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

3D Joint Inversion of Gravity and Magnetic Data in Los Humeros and Acoculco Unconventional Geothermal Systems

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Keywords: Gravity, magnetic, joint inversion

ABSTRACT

Gravity and magnetic data have been largely used to characterize geothermal systems taking advantage of their large coverage and sensitivity to lateral heterogeneities associated with porosity and permeability. In this study, we present a 3D regional joint inversion of gravity and magnetic data from two geothermal targets in Mexico: Los Humeros Volcano Complex (LHVC) and Acoculco that includes the Enhanced (EGS) and Superhot geothermal systems (SHGS) We use a formal joint inversion strategy that relates density and magnetization trough a petrophysical equation. The resulting 3D density and magnetization models are examined. We observed a link between low density, low magnetization and major fault zones with high relevance to geothermal exploration, particularly evident in Los Humeros. Finally, the 3D magnetization and density models are expected to be used as important constraints in the electrical and seismic modeling which as a whole will help us to the construction and understanding of the geothermal conceptual model.

1. INTRODUCTION

In recent years, the increasing interest and high demand for renewable energies have led to the development of unconventional geothermal systems such as Enhanced Geothermal Systems (EGS) or more recently the study of Super Hot Geothermal Systems (SHGS). The GEMex project is a cooperation on geothermal energy research of a Mexican and European consortium focused on the study and development of two sites in Mexico. The first place is a candidate for EGS at Acoculco, within a Pliocene-Pleistocene volcanic complex with high temperatures found from two exploration wells but low permeability. The second place is a SHGS at Humeros, within a Quaternary volcanic complex with super hot temperatures about 380° C near a conventional system that is currently being exploited. In this context, one of the most important steps is the characterization of the reservoirs using multidisciplinary data integration which include geophysical imaging targeting both areas. Gravity and magnetic data modeling have been extensively applied to geothermal targets for structural and physical characterization. In this work, we used a joint inversion approach to take full advantage of both type of data. Joint inversion approaches have gained some attention due to the promise to reduce the range of acceptable models reproducing consistently all the geophysical data. They take advantage of i) the different kernels and null space for different data and, ii) reducing the effect of noise, which impacts in a different way to a different type of data (Moorkamp, et al. 2011).

2. METHODS

2.1 Forward and joint inversion modelling

We implemented a conventional forward formulation to calculate the gravity and magnetic fields for an ensemble of rectangular prisms. We used the formula derived by Plouff et al. (1977) to compute the vertical component of the gravity field due to the i-th rectangular prism with constant density. Similarly, to compute the corresponding total magnetic field of an individual rectangular prism, we use the formulation derived by Bhattacharyya (1966).

We then set an objective function for our 3D joint inversion problem that aims at finding the density (m_1) and magnetization (m_2) three- dimensional models that: i) fit, at a reasonable level, the observed vertical gravity (d_1) and magnetic (d_2) data, ii) are the simplest (the smoothest), iii) resemble any preconceived geological model (m_{01pr} , m_{02pr}), and iv) correlate both parameters through a correspondence map function $p(m_1 , m_2, a)$ following the iterative scheme proposed by Carrillo and Gallardo (2018).

$$\phi = \left\|\boldsymbol{C}_{dd1}^{-1}\left(\boldsymbol{d}_1 - f_1(\boldsymbol{m}_1)\right)\right\|^2 + \left\|\boldsymbol{C}_{dd2}^{-1}\left(\boldsymbol{d}_2 - f_2(\boldsymbol{m}_2)\right)\right\|^2 + \alpha_1\|\boldsymbol{hm}_1\|^2 + \alpha_2\|\boldsymbol{hm_2}\|^2 + \left\|\boldsymbol{C}_{mpr01}^{-1}\left(\boldsymbol{m}_{pr01} - \boldsymbol{m}_1\right)\right\|^2 + \left\|\boldsymbol{C}_{prm02}^{-1}\left(\boldsymbol{m}_{pr02} - \boldsymbol{m}_2\right)\right\|^2 + \left\|\boldsymbol{C}_{pp}^{-1}\left(\boldsymbol{p}_0 - \boldsymbol{p}(\boldsymbol{m}_1, \boldsymbol{m}_2, \boldsymbol{a})\right)\right\|^2 \quad (1)$$

2.2 Data and model parametrization

In Los Humeros, we calculated the Bouguer anomaly from gravity data of 1001 stations provided by the Comisión Nacional de Hidrocarburos (http://www.gob.mx/cnh) using a material density of 2670 kg/m^3. We use a second order polynomial fit to eliminate the regional trend to obtain the residual anomaly in the studied area (Figure 1). Aeromagnetic data were provided by the Mexican Geological Service (http://www.sgm.gob.mx/), 5165 measurements in total, were used along parallel lines in the N-S direction with an offset of 1 km and E-W direction with an offset of 5 km at 300 m flight altitude (Figure 1). The subsurface of the study area was discretized into 11968 rectangular volumes of constant properties with lateral extensions of 1 km (N-S) x 1.5 km (E-W) covering total lengths of 30 km in both, N-S and E-W direction. The Bouguer anomaly (-20.6 to 0.0 mGal total amplitude, Figure 1) and aeromagnetic data reduced to the magnetic pole (-278.7 to 674.7 nT, Figure 2) reveal low gravity and high magnetic responses in the caldera.

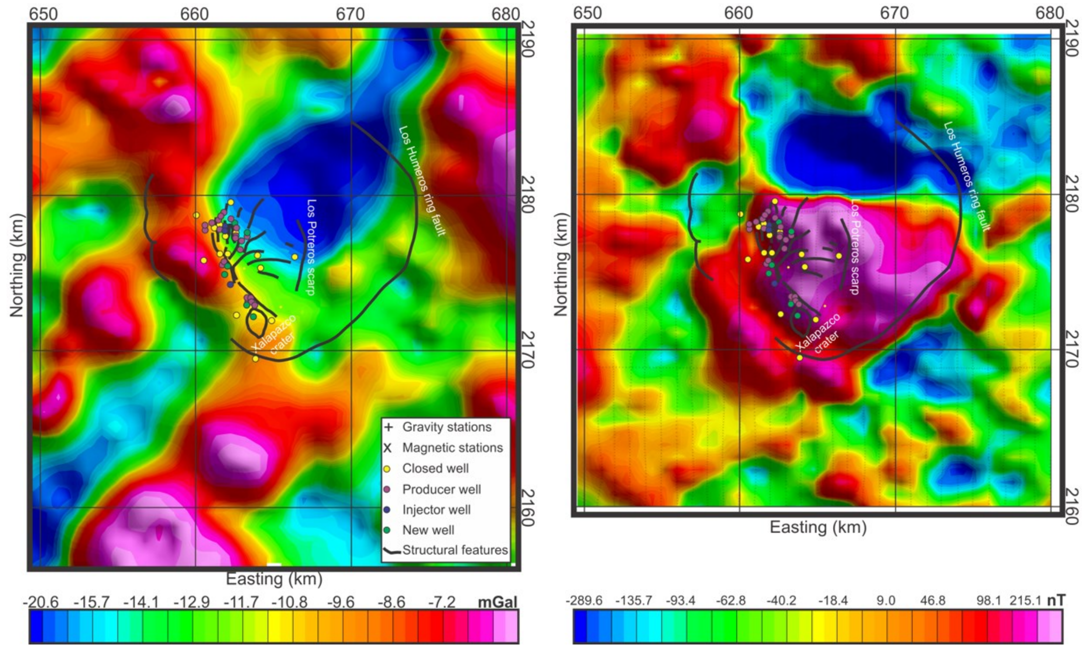

Figure 1: Residual of Bouguer anomaly and aeromagnetic data in Los Humeros.

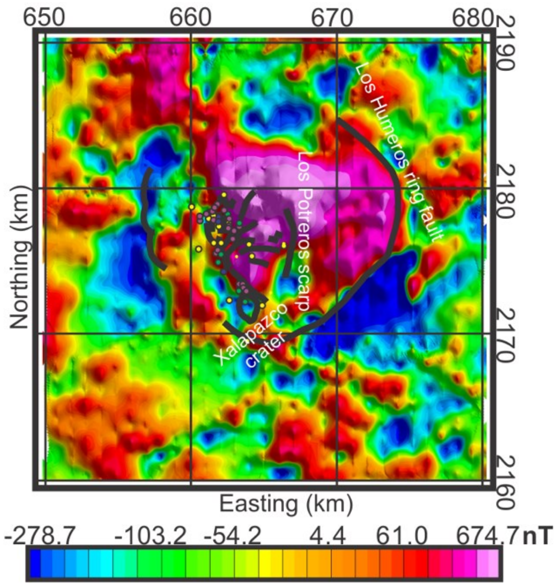

Figure 2: Aeromagnetic data in Los Humeros reduced to magnetic pole (RTP).

Similarly, in Acoculco we used 1483 gravity stations and 9367 aeromagnetic stations (Figure 3). The subsurface of the study area was discretized into 19584 rectangular volumes of constant properties with lateral extensions of 1 km (N-S) x 2.0 km (E-W) covering total lengths of 30 km in NS direction and 50 km in EW direction. In contrast to Los Humeros, the Bouguer anomaly in Acoculco (-9.7 to 8 mGal total amplitude) comprises various high gravity anomalies inside the Acoculco Caldera. The effect of the sedimentary basin expected as a minimum is probably hidden by the influence of intrusive rocks (López-Hernández, et al., 2009). Analogously, the magnetic anomaly reduced to magnetic pole (Figure 4) reveals a high magnetic response in some locations, the more extensive in the East limit of the calderas.

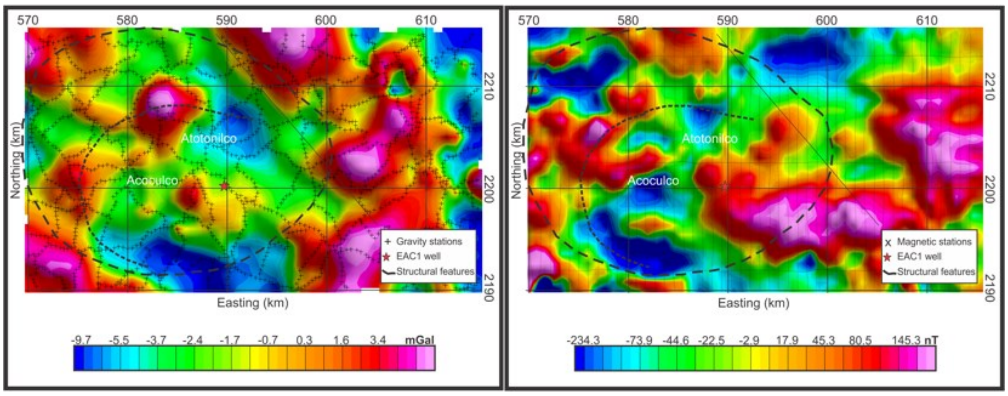

Figure 3: Residual of Bouguer anomaly and aeromagnetic data in Acoculco.

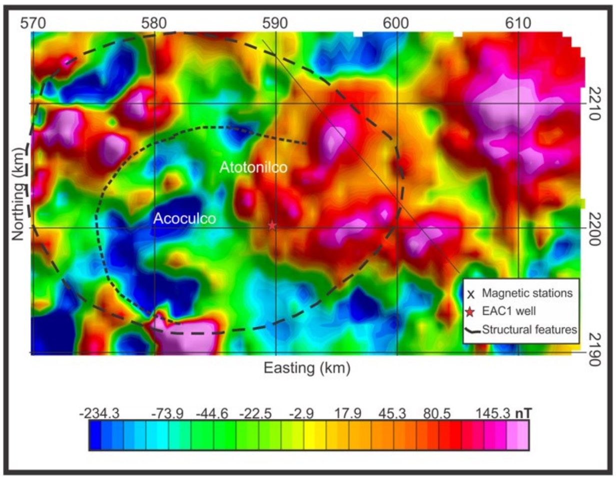

Figure 4: Aeromagnetic data in Acoculco reduced to magnetic pole (RTP).

3. RESULTS AND CONCLUSIONS

3.1 Los Humeros

The 3D model shows a range of densities from -400 to 400 kg/m^3 and magnetization from 0 to 5 A/m. The magnetization distribution reveals an anomalous body with high magnetization (5 A/m) producing the big dipolar anomaly observed in the data (Figure 1). While the gravity anomaly appears more diffuse, the magnetic anomaly is clearly delimited, in particular at depth. However, along the fault zones indicated in the E-W profile by comparably low magnetization between 1-2 A/m are dominant. Simultaneously, in the density contrast model, the same fault zones are characterized by comparably low density. The maximum thickness of the volcano sedimentary basin according to the 3D density distribution is about 4 km in the center of the caldera. The depth of the top of magnetic body seems to be below 2 km. However, other geophysical studies with better resolution at depth are proposed to resolve the ambiguity and there are other possible explanations to this big dipolar anomaly like magnetite accumulated along faulted paths (Árzate et al., 2017) in the volcano sedimentary units.

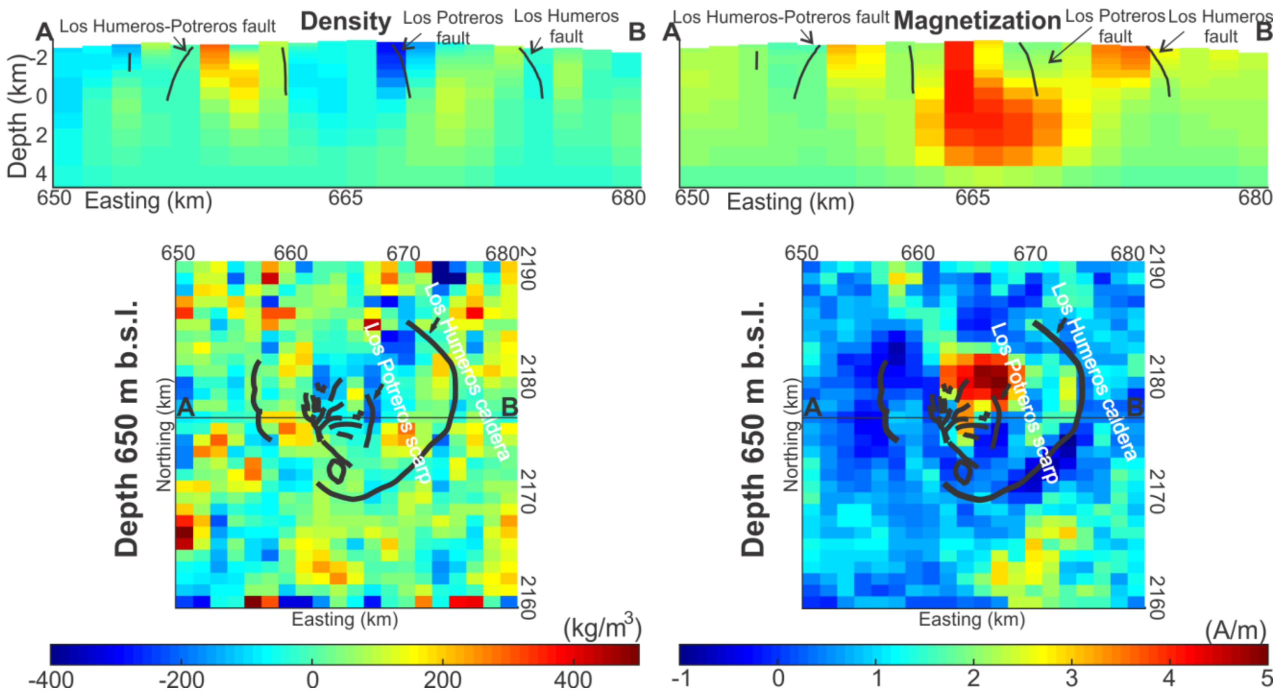

Figure 5: Density and magnetization models obtained from joint inversion in Los Humeros.

3.2 Acoculco

Acoculco density and magnetization distributions show a more complex area with no clear delimitation of the calderas. We have a range of densities from -500 to 350 kg/m^3 and magnetization from 0 to 2.5 A/m. Inside the calderas at least two high density bodies coexist (see Figure 6). As we mentioned in the gravity data analysis, this high density is not expected from the sedimentary basin, but it could be influenced by intrusive rocks. The magnetization distribution reveals a relatively high magnetization body in the Eastern part of the Acoculco Caldera (Figure 6, profile AB). In contrast to values of magnetization in Humeros, Acoculco shows lower values very close to zero.

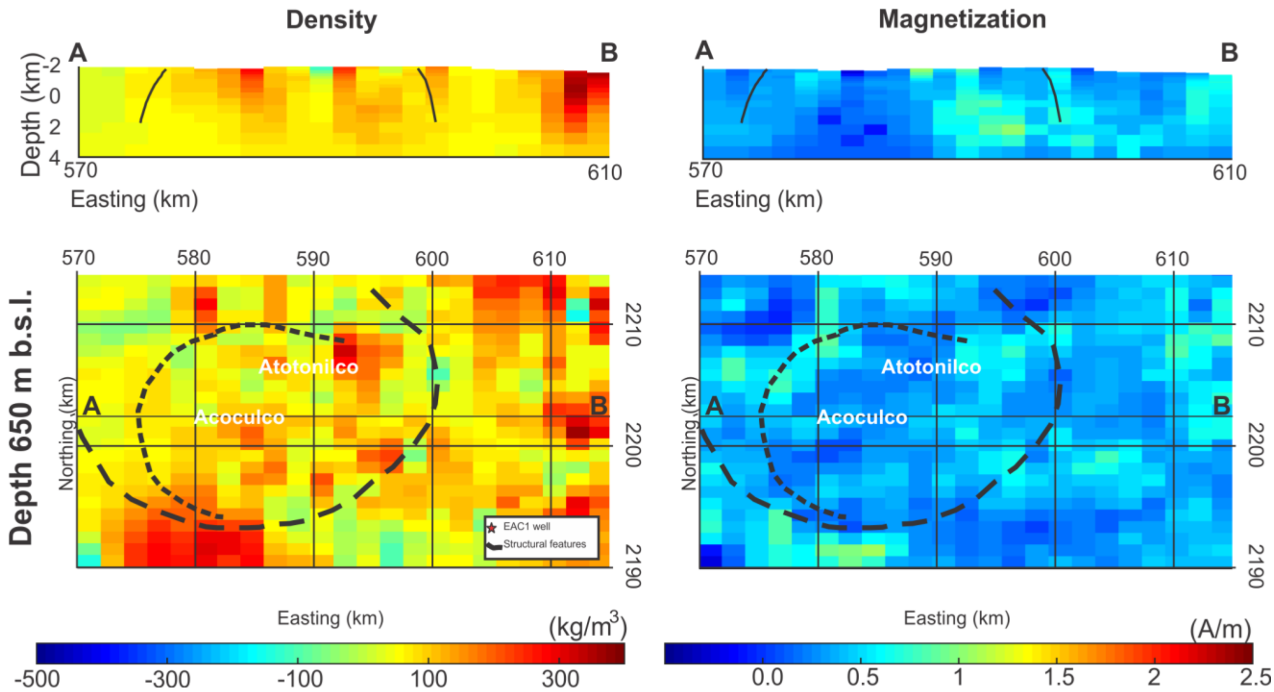

Figure 6: Density and magnetization models obtained from joint inversion in Acoculco.

REFERENCES

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

Bhattacharyya, B. K. (1966). A method for computing the total magnetization vector and the dimensions of a rectangular block-shaped body from magnetic anomalies. Geophysics, 31(1), 74-96.

Carrillo, J., & Gallardo, L. A. (2018). Joint two-dimensional inversion of magnetotelluric and gravity data using correspondence maps. Geophysical Journal International, 214(2), 1061-1071.

López-Hernández, A., García-Estrada, G., Aguirre-Díaz, G., González-Partida, E., Palma-Guzmán, H., & Quijano-León, J. L. (2009). Hydrothermal activity in the Tulancingo–Acoculco Caldera Complex, central Mexico: exploratory studies. Geothermics, 38(3), 279-293.

Moorkamp, M., Heincke, B., Jegen, M., Roberts, A. W., & Hobbs, R. W. (2011). A framework for 3-D joint inversion of MT, gravity and seismic refraction data. Geophysical Journal International, 184(1), 477-493.

Plouff, D. (1977). Preliminary documentation for a FORTRAN program to compute gravity terrain corrections based on topography digitized on a geographic grid (No. 77-535). US Geological Survey,.