Main outcomes for Mexico at the half of the GEMex Project

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Abstract. The GEMex project is a binational endeavour developed by a Mexican and a European consortium coordinated by a common executive board. Each consortium is financed by their own resources, which are approximately 10 million euros for each part. The project is focused on two geothermal areas, Los Humeros and Acoculco, and was started two years ago. In January 2019 it reached its half point for the Mexican partners, and from the Mexican viewpoint the main results up to then can be summarized as follows. There is a new volcano-tectonic framework and characterization that has been rising from the geoscientific work developed, integrated and modelled by the project, which in the case of the Los Humeros geothermal field is profiling the most promising areas where the superhot geothermal fluids could be found. In the case of Acoculco, the integration model has provided the current stress field that can be used to develop an EGS project in the area, which still needs to be completed with the interpretation of the remaining seismic data, and that is planned to be tested at the final stages of the project with a stimulation test. The expected outcomes can be used by the CFE (Comisión Federal de Electricidad), which is the public utility that has the proper permits to explore and develop both geothermal areas.

1. Antecedents

The complete title of the GEMex Project is Cooperation in geothermal energy research Europe-Mexico for development of Enhanced Geothermal Systems (EGS) and Superhot Geothermal Systems (SHGS). It is a joint effort of a Mexican and European consortium on unconventional geothermal systems, particularly superhot and enhanced, intending combine the Mexican knowhow on conventional geothermal systems with the European expertise of developing SHGS and EGS technology. There is no a formal definition for SHGS, but the consensus in the GEMex project is that the term includes any resource with temperature of 350°C or more. On the other hand, the term EGS comprises all technologies aimed to create or enhance the circulation of fluids at depths where sufficiently high temperatures are have been identified or are expected to occur.

This multidisciplinary project is focused on the Los Humeros geothermal field for SHGS and on the Acoculco area for EGS, both zones located in the State of Puebla, eastern Mexico, and currently granted to the CFE. The project covers aspects on resource assessment, reservoir characterization, and concept development for exploitation and utilization, aimed to understand the volcano-tectonic evolution, the fracture distribution and hydrogeology of each area, as well as predicting in-situ stress axis orientations and temperatures at depth. The reservoir characterization includes acquisition of
geophysical data by various methods and their combination in integrated reservoir models, as well as high-pressure and temperature laboratory experiments on rock samples. The conceptual development will propose viable options for development and utilization of those unconventional geothermal resources [9].

The Mexican consortium is led by the Michoacán University (UMSNH) and is composed by the CICESE (Center for Scientific Research and High Education of Ensenada), the INEEL (National Institute of Electricity and Clean Energies), one private company (Geominco) and five entities of the National University (UNAM). It is financed by the federal Fund for Energetic Sustainability (FSE) with the equivalent to 10 million euros, with February 2017 as starting date, and January 2021 as finishing date.

The European consortium is led by the German Center for Geoscientific Research (GFZ), and is composed by other 23 partners from France, Germany, Greece, Iceland, Italy, the Netherlands, Norway, Poland and the United Kingdom. GEMex is one of the projects funded with almost 10 million euros by the Innovation Union program under the Horizon 2020 initiative, with October 2016 as starting date and May 2020 as ending date.

The objective of this paper is present what are the main results obtained at the middle of the project, i.e. by February 2019, since the perspective of the Mexican consortium.

2. Los Humeros and Acoculco backgrounds
Los Humeros is one of the five geothermal fields in operation in Mexico. It is located at the eastern part of state of Puebla at central-eastern Mexico (figure 1), at an average elevation of 2800 masl. The field has been developed inside the Los Humeros volcanic caldera, which lies at the eastern end of the Mexican Volcanic Belt. It is a roughly circular caldera structure of ~20 km diameter, with an inner and younger caldera, known as Los Potreros, with around 7 km in diameter. The first collapse structure of Los Humeros was formed ~0.165 Ma ago and the second around 0.070 Ma, according to recent geochronological dates [4].

![Figure 1. Location of Los Humeros and Acoculco geothermal areas, and the Las Minas exhumed system.](image)

At the subsurface, the several lithological rocks cut by the geothermal wells drilled by the CFE since the eighties, are grouped into four units. The deepest is the basement, composed of limestones, subordinated shales and flint lenses, which were folded and partially metamorphized by the Laramide
Orogeny, and then locally metamorphized by more recent intrusions. The basement includes also Paleozoic intrusive rocks (granite, granodiorite and tonalite) and metamorphic (marble, skarn, hornfels), as well as more recent diabasic to andesitic dikes. In addition to the basement, the volcanic formations have been grouped into three distinct units: pre-caldera, caldera, and post-caldera, and for modelling purposes and to get a more detailed interpretation of the geothermal system, these three volcanic groups were split into eight units: basal pre-caldera, intermediate pre-caldera, upper pre-caldera, Los Humeros caldera, intermediate caldera, Los Potreros caldera, post-caldera, and undefined pyroclastic deposits [3].

The current installed capacity in the Los Humeros geothermal field is 93.9 megawatts (MW) composed of three condensing power units of 26.3 MW each, and three back-pressure units of 5-MW each as backup, even though there are another five 5-MW each units out of operation. The power units are fed by approximately 25 production wells, and the residual brine is injected back to the reservoir by three injection wells [14]. The exploited fluids are of conventional hydrothermal type, contained in the andesites that mainly conform the pre-caldera lithological group. The geothermal field has been exploited by the governmental utility CFE (Federal Commission for Electricity) since the beginning of nineties. The field was chosen for develop the superhot part of the project due to the high temperatures already measured in some of the wells (the maximum temperature reached almost 400°C), which indicates the probable presence of these superhot fluids, though they have not been exploited so far.

The Acoculco Caldera Complex is located 80 km northwestern from Los Humeros (figure 1). It was formed 2.7 Ma ago, with an explosive eruption that produced the Acoculco ignimbrite, with a volume of almost 130 km$^3$ and andesitic composition. The eruption triggered the collapse of the magma chamber roof, giving place to an asymmetric caldera of sides of 18 and 16 km long, with rhombohedral to sub-circular geometry. Since then volcanic activity has persisted up to around 0.06 Ma, forming domes, cinder cones, fissure lava flows and two ignimbrite eruptions. So, several episodes of volcanism have taken place through reactivations of the system or associated magmatism of the nearby Apan–Tezontepac Volcanic Field [1] [7] [15].

The CFE drilled two exploratory wells in that zone, one (EAC-1) in 1995 and other (EAC-2) in 2008. The first well was finished at 1800 m depth and reached a maximum measured temperature of 307°C, while the well EAC-2 was completed at 1900 m depth with a maximum temperature of 264°C. None of the wells produced any fluids [11], which leaded to the conclusion the zone is a hot dry rock system, susceptible to be developed by EGS technologies like the ones the GEMex project is trying to apply. According to that, the geothermal target must be located in the basement, composed of calcareous, granitic and metamorphic rocks, since the overlying volcanic rocks present a total width of 700 m (EAC-1) and 450 m (EAC-2), where maximum temperatures are considerably lower: 140°C in EAC-1 and 110°C in EAC-2. In addition, volcanic rocks show intense hydrothermal alteration [3] [11]. In the well EAC-1 it was found an aplitic dyke dated 0.183 ± 0.036 Ma [1]. Even though this age could have been reset by heat provided by younger intrusions or by magma flux, it suggests the presence of a recent heat source [15].

In the following sections we present what we consider the main outcomes up to now, which consists of improvements and new way of approaching in the characterization of the volcano-tectonic framework of Los Humeros and Acoculco systems through the study of an analogue exhumed system in Las Minas, the development of physical analogue models, and the petrological and geochronometric analyses and interpretation of recent volcanic samples. But also those results include the measurement of physical properties of outcropping rocks similar to those at depth, as well as their behavior under hydro-fracturing tests in laboratory, and some recommendation for drilling and complete wells in superhot and hostile geothermal environments.

3. Study of an exhumed system analogue to Los Humeros and Acoculco

One original contribution of the GEMex project is the comprehensive study of a fossil geothermal system that outcrops in the locality of Las Minas, located around 30 km to the east of Los Humeros (see figure 1). Las Minas is a former mining district whose ore deposits (Au, Cu, Fe, Pb, Zn) were
metamorphic and skarn-related, and is deemed as a proxy of the current geothermal system in Los Humeros and Acooculco. The study of this exhumed system at surface, in order to better understand the active geothermal system at depth, and particularly its deep structural levels where superhot fluids are circulating, is a novel perspective not systematically developed before in Mexico. It is part of the Working Package 4 (WP-4), specifically the activity 4.1, and the most relevant outcomes can be synthetized as follows:

- It was recognized in Las Minas an outcropping unit of lacustrine sediments, whose presence was not reported previously. These sediments are of carbonate composition, present maximum thickness of 60 m, and its age is estimated Pliocene-Pleistocene [10]. This unit could be correlated with a subsurface unit currently classified as tuffs, cut at depth by most of the geothermal wells in Los Humeros, which is located between two andesitic units of the pre-caldera unit.

- Two main fault systems were identified, with NNW-SSE and NE-SW orientations. Both systems were produced by extensional tectonics, seem to be contemporaneous and have been in activity since Miocene. The NNW-SSE structures can conduct geothermal fluids from deep to shallow levels, while the NE-SW structures seem conduct fluids laterally at shallower levels, according to the orientation of the intermediate kinematic axis of the structures of each system [10]. So, it is recommendable that a future well to be drilled in Los Humeros with the aim to find superhot fluids, be designed to cut at depth one or more structures of the NNW-SSE system.

- It is also recommendable that such a future well with that specific objective be designed to be finished into an area near the contact between limestones and intrusive rocks. These contact-areas seem to be prone to host superhot fluids, since they present more fractured areas in the outcropping rocks in Las Minas, which indicate more possibilities of better permeability.

- The present geothermal system in Los Humeros is better classified as a metamorphic-hydrothermal system, which seems to have been initially a dominantly metamorphic system. In spite of being currently a high-temperature hydrothermal system, it still presents characteristics of its metamorphic stage.

- The parent magma in Las Minas, causing the metamorphic stage, seems to have been emplaced at 4-5 km depth and was originally of dioritic composition evolving later to quartz-diorite and finally to tonalite, suggesting continuous magma injections along Miocene [10].

- 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 (500-1000 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 probable superhot geothermal system in Los Humeros could be similar to the second stage of Las Minas, if there is a partially crystalized magma chamber at depth [10].

4. Analogue models: hereditary structures in the Los Humeros caldera

One of the activities of the WP-3 is 3.1 (Analogue Modeling), which consists of preparing 3D physical models at a proper scale of both areas, to reproduce some specific volcano-tectonic processes and learn about their evolution. Up to now, this activity has developed the analogue model of Los Humeros.

Besides some fieldwork, satellite imagery analyses and compilation of geophysical data, the team in charge of this activity constructed an analogue model in a box of Plexiglas at a 1:100,000 scale, filled with a quartz and potassium feldspar sand mix as a proxy of the host rocks, with a magma chamber 12 cm in diameter and a special type of Plexiglas as the magma analogue [12]. After several tests, it was possible to physically reproduce the Los Humeros caldera collapse and the subsequent resurgence inside the caldera.

The team ran four series of tests. In the first series, more than 15 tests were developed each one with minor variations in one or more parameters, up to one of them was able to produce a collapse similar to the actual caldera of Los Humeros. This particular test gave place to the so-called Model 17,
which produced a symmetric collapse (with no trap-door), with faults developed not synchronously. Reverse faults dipping outside the caldera and normal faults dipping inside were formed as consequence of the gravitational collapse [12].

For the second series the Model 17 was used, and several tests were ran on it with additional changes, including for instance a preexistent structure placed tangential, almost tangential, centered or outside the magma chamber, and the presence of one and two rectilinear sides at the chamber. The more viable model (Models 32 and 33) includes the presence of a couple of preexistent rectilinear discontinuities affecting the host rocks and the magma chamber itself. This model inhibits the formation of reverse faults on the linear discontinuity giving place to normal high-angle faults [12]. The presence of such couple of deep preexistent inherited structures, can explain the probable rectilinear lineaments in the southeast and southwest portions of Los Humeros caldera (figure 2).

![Figure 2. Comparing the results of analogue modelling (Model 33, turned to the right as indicated by the yellow arrow) at left [12] with the identified structures in the Los Humeros field, according to the geologic map [14]. The NE-SW (red) and NW-SE (white) structures seems to be previous to the caldera collapse and affect its final shape.](image)

Thus, the more relevant conclusions of the analogue modelling for Los Humeros are as follows:

- The Los Humeros and Los Potreros calderas were of symmetric type.
- It is probable that before the collapse of the first caldera (Los Humeros) there were a couple of regional structures of roughly NE-SW and NW-SE orientations that affected both the basement and the magma chamber, which modified the local structures produced by the collapse.

5. Probable features of the magma chambers in both zones

Another novelty contribution of GEMex comes from activities 3.1 and 3.2 of WP-3, which are the regional conceptual modelling of Los Humeros-Acoculco area, and the thermal modelling of each one. Among other activities, the team in charge of the conceptual regional model selected 13 samples of lavas produced in Los Humeros during the second post-caldera eruptive phase occurred between 10,000 and less than 3,000 years ago.

Based on the age and the silica content of the samples, it was possible differentiate two extreme volcanic sequences: one is of basic composition (SiO$_2$ < 55%) and occurred 7-4 ka, and the other is acidic (SiO$_2$ > 65%) with ages of 10-3 ka. Between both there are two intermediate sequences, one with SiO$_2$ ~ 55% and age of 9-4.5 ka and the last with 57-62% of SiO$_2$ and ages of 10-6 ka. Crystals of
olivine, pyroxenes and alkaline feldspars were carefully chosen from the same samples, and it was estimated the water content of the magma before the eruption according the hygrometric model of liquid plagioclase [13]. With that data the team prepared thermal-barometric models, and inferred that the samples come from a differentiated magma chamber, that has produced several smaller and differentiated chambers located at different depths that probably share the same feeding source located at the lower crust, perhaps up to 30 km depth for the olivine basalts [5] (figure 3).

Thus, the geographic proximity of vents tapping magma compositions that vary from olivine basalts to trachytes and rhyolites, implies that presently there is no a single magma body beneath Los Humeros. The team concludes preliminarily that the current plumbing system is probably composed of a series of small lenses of magmas recharged from a similar Sr and Nd isotopic mantle source, evolving separately in a chemically neutral environment. A temporary connection with the surface and among lenses can be allowed by propagation of fractures and dykes or sills, but the magma recharge rates have not been high enough to promote large interconnection and re-homogenization to a single magma body [5].

**Figure 3.** Scheme showing the probable behavior of lenticular magma bodies giving place to rocks of different composition in Los Humeros [5]. In the upper part a section with the four main lithological groups, the main structures and caldera rim (black dotted lines). In the lower part, scheme taken from [17].

Regarding the thermal models, several of them were ran to define the preliminary thermal structure in both areas. In Acoculco, even though the only data there come from the two exploration wells
drilled in the field, the magma intrusion that better reproduce such temperature information would have the following features [2]:

- Emplacement temperature of 850±50°C.
- The top of the magma chamber would be at 2300±400 m depth.
- The shape of the magma chamber would be a narrow dike of 500 m in diameter and 5 km long.
- If the system is still active and at its warming stage, the thermal wave required about 50-80 ka to reach the depth of the bottom holes.
- If the system is cooling, the intrusion was active up to about 5-6 ka ago or less.

6. Properties of analogue outcropping rocks

More than 250 superficial samples analogue of practically all types of rocks cut by the wells in Los Humeros and Acoculco, were collected as part of the activity 6.1 of WP-6, whose main goal is to better define some key properties of rocks of the reservoir by analyzing outcropping analogues. Cores of 25 to 64 mm in diameter were obtained from each sample, and analyzed to obtain petrophysical (density, porosity, permeability) and thermo-physical (thermal conductivity, thermal diffusivity, heat capacity) properties, besides electric resistivity, magnetic susceptibility and velocities of ultrasonic waves [16].

Some of the most relevant results are from andesitic rocks, which are the host rocks of conventional fluids in Los Humeros, and from sedimentary, intrusive and metamorphic rocks equivalent to the basement where the superhot fluids could be in Los Humeros and where the EGS project could be targeted in Acoculco. Table 1 presents those results, corresponding to the mean value from the different analyses done, which varied between one up to a maximum of 83 analyses. It is reported the standard deviation when more than a single result is presented.

Table 1. Results of some analyses of outcropping rocks in Los Humeros, Acoculco and Las Minas, deemed analogue of the sub-surface rocks (prepared with data from [14]).

| Rock               | \( \rho_p \) (g/cm\(^3\)) | \( \rho_t \) (g/cm\(^3\)) | \( \Phi \) (%)     | \( K \) (m\(^2\)) | \( \lambda \) (W/m\(^°\)K) | \( \alpha \) (10\(^{-6}\) m\(^2\)/s) |
|--------------------|-----------------------------|-----------------------------|-------------------|-------------------|-----------------------------|-----------------------------|
| **Pre-caldera andesites** |                             |                             |                   |                   |                             |                             |
| Los Humeros        | 2.68±0.23                   | 2.37±0.28                   | 6.58±5.11         | 2.38\(^{15}\)±1.47\(^{15}\) | 1.33±0.34                  | 0.73±0.17                   |
| Acoculco           | 2.55±0.06                   | 2.27±0.16                   | 12.11±9.4         | 1.41\(^{16}\)±3.45\(^{16}\) | 1.07±0.05                  | 0.683±0.01                  |
| **Basement rocks** |                             |                             |                   |                   |                             |                             |
| Limestone (LH)     | 2.69±0.02                   | 2.64±0.03                   | 2.08±1.24         | < 1E-18           | 2.94±0.11                  | 1.24±0.17                   |
| Limestone (Ac)     | 2.68±0.03                   | 2.65±0.08                   | 0.96±0.81         | 1.46\(^{16}\)±2.47\(^{16}\) | 2.88±0.39                  | 1.63±0.19                   |
| Flint (Ac)         | 2.63±0.002                  | 2.59±0.01                   | 1.73±0.45         | 3.32\(^{16}\)±3.79\(^{16}\) | 4.21±0.01                  | 2.22±0.99                   |
| Marl (Ac)*         | 2.66                        | 2.505                       | 6.05              | --                | 1.69                       | 1.48                        |
| Argillite (LM)     | 2.69±0.01                   | 2.65±0.03                   | 1.52±0.73         | --                | 2.32±0.79                  | 1.33±0.18                   |
| Marble (LM)        | 2.69±0.03                   | 2.65±0.04                   | 0.56±0.22         | < 1E-18           | 2.71±0.29                  | 1.03                        |
| Granodiorite (LH)  | 2.67±0.02                   | 2.56±0.04                   | 3.02±1.09         | 7.13\(^{18}\)±1.5\(^{17}\) | 1.84±0.08                  | 0.96±0.06                   |
| Skarn (LM)         | 3.38±0.38                   | 3.13±0.48                   | 6.97±4.28         | 2.24\(^{16}\)±4.3\(^{16}\) | 3.77±0.54                  | 1.61±0.28                   |

Notes: Ac: Acoculco, LH: Los Humeros, LM: Las Minas. *Argillaceous limestone, one single sample. \( \rho_p \) is the particle density, \( \rho_t \) is the whole density, \( \Phi \) is porosity, \( K \) is permeability, \( \lambda \) is thermal conductivity, and \( \alpha \) is thermal diffusivity.

Samples from limestones present porosity and permeability relatively homogeneous and low in Acoculco (28 samples) and in Los Humeros (13 samples): porosity lower than 5% and matrix permeability lower than 10-16 m\(^2\), and therefore fluid circulation into them must occur only through fractures and faults. The andesitic samples (83 in Los Humeros, 9 in Acoculco) are more variable in
both zones, but porosity and matrix permeability are also very low. Metamorphic rocks (13 samples of marble and 18 of skarn) present porosity and permeability variable (there was only one permeability result for marble), while granodiorites of Los Humeros (6 samples) have more constant, but also low, values.

7. Hydro-fracturing tests in analogue samples of Acoculco
These tests are the deliverable 6.4 of the WP-6 for the European consortium [6], with the aim of generate benchmark datasets from hydraulic fracturing (HF) experiments under controlled laboratory conditions on samples of granitic and marble rocks analogue to the rocks cut by the wells in Acoculco.

Four HF tests were performed with similar boundary conditions in granite and marble rock samples obtained from outcropping rocks in Las Minas. Uniform prismatic blocks of 0.3 per 0.3 m at the base and 0.45 m high were cut from the rock samples. At the center of each block a borehole with a radius of 10 mm was drilled, and a circumferential notch of radius 17±1 mm was cut into the borehole wall at the half of the height (0.225 m). The borehole is the analogue of the geothermal well where the real-life HF test is programmed to occur. The notch has a thickness of 0.6 mm and a depth of 7±1 mm and is cut into the sample to make the crack initiation and its location reproducible [6].

The injection fluid in the experiment was a mix of 98% Glycerol and 2% ink, the latter to visualize the penetration depth of the fluid when the samples are opened after the experiment. To monitor HF in the sample, 32 micro seismic sensors were attached to the surfaces of each block [6].

The experiment began by applying the initial stresses on the sample (σx, σy, σz), and then the fluid was pumped through a mini-pipe of 1.76 mm in diameter placed inside the central borehole of 10 mm diameter. The injection interval was isolated from the rest of the borehole through a packer. The duration of injection was controlled by injecting a defined volume ∆Vp after the peak pressure. After injecting ∆Vp the pump was stopped at ~30 minutes. When the pressure in the injection system dropped below the minimum confining stress (σz), the pressure in the injection system was released followed by the unloading of the sample [6].

Before the HF tests, the main petro-physical properties of each sample have been determined, with the results presented in Table 2.

### Table 2. Elastic and petro-physical properties of the tested samples (prepared with data from [6]).

| Property                  | Method                          | Units       | Marble | Granite |
|---------------------------|---------------------------------|-------------|--------|---------|
| Bulk density              | MSCL                            | kg/m³       | 2721   | 2707    |
| Matrix density            | Gas pycnometer/Archimedes        | kg/m³       | 2827   | 2743    |
| Young’s Modulus (static)  | Chevron-Bend-Test               | MPa         | 53,600±9150 | 59,500±1450 |
| Poisson’s ratio           | Uniaxial compression            | --          | 0.28±0.02 | 0.28±0.07 |
| Compressive strength      | Uniaxial compression            | MPa         | 121±14 | 164±12 |
| Tensile strength          | Indirect tensile test           | MPa         | 10±2   | 15±1   |
| Permeability              | FC & gas permeameter            | m²          | 10⁻¹⁷* | 9 x 10⁻¹⁸* |
| Porosity                  | Archimedes & MSCL               | %           | 3 a 4  | 1 a 2   |
| P-wave velocity           | MSCL                            | m/s         | 4470±100 (dry) | 4946±57 (dry) |
|                          |                                 |             | 5066±34 (sat) | 5542±80 (sat) |
| Fracture toughness        | Chevron-Bend-Test               | MPa/m       | 1.15±0.52 | 2.39±0.03 |

Notes: FC: Flow cell; MSCL: Multi Sensor Core Logger; *Permeability measurements were made at confining pressure of 30 bar.

The boundary conditions of each test (two on granite samples and two on marble) are presented in Table 3.
Table 3. Boundary conditions of each HF test [6].

| Sample     | Stress state (in MPa) | Injection                  | Notes: $V_{p0}$: Pump volume at the start of injection; $Q_p$: Injection rate during fracturing; $\eta$: Dynamic viscosity of injected fluid. |
|------------|-----------------------|----------------------------|-------------------------------------------------------------------------------|
|            | $\sigma_x$ | $\sigma_y$ | $\sigma_z$ | $V_{p0}$ (cm$^3$) | $Q_p$ (cm$^3$/min) | $\Delta V_p$ (cm$^3$) | $\eta$ (Pa s) |
| Granite 1  | 15        | 15        | 5          | 5                  | 0.1                  | 1.5                 | 0.58±0.02     |
| Granite 2  | 15        | 15        | 5          | 5                  | 0.1                  | 0.5                 | 0.55±0.02     |
| Marble 1   | 15        | 15        | 5          | 5                  | 0.1                  | 1.5                 | 0.56±0.02     |
| Marble 2   | 15        | 15        | 5          | 5                  | 0.1                  | 1.5                 | 0.56±0.02     |

The results of each test are presented graphically in figures 4 and 5. The left portion presents the section of the block and the borehole in its centre, and the right portion is the plant-view of the same block at its half. Points indicate the results of acoustic emission measurements, plotted as dots in the $z$-$x$ plane and the $x$-$y$ plane with time in seconds after the colours of the scale, and superimposed with the outline of the coloured fracture zone produced by the injection (line in magenta).

The peak pressure in the HF test with the granite samples was around 20 MPa. The peak pressure of the marble samples had some deviation with 26 MPa for Marble 1 and 23 MPa for Marble 2. The fracture radii in the marble samples show good agreement (10-12 cm). For the granite samples the fracture radii cannot be compared due to the reduced injection volume in the second test (Granite 2), but in general it is larger than in the marble samples.

A relevant conclusion is that when the real-life HF stimulation test be designed in one of the exploration wells, the aim must be the intervals where granitic intrusive is predominant over the metamorphic rocks.

8. Improvements for designing wells for superhot geothermal fluids
Activity 8.3 of the WP-8 (Drilling and Completion) has the objective to prepare key recommendations and requirements for designing wells capable to produce superhot fluids in Los Humeros. Main results of a compilation of lessons learned in hot and superhot geothermal environments in Greece, Italy, Iceland, Japan, Kenya, New Zealand, the U.S. and one well in Los Humeros, Mexico, were already published [8], and can be summarized as follows.

- Using bits with elastomers in its manufacturing must be avoided, being preferable metal-to-metal sealed drill bits. It is also recommendable use the drilling technique known as MPD (Managed Pressure Drilling). It is a system with a rotating circulation device (RCD) and Coriolis’s flow meter, which allow maintaining well pressures slightly higher than the pore pressure.

- Avoid the use of circulation fluids based on bentonite mud when drilling the lower parts of the well. When high and constant circulation losses occur, it is recommendable to use clean water with polymer pills, or water-based drilling fluid system with ilmenite and sepiolite as drilling suspending agents, to resist high circulating temperatures and eliminate the risk of sagging.

- It is recommendable to use unconventional casing materials including stainless steel grades like API L-80 and T-95, nickel-based alloys, and improved casing materials such as TN80-3%Cr already used for production casing string and liner pipe in the well H-43 of Los Humeros. Another, interesting concept is the method of cladding the casing strings with corrosion-resistant layers, which can be used also in casing connections.

- Conventional API buttress and premium casing couplings will probably fail in wells dealing with supercritical resources, being recommendable flexible couplings: during running casing, these couplings are in open mode, and while heating up, the casing material will expand allowing for each
coupling to expand freely downwards via a slip-joint and closing the system before reaching the expected temperatures, with enough residual axial force to seal the connection.

Figure 4. Results of the hydro-fracturing test in the first sample of granite (Granite 1). See text for explanation [6].

Figure 5. Results of the hydro-fracturing test in the first sample of marble (Marble 1). See text for explanation [6].
- For cementing the deepest casing pipes, and particularly the production casing (diameter of 9 5/8” in Mexico) it is recommendable to use new blends, even without Portland cement, as geopolymers or calcium phosphate sealing systems, lower-density cement blends (or foam cement), or add plasticizers such as liquid latex to the conventional cement mixtures to create more ductile sealing systems. Mixes based on alkali-activated aluminosilicates are also suggested.

- Wellhead assemblages and valves should be manufactured with more resistant materials (ANSI class 1500 master valves with ANSI class 2500 flanges, or class 10.000) and high corrosion resistance. Steel cladding can be made on some parts of the surface valves and spools potentially exposed to aggressive reservoir fluids.

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