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

The Los Humeros Superhot Geothermal Resource in Mexico: Resistivity Survey (TEM and MT); Data Acquisition, Processing and Inversion – Geological Significance

Ásdís Benediktsdóttir[1], Claudia Arango Galván[2], Gylfi Páll Hersir[1], Sebastian Held[3], José Manuel Romo Jones[4], Jose Luis Salas[2], Thalia Aviles[4], Diego Ruiz Aquilar[5], Arnar Már Vilhjálmsson[1], Adele Manzella[6] and Alessandro Santilano[6]

[1]Iceland GeoSurvey, Grensásvegi 9, 108 Reykjavík, Iceland.

[2]Universidad Nacional Autónoma de México, Ciudad Universitaria, Delegación Coyoacán, 04510, México CDMX, México

[3]Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

[4]Centro de Investigación Científica y de Educación Superior de Ensenada, C.P. 22860, Baja California, México

[5]Cátedras Conacyt-Centro de Investigación Científica y de Educación Superior de Ensenada, C.P. 22860, Baja California, México

[6]National Research Council, Institute of Geosciences and Earth Resources, Via G. Moruzzi 1, 56124 Pisa, Italy.

E-mail address: ab@isor.is

Keywords: Los Humeros, superhot geothermal resource, resistivity, magnetotelluris, transient electromagnetics, geophysical interpretation.

ABSTRACT

A joint geothermal project of a European and Mexican consortium began in late 2016 with the purpose to develop geothermal energy in the easternmost region of the Trans-Mexican Volcanic Belt. Two sites that belong to the Comisión Federal de Electricidad (CFE) have been investigated. One of the them, Los Humeros, is the subject of our study. In order to further explore the Los Humeros superhot geothermal resource, extensive geological, geochemical and geophysical studies were carried out. Previously existing regional gravity and magnetic maps were studied, and gravity was measured on a dense grid. Some 23 broadband and 22 short period seismic stations were set up which collected data for one year. Finally, 122 co-located MT and TEM soundings were made in 2017 and 2018 through a joint effort by the European and Mexican partners. Their location was based on the interpretation of already existing resistivity data. The TEM and MT data were acquired with a TerraTEM equipment and Metronix equipment, respectively. The bounded influence remote reference processing method was used for processing of the MT timeseries. Each TEM/MT pair was jointly inverted in 1D, where the TEM data were used to static shift correct the MT data. A 3D inversion was performed on the full impedance tensor of the MT data using different initial models. Two codes were applied for comparison, the WSINV3DMT code was run in Europe and ModEM in Mexico. Finally, the resistivity models were compared with and interpreted together with other geoscientific results from the GEMex project, gravity, seismics and the geological mapping. This abstract 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, Project 2015-04-268074. More information can be found on the GEMex Website: http://www.gemex-h2020.eu

1. INTRODUCTION

The Los Humeros superhot geothermal field lies in the Trans-Mexican Volcanic Belt. In 2017 and 2018 the field was explored extensively with various geoscientific methods, including geophysics, within the frame of the GEMex Project. 122 co-located MT and TEM soundings were acquired in the Los Humeros area (Figure 1). A similar survey was conducted in the close by geothermal area, Acoculco in Mexico (Hersir et al., 2020)

The acquisition period was longer than anticipated because of various problems. However, in the end almost all the planned sites were visited. The quality of the data was good for most of the soundings, despite the electromagnetic noise from the power plant in Los Humeros and the power lines associated with it.

A resistivity model of the survey area was compiled from the 1D joint inversion results of the TEM and MT data. The model was based on inversion of the apparent resistivity and phase calculated from the determinant value of the MT impedance tensor. During the inversion process the MT data were static shift corrected using the TEM data.

Here we discuss the data acquisition, processing and 1D inversion of the MT/TEM data form the Los Humeros area. Phase tensor analyses from the area is presented by Held et al., (2020) and sensitivity study of 3D inversion of MT data from Los Humeros are presented Ruiz-Aguilar et al. (2020).

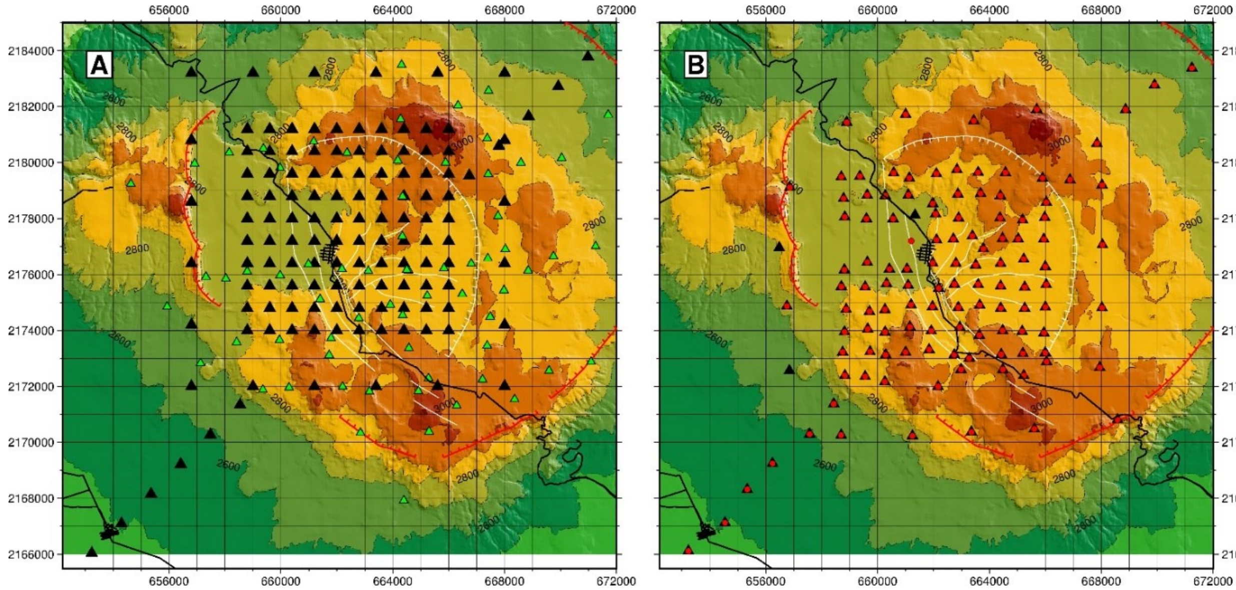

Figure 1: Location map of the survey area in Los Humeros. A. Planned co-located TEM and MT sounding sites and old MT location sites from Aratzte et al. (2018) are black and green triangles, respectively. B. Actual sounding sites; black triangles and red circles are MT and TEM sounding locations, respectively. Red and white hatched lines are the Los Humeros and Los Potreros calderas, respectively. White lines are major faults in the area and black lines are roads. Coordinate system used is UTM WGS zone 14.

2. DATA ACQUISITION

2.1 Survey Design

The survey design in Los Humeros was based on results from previous resistivity data provided by Comisión Federal de Electricidad (CFE) and published in Arzate et al. (2018), and results based on the geological mapping done by Norini et al. (2015). The original survey (Figure 1A) was laid out to cover the main part of the Los Potreros caldera and the area surrounding the town of Los Humeros. The result was a grid with soundings every spacing 720 m, with 10 soundings running east-west and north-south, plus some extra 20 soundings farther out located around the survey area and 16 on a long profile extending southwest-northeast. During the data acquisition it was decided to focus the survey in the southern part of the Los Humeros caldera so the two northern most east-west lines were moved to the south. Out of the planned 136 soundings 122 MT soundings were measured and 120 TEM soundings as some sites were not accessible and some adjustment to the plan had to be made during the data acquisition.

3. DATA PROCESSING

Five sets of MT equipment from Metronix, ADU-07 type, were used, collecting data in the frequency range from 0.0001 Hz to 10 kHz. The sampling frequency was 4096 Hz for 30 minutes and 128 Hz for at least 20 hours. One of the MT stations served as a reference station, measuring a continuous MT signal, located 80 kilometers away close to the town of Acoculco. This recording was used as reference signal to give better data quality (see e.g. Gamble et al., 1979). Some of the MT soundings were of a poor quality, mainly due to noise originating from the proximity of power lines and the power plant in Los Humeros.

The equipment used for the TEM measurements was a TerraTEM equipment from Monex GeoScope; single loop, i.e. the same loop was used for transmitting and receiving. The loop size was 100 m x 100 m and the injected current around 8 A. The sampling frequency used were 30 Hz, 10 Hz and 2.5 Hz.

The MT data from the survey area were processed and quality controlled. PROCMT was used for quality check during fieldwork and BIRRP (Chave and Thomson., 2004) for robust estimation of transfer functions.

To increase the quality of interpretable data the following processing schemes were tested intensively: 1) Robust processing scheme after Egbert and Booker (1986), 2) Robust processing scheme after Chave and Thomson (2004), and 3) Processing scheme implemented in WinGLink Software (© Schlumberger). WinGLink Software processing yielded data of insufficient quality. The results of the processing schemes of Egbert and Booker (1986) and Chave and Thomson (2004) are shown in Figure 2. After quality analysis of a variety of stations considering the whole frequency range, the strongest reduction of uncertainties, the optimal elimination of noise and the generation of smooth curves could be achieved while using Chave's BIRRP code. The bound influence robust processing code was used in advanced mode considering remote referencing. To increase the penetration depth, the processed frequency range was enlarged by decimation of the measured 128 Hz data to 4Hz and subsequent processing of three frequencies bands (4096 Hz, 128 Hz and 4 Hz).

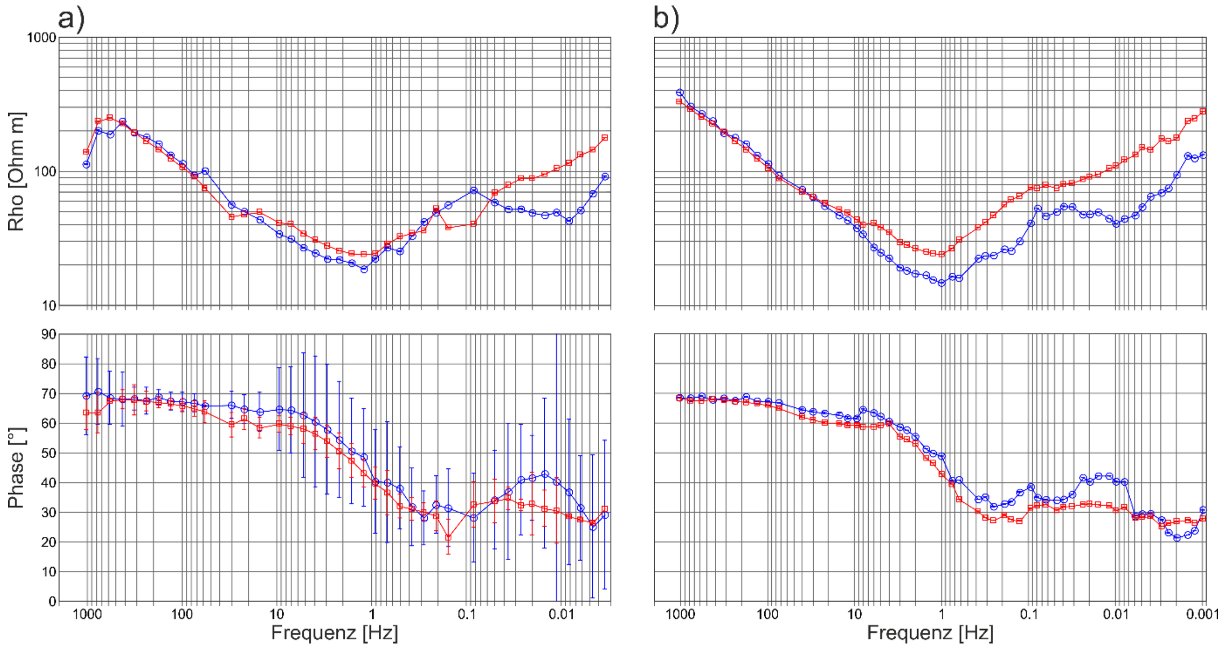

Figure 2: Sample of robust processing of one MT sounding from Los Humeros using the processing scheme of Egbert and Booker (1986) (a) and Chave and Thomson (2004) (b). The uncertainties of the phase angle and the occurrence of individual outliers is decreased in Chave's BIRRP code (b).

.

4. 1D JOINT INVERSION USING TEMTD

In 1D inversion of MT data it is customary to invert for one of the three rotational invariant parameters:

$$Z_{av} = \frac{Z_{xy} - Z_{yx}}{2}$$

$$Z_{det} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}}$$

$$Z_{gm} = \sqrt{-Z_{xy}Z_{yx}}$$

All these parameters give the same values for a 1D earth response, for a 2D earth the *det* (determinant) and the *gm* (geometric mean) reduce to the same value but the *av* (arithmetic mean) is different. For a 3D response, all these parameters are different.

There are different opinions on which of the three invariants, if any, is best suited for a 1D inversion. However, based on the comparison of model responses for 2D and 3D models, it has been suggested that the determinant invariant is the one to use (see e.g. Park and Livelybrook, 1989) and that was done for the data from Los Humeros.

The 1D inversion was done using the TEMTD code (Árnason, 2006b). Apparent resistivity and phase, calculated from the determinant of the MT impedance tensor, were inverted jointly with TEM data. In the joint TEM/MT inversion, a static shift parameter (Árnason, 2015) is obtained; the TEM data are used to shift the MT apparent resistivity curve up (shift < 1), or down (shift > 1).

Occam's inversion (Constable et al, 1987) was used with 100 horizonal layers, distributed over a fixed depth range, below which a homogeneous half-space is present. In the Occam's inversion the thickness of each layer is fixed, with the layer thicknesses increasing exponentially with depth, until the cumulative depth is equal to the depth of the homogeneous half-space. With this parametrization the structure is minimized and the resistivity structure varies smoothly with depth. The parameters inverted for are the resistivity values of each layer. Inversion parameters (e.g. the bottom to the homogeneous half-space and initial model) varied from one sounding to another depending on the data.

When all sounding pairs have been inverted, the resulting 1D models are interpolated in space to form regional one-dimensional model. The results are presented in the forms of horizontal and vertical cross-sections.

5. RESULTS

Figure 3 shows the location of the resistivity soundings in the Los Humeros survey area used in the 1D inversion. A total of 91 MT/TEM sounding pairs were 1D jointly inverted and 13 MT soundings with no co-located TEM data. Some of the TEM soundings are of bad data quality and are therefore, not used in the inversion and in some cases the sounding site was not accessible because of crops which had been planted in the fields where MT sounding data had been acquired. Figure 4 shows examples of inverted MT/TEM pair (Figure 4A) and where only MT data were available (Figure 4B).

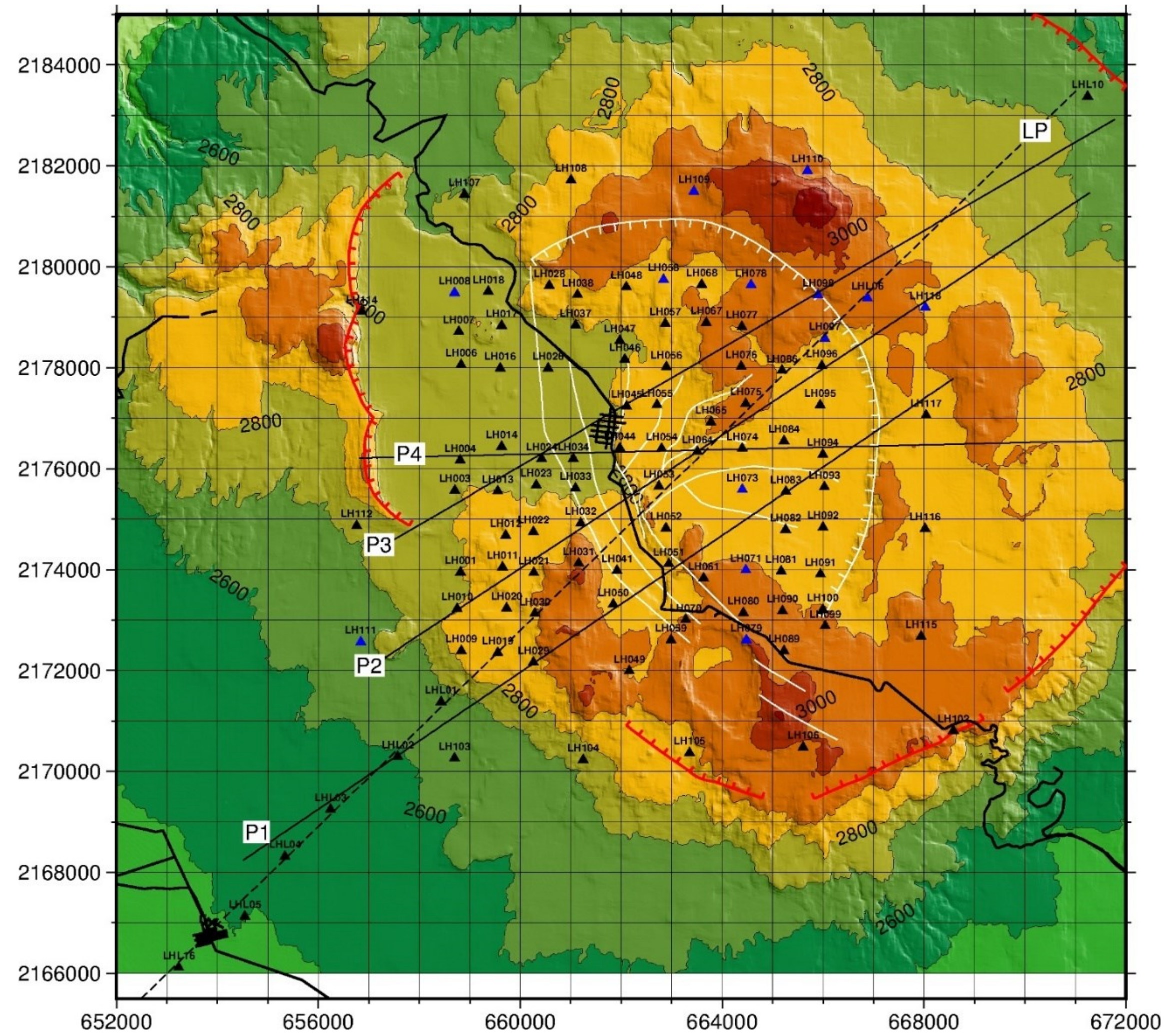

Figure 3: Location map of the Los Humeros survey area. Triangles are the co-located MT and TEM soundings. Black and blue triangles denote soundings that where static shift corrected, and not static shift corrected, respectively. Names of the soundings are labelled above the triangles. Red and white hatched lines are the Los Humeros and Los Potreros calderas, respectively. The thick black lines are roads and white lines are main faults in the region. The location and names of five vertical cross-sections are shown as four black thin lines (P1, P2, P3, P4) and a dashed line (LP).

Figure 5 shows horizontal cross-sections through the 1D model at four different depths. At 2600 meters above sea level (Figure 5A) a conductive clay cap is revealed along the main NW-SE trending faults and it is surrounded by zones of higher resistivity. At 2000 meters above sea level (Figure 5B) intermediate to low resistivity values are present. At this depth some parts of the conductive cap are visible (in the south) and areas of slightly higher resistivity values (≈50 Ωm) are seen north and south of the town of Los Humeros, showing the top of the resistive core.

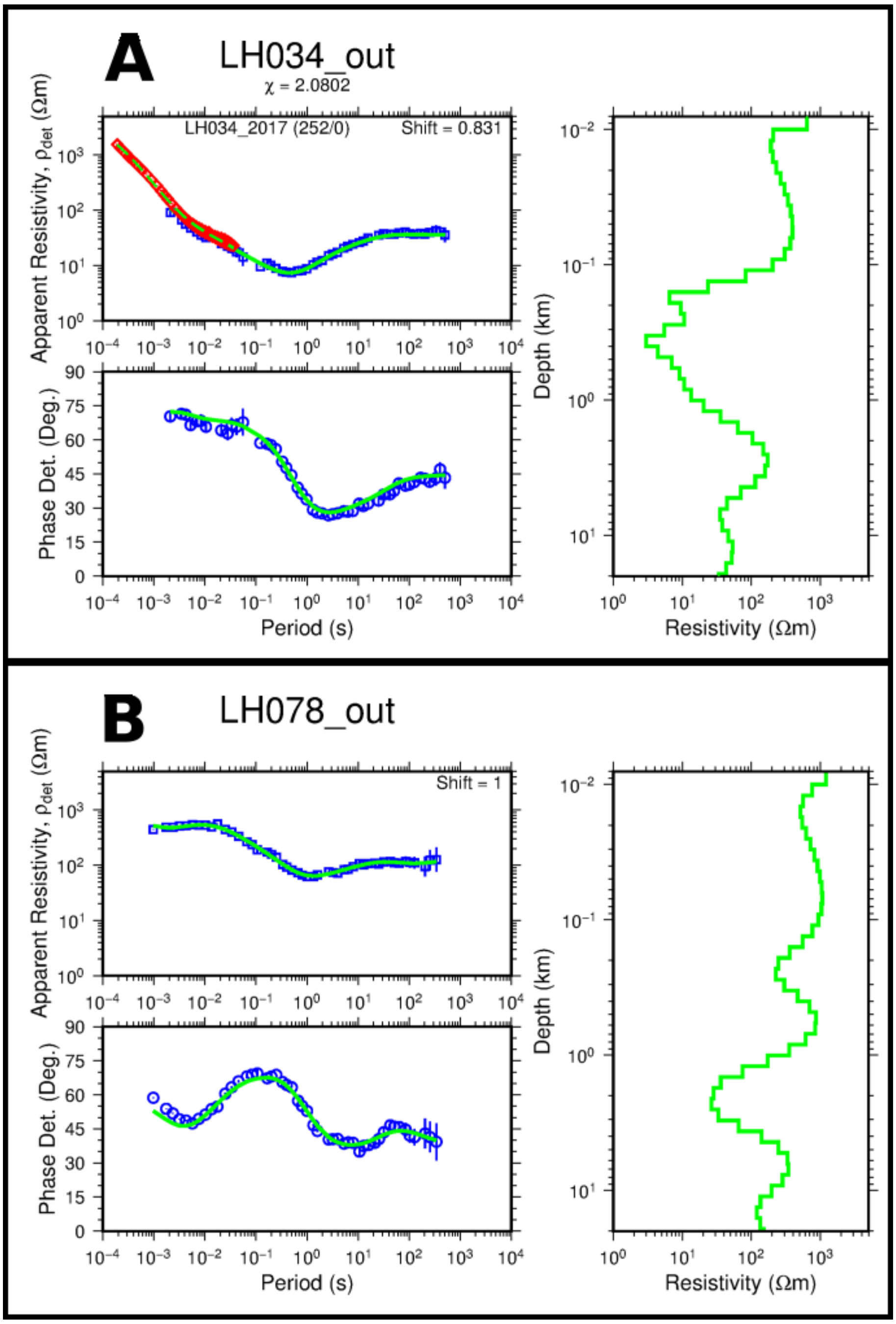

Figure 4: Examples of 1D inverted resistivity data. In both A and B: the upper left panel is the apparent resistivity of TEM data transformed to a pseudo curve (red points only in A) and MT data (blue points). The green curve is the apparent resistivity response of the model shown in the right panel. The lower left panel is the phase of the MT data (blue points) and the green curve is the MT phase response of the model shown in the right panel. A. Inversion of sounding LH034 where both MT and TEM data were inverted for jointly. The static shift is shown in the upper right corner of the upper left panel. B. Inversion of sounding LH078 where only MT data were available. For location of the soundings, see Figure 3.

At 1000 meters above sea level (Figure 5C) the NW-SE trending resistive core is observed. The orientation of the resistive core is the same as the orientation of the conductive clay cap in Figure 5A. A low resistivity zone in the southern end of the survey area is most likely only due to one sounding (sounding LH106). At deeper level, 3000 meters below sea level (Figure 5D), an intermediate NW-SE trending body is seen in a resistive surrounding.

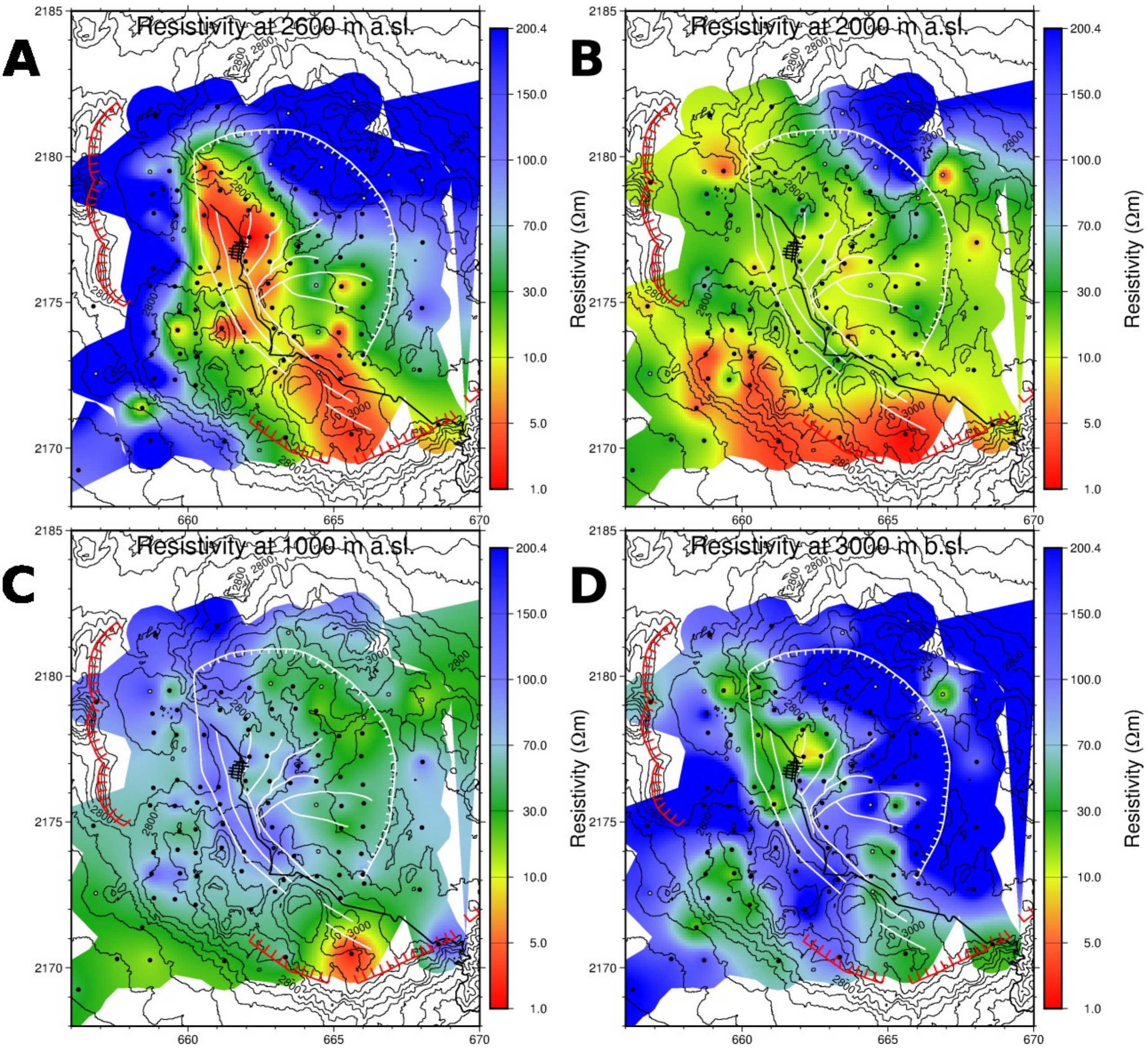

Figure 5: Horizontal cross-sections (depth-slices) through the 1D model of the Los Humeros prospect at 2600 meters above sea level (A), 2000 meters above sea level (B), 1000 meters above sea level (C) and 3000 meters below sea level (D). White and red hatched lines are the Los Potreros and Los Humeros calderas, respectively. Black lines are roads and white lines are main faults in the region. The town of Los Humeros is where the roads form a dense grid. Black circles are MT sounding locations and elevation contour lines are thin black lines, every 100 meters.

Figures 6 and 7 show two vertical cross-sections through the 1D resistivity model of Los Humeros, reaching down to sea level and 5 km below sea level

In Figure 6 a shallow lying conductive cap extends from below sounding LHL101 in the SW to sounding LH064 in the NE. East of sounding LH064 the conductive cap plunges down. In Figure 7 we see the conductive cap in the middle of the profile and a deep-lying low-resistivity body right below the conductive cap. The deep-seated low-resistivity body is also seen in the horizontal cross section at 3000 meters below sea level (Figure 5D).

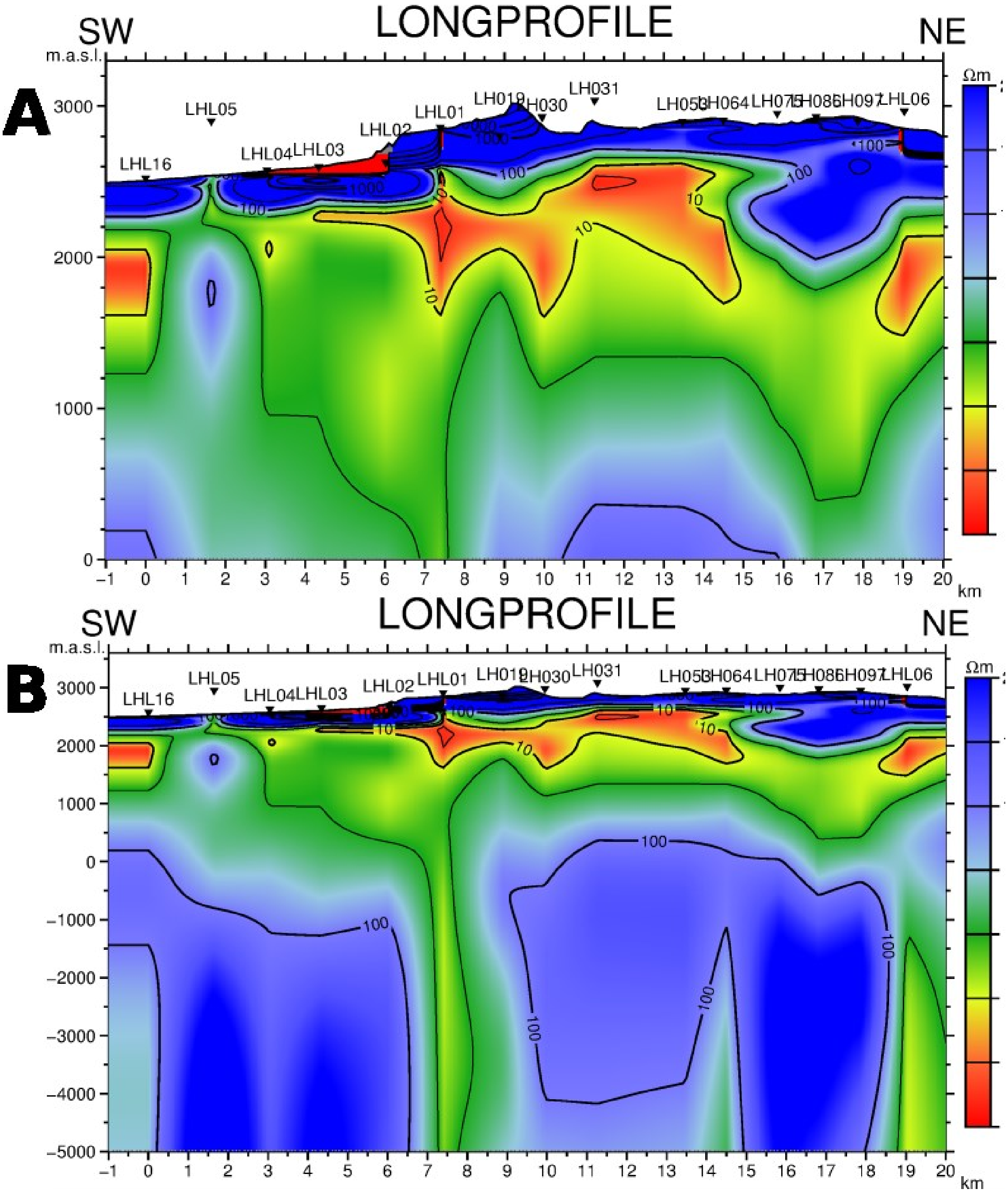

Figure 6: Vertical cross-section through the 1D resistivity model of Los Humeros, plotted down to sea level (A) and 5000 meters below sea level (B). Triangles at the surface are the soundings location with their names. The location of the cross-section is marked as LP on Figure 3.

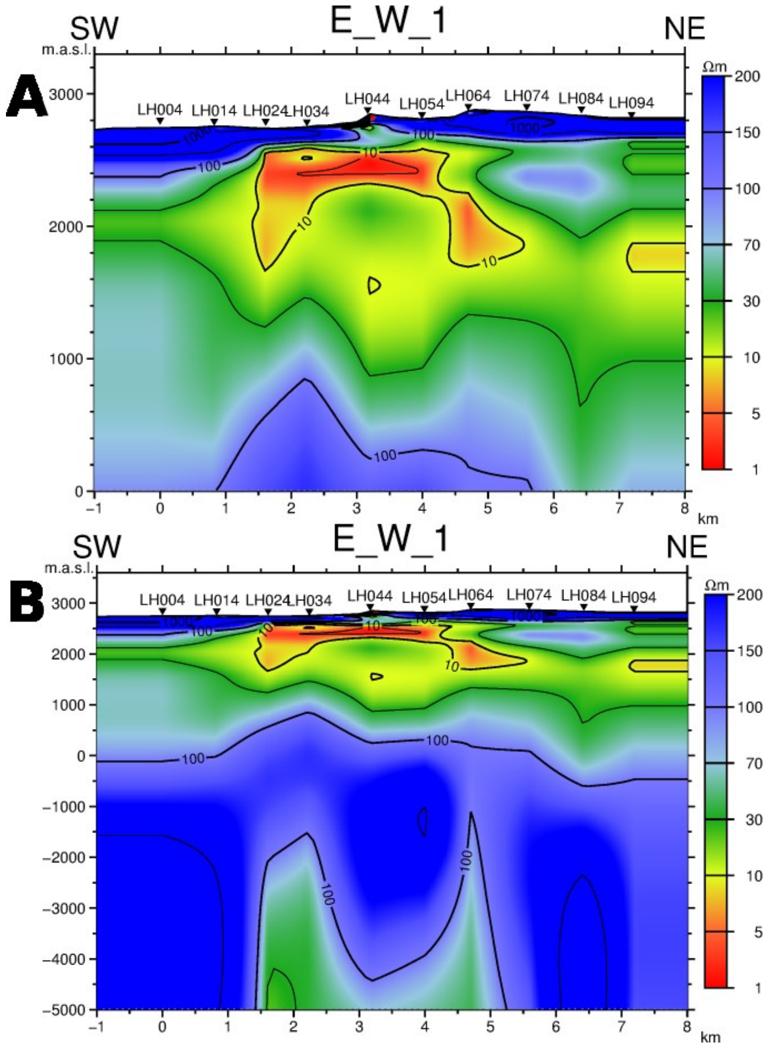

Figure 7: Vertical cross-section through the 1D resistivity model of Los Humeros, plotted down to sea level (A) and 5000 meters below sea level (B). Triangles at the surface are the soundings location with their names. Location of the cross-section is marked as P4 in Figure 3.

6. CONCLUSIONS

A 1D resistivity model of the Los Humeros area has been compiled from co-located MT and TEM soundings. The MT data were proccessed and quality checked prior to inversion. The resistivity structure of the area is complex and exhibits the structure found at high-temperature geothermal areas of volcanic origin.

REFERENCES

Arzate, J., Corbo-Camargo, F., Carrasco-Núñez, G., Hernández, J., & Yutsis, V.: The Los Humeros (Mexico) geothermal field model deduced from new geophysical and geological data. *Geothermics,* **71**, (2018), 200-211.

Árnason, K.: TEMTD a program for 1D inversion of TEM and MT data. Short manual. ISOR internal report, (2006b), 17 pp.

Chave, A. D., & Thomson, D. J.: Bounded influence magnetotelluric response function estimation. *Geophys. J. Int.*, **157**, (2004), 988-1006.

Constable, C.S., Parker, R.L., Constable, C.G.: Occam's inversion: a practical algorithm for generating smooth models from electromagnetic sounding data, *Geophysics,* **52**, (1987), 289-300.

Egbert, G., Booker, J.: Robust estimation of geomagnetic transfer functions, *Geophys. J. Int*., (1986), 173–194.

Gamble, T. D., Goubau, W. M., and Clarke, J.: Magnetotellurics with a remote magnetic reference. *Geophysics*, (1979), **44**, 53-68.

Held, S., Benediktsdóttir, Á., Arango-Galván, C., Hersir, G.P., Romo Jones, J.M., Cornjeco, N., Salas, J.L., Aviles, T., Brogi, A., Vilhjálmsson, A.M., and Schill, E.: The Los Humeros and Acoculco Geothermal Resources in the Trans-Mexican Voclanic Belt: Magnetotelluric Phase Tensor Analyses and its Significance for Tectonic Interpretation *Proceedings World Geothermal Congress Reykjavík, Iceland 2020*

Hersir, G.P., Arango-Galván, C., Benediktsdóttir, Á., Held, S., Romo Jones, J.M., Salas, J.L., Aviles, T., Aquilar, D.R., Vilhjálmsson, A.M., Manzella, A., Santilano, A.: The Acoculco Geothermal Resource in Mexico: Resistivity Survey (TEM and MT); Data Acquisition, Processing and Inversion – Geological Significance. Proceedings, *Proceedings World Geothermal Congress Reykjavík, Iceland 2020*

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. Vol. Geotherm. Res* **301,** (2015), 221-237.

Park, S. K. and Livelybrook, D. W.: Quantitative interpretation of rotationally invariant parameters in magnetotellurics. *Geophysics,* **54**, (1989), 1483–1490.

Ruiz-Aguilar, D., Benediktsdóttir, Á., Vilhjálmsson, A.M., Arango-Galván, C., Hersir, G.P., Romo-Jones, J.M., 2020. Different Strategies Applied to 3D Inversion of MT data from Los Humeros Superhot Geothermal Resource in Mexico- H2020 GEMex Project *Proceedings World Geothermal Congress Reykjavík, Iceland 2020.*