm used consist of applying a Spherical Semi-variogram Model, result of the interpolation (Fig. 13).

It’s possible to observe distribution patterns and several accumulations, in the area surrounding productions well H-37D, H35, H9 and H-3D, the mayor accumulation can be observed, another with less energy indicates minor flow in the west direction of the injection well H-29D, this accumulation are to be consider a leading stress changes in the west-east direction, which confirms the angle of energy dissipation, observed in the anisotropy study and focal mechanism, and granted more certitude for assuming fracture propagation.

**Thermo-poroelasticity**

If we consider the different conceptual models that relate temperature, direction and convergence of fluid flow, the fluid is directed toward the center and North of the field, which includes geothermal fluid source, as of meteoric origin (water), seeping and contribute to the aquifer recharge, additionally there is a large flow of injection, because of the high pressure in the area, the field development has lead to locate the producing wells around and not the center of the hot zone (Fig 14), these factors may be consider primary triggers for dilation and expansion of pore fluid in the storage rock (limestone), and concentrate mechanisms capable of producing the fracturing of the rock skeleton, this kind of fracture is in addition to produced through injection and stimulation, and therefore due to the change in stresses, seismic
activity occurs. After confirming stress changes the fracture aperture and permeability may decrease with pressure reduction caused by the production under isotropic stress conditions. But the magnitude of the change is dependent on the initial effective in-situ stress. (Tao Q., 2010)

Figure 14: Temperature distribution in the study zone obtained with interpolation of the isotherms measured by (Romero, 2009).

Analysis restricts the high temperature zone as the region with the highest seismicity in the entire geothermal field. By coupling the energy dissipation and temperature gradient, we can observe from isotherm 310°C to 295°C is concentrated the largest amount of stress changes in the reservoir (Fig. 14), also indicates a possible contact zone between fluids of different temperatures within a radius of 1 km in the vicinity of the injection wells (Fig 15), also finding that the fluid injected by gravity reach a depth of almost 3.5 km.

The high pressure in the area has forced the shutdown of several production wells additional to tubing acidification.

Fracture Cooling
The influences of thermal processes on fracture opening have been addressed by Ghassemi and Zhang, 2004. These studies and a thermo-poroelastic stress analysis (Li et al., 1998) around a uniformly cooled crack surfaces indicates that large thermally-induced thermal stresses occur around a cooled geothermal well giving rise to tensile cracking. Also, results of 3D simulations of cold water injection into hot fractures (Ghassemi et al., 2007) predict developing of high tensile stresses in the vicinity of cooled surface, indicating a potential for development of secondary thermal fractures (Tarasovs and Ghassemi, 2010).

Cooling induced stresses may exceed the in-situ stresses of the geothermal reservoir, resulting in formation of system of secondary cracks perpendicular to main fracture. These cracks propagate into the rock matrix, increasing the permeability of the reservoir. As a result, thermal stimulation has been suggested as a means of enhancing reservoir permeability. The results show that thermo-poro-mechanical effects influence both the failure mode and potential; cooling tends to prevent compressive failure and radial spalling, whereas heating tends to enhance failure in compression and can cause tensile failure by excessive increase of pore pressure (Tarasovs and Ghassemi, 2010).

It is vital to consider the elastic effect in the pores, to determine not only the percentage of earthquakes corresponding to fracture, but rather complement the studies refer to a change of the properties and behavior during operation, the effect of thermoporoelasticity represents a major knowledge of the permeability in the reservoir.

CONCLUSIONS
1. The two principal permeable horizons (augite andesite and hornblende andesite) present seismic activity, with around 121 micro-earthquakes associated in these two zones.
2. Three focal mechanisms showed normal, oblique, and normal with strike-slip faults, associated to Los Humeros and Morelia faults, located north of the geothermal field.
3. The correlation of seismic anisotropy, and seismic interpolation, allowed to detect injection flow patterns and the possible high permeability...
path towards the vicinity of the wells, that after the earthquake in 2002 (Mw=3.2) were followed with a considerably increased in production.

4. Kriging offers good interpolation and filter of data, allowing the refined observation of high energy zones and possible delimitation of fractured areas near the injection and production wells.

5. The correlation of these studies suggest suitable targets for drilling, 500 m South of the Injection Wells, and another 500 m SE of H-3D Production Well, zones with large energy, temperature and possible high permeability.

6. In the temperature interval of 310 to 290°C a large accumulation of energy has been observed, possible due to fracture cooling, with the presence of these events in a long period of time (10 years).

**Future Work**
The approach proposed provides valuable results that can be used in further seismic investigations such as seismic risk assessment and stress site-response studies. The next step of is to determine the permeability variation due to fracturing mechanism adapting the models mention previously, applying simulations of cold water injection into hot fractures and the wells surroundings, run several scenarios to determine permeability change patterns, fracture opening and closing, and its effects on the reservoir properties, supplemented with a sensitivity analysis.

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**REFERENCES**


