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High-frequency Magnetotelluric Study for Better Understanding of Subsurface Formation of the Geological Manifestation at the Mogod

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Summary

Mogod Soum, Bulgan aimag, is located in the eastern part of Khangai Dome. During the winter, the soum is heavily affected by air pollution due to coal burning. Using geothermal resources in the region, manifested by hot springs, could dramatically reduce air pollution. To understand the nature of the geothermal reservoir feeding the hot springs, we conducted Magnetotelluric surveys in the Mogod hot spring region during the fieldwork in 2020, 2021, 2022 and 2024. To obtain a subsurface electrical conductivity model of the hot spring area with magnetotellurics, we inverted data from 60 unique sites. As a tool for inversion, we used a high-order finite element code available to locally refined unstructured meshes to ensure numerical accuracy with a sufficiently fine discretization of the inversion domain while keeping the computational cost feasible. We inverted the full impedance tensor to recover a 3-D electrical conductivity model. The best-fitting model provides important new insights into the subsurface structure of the Mogod region.

Introduction

In the Khangai region, more than 30 hot springs, with temperatures up to 90°C, suggest that a geothermal resource exists in the subsurface related to past volcanic activity. One hot spring area that appears to hold the largest geothermal energy potential is the Mogod geothermal area, located at Mogod soum in the Bulgan province in central Mongolia. Near Mogod town, there is the Khulij hot spring, which has several manifestations. These hot springs reach temperatures up to 52°C and are interpreted as the surface expressions of a larger low-enthalpy geothermal system. The formation of the Mogod geothermal area can be explained by the remains of quaternary volcanic activity that covered the region with volcanic rocks.

During 2016-2019, a regional magnetotelluric (MT) survey of the Khangai and Gobi-Altai mountains was conducted (Comeau et al, 2018, 2020, 2022; Kaufl et al, 2020) The results of these studies revealed a deep-rooted conductivity anomaly in the eastern Khangai region, including beneath the Mogod geothermal area that reaches down into the upper mantle (Käufl et al. 2020). The anomaly was interpreted to be caused by small fractions of melt, suggesting that a long-lasting geothermal heat source may exist. In addition, several geophysical joint projects from the Institute of Astronomy and Geophysics and international colleagues conducted geomagnetic, gravimetry, and passive seismicity surveys in this region to understand the deep roots of the seismically active fault system. However, the lack of deeper geophysical methods source-related deep structure has not explained the structure of the region.

During the summers of 2020-2024, we conducted separate high-resolution MT surveys in the Mogod geothermal area. The MT method has the highest potential of geophysical methods to image deeper structures that could explain the formation of the Mogod fault. For the MT surveys, we made use of the so-called inter-site transfer function approach, which allows to increase the amount of acquired data by replacing a part of full MT stations with telluric-only stations (TMT), which reduces equipment costs and installation time in the field (Kruglyakov & Kuvshinov, 2019). The presented model was obtained by a 3-D inversion of data from 65 MT sites deployed during the first survey in 2024. We will consider data from all >100 sites deployed in 2020, 2024 and 2025 for the final model. The MT data was inverted using an adaptive finite-element code by Grayver (2015).

Method

The MT method is used to image the subsurface electrical resistivity distribution by making use of natural electromagnetic induction that originated in the atmosphere and ionosphere (e.g., Cagniard, 1953). MT data are especially sensitive to the composition of low-resistivity materials in the subsurface, such as fluids, and are well-suited to image the structure of fault zones, suture zones, and tectonic boundaries, as well as volcanic zones, and mineral zones (see Comeau et al., 2024).

MT forward and inverse modelling techniques and approaches were used to obtain the 3-D conductivity distribution of the subsurface in the region of interest. The MT forward modelling implies computing the electric and magnetic fields at an observation site and specified frequencies in a given 3-D conductivity model excited by a plane wave source of a given polarization. The computed electric and magnetic fields from two orthogonal polarizations are then used to calculate MT responses at specific sites and frequencies in the model. MT inverse modelling implies the recovery of the 3-D conductivity distribution from the observed MT responses from measured electric- and magnetic field variations at specific locations in a survey area. Note that the inversion process involves multiple runs of forward modelling and comparison of observed and predicted MT responses until a good fit is achieved.

Model results

The final model was obtained after 49 iterations when the global root-means squared error (RMSE) misfit decreased from 14.4 to 1.2. The model contains several significant and pronounced electrical conductivity anomalies, which we will discuss in the following. In general, the main sensitivity range of the observed MT data is in the depth range from 200 m to 15 km, given the frequency content of the data (0.01-0.025 Hz) and the aperture of the survey layout. The modelling mesh is coarser in deeper cells, which expresses the lower sensitivity there. Overall, the electrical conductivity features are very heterogeneous and non-uniformly distributed. The model contains numerous prominent electrically conductive features that provide important information about the nature of the geothermal reservoir. A dominant feature is a crustal resistor (2,000 – 10,000 Ω) at depths from 2 km to 15 km in the south. This feature can be explained by the dry, compact, and, therefore, highly resistive Precambrian cratonic basement rock predominantly consisting of granites. Most of the more conductive features have electrical conductivities of 0.001 − 0.1 S/m and exist over the entire region.

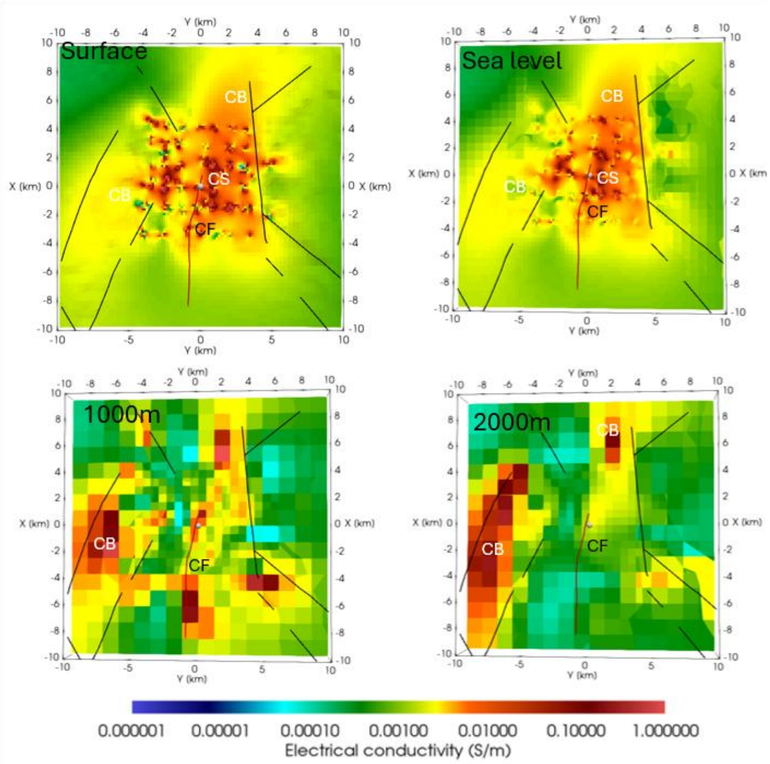

Figure 1 Horizontal slices of the 3-D conductivity model at the surface, sea level, 1000 m below sea level, and 2000 m below sea level. The black and red lines indicate fault traces.

Discussion

We consider the non-deep-rooted near-surface moderate conductivity anomalies in the northern and western parts of the study area, denoted as CS and CB, in the following interpretations (Figure 1 and Figure 2). The spatial characteristics of these anomalies are related to basaltic lava flows CB and the flat sediments along the river basins near the settlements CS. The non-deep-rooted anomalies have a conductivity of 0.01 − 0.02 S/m and are subdivided as sedimentary CS and basaltic CB types based on their spatial distribution and geological formation. Considering the geological situation of the environment, the CS type of conductivity features likely represent water-rich sedimentary rocks, which have high porosities. Sediments are widely distributed in the study area. Geological faults and fractured zones can also play a significant role in saturating porous rocks with river water. The north-to-south-orientated faults (CF) indicate the main direction of the river basin. Therefore, it can be interpreted that CS anomalies are fluid-saturated by fault-controlled shallow-depth river water circulation and saturation of the sedimentary rocks since CS anomalies are widely distributed around the faults. In addition, the CS conductivity anomalies disappear at < 3 km below the surface (Figure 1), likely the depth when the sedimentary overburden meets the more resistive granitoid basement rock. The CB conductors occur correlated with volcanic basalt and basaltic dyke intrusion. They might represent remnants of past volcanic activity, such as hydrothermally altered rock surrounding the area of relic magmatic pathways, where host rock was altered during magma emplacement. The conductors extend continuously down to 5 − 6 km below the surface.

The strongest and most deep-rooted electric conductivity feature appears southwest of the survey area as structure C2 (Figure 1). The plume-shaped body of C2 has high electrical conductivity up to > 1 S/m, rising like a plume from the lower crust. In summary, the recovered 3-D electrical conductivity model contains features such as the intrusive granitic basement, fluid-saturated sediments and volcanic rocks CS and CB, and the essential conductors to explain the Khulij geothermal system CF. Additionally, MT significantly helps in imagining the fault-plane (Figure 2). Figure 2 shows the iso-surface of the dee-rooted conductor and its relation to surface manifestations of the fault traces.

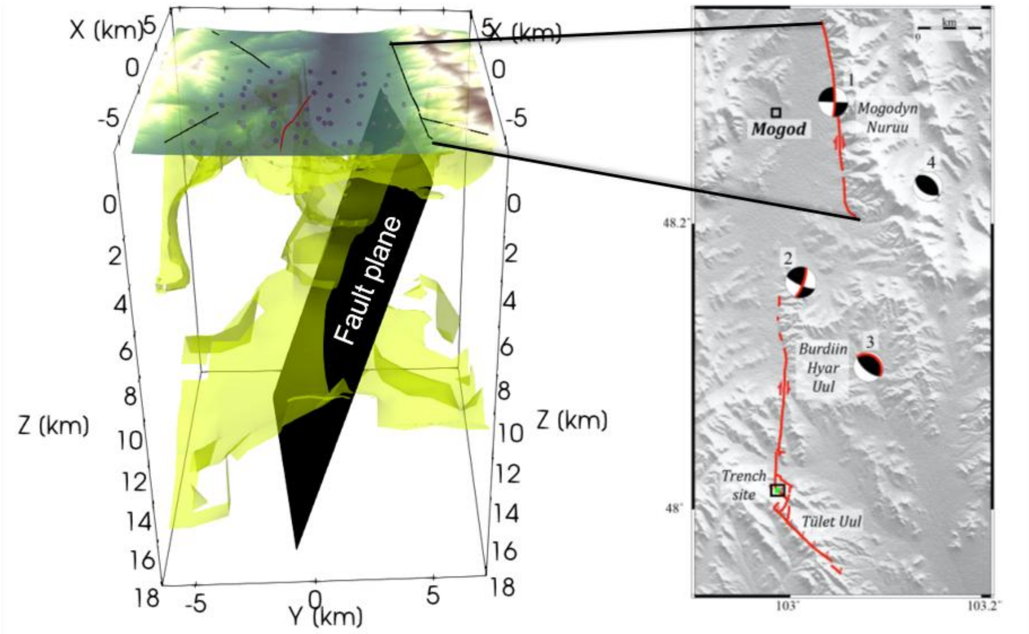

Figure 2: The 3-D electrical conductivity model with annotations of the conductors CS, CB, CF, and C2. Measurement sites are indicated at the surface with black circles. Conductivity is shown as an iso-contour with a value of 50 ohm-m. The right panel shows a map of the fault zone (red lines) and major earthquakes.

Conclusions

We present here the first 3-D electrical conductivity subsurface model obtained to better understand the subsurface structure of the Khulij geothermal area in the Mongolian Khangai. The recovered model shows an electrically conductive anomaly in the electrically resistive upper crust, where the former rises under the Khulij geothermal area from a lower crustal zone of melting to the land surface. Therefore, this anomaly might be a key feature in understanding the heat source's nature and the hot spring's formation at the surface. In general, our MT model suggests that strong deep conductors exist in the north and south of Mogod town, which could be related to the deep source of the hot springs. Moreover, the intersection of the buried faults could explain the hot springs' manifestation. With this concept, we successfully implemented a 3-D inversion in the Mogod region, and the obtained model explains the key parameters of the pathways of thermal fluid flow from source to surface and heat sources.

Outlook

As a next step, we will concentrate on inverting the data from all 77 MT stations on a regional scale to obtain a multi-scale 3-D model. The higher MT site density is expected to promote improved imaging of the channel-like conductor C2 and how it is connected to the hot springs at the surface. This investigation should help identify hot aquifers and promising target zones for future geothermal drilling. In addition, we plan to interpret the electrical conductivity model with geological, geochemical, and other geophysical data, such as seismicity, gravity, and magnetics. This will hopefully enable a better understanding of the location of hydrothermal fluid circulation paths and the geothermal aquifers that feed the hot springs in the region.

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