Updating the 3D Geomodels of Los Humeros and Acoculco Geothermal Systems (Mexico) - H2020 GEMex Project

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ABSTRACT

The European-Mexican geothermal GEMex project aims at developing geothermal energy in the easternmost region of the Trans-Mexican Volcanic Belt. Two sites under development by the Comisión Federal de Electricidad (Mexican National Power Company) are investigated to assess possible superhot resources and to develop an Enhanced Geothermal System, respectively in Los Humeros and Acoculco.

European and Mexican partners constructed preliminary 3D geological models in a collaborative way. They were based on data available at the beginning of the project, including geological maps, cross-sections and well logs. To complement the existing knowledge, geological and geochemical field campaigns were conducted. Data from these surveys have been used to update the preliminary models of both sites. Geophysical surveys are on-going.

The results of this update were dedicated to improve the overall interpretation of the geothermal system in Los Humeros and Acoculco. They were also used as input for further simulations based on the geometry of the updated geomodels. The update presented in this paper is an intermediate step previous than further integration. The last phase of the geomodelling process will consist in integrating geophysical information to strengthen the geothermal interpretation of both sites.

1. INTRODUCTION

This paper presents a transitional step in the acquisition of knowledge regarding Los Humeros active geothermal field and Acoculco geothermal prospect (Mexico), studied under the scope of the GEMex project. The work is based on the building of geomodels that gather data and information to share a common interpretation of both areas. This transitional step consists in the update of the preliminary models, constructed at the beginning of the project (Calcagno et al., 2018), mainly using new geological data from the field, new wells descriptions, and new interpretations.

1.1 The GEMex project

GEMex is a European Union's Horizon 2020 research and innovation programme project (2016-2020) gathering 24 European partners in collaboration with a nine-partners Mexican consortium. It aims at developing Enhanced Geothermal Systems (EGS) and SuperHot Geothermal Systems (SHGS) by designing reliable, efficient, and replicable methodologies. To reach this goal, GEMex deploys a comprehensive range of investigations: geological and geothermal context understanding, deep structures detection, reservoir characterization, and concepts for EGS and SHGS development including a socio-economic approach. More information about the project structure and contents can be found in Jolie et al. (2018) and www.gemex-h2020.eu.

An important pillar of the GEMex ambition is to develop coherent, comprehensive, and reliable 3D GeoModels to: (a) gather and place data and information from various disciplines, (b) serve as reference for further computations and simulations, (c) help to understand the geothermal systems. In that scope, 3D preliminary models are constructed to give a coherent geological interpretation using the existing state of the art.

Two sites are dedicated to GEMex as the most representative examples of the SHGS and EGS: Los Humeros and Acoculco, respectively, both located East of Mexico City (Fig. 1). They belong to the Trans-Mexican Volcanic Belt (TMVB) a continental volcanic arc that turns across central Mexico, where the volcanic activity is reported to have started about 16 Ma ago (Ferrari et al, 1999) and has continued nowadays with some currently active volcanoes (e.g. Popocatépetl, Colima). These young volcanic processes make the TMVB a favourable area for active geothermal fields.

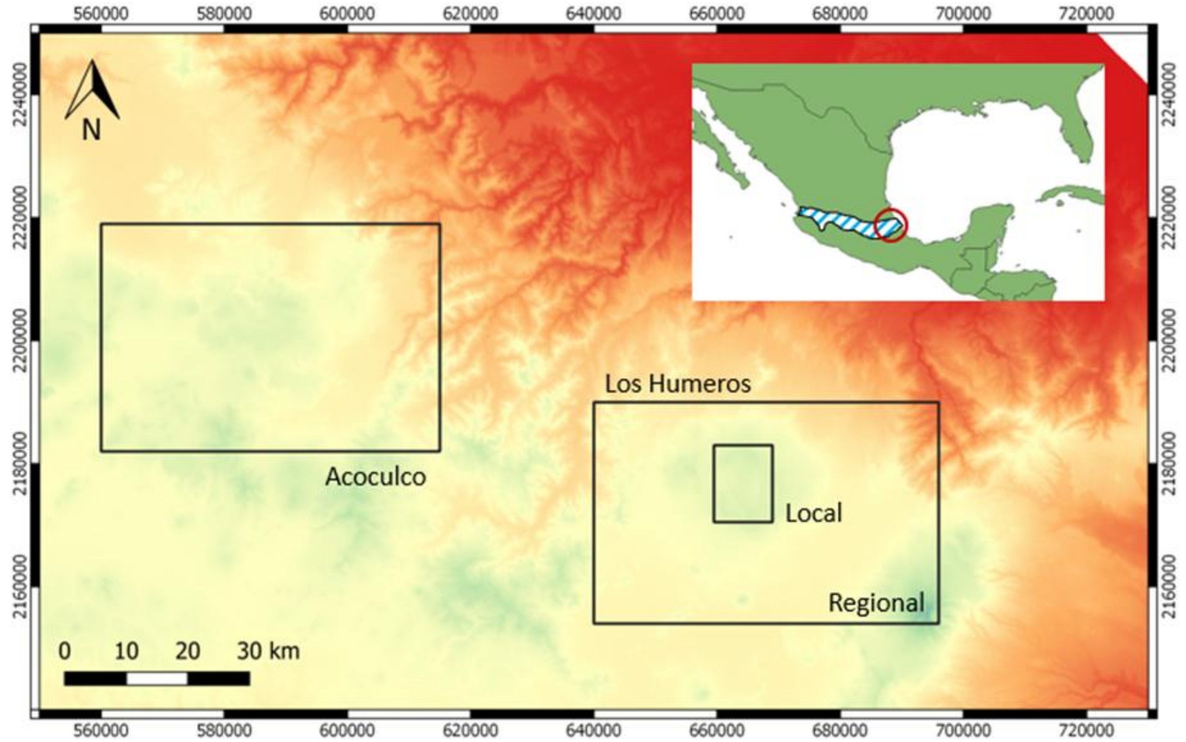

Figure 1: Location of the Los Humeros regional and local areas, and Acoculco area, east of Mexico City in the Trans-Mexican Volcanic Belt (dashed blue area). Area locations are shown on the 90m Digital Elevation Model SRTM. Coordinate system is WGS84/UTM zone 14N. Figure taken from Calcagno et al. (2018).

1.2 Los Humeros

Los Humeros is one of the five geothermal fields currently in operation in Mexico, at an average elevation of 2800 masl. The field has been developed inside the Los Humeros caldera, which is a roughly circular caldera structure of ~18-20 km diameter, with an inner and younger caldera, known as Los Potreros, with 5-8 km in diameter. The first collapse structure of Los Humeros was formed ~165 ka and the second around 70 ka, according to recent geochronological dates by Carrasco-Núñez et al. (2018).

In Los Humeros, geothermal energy has been exploited since the 1990s by the Comisión Federal de Electricidad (CFE), when the first 5 MW power unit started operating. Electricity is currently produced from twenty-five production wells, mainly located in the Los Potreros caldera domain, whose production is used by six power units with a combined installed capacity of 94 MW (Romo-Jones et al., 2018). Geological information from only sixteen wells was available for the preliminary study (Calcagno et al., 2018), and from a total of 52 wells for the next stage that is described here. The maximum temperature measured at approximately 2.5 km depth is around 400°C, but no geothermal fluids at this temperature are currently exploited by CFE. Los Humeros today is a conventional hydrothermal system, with locally super-hot fluids underground. The aim of GEMex is to obtain a better understanding of the geothermal field, especially of the location of these super-hot fluids and the way to exploit them.

The geothermal target for superhot fluids is assumed to be mostly located in the upper portions of the underlying basement, composed of limestones, mainly granitic intrusive rocks and metamorphic rocks as skarn, marble and hornfels. The deepest parts of the pre-caldera volcanic rocks (mainly hornblende andesites), may host also superhot fluids, in all the cases the permeability is basically secondary due to faults and fractures of the two main structural systems recognized, roughly of NW-SE and NE-SW general orientations.

1.3 Acoculco

The Acoculco area is also located at the eastern portion of the TMVB, where three important structural systems intersect each other: the NE–SW Tenochtitlan-Apan, the NW–SE Taxco-San Miguel de Allende, and the E-W Chapala-Tula fault systems, within a regional extensional regime (García-Palomo et al., 2017). The complex rests upon a basement formed by granite, Cretaceous limestone and marble, the Zacatlán-Chignahuapan basalt plateau and Miocene pre-caldera domes and lavas (13–3 Ma; Avellán et al., 2018).

The Acoculco Caldera was formed 2.7 Ma ago, with an explosive eruption that produced the Acoculco andesitic ignimbrite, with a volume of 127 km^3. 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 60 ka, 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-Tezontepec Volcanic Field (García-Palomo et al., 2017; Sosa-Ceballos et al., 2018; Avellán et al., 2018).

CFE has the exploration permit in the area, and has drilled two exploratory wells: the EAC-1 in 1995 and the 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 fluids (Lorenzo-Pulido et al., 2010), and so the zone seems susceptible to be developed by EGS technologies. 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. In the well EAC-1 it was found an aplitic dyke dated 0.183 ± 0.036 Ma (Sosa-Ceballos et al., 2018). 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 (Sosa-Ceballos et al., 2018).

2. METHODOLOGY

The construction of the geomodels of Los Humeros and Acoculco was conducted in a team work gathering European and Mexican colleagues. A loop was established through three main steps under the supervision of a referent geologist: (i) data & knowledge, (ii) modelling, (iii) validation. The shapes of the models were discussed at the team level. Then revised data and knowledge was input in a new loop until the models are fully validated by the partners. The close connection between EU and MX was crucial in this process. Regular meetings were organized to allow the interaction as much as possible. These tele-workshops were organized almost on a weekly basis to share documents, data, interpretation in cross-sections and boreholes, and to discuss the interpretation of the geological objects in 3D.

As for the preliminary models (Calcagno et al., 2018), the update was conducted in an interdisciplinary manner. The overall goal is to complete 3D geomodels representing a joint interpretation implemented interactively by geologists, geophysicists and geochemists rather than a conglomerate of distinct outcomes. The scientists compare, connect, discuss, and adapt their own interpretations in a common geometrical framework for a mutual result. This approach allows a better understanding of the geothermal systems by integrating complementary knowledge in an interactive process. It makes the interpretation co-constructed, more robust, and reliable

To construct the geometry of the 3D geomodels, the interpolation of the data is performed using a co-kriging geostatistical method where 3D points located on the geological interface to be modelled and 3D vectors showing the dip of this geological interface are used at the same time (Lajaunie et al., 1997). The result of the interpolation is a 3D scalar potential field where isovalues represent geological interfaces. A geological pile describes the chronological and topological relations between the geological formations. It allows automatic management of the geological boundaries (gradual or erosional). The links between faults and formations are also described in the modelling process, to compute automatically how faults affect formations. When faults interact with each other, they are combined in a fault network for describing their relations. This methodology is fully described in Calcagno et al. (2008) and implemented in the 3D GeoModeller package[(1)].

3. STATE OF THE ART OF THE LOS HUMEROS AND ACOCULCO GEOMODELS

This section gives an overview of the preliminary geological models constructed in the first period of the GEMex project. In Los Humeros, a regional and a local model were set up. In Acoculco, a regional model was constructed. For a detailed description of this work and for a report of the initial stage of modelling, please refer to Calcagno et al. (2018).

3.1 Los Humeros

3.1.1. Data

From a geothermal standpoint, the geological formations of the Los Humeros area consist of four groups. In addition to the basement (first group), it is important to separate the volcanic formations into three distinct groups: pre-caldera, caldera, and post-caldera. For a more detailed interpretation of the geothermal system, these four are split into nine units: basement, basal pre-caldera, intermediate pre-caldera, upper pre-caldera, Los Humeros caldera, intermediate caldera, Los Potreros caldera, post-caldera, and undefined pyroclastic deposits.

The geological map from Carrasco-Núñez et al. (2017b) and the two geological sections from Carrasco-Núñez et al. (2017a) and Norini et al. (2015) are the main references to set up the geomodels. In addition, the CFE has provided geological description of sixteen wells. Considering the lack of information available on their geometry, the wells were considered as vertical.

A selection of the main faults to be modelled at the regional and local scales was done. The maximum vertical extension of the faults was set to approximately four kilometres (below ground level), assuming that such a depth corresponds to the brittle-ductile transition, on the basis of the local geothermal gradient (100°C/km, López-Hernández et al., 2009) in a quartz-dominated crust. For the modelling process, the geological formations are described into four groups and nine units at the regional and the local scales, respectively.

The Digital Elevation Model (DEM) is provided by INEGI (Instituto Nacional de Estadística y Geografía).

3.1.2. Regional model

The geomodel at regional scale (56 km x 36 km x 12 km, i.e. down to 7 km below sea level) presents four geological groups: basement, pre-caldera rocks, rocks from the caldera, and post-caldera rocks (Fig. 2). The geological map (Carrasco-Núñez, 2017b) and sections (Carrasco-Núñez et al., 2017a; Norini et al., 2015) were re-interpreted accordingly. The geological description of the wells made it possible to match all the information with the four groups selected for the modelling of the regional model.

Eleven complementary cross sections were used to constrain the regional model. They were drawn according to the two references cross-sections cited above to ensure a coherent interpretation, for instance in terms of geological formations thickness.

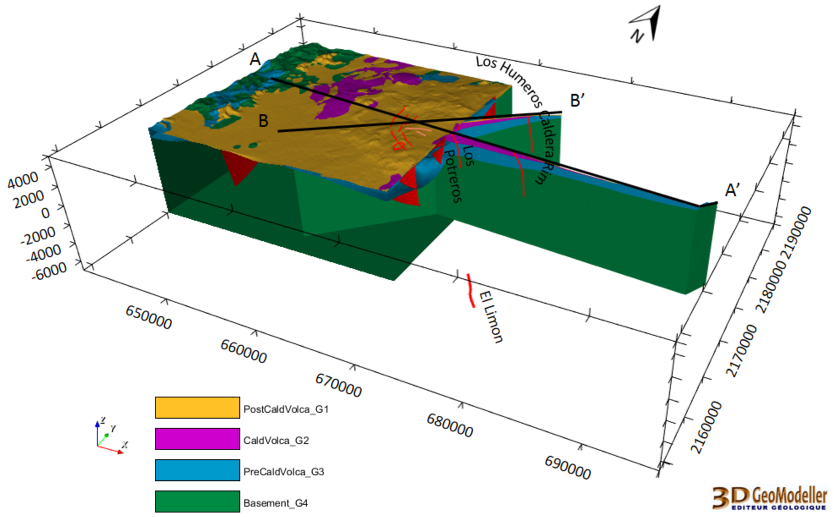

Figure 2. The Los Humeros regional geomodel of the four geological groups listed at legend (bottom left). Coordinate system is WGS84/UTM zone 14N (after Calcagno et al., 2018).

3.1.3 Local model

The geomodel at local scale (9.5 km x 12.5 km x 12 km, i.e. down to 7 km below sea level) presents nine units: basement, basal pre-caldera, intermediate pre-caldera, upper pre-caldera, Los Humeros caldera, Intermediate caldera, Los Potreros caldera, post-caldera, and undefined pyroclastic rocks (Fig. 3). One complementary cross section was used to constrain the local model.

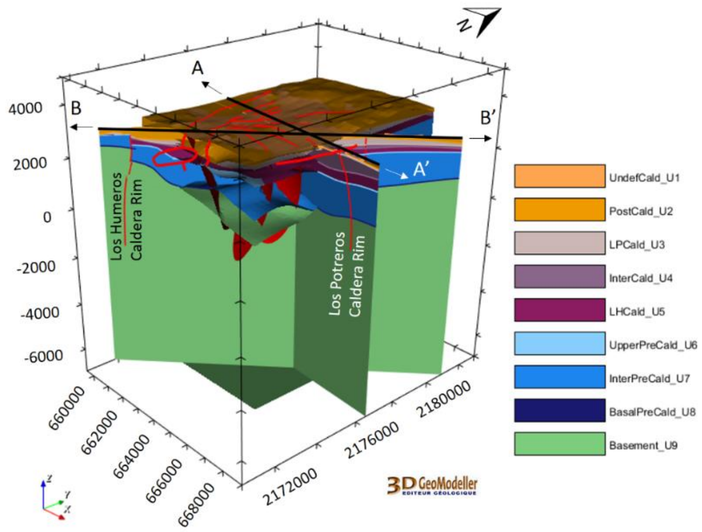

Figure 3. The Los Humeros local geomodel of the nine geological units listed on the right hand side. Fault traces are in red. Coordinate system is WGS84/UTM zone 14N (after Calcagno et al., 2018).

3.2 Acoculco

3.2.1. Data

The geological map from Avellán et al. (2018) is the main reference to set up the geomodels. In addition, the 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). Results from Fieldwork, done by a joint EU-MEX team, were also considered.

A selection of the main faults to be modelled was done. As for the Los Humeros area, a maximum depth of four kilometres (below ground level) was accepted for the faults (see 3.1.1). For the modelling process, the geological formations are described as five groups listed below.

The Digital Elevation Model (DEM) is provided by INEGI (Instituto Nacional de Estadística y Geografía).

3.2.2. Regional model

The geomodel at regional scale (56 km x 37 km x 10.5 km, i.e. down to 7 km below sea level) presents five geological groups: basement, granite, skarns, limestones, and volcanics (Fig. 4). The geological map (Avellán et al., 2018) was re-interpreted accordingly.

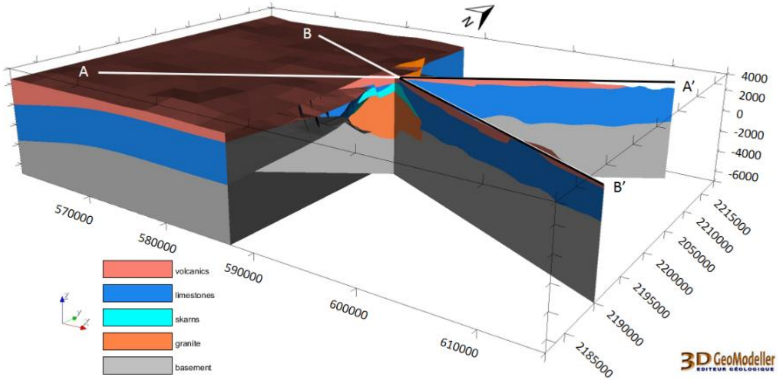

Figure 4. The Acoculco regional geomodel with the five geological groups listed at bottom. Coordinate system is WGS84/UTM zone 14N (after Calcagno et al., 2018).

Two geological cross-sections were drawn to interpret the deep structures, serving as reference for the 3D 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.

4. UPDATE OF THE LOS HUMEROS AND ACOCULCO GEOMODELS

The methodology used to update the geomodels in Los Humeros and Acoculco was the same than the one deployed for the preliminary models (see section 2. and Calcagno et al., 2018). The update was mainly fed by new data added to, or replacing, the ones used for the preliminary models (see section 3.). New interpretations and way of describing the modelled bodies were also used for the update.

4.1 Los Humeros

In Los Humeros, the update focussed on the local scale area (see Fig. 1).

4.1.1 New data and interpretations

The Los Humeros Volcanic Complex (LHVC) basement underwent two main tectonic events: first, the Cretaceous to Paleogene Mexican Fold and Thrust Belt (MFTB) compressional orogeny, under a NE–SW-oriented maximum horizontal stress ($\sigma 1$), generated NW–SE-trending thrusts and a major ramp anticline below the LHVC. Second, a minor Neogene-Quaternary extensional tectonic phase, characterised by NW–SE-oriented minimum horizontal stress ($\sigma 3$) and NE-SW-trending maximum horizontal stress ($\sigma 2$), mainly produced discontinuous ca. NE–striking normal faults.

The results of the kinematic analysis of the MFTB compressive structures and younger normal faults indicates that the direction of the maximum horizontal stress (first $\sigma 1$ and then $\sigma 2$), exerting a control on the direction of magmatic intrusions and transport of fluids in the crust, maintained a constant NE–SW trend during time, suggesting a permutation of the principal stress axis.

The preferential trends of the mafic intrusions in the pre-volcanic sedimentary basement suggest that fluids in the crust moved along two orthogonal preferential directions, which are parallel to (1) NW–SE-trending weak planes, coinciding with sedimentary bedding and inherited MFTB structures (i.e., folds and faults), and (2) NE–SW-trending maximum horizontal stress and normal faults. In particular, the same directions may also control the flow and recharge of groundwater.

The structural study of the LHVC indicates that the structure of the caldera complex, the local stress field and the occurrence of hydrothermal fluids in the geothermal reservoir result from the interplay among the heat source (inferred magma intrusion), the recent ground faulting (caldera resurgence) and intense post-calderas volcanic activity.

On the whole, the mainly dip-slip displacements (both normal and reverse) determined for the NNW-SSE, N-S, NE-SW and E-W prominent fault strands in the Los Potreros caldera define semi-radial displacement vectors centred around the south-western/central portion of the caldera floor and generated by the local radial stress field of magmatic origin. The change in strike of induced fractures along well H43 observed by Formation Micro-Imaging, i.e. resistivity log in geothermal well, and the corresponding change in maximum horizontal stress trend, suggests a possible pressure source of magmatic origin below the centre of the Los Potreros caldera, generating the local radial stress field and the doming of the caldera floor.

The recent/active volcanotectonic deformations, induced by the active resurgence of the caldera, are inferred to control the secondary permeability within the Los Humeros geothermal field and should be regarded as the most important targets for geothermal exploration. The geometry of these deformation features is partly inherited from pre-existing, regional tectonic structures (Norini et al., accepted).

The geological formations were described in four groups and nine units, such as for the preliminary models. Nevertheless, the structure of the third group (G3) gathering the pre-caldera units was revised during the update process. Initially, G3 was split in basal, intermediate, and upper units. To be more relevant regarding the rocks representative of potential reservoir, it was decided to include a package of undifferentiated rocks that was previously identified by the CFE in the lithological columns of its wells and classified as lithic, vitreous or crystalline tuffs (Tobas Líticas, Tobas Vítreas, Tobas Cristalinas), among other denominations. These rocks are usually located between the upper pyroxene andesites (AP) and the lower hornblende andesites (AH), see Figure 5. The actual composition of the rocks of this package is practically impossible to define with the present information, due to its almost complete alteration, and does not have an outcropping unit to whom it can be correlated. However, it has been included in the model (Unit U7) mainly to facilitate reservoir simulation computation based on the geomodel, because its petrophysical properties are quite different of the andesitic packages.

Group	Unit	Rock	Age (Ma)
G1 Post-caldera	U1 Undefined pyroclastic	Tuff, pumice and some alluvium	< 0.003
	U2 Post-caldera	Rhyodacite, andesite, basaltic andesite, and olivine basalt lava flows	0.003-0.050
G2 Caldera	U3 Los Potreros caldera	Rhyodacitic flows and Zaragoza ignimbrite	0.069
	U4 Intermediate caldera	Faby tuff with andesitic-dacitic lava flows	0.07
		Rhyolitic and obsidian domes	0.074
	U5 Los Humeros caldera	Mainly composed of Xaltipan ignimbrite with minor andesitic and rhyolitic lava	0.165
G3 Pre-caldera	U6 Upper pre-caldera	Pyroxene andesites (Teziutlán Andesites) with mafic andesites in the basal part and/or dacites and rhyolites	1.46-2.61
	U7 Intermediate pre-caldera	Undifferentiated Rocks: Package of rocks highly altered whose origin has not been defined so far	2.62-8.8
	U8 Basal pre-caldera	Hornblende andesites (Alseseca Andesites & Cerro Grande), and dacites	8.9-10.5
G4 Basement	U9 Basement	Middle Miocene granite	15.12
		Cretacic limestone, shale and minor flint	~140
		Jurassic limestone and shale	~190
		Paleozoic granite and schist (Teziutlán Massif)	>251

Figure 5. Updated description of the geological formations modelled at Los Humeros where G3's units have been revised after the preliminary models.

The preliminary models of Los Humeros were constructed using sixteen wells considered as vertical (see 3.1.1). In addition to these wells, the CFE provided records for forty more wells, leading to fifty-six wells used to update the Los Humeros area. Among them, ten are deviated wells. The drilling parameters given by the CFE were used to compute the geometry of their deviations and to integrate them at proper location in 3D. The wells presented in Figure 6 were described according to the updated geological description (Fig. 5) and taken into account in the modelling.

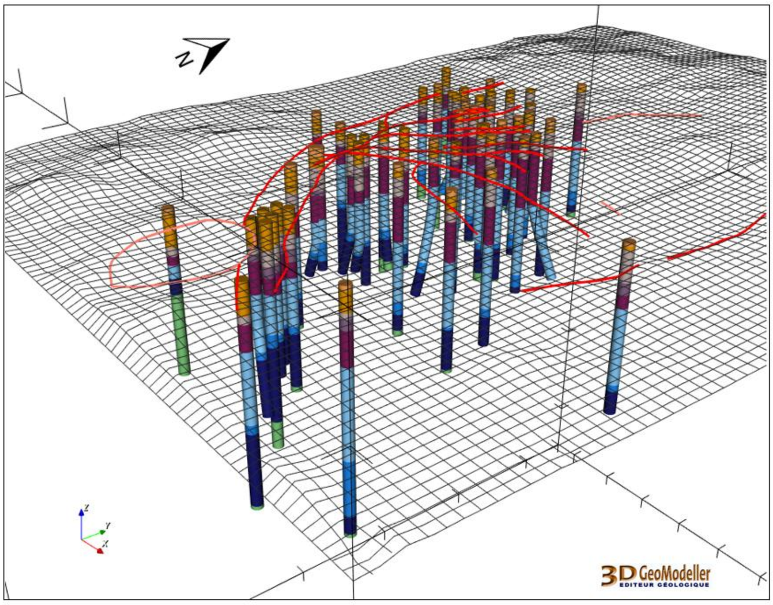

Figure 6. Fifty-six wells were used for the update of the Los Humeros local model. Ten of them are deviated. They are described according to the new geological description presented in Figure 5. DEM is displayed as a grid including the fault network traces (see Fig. 7).

4.1.2 Local model

The fault model was set up before integrating the geological formations. The update of the structures inside the Los Potreros caldera consisted in a review of the faults modelled at the preliminary stage in the light of the new fieldwork described in 4.1.1. Most of the preliminary faults were re-investigated, especially regarding their traces and dips. Only four faults have kept their preliminary geometry: Antigua, Las Lomas, Pedernal, and the Mastaloya crater. On top of that, four new faults, Fault 1 to Fault 4, were identified on the field (Norini et al., accepted) and integrated in the local model. Figure 7 presents the updated fault model of Los Humeros at the local scale.

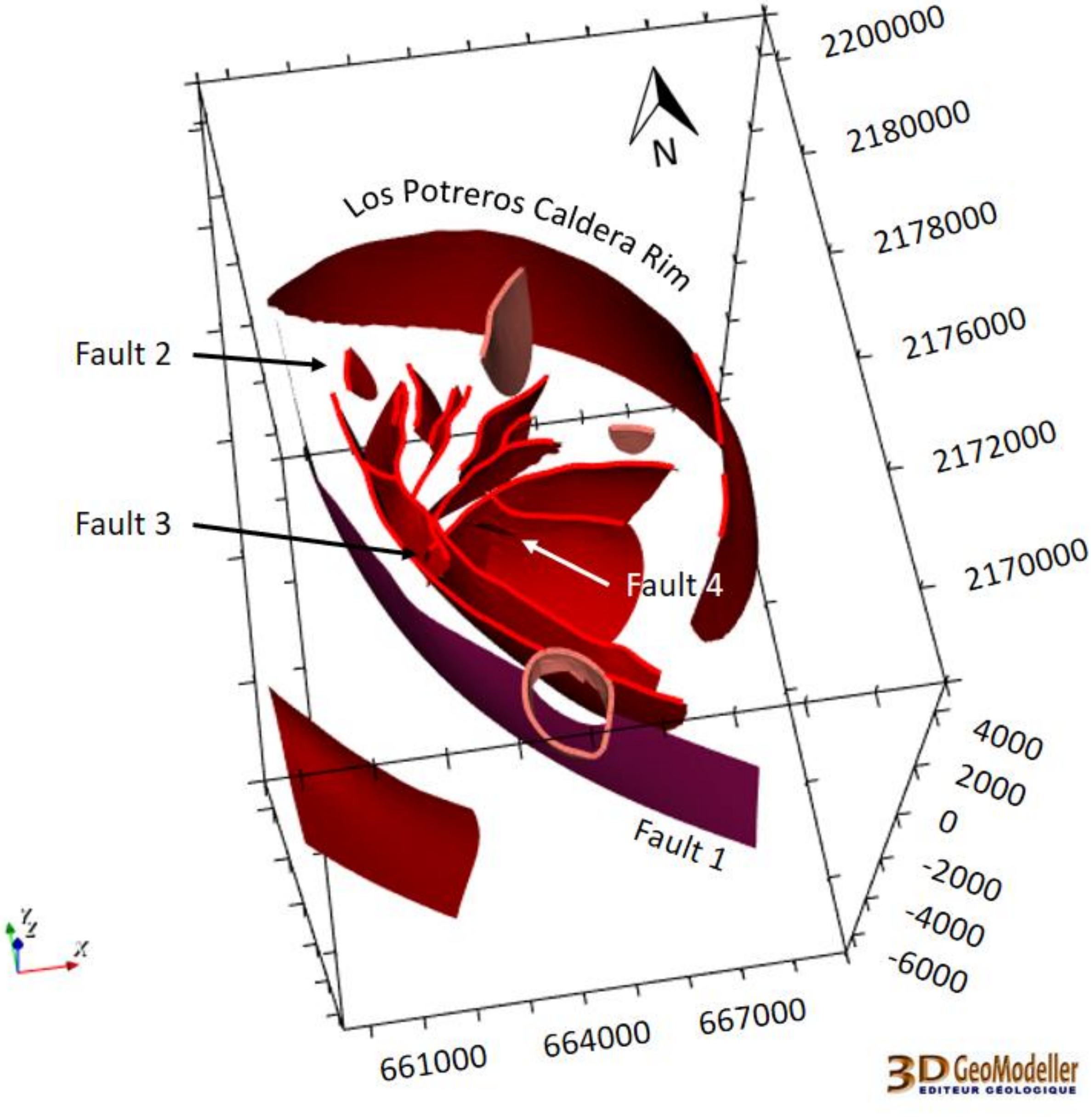

Figure 7. New fieldwork data led to the update of almost all the faults of the local model of Los Humeros and to the addition of Fault 1 to Fault 4. Coordinate system is WGS84/UTM zone 14N.

The second phase of the update process after the completion of the fault model consisted in reworking the geological units. This work was based on two main pillars. The first one was a new description of the pre-caldera geological units, and the second one was the integration of geological columns from forty more wells (see 4.1.1). A new interpretation of the nine units, coherent in 3D, is proposed in agreement with the geological description of the wells (Fig. 6). The updated geomodel at the local scale is presented in Figure 8, including the updated faults (Fig. 7).

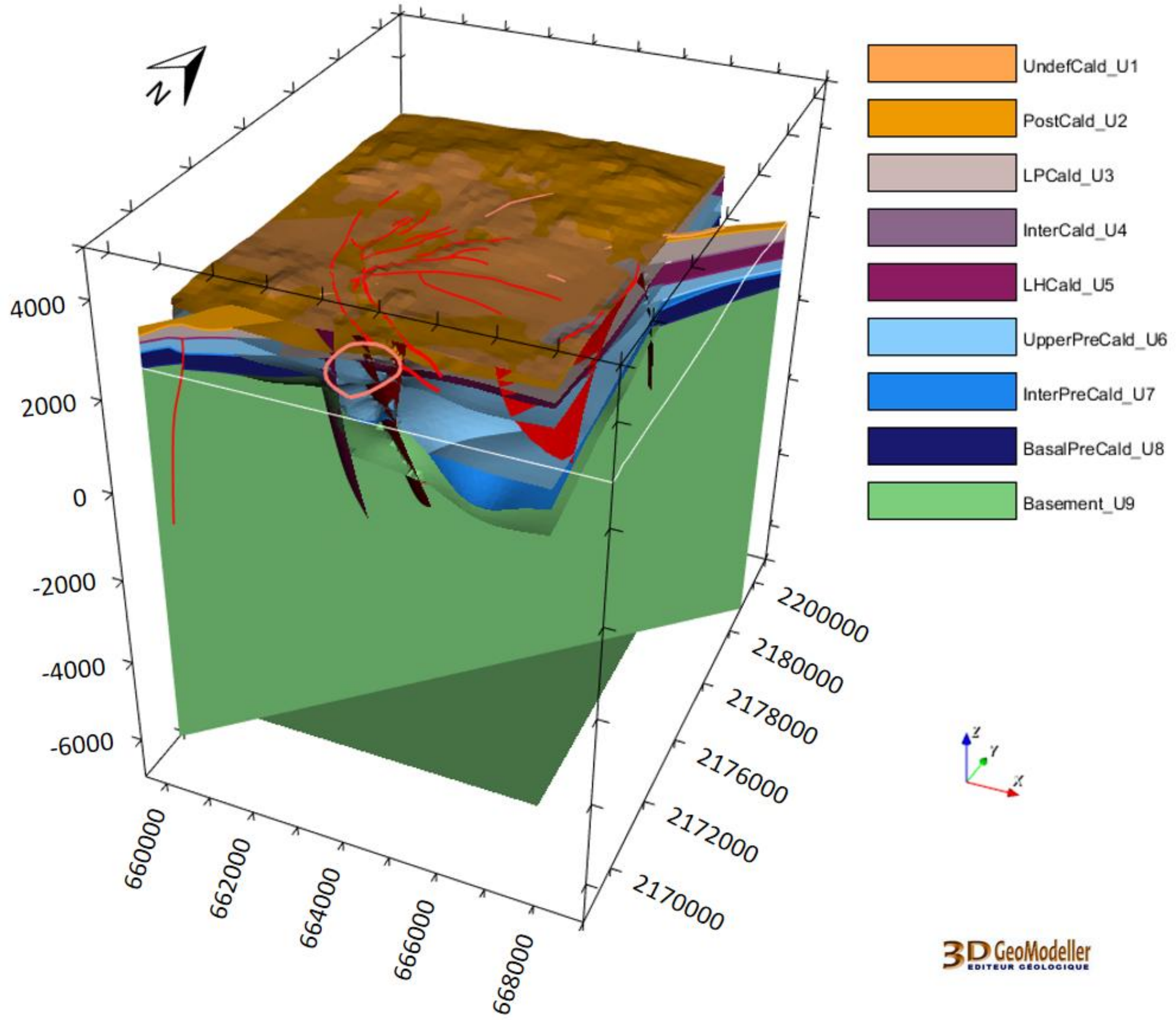

Figure 8. The 3D geomodel of Los Humeros updated at the local scale. It includes the updated faults (Fig. 7) and nine geological units listed on the right hand side (see also Fig. 5). Coordinate system is WGS84/UTM zone 14N.

4.2 Acoculco

The Acoculco regional model (see Fig. 1) was updated using new insights developed after the preliminary phase (Calcagno et al., 2018).

4.2.1 New data and interpretations

As previously mentioned, underground data to constrain the geomodelling process are limited to the two boreholes drilled by the CFE in the study area (López-Hernández et al., 2009). By this, the main data source for the model is from the fieldwork, carried on by a joint EU-MEX group since the beginning of the GEMex project.

The geological map from Avellán et al. (2018) has been updated (Fig. 9): apart from the caldera faults, which didn't change from the preliminary model (Calcagno et al., 2018), the location of faults was refined according to the new outcomes from the fieldwork. The main changes affected the NNW-SSE fault systems: field observations pointed out the occurrence of many individual fault segments, mainly oriented NNW-SSE, thus defining two main brittle corridors, where permeability is reasonably increased. In order to highlight this new outcome, the updated map reports stripes described as 'damage zones' 500-600m width.

Near the Acoculco village (i.e. in the west and east side) two shallow hydrothermal alteration zones were recognised. The two zones show the typical hydrothermal silica-sinter alteration that however don't affect the possible deeper EGS reservoir of Acoculco.

The geological cross-sections used as reference were consequently modified and used as main constraints for the model.

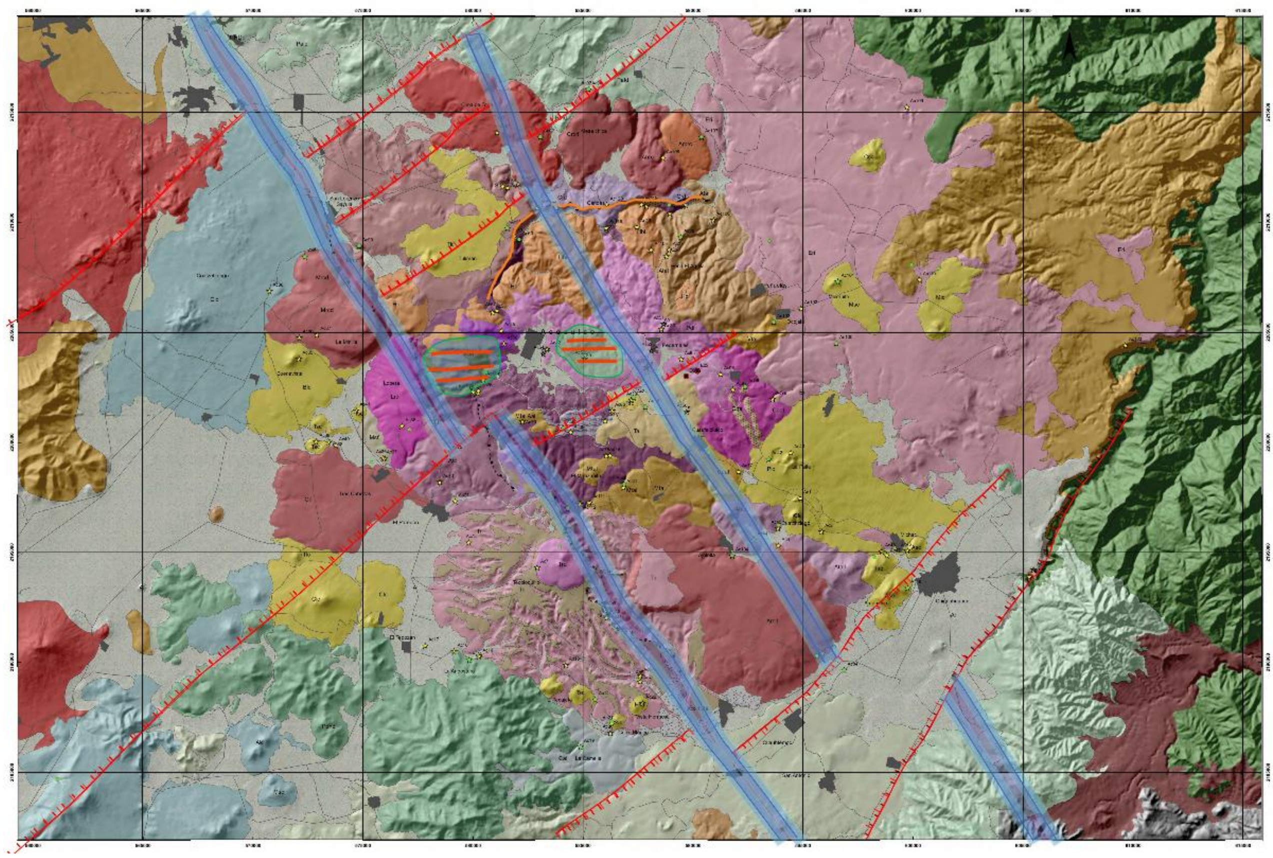

Figure 9. The updated geological map (modified after Avellan et al. 2019). The blue stripes represent the 'damage' zones, mainly including NNW-SSE striking fault segments. Differently, the SW-NE striking normal faults are indicated in red. In orange, the caldera fault traces. The two green with horizontal red lines showed two superficial alteration zones with a very shallow influencing.

4.1.2 Regional model

The new geological map of the area was firstly georeferenced in Geomodeller in order to update the new structural framework. Only the normal faults in the Chignahuapan structural depression (in the southeastern mapped area) and the caldera faults did not change their locations (Fig.9).

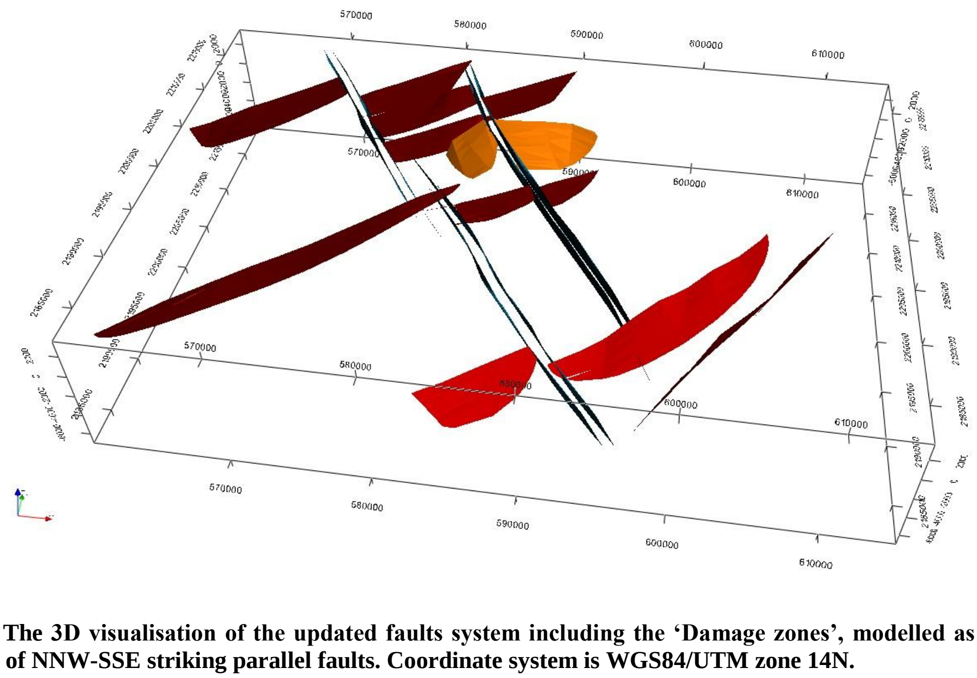

Figure 10. The 3D visualisation of the updated faults system including the 'Damage zones', modelled as delimited by two sets of NNW-SSE striking parallel faults. Coordinate system is WGS84/UTM zone 14N.

In order to model the damage zones, the rock volume between the stripe boundaries is limited by two parallel faults. In agreement with this conceptualisation, the damage zones are now reported. Regarding the other faults, all their lengths and dips were checked and modified according to the geologists' observations, when necessary. Similarly to the preliminary model (Calcagno et al., 2018), the vertical influence of all the faults was maintained down to 4 km, according to the thermal gradient recorded in the area. The updated fault model is presented in Figure 10.

The updated model is still based on the geological pile adopted in the previous version (Calcagno et al., 2018), consisting, from top to bottom, in: i) volcanites (i.e., pre, syn, post-caldera) grouped out with the extra caldera and alluvial units; ii) limestones (cropping out in eastern part of the geological map and reported in the two CFE EAC1 and EAC2 boreholes drilled in the area) that locally include marbles; iii) skarns (observed in the two boreholes); iv) granite, consisting in an old, probably fractured, cold tertiary granite, later crosscut by younger magmatic events (183±36 Ky: Sosa-Ceballos et al., 2018), hosted in the limestone and in the (v) basement, mainly made up of Paleozoic phyllites (Fig.11).

Group	Rock	Age
Volcanites (pre-syn-late/post caldera volcanites plus extra caldera and alluvional units)	Ignimbrites, dacites, rhyodacites, andesite	< 12.7 +/- 0.6 Ma
Limestones	Limestones, marbles, hornfels	Cretaceous
Skarns	Limestone skarns	Cretaceous
Granite	Hornblende granite and microgranite	Mid-Miocene
Basement	Phyllites	Paleozoic

Figure 11. Description of the geological pile used for Acoculco (Lopez-Hernandez et al., 2009; Polido et al., 2010; Sosa-Ceballos et al., 2018; Avellán et al., 2019).

The new faults systems, the geological pile and the updated geological cross-sections were used to set up the link among the faults and their relationship with the group of formations in the 3D Geomodeller environment as needed steps to provide new interpretation and hence a new 3D geological model version.

Figure 12 presents the updated geomodel at the regional scale.

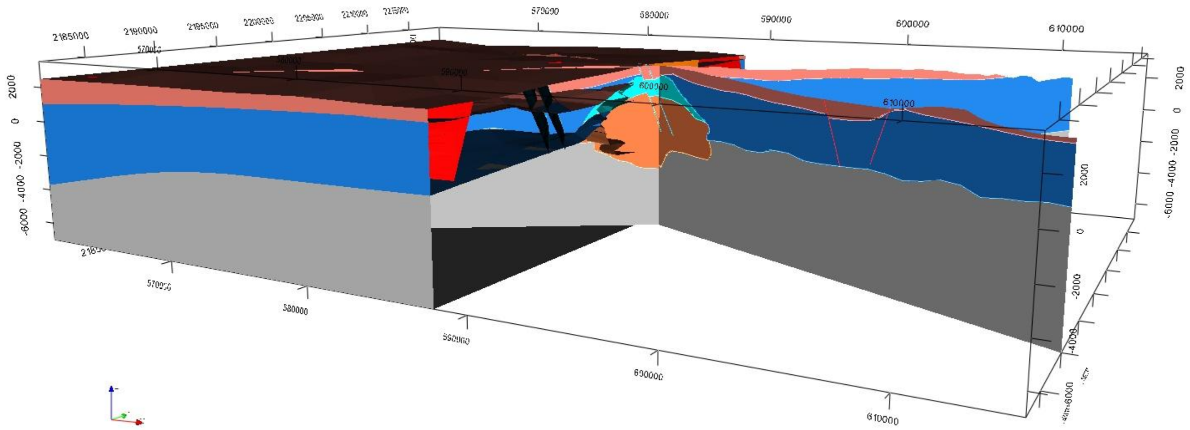

Figure 12. The updated regional 3D geomodel of Acoculco with the new faults and the 'Damage zones'. Coordinate system is WGS84/UTM zone 14N.

5. CONCLUSIONS

In the scope of the GEMex project, the preliminary 3D geomodel of Los Humeros at local scale, and the one of Acoculco at regional were revisited. The update was mainly based on new geological acquisition made on the field and new data that have been released since the preliminary stage. As for the preliminary version, these geomodels served as geometrical framework for simulations (references to come, ongoing work).

The last phase of the geomodelling process will consist in integrating information and knowledge mainly from geophysics to improve the interpretation of the Los Humeros and Acoculco geothermal fields. In Los Humeros 120 co-located MT and TEM resistivity soundings were done on a grid with 720 m spacing. In Acoculco the sounding pairs were 65, arranged on a grid with 400 m spacing for a fine grid and with 800 m spacing for a coarser grid. These data sets have been 1D jointy inverted to correct for the static shift of the MT data to produce a resistivity model for the two areas. Later the static shift corrected MT data for the two areas were 3D inverted resulting in a more detailed and more "correct" resistivity model of the areas. In Los Humeros 344 gravity sites were measured on a grid with 200 m spacing and in Acuculco 84 sites with 400 m spacing. Bouguer gravity maps were produced as well and density maps of the two areas. Regional gravity and magnetic maps exist from both areas. In Acoculco 15 broadband seismological stations were deployed, collecting data for over a year. Almost no activity was registered in Acoculco – ambient noise tomography might give some information. In Los Humeros 20 short period and 25 broad band sensors were deployed, collecting data for over a year. Seismic tomography seems to be giving interesting results. Active seismic data for Los Humeros have been studies as well. InSAR and GPS data for both areas have been studied as well. All these geophysical data will be interpreted together and compared with the geological structure of the areas and results from boreholes.

Regarding Los Humeros, the integration phase to come will be the opportunity to update the regional 3D model. In particular, the regional fault system will be reinterpreted in the light of geophysical input. In addition, the basement will be differentiated to separate limestones that are supposed to play a role in the geothermal system. The final goal is to identify the most promising zone to develop super-hot geothermal resource in Los Humeros.

For Acoculco the geophysical surveys will be also crucial to better constrain the existing structures in view of the foreseen EGS development of this site. Gravimetric data should be useful to improve the regional model. New insights from the next geological field work dedicated to the area nearby the EAC1 and EAC2 boreholes beside geophysical surveys (e.g., magneto-telluric resistivity data) on going on the same area give the possibility to have a better understanding of the boreholes area. For this reason, a local model for Acoculco is under development.

The methodology used in the GEMex project provides interesting perspectives for future interdisciplinary works.

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FOOTNOTE

(1) 3D GeoModeller is a commercial software developed by BRGM and Intrepid Geophysics. For further information, please refer to Calcagno et al. (2008) and Guillen et al. (2008), and visit: https://www.geomodeller.com.

REFERENCES

Avellán, D. R., Macías, J. L., Layer, P. W., Cisneros, G., Sánchez-Núñez, J. M., Gómez-Vasconcelos, Pola, A., Sosa-Ceballos, G., García-Tenorio, F., Reyes-Agustín, G., Osorio-Ocampo, S., García-Sánchez, L., Mendiola, F., Marti, J., López-Loera, H., and Benowitz, J.: Geology of the Late Pliocene – Pleistocene Acoculco caldera complex, eastern Trans-Mexican Volcanic Belt (México), J. Maps, in press, https://doi.org/10.1080/17445647.2018.153107, 2018.

Calcagno, P., Evanno, G., Trumpy, E., Gutiérrez-Negrín, L. C., Macías, J. L., Carrasco-Núñez, G., and Liotta, D.: Preliminary 3-D geological models of Los Humeros and Acoculco geothermal fields (Mexico) – H2020 GEMex Project, Adv. Geosci., 45, 321-333, https://doi.org/10.5194/adgeo-45-321-2018, 2018.

Calcagno, P., Courrioux, G., Guillen, A., and Chilès, J. P.: Geological modelling from field data and geological knowledge, Part I – Modelling method coupling 3-D potential-field interpolation and geological rules, Phys. Earth Planet. Int., 171, 147–157, 2008.

Carrasco-Núñez, G., Bernal, J.P., Dávila, P., Jicha, B., Giordano, G., and Hernández, J., 2018. Reappraisal of Los Humeros volcanic complex by new U/Th zircon and 40Ar/39Ar dating: Implications for greater geothermal potential. Geochemistry, Geophysics, Geosystems, 19, pp. 132–149. Available at: https://doi.org/10.1002/2017GC007044.

Carrasco-Núñez, G., López-Martínez, M., Hernández, J., and Vargas, V.: Subsurface stratigraphy and its correlation with the surficial geology at Los Humeros geothermal field, eastern Trans-Mexican Volcanic Belt, Geothermics, 67, 1–17, https://doi.org/10.1016/j.geothermics.2017.01.001, 2017a.

Carrasco-Núñez, G., Hernández, J., De León, L., Dávila, P., Norini, G., Bernal, J. P., Jicha, B., Navarro, M., and López, P.: Geologic Map of Los Humeros volcanic complex and geothermal field, eastern Trans-Mexican Volcanic Belt, Terra Digitalis, 1, 1–11, https://doi.org/10.22201/igg.terradigitalis.2017.2.24, 2017b.

Guillen, A., Calcagno, P., Courrioux, G., Joly, A., and Ledru, P.: Geological modelling from field data and geological knowledge, Part II, Modelling validation using gravity and magnetic data inversion, Phys. Earth Planet. Int., 171, 158–169, 2008.

Lajaunie, C., Courrioux, G., and Manuel, L.: Foliation fields and 3-D cartography in geology; principles of a method based on potential interpolation, Mathemat. Geol., 29, 571–584, 1997.

López-Hernández, A., García-Estrada, G., Aguirre-Díaz, G., González-Partida, E., Palma-Guzmán, H., and Quijano-León, J. L.: Hydrothermal activity in the Tulancingo–Acoculco Caldera Complex, central Mexico: Exploratory studies, Geothermics, 38, 25 279–293, 2009.

Lorenzo-Pulido, C., Armenta-Flores, M., and Ramírez-Silva, G. Characterization of the Acoculco Geothermal Zone as a HDR System, GRC Transactions, 34, 369–372, 2010.

Norini, G., Carrasco–Núñez, G., Corbo-Camargo, F., Lermo, J., Hernández Rojas, J., Castro, C., Bonini, M., Montanari, D., Corti, G., Moratti, G., Piccardi, L., Chavez, G., Zuluaga, M.C., Ramirez, M., Cedillo, F. The structural architecture of the Los Humeros volcanic complex and geothermal field. Accepted, Journal of Volcanology and Geothermal Research.

Norini, G., Groppelli, G., Sulpizio, R., Carrasco-Núñez, G., Dávila-Harris, P., Pellicioli, C., Zucca, F., and De Franco, R.: Structural analysis and thermal remote sensing of the Los Humeros Volcanic Complex: Implications for volcano structure and geothermal exploration, J. Volcanol. Geoth. Res., 301, 221–237, https://doi.org/10.1016/j.jvolgeores.2015.05.014, 2015.

Sosa-Ceballos, G., Macías, J.L., Avellán, D.R, Salazar-Hermenegildo, N., Boijseauneau-López, M.E., and Pérez-Orozco, J.D., 2018. The Acoculco Caldera Complex magmas: Genesis, evolution and relation with the Acoculco geothermal system. Journal of Volcanology and Geothermal Research, 358, pp. 288-306. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0377027318300131?via%3Dihub