Topographic influence on 3D MT data from Paucarani - Peru

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Abstract

The region of Paucarani, Peru, features highly rugged terrain with altitude variations of up to 2000 meters across a 60-kilometer radius. A model approximating the region's topography was constructed, and the topographic influence on MT data was quantitatively analyzed. Data were collected from 43 stations along six survey lines covering 80 km². An unstructured tetrahedral mesh was created using TetGen, incorporating digital elevation data from ALOS World 3D - 30 meters. Results show that topographic effects increase with frequency, significantly impacting MT responses, and highlighting the importance of accounting for topography in MT data interpretation.

Introduction

The topographic influence on 2D magnetotelluric data has been verified by Wannamaker et al. (1986), who observed that the H_x component parallel to the strike is particularly susceptible to topographic features. For 3D data, Nam et al. (2007) noted that topography induces galvanic effects in both TM and TE modes, with these effects increasing with the terrain slope. Consequently, several studies on 3D magnetotelluric inversion have incorporated topographic information into their models. For instance, Müller & Haak (2004) examined the effects of steep topography on the finite-difference inversion of the Merapi volcano dataset, while Usui et al. (2017) constructed an unstructured finite-element resistivity model of the Asama volcano, an area with significant surface topography variation. Additionally, Kumar et al. (2018) applied topography correction to magnetotelluric data from the Sikkim Himalayas. All these studies incorporated Digital Elevation Models (DEMs) to approximate the surface features in their meshes.

The incorporation of topographic information can increase the complexity and computational cost of calculating an inversion mesh, which makes necessary an analysis of its influence on 3D MT data and evaluation of the need to incorporate it into the inversion mesh. As a first step to set up the inversion mesh for the study of 3D MT data of Paucarani, Peru, we have built a simplified model approximating the region's topography and another with a plain surface, in each one we simulated surveys and compared the results to quantify the influence of the region's topography on the dataset.

To build the model with topography, we used a strategy similar to Usui et al. (2017), which extracted altitude information from a high-resolution DEM, constructed a triangular surface, and built an unstructured mesh using TetGen.

Region of Study

The Paucarani Region is in southern Peru, in the occidental region of the Andes Mountains at Palca District. This region has highly active volcanism and very sharp relief, as shown in Figure 1, featuring 64 volcanic fields, of which 4 have shown eruptive action in the last 500 years. The main morphological features of the region are the Nevado Barroso, a formation that comprises snow-capped mountains with up to a 60-degree slope, between 5100 and 5600 meters above sea level, composed of andesitic rocks. Swamps and bodies of water are located in its southeast region, at 4600 meters, some of which show brine or silica precipitations.

Associated with the region's volcanic fields, geothermal systems with high energy potential were identified in five areas: Tutupaca, Calientes, Borateras, Ancocollo, and Kallapuma-Chungara (Cruz Pauccara et al., 2019). To make this resource viable, a geophysical study was developed in 2017 employing several methods, including the magnetotelluric method.

The magnetotelluric survey was conducted over an 80 km² area along six measurement lines and 43 stations, with frequencies varying from 10^{-3} Hz to 10^{3} Hz in a NW-SE direction, perpendicular to the geological structures. In Robles (2022), the 2D inversion of the data indicated that conductive zones associated with geothermal sources are located in the eastern portion of the study region.

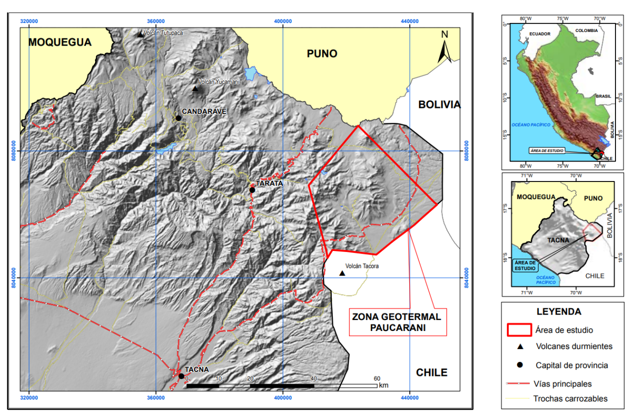

Figure 1 – Paucarani Geothermal Zone. (Cruz Pauccara et al., 2019)

Model Setup

The region's simplified model is an unstructured tetrahedral mesh built using TetGen (Si, 2015), and consists of an approximation of the region's topography. The simulated surveys were conducted at the same coordinates as the real survey, at 43 stations and the same frequency range. The reference height level of the coordinate system was chosen as the smallest height among the stations; the simulation with plain terrain puts all the stations at the smallest height.

We built the model in two stages. The first stage used Triangle (Shewchuk, 1996) to generate a bidimensional unstructured mesh of triangular elements using the coordinates of the Paucarani survey MT stations. We set up three regions in which the refining level decreases from inside out. In total, the simulated topography area is 5600 km², with 9385 nodes and 18,740 elements.

In the second step, the (x,y) node coordinates of the 2D mesh were used to extract the z coordinate from a Digital Elevation Model (DEM) in QGIS (QGIS Development Team, 2009). Following the criteria of free access, spatial resolution, and best accuracy, we chose the *ALOS World 3D - 30m* (JAXA, 2021), with 30 meters spatial resolution, generated with remote sensing information.

At last, the triangular elements were integrated in a .poly file as face composing the air-half space interface, then the file was processed by TetGen to generate the 3D mesh, as seen in Figure 2 and detailed in Figure 3.

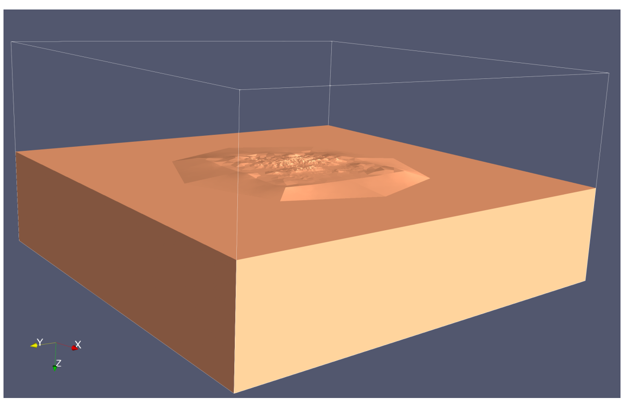

Figure 2 – 3D simplified model mesh, comprised of $97,612$ *nodes and* $711,070$ *edges.*

3D MT Modelling

We chose the mMT3D-TIV, which was implemented using the finite edge element method (Jin, 2015). The program was developed and validated by Professor Anderson Piedade (UFOPA) as part of the research project *Estudos de Métodos Eletromagnéticos Aplicados à Exploração de Hidrocarbonetos*, which seeks to develop human and technical resources applied to the oil and gas industry.

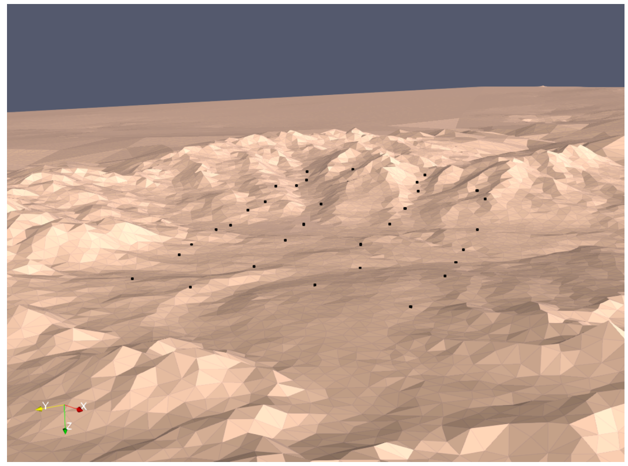

Figure 3 – 3D Topographic mesh detailed near to MT stations, shown as black dots..

Comparison Method

In a homogeneous half-space model, any variation in the magnetotelluric response will be a consequence of variations in the relief, according to the position of the stations along the surface. We simulated the magnetotelluric response, xy and yx impedance components, in the simplified model and compared it to the half-space plain topography response using the relative difference $D_r(\%)$ between both responses. Let d_p be the response of plain topography and d_t the response of the simplified model, we have

$$D_r(\%) = 100\% \times \frac{d_t - d_p}{d_p}. \tag{1}$$

These values are presented as colormaps with all stations' data at 2 Hz frequency. For the half-space, we chose 10 ohm-m as the resistivity.

Results

Our tests indicate that the relative difference between the responses with and without topography tends to increase with frequency. As expected, the apparent resistivity of the plain topography model is always 10 ohm-m and the phase $45°$. The mean of the relative difference for all apparent resistivity is 6.5%, and 3.3% for phase data.

To highlight the relation between topography and magnetotelluric response, we overlapped the simplified terrain contour with the colormaps.

For the frequency of 1 Khz, the difference in apparent has an overall increase, as shown in Figures 4-a and 4-b, with a mean difference of 13 %, almost twice the value for all frequencies. In this frequency, we can see a more pronounced polarized pattern difference, with the xy component even more affected.

The differences in phase results are shown in Figures 4-c and 4-d, with a mean difference of 13 %. We noted that for this frequency, the phase is more susceptible to variations than the apparent resistivity, and that the difference tends to increase near high slope.

At the frequency of 2 Hz, the differences in apparent resistivity results are shown in Figures 5-a and 5-b, with a mean relative difference of 7%. The observed difference is similar to the 2D case (Wannamaker et al., 1986); here, the xy difference tends to increase near high slope regions in the NE-SW direction, and the yx is more susceptible to the NW-SE slope.

At last the differences in phase, as shown in Figures 5-c and 5-d. For the frequency shown, the average value of the difference is 2.5%, indicating that the difference is phase reduces faster with the frequency than the apparent resistivity. In these results, we noted that the yx phase component is more susceptible to the topography, with higher variation; the behavior of both curves tends to oppose in value to those observed in the apparent resistivity.

Conclusion

This study highlights the significant impact of topography on the 3D magnetotelluric (MT) response in the Paucarani region, characterized by highly variable terrain with altitude differences up to 2000 meters within a 60-kilometer radius. By constructing a detailed unstructured tetrahedral mesh and incorporating high-resolution digital elevation data, we simulated and analyzed the topographic influence on MT data from 43 stations across an 80 km² area.

Our results show that topographic effects on MT responses increase with frequency, significantly impacting both apparent resistivity and phase data. Mean relative differences of 6.5 % for apparent resistivity and 3.3 % for phase data underscore the need to account for topography in MT data interpretation. At 1 kHz, differences in apparent resistivity and phase components were especially notable, with the xy component more affected by high slopes oriented NE-SW and the yx component by NW-SE slopes.

These findings align with previous studies on 2D and 3D MT data, highlighting the importance of including topographic information in MT inversion models for accurate subsurface characterization. Ignoring topographic effects can lead to significant misinterpretations, particularly in steep, complex terrains like Paucarani.

Incorporating topographic details into the MT model provides a more accurate subsurface representation and lays the groundwork for future inversion studies. This approach will improve the accuracy of identifying and characterizing subsurface conductive zones associated with geothermal sources.

The next step involves performing 3D MT inversion using the developed mesh to refine our understanding of subsurface structures and enhance the resolution of conductive zones. These insights will be crucial for advancing geothermal exploration and exploitation in the Paucarani region and similar geologically complex areas.

Acknowledgments

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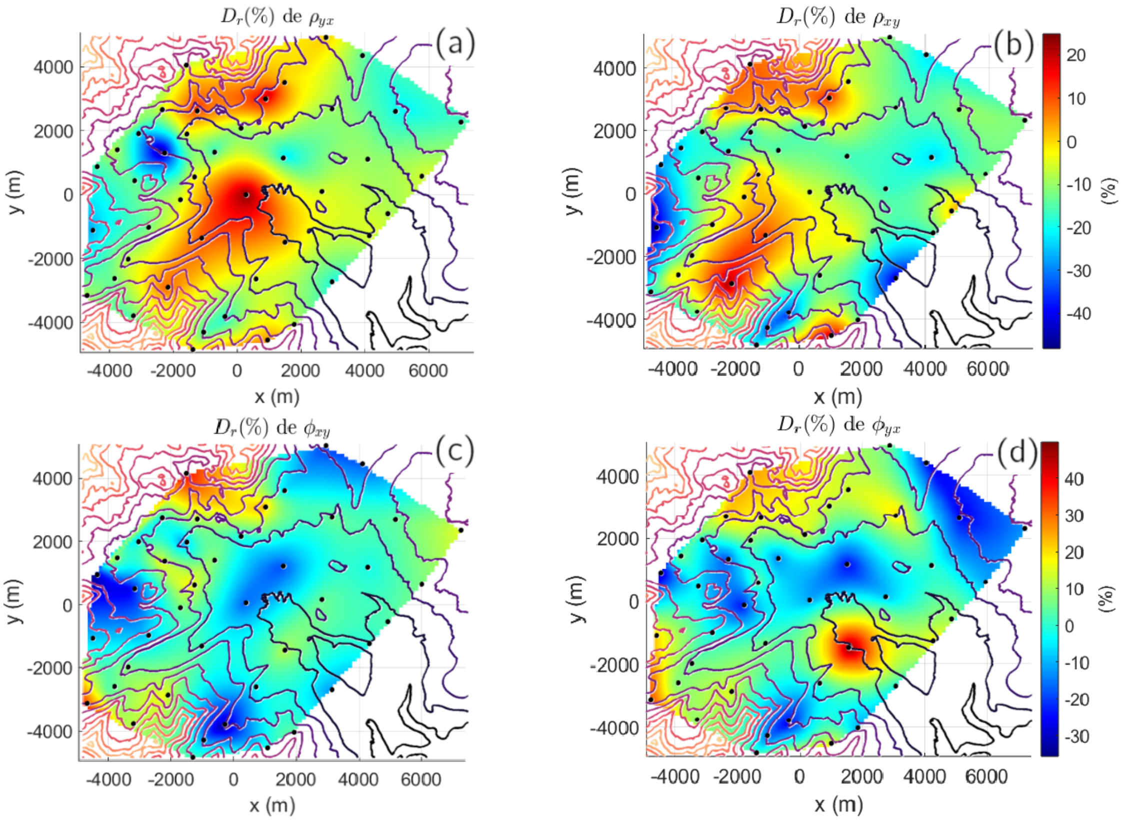

Figure 4 – Relative Differences to the true values at 1 kHz: Apparent Resistivity yx (a) and xy (b), and phase xy (c) and yx (d).

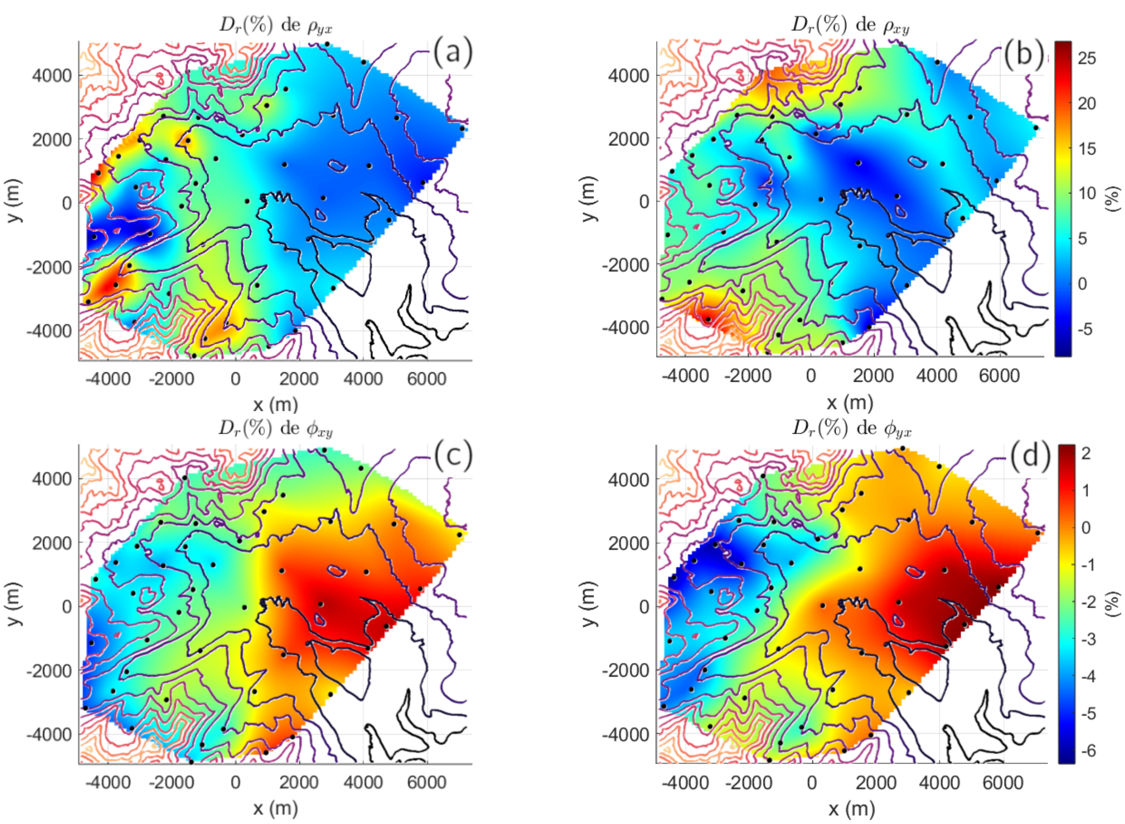

Figure 5 – Relative Differences to the true values at 2 Hz: Apparent Resistivity yx (a) and xy (b), and phase xy (c) and yx (d).