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Deep-rooted geothermal system imaged by magnetotelluric surveys under the Tsenkher hot spring area, Mongolian Hangai

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ABSTRACT

Tsetserleg city is located in the eastern part of Hangai dome. During the winter, the city is heavily affected by air pollution due to the burning of coal. Using geothermal resources in the region, manifested by the presence of hot springs in the region, could dramatically reduce air pollution. To understand the nature of the geothermal reservoir feeding the hot springs, we conducted magnetotelluric surveys in the Tsenkher hot spring region south of Tsetserleg in 2019 and 2020.

To obtain a subsurface electrical conductivity model of the hot spring area with magnetotellurics (MT), we inverted data collected in 2019 and 2020 at 126 MT sites, from a total of 306 sites, obtained in the Tsenkher geothermal area. For 3-D modelling and inversion of the MT data we used the high order finite element code GoFEM (Grayver, 2015). Locally refined unstructured meshes are used to ensure numerical accuracy with a sufficiently fine discretization of the inversion domain, while keeping the computational cost feasible. To recover a 3-D electrical conductivity model, we invert the full impedance tensor rotated into geoelectric strike direction.

The best fitting model provides important new insights into the subsurface structure of the Tsenkher geothermal region. The model is characterized by a prominent crustal conductor that appears under the hot spring areas and rises from depths of more than 10 km to the surface. We interpret the conductor as being related to local volcanism and as a zone rich in partial melt and magma-derived fluids, serving as the heat source feeding the hot springs.

1. INTRODUCTION

The Mongolian Hangai dome is an intra-continental mountain range, located far away from tectonic plate boundaries. The dome is characterized by young dispersed low-volume intraplate Cenozoic volcanism (Walker et al. 2007, 2008; Barry et al 2003; Hunt et al. 2012; Ancuta et al. 2018). Present volcanism and its origin mechanisms are often explained by the uplift of the dome. In the Hangai region, more than 40 hot springs, with temperatures of up to 90℃, suggest that a geothermal resource exists in the subsurface. One of the hot spring areas that appear to hold the largest geothermal energy potential is the Tsenkher geothermal area, located near Tsetserleg in the Arkhangai province in central Mongolia. Near Tsetserleg city, three main hot springs exist, namely Tsenkher, Gylgar and Bortal. These hot springs reach temperatures of up to 87℃ and are interpreted as the surface expressions of a larger mid-enthalpy geothermal system. The formation of the Tsenkher geothermal area can be explained by the remains of quarternary volcanic activity, that covered the region with volcanic rocks.

Currently, geothermal fluids of hot springs in the Arkhangai province are used in a few places for greenhouse heating and for recreational spas. Hosting the largest hot spring, and due to its proximity to the region's capital Tsetserleg, the Tsenkher geothermal area is where geothermal energy utilization and studies are most advanced. Feasibility studies for the construction of a geothermal combined heat and power plant (CHP) at the Tsenkher hot springs have concluded that using geothermal energy for heat and electricity generation in Tsetserleg city would be economically viable and cheaper than burning coal (Dorj et al. 2005; Javzan 2006). The studies estimated that a CHP plant could achieve a capacity of 1.9 MWe of electrical power and of 16.7 MWth of heat production with an inlet flowrate of 80 kg/s at a temperature of 120℃ (Dorj et al. 2005). Hence, the construction of a CHP plant, utilizing the geothermal resources near Tsetserleg, is strongly recommended, employing economical, environmental, and social considerations. However, geothermal exploration wells, drilled in the Tsenkher geothermal region, were, until now, not productive. A reason for this is that the geophysical exploration program conducted prior to drilling was not complete. Although geophysical surveys had been conducted at the Tsenkher hot springs, they only focused on the shallow subsurface (depth ≤150m), i.e. excluding any imaging of the deeper geothermal reservoir and its source region.

A geophysical exploration method, that is especially useful in geothermal exploration, is magnetotellurics (MT). MT measures natural time-varying electromagnetic fields, from which the subsurface electrical conductivity structure can be recovered by solving a numerical inverse problem. During geothermal exploration, probing electrical conductivity is especially useful in order to interpret subsurface geological structures, as, for example, water-bearing rocks, faults, and hydrothermal alteration zones can be identified relatively easily, given their relative higher electric conductivity, compared to undisturbed basement rock. During, 2016-2019, a regional MT surveys of the Hangai and Gobi-Altai mountains were conducted (cf. Comeau et al, 2018, 2020, Kaufl et al, 2020) The results of these studies revealed a deep-rooted conductivity anomaly beneath the Tsenkher 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.

During the summers of 2019 and 2020, we conducted a separate high-resolution MT surveys in the Tsenkher geothermal area south of Tsetserleg. In addition to MT investigations, we conducted geomagnetics, gravimetry, and a passive seismicity surveys. For the MT surveys, we made use of the so-called inter-site transfer function approach, which allowed us 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 et al. 2019). The here-presented model was obtained by 3-D inversion of the data from 126 MT sites deployed duringthe first survey in 2019. For the final model we will consider data from all 306 sites deployed both in 2019 and 2020. The MT data were inverted using an adaptive finite-element code by Grayver (2015).

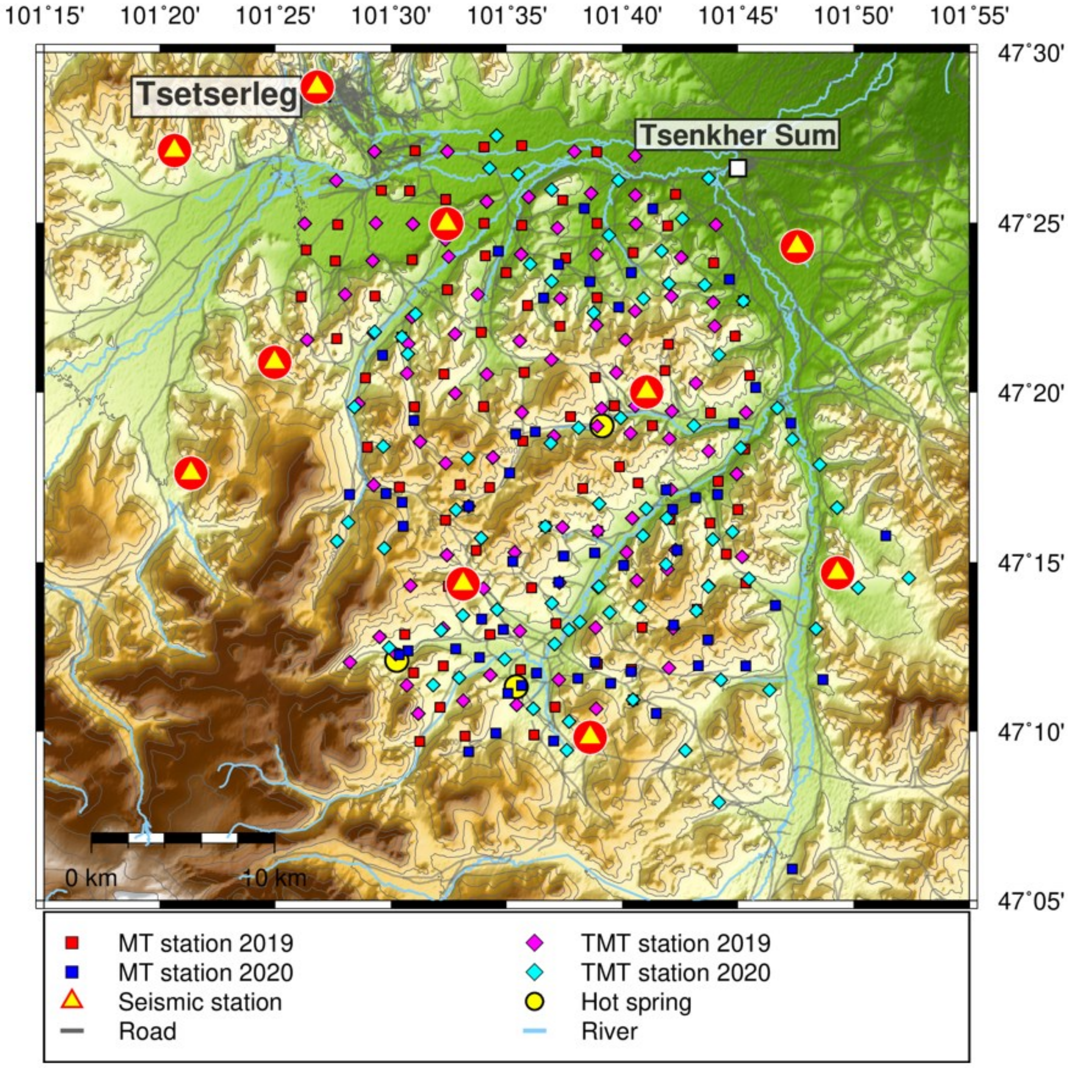

Figure.1: Map of the study region with the locations of the hot springs as well as the MT and seismicity sites from the surveys conducted in 2019 and 2020.

2. MT METHOD

Magnetotellurics is a passive geophysical sounding method to determine the electrical conductivity distribution in the Earth's subsurface. The main transfer function of the MT method is the impedance tensor, ***Z***. ***Z*** relates the frequency-dependent electric, ***E***, and magnetic, ***H***, fields at a location, ***r***, at the Earth surface. Here, we supplement the standard MT method by also using the telluric-magnetotelluric method (TMT), which makes use of so-called inter-site impedance tensors. The inter-site impedance tensor relates the electric field at site $\boldsymbol{r}_f$ with the magnetic field at a base site, $\mathbf{r}_b$, for an angular frequency ω:

$$E(r_f, \omega) = Z(r_f, r_b, \omega) H(r_b, \omega). \quad (1)$$

The advantage of the TMT method is that measurements can be performed using a reduced number of full MT-stations, which minimizes the time required for fieldwork. The impedance tensor, ***Z***, contains information about the 3-D electrical conductivity distribution in the subsurface (e.g. Simpson & Bahr, 2005). $\boldsymbol{Z}$ is the magnetotelluric impedance tensor in a Cartesian coordinate system, where x points north, y points east, and z is positive downwards. The elements of the impedance tensor, $\boldsymbol{Z}$, are defined as:

$$\boldsymbol{Z} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}. \tag{2}$$

Hence, we can determine the electrical conductivity distribution of the subsurface from a 3-D numerical inversion of the impedance tensor. In this study we used the GoFEM code for solving the forward and inverse problem (Grayver, 2015). An advantage of this code are automatic mesh refinements that account for site locations and resolution of the data, enabling accurate incorporation of topography (Käufl et al., 2018).

3. DATA PROCESSING AND RESULTS

In this study, we analyze MT data from 126 measurement stations that were collected during a survey in 2019. MT transfer functions were calculated using robust single site and remote reference processing routines and applying notch filtering to the measured time series in order to eliminate periodic cultural noise (Harpering, 2018). The time series were manually pre-selected and remote reference processing gave transfer functions of generally high quality. We also performed a geoelectric strike analysis using the phase tensor formalism (Caldwell, 2004). Figure 2 shows the obtained MT phase tensor ellipses at two periods: T= 1/32s and T = 1s. The orientations of the ellipses show the geoelectrical strike direction. We observed that the dominating strike direction for those periods is approximately 15-45° clockwise from north. This is in agreement with the orientation of the main fault system in the area. Hence, for the 3-D inversion of the data, we rotated the MT responses by 40° into the geoelectric strike direction.

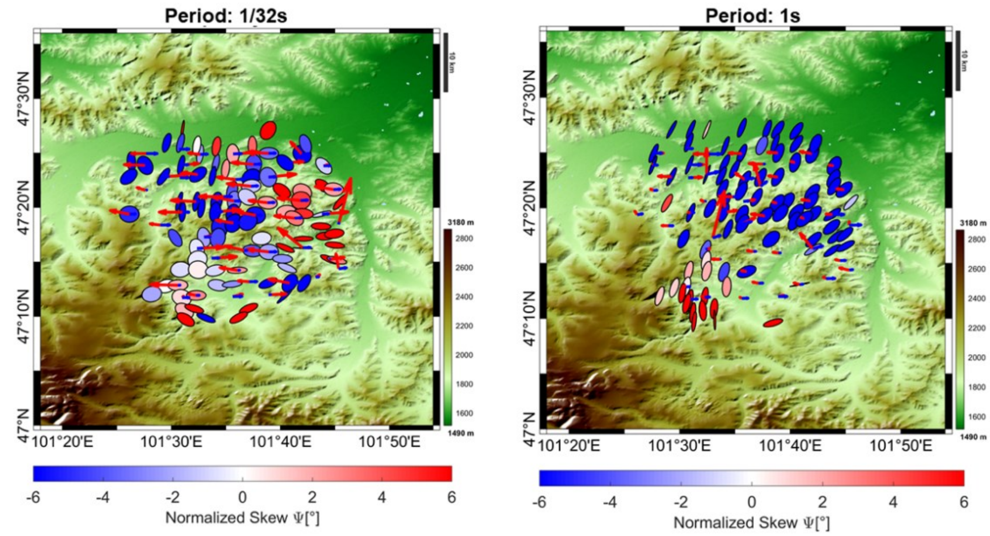

Figure 2: Induction arrows and phase tensor ellipses at two periods: T= 1/32s (left) and T = 1s (right). Phase tensor ellipses provide information on geoelectric strike and dimensionality of the subsurface. The real parts of the induction arrows (red arrows) provide information about the lateral conductivity contrasts and the orientation of faults. Here they are plotted in Wiese convention pointing away from conductors.

We use the high order finite element code GoFEM written by Grayver (2015) for 3-D modelling and inversion of the MT data. The inversion mesh has 108'770 cells and it incorporates topography obtained from NASA SRTM data. To obtain a preliminary model, we inverted impedance tensors from 50 MT and 76 TMT stations. The initial RMS was 10.5 and converged after 24 iterations to 0.9 for a given error floor of 5%.

A striking feature in the preliminary model (Fig. 3) is a conductor C3 that rises from depths below 15km under the hot spring area to the surface. Our recovered model shows a highly conductive lower crust (C4), higher resistivities R1 in the middle crust and a more scattered conductivity distribution C1 and C2 in the shallow crust. The lateral contrasts in the shallow layers possibly indicate different geological units. Contact zones between intrusive rock and sedimentary rock likely act as permeable pathways for hot fluids (Ganbat, 2010). The electrical conductor C3 is connected to the conductive zone (C4) in the lower crust. In the regional study by Käufl et al. (2020), C4 was interpreted as a lower crustal zone of melting. Hence, C3 might be the key feature for understanding the heat source and the nature of the hot springs in the study area. C3 could represent a zone with partial melt and/or magma-derived fluids and may act as the heat source for thermal fluids emerging at the hot springs (Gendenjamts, 2005; Oyuntsetseg et al., 2015).

4. CONCLUSION

We presented a preliminary 3-D electrical conductivity subsurface model that we obtained in order to better understand the subsurface structure of the Tsenkher geothermal area in the Mongolian Hangai. The recovered model shows an electrically conductive anomaly in the electrically resistive upper crust, where the former rises under the Tsenkher geothermal area from a lower crustal zone of melting to the land surface. This anomaly might therefore be a key feature in order to understand the nature of the heat source and the formation of the hot springs at the surface.

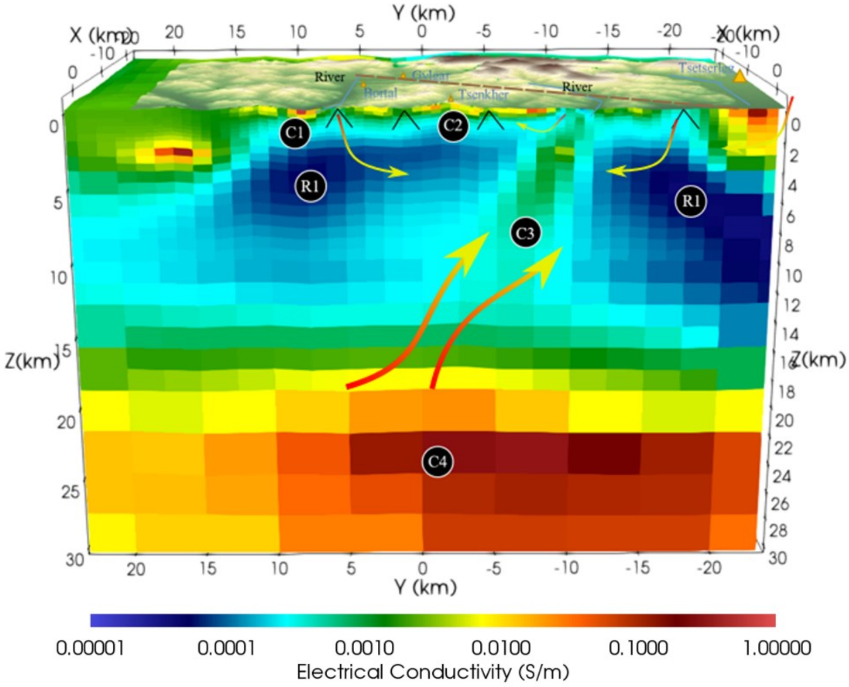

Figure 3: 3-D MT model. C1: Electrically conductive sediments: C2 lateral contrast zones between different geological units. C3: crustal conductor that might represent a permeable up-flow zone of magma-derived fluids. C4: Partial melting zone (see also Käufl et al., 2020).

5. OUTLOOK

Our future study will concentrate on inverting the data from all 306 MT stations that we installed during our MT surveys in 2019 and 2020. The higher MT site density is expected to promote improved imaging of the channel-like conductor C3 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 conducitivity model together with geological, geochemical, and other geophysical data, such as seismicity, gravity, and magnetics. This will hopefully enable better understanding and locating hydrothermal fluid circulation paths as well as the geothermal aquifers that feed the hot springs in the region.

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