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GEMex – A Mexican-European Research Cooperation on Development of Superhot and Engineered Geothermal Systems

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ABSTRACT

Unconventional geothermal systems such as Engineered Geothermal Systems (EGS) have been in the focus of interest for geothermal exploitation for several decades. In addition, the development and exploitation of high-temperature geothermal fields with supercritical conditions are emerging as a new hot topic in various parts of the world. In the GEMex project, these two unconventional geothermal resources are investigated, building on previous efforts within the Mexican CeMIEGeo project (Centro Mexicano de Innovación en Energía Geotérmica). For this purpose, two sites have been selected in the eastern part of the Trans-Mexican Volcanic Belt (Los Humeros and Acoculco, Puebla) with the goal to develop transferable concepts for other high-temperature geothermal fields.

Los Humeros is a geothermal field within a Quaternary volcanic complex with an existing geothermal power plant in operation since 1990. Temperatures around 380°C were found at depths below 2000 m; however, geothermal fluids at such high temperatures could only be used to some extent for energy production, due to their aggressive physicochemical characteristics. Focus of our research is on an improved and comprehensive understanding of the location and characteristics of the deeper superhot/supercritical geothermal reservoir and its connection to the known conventional geothermal system. Tests of different materials for the technical components, for downhole and surface installations, will address the special characteristics of the geothermal fluids and the very high temperatures.

Acoculco is described as a high-temperature geothermal system within a Pliocene-Pleistocene volcanic complex. Two wells have been drilled and found temperatures above 300°C (EAC-1) at depths below 1800 m, but hardly any fluids. Preliminary geological studies consider Acoculco a candidate for the application of EGS technologies. In GEMex it will be evaluated if the existing wells can be hydraulically linked to permeable and fluid bearing fracture zones nearby.

1. INTRODUCTION

The GEMex project is a complementary effort of a European and Mexican consortium on unconventional geothermal systems. Focus of this multidisciplinary project is on 1) Resource assessment, 2) Reservoir characterization, and 3) Concept development for exploitation and utilization (Fig. 1).

1) **Resource assessment:** This part 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.

2) **Reservoir characterization:** Geophysical data will be acquired by various methods and the resulting data will be combined in integrated reservoir models. For the interpretation of these data, high-pressure/high-temperature laboratory experiments will be performed on rock samples from Mexico or equivalent materials to derive the physical properties required for the key lithologies encountered.

3) **Concepts for site development:** As final deliverables of the project, concepts for the development and utilization of unconventional geothermal sites will be proposed. This 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.

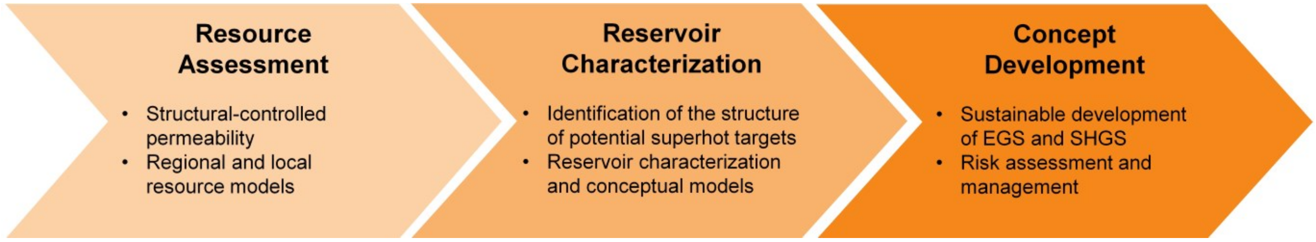

Figure 1: GEMex workflow

2. STUDY AREAS

2.1 Los Humeros caldera

Los Humeros is a Quaternary volcanic complex with existing geothermal power plant facilities (Installed capacity 95.7MWe, ~ 30 wells under production), 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) on 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.

2.2 Acoculco caldera

Preliminary geological studies consider the Pliocene-Pleistocene Volcanic Complex of Acoculco a candidate for application of EGS technology. Focus within GEMex is on (1) an improved characterization of the geothermal system, (2) an evaluation if application of EGS technologies can hydraulically connect existing wells (~300°C at 2 km depth; hardly any fluids) to permeable and fluid bearing fracture zones nearby, and (3) defining the requirements for and designing of suitable stimulation procedures. The concept includes mitigation of induced seismicity and other potential environmental impacts.

3. SCIENTIFIC OBJECTIVE

3.1 Tectonic control on fluid flow

The following aspects will be investigated

- Structural mapping, including analysis of fault kinematic indicators from active and exhumed systems
- Geochemical characterization of fluids from natural manifestations and comparison with reservoir fluids
- Comprehensive soil gas studies (including long-term CO_2 flux monitoring)
- Integration of soil gas and structural data

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 Acoculco and Los Humeros systems, but also from exhumed systems (e.g., Las Minas) nearby, in outcrops of the deep part of fossil geothermal reservoirs (Fig. 2). The fieldwork activity is based on the classical approach of structural geology, and is enhanced through scanlines and imaged fracture analyses, both at outcrop and thin-section scale. New data will be used to continuously update developed regional resource models. Distribution of fractures and analysis of kinematic indicators on fault surfaces allow to estimate stress axis orientations and preferential fluid pathways through the main geological structures. Furthermore, the reliability of the derived conceptual models of both areas will increase by taking the results of the exhumed geothermal system Las Minas into account. Las Minas is a hydrothermally mineralized mining area, and considered as the analogue of Los Humeros and Acoculco at depth and therefore representing the analogue deep roots of the active geothermal areas. In Las Minas fluid inclusion analyses will be 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 will be derived.

Hydrological and geochemical data will be collected from natural cold and warm springs and wells (including geothermal wells) within both geothermal systems, but also at the boundary and outside the system, taking into account altitude distribution, morphology and geo-structural characteristics. Scientific activities will address the geochemical characterization of the fluids, as well as temperature and pressure conditions present at depth for (1) the identification of the main recharge areas/origin of geothermal fluids, and (2) the physico-chemical evolution of fluids by water-rock interaction and secondary processes. Novel high-temperature tracers will be tested and applied to understand recharge and communication, based on the thermal stability of isotopes at high temperatures. Furthermore, area-wide, multi-parameter soil gas analyses (e.g., CO_2, ^{222}Rn) will focus on the spatial distribution of different gas concentrations/gas fluxes to identify and characterize permeable segments of major faults and fractures (Jolie and Rodríguez García, 2018; Fig. 3). Airborne thermal imaging will be applied in the same area to correlate results with soil gas data. It will be analyzed if the soil gas composition at Earth's surface can be used as an indicator for the presence, dimension and characteristics of the deep superhot/supercritical geothermal system. Based on recent findings (Jolie et al., 2016) the link between soil gas, structural and fault stress data will be investigated. Techniques for the correlation of soil gas (including continuous CO_2 flux monitoring) and seismic data will be tested as well. The integration of the different structural-geological and geochemical data will allow to obtain key information regarding the conceptual model of the studied systems, such as main recharge areas, origin of geothermal fluids, thermodynamic conditions present at depth and active fluid pathways.

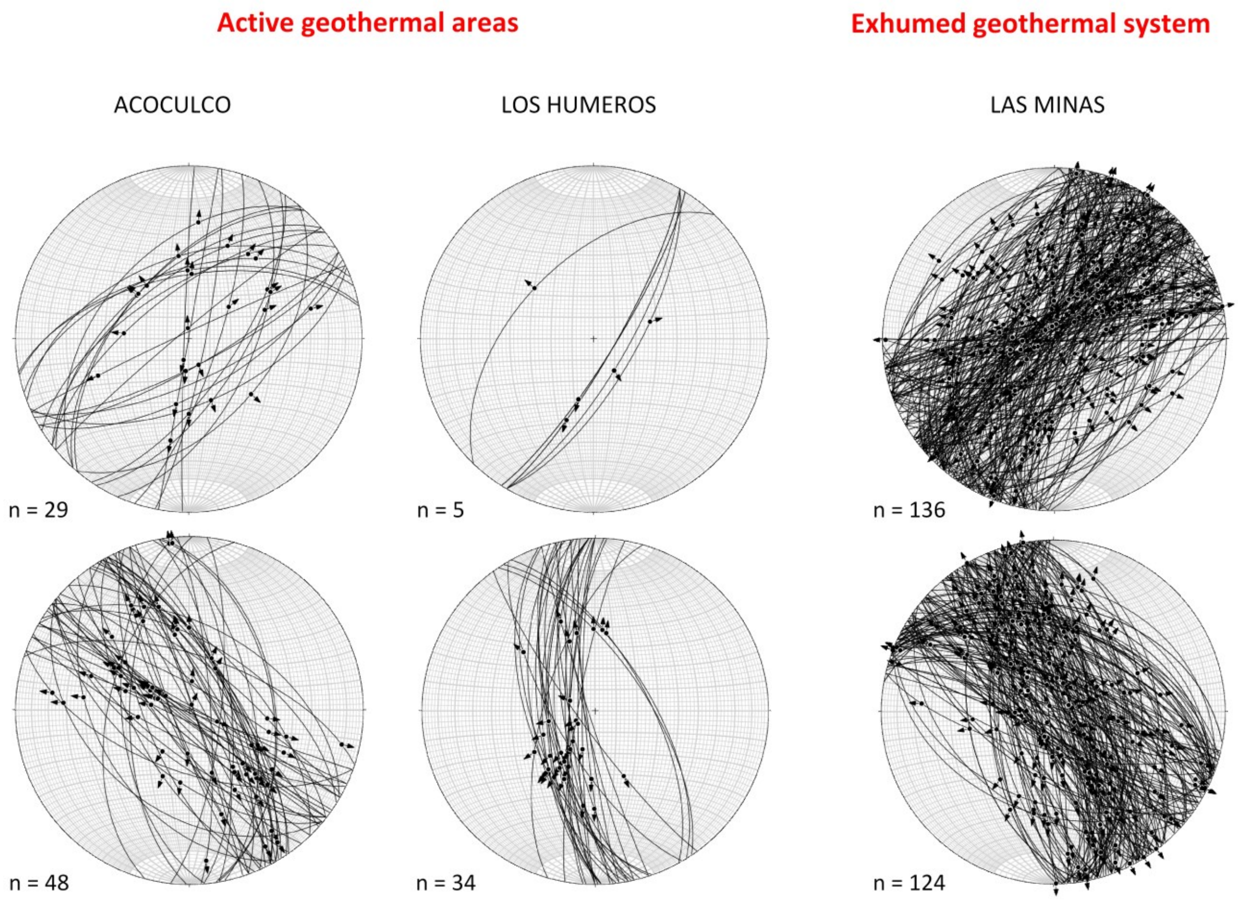

Figure 2: Stereonets - lower hemisphere, equiangular projection - with preliminary data collected in three study areas. Two main trends of meso-faults (regional) have been observed. The NW-SE trend is predominantly defined by an oblique movement, whereas the SW-NE trend is characterized by a dominant normal component. The difference in number of samples is a consequence of the outcrop conditions in the different localities. The strength of weathering effects on preserved kinematic indicators is influenced by the mechanical properties of outcropping rocks (e.g., consolidated/unconsolidated).

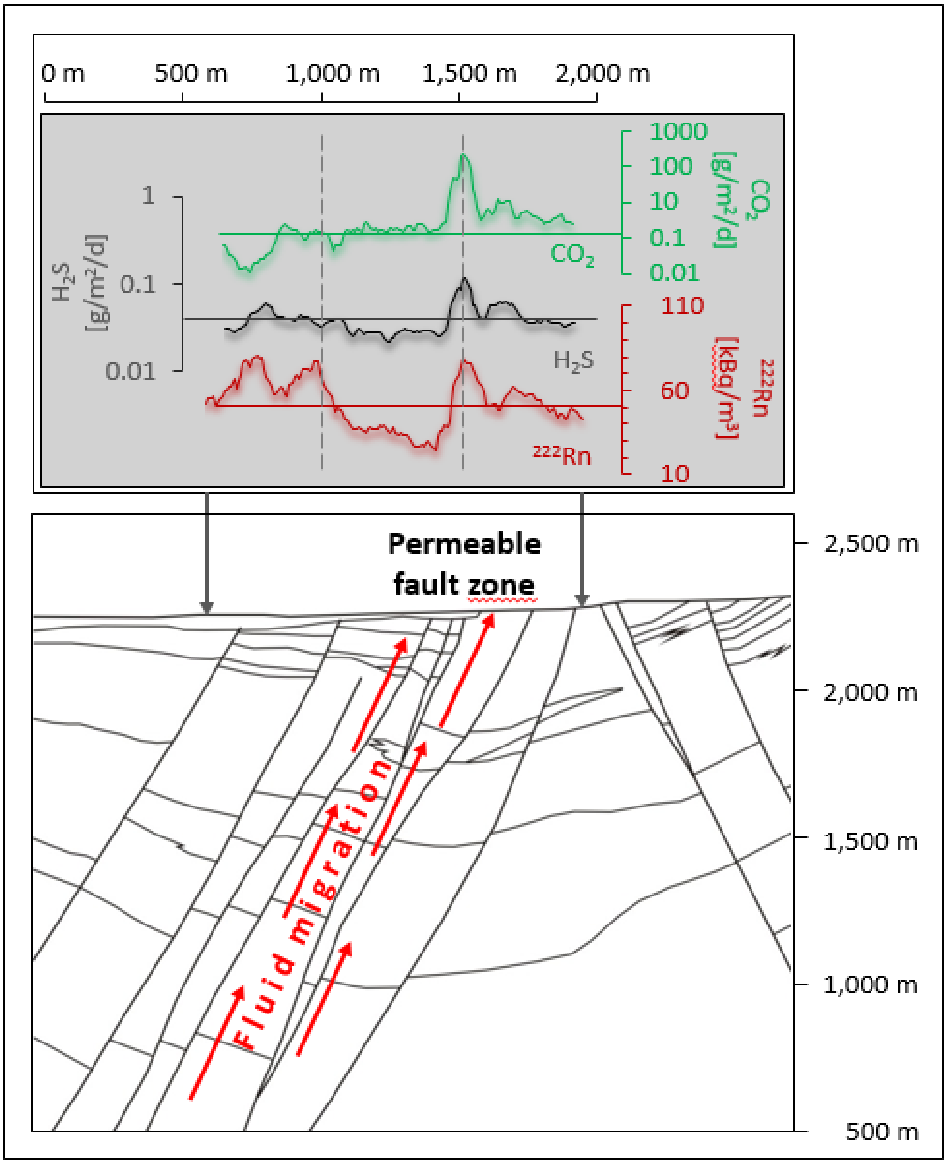

Figure 3: Concept of fluid migration along permeable fault segments (modified after Jolie et al., 2015a and b). Area-wide sampling and analysis of geothermal fluids (water and gas) allows a correlation of anomalous values with permeable fracture zones.

3.2 Detection of deep structures

The following aspects will be investigated

- Integrated geophysical imaging
- Integration of geophysical data with other relevant data (e.g., soil gas)

The detection of deep structures in both Acoculco and Los Humeros geothermal systems will be performed by developing innovative and optimized geophysical methods. The integration of all the applied techniques (Fig. 4) will allow generating comprehensive three-dimensional models to know the distribution of the main physical properties at depth and their relationship with the geothermal system dynamics. The activities involved to fulfill this goal include:

- The electrical resistivity characterization through the magnetotelluric method (MT) and transient electromagnetics (TEM). This activity involves not only new data acquisition at both sites but also the generation of synthetic models to improve three-dimensional inversion schemes, implementation of novel methodologies in data processing as well as the comparison of obtained results with others models previously generated in similar geothermal fields. The first part of the resistivity survey in Los Humeros consisting of 72 out of 150 planned MT and TEM soundings was concluded in November/December 2017. Based on a preliminary 1D inversion of the data, the location of the remaining sounding pairs was determined. For Acoculco a similar survey consisting of around 100 MT/TEM sounding pairs is planned. Acquisition of resistivity data in Los Humeros and Acoculco will result in 3D resistivity models for the two areas.

- The characterization of the seismicity in both geothermal systems includes techniques such as two-dimensional modeling of surface wave dispersion, three-dimensional modeling of seismic velocities, radial-anisotropy modeling and the determination of focal mechanisms. All these activities will be performed to characterize active faulting, large discontinuities of the shallow crust and the fluid dynamics in the reservoirs. In Los Humeros 42 seismic stations have been deployed and will keep recording for one year. Another 15 seismometers will be installed in Acoculco. Prior to the deployment of the stations, synthetic model calculations helped to optimize the setup in the field. Seismic monitoring of the two fields will give important information on the tectonic movements/activity of the subsurface.
- A full characterization of the heat flow in the Acoculco prospect is part of the planned work program. A map will be generated from information collected in a grid of shallow wells (50-100 m) drilled specifically for the project. This map will include anomalous heat transfer areas related to convective effects and presence of permeable conduits for the Acoculco prospect.
- Geophysical potential methods will be applied, including magnetic and gravity measurements. In the first case, already available airborne magnetic data will be used to obtain a three-dimensional regional model that can provide information on the regional geological structures. New gravity data will be acquired for both geothermal systems to generate three-dimensional models in order to infer structures related to permeability. One gravity survey has already been conducted in Los Humeros and another one is planned in Acoculco. Interpretation of gravity in the two areas will be a valuable addition to the knowledge on mapped tectonic structures.
- Results from seismic and gravity measurements will be an important constraint in the modeling of the resistivity data which helps in constructing conceptual models of the two areas.
- Subsequently, the generated models will be included in an integrated geophysical image based on MT, TEM, Seismic, Gravity, InSAR, GPS (i.e., joint inversion, geospectral modeling, structural coupling approach) in order to determine the variation of the physical subsurface parameters relevant for reservoir characterization.

3.3 Regional Resource Models

The following aspects will be investigated

- 3D structural-geological models of the volcanological systems of Acoculco and Los Humeros
- Temperature models at scale of the volcanic system
- 3D Integration platform
- Analogue modeling to understand tectono-volcanic interactions

The complexity of the different datasets from geothermal exploration will be consolidated by data integration in cooperative 3D GeoModels (Calcagno, 2015). The primary objective is a comprehensive understanding of the tectonic and volcanological evolution of Acoculco and Los Humeros by understanding conditions and processes determining the development of these unconventional geothermal systems. The developed models including volcanological, structural, thermal, physical and hydrological parameters from the geothermal system and beyond will help understand the resource and improve numerical reservoir models. This involves information on heat source, fluid migration and fluid pathways, as well as characteristics of reservoir and surrounding rocks. Results of analogue modeling will help to assess tectono-volcanic interactions. Preliminary geological models are built using the initial database. An iterative "Knowledge and Data Sharing - Modeling - Validation" cycle has been established to maintain the boundary conditions and input parameters for the integrated 3D models up to date. The 3D geological models are constructed with GeoModeller software using a potential field interpolation method (Lajaunie et al., 1997) combined with geological rules (Calcagno et al., 2008).

The first step for the characterization of the two geothermal systems, before conceptual modeling at supra-regional scale, is the development of 3D models at regional and local scale (Fig. 5). The following information is considered for the modeling process: surface information, such as geological maps and structural features, as well as subsurface information from geothermal wells, geological cross-sections, geophysical and geochemical information. This information is integrated into a 3D modeling platform as the basis for further modeling. In return, new geological data will be continuously integrated into the model to keep it updated. In an initial step, two preliminary models have been developed for Los Humeros. A regional model (56 km x 36 km x 7 km) describes the fault system geometry and four geological groups: basement, pre-caldera, caldera, and post-caldera rocks. A local model (9.5 km x 12.5 km x 7 km), focusing on the exploited field, presents nine units and the associated faults (Fig. 5). Both are based on the interpretation by Carrasco-Nuñez et al. (2017), Norini et al. (2015), and López-Hernández (1995). Models are constrained by data from 16 wells provided by CFE. A preliminary regional model is also developed for Acoculco (56 km x 36 km x 7 km). It combines the work from Avellan et al. (submitted), a preliminary analysis on the existing faults, and the data provided by CFE from the two existing wells. Five groups of geological formations are modeled: undifferentiated basement, granite, skarns, limestones, and volcanic rock units, along with the regional fault system. The preliminary geological models will serve as geometrical framework for computations within GEMex, such as heat transport and fluid flow simulations. They will be updated and refined along the course of the project, using new data and interpretations from the ongoing field work in geology, geophysics, and geochemistry.

The second step is the development of thermal models based on the 3D geological models, including all subsurface information from the deep wells. The hydrogeology will be included to understand the geothermal system boundaries at the scale of the volcanic edifice and beyond.

The third step aims to gain a better understanding of the system, using analogue modeling techniques simulating field observations at the two sites. 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 collapse. 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.

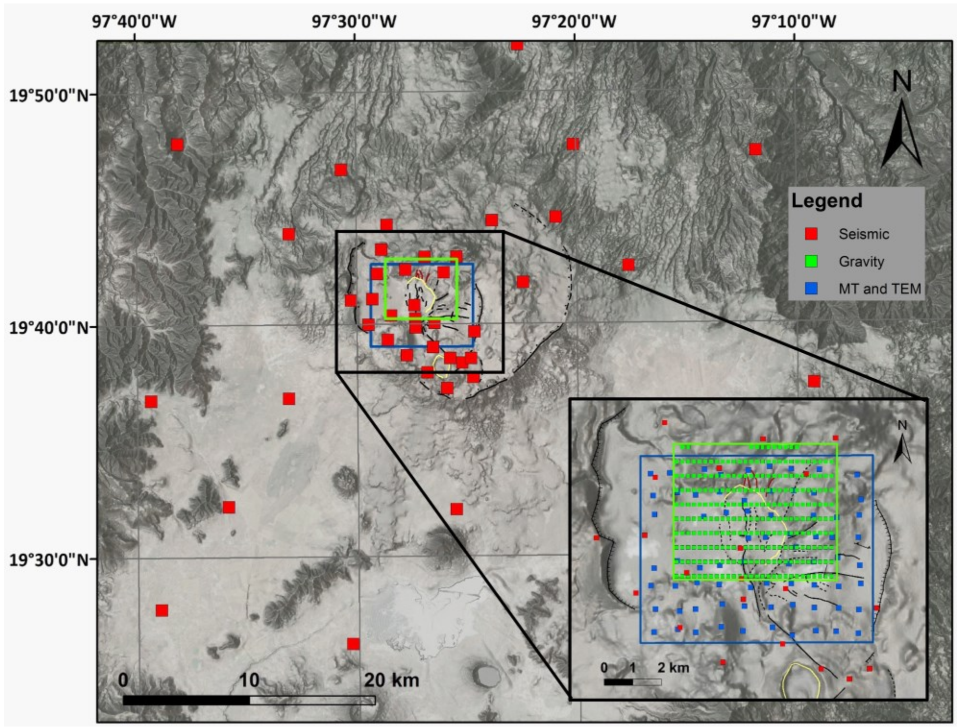

Figure 4: Los Humeros geophysical network consisting of 42 seismic stations, 72 MT/TEM and 263 gravity measurements.

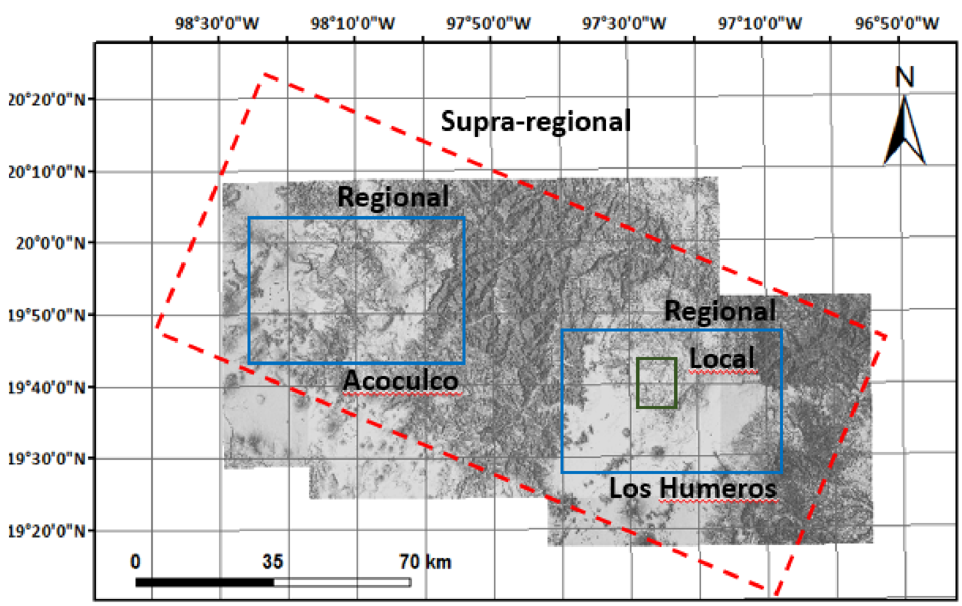

Figure 5: Overview of the study areas outlining the dimension of the models from supra-regional to local scale.

3.4 Reservoir characterization and conceptual models

The following aspects will be investigated

- Petrophysical analysis of rock samples at high temperature and high pressure
- Verification of simulation codes against laboratory fracturing experiments
- Stochastic simulation to quantify uncertainties

Fluid flow in the Los Humeros geothermal field is dominated strongly by faults and fractures formed during tectonic and volcanic episodes. Therefore, one of our major targets is characterizing those faults and fractures, which permit fluid flow. We will investigate fracture patterns and geometry through shallow geophysical investigations (i.e., electrical resistivity tomography, p-wave refraction tomography) at surface outcrops of reservoir analogues, geological information obtained from surface measurements, FMI image logs and integrate them with information obtained through hyperspectral analyses performed within the project. This integration will allow us to estimate fracture dimensions relevant for simulating fluid flow. In addition, an extensive record of pressure and temperature data exists from production and injection wells collected over time by CFE. This enables us to study the feed zones based on pressure-temperature and production data and achieve reliable estimates of permeability by simulating well bore performances (Montegrossi et al., 2015). These property values will then be used for simulating static models and thereafter predicting transient behavior of the geothermal field in production.

Geometric models of size 6 km × 10 km ×12 km containing structural information of the caldera region, the stratigraphic units, and the bounding faults are created using information from published literature. These models are continuously refined using additional geophysical data and geological information during the course of the project. The geometric models are then 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. Absence of standard petrophysical well logs and very limited availability of core data from wells imposes a great challenge to produce models with reliable rock property distributions. To fill this gap, we undertake exhaustive studies on outcrop samples obtained from exhumed and active systems in and around Los Humeros and Acoculco. Petrophysical, mineralogical and geochemical measurements are performed on the rock and fluid samples for characterizing their behavior under different temperature and pressure conditions. We envisage creating a petrophysical catalogue, which will report rock property values for different stratigraphic units of the Los Humeros and Acoculco fields based on outcrop measurements to be calibrated with the limited available information from cores. Being aware of the fact that the rock properties obtained from measurements only on outcrop samples entails an inherent error regarding the initial property estimation, we apply stochastic modeling for handling heterogeneities and quantifying uncertainties for each reservoir property. We will use a Monte Carlo algorithm based on Sequential Gaussian Simulation (SGSIM) to generate statistically reliable spatial distributions of rock properties such as porosity, thermal conductivity, heat generation rate, etc. (Vogt et al., 2010).

The Acoculco geothermal field has been selected as a candidate for the application of EGS technologies. Previous studies define Acoculco as a hot, dry, and virtually impermeable system (Pulido et al., 2010). This characterization is based on two wells drilled until now and related literature. The success of EGS depends largely on our ability to understand the fracture growth and connectivity of the fractures created. To this extent, we perform hydraulic fracturing experiments of rocks under controlled conditions at a scale sufficiently controllable in the laboratory but, at the same time, adequate for providing a reliable data set for verifying different numerical codes used for the layout of hydraulic stimulation operations. Experiments are performed on samples of granite and skarn sized 30 cm × 30 cm × 45 cm (Siebert, 2017; Clauser et al., 2015) collected from regions around Acoculco and believed to be representative of an optimal target formation for EGS in Acoculco.

3.5 Concepts for reservoir development and utilization

The following aspects will be investigated

- Transferable concepts for EGS and SHGS
- Comprehensive risk assessment and management
- Identification of suitable materials for high temperatures and fluids with aggressive physicochemical characteristics

GEMex will provide options to make a reliable use of the geothermal reservoirs at both locations possible. For a safe and sustainable development of EGS and SHGS detailed risk assessment needs to be carried out. The extensive site exploration described in the previous chapters gives input for the analysis of the technological (see 3.5.1 and 3.5.2) and environmental risk (3.5.3) such as seismic and legal issues. This will lead to a model for potential aggregated evaluation of the risk, which should be the base for further decisions. Part of the decision is solving the question how the risks will be controlled, governed and managed. This is the prerequisite for a decision-tree structure that leads to a site-specific development concept. Advanced traffic light systems for operative development steps have to be developed.

3.5.1 Concepts for the development and utilization of engineered geothermal systems

Acoculco is a geothermal system with a number of fundamental questions that need to be addressed before a development of stimulation scenarios is meaningful. For that reason, we focus in an initial phase on an improved understanding of the permeable structures, the presence and characterization of geothermal fluids in the subsurface and the classification of the geothermal system by different exploration activities in the field. Once all required data are available, an optimized EGS stimulation design for Acoculco will be developed using an existing or a new well, while honoring environmental safety and public engagement. The design will be supported by integrated, numerical, coupled modeling. The input for the models will be based on the results of the resource assessment and reservoir characterization, including characterization from deep structural imaging, chemical analysis, temperature, and in-situ stress-field as well as on rock and fluid properties. Potential drill targets/paths will be proposed to develop the reservoir using different stimulation approaches (hydraulic, hydroshearing, thermal or chemical) and pumping types (continuous, cyclic, etc.).

Concepts for advanced downhole measurements such as distributed acoustic sensing (DAS) or seismic interferometry will be developed to optimize technical performance of the stimulation. Performance and sustainability prediction of the proposed developments will be accomplished via numerical modeling. The Mexican GEMex consortium is considering the stimulation of a well in Acoculco in the fourth year, provided that a safe stimulation is possible and the results of the site assessment recommend such measures. Here, the experience from the Pohang EGS project site in Korea will be taken into account. For this purpose, Hofmann et al. (2017) designed a cyclic injection protocol and an advanced traffic light system, which was successfully applied to mitigate seismic events above a site-specific target threshold. This approach will be further tested and refined, if appropriate.

3.5.2 Concepts for the development of superhot resources

Planning concepts for the development of superhot resources includes a number of high-temperature approaches and techniques, both for laboratory testing and for downhole monitoring and installations. To characterize the physical properties of rocks at conditions above the critical point of water, high-temperature and high-pressure lab measurements were designed. A new experimental set-up, especially built for these measurements, enables flow-through experiments on rock samples under controlled confining and pore pressure at near critical temperature (Kummerow and Raab, 2015). The experience gained in supercritical geothermal systems (Reinsch et al., 2017) will be transferred to the site in Mexico, and a concept for utilization will be developed for the superhot wells at Los Humeros.

The basic idea is to consider a target beneath existing wells in Los Humeros. The open key questions are:

- Are there existing or induced fractures and permeability within these zones that can act as potential fluid pathways?
- Does the rheology allow drilling?
- Is drilling feasible?
- How to utilize a SHGS?

To answer these questions data on stratigraphy, temperature, fluids, stresses are compiled from geophysics, the existing wells above the target area, and also from SAR data. Models of the geological structure will be generated including gridded properties and concepts of the volcanic situation. Based on this first modeling step, dynamic models should enlighten the multi-phase conditions and the fracture properties at higher pressures and temperatures. The outcome will allow conclusions on the thermal-hydraulic-mechanical situation in the target area. Within this model of the potential drill target we will investigate at least one potential drill path. The feasibility includes knowledge of material properties, which is required in this system. Therefore, special experiments are proposed in existing geothermal wells in order to test the reliability of different materials. This will be part of a list of key requirements and recommendations for design and well completion.

3.5.3 Environmental, social and economic impact assessment

The impact on environment, society and economy (ESE) will depend mainly on the natural characteristics of the reservoir, the social complexity of the human communities and the applied technology of the project. Therefore, it is critical to integrate the ESE aspects of sustainable development during every stage of the planning of any geothermal project (exploration, production tests, construction and operation). This information will be standardized, allowing its update, exterior validation and to generate essential data to propose strategies of prevention, mitigation, restauration, and improved practices for the use and management of EGS and SHGS resources.

Environmental impact assessment includes a description of the sites (e.g., climate, vegetation, hydrogeology, etc.), appraisal of the actual state of the sites/ baseline studies (e.g., water/air/soil quality, diversity) and description of effects, characteristics and circumstances that may alter the environment (anthropogenic, natural). Social impact assessment includes a description of the localities (e.g., demography, economy, indigenous groups, etc.), territorial dynamics (identification of economic, social and natural interrelationships) and outreach strategies (previous and present conflict situations, social acceptance of the project). Economic impact assessment includes a socio-economic (e.g., determination of direct and indirect impacts on the local economy) and socio-environmental impact assessment.

The objective is to develop, calibrate and test a model that can be subsequently used to monitor, ex-ante, the possible sustainability-related consequences of the introduction of new geothermal energy technologies, in particular EGS and SHGS. The typical result of this activity would be a series of scenarios of future impacts (for both technologies), an assessment of the state of development of the green innovation system for geothermal energy technologies, a proxy measure of the ex-ante and ex-post impacts of the technology.

4. CONCLUSIONS

GEMex will ultimately result in the compilation of a substantial database for an integration of the different scientific disciplines. This will accelerate the methodological and technological advancement for the exploration, assessment and utilization of unconventional high-temperature geothermal systems driving the development of transferable concepts. The key to success is the concept of a comprehensive multidisciplinary data integration targeting the same area. Finally, development concepts for unconventional geothermal resources will be delivered, based on the comprehensive workflow and experience gathered at the two tests sites in the project. Ideally, implementation of these concepts at a later stage will help further refine and validate the proposed concepts.

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