Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Towards visualization of the reservoir settings in the Los Humeros and Acoculco geothermal fields using gravity

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Keywords: EGS, super-hot geothermal system, gravity, reservoir characterization, fracture porosity.

ABSTRACT

The GEMex project addresses different challenges in the development of Enhanced Geothermal Systems (EGS) and Superhot Geothermal Systems (SHGS) in the Trans-Mexican Volcanic Belt. Although they are located in similar tectonic settings, the geothermal conditions in Acoculco and Los Humeros differ and they can be categorized as an EGS and a SHGS system, respectively. The Los Humeros field is currently under conventional exploitation. North of the current production area, temperatures higher than 380°C are expected. The Acoculco site presents temperatures >300°C at a depth of 2 km, but a reservoir has not been identified.

The main goal of this work is to visualize and characterize the reservoir conditions using gravity data. To accomplish this, we processed data from a total of 344 gravity stations at Los Humeros and 84 stations at Acoculco. In Los Humeros, the Bouguer anomaly shows a clear trend of decreasing gravity from the NE to the SW, fitting with the Bouguer anomaly of the regional gravity data, where a minimum gravity anomaly was found in the center of the caldera. At the reservoir level in Acoculco, an area with a high-density anomaly coincides with an area of low permeability, revealed by the absence of water at depth were two non-productive exploration wells were drilled (Peiffer et al., 2014b).

1. INTRODUCTION

In geothermal exploration, a detailed structural 3D geological model of the reservoir is crucial to understand the fault systems and fluid pathways. Aiming at EGS development, the detection and characterization of fault patterns allows for estimating the fault reactivation potential (Faulds et al., 2010). Typically, 3D geological models are constrained by geological information. Intrinsic properties such as density, magnetic susceptibility, porosity and thermal conductivity may be deduced from geophysical measurements (Guillen et al., 2008).

Gravity and magnetic geophysical methods can both be used to inspect the geothermal potential of a site. Gravity measurements are used to estimate the spatial variability of subsurface formation densities in the field. Those measurements can be used to support modelling of geological structures, depending on the different bulk densities producing variation in the gravity field or lateral changes caused by fracture porosity (see, e.g., (Baillieux et al., 2013, 2014; Altwegg et al., 2015)).

To infer subsurface conditions, two different techniques can be applied: (i) forward modelling involves a starting model for the source body of an anomaly that is constructed based on geological and geophysical constraints. The anomaly of the model is calculated and compared with the observed anomaly. The model parameters are adjusted iteratively in order to improve the fit between the two anomalies. In the (ii) inverse modelling, the parameters of the body are calculated automatically and directly from the observed anomaly (Blakely, 1996).

According to the fluid phase, porosity changes have been attributed to density changes in reservoir zones of an extension of several kilometers at the Geyser field (Denlinger et al., 1981), associating the density changes to porosity through measurements of the interconnected porosity of samples. In low-temperature geothermal systems, negative gravity anomalies have been linked to faults along which geothermal fluid rises naturally (Guglielmetti et al., 2013). At a regional scale in the Upper Rhine Graben of Central Europe, spatial coincidence of low density and thermal anomalies has been attributed to fracture porosity occurring in the fault zones that host the geothermal reservoir (Baillieux et al., 2013). Gravity in combination with 3-D geological modelling has also proven to be an appropriate tool for visualization of fracture porosity in the granitic basement (Baillieux et al., 2013, 2014).

Another approach involves calculating the effect of the structures that are irrelevant for the determination of fracture porosity, and then subtracting them from the observed residual anomaly by sequential stripping in order to attribute the remaining anomalies to the local faults. This approach was successfully applied to the Sankt Gallen geothermal project in Switzerland (Altwegg et al., 2015) that targeted a fault zone that affects Mesozoic sediments at a depth of about 4500 m. The spatial extension of these sediments, a major fault zone and indications of graben structures in the crystalline basement were observed in the 3-D seismic model. Both the graben and the fault zone coincided with negative gravity anomalies. Microgravity surveys have also been successfully used for monitoring of mass changes in geothermal reservoirs (Allis and Hunt, 1986).

2. STRUCTURAL SETTING

The Los Humeros and Acoculco volcanic complexes are located in the eastern part of the Trans Mexican Volcanic Belt, an active continental volcanic arc formed by the subduction of the Cocos and Rivera plates beneath the North American plate along the Middle

American trench (Ferrari et al., 2012). Their emplacement is associated with Pleistocene-Holocene volcano tectonic structures (see, e.g., (Norini et al., 2015)).

The complex evolution of the Los Humeros Complex (LHVC) involves alternating episodes of effusive and explosive eruptions in a basaltic-andesite-rhyolite system (see, e.g., (Yáñez and García, 1982)), which are attributed to the formation of the Los Humeros caldera with the inner Los Potreros caldera (Carrasco-Núñez et al., 2017a). The LHVC is characterized by the coexistence of two volcano-tectonic structural systems: (1) the caldera faults of the Los Humeros and Los Potreros calderas, and (2) the NNW–SSE, N–S, NE–SW and E–W-striking faults in the Los Potreros Caldera (Norini et al., 2015).

Outside the caldera, a morpho-structural analysis revealed NW-SE, SE-NW and E-W striking structures (Piccardi 2018). The NE-SW oriented structures at LHVC and Las Minas, an exhumed system to the east of LHVC, seem to be the oldest structures without pronounced evidence of recent activity, and exhibit the major control on the intrusion of magma in both areas. Nevertheless, the Perote fault seems to have been reactivated by the volcanic ring-structures (Piccardi, 2018).

The magma emplacement at depth is controlled by the E-W to ENE-WSW oriented structures and represent a conduit for lava flow at least since about 3000 years ago (Carrasco-Núñez et al., 2017a). The NW-SE oriented structures are related to the similarly oriented compressional structures observed in the far-field of the caldera and with the normal faults affecting the volcanic complex inside and outside of the caldera area. The approximately N-S oriented structures appear to be the most recent ones, controlling the main caldera rims of Los Humeros and Los Potreros calderas. They represent the main conduits for the fluid circulating in the geothermal field, being limited in extension within the volcanic edifice (Piccardi, 2018).

The Acoculco caldera shows the Atotonilco scarp in the north, the Manzanito fault to the southwest and the venting sites on the eastern and southern part, defining an asymmetric caldera extending over 18×16 km (Avellán et al., 2018). Faults with similar orientation were detected in the Acoculco area (Sosa-Cabellos et al., 2018). The NW-SE faults are the most prominent and appear to intersect the SW-NE oriented fault systems. The NW-SE faults generally dip at high angle (between 70° and 80°) to the SW. Minor E-W structures framed in the caldera evolution are also reported.

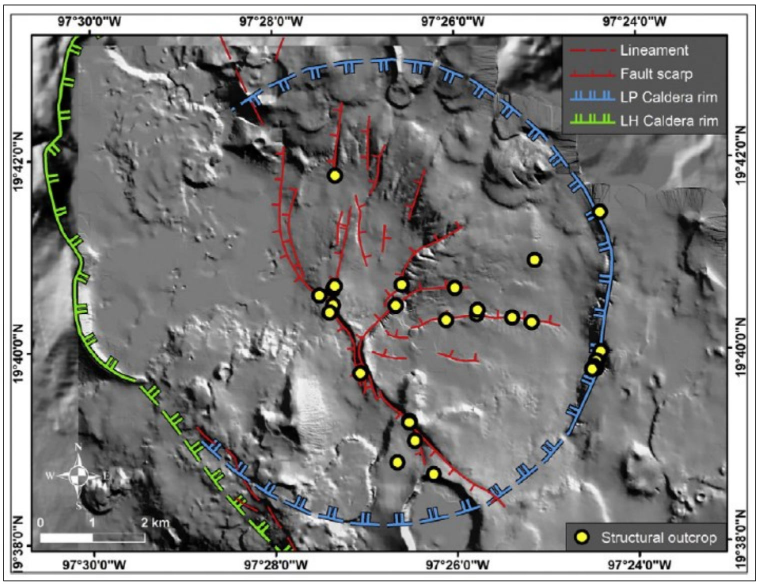

Figure 1: Morpho-structural map of the Los Humeros geothermal system and location of the structural outcrops. Shaded relief image obtained from the 10 m and 30 m resolution DEM (Norini et al., 2015).

3. GRAVITY DATA

3.1 Regional Data

In the following, we provide information on the regional gravity data of both areas, Los Humeros and Acoculco, which were kindly provided to the GEMex consortium by the *Comisión Nacional de Hidrocarburos* (http://www.gob.mx/cnh). The data were presented in form of Bouguer-corrected values using a material density of 2670 kg cm^{-3}. Figure 2 shows an interpolation of these data from 12373 and 3593 measurement stations of Los Humeros and Acoculco, respectively.

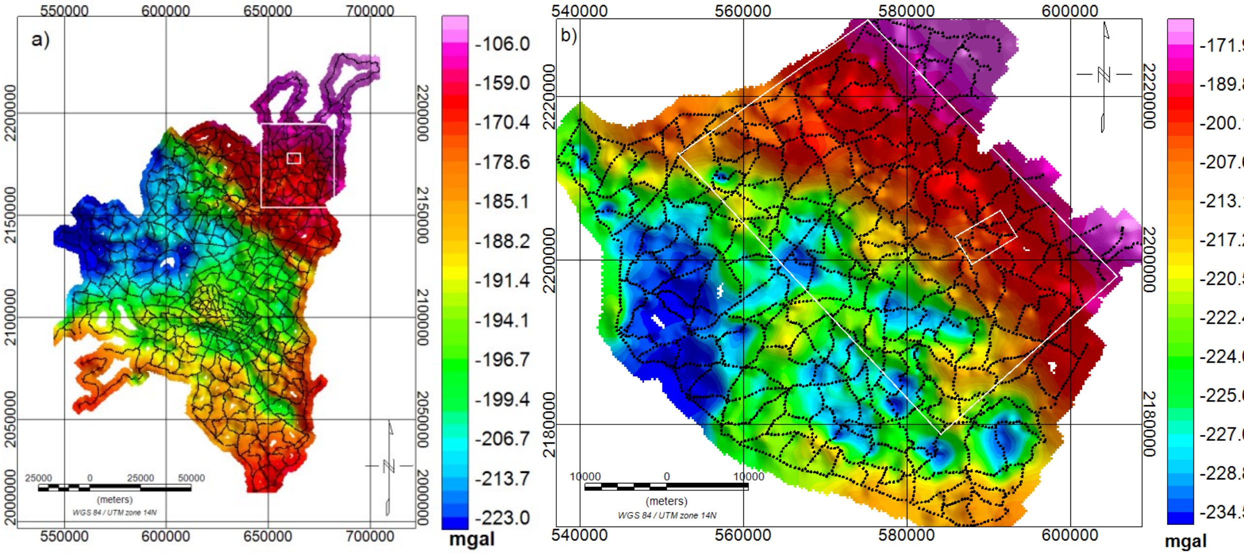

Figure 2: Regional Bouguer anomalies for a material density of 2670 kg cm^{-3} including the study areas of a) Los Humeros and b) Acoculco (source: *Comisión Nacional de Hidrocarburos*, http://www.gob.mx/cnh). Large white square: extension of the caldera areas; small white square: extension of the geothermal field and newly acquired field surveys.

3.2 Local Data

The local gravity data have been acquired during two field surveys using a CG-5 Autograv Gravity Meter (Scintrex Ltd.) with an accuracy of 0.001 mGal. This gravimeter measures continuously by averaging a series of 6 Hz samples. At each gravity station, three measurements of 120 s (first campaign) and of 240 s (second campaign) were acquired. The coordinates of each gravity station were determined by differential GPS using two Trimble 5700 receivers and two Trimble antennas (TRM39105 and TRM41249).

In Acoculco, a total of 84 gravity stations were used in an about 5×3 km rectangular grid oriented NE-SW and NW-SE with stations typically spaced 400 m from each other.

In Los Humeros, a total of 344 gravity stations were used in two different surveys. In the first survey, 263 stations were used along ten E-W profiles 5.5 km in length with typical inter-station and inter-profile distances of 200 m and 500 m, respectively. Two measurements were rejected due to unreliable GPS records. During the second campaign, the survey was completed by a NE-SW oriented and 31 km long profile across the study area. This profile includes 81 gravity stations with an inter-station spacing of about 375 m, of which one measurement was rejected due to unreliable GPS record. This profile runs parallel to the most prominent negative gravity anomaly of the study area and will be used to investigate local density variations within this prominent structure. In total, 341 stations were used for further evaluation of the Los Humeros field.

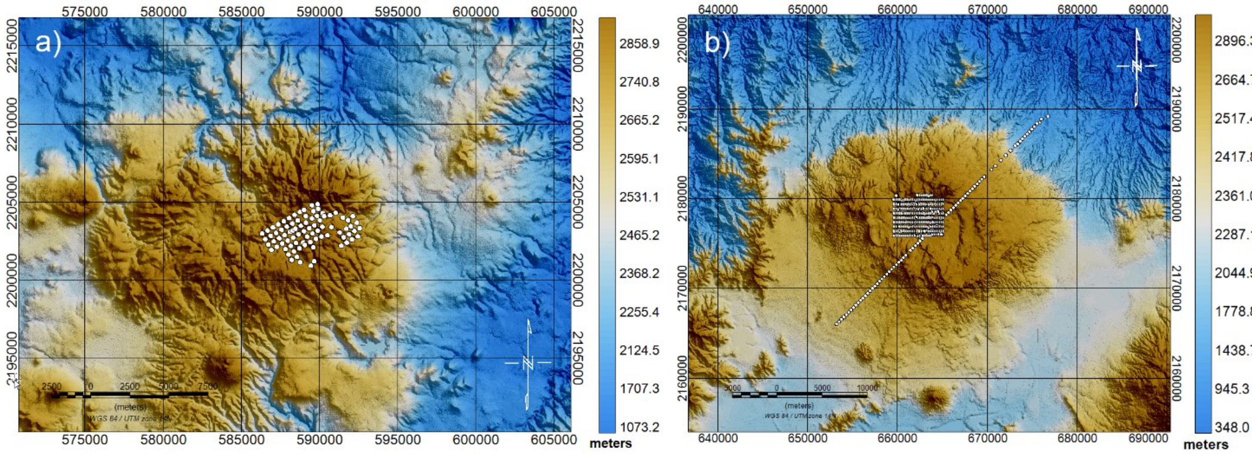

Figure 3: Location of the local gravity stations (white dots). a) Acoculco. b) Los Humeros. The color bars indicate elevation in meters (WGS 84 / UTM zone 14N).

3.3 Data Quality

The data quality depends on the measurement accuracy of the differential GPS (vertical: 5 mm), the gravimeter (0.001 mGal), and the standard deviation of the gravity and GPS measurements. The measurement with lowest standard deviation was selected for further investigation.

In Acoculco, the standard deviation of the raw gravity measurements of 240 s at each station ranged from 0.004 to 0.197 mGal (Figure 4a). 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.

The standard deviation of the GPS measurements ranged from 0.0015 to 1.18 m (Figure 4b). The quality of the differential GPS measurements is comparably high with about 92.8% of the data revealing a standard deviation < 0.05 m. Setting a threshold of 0.2 m of maximum standard deviation, 97.6% of the data (82 stations) were used for further evaluation. Taking into account the quality of the gravity and GPS measurements, a total of 79 stations were later processed in Acoculco.

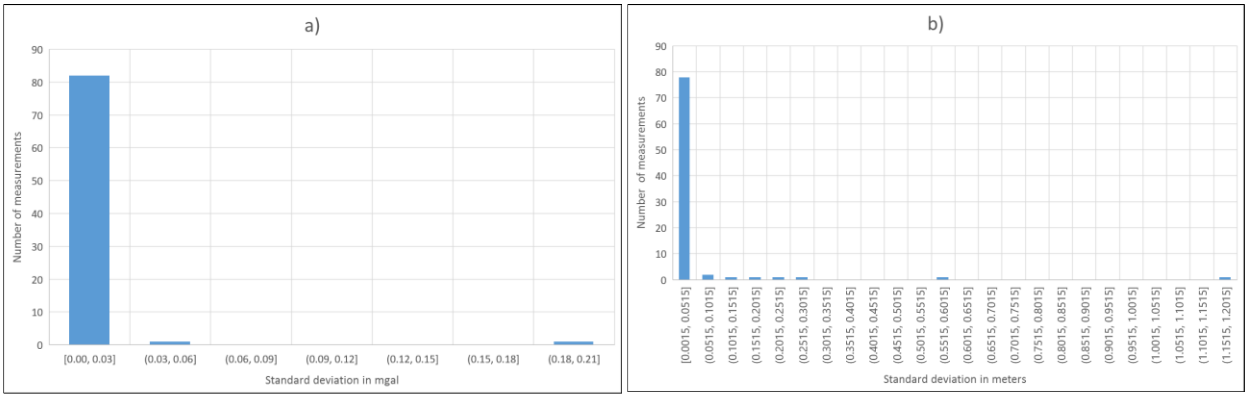

Figure 4: a) Number of gravity measurements in the 0.03 mGal-standard deviation windows of the Acoculco survey. b) Number of GPS measurements in the 0.05 m standard deviation windows of vertical position for the Acoculco survey.

Figure 5a shows the distribution of standard deviations of the raw gravity measurements acquired during the first survey of the Los Humeros campaign. The values range between 0.008 and 0.119 mGal. Compared to Acoculco, the quality of gravity measurements is lower, with about 63.2% of the data revealing a standard deviation ≤ 0.03 mGal. Therefore, during the second survey, the measurement duration was increased to 240 s. Nevertheless, this still resulted in a comparable range of standard deviations, with 62.5% of the data revealing a standard deviation ≤ 0.03 mGal (Figure 5b). In Los Humeros, a threshold of 0.05 mGal of maximum standard deviation results in 93.5% of the data (319 stations) being used for further evaluation.

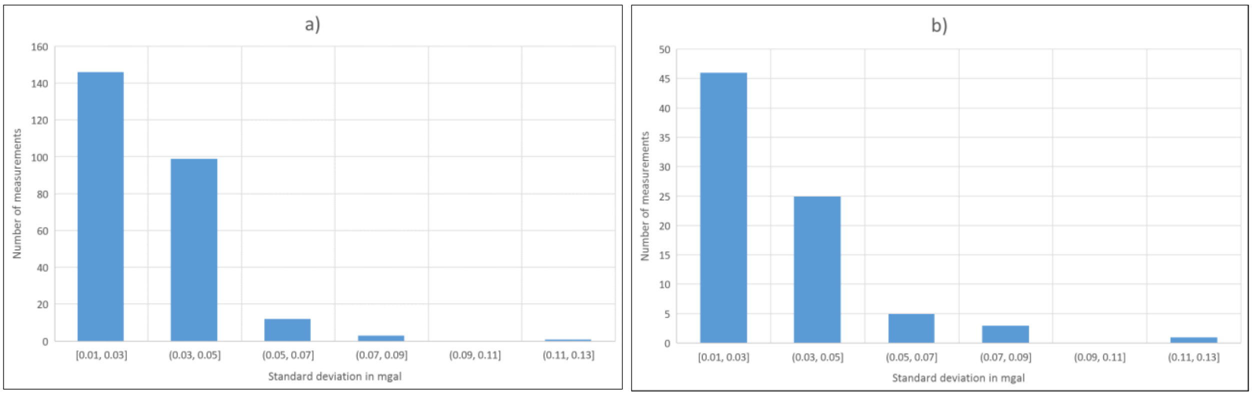

Figure 5: Number of gravity measurements in the 0.02 mGal-standard deviation windows for Los Humeros. a) First survey. b) Second survey.

The standard deviations of the GPS measurements ranged from 0.0012 to 0.38 m (Figure 6). The quality of the differential GPS measurements is relatively high with about 91.2% of the data revealing a standard deviation < 0.05 m. Setting a threshold of 0.2 m of maximum standard deviation, 99.4% of the data (339 stations) were used for further evaluation. Taking the quality of the gravity and the GPS measurements into account, a total of 318 station were later processed in the Los Humeros field.

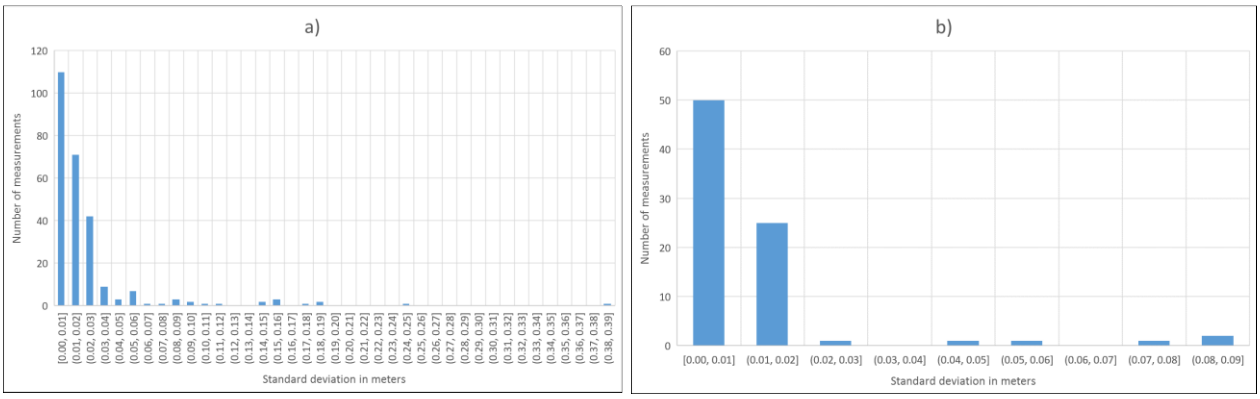

Figure 6: Number of GPS measurements in the 0.01 m standard deviation windows of vertical position in Los Humeros. a) First survey. b) Second survey.

4. PROCESSING DATA

Processing of the data was carried out using the software GravProcess (Cattin et al., 2015). The procedure included the following steps:

1) integration of gravity data, station location, and gravity line connection input files,
2) gravity data reduction applying solid-Earth tide and instrumental drift corrections,
3) automatic network adjustment and alignment to the base stations, and
4) free air and simple Bouguer reduction.

Simple Bouguer reduction was calculated from the plateau formulation for 10 different densities ρ between 1300 and 3300 kg m^{-3} and using the gravitational constant $G = 6.67 \cdot 10^{-11}$ N m^2 kg^{-2}. Due to the large amount of data of the DEM, the calculation of the terrain correction was performed with the software Oasis Montaj™ Gravity and terrain Correction extension (Geosoft). This software is based on algorithms formulated in Kane (1962) and Nagy (1966) and incorporates advancements in grid-mesh interpolation, zoning and resampling techniques.

4.1 Bouguer Anomalies

Complete Bouguer reduction was obtained by using Oasis Montaj™. The terrain correction was carried out at a distance of 167 km from each gravity station. For the Acoculco gravity data, a digital elevation model (DEM) with a resolution of 15 m from the *Instituto Nacional de Estadística y Geografía* (INEGI) was used, whereas for Los Humeros an additional dataset with 1 m resolution was kindly provided by the *Centro Mexicano de Innovación en Energía Geotérmica* (CeMIEGeo) for the near-field. The vertical uncertainty of the CeMIEGeo data set is reported to be 1-2 m.

As the gravitational effect of a prism decreases with the square of the distance, we reduced the resolution of the DEM with increasing distance from the gravity station as follows:

1) for Acoculco: (a) from the station, 0 m, to 100 m using the DEM with a cell size of 15 m; (b) from 100 m to 10 km a reduced cell size of 100 m; (c) to 100 km a reduced cell size of 500 m; and to 167 km a reduced cell size of 5000 m, and
2) for Los Humeros: (a) from the station, 0 m, to 10 m using the DEM with a cell size of 1 m (for points outside of the high resolution DEM: from the station, 0 m, to 150 m using the DEM with a cell size of 15 m); (b) from 10 m to 20 km a reduced cell size of 50 m; (c) to 100 km a reduced cell size of 500 m; and to 167 km a reduced cell size of 5000 m.

Given the standard deviation threshold of the GPS measurements, the uncertainty introduced by the terrain correction is estimated to be <0.06 mGal. The uncertainty introduced by the DEM is approximately 0.6 mGal, summing up with the standard deviation threshold of the gravity measurements of 0.05 mGal to a mean uncertainty of about 0.7 mGal.

5. RESULTS AND DISCUSSION

We present the complete Bouguer anomalies of Acoculco and Los Humeros combining the local and a selection of the regional gravity data. While local data have been acquired in high resolution for the geothermal fields, the regional data are required for connecting the geothermal fields to relevant dominant structures within and outside of the calderas. Note that the regional data was provided in form of Bouguer corrected values using a material density of 2670 kg cm^{-3}. In order to merge the two data sets, the same density was used at the local scale.

Both Bouguer anomalies show decreasing gravity from the NE to SW in the caldera area (Figure 7a and Figure 8a). This regional trend of the Bouguer anomaly is well known in the area (see, e.g., (Urrutia-Fucugauchi and Flores-Ruiz, 1996)), since it represents the crustal thickness increase from the Gulf of Mexico margin toward the continental interior.

At the geothermal field scale in Acoculco, a high anomaly coincides with the site where two exploration wells show low quality geothermal conditions, due to absence of reservoir water at depth which is caused by a lack of permeability (Peiffer et al., 2014b).

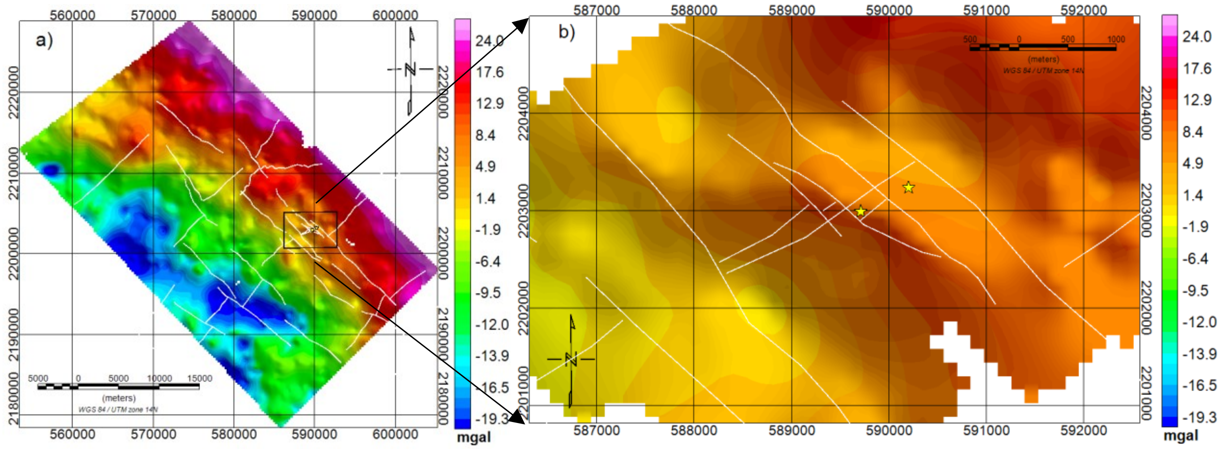

Figure 7: Bouguer anomaly of Acoculco compared to the fault zones. a) Aaldera area. b) Geothermal field. Stars indicate exploration wells.

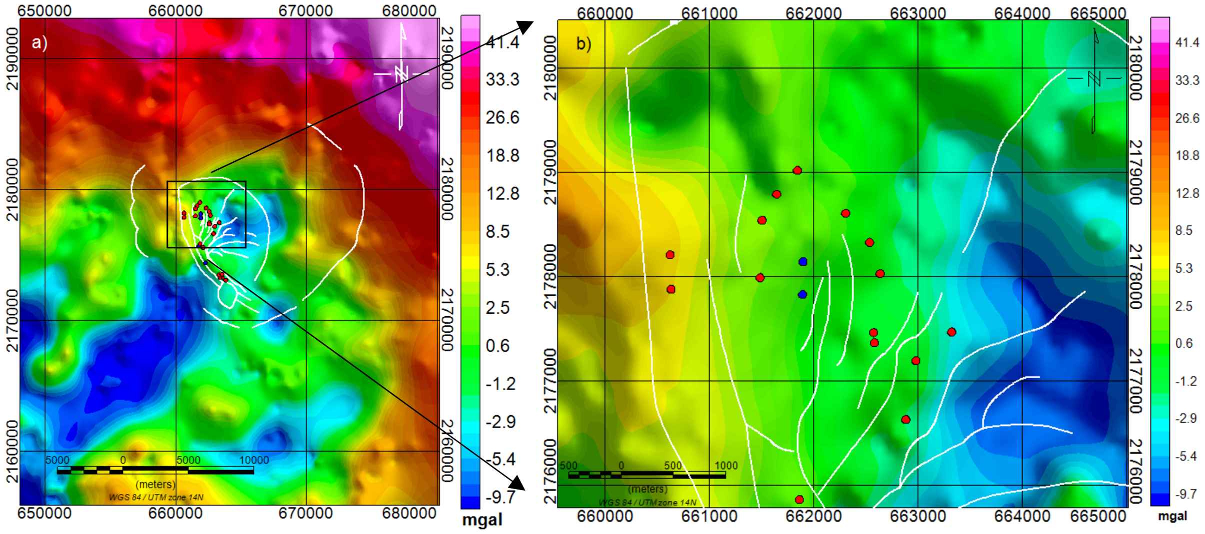

Figure 8: Bouguer anomaly at Los Humeros compared to the fault zones according suggested by Piccardi (2018). a) Caldera area. b) Geothermal field. Red dots indicate production wells and blue dots indicate injection wells.

6. OUTLOOK

In the framework of the GEMex project, high-resolution Bouguer maps have been obtained locally in the Los Humeros and Acoculco fields. Nevertheless, for further evaluation and modelling, these newly acquired data were merged with regional data in order link them to regional structures.

In order to obtain residual anomalies, a regional trend will be subtracted from the Bouguer anomalies. This trend is associated with the tectonic setting of the study areas, which is of no concern to geothermal reservoir exploration. Afterward, residual anomalies will be modeled and linked with the local faults, and new insights into the structural setting of both areas may contribute to the improvement of geological models.

7. ACKNOWLEDGEMENTS

This paper presents results of the GEMex Project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No.727550, and by the Mexican Energy Sustainability Fund CONACYT-SENER, Project2015-04-268074. The authors wish to thank the Comisión Federal de Electricidad of Mexico (CFE) for their support, and access to Los Humeros geothermal field.

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