One year of passive seismic monitoring of the Los Humeros (Mexico) geothermal field

Emmanuel Gaucher[1], Tania Toledo[2], Malte Metz[2], Angel G. Figueroa-Soto[3] and Marco Calò[4]

[1] Karlsruhe Institute of Technology, Geothermal Research/AGW, Kaiserstr. 12, 76131 Karlsuhe, Germany

[2] Helmholtz Centre GFZ, Geoenergy, Telegrafenberg, 14473 Potsdam, Germany

[3] Universidad Michoacana de San Nicolás de Hidalgo, CONACyT - Instituto de Investigaciones en Ciencias de la Tierra, Ciudad Universitaria, CP 58060 Morelia, Mich., México

[4] UNAM, Instituto de Geofísica, Ciudad Universitaria, CP04510, México, México

emmanuel.gaucher@kit.edu

Keywords: Horizon 2020, GEMex project, Seismicity, Passive imaging, Superhot system.

ABSTRACT

Extensive passive seismic monitoring was carried out between Sep. 17 and Sep. 18 over the Los Humeros (Mexico) geothermal field. This acquisition operation was conducted in the framework of the European H2020 project GEMex among different geophysical, geochemical and geological surveys. Seismic monitoring provided numerous data, whose processing is still on-going, to better characterize the underground structures and properties of the geothermal field. These results participate to the increase of our understanding of the local geothermal system. They can be utilized to propose new development areas, especially, to the north-west of the currently exploited zone, which showed temperatures greater than 380°C at ca. 2.5 km depth.

For one year, a network of 45 short- and long-period seismometers was deployed in the surrounding of the Los Humeros geothermal field. The network layout was chosen to comply with several types of passive seismic processing methods: induced and natural seismicity characterization, travel-time tomography, ambient noise tomography, among others.

We present here the results associated with the recorded seismicity. Besides several natural earthquakes in the region, induced earthquakes were regularly detected, at a rate higher than one event per day. Most of them were clustered in the vicinity of geothermal wells or known geological structures, at a depth between 1 and 3 km, consistent with the exploited reservoir interval.

1. INTRODUCTION

1.1 The GEMex Project

The GEMex project, which is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 727550, is a cooperation project between a European consortium and a Mexican consortium. Twenty-four partners, all members of the European Energy Research Alliance (EERA), constitute the European consortium and three partners constitute the Mexican consortium. The project is based on three pillars: 1) the assessment of geothermal resources at unconventional geothermal sites in the Trans-Mexican Volcanic Belt (TMVB), namely the Acoculco enhanced geothermal system (EGS) and the Los Humeros superhot system; 2) the characterization of the geothermal reservoirs; and 3) the design of concepts to (further) develop these sites in the light of the information gained. In this work, we focus on the second pillar, for the Los Humeros site.

1.2 Los Humeros context

The Los Humeros geothermal field is located in the state of Puebla, near the border of Veracruz at about 100 km from the Gulf of Mexico. It sits at the eastern side of the young and active TMVB, a favourable place for geothermal energy exploitation. Hence, starting with a 5 MW capacity in the 1990s, the Federal Electric Commission (CFE) currently operates the field with a 94 MW capacity, which makes this site one of the largest exploited in Mexico. Twenty-five wells are producing 6 Mt of steam every year from the 2-km deep reservoir (Calcagno *et al.* 2018). Locally, temperatures up to 400°C have been measured at 2.5 km depth, however, this resource is not exploited yet and is therefore one target of the GEMex project. The exploitation takes place in the Los Potreros caldera (5-8 km radius), the relatively young caldera (ca. 70-100 ka) which sits in the centre of the older (ca. 165-460 ka), larger Los Humeros caldera (18-20 km radius). Geologically, the Los Humeros volcanic system is a Pleistocene basalt-andesite-rhyolite system (Calcagno *et al.* 2018).

1.3 Passive seismic monitoring objectives

One of the project goals is to describe geological structures at depth and to identify super-hot resources. Consequently, several geophysical, geochemical and geological investigations have been carried out on-site. The objectives of the passive seismic monitoring are multi-fold. With the recording of the local seismicity, it is expected to image the most active zones of the geothermal field and to investigate the relationship with the production and injection operations carried out on-site. Furthermore, earthquake-based tomography should provide continuous imaging of the underground seismic properties and insight on the geothermal fluid properties. With the installation of a dense network, seismic ambient-noise imaging is possible and surface wave tomography and interferometry are currently carried out.

Previous studies (Lermo *et al.* 2007; Urban and Lermo 2013) highlight the occurrence of local seismic activity in the Los Humeros geothermal field, mainly in the exploited Los Potreros caldera zone. These studies cover different periods (between 1997 and 2008, and 2014 and 2016) during which earthquakes up to moment magnitude 4.2 were recorded. They discuss the possible relationship between the seismicity and the injection operations in the field (Lermo *et al.* 2016). The analyses are based on a telemetered permanent seismic network of six three-component stations installed by CFE in 1997, and on temporary networks installed in the area for the sake of the studies (Gutiérrez-Negrín and Quijano-León 2004; Lermo *et al.* 2007).

For the GEMex project, it was decided to install a dense seismic network for a one-year period. Such a network should provide basic data to image the underground structures with enough details to reach the project objectives. In the following, we will focus on the local seismicity recorded by that network.

2. PASSIVE SEISMIC NETWORK

Between Sep. 17 and Sep. 18, a temporary seismic network was deployed and maintain to monitoring continuously the Los Humeros geothermal field area (Fig. 1). Twenty short-period three-components sensors (Mark L-4C-3D) recording at 100 sps and 25 broad-band three-components sensors (Nanometrics Trillium compact 120 s) recording at 200 sps composed the network, which is divided in two sub-networks. The first one, consists of 27 stations spaced every 2 km to cover the producing zone, in the Los Potreros caldera. The second one is sparser, with a 5-km minimum spacing between the remaining stations, and covers an area of about 30 km radius around the centre of the Los Potreros caldera.

These sub-networks are complementary and designed to answer specific questions. The dense inner sub-network is intended to focus on the local seismicity and to comply with beamforming and time reverse imaging techniques. The sparser sub-network is dedicated to larger scale imaging techniques, such as seismic ambient noise tomography or interferometry, or regional earthquakes tomography.

Fifty percent of the stations recorded continuously more than 75% of the monitoring period. The site noise levels were, on average, between 2 and 10 dB below the high noise model from 1 to 10 s. For frequencies higher than 1 Hz, the daily varying anthropogenic noise could be observed for several stations.

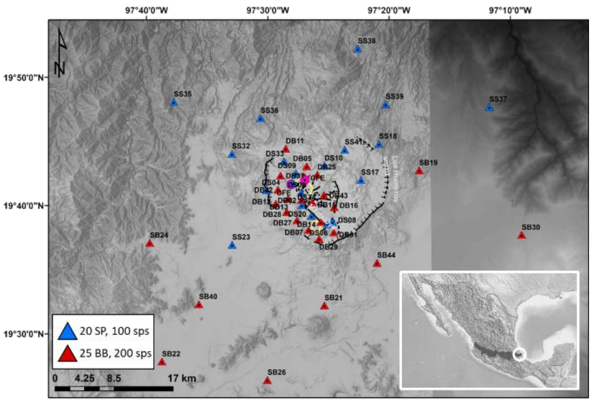

Figure 1: Layout of the passive seismic monitoring network deployed around Los Humeros. The network comprised 3C short-period sensors (blue triangles) and 3C broad-band sensors (red triangles).

3. SEISMIC DATA PROCESSING

3.1 Detection of local seismicity

From the continuous recordings, the first task consisted in detecting local seismicity in the Los Potreros area. To do so, we applied a recursive STA-LTA detection algorithm, which was calibrated on local events recorded in 2005 and 2006 by the permanent CFE network, and checked exhaustively on several days of the GEMex seismic database. The optimum detection parameters combine a band-pass filtering between 10 and 30 Hz, STA and LTA windows of 0.2 s and 2 s respectively, an activating threshold for a STA/LTA ratio of 3.5 and a deactivating threshold of 1. In order to detect either on the P- or the S-wave, the STA/LTA ratio was computed on a three-component amplitude trace, which corresponds to the square root of the sum of each squared component. Finally, the detection was applied only on the stations belonging to the dense inner sub-network and validated if at least five stations were triggering. The processing suite applied is developed under the Python programming language and makes use of the numerous capabilities of the Obspy reference library (Beyreuther *et al.* 2010).

From the continuous records, ca. 1570 possible seismic events were detected. Using the Obspyck software (Megies 2016), they were manually reviewed, classified and picked when relevant. Many of the detections were associated to storms and noise. Regional earthquakes were also identified, part of them being listed in the Mexican earthquake catalogue of the Universidad Nacional Autónoma de México (UNAM).

These 88 regional earthquakes typically exhibit P- to S-arrival time difference larger than 10 s. Finally, 482 local earthquakes were isolated, and typically last less than 10 s (Fig. 2).

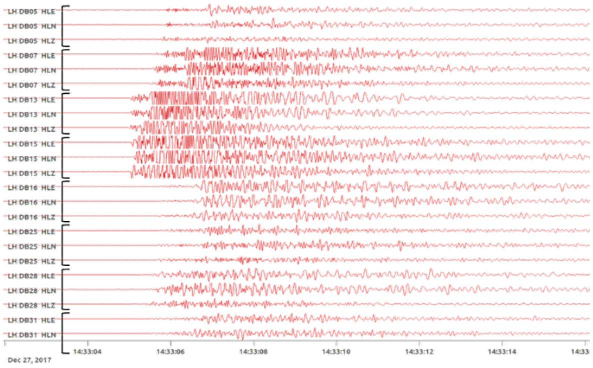

Figure 2: Seismogram of a local earthquake recorded at eight 3C-stations of the dense inner sub-network. The traces are sorted East, North, Up for each station. The amplitude scale is common to all traces and chosen to highlight the P- and S-wave arrivals.

3.2 Location of earthquakes

In order to locate the local earthquakes, a 1D velocity model was selected. It is rather a simplistic view within this volcanic geomorphology, as described by Calcagno *et al.* (2018), but this initial choice is motivated by the fact that several tomography techniques will be applied to better describe the velocity model in 3D.

Although Lermo *et al.* (2007) proposed a 1D P-wave velocity model for the zone, it was decided to use a so-called minimum 1D-velocity model. Indeed, such a model, obtained from the joint inversion of the earthquake location and the 1D-velocity model, will be used as initial model for future travel-time tomography. This model was computed using the VELEST software, which applies the methodology described by Kissling *et al.* (1994). A P- to S-wave velocity ratio of $\sqrt{3}$ was applied.

Once the earthquake hypocentre is obtained, a local earthquake magnitude (Mlv) is estimated using the Obspy library (Beyreuther *et al.* 2010), which applies the formula of Bakun and Joyner (1984). This local magnitude is computed from the peak-to-peak amplitude of the vertical components and the associated half-period.

4. RESULTS AND DISCUSSION

4.1 Time and magnitude distribution

Fig. 3 (top) shows the time distribution of the local seismicity rate computed for five-days bins. In average, about six events are detected every five days. A maximum of ten earthquakes was recorded in one day, on the 04/11/17. At a first glance, no specific feature can be observed, however, parallel analysis with production and injection operations in the field will be done in the near future to investigate possible links.

The local earthquakes have Mlv ranging between -0.9 and 2.1 (Fig. 3, bottom). A first analysis of the magnitude distribution shows that the network reached a magnitude of completeness around 0 and that the b-value is slightly larger than 1 (Fig. 4). These are general observations, which will be further investigated in time and space.

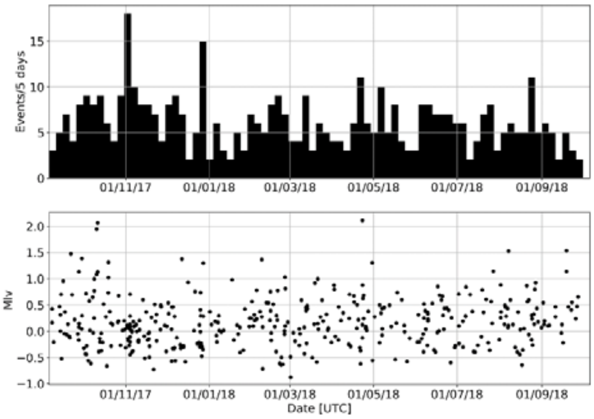

Figure 3: Time distribution of the seismicity: event rate for 5-days bins (top) and event local magnitude (bottom).

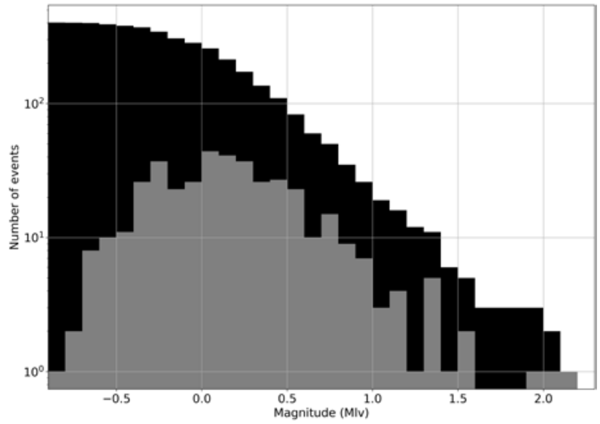

Figure 4: Magnitude distribution of the local earthquakes: cumulative number (black histogram) and number of events (grey histogram). Both numbers are plotted on a log scale.

4.2 Spatial distribution

Fig. 5 shows the epicentres of the local earthquakes. As observed, the recorded seismicity is not sparse but rather distributed in clusters, well within the coverage of the dense inner network. Four main clusters can be identified and are located in the central and North zone of the Los Potreros caldera. The two most western clusters are located below production and injection wells whereas the other two clusters are not directly located below geothermal wells but located in a known faulted area. Lermo *et al.* (2007) observe a seismogenic zone located to the east of the northernmost cluster we see, but they do not observe activity close to the other three clusters. However, Lermo *et al.* (2016) observe a new active zone close to the Las Papas fault, which is consistent with the easternmost cluster we do see. Hence, the GEMex dataset highlights a new seismogenic zone besides existing ones. More detailed analysis of the spatial evolution of the seismicity with time will require improved data processing of our current dataset and information about the production history of the field. This work is planned for the near future.

In depth, most of the seismicity is located between 1 and 3 km, with the largest distribution at 2 km depth. This depth corresponds to the currently exploited reservoir interval. Detailed analysis will require enhanced processing and, more importantly, tomography results.

5. CONCLUSIONS AND PERSPECTIVES

The temporary monitoring network deployed for one year around the Los Humeros geothermal field, in the framework of the GEMex project, was fruitful. Local earthquakes were regularly detected, at a rate of about 1.2 events per day. The network was able to record earthquakes of local magnitude ranging between -0.9 and 2.1, with a magnitude of completeness close to 0. The magnitude distribution, taken as a whole, is consistent with a b-value slightly smaller than 1.

Around 470 events have been located, almost exclusively below the central part of the network. The seismicity takes place exclusively in the Los Potreros caldera, which is currently exploited. The hypocentres are located in the central and northern parts of the production area and are clustered horizontally and in depth at the reservoir level. Hence, four main clusters have been identified and are located in the vicinity of geothermal wells or known geological structures.

Further work to improve the structure imaging from the local earthquakes is necessary. The first next step will consist in performing multiplet analysis and relative locations to provide more details on the clusters identified so far. Analysis in combination with focal mechanism is also foreseen. The spatial and temporal behaviour of the local seismicity must be investigated in detail in the light of geothermal well locations and production and injection operations. This is of main interest to better understand the interaction between the field operations and the seismicity, and thus the impact of the exploitation on the stability of the underground structures. Finally, these results should be integrated and compared to other results obtained within the framework of the GEMex project, especially the complementary geophysical investigations (tomography, magneto-telluric, gravity), the geochemical and geological ones, but also reservoir modelling results.

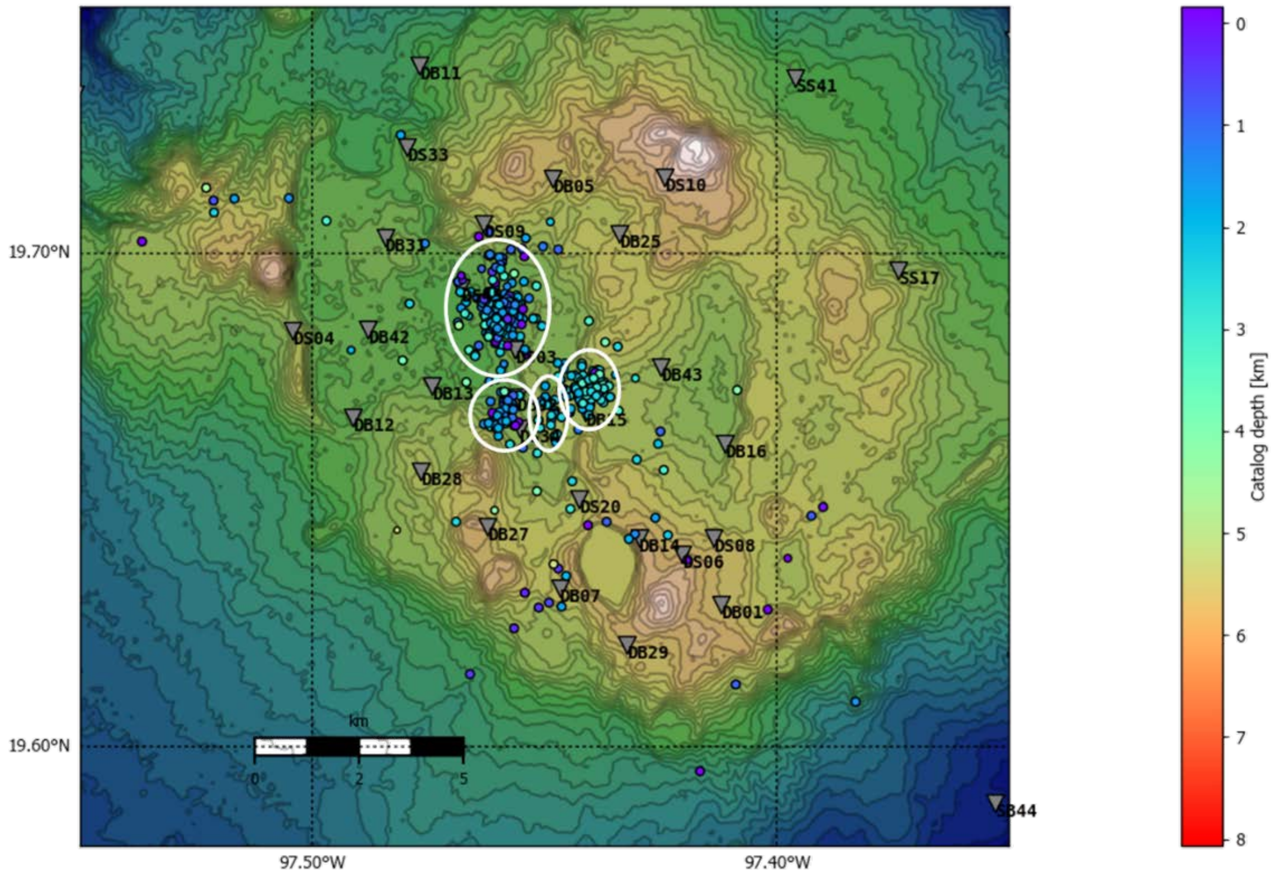

Figure 5: Epicentre map of the local seismicity recorded at Los Humeros on top of the topographic map. The earthquake colour corresponds to its depth (see colour bar). The stations of the dense inner sub-network are all visible at this scale (inverted grey triangles).

REFERENCES

Bakun W.H. and Joyner W.B. 1984. The ML scale in central California. *Bulletin of the Seismological Society of America* **74** (5), 1827–1843.

Beyreuther M., Barsch R., Krischer L., Megies T., Behr Y. and Wassermann J. 2010. ObsPy: A Python Toolbox for Seismology. *Seismological Research Letters* **81** (3), 530–533.

Calcagno P., Evanno G., Trumpy E., Gutiérrez-Negrín L.C., Macías J.L., Carrasco-Núñez G. and Liotta D. 2018. Preliminary 3-D geological models of Los Humeros and Acoculco geothermal fields (Mexico) – H2020 GEMex Project. *Advances in Geosciences* **45**, 321–333.

Gutiérrez-Negrín L.C.A. and Quijano-León J.L. 2004. Analysis of seismicity in the Los Humeros, Mexico, geothermal field. In: *Geothermal Resources Council Transactions*, pp. 467–472.

Kissling E., Ellsworth W.L., Eberhartphillips D. and Kradolfer U. 1994. Initial reference models in local earthquake tomography. *Journal of Geophysical Research-Solid Earth* **99** (B10), 19635–19646.

Lermo J., Antayhua Y., Quintanar L. and Lorenzo C. 2007. Estudio sismológico del campo geotérmico de Los Humeros, Puebla, México. Parte I: Sismicidad, mecanismos de fuente y distribución de esfuerzos. In: *Congreso Anual 2007*, Puebla, Mexico.

Lermo J., Lorenzo C., Antayhua Y., Ramos E. and Jiménez N. 2016. Sísmica pasiva en el campo geotérmico de Los Humeros, Puebla-México y su relación con los pozos inyectores. In: *XVIII Congreso Peruano de Geología*.

Megies T. 2016. Obspyck 0.4.1. Available at: https://github.com/megies/obspyck/wiki.

Urban E. and Lermo J. 2013. Local seismicity in the exploitation of Los Humeros geothermal field, Mexico. In: *38th Workshop on Geothermal Reservoir Engineering*, 38th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, SGP-TR-198.

Acknowledgements

This work was carried out in the frame of the GEMex Project, which is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 727550. The authors wish to thank the Comisión Federal de Electricidad (CFE, Mexico) for their assistance and support, the Mexican Energy Sustainability Fund CONACYT-SENER, project No. 2015-04-68074, all colleagues who participated to the set-up and maintenance of the passive seismic network and the colleagues of the GEMex work-package 5 for their help.