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The GEMex project: Developing Los Humeros (Mexico) as a Superhot Geothermal Site

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ABSTRACT

The GEMex project is a Mexican-European research cooperation on developing concepts for the use of superhot and engineered geothermal systems (i.e., Los Humeros and Acoculco) for power generation. Key focus in the first stage of the project is the confirmation and characterization of a superhot geothermal reservoir, which is expected in the deeper structural level of the Los Humeros volcanic complex. Los Humeros is located at the eastern tip of the Mexican Volcanic Belt within a Quaternary volcanic complex. The conventional hydrothermal reservoir in Los Humeros has been harnessed by the governmental utility CFE (Comisión Federal de Electricidad) since 1990 with a current operating capacity of 94 MWe. Reservoir temperatures around 380°C were found at depths below 2,000 m, indicating the presence of a superhot geothermal reservoir. However, geothermal fluids at such high temperatures could only be used to some extent for energy production, due to their aggressive physicochemical characteristics. For that reason, research is also required on the development of novel technological concepts. The complexity of the available data and the heterogeneity of the geothermal system requires sophisticated solutions for a meaningful integration of information. The paper will give an overview of the exploration strategy, selected results and interpretation.

1. INTRODUCTION

The GEMex project is a complementary effort of a European and Mexican consortium on unconventional geothermal systems (i.e., Los Humeros and Acoculco). Focus of this multidisciplinary project is on 1) Resource assessment, 2) Reservoir characterization, and 3) Concept development for exploitation and utilization (Fig. 1). Resource assessment focuses on understanding the volcano-tectonic evolution, the fracture distribution and hydrogeology of the respective region, as well as predicting in-situ stress axis orientations and temperatures at depth. This includes structural mapping, analysis of fault kinematic indicators from active and exhumed systems, geochemical characterization of fluids from natural manifestations and comparison with reservoir fluids. Geophysical data have been acquired by various methods for reservoir characterization, and the resulting data will be combined in integrated reservoir models. For the interpretation of these data, high-pressure/high-temperature laboratory experiments have been performed on rock samples from Mexico or equivalent materials to derive the physical properties required for the key lithologies encountered. The development of a concept includes adaption of technologies and identification of suitable materials for superhot reservoirs. Existing and newly collected information will be used to define drill paths, to recommend a design for well completion, and to investigate optimum stimulation and operation procedures for safe and economic exploitation with control of undesired side effects. These steps will include appropriate measures and recommendations for public acceptance and outreach, as well as for monitoring environmental impact.

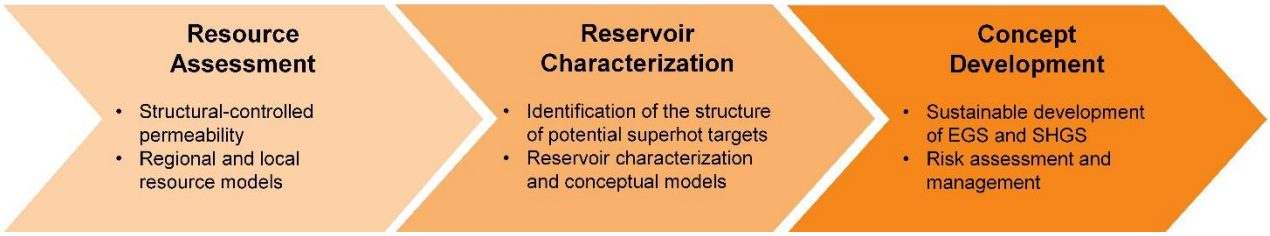

Figure 1: GEMex workflow (Jolie et al., 2018).

Los Humeros is a Quaternary volcanic complex with existing geothermal power plant facilities (installed capacity 94.8MWe, and around ~30 wells under production and injection), developed and operated by the Comisión Federal de Electricidad (CFE). The focus within GEMex is on (1) an improved and comprehensive understanding of the location and characteristics of the deep superhot geothermal reservoir (SHGS), (2) its connection to the known conventional system based on a complementary, interdisciplinary approach of novel and established exploration and assessment methods, and (3) concepts for the development of the superhot geothermal resource. Los Humeros is a system with reservoir temperatures > 380°C (> 2 km depth); however, due to the aggressive physicochemical characteristics of the geothermal fluids, a sustainable operation at superhot conditions has not yet been fully manageable for power generation.

2. REGIONAL AND LOCAL TECTONIC CONTROL ON FLUID FLOW

2.1 Structural geology

Intensive efforts in geothermal exploration focus on a comprehensive understanding of the tectonic control on fluid flow in the subsurface. Therefore, structural and kinematic data are not only collected from the active Los Humeros system, but also from exhumed systems (e.g., Las Minas) nearby, in outcrops analogue of the deep part of the Los Humeros potential reservoirs (Fig. 2). The fieldwork activity was based on the classical approach of structural geology, and enhanced through scanlines and imaged fracture analyses, both at outcrop and thin-section scale. Distribution of fractures and analysis of kinematic indicators on fault surfaces allowed to estimate stress axis orientations and preferential fluid pathways through the main geological structures. In Las Minas fluid inclusion analyses were performed for the characterization of the palaeo-fluids. By comparing the results from active and fossil systems, a conceptual model on the relationship between geological structures and fluid pathways is derived. It includes structures from the Los Humeros caldera collapse and NNW-SSE and SW-NE striking regional structures, both contributing to enhance permeability although at different structural levels. Information from the exhumed system indicates that superhot fluids are localized at depth of about 3-4 km, preferentially where the two regional systems are crosscutting each other. Fluid inclusions analyses, carried out on hydrothermal minerals, suggest a hypersaline brine with temperature up to 500°C, at depth. The interaction of fluids with the host rocks (mainly limestone) includes CO_2 production and further effects on enhancing local permeability. Meteoric fluids are mixed with the deep fluids, at shallower structural levels (Fig.2).

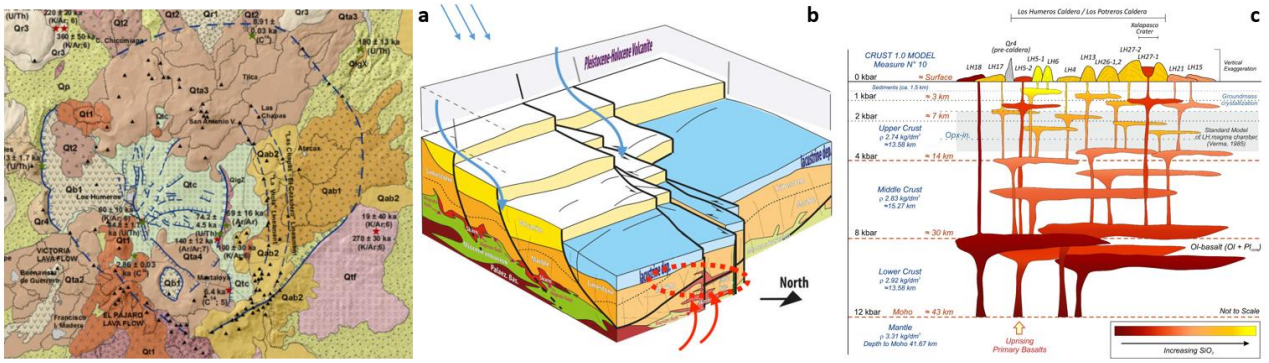

Figure 2: Three different map and sketches illustrating the structures in Los Humeros: (a) part of the geological map from Carrasco-Núñez et al. (2017) showing the distribution of the caldera collapse structures, affecting the shallow part (down to 2 km, at least) of the geothermal system; (b) conceptual model of the relationships between geological structures and geothermal fluid flow in the paleo-geothermal system of Las Minas, as analogue of the deep part of the Los Humeros area: the dashed line indicates the volume of rocks where superhot fluids circulate, corresponding to a depth of about 3-4 km and at the intersection between the two regional fault systems (after Liotta et al., 2019); (c) conceptual model illustrating the plumbing mechanism of magma differentiation and feeding at different structural levels at Los Humeros, on the basis of petrological studies (after Lucci et al., 2019).

2.2 Geochemistry

Specific tasks of the hydro-geochemical study are related to define chemical and isotopic characteristics of cold and thermal waters and geothermal gases, in order to: i) identify "feeding zones" of geothermal fluids; ii) constrain the equilibrium temperature reached by the fluid at depth; iii) identify the secondary processes (i.e. phase separation, precipitation of mineral phases), which take part during the evolution of geothermal fluids from reservoir conditions to surface levels. Water samples from cold springs, cold water wells, maar lakes, thermal springs and reinjection wells were collected in June 2017 and March 2018, respectively.

Langelier-Ludwig (LL) diagrams show that most collected waters have HCO_3 and Na or Ca as dominant anion or cations dissolved species, respectively. The distributions of points in the LL classification diagrams allow to identify three main "hydrochemical types": 1) Na-HCO_3, 2) Ca-$HCO_3$and 3) Ca-SO_4(HCO_3) waters. The first one is represented by spring waters located at high altitude in the Cofre de Perote volcano or close to Zaragoza village, in which outcrops of lava rocks (i.e. andesites, trachyandesites, dacites) are extensively present. This hydrochemical type represents the first stage of water-rock interaction between meteoric water and andesites. Calcium bicarbonate waters (Ca-HCO_3) is the most abundant hydrochemical type in the study area and is composed of waters from cold springs and wells located at different altitude. It represents different evolution stage of interaction between meteoric waters and carbonate rocks (i.e. limestone). The third hydrochemical type (Ca-SO_4-HCO_3) characterizes some wells located in the south part of the study area close to Laguna de Totolcingo, in which higher SO_4 concentrations are shown. The arid climate conditions characterizing this sector of the study area result in intense evapotranspiration/evaporation.

Stable isotopes data of geothermal fluids are compatible with physico-chemical processes commonly identified in several geothermal wells worldwide (e.g. oxygen-shift due to interaction of meteoric water with reservoir rocks). Mean values of δ^2H and $\delta^{18}O$ for cold water collected in the LHGF (excluding the acid waters) are similar to those for Acoculco. This feature points out to the regionalization of the meteoric component. Regional recharge cannot be ruled out for LHGF and it could represent an important percentage of the total amount.

A detailed study of soil degassing was performed inside the LHGF producing zone. Some areas are characterized by good correlation between fault zones and increased CO_2 efflux and elevated radon and thoron activity concentrations (Jentsch et al, in prep.). The presence of sectors characterized by very high CO_2 efflux > 300 g m^{-2} d^{-1} at the surface can only be explained by convection along permeable faults. In selected areas, higher resolution data have been collected by mobile laser survey. Carbon isotopic analysis of

CO_2 and $^3He/^4He$ isotopic analysis from soil gas samples indicate that faults and fractures in the subsurface have a link to the deep geothermal reservoir and favor the upflow of hydrothermal fluids. The results of soil degassing study suggest that the most permeable zone in the Los Humeros geothermal field is located in SW area and extends towards the north and northeast.

In the Perote plain and toward the south side of the Los Humeros study area, a cluster of "warm" water wells (T up to ≈33°C) aligned in NE-SW direction were identified for the first time. These wells are exploited by farms and have depths ranging from 120 to 180m and flow rates of about 60-70 l/s. Productive levels are located in rock formations, probably represented by andesites and dacites lavas located at shallow level close to Perote (see stratigraphic section in Carrasco et al., 2017). Their composition is Na-Ca-HCO_3.

3. DETECTION OF DEEP STRUCTURES BY GEOPHYSICAL SURVEYS

3.1 Resistivity

A total of 122 MT and 120 co-located TEM soundings were performed in Los Humeros. The dimensionality of the data and geoelectrical structure of the area were analyzed through phase tensor analysis and strike analysis and compared with the geological structure (Benediktsdóttir et al., 2019). A joint one-dimensional (1D) inversion of the TEM and MT data and three-dimensional inversion of the static shift corrected MT data has been performed (Benediktsdóttir et al., 2019). The results are compared with the geological results. The Los Humeros survey area is characterized by a complex three-dimensional resistivity structure with considerable horizontal contrasts. The results of the 1D inversion show that the resistivity structure is aligned with the main NNW-SSE faults in the region (Fig. 3). A conductive cap is seen to align with that direction at 2,600 meters above sea level. The main up-doming feature in the area lies at the main NNW-SSE faults in the region, which is underlain by an intermediate-resistivity layer at depths greater than 2,000 meters.

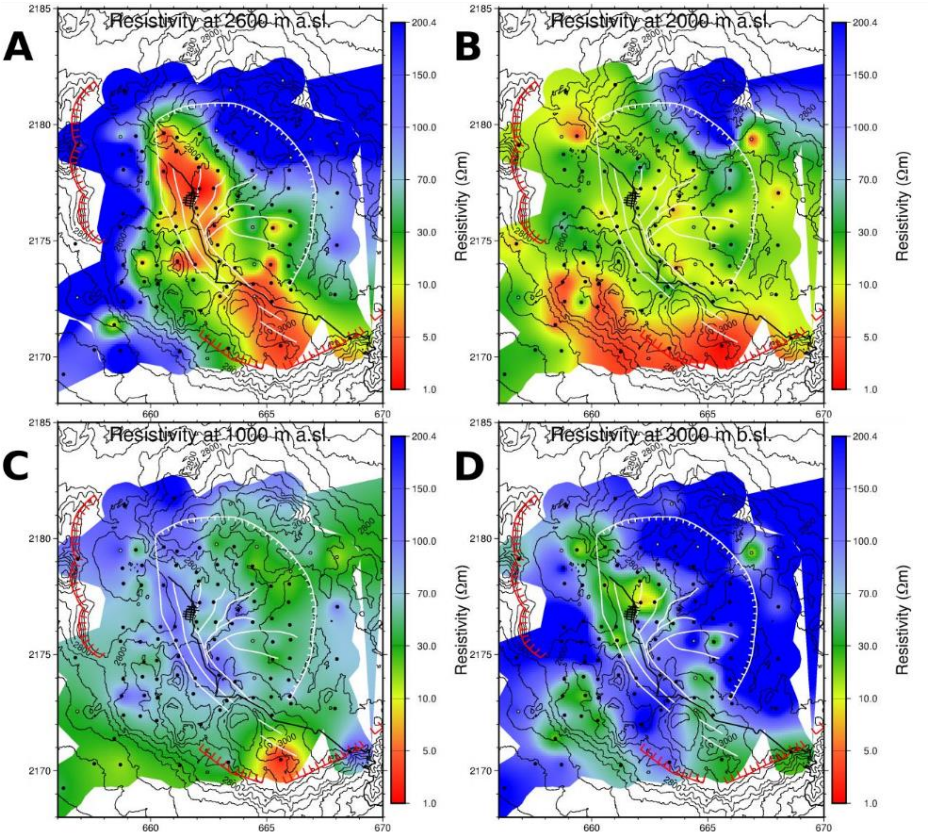

Figure 3: Horizontal cross-sections (depth-slices) through the resistivity model of the Los Humeros prospect bases on 1D inversion at 2,600 meters above sea level (A), 2,000 meters above sea level (B), 1,000 meters above sea level (C) and 3,000 meters below sea level (D). White and red hatched lines are the Los Potreros and Los Humeros calderas, respectively. Black lines are roads and white lines are main faults in the region. The town of Los Humeros is where the roads form a dense grid. Black circles are MT sounding locations and elevation contour lines are thin black lines, every 100 meters. Figure from Benediktsdóttir et al., 2019.

3.2 Seismicity

Figure 4 shows a map of the epicenters of the local earthquakes, from the dataset recorded by the GEMex network (43 stations deployed from September 2017 to September 2018). As observed (Gaucher et al., 2019), the recorded seismicity is not sparse but rather distributed in clusters, well within the coverage of the dense inner network. 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 -0.8 and 2.2, 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 mostly in the Los Potreros caldera, which is currently exploited. The hypocenters are located in the central and northern parts of the production area and are clustered horizontally and in depth at the reservoir level. Three main clusters have been identified and are

located in the vicinity of geothermal wells or known geological structures. The cluster containing most of the seismicity is the northern one. It is located in the area known as central collapse, between the La Cuesta and Loma Blanca faults. This zone was already seismogenic, as noticed by the previous studies of Gutiérrez-Negrín and Quijano-León (2004), Lermo et al. (2007) and Lermo et al. (2016). It is located at the level of two injection wells (H29 and H38). A second cluster is located to the west side of the Los Humeros fault, at the level of the wells H-40 and H-7, near station DB02. As far as we know from available bibliography, seismicity was not previously observed in this area. Finally, the third cluster, is located between the central collapse to the west, the Las Papas fault to the south and the Las Víboras fault to the north. Seismicity was observed by Lermo et al. (2016) to the west of this zone. There, the local earthquakes seem not to be directly related to geothermal wells. Hence, the GEMex dataset highlights a new seismogenic zone besides the previously identified. 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 behavior 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 exploitation and injection on stability of the underground structures.

In depth, most of the seismicity is located between 1 and 3 km, with the largest distribution at 2.5 km (below 3200 m TVD MSL). This depth range corresponds to the currently exploited reservoir interval. To further investigate the depth distribution of the seismicity, it is necessary to incorporate the tomography results and thus provide more reliable absolute depth values. As a matter of fact, even with the simplistic 1D velocity model used here for the preliminary earthquake location, relatively certain earthquake epicenters were obtained thanks to the seismic network density. This is however not the case for the event depths. Hypocenters uncertainties in depth are in average ±350m, about twice as large as the average horizontal uncertainties.

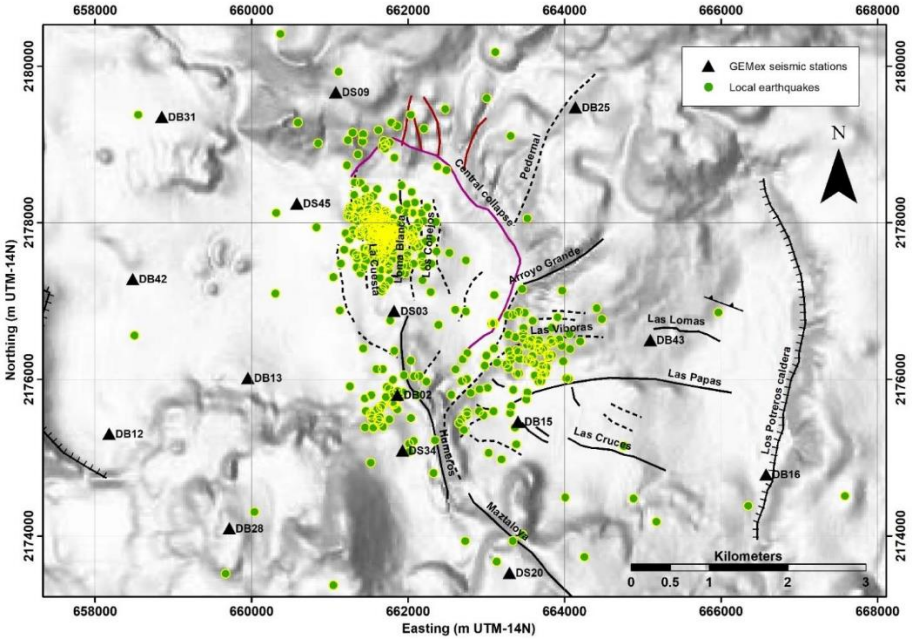

Figure 4: Epicenter map of the local seismicity (green with yellow contour circles) recorded at Los Humeros on top of the topographic map. The temporary seismic stations are displayed as black triangles (from Jousset et al, 2019).

3.3 INSAR

Surface deformation at the Los Humeros was mapped through PS-InSAR (Persistent Scatterer by Synthetic Aperture Radar Interferometry) time-series between April 2003–March 2007 (Békési et al., 2019). The observed deformation is attributed to field operations, since volcano-tectonic movements are only expected with magnitudes below the resolution of the InSAR data. The area of maximum subsidence is relatively small, located at the northern part of the geothermal field. The subsidence pattern with movements up to 8 mm/yr, indicates that the geothermal field is controlled by sealing faults separating the reservoir into several blocks. Surface movements are related with volume changes in the reservoir through analytical solutions for different types of nuclei of strain. Furthermore, the InSAR derived motions during the M4.2 event in 2008 were analyzed and inverted for fault source scenarios. The event occurred after a sharp increase in the injection rate at the Los Humeros Geothermal Field and it was recorded by the seismic monitoring network of the power plant. Despite the inaccuracy of the fault models, all the models locate the activation of the fault at shallow depth: no activation was predicted below ~1,200m depth. This implies that the earthquake most likely originated in the top of the reservoir.

To perform GPS it was used a measurement procedure called DGPS (Differential GPS) in which two or more GPS receivers are employed. The data collection is done every six months and will be done for four years (three campaigns have been carried out at the present). It was fortunate that during the first and second monitoring there was a large earthquake that affected the study area and whose effects are showing a more solid displacement vector. As preliminary results, motion vectors that act on the regional structures were obtained, with horizontal displacements (σ_{minH}) of up to 3 cm in NW-SE direction. This means that both calderas are in a tectonically active zone, where the faults and the blocks present relative movements, which is ideal for the reopening of fractures and

faults previously sealed and for the mobility of fluids in the geothermal systems. The observation deformation rates (up to 8 mm per year) are well in accordance with similar geothermal fields in Iceland.

3.4 Gravity

In Los Humeros, a total of 344 gravity stations were measured in two different surveys (Schill et al., 2019). Between 11/17 and 12/17, 263 stations were measured along ten E-W profiles of 5.5km length with typical inter-station and inter-profile distances of 200m and 500m, respectively. In 04/18, the survey was completed by a NE-SW oriented and 31km long profile across the 11-12/17 study area. This profile includes 81 gravity stations with an inter-station distance of about 375m. In total, 341 stations were used for further evaluation in Los Humeros field. From the Bouguer gravity map residual anomalies were calculated and analyzed in a pseudo-tomography by Butterworth filtering. The residual anomalies were related to the structural inventory. Indication for caldera structures as well as faults were identified. To obtain unconstrained information on the influence of the caldera and fault structures, the planned forward modelling was replaced by inverse modelling. With the aim of forecasting potential new reservoir zones the subsurface density distribution of Los Humeros was analyzed for lateral variation related to fault zones. Both, residual anomalies and inversion results reveal a high fault control on the gravity and thus the density distribution. The alignment of the majority of the anomalies follows NE-SW and NW-SE trending fault orientations. At Los Humeros, the N-S trending secondary faults in the northern part of the geothermal field also coincide with relatively high-density anomalies, whereas the NE-SW to E-W trending secondary faults are characterized by low-density. Assuming a link between low density zones related to faults and fractures, it is recommended to compare the gravity and density distributions to active faults with high reactivation potential.

4. REGIONAL MODELS AND RESERVOIR CHARACTERIZATION

4.1 Regional model

The complexity of the different datasets from geothermal exploration were consolidated by data integration in cooperative 3D GeoModels (Calcagno, 2015). The primary objective was a comprehensive understanding of the tectonic and volcanological evolution of Los Humeros by understanding conditions and processes determining the development of these unconventional geothermal systems. The first step for the characterization of the geothermal systems, before conceptual modeling at supra-regional scale, was the development of 3D models at regional and local scale (Fig. 5), by integrating surface information, such as geological maps and structural features, as well as subsurface information from geothermal wells, geological cross-sections, geophysical and geochemical information.

In Los Humeros, the geomodel at regional scale (56 km x 36 km x 12 km, i.e. down to 7 km below sea level) presents four geological groups: basement, pre-caldera rocks, rocks from the caldera, and post-caldera rocks. The geological map (Carrasco-Núñez, 2017b) and sections (Carrasco-Núñez et al., 2017a; Norini et al., 2015) were re-interpreted accordingly. The geological description of the wells made it possible to match all the information with the four groups selected for the modelling of the regional model. Eleven complementary cross sections were used to constrain the regional model. They were drawn according to the two references cross-sections cited above to ensure a coherent interpretation, for instance in terms of geological formations thickness. The geomodel at local scale (9.5 km x 12.5 km x 12 km, i.e. down to 7 km below sea level), shown in Figure 5, presents nine units: basement, basal pre-caldera, intermediate pre-caldera, upper pre-caldera, Los Humeros caldera, Intermediate caldera, Los Potreros caldera, post-caldera, and undefined pyroclastic rocks. One complementary cross section was used to constrain the local model (Calcagno et al., 2020).

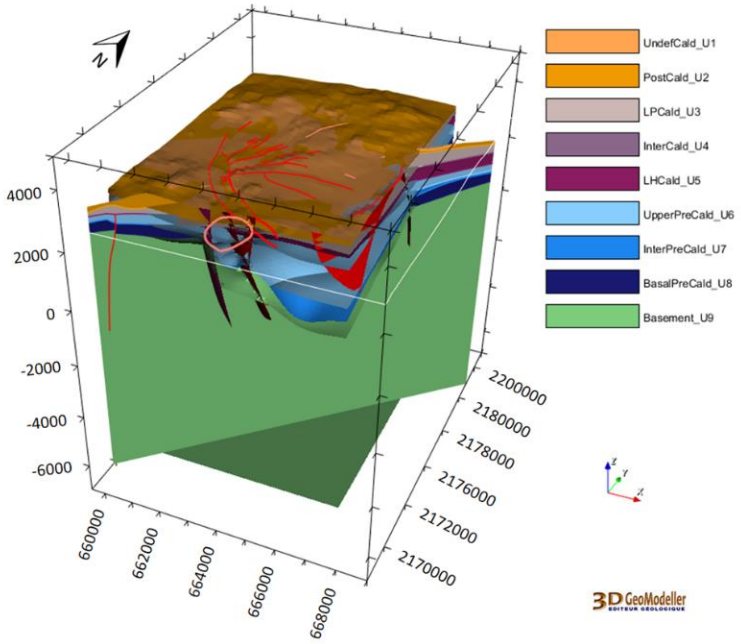

Figure 5: 3D geomodel of Los Humeros updated at the local scale (taken from Calcagno et al., 2020).

The preliminary models of Los Humeros were constructed using 16 wells considered as vertical. In addition to these wells, the CFE provided records for forty more wells, leading to 56 wells used to update the Los Humeros area. Among them, ten are deviated wells.

The drilling parameters given by the CFE were used to compute the geometry of their deviations and to integrate them at proper location in 3D. The 56 wells were described according to the updated geological description and taken into account in the modelling.

The second step was the development of thermal models based on the 3D geological models, including all subsurface information from the deep wells. The third step aims to gain a better understanding of the system, using analogue modeling techniques simulating field observations. The focus is on clarifying the relationship between the supra-regional and regional tectonic and volcanic features, including the comprehension of the deformation patterns related to the location of the volcanic edifices and the collapses. Expected results will produce information for the reconstruction of the structures controlling the geothermal reservoir at depth and the ability to discriminate between volcanic and tectonic origins of deformation.

4.2 Reservoir characterization

The Los Humeros Geothemal field (LHGF) is classified as a "super-hot" geothermal system based on its thermodynamic properties. It is characterized by high enthalpy fluid, very low permeability and low mass flow production (Arellano et al., 2003; Aragón-Aguilar et al., 2017). The complex tectonic history of this nested caldera system resulted in high variation of petrophysical and thermal properties of the associated rock units. Fluid flow is dominated strongly by faults and fractures formed during tectonic and volcanic episodes. One of the main aims of reservoir characterization is modeling the heat and fluid flow within these volcanic units. Static 3D numerical models is developed within Work Package 6 of GEMex to simulate the initial natural conditions of the super-hot reservoir system at different scales (Deb et al., 2019). To this end, geometries based on the preliminary geological models described in section 3.3.1 are imported into a numerical Simulator for Heat and Mass Transport (Shemat-Suite; Clauser, 2003; Rath et al., 2006) to form discretized and parameterized numerical models for simulating heat and fluid flow.

The simulation is performed at two scales, regional and reservoir. The regional model domain comprises of an area of 56 km × 36 km × 9.6 km with a total six million grid cells and provides the required boundary conditions for the reservoir model. The reservoir model is 9.5 km × 12.5 km × 6.5 km and is discretized in cells of dimension 50 m × 50 m × 50 m. Parametrization (assigning property values to the discrete cells) of the numerical model is based on measurements performed in outcrop samples obtained from exhumed and active systems in and around Los Humeros and Acoculco. Due to very limited availability of core samples from the geothermal wells, exhaustive studies on outcrop samples are undertaken. Petrophysical, mineralogical and geochemical measurements are performed on the outcrop analogues for characterizing their behavior under different temperature and pressure conditions. A petrophysical record documenting rock property values for different stratigraphic units based on outcrop measurements of the Los Humeros and Acoculco fields is developed (Bar et al., 2019).

Temperature and pressure records provided by Comisión Federal de Electricidad (CFE) for more than 50 wells are used as primary information to constrain temperature-depth distribution. For calibration of thermal models, temperature data used are restricted to measurements performed in wells before injection began in the field. Measurements in each well consisted of temperature and pressure surveys conducted immediately after drilling, normally after 4, 8 and 12 hours. In addition, temperature and pressure surveys recorded during heating and sometimes during flowing conditions were also available. Information on fluid circulation losses during drilling indicate that the major quantity of lost fluid (about 50 m3/hour) occurred at very shallow depth, while at deeper depths; fluid losses were only between 4 to 10 m3/hour hinting towards the very tight nature of the deep formations.

Initial static characterization indicates that the geological structures compartmentalize the field into three main sectors: North, Central and South (Aragón-Aguilar et al., 2019). The north zone consists of the highest density of productive wells. Figure 6(A) shows the temperature profiles at static conditions of wells of north zone of LHGF. Analysis of the shapes of temperature and pressure profiles of the geothermal wells combined with information obtained from circulation losses and drill cuttings provide a basis to classify wells with similar behavior and enable identification of feed-zones. Figure 6(B) shows a group of temperature profiles with similar trend indicating possible feed zones. Figure 6(C) is a 3D representation of the static temperature distribution model.

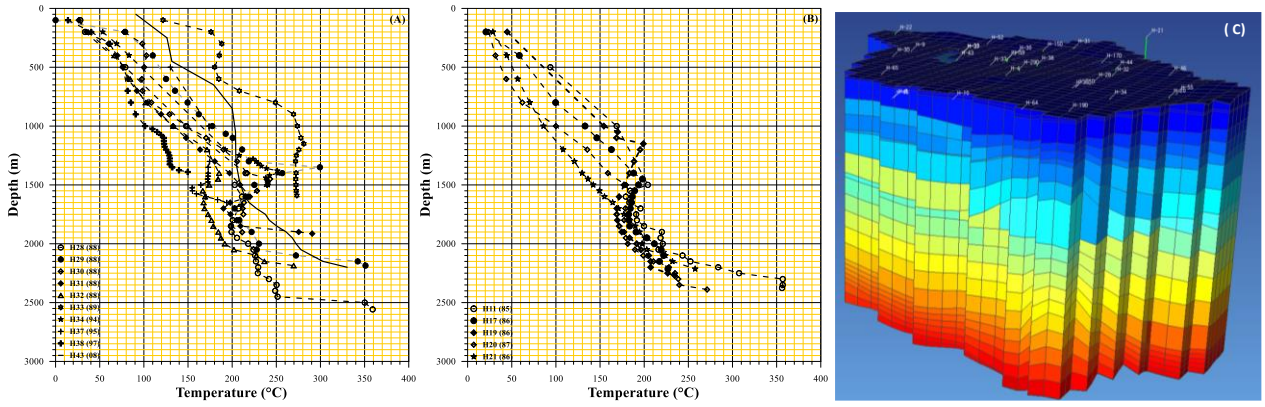

Figure 6: Reservoir temperatures distribution for numerical model construction of LHGF, (A) general temperature profiles at static conditions of north zone wells of LHGF; (B) group of temperature profiles with similar shape indicating possible feed zones and (C) 3D representation of static temperatures distribution.

Static characterization of the geothermal field and detailed well data analysis indicate that the geological structures (faults and fractures) dominate the underground flow. High temperature areas (>340 °C) are confirmed by wells; however lack of permeability and water recharge are the main reasons contributing to non-productivity in wells. The very low porosity and permeability of the overlying volcanic units inhibits recharge into the caldera complex. The recharge and discharge processes are therefore strongly

controlled by the vertical fractures and faults leading to fluid movement only in areas, which are intersected by these structures and are not sealed due to mineral precipitation.

5. CONCEPTS FOR DATA INTEGRATION AND IDENTIFICATION OF TARGET AREAS

The generation of complex datasets in the frame of major research projects requires integrated solutions for data processing, interpretation and visualization, in particular if multi-disciplinary 2D and 3D datasets are involved. Different software packages can be used to work with the data and illustrate results. However, this would not involve any integrated, quantitative measures and relates more to a digital mapping approach. The key parameter will be defined by the exploration concept. A priori information based on structural-geological surface mapping is the minimum input information, usually complemented by geochemical surveys to assess the possible reservoir conditions and geophysical surveys designed on the basis of geological mapping and geochemical analyses. In particular resistivity measurements is a standard technique for exploration and targeting production wells. In the case of Los Humeros a large database already existed before the GEMex project began. For that reason, an adapted strategy needs to be defined to take into consideration existing information and make use of it for the purpose of the planning of a geothermal well targeting the deep and superhot geothermal reservoir, which is expected below the conventional hydrothermal system.

Within GEMex we have formed a Task Force to address the specific conditions and work on the integration of data. One of the preliminary objectives is the development of a geoinformation-project, containing all raster and point file datasets. This project will facilitate the selection process of recommended target area(s) based on the available data for the possible development of Los Humeros as a superhot geothermal field. Here, adapted GIS requests will be possible.

Automated measures, e.g., data mining concepts for a more quantitative integration of large datasets, should become more important in such context. In this way, the understanding of cross-topic relationships could be understood more comprehensively (i.e., deep learning). Such concepts need to be defined specifically for each site and depend on the existing information. The lessons learnt in Los Humeros can serve to calibrate data mining concepts.

6. CONCEPTS FOR RESERVOIR DEVELOPMENT AND UTILIZATION

6.1 Materials

Corrosion of selected candidate materials used for downhole casings have been tested in superhot well H64 in the Los Humeros geothermal field. This well has well head pressure around 40 bar and temperature at well head is around 250°C and bottom hole temperature of 290°C at 2300 m. The pH at well head is measured as 3.5. For corrosion testing, a hexagonal bar was constructed with total of 35 test specimens from 7 different alloys was made. All test specimens were insulated with ceramic from the hexagonal bar. The hexagonal bar was lowered down to 1290m depth and kept in the steam downhole for 14 days. Temperature at 1290 m is around 260°C with superheated steam of 6°C.

Preliminary results from weight loss measurements indicate that the corrosion rate is high for commercial used casing materials from medium carbon steels. The experience from testing in superheated steam in Iceland (Thorbjornsson et al. WGC2020) reveal that the corrosion rate is much higher in H64 than in Iceland. These results are at present not fully analyzed but it can be concluded that the more noble materials tested were all under the commonly used corrosion limit of 0.1 mm per year.

This testing of corrosion behavior of materials includes not only weight loss measurements but as well slow strain tensile testing and microstructural analyses. These tests are currently ongoing in Mexico and Iceland. Verification of results will help to guide power producers in Los Humeros towards better materials for mainly production casings and by that increase both lifetime and productivity of the geothermal wells. All these testing have been conducted in good cooperation with the power company CFE, Geominco and Mexican Universities.

6.2 Tracer

Within GEMex, researchers investigated the suitability of anionic metal complexes as water tracers for geothermal reservoirs by testing their thermal stability and flooding properties, and measure their natural occurrence in geothermal fluids (Muller, 2019). One advantage when analyzing metal ions in water is the high detectability that can be achieved using advanced analytical instrumentations like inductively coupled plasma mass spectrometry (ICP-MS) or neutron activation analysis.

Of the seven tracer candidates tested for static thermal stability up to 250°C, three were regarded as sufficiently stable to qualify for further stability and flooding property tests. The three candidates (Tracer A, B and C) were tested further for thermal stability in closed quarts vials in 4% NaCl solution and with oxygen removed and exchanged by argon. The vials were tested at temperatures up to 350°C, with and without basaltic particles present in the vials during one week. When basalt particles were not present, the recoveries of Tracer A, B and C were near 100% for all the three candidates. When basalt was present, the recoveries of Tracer A and B were considerably reduced, while the recovery for Tracer C remained unchanged. Flooding experiments were performed at temperatures up to 375°C using a column filled with basaltic particles. The Tracer B was not recovered in the flooding experiments. Tracer A was slightly retained while Tracer C was eluted in nearly the same volume as the ideal tracer tritiated water. Tracer A was leaking from the basaltic particles in the column when it was heated to 300°C or above. Tracer A will therefore be less suitable in this type of rock, but may perhaps be suitable in others. Tracer B is not regarded as suitable due to adsorption. It was observed that Tracer C was partly transformed to another compound containing sulfur when heated above 250°C with basalt present in the vials. The sulfur compound of Tracer C was not retained during the flooding experiment, resulting in near 100% recovery when the measurement was based on analysis of the metal element and not of any of the species of the metal element.

Of the seven compounds tested, one tracer candidate (Tracer C) showed satisfactory properties as geothermal tracer and is expected to be suitable at temperatures up to at least 375°C. Further testing of Tracer C in field experiments is therefore recommended. The idea of using such metal containing anions as tracers for geothermal reservoirs and other fields of tracer research, has led to patent WO2018/093272 A1.

6.3 Drilling and completion

Deep drilling projects exploring supercritical resources such as these carried out in Mexico, Iceland, Italy or Japan, where encountered bottom hole temperatures significantly exceeded the critical point of pure water and hostile geothermal fluids were produced, faced a variety of challenges during drilling operations and geothermal fluid production. The most critical of these included high thermally-driven loads exerted upon cemented casing strings and couplings during operations such as well quenching or production kick-off causing casing collapse and/or connections rupture eventually leading to the well abandonment. Casing collapse in some cases might have been propagated by poor primary cementing job execution in zones of partial or total circulation loss. Within the GEMex project, Kruszewski and Wittig (2018) reviewed major failure modes in supercritical geothermal drilling projects carried out so far, including experience from one well in Los Humeros. According to the work carried out by Diez et al. 2015, most significant problems in the Los Humeros field are: (i) corrosion of mechanical infrastructure by hostile steam due to gaseous HCl and H_3BO_3, (ii) erosion from powerful superheated steam, (iii) extensive precipitation. Consequently, in the case of the Los Humeros not so much the drilling to the superhot target but the completion of the superhot wells creates main challenges.

Kruszewski et al. (2019) investigated cement sheath damage in one of the high-temperature wells in the Los Humeros field. The analysis of the cement quality logs concluded the presence of, potentially wet, micro-annulus as due to the high differences between recorded values of acoustic impedance obtained from both sonic and ultrasonic logs. After reviewing well history and specifics of the operations carried out, it was concluded that micro-annulus was potentially caused by a debonding fracture. The key question is whether such layer is isolated or not. The isolated liquid pocket will eventually expand during heating-up of the well and potentially threaten the integrity of the wellbore. It is however believed that debonding fractures are connected and pressure might be self-regulated either at the source (i.e. aquifer) or at the surface (or shallower aquifer). It is of high importance for future cementing operations in the LHGF, that prior to cement slurry pumping, any fluid losses in the well will be mitigated or in the best-case scenario, excluded in order to prevent the creation of micro-annulus.

For a properly designed wellbore cement in terms of general pressure management, any possibilities of abrupt temperature changes between well and surrounding rock formations shall be excluded. To decrease stresses created in the cement sheath during various well operations and prevent pre-mature cement failures, it is advised to improve the elastic properties of the hardened cement slurry.

As a result of the study on the cement sheath failures in the Los Humeros field, a new non-Portland sealing system based on the alkali-activated aluminosilicates was developed and laboratory tested under extreme temperature conditions in excess of 400°C including cyclic loading tests. Such non-Portland systems are believed to be good candidates for future super-hot geothermal well completions due to their more stable and higher, than conventional Portland cement, compressive and flexural strength, better resistance towards thermal cyclic loading and acid insensitivity as well as improved water permeability, while having marginal self-induced shrinkage.

6.4 Environmental, social and economic impact assessment

The socio-economic analysis within the GEMex project aims at defining a conceptual model for implementing a public engagement strategy to support and improve the local acceptance of geothermal developments. The analysis have used qualitative-quantitative methods focusing on relevant stakeholders involved in the geothermal energy development: consumers, local communities, public authorities and energy companies. The questionnaire survey with consumers contributes to the model by informing about the consumer's desired positive impact when geothermal energy is developed, so as to orient energy company's behaviour and achieve market benefits. The unstructured interviews performed with energy companies inform the model depicting different internal organisational structures when varying the level of engagement across different strategies. The unstructured interviews with local communities and public authorities analyzed by the Social Impact Assessment method inform the model by identifying the type of contribute communities can provide, and the role public authorities can assume per each level of engagement across different strategies. Thus, the model presents a scheme in which energy companies, local communities and public authorities cooperate by sharing information and processes and build a shared and multi-perspective vision of the social aspects to be addressed and of the public engagement strategies to be implemented. Moreover, the model identify four level of public engagement achievable: information, communication, collaboration and participation. Information relies entirely on the information provided to the public about the project's details and potential impacts on the local and wider community. Communication includes an active engagement of the public. Collaboration asks to actually engage the public in being part of the project development by adapting to the specific local/social needs both the project and their impacts evaluation. Participation represents the highest level of public engagement and consists of the actual engagement of the public in the design of the project. Then, the analysis concludes by providing policy and managerial recommendations for supporting the implementation of public engagement strategies.

7. CONCLUSION

The main challenge in a project like GEMex, designed to combine the Mexican knowhow on conventional geothermal systems with the European expertise of developing SHGS and EGS, is the integration of the wide spectrum of new outcomes produced by the multidisciplinary and multinational character of the project. To reach the poject's goals, the most crucial findings have to be selected and combined with existing knowledge collected during field operations over the past years.

In the case of Los Humeros, the main objective is to confirm the presence of superhot geothermal fluids at depth, characterize and locate them, and develop an adapted exploitation strategy. This is work in progress, which will be concluded by the end of the project. In addition to exploration, this includes also technical aspects, such as borehole planning and installations design to collect the superhot fluids, which may require specific concepts in comparison to the development of conventional hydrothermal resources, which is not the main purpose of this project.

The different tasks in the project have produced a huge amount of data and information. For Los Humeros, the re-interpreted old, and newly collected information, considered as the most relevant to reach the goal can be summarized as follows:

- Thermo-barometric modeling based on the age and silica content of samples of recent lavas (produced 10,000-3,000 years ago), reflecting magma compositions from olivine basalts to trachytes and rhyolites, implies that presently there is not a single magma body beneath Los Humeros.

- The extinct geothermal fluids in Las Minas were originally of saline to hyper-saline composition (18-50% of NaCl equivalent) with temperatures of 470-650°C and a vapor phase at sub-lithostatic or hydrostatic pressures (500-1,000 bar). The system evolved to metamorphic-hydrothermal with carbonic fluids produced by high-temperature metamorphism of limestones, and finally to a low-salinity and low-temperature system when the residual fluids mixed with groundwater. The current conditions of the superhot fluids in Los Humeros could be similar to the second stage of Las Minas.

- Superhot fluids are probably located at 3-4 km depth and possible exploration targets are intersections of the two regional structural systems (NNW-SSE and NE-SW).

- Rock formations containing superhot fluids are mainly of metamorphic origin (marble and skarn), with minor amount of intrusive (granitic composition) and sedimentary (more or less re-crystallized limestones) rocks. All of them will present low values of porosity, from 0.56% for marble to 7% for skarn, and permeability, from less than 1-18 m^2 for limestone and marble to 7-18 m^2 for granodiorite.

- Los Humeros is a system with reservoir temperatures > 380°C; however, due to the aggressive physicochemical characteristics of the geothermal fluids, a sustainable operation at superhot conditions has not yet been fully manageable for power generation.

- Conventional API buttress and premium casing couplings are prone to fail in wells dealing with supercritical resources. For that reason, it is recommendable to use flexible couplings for the casings.

- Wellhead assemblages and valves for a superhot well in Los Humeros should be manufactured with more resistant materials. Preliminary results of a corrosion test carried out in a well of the field, indicate that only alloyed materials are suitable for superficial installations in the superhot wells of Los Humeros.

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