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The GEMex Project: Investigation of Acoculco (Mexico) as a Potential EGS Site

David F. Bruhn*, Domenico Liotta, Víctor Hugo Garduño-Monroy, Claudia Arango Galván, Gylfi Páll Hersir, Jan Diederik van Wees, Philippe Calcagno, Alfonso Aragón Aguilar, Paromita Deb, Aída López Hernández, Egbert Jolie*, Katrin Kieling*, and the GEMex **team**

***Helmholtz Centre Potsdam German Research Centre for Geosciences GFZ, 14473 Potsdam, Germany**

dbruhn@gfz-potsdam.de

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ABSTRACT

The GEMex project is a Mexican-European research cooperation on developing concepts for the use of superhot and engineered geothermal systems for power generation. A major focus in the first stage of the project is the characterization of a potential EGS test site, which has been proposed for the Acoculco caldera in the Eastern Mexican Volcanic Belt. Two wells have shown high temperatures around 300 °C at 2km depth at Acoculco, but hardly any fluids were found. During the project we have used the full range of geological, geophysical and geochemical exploration methods to find out more about the geothermal system and to recommend EGS measures for the economic usage of the Acoculco reservoir. As a starting point, the geological characterization of the area and development of novel model approaches were used to build state-of-the-art models for simulation of both - the stimulation treatment and the lifetime performance of the EGS. The goal is to design an optimal stimulation treatment (including chemical stimulations, hydraulic fracturing, shear fracturing), reducing the potential negative impact of environmental effects such as induced seismicity. Dedicated simulation models are used to predict performance indicators related to economic performance, sustainability and environmental safety. Special attention will be paid to the mapping of seismically sensitive areas and the potential impact on drinking water aquifers. The paper will give an overview of the exploration strategy, selected results and interpretation. Based on the available data possible stimulation scenarios to connect the wells to a productive zone will be discussed.

1. GEOLOGICAL BACKGROUND

The Acoculco Caldera Complex is located in the eastern part of the Trans-Mexican Volcanic Belt. The Acoculco Caldera was formed 2.7 Ma, and since then, volcanic activity has persisted until 0.06 Ma, through the emission of domes, cinder cones, fissure lava flows and two ignimbrite eruptions dated at 1.2 and 0.65 Ma. After the caldera collapse 2.7 Ma, the local stress field was probably modified and allowed the ascent of peralkaline magmas through new plumbing systems. Such magmas mixed with calc-alkaline magmas and formed the post-caldera volcanism (Sosa-Ceballos et al., 2018).

The Acoculco caldera rests upon sedimentary marine Cretaceous limestones of the Sierra Madre Oriental,and Miocene volcanic rocks belonging to early stages of the Trans-Mexican Volcanic Belt. The Cretaceous limestones do not crop out inside the Acoculco caldera but were cut in the geothermal exploration drill-holes of CFE, from 800 to 1200 m of depth in well EAC1 (Figure 1), and from 350 to 450 m of depth in well EAC-2. The Acoculco caldera succession is also interbedded with deposits of the Apan-Tezontepec Volcanic Field that consists of 280 scoria cones, 10 shield volcanoes, and 5 domes. Most volcanoes are made of basaltic andesitic lavas with phenocrysts of olivine and plagioclase, and dacitic domes. The age of the ATVF spans from at least 2.25 ± 0.04 Ma to the Holocene (Avellán et al., 2019).

Underneath the Acoculco caldera, a hornblende granite intrusion emplaced within the cretaceous limestone sequence was cut by the two wells. The composition of rock samples and their ages (183 ±36ka) led to the interpretation of a young aplitic dike intrusion (or dike swarm) beneath Acoculco (Sosa-Ceballos et al.,2018). The result of this emplacement is a metamorphic contact aureole of skarn and marble rocks. The main lithological units within the Acoculco caldera are interpreted based on the drilling data of the wells EAC-1 and EAC-2 (Figure 1).

The pervasive hydrothermal alteration in the central part of thFe Acoculco caldera has motivated considerable geothermal exploration. In the above mentioned exploration wells (i.e., EAC1 and EAC2) the temperature of 300°C at 2 km depth was measured, but no exploitable fluid has been discovered. Preliminary geological studies consider the site a candidate for the application of EGS technology to develop the field (Lorenzo-Pulido et al., 2010; Canet et al., 2015). According to these studies, the geothermal target is probably located in the basement composed of calcareous, granitic and metamorphic rocks, since the overlying volcanic rocks show intense hydrothermal alteration (Calcagno et al., 2018).

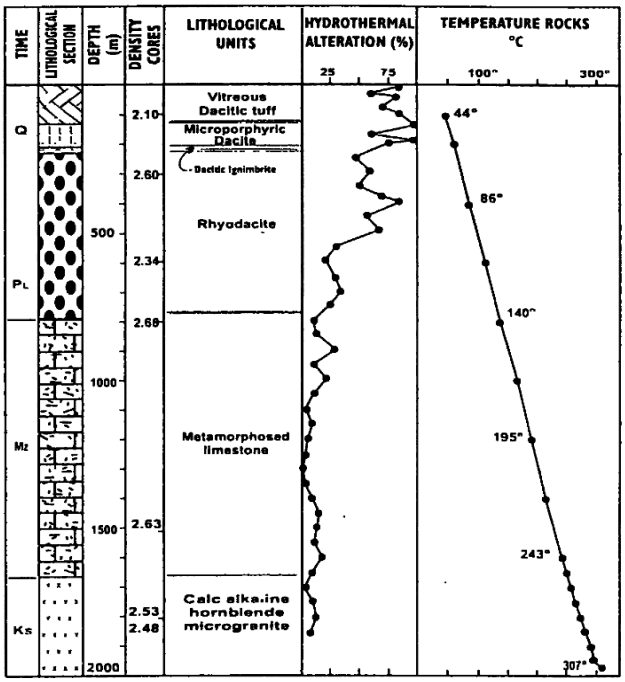

Figure 1: Profile and results from Acoculco well EAC1 (from Lopez Hernández et al. (2009)

2. RESOURCE ASSESSMENT

2.1. Geological models

The Acoculco area was modelled at a regional scale (Figure 2). The geological map from Avellán et al. (2018) is the main reference to set up the geomodel. In addition, the Comisión Federal de Electricidad (CFE) has provided a general geological description of two exploration wells. Moreover, other information on the two exploration wells and on the geological setting were retrieved from literature (e.g. López-Hernández et al., 2009; Lorenzo-Pulido et al. 2010). The model also includes new data from field work performed within the project. The main faults have a maximum extension of four kilometres (below ground level) corresponding to the interpreted depth of the brittle-ductile transition. For the modelling process, the geological formations are described as five groups (see Figure 1): basement, granite, skarns, limestones, and volcanics. The geological map (Avellán et al., 2018) was re-interpreted accordingly. Two geological cross-sections were drawn to interpret the deep structures. They serve as reference for the geological interpretation. Nine complementary cross sections were drawn according to the two references cross-sections to ensure a coherent interpretation, for instance in terms of geological formations thickness.

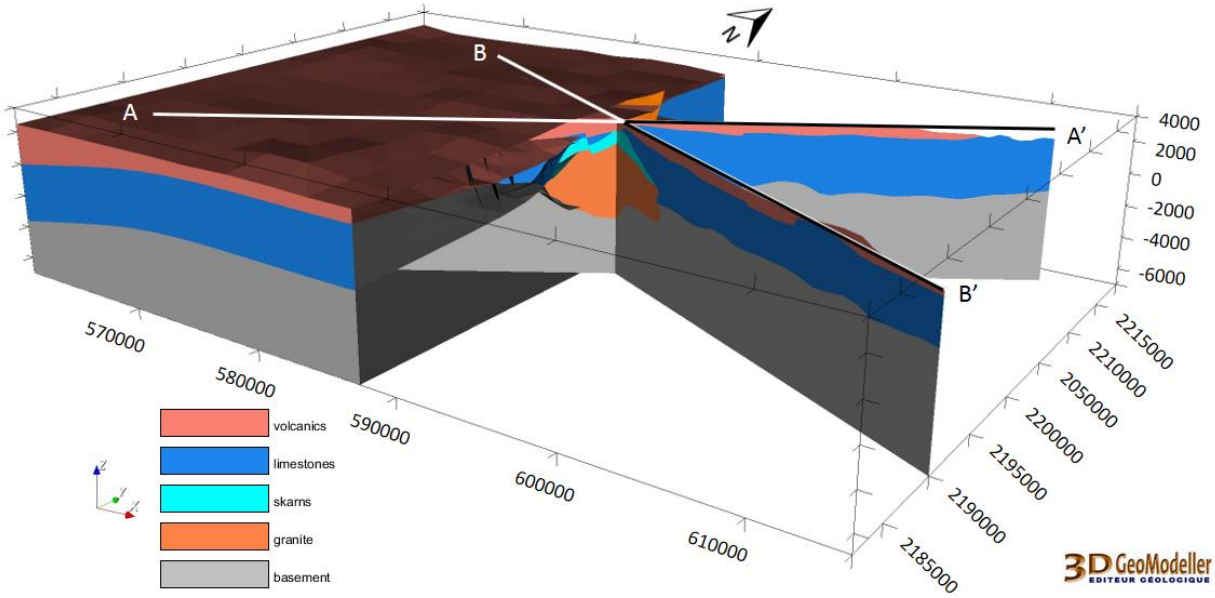

Figure 2: The Acoculco regional geomodel of the five geological groups listed at bottom. Coordinate system is WGS84/UTM zone 14N. Figure taken from Calcagno et al. (2018).

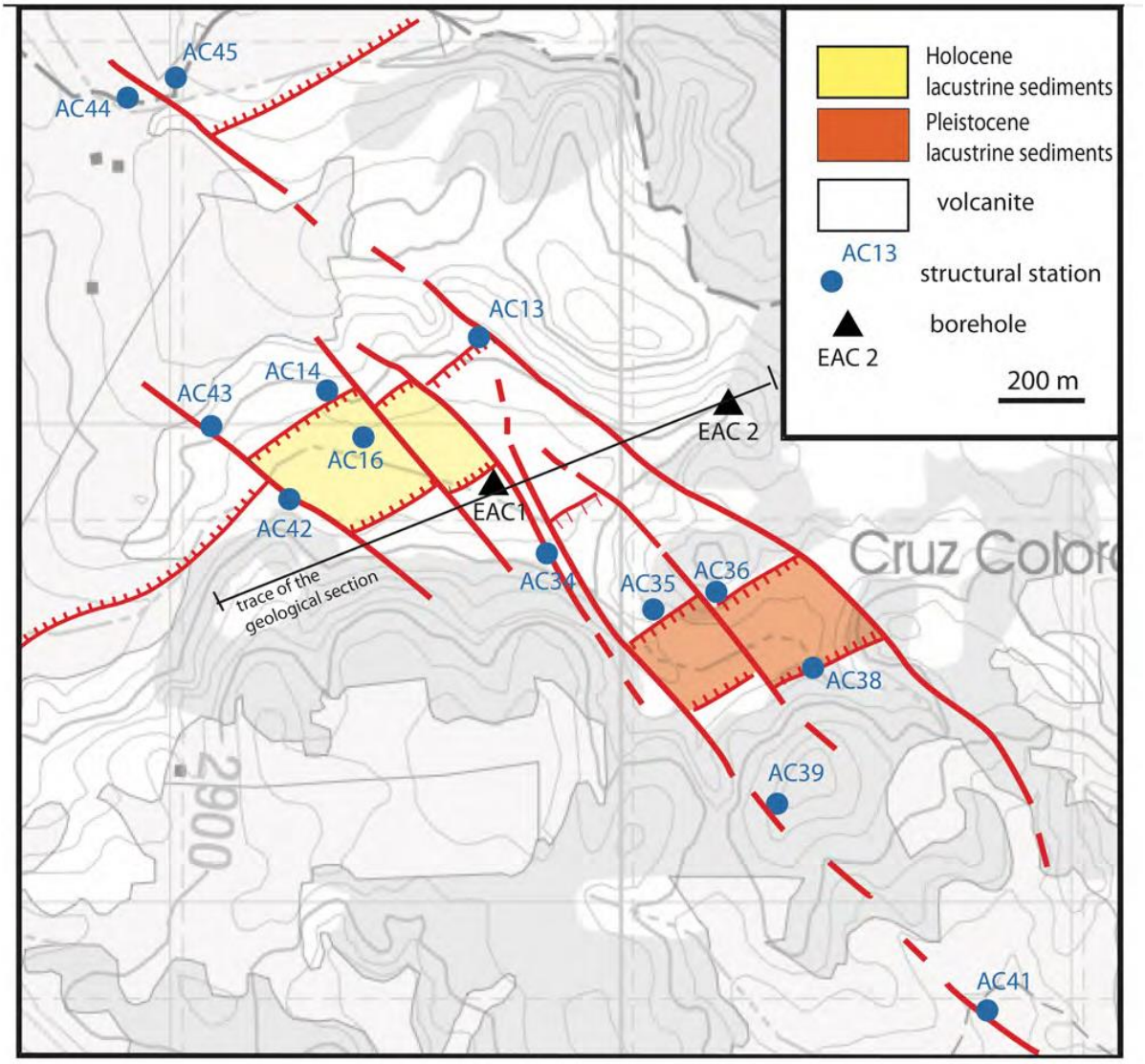

Figure 3: Structural map of the area where the exploration wells are located. The geological section is shown in Figure 5

For a thermal model, using the limited data availability for the Acoculco region, the actual trend of the measured temperature profiles is explained as the shallow expression of a recent magmatic event. Assumptions are the presence of an active deep-seated magmatic source, which is suggested by reported 3He/4He values, and a dominant conductive heat transfer mechanism requiring very low permeability values (no convection). This assumption is supported by the thermal evidence recorded in the wells and the observed pervasive secondary mineralization both at surface and in the cores that reduced the permeability of the rocks. The period considered is the last 155 kyrs. In case of a still active heat source, 50 to 80 kyr is necessary to reach the well depth; if the intrusion is at cooling stage then the intrusion was active 5-6 kyr ago. A main outcome about the heat source in Acoculco is that the intrusion is believed to be a narrow shape (dyke?) with the top at 2300±400 m depth and a temperature of 850±50°C.

2.2. Structural Geology

The two orthogonal fault systems, one trending NW and the other one trending NE, have been explained by regional tectonic deformation controlled by NW-trending extension (Garcia-Palomo et al., 2018). In that case, the NW-SE faults can be interpreted as transfer faults, partitioning the crust in separated sectors where NW-SE normal faults produced extension. This interpretation would also explain the dominantly right-lateral movement along the NW-SE faults and the dominantly normal movement along the SW-NE trending structures, corresponding to the first kinematic event of the NW-SE trending structures. In this general framework the orientation of the intermediate stress-axis is crucial, as it indicates the preferential direction of the fluid flow where permeability is controlled by fractures (Sibson, 2000), as it is the case of the Acoculco area. It is therefore concluded that the deep geothermal fluids are channeled by the NW-SE structures up to shallow levels and then laterally stored in the damage zones of the dominantly SW-NE trending normal faults.

To investigate the local structures around the deep boreholes foreseen for ES development detailed structural and tectonic survey was carried out in the area. The adopted methodology follows the classical approach of structural geology, based on fieldwork

measurements, mapping and observation of the texture and structures of rock-volumes in key-outcrops. The investigated area is of about 9 km^2. It is characterized by altitudes between 2950 and 2800m and by small valleys in almost flat areas.

The results of the structural survey are shown in Fig.3. The area is dominated by NW-SE trending faults, delimiting crustal sectors where SW-NE normal faults developed. The two boreholes are located in proximity of natural manifestation of CO_2, displayed by bubbling in the local swamps (Figure 4). The direction of bubbling (three aligned emission points) follows the two NW-SE and SW-NE structural trends recognized in the area (Figure 3), thus suggesting a fracture control of their orientation.The geological cross section (Fig.5) was drawn connecting the two wells, of which stratigraphic logs have been published in Lopez-Hernandez et al. (2009). In the geological section, the stratigraphic information is grouped in four main units, in order to highlight the fracture network. observation. Their extension to depth is uncertain, since the fault trace at surface is not always recognizable.

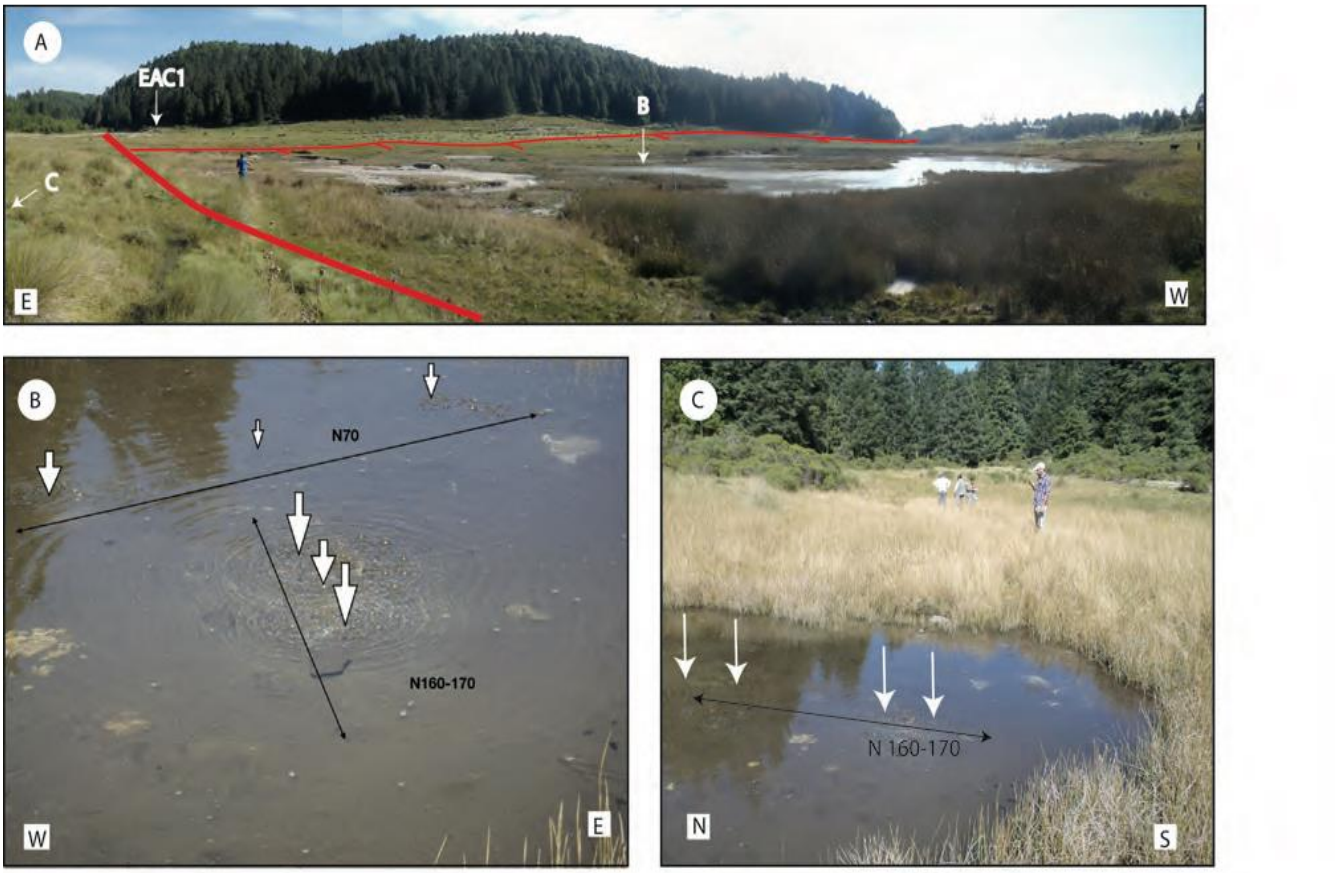

Figure 4: A) Panoramic view of the swamp area where the EAC1 well is located B-C) Examples of the CO2 emission in the water. Bubbling is oriented following the main structural trends recognized in the study area

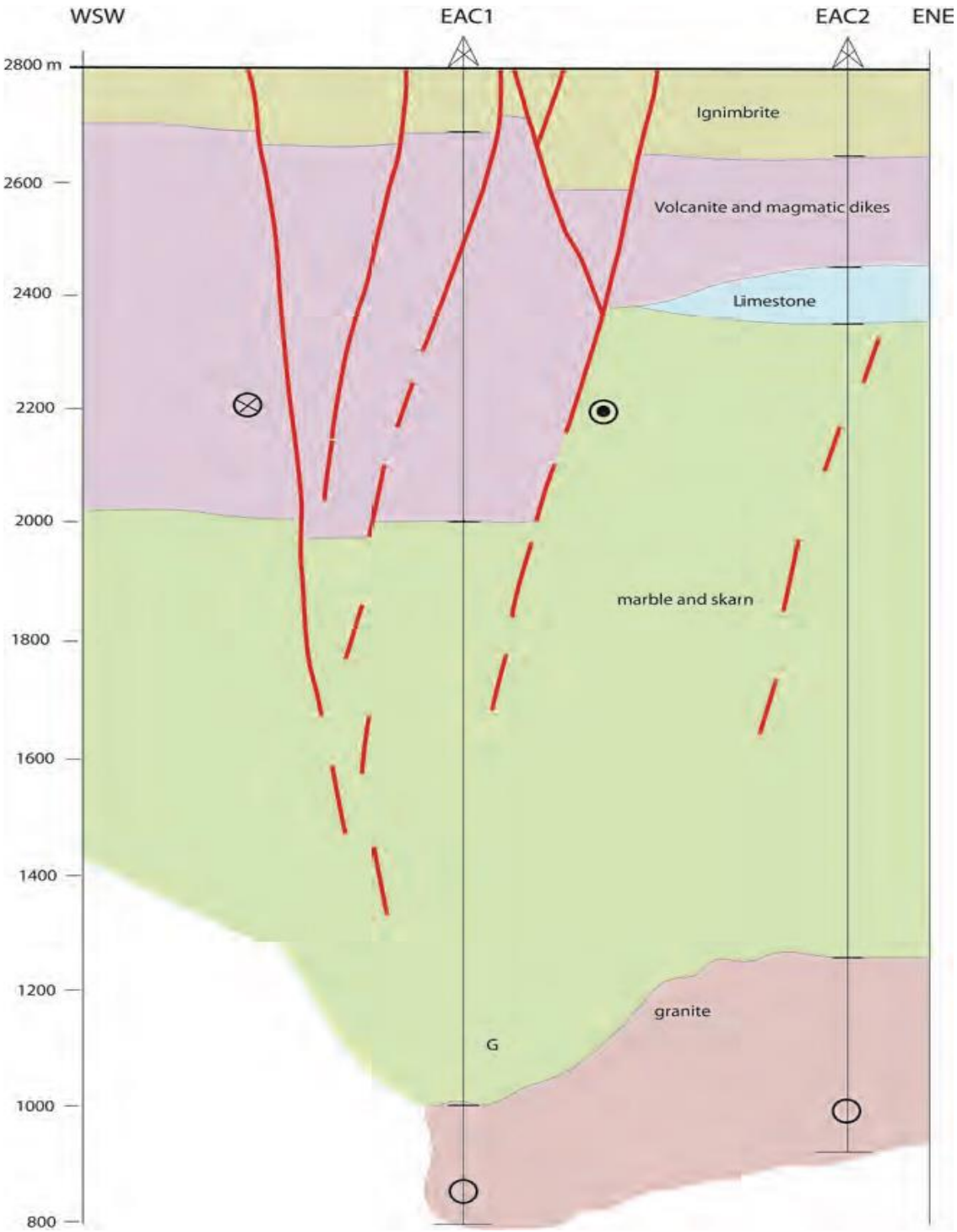

Figure 5: Geological cross section through the study area. For its location, see Figure 3. Borehole stratigraphic logs are from López Hernández et al. (2009)

3. DETECTION OF DEEP STRUCTURES BY GEOPHYSICAL SURVEYS

3.1. Resistivity

A total of 65 TEM/MT sounding pairs were jointly inverted and one MT sounding with no co-located TEM data (Figure 6). Data from Hersir et al. (2020).

The resistivity model based on 1D inversion in the Acoculco survey area exhibits a one-dimensional resistivity structure, as predicted by the dimensionality analyses. The area explored is divided into two areas that can be distinguished from one another, maybe the boundary is a buried fault. The conductive cap becomes thinner close to the western EAC well. It is in this area where the resistive core is the shallowest in a very confined area, suggesting the existence of a zone of geothermal interest.

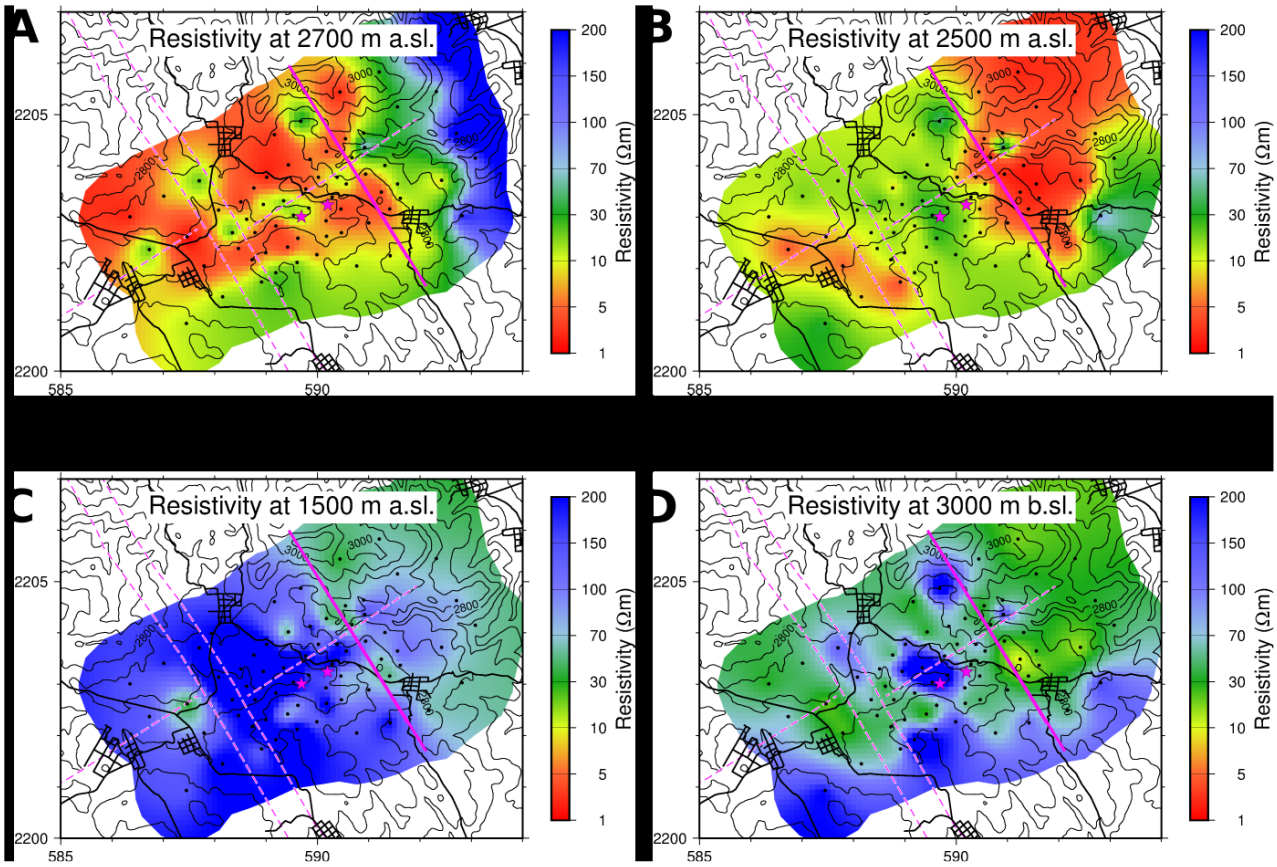

Figure 6: Horizontal cross-sections through the 1D model of the Acoculco area at 2700 meters above sea level (A), 2500 meters above sea level (B), 1500 meters above sea level (C) and 3000 meters below sea level (D). Thick black lines are roads, thin black lines are elevation contours every 50 meters. Pink starts are the locations of the EAC wells, dashed pink lines are major fault lines and thick pink line is the discontinuity as observed from the resistivity data.

3.2. Seismicity

16 stations were deployed in the Acoculco and they were still recording at the time this contribution was submitted. So far, there have been no local earthquakes detected, neither by using automatic detection algorithms nor with manual inspection. There is considerable noise in the data, both tremor and spikes. As far as we know, there is no human activity in the area that may cause this except some mining activities. Whether some of these signals originate in the geothermal reservoir is an open question.

As there was no earthquake recorded in Acoculco area, no travel time tomography can be performed. Only ambient noise could be analyzed. As data are still being acquired, only preliminary results.could be derived.

3.3. Gravity

In Acoculco, a total of 84 gravity stations were deployed in 05/18 in an about 5 x 3 km rectangular grid oriented NE-SW and NW-SE with a typical station distance of 400 m to each other (see the contribution by Cornejo et al., 2020). The quality of gravity measurements is comparably high with about 95.2% of the data revealing a standard deviation ≤ 0.03 mGal. Setting a threshold of 0.05 mGal of maximum standard deviation, 98.8% of the data (83 stations) were used for further evaluation.

Both, residual anomalies and inversion results reveal a high fault control on the gravity and thus the density distribution. The alignment of the majority of the anomalies follows NE-SW and NW-SE trending fault orientations. At reservoir level, areas of high-density anomalies in Acoculco coincide with areas of relatively low-quality geothermal condition. A significant high-density anomaly is observed down to sea level in the area, where the two geothermal wells were drilled. At Los Humeros, the N-S trending secondary

faults in the northern part of the geothermal field also coincide with relatively high-density anomalies, whereas the NE-SW to E-W trending secondary faults are characterized by low-density.

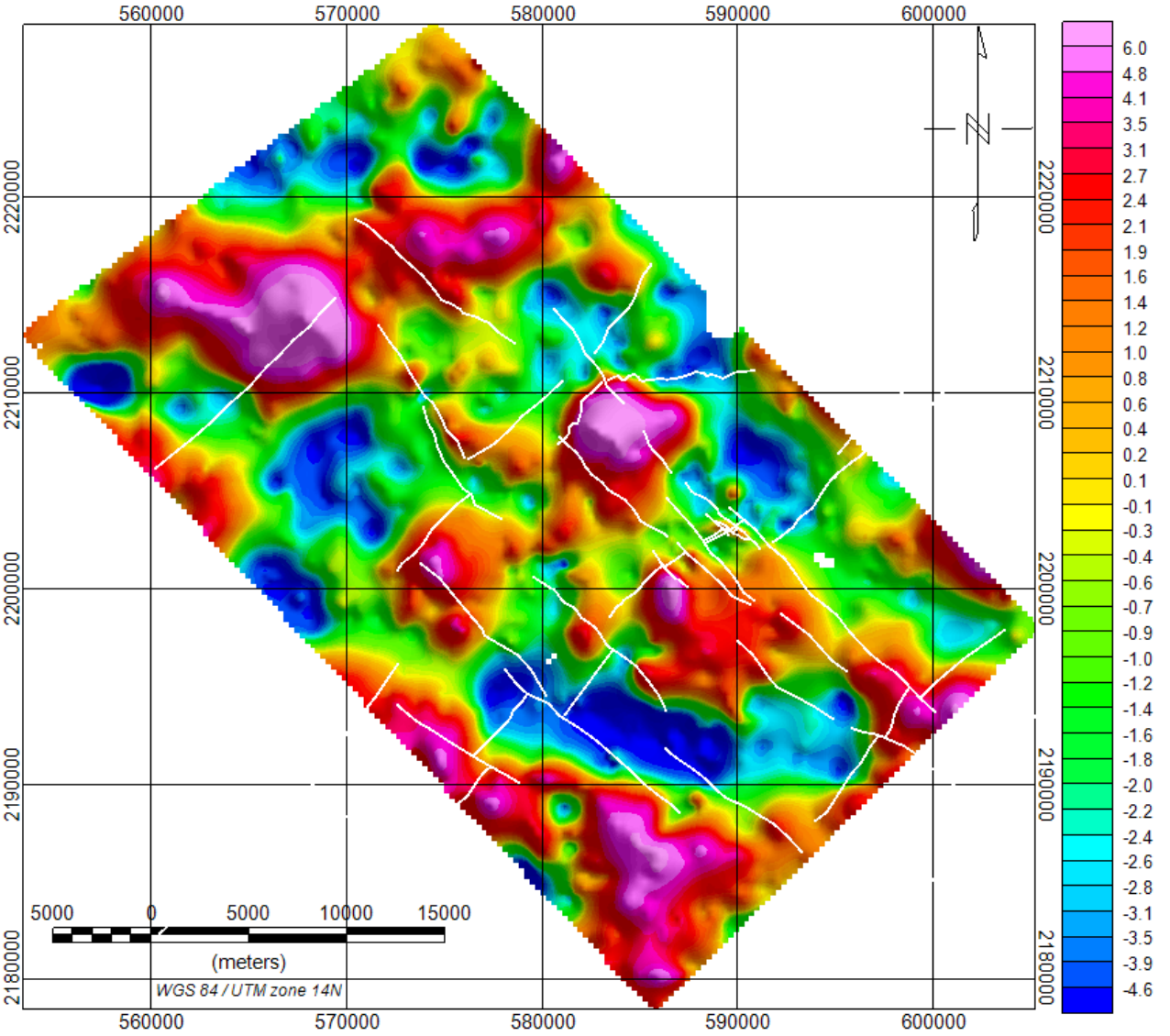

Figure 7: Residual anomaly of the Acoculco caldera area compared to the fault zones

4. RESERVOIR MODEL

Despite the surface manifestations of fault permeability found near the Acoculco wells EAC1 and EAC2, no natural permeability was encountered. Temperature data from EAC-1 and EAC-2 indicated a high temperature and conductive gradient. Low permeability formations were inferred from the negligible circulation losses encountered in both the wells (Lorenzo Pulido et al., 2010). From core sample investigation of well EAC-1, intense hydrothermal alteration and mineral precipitation has been observed, which resulted in fracture self-sealing and inhibition of flow (López-Hernández et al., 2009). Within the limestone and skarn sections, intense intervals of fractures and microfractures filled with calcite and pyrite precipitates have been reported (Lorenzo Pulido et al., 2010). The low permeability of the rocks encountered by EAC-1 is additionally enforced by the negligible intrinsic permeability of granite, marble and skarn and the lack of recent tectonic and magmatic activity (López Hernández et al., 2009). Based on these observations, we consider that the dominant process for heat transport is conduction.

Regionally mineralization has been observed in structures oriented along the NW-SE and NE-SW faults indicating that the faults were active fluid pathways in the past (López-Hernández et al., 2009). Therefore, it can be expected that the dissolution channels and fracture networks existed in the limestone and the skarns which are now sealed as a result of mineralization. These rocks are not a viable geothermal reservoir and have therefore been selected to run test scenarios for EGS development. A static model, taking into account petrophysical properties derived on actual rock samples from the field area (see contribution by Weydt et al., 2020) was developed by Deb et al. (2020) to run simulations of potential production scenarios in an EGS within the granite or skarn units of the Acoculco system.

To better simulate flow in the EGS, a reliable set of hydraulic fracturing data under controlled conditions had to be generated in a laboratory. These data were then used to run different of different numerical hydraulic stimulation design tools (Deb et al., 2020,

Hofmann et al., 2020). The Hydraulic fracturing experiments were analyzed with numerical and analytical means. The numerical analysis required a scaling of the experiments. Scaling the injection rate linearly led to the most accurate model. Additionally, it is crucial to scale the fracture toughness. An approximate solution from the literature was used to perform an analytical assessment of the time-resolved response of the pressure in the experiments. Some of the numerical models compared well with the analytical solution in terms of normalized pressure field and normalized crack length (Parisio et al., 2020).

5. CONCEPTS FOR RESERVOIR DEVELOPMENT AND UTILIZATION

5.1. Stimulation

To assess the feasibility of generating an EGS reservoir at depth in the Acoculco wells, Lepillier et al. (2020) developed a workflow to generate a realistic predictive mechanical model for fracture stimulation from the boreholes. The method uses a combination of reliable data obtained from field work and experimental measurements on mechanical properties of the target rocks, used together to populate a numerical model. The results of these simulations are then evaluated in a finite element method program using a flow model for fractured media. Finally, combining the fracture flow model and the mechanical properties measured in the rock physics laboratory, they propose a workflow to predict the fracture propagation from the borehole and its interaction with the pre-existing fracture network.

Hydraulic stimulation scenarios are proposed by Parisio et al. (2020) and by Hofmann et al. (2020). Taking all the geological data and models, and the geophysical constraints collected during the project, and combining them with the downhole information provided by the CFE, a stimulation concept will be developed in GEMex. This concept will be proposed for validation by the developer.

5.2. Environmental Impact

An extensive survey to identify potentially undesired impacts on the environment, society and economy by the EGS development at Acoculco was performed by Gonzalez et al. (2020). One of the major concerns related to EGS development is related to injection and production induced seismicity. The seismic hazard for the Acoculco has therefore been investigated within the projects. The region of Acoculco seems to be affected by low natural seismicity. It is still compulsory to install a regional seismic network to be able to discriminate the existing natural seismicity, including seismic sources, from any future induced seismicity. Recommendations for the monitoring of EGS systems and for appropriate traffic light systems will be delivered as part of the project

5.3. Public Engagement

To engage with the public of the communities affected by the developments at Acoculco, a communication strategy was proposed that involved, amongst other tolls, information events and unstructured interviews with different stakeholders such as representatives of the different communities, public authorities such as the mayor, an assessor of the environment, or the assessor to agriculture, and representatives of industry, her a director of operations at Los Humeros of the CFE.. In addition, Moreno et al. (2020) performed research to analyze the probable direct and indirect economic impact of the exploitation of the geothermal resource in the communities. For this, a questionnaire was sent to a representative sample of households in each community. The purpose of the approach was to relate the income and expenditure transactions of households, to internal and external factors within the community. This approach serves to identify the impact of external factors on communities, such as the development of infrastructure, and how it is transmitted in the inside and outside of the local economy.

6. CONCLUSION

The numerous coordinated efforts around the Acoculco test site are designed to facilitate EGS development. Of course they cannot compensate for the lack of measured downhole data, especially missing information on the local stress field. Nonetheless, the collected information and data, the well defined rock properties and the detailed analyses and models provide a broad basis for a decision on how and where to plan stimulation procedures. At the end of the GEMex projects (May 2020 in Europe and January 2021 in Mexico), the information available to the developer will allow a well founded decision on the development of the EGS at Acoculco.

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