Cooperation in Geothermal energy research Europe-Mexico for development of Enhanced Geothermal Systems and Superhot Geothermal Systems

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About GEMex

The EU-funded GEMex project was formed as a European consortium, in conjunction with a Mexican consortium, under the auspices of the EERA joint programme of geothermal energy. Working at two geothermal project sites in Mexico, it assessed their resources, characterising reservoirs and developing concepts for future site development.

While geothermal energy has been used in Europe and in Mexico for some time, both regions' consortium members were interested in unconventional geothermal systems: enhanced geothermal systems (EGS) and superhot geothermal systems (SHGS). GEMex had the ambition to bring together the extended Mexican knowhow of discovering, developing, and deploying geothermal energy systems with a variety of European expertise from similar geothermal energy systems (Italy, Iceland etc.), of enhancing EGS technology, and finding new approaches to make a sustainable use of super-hot geothermal systems. The two consortia thus cooperated on research for site developments, one for hot-EGS and one for SHGS. This cooperation laid the foundation to open synergies of competencies and technologies and leaded to an acceleration of the learning curve for geothermal development.

EGS are geothermal reservoirs with promising high temperatures but without enough initial rock permeability or fluids in the rock to transfer sufficient heat to the surface. SHGS are geothermal reservoirs with very high reservoir temperatures (regularly above 350 °C), higher than currently exploited anywhere. Such high temperatures would provide more energy per exploration wells previously drilled than the standard geothermal installations. While ideal for geothermal electricity production, the harsh subsurface conditions challenge drilling and well completion methods and materials.

To address the development of EGS, the Acoculco site was selected. It is very hot (300 °C at 2 km depth), but two deep wells encountered hardly any fluids, necessitating an EGS – never before accomplished in Mexico. For SHGS development, Los Humeros was selected. Los Humeros is an operating geothermal system where a superhot part of the geothermal field, with temperatures above 400 °C, remains undeveloped.

GEMex researchers applied geological, geochemical, geophysical, volcanological and hydrological studies (including passive and active seismic, resistivity, gravity and magnetics, surface deformation and soil gas) to characterise the reservoirs at depth and determined rock and fluid properties and their response to temperature and pressure changes in laboratory tests. The results of this research were combined with updated regional and reservoir models as the basis for further development and exploitation. Finally, concepts for the sustainable development of the superhot system and a stimulation concept for the EGS site have been designed.

Improving our understanding of superhot geothermal systems: Case study of Los Humeros

Los Humeros is a Quaternary volcanic complex composed of the Los Humeros caldera, with 16-18 km in diameter and formed 164 ka ago, and the smaller (6-8 km) and younger (65 ka) Los Potreros caldera nested in the first one. It is a geothermal field operated by the Comisión Federal de Electricidad (CFE), with 95 MW of running capacity and 30 production wells.. The focus within GEMex was 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 hydrothermal system at shallower depth (< 2 km) based on a complementary, interdisciplinary approach of novel and established exploration and assessment methods, and (3) on concepts for the development of the superhot geothermal resource. Los Humeros is a geothermal system with reservoir temperatures above 380°C at depths > 2 km; however, due to the aggressive physicochemical characteristics of the deep geothermal fluids, a sustainable operation has not yet been fully manageable for power generation.

Magmatic plumbing system and heat source

With the aim to decipher the configuration of the existing magmatic plumbing system heating the Los Humeros geothermal field, the GEMex team carried out an extensive field-based petrological study of the exposed Holocene lavas. The results obtained converge to a scenario (Fig. 1c) characterized by a heterogeneous, multilayered system of magma pockets, vertically distributed, from the Moho to the Earth's surface. A deep basaltic reservoir (~30 km) feeds progressively shallower and discrete magma stagnation layers and batches, up to the shallow crust (depth of ca. 3 km).

The main outcome for the petrological modelling of the magmatic heat source of the Los Humeros geothermal system is the inadequacy of conservative conceptual models based on the classical single, long-lived and voluminous magma chamber, favouring a more realistic view of a magmatic plumbing system made of multiple, partly interconnected magma conduits and storage layers within the crust, feeding small magma pockets at shallow-crust conditions (Fig. 1c). Detailed results are described in Lucci et al., 2020 and in Urbani et al, 2020.

Structures and permeable pathways

Intensive efforts in geothermal exploration focused on a comprehensive understanding of the volcano-tectonic control on fluid flow at the subsurface. 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. The basement underwent two main tectonic events: first, the Cretaceous to Paleogene compressional Mexican Fold and Thrust Belt (MFTB) generated NW–SE structures. Second, the Neogene-Quaternary extensional tectonic phase related to the Mexican Volcanic Belt produced mainly normal faults of NE-SW orientation. Recent, < 50 ka, volcanotectonic deformations, induced by active resurgence of the Los Potreros caldera floor, added considerable secondary permeability. The geometry of these deformations is partly inherited from regional tectonic structures.

Investigations from the exhumed system in Las Minas indicate that superhot fluids are localized at depth of about 3-4 km, preferentially where the two regional systems are crosscutting each other. This finding can be transferred from the exhumed system at Las Minas to the active geothermal system in Los Humeros.

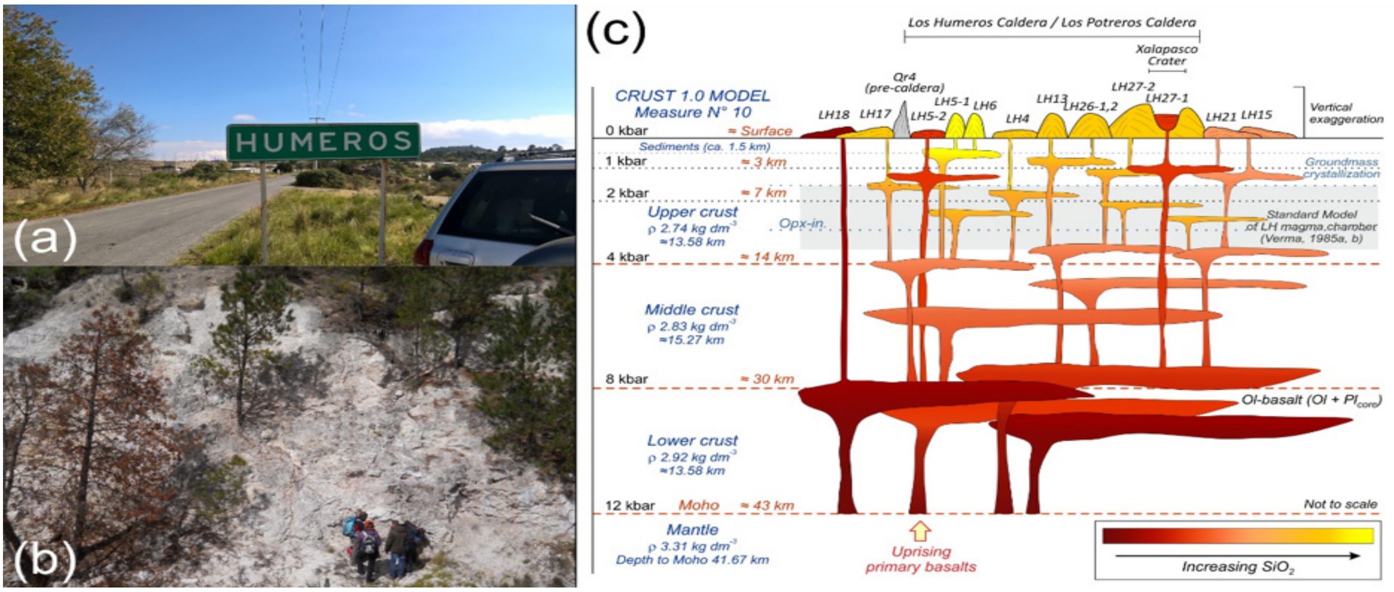


Figure 1 (a and b) Fieldwork at Los Humeros, particularly in the Loma Blanca outcrop. (c) Conceptual model of the magmatic plumbing system feeding the Los Humeros Holocene activity as derived by thermobarometry models. (From Lucci et al., 2020)

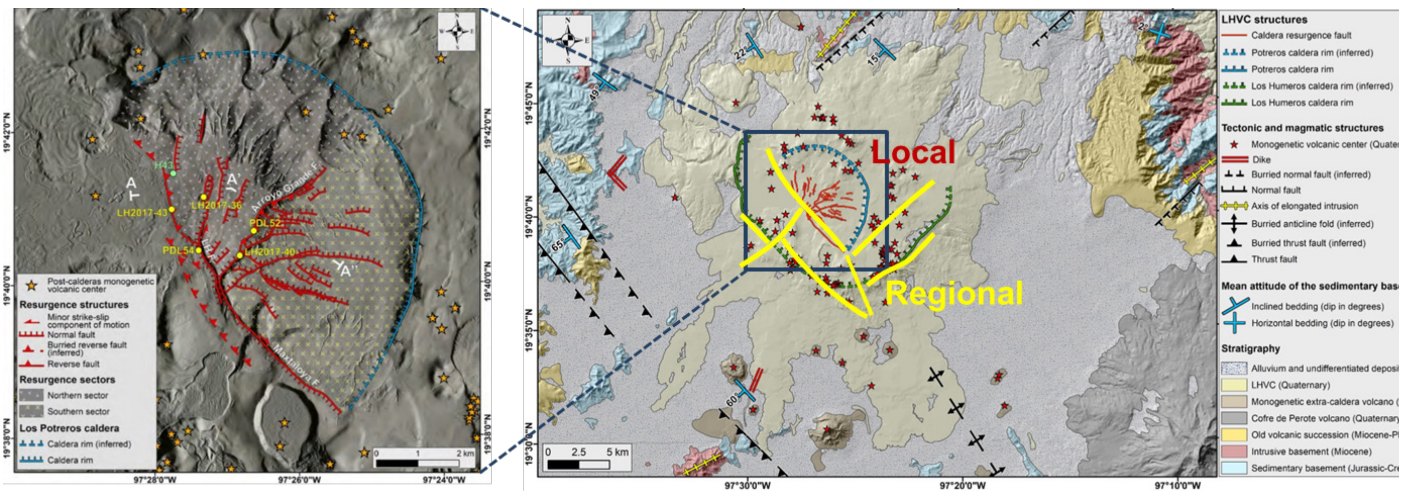


Figure 2: Faults and structures in the Los Humeros geothermal field. Secondary permeability results from a combination of (a) volcanotectonic structures induced by the caldera resurgence and (b) regional NW-SE and NE-SW striking faults. Superhot fluids are most probable where the regional structures are crosscutting each other in combination with sufficient heat supply from below. Figure adapted from Norini et al., 2019.

Analogue Modelling

Analogue modelling is an experimental technique that allows to study geological processes in the laboratory, through the analysis of physical models built with suitable analogue materials and deformed at reduced geometrical and temporal scales.

Experimental series conducted within GEMex have shown that:

- Pre-existing faults have been reactivated during the collapse of the Los Humeros and Acoculco calderas, producing sub-rectilinear caldera boundaries.
- Intra-caldera magma resurgence was simulated in the analague model producing a superficial fault pattern characterized by sub-orhogonal fault segments, similar to the current Los Potreros intra-caldera fault system (Fig. 3)

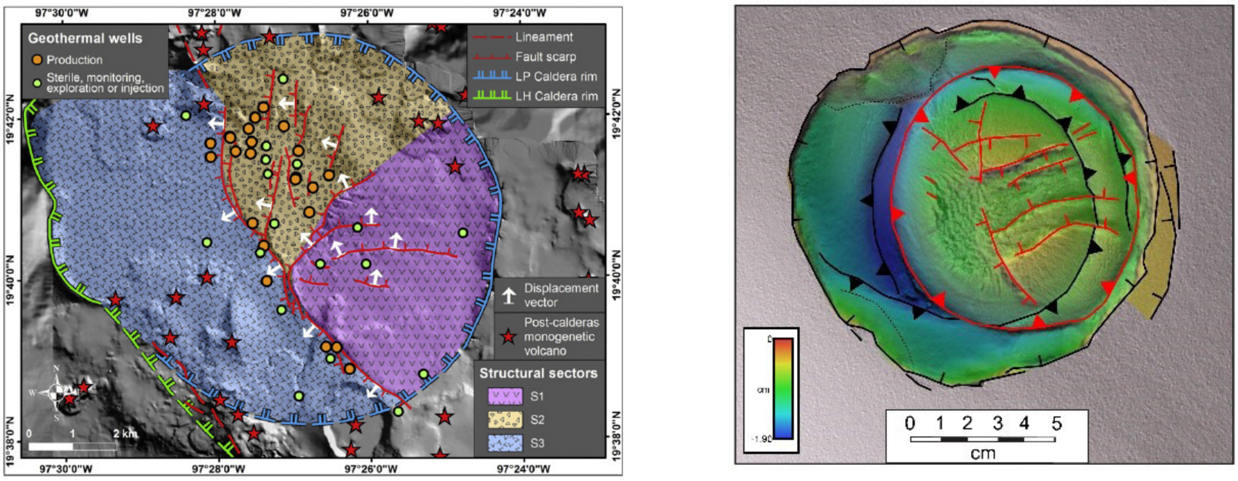


Figure 3: Los Potreros fault pattern in nature (left panel; from Norini et al., 2015) and from analogue modelling (right panel; Model GE-Mex_80, GEMex Deliverable 3.6), which show remarkably similar patterns (from Bonini et al., 2020).

Hydro-geochemistry of cold and thermal fluids

For hydro-geochemical studies, 57 and 87 water samples from cold and thermal springs, wells taping cold or warm water, maar lakes, reinjection wells and natural gas emissions were collected in GEMex.

Stable water isotopes of geothermal fluids are compatible with the occurrence of physical-chemical processes commonly observed in several geothermal fields worldwide, such as oxygen-shift process due to the interaction of meteoric water with reservoir rocks and fractionation due to boiling and phase separation. Isotopes data are in agreement with the hypothesis of regional meteoric component as source of geothermal fluids. Regional recharge could significantly contribute to the total recharge of the Los Humeros Geothermal Field. Mean values of δ2H and δ18O for cold water collected in the Acoculco geothermal field (excluding the acid waters) are similar to those of Los Humeros. This is consistent with the regionalization of a meteoric component.

Magmatic volatiles to assess permeable volcano-tectonic structures

The spatial variability of magmatic volatiles at Earth's surface is a proxy for structural discontinuities in the subsurface of volcanic systems. A multi-scale soil gas survey was performed across the main geothermal production zone of Los Humeros. CO_2 efflux values (Figure 5) range from below detection limit to 1,464 g m^{-2} d^{-1} with a total output of 87 t d-1 across an area of 13.7 km^2. Determined 3He/4He ratios indicate a mantle component in the samples of up to 65% being most evident in the northwestern and southwestern part of the study area. The combined processing of CO_2 efflux and $\delta^{13}C$-CO_2 facilitated the detection of permeable structural segments with a connection to the deep, high-temperature geothermal reservoir, also in areas with low to intermediate CO_2 emissions. One of the most significant areas is a permeable, NNW-SSE oriented structural corridor (including the La Cuesta and La Antigua fault), which shows the strongest mantle contribution in helium and carbon isotopes. Furthermore, high gas emissions were observed along another N-S oriented, structurally confined compartment (including Los Conejos and Area B in Figure 5). A promising area of enhanced structural permeability was identified south of Humeros village (Area E), making it a possible target for future geothermal exploration activities.

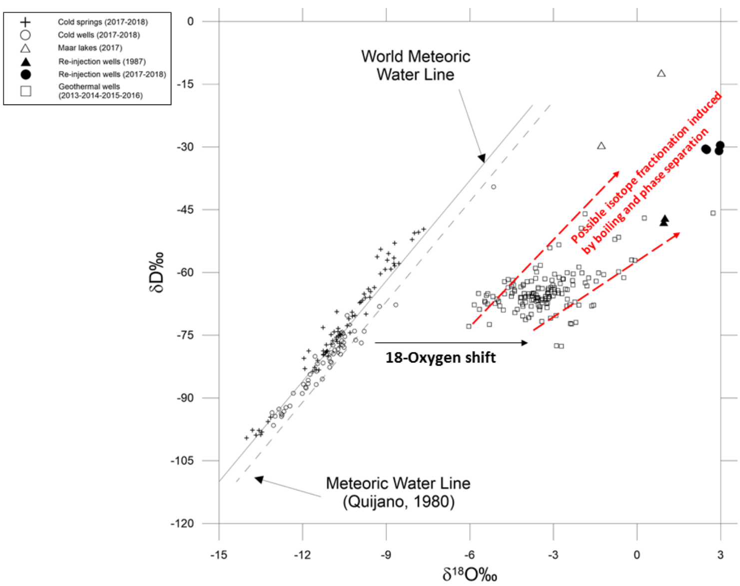


Figure 4: Deuterium vs 18-Oxygen correlation diagram for water samples (cold and thermal springs and water wells) inside and outside the LHGF, as well as geothermal wells

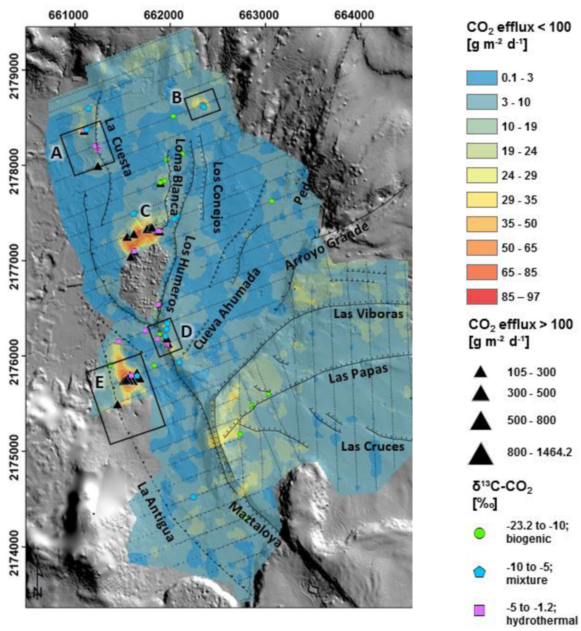


Figure 5: Results of sequential Gaussian simulation for CO_2 efflux showing the distribution degassing. Small black dots represent CO2 efflux sampling sites. Solid and dashed black lines illustrate known and inferred faults. Adapted from Jentsch et al., 2020

Studies in exhumed system Las Minas

In order to understand what is happening in depth reservoir at Los Humeros, an exhumed system was studied: Las Minas placed to located 30 km east. Studies on in this area indicated that the deep geothermal circulation (i.e. within the carbonate substratum) is controlled by fractures intersection and their damage zones. In particular, permeability was mainly controlled by the NNW-striking fractures, by their intersection with the NE-striking fractures and by the pre-existing foliations (i.e., bedding and granite/limestone boundary), where fluids were channelled when hydraulically connected to the main structural conduits. Hydrothermal fluid properties, studied by fluid inclusions and geochemical analyses, indicated circulation of hyper- to low- saline (meteoric) fluids, and from high (>600°C) to low (about 250°C) temperatures. Hyper-saline and hot to super-hot fluids were present at the deeper structural levels, while fluids with decreasing temperatures and salinity were recognized at shallower structural levels, these latter comparable with the present exploitation carried out in Los Humeros geothermal area. By this, the lesson we learnt is that the research should be addressed to the identification of similar structural relationships in the Los Humeros basement by integration and interpretation of indirect methods, since the outcrop conditions are not favourable.

Fluid inclusions – indicators from exhumed geothermal systems

The main goals of fluid inclusion studies were to characterize the paleo-fluids stored in the exhumed reservoir of Las Minas and to obtain from this characterization information on the physical-chemical conditions of the fluids that could be present in the deep part of the present-day Los Humeros geothermal system. Fluid inclusions were examined in quartz, garnet, tremolite and calcite. On the basis of the phases (i.e. liquid, vapor, solid/s) present at room temperature, the relative volumetric proportion and microthermometric data, four main fluid inclusions types have been distinguished (see Figure 6).

The present-day exploited geothermal reservoir in Los Humeros has a temperature of 300-400°C and is mostly recharged by meteoric water. Thus, it could be expected that the temperature conditions of the deeper super-hot system in Los Humeros can be comparable to those during the late stage of Las Minas (i.e. up to 450°C). In this case the fluid expected in the super-hot system is a mixture of low-salinity meteoric water and magmatic derived brine at a depth between 3 - 4 km, and fluid immiscibility occurred at times in the system.

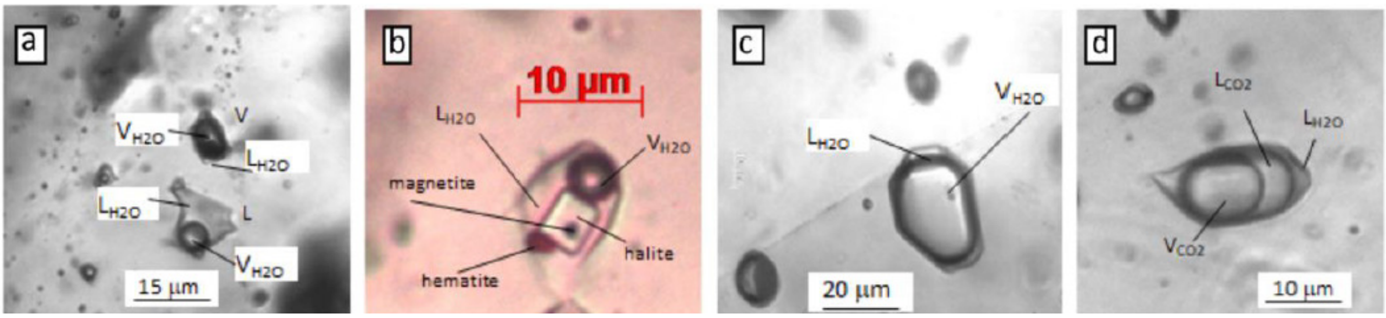


Figure 6: Main fluid inclusion types found in the skarn-hydrothermal minerals at Las Minas. a) Two-phases liquid-rich (L) inclusion coexisting with two-phases vapor-rich (V) inclusion in quartz. b) Multi-phases (LH) inclusion in quartz. c) Two-phases vapor-rich inclusion in quartz. d) Three-phases inclusion (VCO2). Abbreviations: LH2O: aqueous liquid, VH2O: aqueous vapor, LCO2: carbonic liquid, VCO2: carbonic vapor. From Liotta et al., 2020.

Resistivity modelling from MT and TEM surveys

In Los Humeros 122 Magnetotelluric (MT) and 120 co-located Transient Electromagnetic (TEM) soundings were performed. The MT and TEM resistivity data sets have been jointly 1D inverted and static shift corrected. The MT data were inverted in 3D using two different inversion codes – resulting in resistivity models for the Los Humeros area. Strike analysis was carried out, adding structural information to the area. Finally, the resistivity model was further refined using other geoscientific results. The resulting resistivity structure of Los Humeros shows a clear alignment with some of main geological structures, i.e. the Mastaloya and Antigua faults striking approximately NNW-SSE. In two areas the typical resistivity signature of a volcanic geothermal system has been observed (Figure 7 a, b), with an updoming resistive core, connected to high-temperature alteration minerals, overlain by a conductive clay cap, connected to the low-temperature alteration mineral smectite.

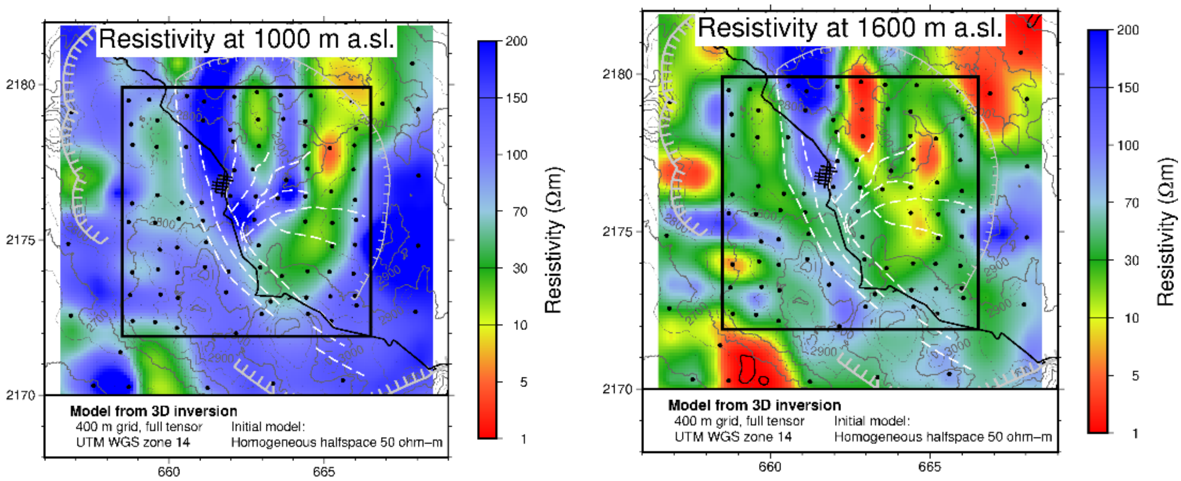


Figure 7: Depth slices through the resistivity model of Los Humeros at 1000 m above sea level (a) and 1600 m above sea level (b). The resistive core in the northern part is clearly seen as two anomalies; a more pronounced one striking NNW-SSE, parallel to the Antigua fault and the other one N-S oriented a little further east. From Hersir et al., 2019, GEMex Deliverable 5.2.

Passive seismic monitoring

A seismic network consisting of 45 stations was installed in the region of Los Humeros between September 2017 and September 2018. Around 470 events have been located, and are mainly grouped in three clusters. One cluster is located at the northern part of the caldera, below the main production area; a second one in the southern part of the caldera close to an injection well. For both clusters, seismicity is ranging around 2 km depth below surface. A third, deeper (2.5-3 km below surface) cluster is located in the eastern part of the caldera, just north of the Las Papas fault. This last cluster is not directly connected to any geothermal wells.

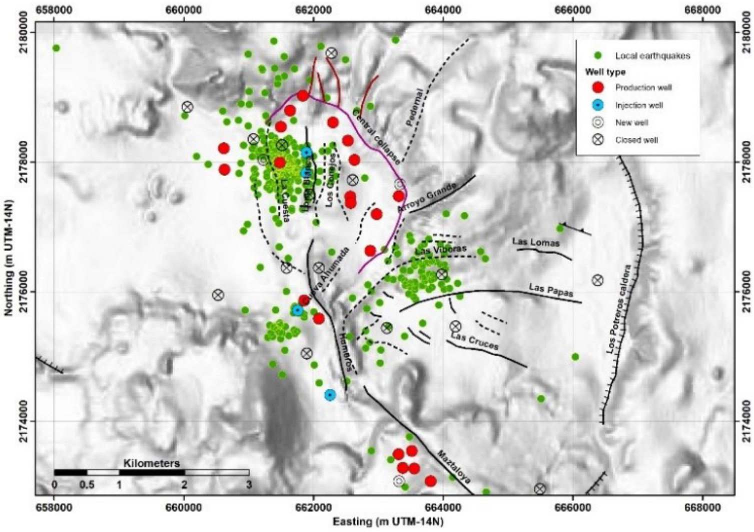


Figure 8: Location of seismic events detected by the seismic network deployed in the GEMex project. From Hersir et al., 2020, GEMex Deliverable 5.3.

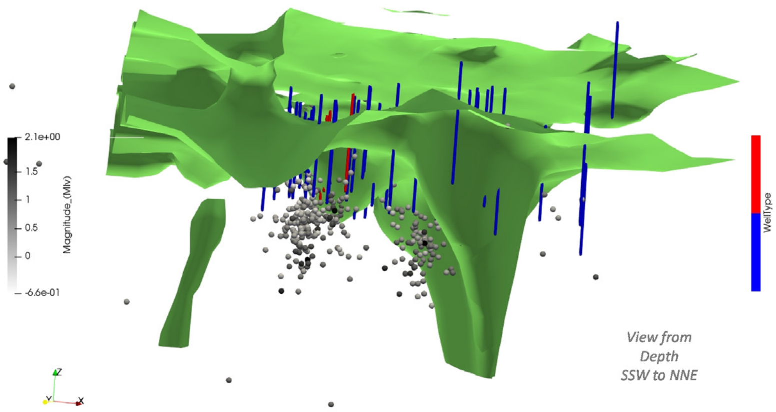


Figure 10: The 50 Ωm iso-resistivity surface (green), earthquakes (grey, magnitude scale left) and wells (blue: production, red: injection). From Hersir et al., 2020, GEMex Deliverable 5.10.

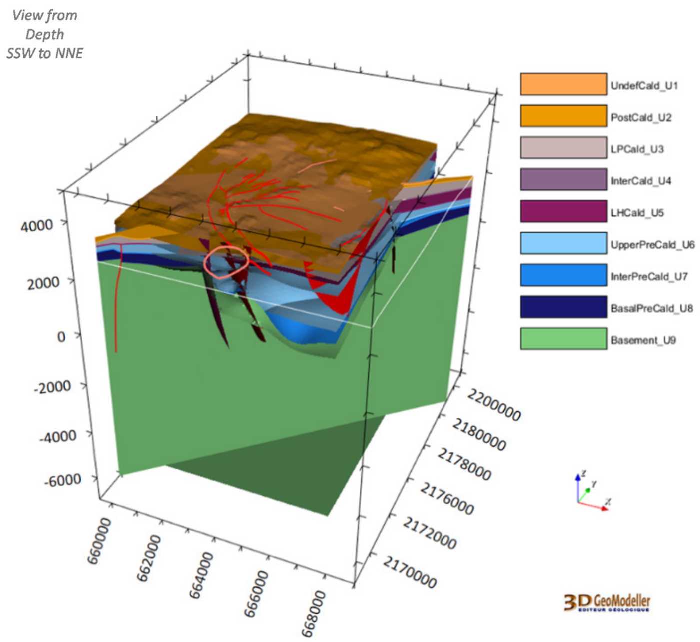


Figure 9: 3D geomodel of Los Humeros updated at the local scale. From Calcagno et al., 2019 and GEMex Deliverable 3.1.

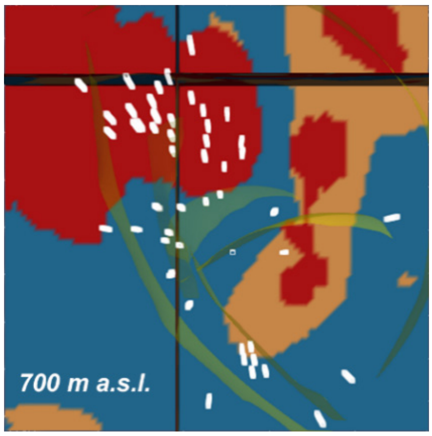
Data integration

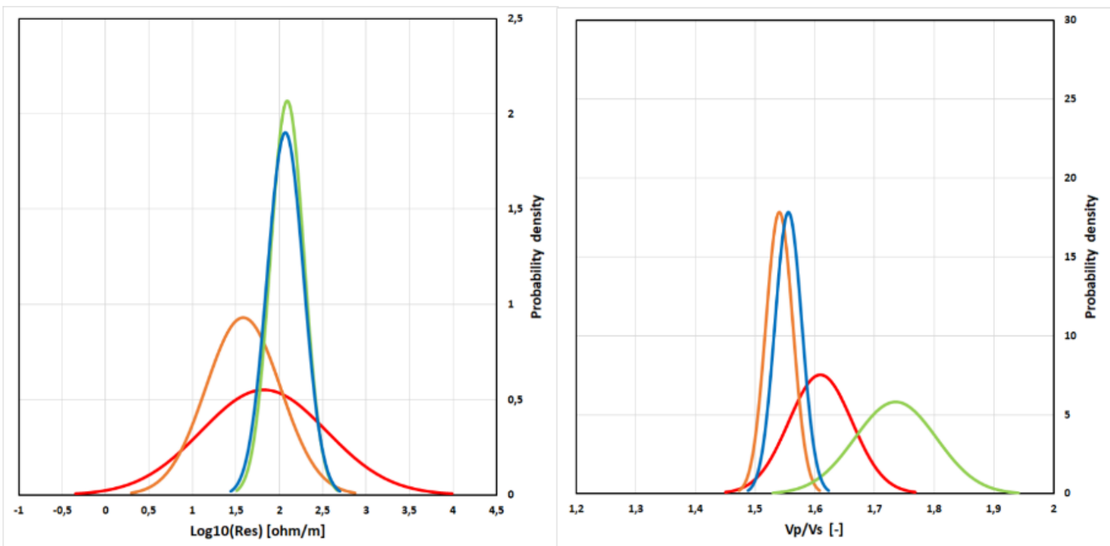
Due to the enormous amount of data collected during the GEMex project as well as prior to the project, the integration of different datasets played a major role during the project. Three different approaches have been taken:

1) Results previously published and results which were considered final have been integrated in a 3D geological model (fig 9). This model is strongly based on available geological maps, the lithology observed in the wells in Los Humeros and the structural geological work performed in the project.

2) Geophysical results are jointly visualized in a Paraview project, which permits the qualitative comparison and the identification of common areas of interest. The integration revealed for example that seismic events are mostly located under the 50 Ωm iso-resistivity surface (Figure 10). That means that the seismicity, which can, among other things, indicate stress changes due to fluid movements in the underground, is mainly found in areas characterised by updoming of high-resistivity features. 3) Geophysical data were additionally analysed by cluster analysis in order to provide a quantitative analysis of similarities. Datasets were interpolated on the same grid and e. g. an unsupervised Gaussian Mixture Model was applied (Figure 11). The GMM revealed some clusters, where favorable conditions of resistivity, density and seismic wave ratio (Vp/Vs) could indicate the presence of hot geothermal fluids at depth

Figure 11: Cluster analysis for resistivity and Vp/Vs-ratio resulting from earthquake travel-time tomography. Dark red clusters indicate regions with favorable conditions for the presence of fluids at depth. Light-green lineaments indicate the main structures and faults. From Gola et al., 2020, GEMex Deliverable 5.12.





Materials for installation in SHGS

Corrosion of selected candidate materials used for downhole casings have been tested in the well H-64 of the Los Humeros geothermal field. This well has a pressure around 40 bar and a temperature of around 250°C at well-head conditions, and temperature of 290°C at 2300 m depth. The pH at the well-head is measured as 3.5. For corrosion testing, a hexagonal bar was constructed with a total of 35 test specimens from seven different alloys, both samples for weight loss measurements and slow strain tensile tests. The hexagonal bar was lowered down to 1290m depth (T ~260°C and superheated steam of 6°C) and kept in the steam downhole for 14 days.

Weight loss measurements indicate that the corrosion rate is very high for commercial used casing materials from medium carbon steels, much higher than corrosion rates observed in similar tests in superheated steam in Iceland (Thorbjornsson et al., 2020). The more noble materials tested were all under the commonly used corrosion limit of 0.1 mm per year, though evidence was found of more complex corrosion as shown by reduction in ductility in slow strain tensile test.

This testing of corrosion behaviour of materials includes not only weight loss measurements but also slow strain tensile testing. Verification of the results will help to guide CFE in Los Humeros in the selection of materials for casings and liners to be used in superhot wells, and in some critical superficial installations. It will also help to increase both lifetime and productivity of the geothermal wells.

Drilling and completion of superhot geothermal wells

Based on the review of 20 super-hot drilling campaigns worldwide, researcher of the GEMex project noted that well failures were caused mainly by excessively high thermally induced stresses exerted upon the cemented casing strings and couplings during operations such as well quenching or production kick-off causing casing collapse and/or connections rupture. Casing collapse was propagated by poor cementing job executed in zones of circulation loss. The heavy precipitation, corrosion, and erosion due to high flow rates of hostile and oftentimes hypersaline geothermal brines are also noted as critical issues, especially during fluid production and well testing.

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 taken into account.. It was proved that the temperature effect contributes greatly to the stress state in the cement sheath. The drastic temperature changes occurring during the well life cycle exert high thermal stresses onto cement sheath in the different sections of the well, increasing the probability of failure of the cement material. It is suggested to exclude abrupt temperature jumps in the critical well sections and allow for slow heating and cooling before well handling. In order to decrease stresses created in the cement sheath it is advised to improve the elastic properties of the hardened cement slurry being used for primary cementing operations.

Summary on Los Humeros and conclusion

The conceptual model of the Los Humeros geothermal system is based on the integration of the results obtained: (i) during the laboratory and fieldwork in the analogue exhumed system of Las Minas; and (ii) during the laboratory and fieldwork, including geophysics, carried out in the active geothermal areas. The outcome led us to define the area to the south of the Los Humeros village as of interest for future studies and possible exploitation programs.

Petrological studies performed in samples from lavas indicate that the recent volcanic evolution is characterized by small and diffuse magma chambers, located at different depths. Deep structures related to these magma pockets have been favoring heat transfer and, presumably, trapping of hot to super-hot fluids. Permeability in the area is related to faults and fractures. Regional studies carried out in the surroundings of Los Humeros indicate three main groups of structures:

a) structures connected to the Laramide Orogeny originally affecting carbonate rocks;

b) regional structures connected to the extensional tectonics, active since Miocene;

c) structures developed during the caldera collapse. Looking to structures affecting the basement (i.e. where hot to super-hot fluids are located), the main point to be discussed was about the location of the regional faults since outcrop analyses do not permit to clearly recognize them, as a consequence of the rheological behavior of the Pleistocene-Holocene ignimbrites, hiding brittle deformation and widely covering the area.

An indirect way to analyze regional structures is through the study of the morpho-tectonic lineaments and alignment of monogenetic volcanic vents cones löschen. Both methodologies suggested two main trends of fractures, NNW- and NE-striking, coherent with the previous knowledge. These faults are delimiting and affecting the Los Humeros caldera rim, reasonably representing pre-existing discontinuities, also activated during the caldera collapse. In this view, analogue models were tested in laboratory, producing compatible geometries. Moreover, the existence of regional structures is crucial to explain how meteoric waters can be channelled from the surroundings to depth, into the Los Humeros geothermal system, as it is documented by geochemical analyses of the waters. Moreover, the study of the ground gas natural emission indicates a significant area to the south of Humeros village.

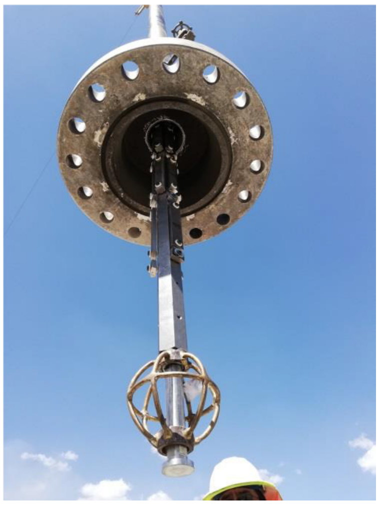


Figure 12: (Left) Hexagonal bar with test speciments which is lowered into well H-64 in Los Humeros. (Right) Well head of the H-43 high-temperature well in the Los Humeros geothermal field (Kruszewski & Wittig, 2018).

Geophysical studies carried out in the Los Humeros area indicate:

- Gravity data support discontinuities with the same trend of the regional structures, delimiting and passing through the volcanic caldera area.

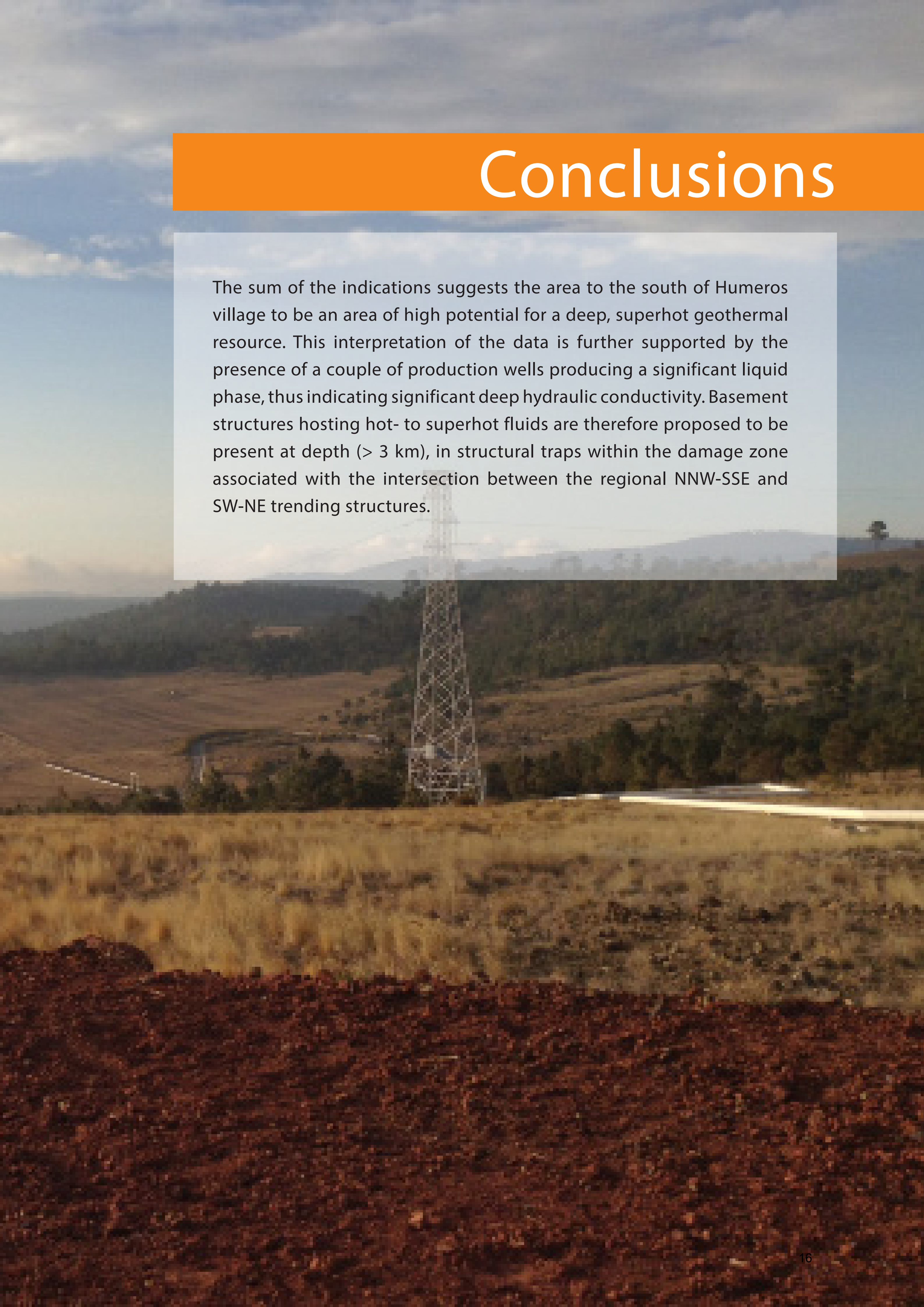
- T-strike alignments (based on strike analysis of MT data) are in agreement with the trend of the regional structures, suggesting these are passing through the caldera and delimiting the caldera rim. Interestingly, the SW-NE trend is interrupted by the NNW-SSE trend to the south of the Los Humeros village.

- Resistivity-maps and cross-sections show the strong influence of the hydrothermal alteration on the values of the resistivity data. Nevertheless, structures delimiting the caldera remain well detectable. The resistivity data give a slight indication of a conductive body at a depth of around 3 km at the structural intersection.

- The model of Vp/Vs ratio from the analysis of passive seismic data indicate a clear change at the sea-level depth, accounting for the caldera base, thus suggesting a basal limit for the shallower permeable zone.

- The distribution of hypocentres indicates clusters, mostly determined by re-injection. Nevertheless, a cluster at about 2-3 km depth is located in the eastern part of the caldera, far from re-injection operations. This is apparently related to the NNW-SSE trending regional fractures, in agreement with the T-strike and the possible interaction with the structures related to the caldera collapse.

- Apart from the production area, a significant aligned cluster of epicentres is marked along an almost SW-NE striking direction, intersecting the western rim of the Los Humeros caldera. This alignment is in agreement with the T-strike results and morpho-tectonic lineaments.



Conclusions

The sum of the indications suggests the area to the south of Humeros village to be an area of high potential for a deep, superhot geothermal resource. This interpretation of the data is further supported by the presence of a couple of production wells producing a significant liquid phase, thus indicating significant deep hydraulic conductivity. Basement structures hosting hot- to superhot fluids are therefore proposed to be present at depth (> 3 km), in structural traps within the damage zone associated with the intersection between the regional NNW-SSE and SW-NE trending structures.

Developing concepts for Engineered Geothermal Systems: Case study of Acoculco

Acoculco is one of the exploration geothermal areas in Mexico, which is located at the eastern part of the Trans-Mexican Volcanic Belt. This geothermally active zone attracted attention of Comisión Federal de Electricidad (CFE), the state-owned electric company, due to the extensive surface manifestations observed in the form of acid springs, hydrothermal alteration and gas discharges. CFE drilled two exploration wells in this area, EAC-1 in 1995 and EAC-2 in 2008. Those wells did not encounter any fluids, although fractures are in the vicinity of the boreholes. Therefore, the area is regarded as a potential site for an Engineered Geothermal System. Within the GEMex project the main goal was the development of one or multiple stimulation concepts for Acoculco. Since the available data for the system was sparse, this also included geological, geophysical and petrological investigations.

Thermal evolution of Acoculco geothermal field

Based on the measured temperature profiles in the two exploratory wells in Acoculco, a time-dependent thermal modelling was performed in order to characterize the deep-seated heat source, in terms of emplacement depth and temperature as well as the age of the last magmatic event.

The heat source was approximated by a simple geometrical shape, i.e. prolate or oblate spheroid, which mimics the ensemble of dikes or laccolithes, respectively. Via a Monte Carlo approach, a number of possible scenarios was investigated by varying the geometrical parameters, i.e. radius, lentgh/radius ratio and centroid depth, and the emplacement temperature.

The best fit to the temperature data was obtained for an emplacement temperature of 850±50°C with the top of the intrusion at 2300±400 m below ground level and a preferred narrow shape of the dike shape, i.e. a prolate spheroid (radius of 500 m and length of 5000 m). If the magmatic system is still active and is in its warming phase, the thermal wave required about 50-80 ka to reach the depth of the bottom holes. Conversely, if the system is now cooling, the intrusion was active up to about 5-6 ka ago or less.

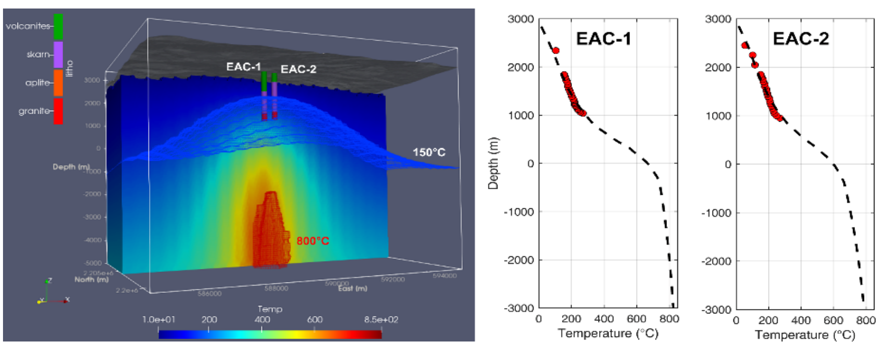


Figure 13: 3D temperature distribution and thermal profiles evaluated at the initial cooling phase (5 ka of cooling) for an emplacement temperature of 900°C and the top at 2300 m b.g.l. Red dots indicate the measured temperatures

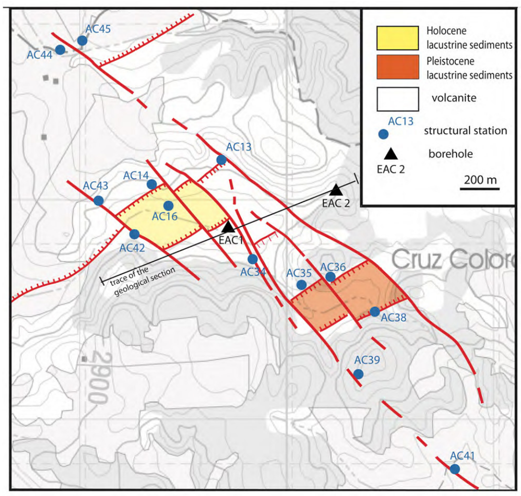
Structural geology

Through extensive fieldworks in structural geology, the local map for the Acoculco area was updated and refined. The following are main findings:

- The Acoculco area is affected by two fault systems: NW- and NE-striking faults, parallel to the regional structures, which controlled the caldera location and development. Both fault systems are contemporaneous and developed in response to a NW-SE trending extension. Some of the faults are located very close to the existing wells.
- The faults are sealed by neoformational minerals related to a past (Holocene) geothermal fluids circulation especially where the two orthogonal fault systems interacted
- Faults affecting pyroclastic units consist of deformation bands with grain size reduction due to comminution process, which leads to a reduction of porosity
- In some places (Alcaparrosa and near the EAC1 well), the damage generated by the intersection of the two fault systems increased permeability, however, currently deposition of secondary minerals only allows the emission of cold gases (mainly CO2).

T-strike (i.e. the direction of the main lateral resistivity contrasts) is sometimes parallel with the main faults and fractures that are not necessarily seen on the surface. Since analysis of strike can give further information on the underground, T-strike analyses were done for the MT soundings in Acoculco, where the vertical component of the magnetic field was available. The T-strike in the period range 0.1 s – 1 s, corresponding to a depth of a few hundred meters (Figure 14) is scattered, although some patterns can be recognised. The preferred orientation of the soundings is either SW-NE or SE-NW, parallel to the orientation of the main fault trends in the area. Thus, the geophysical data supported the findings of the structural geologists.

Judging from structural geology, a stimulation test should aim at improving the permeability at depth, in those damaged rock volumes related to deformation induced by the two orthogonal fault systems



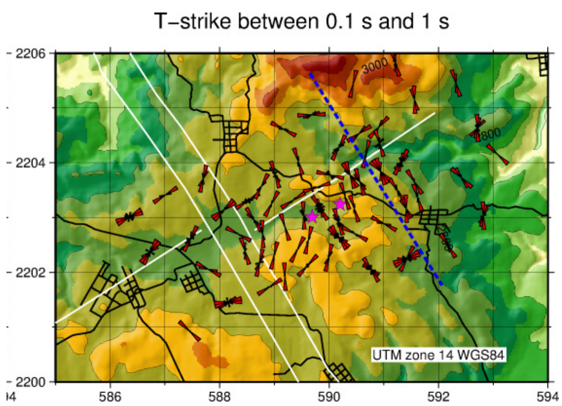


Figure 14: (Left) Structural map of Acoculco, indicating the principal structures clos to the two exploration wells. (Right)T-strike obtained from strike analysis of MT-data from Acoculco. White lines indicate main faults, purple stars the two wells and the blue dashed line marks a transition seen in the strike analysis.

For the hydrogeological and hydrochemical studies of the Acoculco and Los Humeros watersheds, a total of 340 water samples from cold and thermal springs, wells taping cold or warm water, maar lakes, reinjection wells, and rivers were collected from June 2017 to November 2019. Furthermore, infiltration tests and discharge measurements were carried out. The surface water budget we calculated for all watersheds indicating the water quantities available for subsurface recharge, which takes places preferentially in the mountain block and mountain front zones of these watersheds. The hydrochemical data, including the organic compounds suggest, in combination with the hydrogeological data, regional flow pattern for recharge but also for discharge areas. One possible discharge area of the reservoir was found within the Perote shallow aquifer by relatively high groundwater temperatures and chemical components indicating a mixture of local recharge from the surrounding hills with waters probably upwelling from the reservoir.

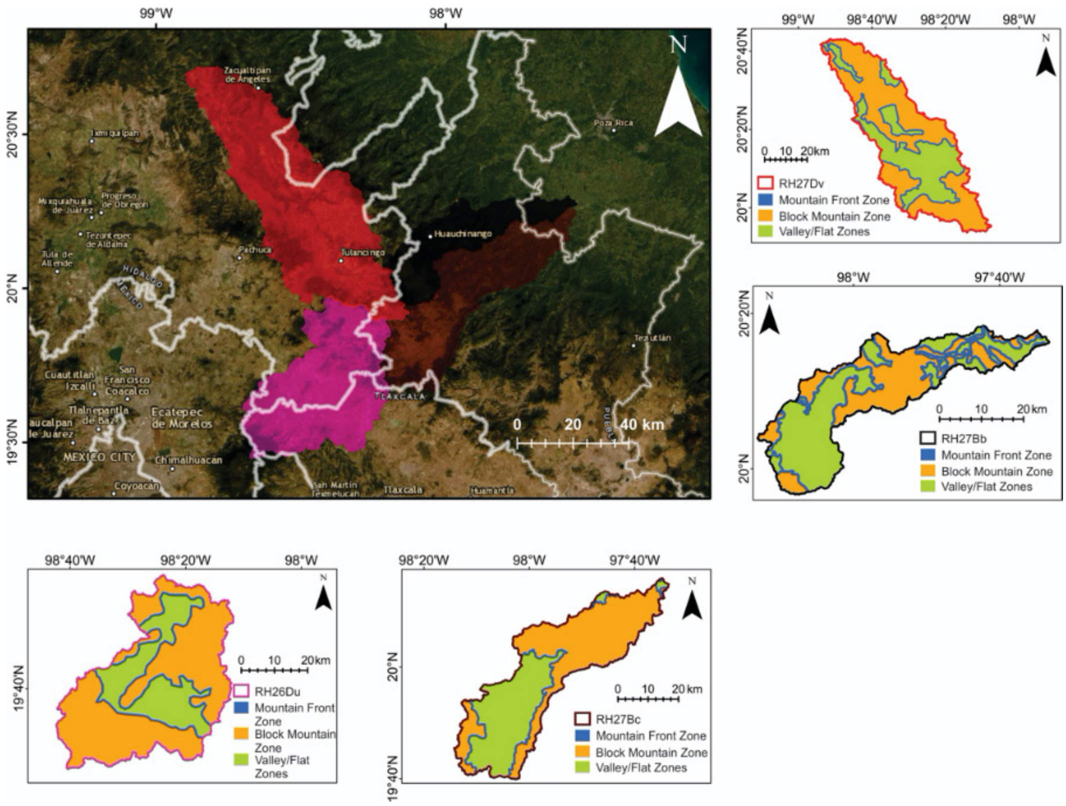


Figure 15: Localization of the four watersheds surrounding the Acoculco geothermal area (satellite picture). Identification of mountain block, mountain front, and valley zones within the watersheds to identify probable recharge areas for the Northern watersheds (right-side) and southern watersheds (bottom).

Resistivity analysis

For the investigation of the resistivity structure of Acoculco, 68 MT and 65 co-located TEM soundings were acquired. Figure 16 shows the results from a 3D inversion of the static-shift corrected MT data which was performed for the full impedance tensor. The Acoculco area can be divided into two sub-areas that are distinguished from one another; the boundary could well be a buried fault. The low resistivity cap (presumably reflecting smectite hydrothermal alteration) becomes thin and shallow almost reaching the surface close to the western EAC well (below sounding 0037 in Figure 16A). It is in this area where the resistive core (presumably reflecting chlorite/epidote hydrothermal alteration) is the shallowest in a very confined area, suggesting the existence of a zone of geothermal interest.

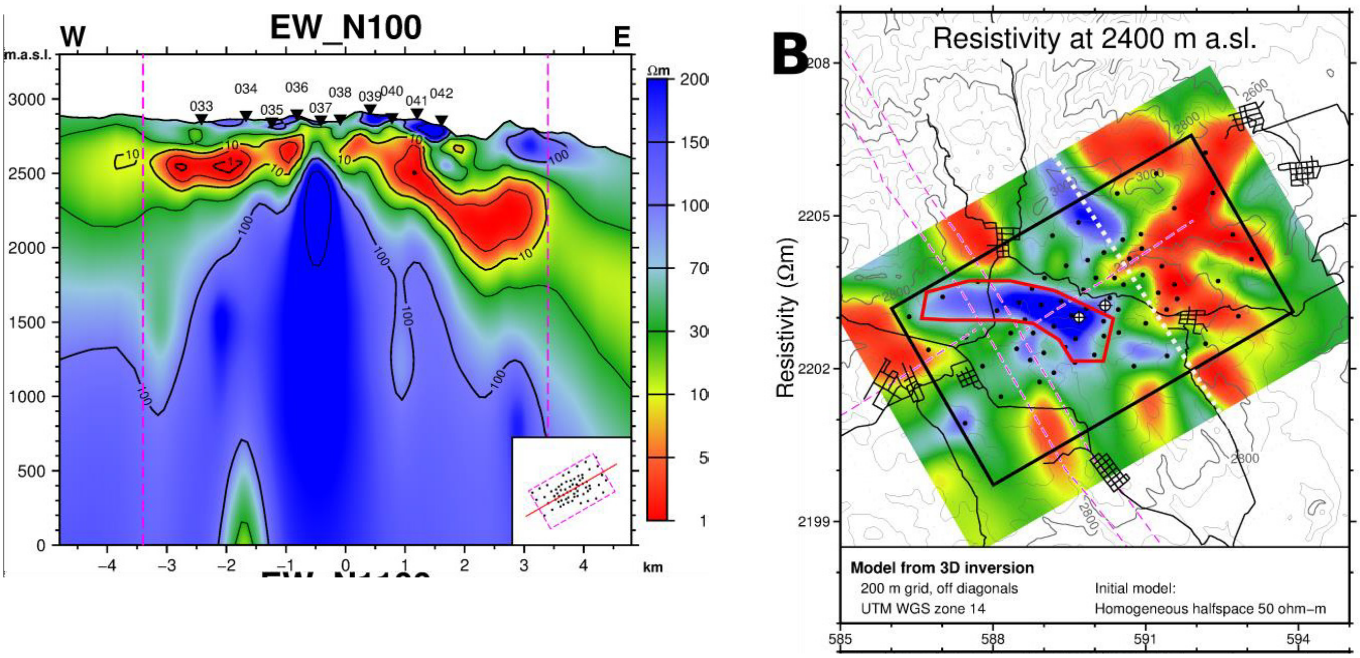


Figure 16 (A): Vertical cross-section through the resistivity model. Black triangles at the surface are the sounding locations. Small inlet: Red line shows the location of the cross-section. Black dots are locations of soundings. (B) Horizontal cross-sections through the resistivity model at 2400 m a.sl. The white dashed line marks a transition seen in the strike analysis, the red line encircles the resistive core and dashed pink lines are main fault lines in the area. Black crosses on a white circle indicate the two EAC wells. From Hersir et al., 2019, GEMex Deliverable 5.2.

Data integration

3D geological modelling (using Geomodeller) was performed for a regional model covering the Acoculco caldera, as well as for a local model which was centered around the location of the two test wells in Acoculco. Pre-existing maps and cross sections were updated with the results from structural geology and improved geological maps in GEMex. These 3D-models were the basis for further investigations, such as temperature modelling.

A new young (6-5 ka if cooling – 50-80 ka if heating) magmatic intrusive body (or an assemblage of more than one smaller), at a depth of 2300 ± 400 m , with a prolate ellipsoid shape (aspect ratio of 10 and a radius 500m) is supposed to be. This intrusion is resulting from the regional thermal numerical simulation and can justify the current thermal anomaly measured in the two boreholes (see Figure 19).

The geophysical results were integrated in a Paraview project, which permitted to identify areas showing anomalies in different datasets. The integrated geophysical study (Figure 18) reveals the occurrence of a main 3D structure (A1) elongated with a N100E strike, located in the central part of the area close to the two drilled wells. This structure, characterized by high-density and high-resistivity anomalous values, extends from about 2400 m a.s.l. down to at least the sea level. Data from wells indicate low permeability conditions of the volume. This volume of rock, which includes limestones and skarns is the target for the stimulation modelling in Acoculco needed to assess the EGS feasibility of the area. A smaller seated body (A2) with the same high density and medium resistivity is recognised northward the two boreholes and can be referred again to limestones alterated to skarn. The permeability of the shallow levels of the Acoculco system is probably strongly reduced, due to the intense sealing effects of hydrothermal alteration on volcanic rocks.

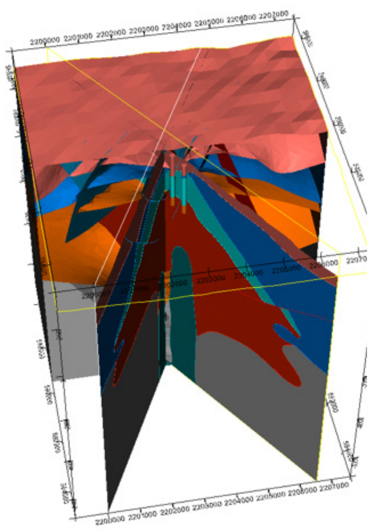


Figure 17: Integrated 3D geological model of the Acoculco at local scale. In dark green the new geological body referred to the young magmatic intrusion (GEMex Deliverables 3.1 and 3.4

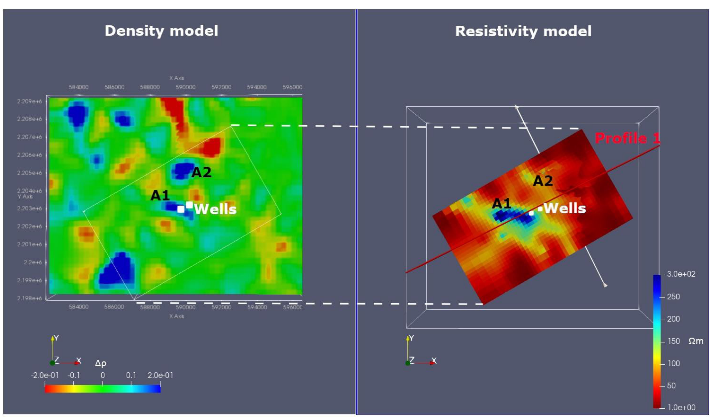


Figure 18: Depth slices at 2000 m asl across the density (left) and resistivity (right) models at Los Humeros in the Paraview project. A1 and A2 denote two anomalies in the different datasets. From Hersir et al., 2020, GEMex Deliverable 5.10.

Cluster analysis

Cluster analysis is a procedure aimed at performing an effective integration from different geophysical methods providing an unambiguous, self-constrained model of a geothermal system. For the analysis of the local density and resistivity models produced for Acoculco, a supervised clustering approach was used. The chosen classification consists of 9 groups defined by the threshold values –0.05, +0.05 g/cm3 and 60, 150 Ω m for the density contrast and resistivity, respectively (Figure 19). Four groups are of special interest:

- Cluster 21 - medium density-low resistivity: has a roughly dome-shaped character with minimum thickness in proximity of the drilled wells; it seams to image the alteration cap.
- Cluster 11 - low density-low resistivity: should be indicative of occurrence of liquid phase hosted in high porosity rocks; in the analysis this cluster produces isolated bodies, underlying cluster 21
- Cluster 33 - high density-high resistivity: located in the vicinity of the wells; the top of this anomalous body, corresponds to bottom of volcanites so that the anomaly falls into the metamorphized rocks (skarn and hornfels) following the stratigraphy. Cluster 23 - medium density-high resistivity: located at the centre of the area of study, it could represent part of the granitic intrusion drilled by both the wells.

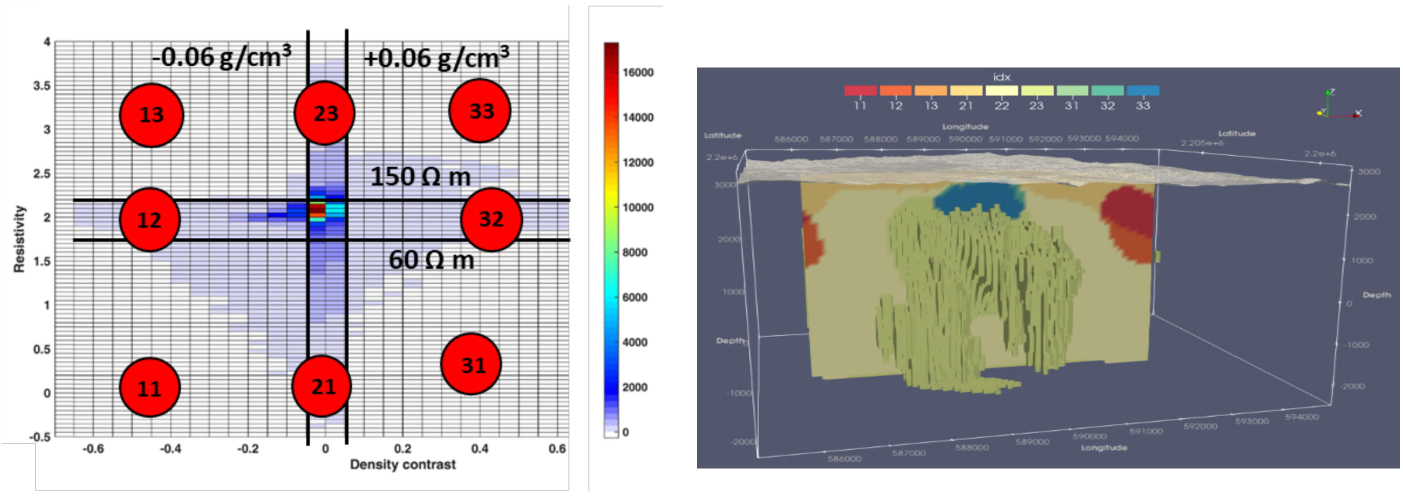


Figure19: (above) Density-Plot of the Acoculco Local Resistivity and Density interpolated dataset. With 9 groups defined for the clustering. (Above) 3D-visualisation of cluster 23, which mimics the shape of the granitic intrusion. Adapted from Gola et al., 2020, GEMex Deliverable 5.12.

Integrated stress field estimation and implications for EGS development

For designing a stimulation operation, in-situ stress tensor has to be well constrained. This heavily relies on the availability of stress data. From the previous studies, it is known that the present stress field of Acoculco, since the Pliocene, is an NW-SE trending extension. Two regional fault systems affecting Acoculco area are NW- and NE-striking. NW-striking faults present right-lateral strike-slip to moderately-oblique-slip and vertical movement, whereas NE-striking faults present vertical movement.

A Monte Carlo analysis of the existing stress information was based on structural geology studies, laboratory experiments on rock samples, and drilling and logging data from the two Acoculco wells. Average in-situ stress values remain in strike-slip regime with high uncertainty of the maximum horizontal stress and therefore also stimulation pressures. For a stimulation test, this would have significant implications i.e.: hydrofracking would develop new vertical fractures parallel to NE- and perpendicular to NW-striking fault systems. It is unlikely that a connection between the two wells can be established. Instead, the intersections of the two faulting systems might be a suitable target for the stimulation. Due to the high uncertainties of SHmax it is advised to carry out (extended) leak-off/hydrofrac tests, borehole image logs, and caliper logs before the final design of the stimulation test.

Stimulation scenarios

In order to meet the requirements from the Mexican project partners, who are responsible for implementing a stimulation test in an additional project year, stimulation scenarios have been investigated for the stimulation of the existing EAC-1 and EAC-2 wells. This requirement poses several challenges:

- The condition of the wells is unclear; before any stimulation is performed, a thorough check of the integrity of the casing, the effect of temperature and pressure on casing integrity and the wellbore shape is necessary

- Zonal isolation of the deep target interval by open hole packers is not feasible due to the well condition, high temperature and fracture orientations; installing a liner is not practicable due to the small well diameter; therefore, an open hole stimulation, potentially with casing packer, is the only option, which would likely stimulate the well directly below the casing or in the deeper inflow zones of the well (Figure 21)

- Due to the limited information on the local stress field and fractures at depth, it is impossible to reliably forecast the length and orientation of fractures induced by hydraulic stimulation without injection tests

The primary target is the stimulation of existing fractures and connection of permeable fault damage zones/intersections to the stimulated well (Figure 21). For the stimulation of EAC-1 the following procedure is recommended:

• Baseline microseismic monitoring and seismic risk assessment

• Ream the well to clear obstructions and ensure accessibility

• Temperature and caliper (better televiewer) log to establish initial wellbore condition and refine stimulation targets

• Check casing integrity and effect of temperature and pressure on casing integrity for open hole stimulation

• Short open hole injection test at low flow rate followed by temperature log to establish initial hydraulic performance and identify inflow zones

• Open hole thermal stimulation with low pressures to improve permeability of existing inflow zone below 1600 m close to the well

Figure 20: Well-head of the well EAC-1 in the Acoculco caldera.

• Stepwise pressure increase when the stimulation efficiency drops to identify fracture opening and closure pressure and stimulate fracture network away from well

• Microseismic monitoring, temperature monitoring and hydraulic tests to detect and characterize stimulated structures

A safe and successful EGS development in Acoculco requires drilling wells specifically designed for multi-stage stimulation considering geology and stress field, but stimulation tests in the exploration wells can enhance the knowledge base for such operations.

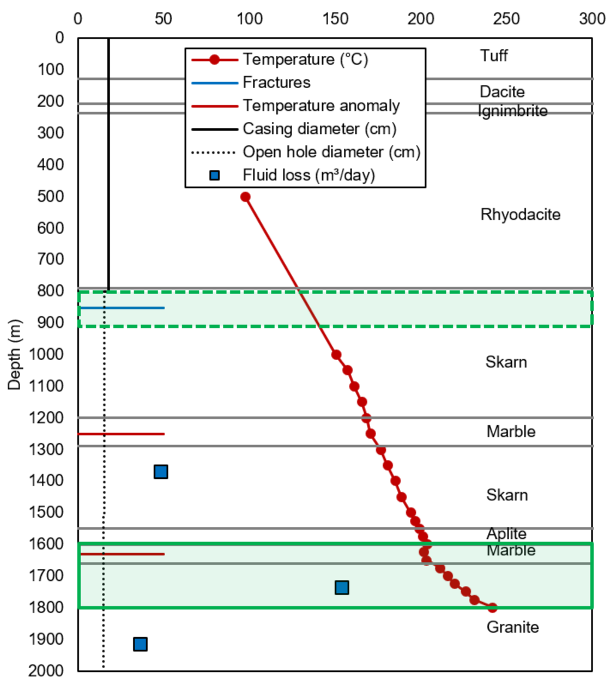


Figure 21: Temperature and lithology in EAC-1. The most promising stimulation targets are the Marbles and Granites below 1600 m (solid green) based on a temperature anomaly and fluid loss. Open hole stimulation will likely stimulate the well directly below the casing (dashed green).

Conceptual models for public engagement

The theme of public engagement is particularly relevant when, as in the case of geothermal technologies, switching the energy system to renewable sources may produce relevant economic, environmental and social impacts. A multidisciplinary approach to deal with public engagement in geothermal development was adopted including e. g. Questionnaires and open-ended interviews conducted with citizens, companies, public authorities and local communities both in Mexico, Europe and a selection of developing countries. Investigations were carried out on local public perception of (geothermal) energy and on the overall boundary conditions (e.g. social, environmental, economic, etc.). Suitable variables and quantitative models were defined to monitor, ex-ante, the possible sustainability-related consequences

Based on the above, a conceptual model was built to combine public authorities' and private companies' efforts in fostering sustainable energy transition by taking into account local communities' socio-economic characteristics. Different levels are identified as follow, according to an increasing public engagement.

• The Information level relies entirely on the information provided to the public about the project's details and potential impacts on the local and wider community.

• The Communication level includes active engagement of the public, and it is contingent upon the company's willingness to engage in conversation with communities.

• The Collaboration level considers the public as being part of the project development, while the project and its impacts' evaluation need to be adapted to the specific local/social needs.

• The Participation level consists in the actual engagement of the public in the design of the project. Companies adopt the set of engagement practices based on the diversity of expectations while public authorities are co-designers of the initiative, providing the institutional environment where the process takes place.

Figure 22: Information event on geothermal energy technologies in the local community of Acoculco.

Summary for Acoculco and conclusions

The conceptual model of Acoculco area is based on the integration of the results obtained: (i) during structural fieldwork, aimed to the reconstruction of the regional stress field; and (ii) during geochemical and geophysical laboratory and fieldwork, carried out in the surroundings of the two existing boreholes, to be considered for EGS developments.

The structural fieldwork was mainly dedicated to collection of kinematic data on recent fault-slip surfaces. The results are summarized as follows:

• Under the regional stress field, defined by a NNW-striking stretching direction, two main NNW- and NE-striking fault systems developed. These are accompanied by minor faults, with a slightly different orientation, N- and E-striking respectively. The age of deformation is from Miocene to Present, as testified by the age of rocks, sediments and soil, involved in the faults activity.

• The NNW- and NE- striking faults are characterized by a dominant oblique right-lateral and normal movements, respectively. A second kinematic movement, with a dominant vertical displacement, is recognizable in the NNW-striking fault system. These features account for interpreting the NNW-striking faults as transfer faults, acting in the regional extensional regime which causes the NE-striking faults, too. Coeval processes of crustal uplift reactivated pre-existing structures with a dominant vertical movement.

• Although the regional stress is well defined, in terms of local stress, these results indicated a variability depending on kinematics.

• In the borehole areas, the two previously mentioned fractures trends were also detected, in the frame of a general migration of deformation toward north-northwest. This latter process implies that the EGS chosen area, having sealed fractures, seems to be far from the most favorable area from a structural viewpoint.

Geochemical and geophysical studies carried out in the boreholes area indicate:

• CO_2 ground emission implies that most data are associated to soil respiration, reflecting low permeability conditions.

• T-strikes (based on strike analysis of MT data) are in agreement with the trend of the regional structures.

• Resistivity-maps and cross-sections show the strong influence of the hydrothermal alteration on the values of the resistivity data.

• Gravity data support discontinuities with the same trend of the regional structures.

• Seismicity activity is very scarce to absent.

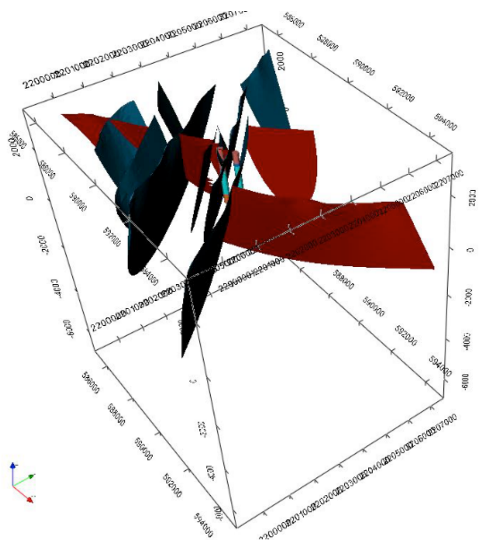


Figure 23: Local 3D structural model of Acoculco with the lithology of the two test wells.

Conclusions

Studies carried out on the EGS feasibility indicate:

- The potential EGS development depends on the fracture system and not on the low permeability rock matrix.

- Thermal and hydraulic stimulation of existing inflow zones is considered the most promising stimulation method for both high-temperature wells, especially in the deep granites.

- The knowledge gained by the proposed injection tests in the existing exploration wells will be the basis for a controlled development of an EGS in Acoculco with new wells specifically designed for stimulation.

GEMex website: www.gemex-h2020.eu

More details on GEMex results, publications and project reports can be found on the GEMex website www.gemex-h2020.eu . All technical deliverables are available in open access and can be downloaded from the website.

GEMex Open Access Database

The GEMex Open Access DataBase (OADB) was established to collect and make available the datasets produced in the frame of the GEMex project. The used software (GeoNode) allowed to store and describe with metadata the collected datasets and to organise them in aggregated maps: http://gemex.igg.cnr.it/

At the end of the project, the OADB includes more than 100 spatial layers all available for download. The layers include some freely available datasets from the Mexican authorities (e.g., DEM, a vectorial geological map) and the locations of the sampling sites recorded by the GEMex scientists as well as the complete datasets with e. g. measurements, inversion results, or models. 10 dedicated maps were created to aggregate the datasets by location and typology. 2 maps include all the datasets available for Los Humeros and Acoculco, while the other four group the geological, geophysical, geochemical and sampling points datasets. Other maps compile specific datasets, for example thermal models results and resources assessment, gravity and resistivity results from 3D models, analogue geological models results. In each map, the features are represented with a specific symbology and can be queried by using the dedicated tool of the WebGIS. All cross-sections traces (i.e., from resistivity 3D model, from density 3D model, from 3D thermal models) were linked to the cross-sections images (Figure 24).

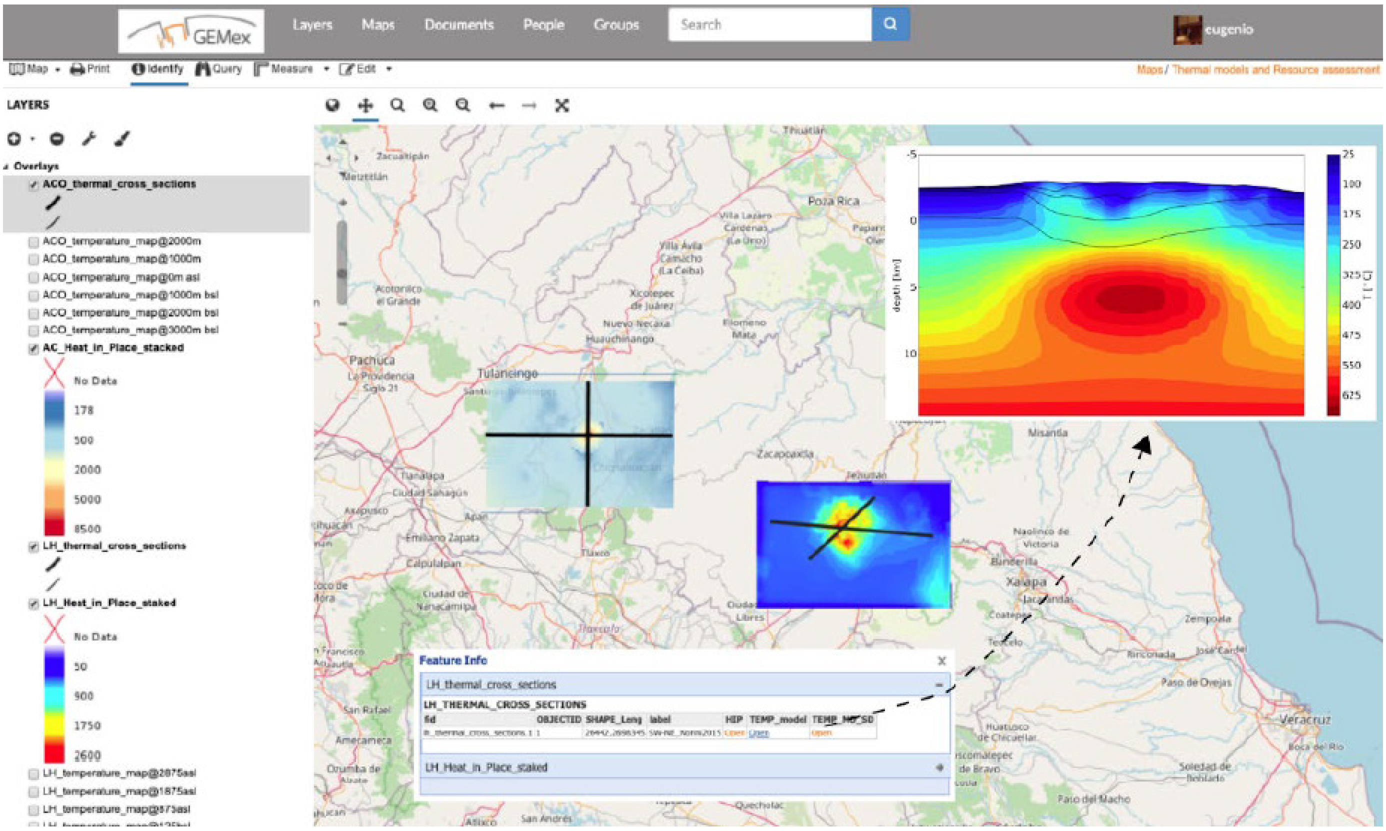


Figure 24 - The webGIS interface of the OADB. Here, we show the thermal models and resource assessment results of the two GEMex areas. In particular, the table results from a query on Los Humeros area performed with the 'Identity' tool button. From the resulting table, it is possible to 'Open' (see the dashed arrow) the related iconografic material, in this case the cross-section from the 3D thermal model.

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