A magnetotelluric exploration of volcanic structures in the San Pedro - Ceboruco graben (Mexico): insights from 3D modeling

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Introduction

Imaging the architecture of volcanic systems is essential for understanding their evolution and assessing their potential as renewable energy resources. The magnetotelluric method (MT) effectively images volcanic plumbing systems by mapping the electrical resistivity distribution at depth. It places particular interest on **highly conductive zones**, which may be linked to magma, partial melt, or related fluids.
The **San Pedro-Ceboruco graben (SPCG)** is an extensional basin located in the central part of a wider tectonic structure called Tepic-Zacoalco rift in western Mexico. In this region, complex extensional tectonism is associated with the emplacement of volcanic and subvolcanic bodies, such as the active **Ceboruco stratovolcano** and the **San Pedro dome-caldera complex** (Ferrari et al., 2003).
As part of the DFG[1] and SPG[2] projects, a broad-band MT dataset was collected along the SPCG (**Fig.1**). These projects aim to characterize the electrical resistivity distribution of the magmatic systems located in this complex structural feature. The dataset was processed using the multivariate processing approach included within the FFMT software package developed at Frankfurt University. Here we present an **electrical resistivity model of the SPCG** derived from the **3-D inversion** of the full impedance tensor (**Z**) and tipper (**T**) of 41 sites. Geological and geophysical interpretations to understand the subsurface structures beneath the main volcanic features are still in progress.

Field campaign

From November 2021 to April 2022, a MT data acquisition campaign was designed to collect **25 stations** with 5 km spacing across a 30 km x 40 km area in the SPCG. Broad-band data were recorded between 400 Hz – 1,000 s at each station for about 72 h. Simultaneous MT stations at different locations were deployed to allow for multi-site processing. An MT dataset was previously acquired by Reykjavik Geothermal (RG) for geothermal exploration purposes. We have incorporated **16** of the RG sites to complement the information of our study area.

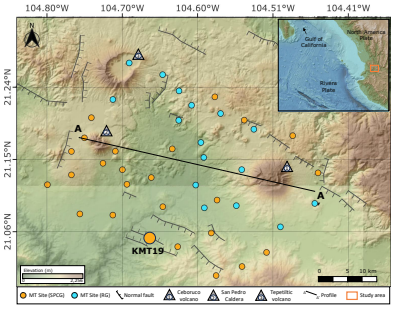

Figure 1. Location map of the MT sites distributed along the San Pedro-Ceboruco graben. Main volcanic structures are shown as (1) Ceboruco volcano, (2) San Pedro Caldera, and (3) Tepetitlic volcano.

Data processing

MT transfer functions (TF) were estimated using a multivariate processing approach based on the Eigenvalue decomposition method of Egbert (1997) and implemented in the **FFMT** software package developed in Frankfurt University. The algorithm minimizes coherent and incoherent noise, yielding better results compared to standard processing approaches (Hering, 2019). During the field campaign, at least three stations recorded simultaneously, allowing the application of multivariate processing scheme. **Figure 2** shows a representative site, illustrating the data quality, and highlighting the improvements in TFs achieved with **multi-site processing** compared to single-site.

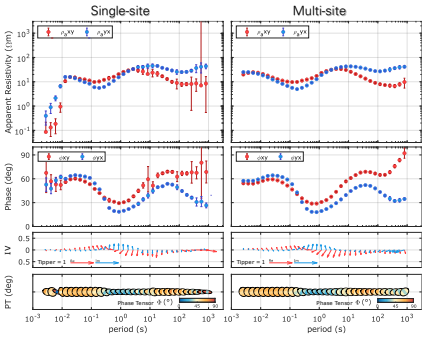

Figure 2. Period-dependent transfer functions (TF) for site KMT19. TF estimations are compared between single-site (left) and multi-site (right) processing. Notable improvements are observed at high frequencies. For longer periods, multi-site processing provides more consistent estimates with smaller error bars. From top to bottom: impedance tensor (z), phase, tipper, and phase tensor.

MT responses

The distribution of Phase Tensor (PT; Caldwell et al., 2004) and induction vectors (IV) throughout the GSPC dataset are shown in **Figure 3**. PT invariants are represented by an ellipse and orthogonal bar, color-coded by the maximum and minimum phase, respectively. For high frequencies (100 Hz), circular-shaped PTs suggest a 1-D conductivity distribution (Figure 3a). With increasing period, a split between the off-diagonal Impedance TFs (**Figure 2**) and the PT principal axes indicate a more complex geoelectric structure. **Figure 3b** displays large IVs pointing away from the center of the SPCG at 1 s, suggesting the presence of a conductive layer extending throughout the main study area.

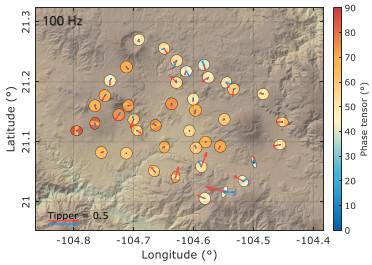

Figure 3a. Phase tensor ellipses map at 100 Hz. The color of the ellipses represents the maximum phase and the bar color the minimum phase of the PT. Phases above 45° suggest a transition to a conductive zone.

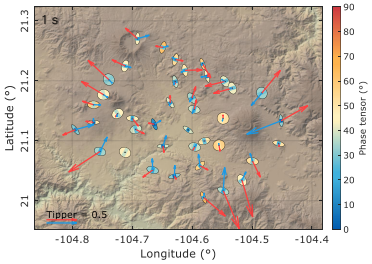

Figure 3b. Phase tensor ellipses map at 1 s. Phases below 45° suggest a transition to a resistive zone. Induction vectors point away from the center of the SPCG (Wiese convention), indicating a conductive structure beneath.

3-D Modeling

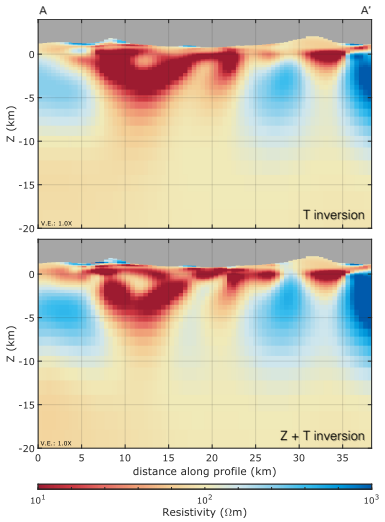

Figure 4. 3-D resistivity image derived from GSPC data revealed by individual inversion of tipper (top) and the joint inversion of both impedance tensor (Z) and tipper (bottom). Inversion models are displayed as slices along the A-A' profile. The resulting model from the tipper inversion was used as the initial resistivity model for the impedance tensor inversion. Results of both inversions are visually similar, as structures exposed by tippers remain. However, results from the inversion of both Z and T, refine and accentuate resistivity values of main geoelectric structures (bottom).

Model dimensions

The SPCG dataset was modeled using the **ModEM** 3D code (Kelbert et al., 2014). The model has a 40 km x 35 km inner mesh with 0.5 km horizontal cells. 23 padding cells were added laterally, increasing by a factor of 1.225. In the vertical direction, the first layer was 25 m thick, increasing by a factor of 1.125 to a depth of 479.79 km. Topography was included using **61 horizontal thin layers**. The size of the full mesh was 949 km x 944 km, comprising 126 x 116 x 126 cells in x, y a z. **41 sites** were inverted for periods between 0.0025 s and 1,000 s. The geomagnetic coast effect was considered assigning a resistivity of 0.3 Ωm to the ocean cells, as discussed in Castro et al. (2023).

Inversion parameters

Different inversion tests were performed to identify the optimal parameters setup for our dataset. The preferred model started from a 100 Ωm homogeneous half space. The selected initial damping factor was set to 1, with a chosen value of 0.3 for the smoothing parameter in all directions.

Tipper data was initially inverted to constrain lateral resistivity changes within the study area. Using the preferred setup, different error-floors were also tested, and the chosen value for tipper was set to 0.025 (absolute units). After a total of 36 iterations, the RMS misfit was reduced from 3.646 to 1.023.

Starting with the resistivity model derived from the tipper inversion, a stepwise methodology was applied for the joint **inversion of both full impedance tensor and tipper components**. We used error-floors ranging from 25% to 5% for the off-diagonal elements, represented as |Zxy*Zyx| ½ and 5% of |Zij| for diagonal elements. The error-floor for tipper was set to 0.025. Despite the attempts to achieve model convergence, the exit RMS value was not reached.

Inversion results

The 3-D resistivity model shows three different features along the A-A' profile: A **shallow conductive horizontal layer** is observed up to -1.5 km, centrally located and extending across the SPCG. This layer may correspond to **rock alteration** caused by hydrothermal fluids, aligning with some existing surface manifestations. Below this conductive layer lies an **intermediate resistive structure** that extends down to **-10 km**, potentially associated with the **granitic rocks of the Jalisco Block** (Ferrari et al., 2003). This resistive structure appears to be interrupted by **vertical conduits** beneath the Ceboruco volcano and the San Pedro Caldera edifices, which might represent pathways for fluid motion.

Outlook

The resulting model from the newly acquired MT data can aid to improve the regional geological understanding of western Mexico. It also provides additional information to the inferred knowledge from research done by Hering (2019) and Castro et al. (2023) along the SPCG. To improve the estimation of horizontal transfer functions, several inversion tests are required. Sensitivity studies will also be necessary to determine the existence of conductive structures beneath the SPCG. Our next step will be the inversion of the distortion-free phase tensor to tackle galvanic distortion.

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