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Research Paper

Determination of Subsurface Electrical Structures in Southern Sabalan Using Two-Dimensional Inversion of Magnetotelluric Data with the Adaptive Finite Element Method

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Abstract: The presence of numerous hot springs in the Sabalan region makes it a highly favorable area for geothermal exploration. In this study, magnetotelluric (MT) data were used to investigate the thermal origin of geothermal resources in the southern part of the Sabalan volcanic region. For this purpose, data from 13 MT stations along a survey line with varying station spacing were employed. Since magma exhibits lower electrical resistivity compared to the surrounding host rocks, it can be detected through the magnetotelluric method. Dimensionality analysis revealed shallow-to-medium-depth structures dominated by one-dimensional (1D) and two-dimensional (2D) geometries, while deeper structures exhibited three-dimensional (3D) complexity. A 2D isotropic inversion was performed using an adaptive finite element method, incorporating rapid Occam inversion to minimize the objective function. Sensitivity analysis was conducted to evaluate the reliability of the conductive structures resolved in the final model, confirming high accuracy and robustness. The model resulting from 2D inversion of the MT data demonstrates that one of the thermal sources of the geothermal system originates from the southern part of the Sabalan region. Furthermore, the migration of high-temperature fluids is controlled by fault-induced fractures in the southern part of the region, directing the fluids toward the northwest.

Keywords: Magnetotelluric (MT), Inversion, Adaptive finite element, Geothermal, Sabalan.

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INTRODUCTION

The Sabalan geothermal field, located in the northwestern region of Iran, is considered one of the most promising geothermal zones in the country. Its geothermal potential is evidenced by the presence of numerous hot springs, surface hydrothermal manifestations, and its location near the Sabalan stratovolcano [1,2]. These features have attracted continuous geophysical exploration since the late 1990s [3]. The region's geological complexity stems from its tectonic position over the collision zone of the Arabian and Eurasian plates. This tectonic interaction has resulted in significant volcanic activity, faulting, and the formation of a stratovolcano characterized by andesitic to rhyolitic lava flows. The Quaternary volcanic activity plays a crucial role in feeding and sustaining the hydrothermal system [4].

Historical MT surveys in 1997 and later campaigns in 2007 and 2009 have indicated the presence of multiple low-resistivity anomalies around the volcano. However, interpretations varied due to differences in modelling approaches, dimensional assumptions, and sparse data density in key areas like the southern flank [1].

In this study, a new 13-station MT survey line has been established across the southern slopes of Sabalan in the Dolar area. The goal has been to accurately delineate the subsurface resistivity structure using adaptive finite element 2D inversion, identify potential heat sources, and understand the influence of tectonic features such as faults in controlling geothermal fluid migration.

METHODS

MT data were acquired using Phoenix MTU-5A equipment capable of capturing natural electromagnetic signals across a wide frequency range. The MT dataset consisted of five-component time series (three magnetic and two electric fields) recorded at 13 stations with variable spacing across a 12.3 km transect crossing several fault zones. The raw data were processed using the SSMT200 software to obtain impedance tensors, from which apparent resistivity and phase responses were derived [5]. Dimensionality analysis was performed using the phase tensor method [6], which indicated dominantly 1D and 2D behavior at shallow to intermediate depths and 3D structures at greater depths. To assess signal penetration, the Niblett-Bostick skin depth [7-9] approach was applied, estimating reliable penetration depths of up to 10 km depending on the station and mode (TE or TM).

The inversion was carried out using MARE2DEM [10], an adaptive finite element inversion tool. This method constructs an unstructured triangular mesh that conforms to topography and subsurface gradients. The Occam inversion algorithm was employed to regularize the model, minimize the RMS error, and balance model smoothness with data fit. The initial model was a homogeneous half-space of 10 Ωm.

FINDINGS AND DISCUSSION

The final resistivity model revealed four main structural units: (1) a shallow resistive layer (R1) associated with surface rocks, (2) a conductive cap (C1) interpreted as a clay-rich alteration zone, (3) a mid-depth resistive layer (R2), and (4) a prominent deep conductive anomaly (C2) situated between 4.5 and 8 km depth (see Figure 1). This C2 anomaly is spatially associated with mapped faults and is interpreted as a geothermal heat source.

Sensitivity analysis was conducted by replacing the C2 anomaly with a high-resistivity (1000 Ωm) body. The resulting increase in RMS error (by 19%) validated the importance and reliability of the C2 feature in the obtained model from the inversion. This suggests a fluid- or melt-rich zone likely contributing to the regional geothermal system.

A comparison of the inversion-resulting model with previously obtained models and geological maps shows good agreement between them in terms of fault alignments and low-resistivity bodies. The role of fault structures, particularly those trending northwest-southeast, appears critical in controlling the ascent and horizontal flow of geothermal fluids, aligning with global conceptual models of geothermal systems.

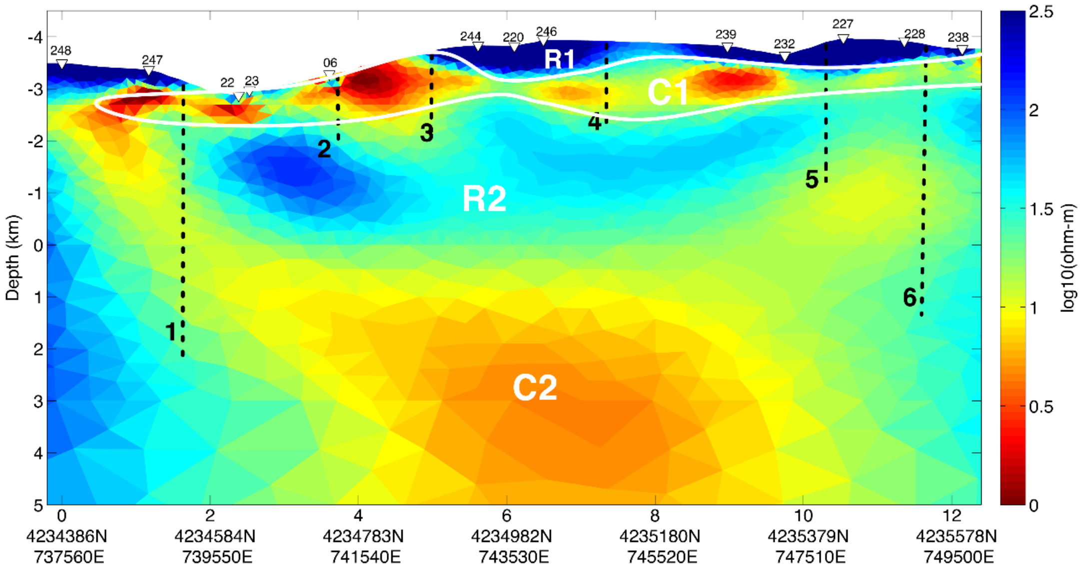

Figure 1. The final section resulting from 2D inversion of the MT data. Inferred faults are shown with black dashed lines

CONCLUSION

The application of adaptive finite element 2D inversion to MT data in the southern Sabalan geothermal field successfully leads to delineation of major resistivity structures. The identification of a deep conductive zone (C2) and its association with regional faults confirms the presence of a magmatic heat source and active fluid pathways.

These findings enhance understanding of the geothermal system in the Sabalan region and support further exploration. By integrating resistivity modelling, geological context, and structural interpretation, this study provides a robust geophysical basis for future drilling and sustainable geothermal resource development.

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