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# A New Geothermal Exploration Program at Los Humeros Volcanic and Geothermal Field (Eastern Mexican Volcanic Belt)

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## ABSTRACT

A national plan to develop alternative sources of energy is underway in Mexico. As part of this program, studies are carried out to improve methodologies that should result in increased energy production from existing geothermal fields as well as to improve our understanding about enhanced geothermal systems. We are carrying on an extensive study at the Los Humeros geothermal field in the Eastern Mexican Volcanic Belt, the third largest field in Mexico, which is currently producing about 50 MW. The geothermal field is situated in a Quaternary volcanic complex that includes two nested calderas; the first one formed following the catastrophic eruption of the 115 $km^3$ Xaltipan ignimbrite at 0.5 Ma, and the younger caldera formed following the eruption of the 15 $km^3$ Zaragoza ignimbrite at 0.14 Ma. Several other large explosive and effusive eruptions occurred in the late Pleistocene and Holocene. The heterogeneous and irregular magma reservoir of the volcanic complex is a long-lived heat source with shallow and deep faults that control fluid flow and heat transport. To better understand the dynamic and heterogeneous permeability structure of the volcanic complex, detailed and multi-disciplinary studies are required. The goal of our research project is to develop a quantitative model that integrates results from geological, geochemical, and geophysical data bases, allowing for an improved assessment of geothermal resources in this reservoir. We will take advantage of modern and innovative technologies to obtain better images of subsurface structures, improve the chronology of volcanic processes, and obtain accurate and quantitative information on fluid flow, heat transport and rates of water-gas-rock interaction. Methods to be used in this study include: detailed mapping of structure and stratigraphy, geochemical characterization of hydrothermal fluids, geochemical and petrographic characterization of volcanic rocks, X-ray tomography of reservoir rocks from core samples to determine the porosity and permeability of source rocks, magnetotellurics and microgravity surveys to locate and characterize shallow and deep structures, microseismicity to locate active faults through which thermal fluids flow, thermal remote sensing InSAR (Satellite Interferometric Synthetic Aperture Radar) techniques to detect anomalies at the ground surface associated with hydrothermal processes at depth, and numerical models of fluid flow and heat and mass transport to quantify rates of heat transport from source to surface. All of these will integrate an innovative geothermal exploration methodology for Los Humeros caldera.

## 1. INTRODUCTION

In regards to the generation of geoelectric energy, Mexico is currently at the fourth place worldwide with about 1,000 MW of installed capacity, which represents only 2-3% of electricity production nationwide. Due to the current oil high prices, alternative sources of energy are required to be developed, and geothermal energy strongly qualifies to increase importantly the national energy inventory. Recent studies reveal that geothermal energy in Mexico has a great potential to be developed as a clean renewable energy source (e.g. Hiriat, 2011; Ordaz et al, 2011) with very low environmental impact. As part of this program, a combination of innovative and conventional studies are proposed in order to enhance energy production from existing geothermal fields. Much of the geothermal resources in Mexico are associated with active tectonic environments such as long-lived active volcanic complexes, or as volcanic domes or large volcanic calderas. In these tectonic environments, it is of key importance the knowledge of the heat source configuration, the residual magma chamber, and the hydrothermal system that works over long periods of time after the different episodes of caldera-forming super-eruptions to produce the geothermal reservoir. In these conditions the circulation of hydrothermal fluids carries the sealing and waterproofing of the entire system, enhancing the establishment of a geothermal system underneath the seal. Therefore the origin of many geothermal reservoir systems in Mexico is directly linked to the magmatic and eruptive processes that occurred through silicic volcanic complexes.

Los Humeros caldera complex is located in the Eastern sector of the Trans-Mexican Volcanic Belt (TMVB; Fig. 1), where this province covers the western limits of the Sierra Madre Oriental fold and thrust province, lying at the back area of the active andesite stratovolcanoes. The basement rocks of the area consists of Palaeozoic intrusive and metamorphic rocks, which are covered by highly deformed sedimentary sequence of Jurassic and Cretaceous age, intruded by Tertiary granodiorite and syenite. Miocene andesites and pre-caldera volcanic rocks dated at 3.5 Ma and 1.55 Ma are exposed outside the caldera (Yáñez and García, 1982; Ferriz and Mahood, 1984).

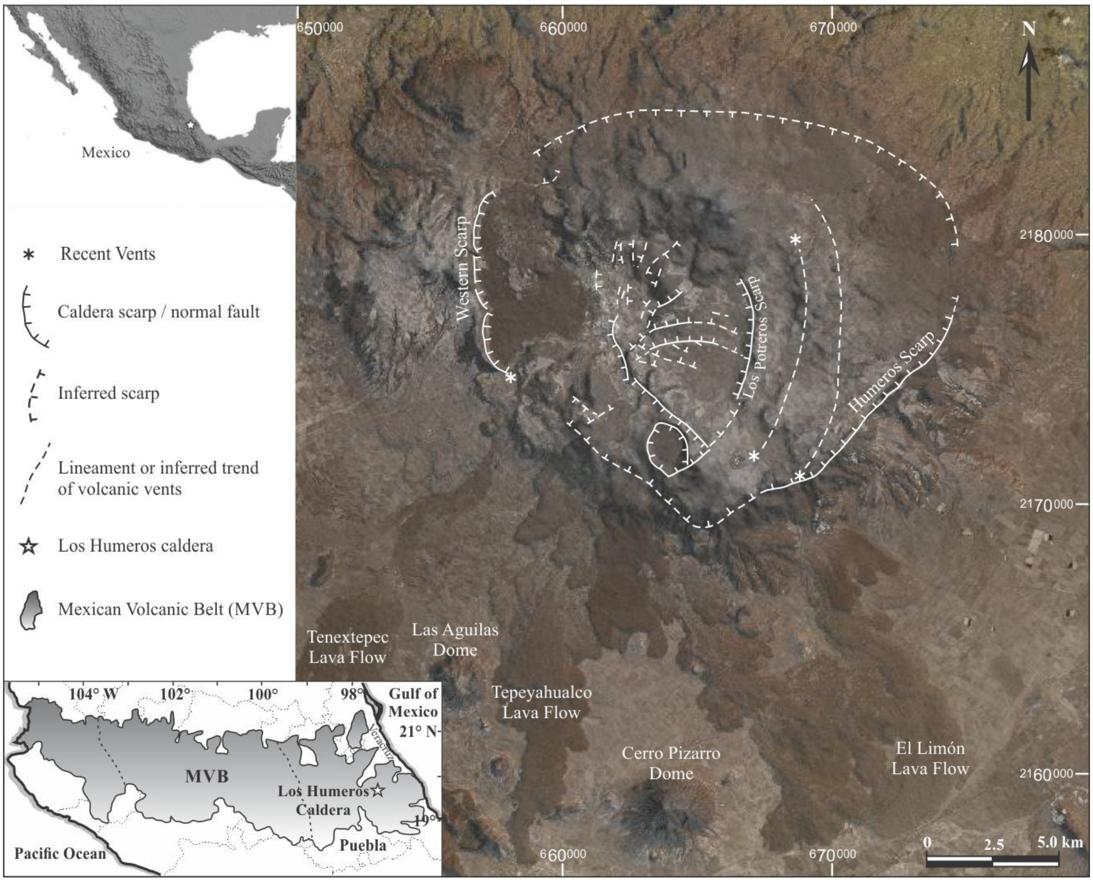


**Fig. 1. Location of Los Humeros caldera and geothermal field at the eastern Mexican Volcanic Belt (lower inset box), central Mexico. The main map, based on a Landsat image and digital elevation model, shows the main structures that define the outer and older Humeros caldera, formed about 0.5 Ma (Ferriz and Mahood, 1984), and the inner and younger Los Potreros caldera at 0.14 Ma (Willcox, 2011), where only the eastern scarp is exposed.**

Los Humeros geothermal field has been studied from different disciplines related to the evolution of the caldera volcano and the development of the geothermal system. Most of the studies derived from internal reports made by the Geo-thermoelectric Project Management from the Electricity Federal Commission (CFE), were performed mainly during the 80's and 90's, when geothermal prospection in Mexico was booming, before oil cheap prices led to poor interest for alternative energy sources. A few papers have been published more recently as well as many internal reports, which are not usually of open access. Current conceptual models are based on these works and are supported by a large data base from well logs of physical and chemical standard parameters. However, despite the large amount of studies on Los Humeros, there is still a lot of work to understand the whole geothermal system, particularly the structural architecture of the calderas complex, which has a profound impact on the heat source, rock permeability conditions, and the origin and evolution of the geothermal reservoir.

The purpose of this study is to develop strategies and a comprehensive methodology to integrate geophysical methods and modern concepts on geology taking advantage of leading high precision geochemistry laboratories to generate an improved geothermal conceptual model of the Los Humeros system. An additional important topic that is considered in this study is the assessment of the volcanic hazards as well as the induced micro-seismicity, which could indeed prove beneficial, in that it can be used to monitor the effectiveness of the geothermal system operations and shed light on geothermal reservoir process.

## 2. TOWARDS AN INTEGRATED METHODOLOGY

The integration of combined conventional and innovative geological, geophysical and geochemical methods, state-of art analytical techniques, and modern conceptual models will provide the key elements to develop best practice strategies for geothermal exploration. The independent knowledge derived from the structural geology, volcanology, petrology, geophysical, geochemical and hydrological models would be integrated to construct a more robust conceptual geothermal model.

### 2.1 Geology

Geologic studies range from regional (Negendank et al., 1985; Campos and Garduño, 1989) to local papers (Pérez-Reynoso, 1979; Yañez and García, 1982, for CFE), highlighting the work by Ferríz and Mahood (1984, 1987), who propose a general evolutionary geologic model for Los Humeros volcanic complex, based on K/Ar dating and petrology. Some other reports provide additional structural information (González-Morán and Suro, 1982; De la Cruz, 1983; López, 1995), while the subsurface geology was described by Cedillo et al. (1994). Other publications deal with some particular deposits related with the origin of the caldera (Carrasco-Núñez y Branney, 2005; Carrasco-Núñez et al., 2012), or the thermal flux (Prol and González-Morán, 1982). Regarding hydrogeologic studies (González–Partida et al., 2001) there are two geothermal reservoirs in Los Humeros (Cedillo-Rodríguez, 2000). The deeper reservoir is related to basalts and hornblende andesites, while the shallow reservoir is located in augite andesites (Portugal et al., 2002). The shallow reservoir, which is liquid-dominant with temperatures between 300-330 ºC seems to be located between 1025 and 1600 m a.s.l., while the deeper reservoir is located between 850 and 100 m a.s.l. with temperatures between 300-400 ºC and is considered a low liquid saturation reservoir (Arellano et al., 2003). According to Cedillo-Rodríguez (2000), the reservoirs are laterally limited by the Los Potreros collapse and the main Los Humeros collapse caldera. The distribution of low-permeability geologic units (granites and clayey limestone) around Los Humeros caldera, combined with the annular faults, isolate the geothermal reservoirs from regional recharge. Recharge occurs from rainfall that is transmitted through the fault system and fractures (Cedillo-Rodríguez, 2000).

Different methods and modern concepts will be considered in this project, including the following: Conventional geologic and structural mapping can be improved applying modern techniques of pyroclastic stratigraphy, physical volcanology, and structural mapping, resulting in more precise and deterministic approach. This analysis is key to determine the most favourable conditions of permeability for the geothermal reservoir, which is mainly controlled by the main fault and fracture patterns.

Detailed morphostructural mapping allow identification of faults interpreted from remote sensing techniques to be confirmed by field verification. Different features are considered such as mapping of fault scarps (Fig. 2), breaks of slope, draping and cross-cutting relationships, dip slopes, type of surface, alignment of vents and shape of alluvial fans. Scarp age can be assessed based on the angle and degree of erosion as well as draping and cross-cutting relationships with stratigraphic units of strata of known age. Extensive field work including detailed log mapping, unit correlation, isopach and isopleths maps, field data including indicators of proximal vent facies (variations in size and abundance of spatter blocks, ballistic bombs, impact structures, etc.) are important to identify the vent sources, to infer connected fractures and faults, and to complete the structural analysis that will allow us to propose an updated structural configuration.

Some structures are interpreted by the identification of volcanic vents, not always exposed, that can be recognized from physical volcanology methods (isopach and isopleth maps). Identification of the magnitude and frequency of caldera-forming eruptions and other important parameters provide important information of the magmatic system and the internal structure of the volcanic system, timing, residence periods, which are critical factors to understand how the hydrothermal system works. To complement this information, heat flux measurements would be used to reinforce the structural trends defined by field and remote sensing methodologies. On the other hand, the spatial-temporal variation of recharge through rainfall has been determined using long-term data from Mexico's meteorological service network of climatological stations. Numerical modeling of the geothermal system will be developed through the numerical code FEFLOW, which is capable of simulating groundwater flow and heat transport processes.

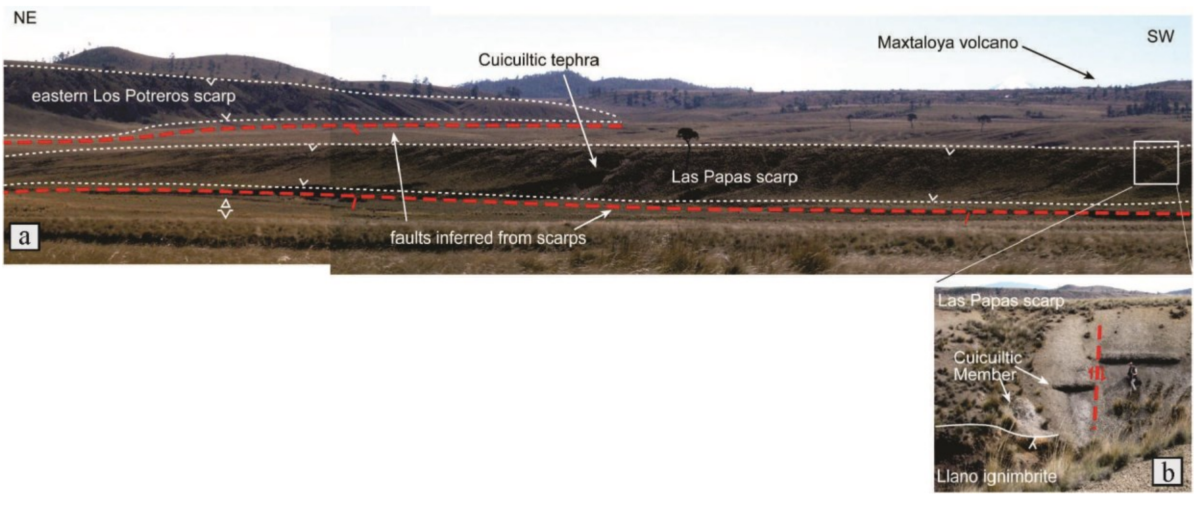


**Fig. 2. Main structures in the central part of Los Humeros caldera, including the Los Potreros caldera-forming structure in the background of the main picture (a), and the well-defined scarp of Las Papas fault (see location on Fig. 3). This area has been affected by several other faults that are not so obvious by conventional methods and then it is interpreted as being highly piecemeal. However, small displacement faults were identified and confirmed in the field (see inset picture "b"); some of them cut the Cuicuiltic sequence, which has been dated younger than 7 ky, and therefore indicate reactivated faults. (Modified from Willcox, 2011).**

By applying novel high-precision geochronological methods, such as Ar/Ar, U/Th, and U-Th/He dating, we will not only refine the stratigraphic column, but it will also allow to establish a high-resolution history of the caldera. Indeed, by applying novel in-situ techniques (such as EMPA, and LA(MC) ICPMS), a detailed reconstruction on the thermal and chemical evolution of the magma chamber will be achieved. Younger deposits will be a challenge, conventional $C^{14}$ dating together with new radiometric decay series of U-Th isotopes, U-Th/He thermochronometry (Gorynski et al., 2014) and paleomagnetic dating (secular variation) will be applied to date primary minerals as well as hydrothermal events. Analogue modelling will be used to reproduce the structural architecture and better understand the interaction mechanisms among the heat source, the reservoir and cap rocks, the fractures and faults and the circulation of geothermal fluids in the crust (Martí et al., 2008); Geographic Information System (GIS) and 3D structural models will provide integrated visualization of surface and subsurface data, including geological, geophysical, geochemical and borehole data. The use of X-ray microtomography will be used to measure 3D sections and the internal properties of the collected samples, defining textures, structures, composition, porosity, permeability, and componentry, which are fundamental features to understand the hydrothermal and magmatic system.

### 2.2 Geophysics

There is a wide variety of geophysical studies that have been applied in Los Humeros geothermal field, some of which were done during the prospecting phase before its full development (e.g. Alvarez, 1978; Flores et al. 1978; Ponce and Rodrigues, 1978; Mena and Gonzalez-Morán, 1978), and some others on particular fields such as gravity surveys (Campos et al., 1992). Temperature modeling of magma chamber of the reservoir followed (e.g. Verma, 1985; Castillo-Román et al., 1991) once the geothermal system was in operation and the thermal and geologic structures of the producing zone were better known. As a result of well logs of many drilled wells followed the analysis of the thermodynamic properties of the magma chamber, the heat source and the conceptual geothermal model (e.g. García-Gutierrez et al., 2002; Arellano el al., 2003; Verma et al., 2009). More recently, several micro-seismic studies were carried out (e.g. Lermo et al., 2008; Antayhua et al., 2008; Urban y Lermo, 2012; Rodriguez et al., 2012) derived from the observed induced seismicity associated to the production stage, mainly related to fluid injection processes (Antayhua et al., 2008). These studies were focused in providing explanation to the intense micro-seismic activity induced as the geothermal field is under development.

In this project, a combination of magnetotelluric, gravity and natural seismicity methods will be applied to monitor the geothermal system of Los Humeros, that counts with large number of producing wells growing steadily since it is in operation in the late 70s. Electric and electromagnetic (EM) techniques have been applied worldwide to study potential geothermal systems with great success, particularly the magnetotelluric soundings, as their depth of exploration is larger than most used artificial-source EM methods. Also important is that natural EM geophysical methods can be used not only with prospecting purposes but also for mid or long-term geothermal systems monitoring (e.g. Sasai et al., 1997). A main geophysical goal of the present study is to map in space zones of high seismic anisotropy for which we are preparing to carry on a geophysical survey that includes 50 magnetotelluric soundings in the frequency range of $10^{3}$-$10^{-3}$ Hz in combination with the measurement of at least 300 geo-referenced gravity stations and a temporal network of 5 broadband seismic stations. At present, there is not known magnetotelluric survey done at Los Humeros geothermal field despite the amount of geophysical work done in the area. Electrical resistivity mapping using 3D inversion algorithms have shown the capabilities of the method to image structural and lithological features of volcanic reservoirs, such as the distribution of the clay cap (Cumming and Mackie, 2010), regarded as the upper limit of the production zone.

Passive micro-seismicity and naturally occurring EM fields is a powerful combination to study Earth anisotropy. Earth anisotropy allows identify areas of deformation and stress to recognise fracture patterns and fault trends outer and within the inner caldera. Anomalous conductivity and seismic attenuation are expected to occur together at fractured fluid-saturated zones of great relevance when understanding the enhanced geothermal systems. One of the main goals in developed geothermal fields, apart from finding new production areas, is to understand the geophysical evolution of the geothermal system as the production is enhanced. This is normally done through monitoring the thermodynamic conditions at a number of observation wells, which however is limited to the shallow part of the whole system. There is great interest of the geothermal community to develop techniques or experiment a combination of them to effectively trace ascendant fluid saturated fractured zones with production purposes. But not less important is to explain induced seismicity, which in many cases is of great concern of communities located in the surroundings of the enhanced geothermal fields, despite that no large earthquakes have been reported related to geothermal exploitation (Majer et al. 2007). In this case, it is of relevance to provide data that improve our understanding of the mechanisms generating the seismicity for the proper development of the geothermal system. Induced seismicity should be used to monitor the effectiveness of geothermal systems operations and shed light on geothermal reservoir processes (Majer et al. 2007).

In addition to the above techniques, we will be using Interferometric Synthetic Aperture Radar (InSAR), a useful technique to measure deformation on Earth's surface and to detect anomalies at the ground surface associated with hydrothermal processes at depth. Its advantages include overcoming the limitations of traditional geodetic techniques like leveling or GPS, in terms of spatial coverage. As Brunori et al. (2013) states, InSAR is one of the best techniques to analyze volcanic activity and the evolution of volcanic structures, contributing to understand the genesis of a volcanic caldera and thus of deeper ancient systems (Hooper et al. 2004; Pritchard & Simons, 2004; Hooper, 2008; Neri et al. 2009, Sarychikhina et al., 2011). In this study, we aim to perform the deformation measurement of Los Humeros caldera using InSAR. A set of 21 SAR images, spanning the period between April 2003 and March 2007, acquired by the ENVISAT satellite from the European Space Agency (ESA), has been used. ENVISAT satellite mission, which operations ended on April 2012, was equipped with a SAR sensor working in a C- band frequency (f=5.3 GHz, $\lambda$=5.6 cm). The pixel spatial resolution of SAR images is about 20 m x 5 m, the scene spatial coverage is 100 km x 100 km, and the repeating orbital cycle is 35 days.

Interferometric processing is being performed using the JPL/CalTech Repeat Orbit Interferometry Package (ROI_PAC) (Rosen et al., 2004) to construct the differential interferograms and unwrap them. Orbital fringes were removed using orbits provided by the Department of Earth Observation and Space Systems (DEOS) of the Delft University of Technology (Scharroo et al., 1998). The topographic contribution is removed using the 3-arc second (90 m) sampled Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (Farr and Kobrick, 2000). The flattened and topographically corrected interferograms phase, $\varphi$ifg, can be represented as the sum: $\varphi ifg = \varphi def + \varphi atm + \varphi orb + \varphi DEM + n$, where $\varphi$def is the phase change due to the ground displacement in the satellite line-of-sight (LOS) direction, φatm is the phase due to differential atmospheric delay between the two passes, φorb is the residual phase due to orbit inaccuracies, φDEM represents residual DEM errors and n is the noise phase.

### 2.3 Geochemistry

There are numerous studies about geochemistry that cover different aspects on Los Humeros (Verma and López, 1982; Verma, 1983; Verma, 1984; Verma et al., 1990; Tello-Hinojosa, 1992; Verma, 2000; Martínez-Serrano, 2002; Bienkowski et al., 2005; Verma and Andaverde, 2007).

The strategy in this area consists in the combined use of a series of analytical methods for the geochemical characterization of the hydrothermal system. The tools that will be used are: X-Ray diffraction (XRD), Scanning Electron Microscopy (SEM), Petrography (PETRO) and state-of-art Electron Microprobe Analyser (EMPA). The results obtained with some of these modern tools are of great importance in the identification of thermal areas with geothermal possibilities. It is important to highlight the use of a top-end Electron Microprobe Analyser as an innovative tool within geothermal exploration, mainly because it combines the potential of basic microscopy (optics, SEM, cathodoluminescence) and the powerful punctual analytical resolution that is required for the identification of hydrothermal alterations and other quantitative compositions from minerals that are difficult to obtain with other conventional methods. This characterization is of broad interest due to the possibility of determine the limits of the alteration halo, estimate thermal properties, calculate geothermometers and geobarometers, PH and the pressure at which thermal fluids occur. With this knowledge it can be possible to calculate the intensity of the hydrothermal system, scope, porosity variations and depths expected, all this features would refine the estimations of the geothermal source.

We will be using a state-of-the-art numerical simulator currently developed at the US Geological Survey that originally derived from the OpenGeoSys project (opengeosys.org). This simulator couples multiphase hydrothermal flow and rock mechanics, and is capable of incorporating realistic physics under flexible degrees of coupling between the dominant energy conservation, momentum and mass balance relationships. The simulations will utilize all available data collected at Los Humeros, including new data collected during this project. Input will include for example, temperature distribution, regional and local stress field, fracture orientations, and rock properties. Simulation results are expected to provide guidance for optimal future exploration of geothermal energy. Simulations will also try to assess the longevity of the geothermal system under various production scenarios.

Additionally, geothermometers are valuable geochemical tools used for the prediction of deep equilibrium temperatures, the estimation of energy reserves of geothermal systems, and the geochemical monitoring of processes under exploration and exploitation conditions (García-López et al., 2014). Numerous solute and gas geothermometers have been historically proposed to determine deep reservoir temperatures by using the chemical composition of geothermal brines and gases, respectively (Verma and Santoyo, 1997; Verma et al. 2008; Díaz-González, *et al.* 2008). Los Humeros geothermal field is recognized as a vapor-dominated geothermal system, where the gas geothermometry would seem to provide a correct knowledge about the equilibrium temperatures that dominate in the reservoir (Barragán et al. 1991; Tello, 1992). However, some recent studies carried out by García-López et al (2014) reported significant statistical differences between the temperature estimates inferred from twenty-one gas geothermometers and bottomhole temperature measurements. We are planning to develop new comprehensive studies of geochemometrics for a reliable assessment among the geothermometric temperature estimates and the BHT measurements, including the possibility to compare with static formation temperatures (SFT), which require to be determined from shut-in temperature logs collected during the well drilling) and the development and calibration of new and improved gas geothermometers for estimating reliable deep equilibrium temperatures that enable to minimize the differences between these estimates and temperature logs measured in drilled wells.

## 3. PRELIMINARY RESULTS

This project is ongoing, so we will present here preliminary results for some particular disciplines.

### 3.1 Geology

The geologic evolution of the Los Humeros caldera includes two major caldera-forming catastrophic eruptive episodes. The first episode consists of one of the largest Quaternary explosive eruption in México, associated with the emplacement of the Xaltipan Ignimbrite (~460 ka) and the subsidence of Los Humeros caldera. The second episode corresponds to the formation of Los Potreros caldera producing the Zaragoza Ignimbrite (100–140 ky), which is nested in the central sector of the Los Humeros structure (see main scarps in Fig. 1). A complex compositional zoning has been identified in this eruption (Carrasco-Núñez and Branney, 2005; Carrasco-Núñez et al., 2012). An intermediate explosive episode occurred between ~360 ka to ~240 ka, producing a remarkable thick rhyolite pumice-fall sequence known as the Faby Tuff (Ferriz and Mahood, 1984; Willcox, 2011). Several episodes of dome emplacement and pyroclastic activity occurred during the Late Pleistocene until de Holocene (<6,400 years B.P) with the emplacement of the Cuicuiltic Member (Dávila-Harris and Carrasco-Núñez, 2014). This is a remarkable sequence that shows a rhythmic alternation of pumice and scoria fall layers, indicating a contemporaneous eruption of magmas of contrasting composition erupted from multiple vents, which suggest a recurrent model with the activation of high melt zones within a largely heterogeneous magmatic reservoir for Los Humeros caldera. Finally, younger scoria cones, basaltic andesites and olivine-bearing basalt lavas are structurally controlled and erupted along the southern Humeros caldera rim.

As seen before, the geologic evolution of the long-lived Los Humeros caldera has been very complex, involving two main caldera-forming events, several intra-caldera eruptions and the regional stress regime that all together are responsible of the present piecemeal-trapdoor internal configuration of Los Humeros caldera formed through time. As a result of our careful geologic and morphostructural analysis we propose an updated structural map for the central sector of Los Humeros where the active geothermal system is located (Figs. 3 and 4), which correlates well with surficial morphology (Fig. 4). We were able to discriminate structures from the varied previous interpretations, confirming some of them, modifying some others and adding new ones to finally obtain this improved structural interpretation. We can define at least three main structural systems controlling the ascent of geothermal fluids: the NW-SE trending faults are dominated by the Maztaloya fault, which is mostly limited to the south, but it apparently shifts gradually to the NNW-SSE and then to a N-S trending system, that is where the main part of the active geothermal activity occur. The nearly E-W trending system is mostly limited to the Eastern side of the Los Potreros caldera and is cut by a secondary oblique local WNW system that represents a clear evidence of reactivation in the Holocene as it cuts the Cuicuiltic sequence, which is younger than 6.4 ky (see Fig. 2b).

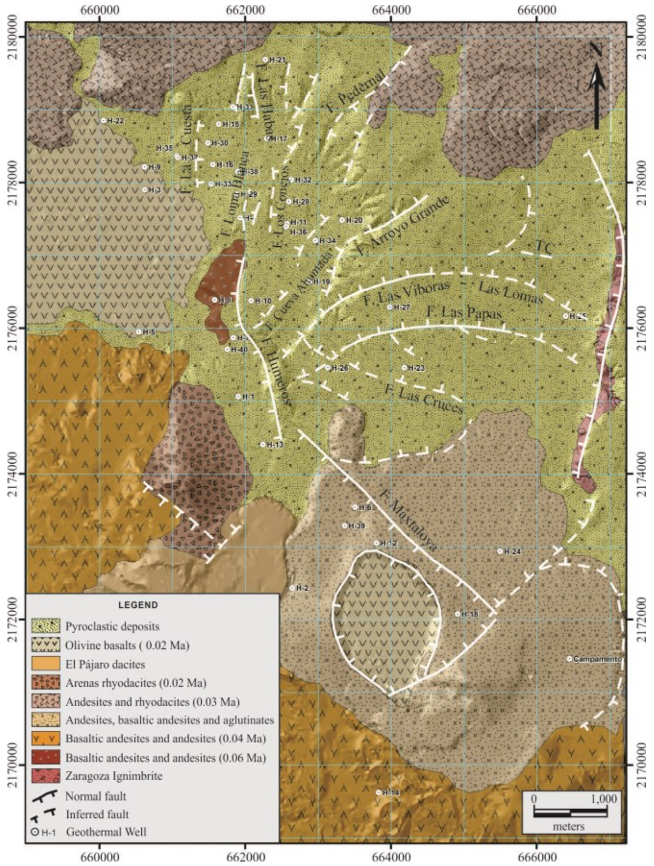


**Fig. 3. Geologic and structural mapping of central sector of Los Humeros caldera, where the geothermal field is located. Solid continuous lines indicates confirmed faulting, while discontinuous lines indicates structures proposed using a detailed morpho-structural analysis**

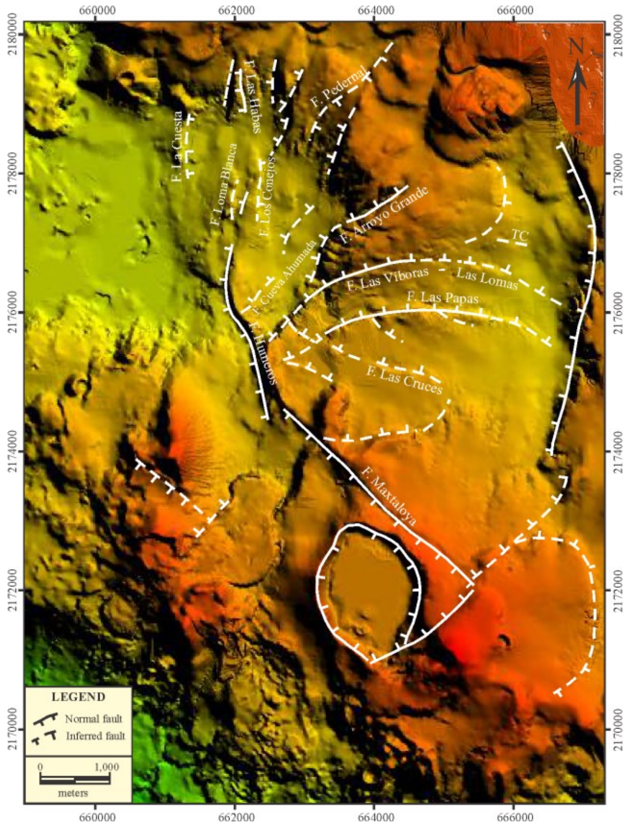

**Fig. 4. Digital elevation model of the central part of Los Humeros caldera complex confirming the main structural features. There are at least three main evident structural trends: NW, N and E-W, from which it is apparently the north-south pattern the one controlling the geothermal fluids.**

### 3.2 Geophysics

Current work on INSAR reveals that the calculated interferograms over Los Humeros caldera show decorrelation of the phase signal when time spans are greater than 70 days. This can be due to the presence of highly vegetated areas surrounding the caldera. For those with good signal correlation, because of the high humidity prevailing in the study zone, the atmospheric signal seems to dominate the interferogram, masking completely the deformation. Moreover, residual orbital ramps can be detected in some of the interferograms. An algorithm aiming to remove all the interferogram signal contributions but the related deformation, must be implemented. Future work plans include, testing on interferograms: the twisted plane technique to remove the residual orbital contribution (Cavalié et al., 2007, López-Quiroz, 2009) and the phase-height correlation to correct from vertically stratified atmosphere (Remy et al., 2003; Cavalié et al., 2007; Elliott et al., 2008, Doin et al. 2009); however, the latter must be interpreted carefully because, in our study zone, deformation is also correlated with height.

Since 1997, a Permanent Telemetric Seismic Network was installed by CFE comprising six digital triaxial seismographs and some temporary stations around the geothermal field. An analysis of a total of 237 local earthquakes during December 1997 to October 2008 (Lermo et al, 2008), shows that the highest concentration is distributed over the traces of main faults of La Cuesta, Los Humeros, Loma Blanca (reactivation) and Las Papas, coincidentally very close to the injection and producer wells (Fig. 5). The largest number of earthquakes (121) is concentrated in the north of the field in positions close to the injection wells, within a range from 2000 to 2700 meters deep. Lermo et al. (2008) studied the relationship between the producing wells and local seismic activity, linking production rate and the number of local earthquakes for nearly 8 years in the geothermal field. In fact, an increase in production after the occurrence of January 21, 2002 earthquake (Mw = 3.2) was observed (Fig. 6), which was probably due to the expansion in the pores and reservoir system, which facilitated the flow of fluids through permeable areas, therefore increasing the production of steam in the field, despite the interruption of some important production wells.

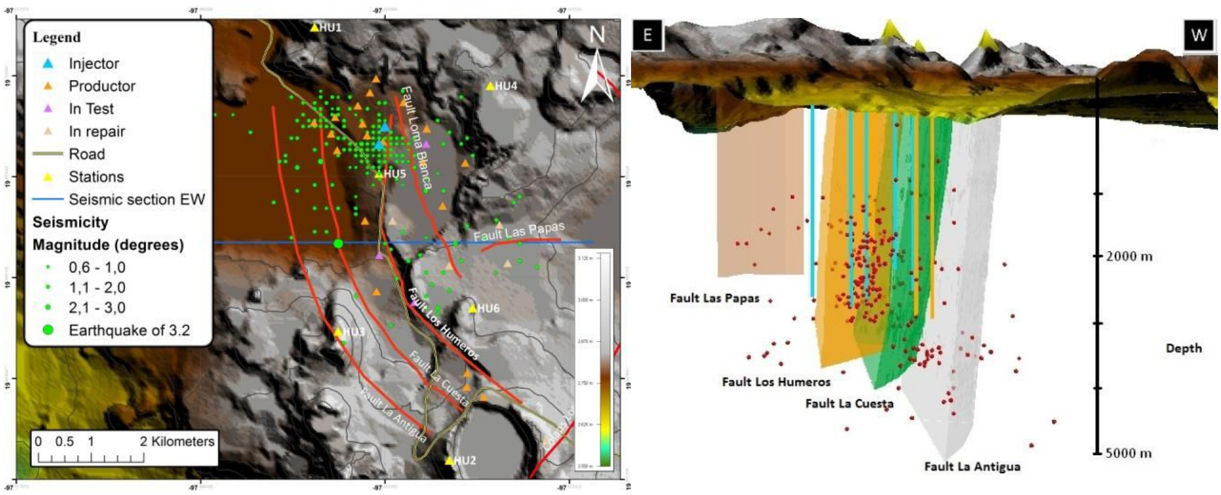


**Fig. 5. Left, spatial distribution in surface of the 237 selected earthquakes in Los Humeros active geothermal field (red lines are not exposed faults except for Los Humeros and Las Papas faults); Right, E-W-trending seismic section, showing seismicity (red dots), and projection of hidden faults: La Cuesta (green polygon), Antigua (gray polygon), and exposed faults: Los Humeros (orange polygon), and Las Papas (brown polygon) (see Figs. 3 and 4) Injection (blue lines) and producers (orange lines) wells (modified by Lermo et al., 2008).**

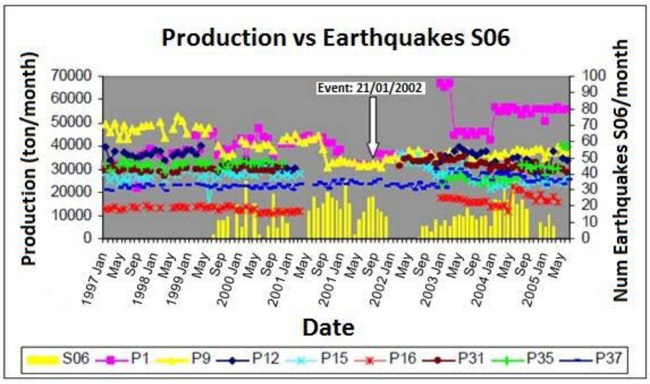


**Fig. 6. Plot showing the correlation of seismicity recorded at station S06 and production rate, in different colors the rate of production and in yellow bars, the number of events in Los Humeros Geothermal Field (modified from Lermo et al., 2008).**

Large seismic activity is reported in the North area, where the rate of production and injection are higher, casually the area of higher temperature (310 ° C). Because of the injection and high pressure in the area, the field development has lead to locate the producing wells around and not the center of the hot zone, as observed in Fig. 7, these factors may be considered 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 produced through injection and stimulation, and therefore due to the change in stresses, and seismic activity (Urban and Lermo, 2012). It is necessary to consider the elastic effect in the pores, to determine not only the percentage of earthquakes corresponding to fracture, but rather complement the studies refered to a change of the properties and behavior during operation. The effect of thermoporoelasticity represents a major knowledge of the permeability in the reservoir.

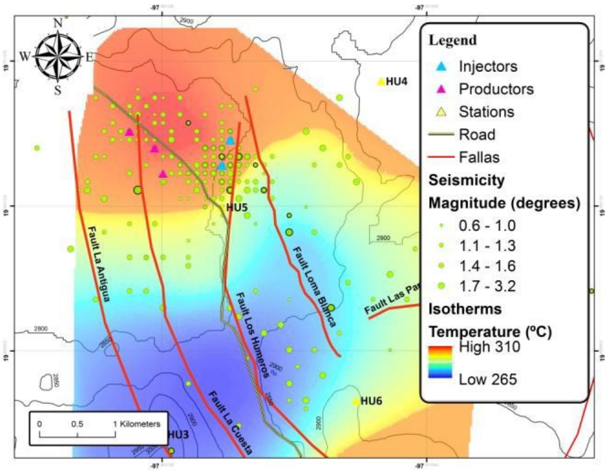


**Fig. 7. Map of isotherms with deep well temperatures, seismic activity and major faults at Los Humeros geothermal field (modified from Urban and Lermo, 2012)**

## SUMMARY

Long-lived recent volcanic calderas offer a great geothermal potential for future renewable energy resources worldwide, but particularly in central Mexico, along the Mexican Volcanic Belt (MVB). This is a Neogene-Quaternary volcanic province, which is characterized by a diverse volcanism including large andesitic stratovolcanoes and silicic calderas, as well as monogenetic fields with domes, maar volcanoes and cinder cones. Los Humeros geothermal field, located at Eastern MVB, is sitting on a large structurally complex caldera with a still not entirely well-known geologic evolutionary history. Los Humeros is a perfect place to propose an extensive multidisciplinary project aiming for a general enlargement of its geothermal potential and widening prospective areas for increasing power production. The strategy of this research project is to use modern and innovative technologies to solve the subsurface structural complexity, improve the chronology of volcanic processes, and obtain comprehensive information on fluid flow, heat transport and rates of water-rock interaction. The integrated geological, geochemical, and geophysical information will allow the development of a quantitative model, which allow for an improved assessment of geothermal resources in Los Humeros geothermal field.

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