The electrical resistivity structure of central Mongolia observed with magnetotelluric data

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Summary

The Hangai Dome in central Mongolia is an intra-continental plateau characterized by dispersed intraplate volcanism. This region is an ideal natural laboratory for studying intra-continental orogenic and magmatic processes resulting from crust-mantle interactions. A large magnetotelluric survey was carried out across central Mongolia, and a preliminary resistivity model is presented here. While the upper crust is highly resistive, the presence of low resistivity in the lower crust indicates the existence of fluids and a weakened lower crust. The South Hangai fault system is detected and is revealed to be a major crustal boundary, separating terranes. A large low-resistivity zone detected in the upper mantle is attributed to partial melting due to decompression within an asthenospheric upwelling, which is believed to be responsible for the intraplate volcanism and uplift of the Hangai Dome.

1. Introduction

The Hangai Dome in central Mongolia is an uplifted intra-continental plateau located far from tectonic plate boundaries [Cunningham, 2001]. The Hangai region occupies a unique position in central Asia between the rigid Siberian craton to the north and the northward-converging Tibetan Plateau to the south, and is an important kinematic link between these regions [Calais et al., 2003]. The Hangai block is believed to be a rigid pre-Cambrian crustal block that is bounded by large, lithospheric scale, faults [Cunningham, 2001; Calais et al., 2003]. The Hangai region is also characterized by dispersed, basaltic, intraplate volcanism [Barry et al., 2003], which is believed to be coincident with the onset of uplift [e.g., Walker et al., 2007], indicating that the processes may be linked.

Past seismic studies detected a thin lithosphere below the Hangai region of ~70 km, and a thick crust of ~50 km [Petit et al., 2008]. Other geophysical studies detected a very low negative Bouguer anomaly below the Hangai Dome [Tiberi et al., 2008]. However, the lithospheric structure, and specifically the crustal structure, of the Hangai region is poorly understood. Magnetotelluric (MT) data measure the electrical resistivity of the subsurface using natural electromagnetic signals [see Unsworth and Rondenay, 2012]. The method is particularly useful for investigating subsurface fluid and melt distribution and therefore MT data have the potential to give insights on the structure and development of central Mongolia and the Hangai Dome.

2. Magnetotelluric measurements

Here we present broadband and long period (0.002 – 10,000 s) magnetotelluric data collected in 2016 and 2017 in central Mongolia. This data set consists of a large array with a nominal site spacing of 50 km and several profiles which are long (500 - 600 km) and dense (5 - 10 km site spacing). A total of 294 sites were collected. The survey area crosses the uplifted Hangai Dome and extends across the bounding faults of the Hangai block to the north and to the south (across the Altai), as shown in Figure 1.

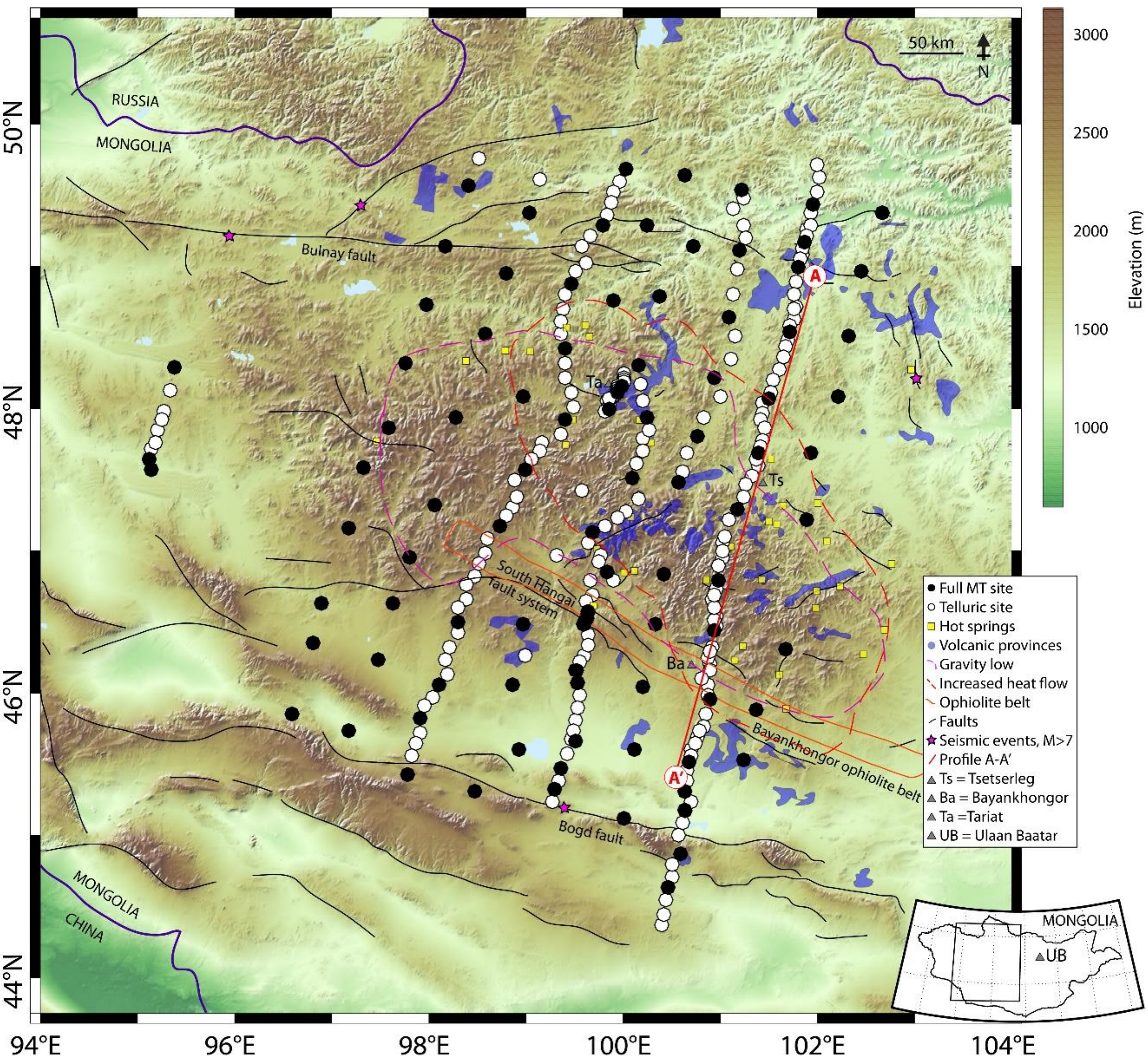

Figure 1. Map of the study area. All 294 magnetotelluric (MT) sites are shown (circles) and are identified as full sites (black) or telluric-only sites (white). Profile A-A' is marked as a red line. Also shown are: hot springs (gold squares) [from Ganbat and Demberel, 2010]; volcanic provinces (blue) [from Sahagian et al., 2014; Hunt et al., 2012]; low Bouguer anomaly, -275 mGal contour (dashed pink line) [from Tiberi et al., 2008]; heat flow contour of 70 mW/m^2 (compared to Mongolian background of ~50 mW/m^2 (dashed red line) [from Tseesuren, 2001]; Ophiolite belt (orange lines) [from Bardarch et al., 2002]; identified faults (black lines) [from Walker et al., 2007; Walker et al., 2008; Ganbat and Demberel, 2010]; epicenters of large (M>7) seismic events (pink stars) [Rizza et al., 2015].

We deployed both telluric-only data-loggers (EDEs), developed by the University of Münster, and full MT sites as a combination of broadband (SPAMs) and long-period (EDL) instruments, provided by the Geophysical Instrument Pool Potsdam (GIPP). Deploying the full MT sites primarily on the array with sparser spacing allowed fast and efficient data collection in the field. Data collection at each site was typically 1 – 6 days for the broadband instruments and 16 - 37 days for the long-period instruments. The MT data are generally high quality and have a very low noise level, primarily due to the remote location.

3. Electrical resistivity model

The MT data along profile A-A' (59 sites) were inverted with the EMILIA inversion algorithm from Kalscheuer et al. [2010]. The two-dimensional (2-D) electrical resistivity model is shown in Figure 2. Importantly, the inversion algorithm can properly handle inter-site transfer functions for the telluric-only sites. All model depths are below the average surface elevation which is defined as 2000 m. The data were rotated to the regional geo-electric strike direction of N105°E, aligned with the Hangai Mountains and with the main fault systems in the area. Both the TE and TM mode phase components were assigned an error floor of 1.4°. The TM mode apparent resistivity was assigned an error floor of 10%, while the TE mode apparent resistivity was assigned a higher error floor of 100%. This was done to reduce the influence of the static shift effect [e.g., Jones, 1988]. The inversion algorithm reduced the root-mean-square (RMS) misfit from 12.54 to 2.50 after 14 iterations. This indicates that the 2-D model fits the measured MT data. Future work will model all the profiles in 2-D and the entire dataset in 3-D.

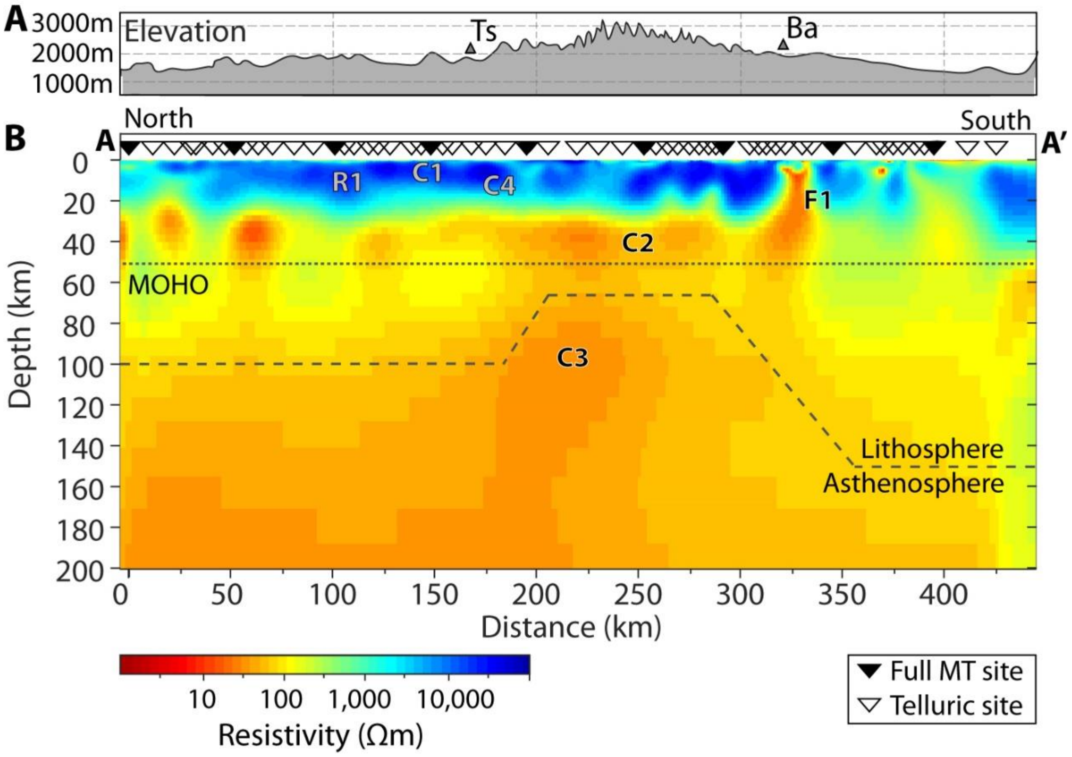

Figure 2. A: Elevation along profile A-A' (as in Figure 1). Ts = Tsetserleg; Ba = Bayankhongor. **B:** The 2-D resistivity model obtained from the inversion of magnetotelluric (MT) data at 59 sites (triangles) along profile A-A'. Dotted line indicates approximate location of crust-mantle boundary (MOHO) and dashed line indicates simplified lithosphere-asthenosphere boundary [from Petit et al., 2008].

4. Model features

4.1 Upper crust

The near-surface layer (C1; <0.5 km) has a highly variable resistivity (10 – 2,000 ohm-m) likely caused by porous sediments [Ganbat and Demeberel, 2010]. Most of the upper crust appears highly resistive (R1; >2,000 ohm-m) and can be explained by pre-Cambrian cratonic rocks [Cunningham, 2001]. Vertically elongated features observed in the upper crust (C4; 300 - 1,300 ohm-m) may represent hydrothermal alteration from past conduits of hot magma [e.g., Comeau, 2015; Hill et al., 2009]. On the southern portion of the profile there is an anomalous, vertical, low-resistivity feature (F1; 20 - 40 ohm-m) in the upper crust. It is interpreted to be the South Hangai fault system [Walker et al., 2007], which marks an important terrane boundary and a zone of mineralization (the Bayankhongor ophiolite belt) [Badarch et al., 2002].

4.2 Lower crust

Beneath the Hangai Dome the lower crust is a heterogeneous low-resistivity zone (C2; 20 – 80 ohm-m). It is interpreted as being caused by accumulations of fluid distributed within the lower crust. The depth to the top of this zone matches the estimated local brittle-ductile transition depth of 25 km [Deverchere et al., 2001], and crustal fluids are known to accumulate below this transition [Connolly and Podlachikov, 2004]. The results imply that a weak lower crust exists below the Hangai Dome. Interestingly, this feature terminates sharply at the South Hangai fault system, south of which we see moderate resistivity values in the lower crust (100 – 500 ohm-m). This demonstrates that any lower crustal fluids are confined below the Hangai Dome. The lower-crustal low-resistivity anomalies appear to be spatially associated with the surface expressions of past volcanism, modern-day hydrothermal activity, and an increase in heat flow (see Figure 1).

4.3 Upper mantle

Upper-most mantle depths (50 – 100 km) are characterized by a moderate resistivity (R2; 150 – 500 ohm-m), while depths below 100 - 150 km have a low resistivity (<50 ohm-m) and indicate the asthenosphere. However, at depths >70 km directly below the Hangai Dome a large low-resistivity feature is imaged (C3; <50 ohm-m). This feature can be explained by a shallow, upwelling, asthenosphere that contains partial melt. Furthermore, this zone likely represents the region of melt generation for Hangai intraplate volcanism. This interpretation is supported by petrological analysis that indicates that the basaltic lavas spread across the Hangai Dome have originated by long-term partial melting from a single mantle source at depths of 70 – 100 km [Barry et al., 2003; Hunt et al., 2012]. What's more, the results are consistent with seismic data which show a thin lithosphere directly below the Hangai Dome (60 – 80 km), which thickens rapidly at the edges (to a thickness of ~200 km below the Siberian craton to the north) [Petit et al., 2008]. Additionally, Bouguer gravity models revealed a localized low-density structure at a depth of 80 – 125 km below the central Hangai [Tiberi et al., 2008], coincident with the location of the low-resistivity feature C3.

The resistivity model presented here gives compelling evidence for a small-scale asthenospheric upwelling. Such a small-scale (~100 km wide) upwelling could be caused by hot and buoyant asthenospheric material replacing lithospheric material. This could be caused by convective removal of the lithosphere or removal due to an instability [Barry et al., 2003; Hunt et al., 2012]. Alternatively, edge-driven convection influenced by the lithospheric step between the Siberian craton and central Mongolia could have triggered such lithospheric removal. Such a small-scale asthenospheric melt-generating upwelling could thermally modify the lithospheric mantle and could explain both dome-like uplift and sporadic volcanism in the Hangai region [Comeau et al., 2017].

5. Estimating melt fraction

If the low-resistivity anomalies detected below the Hangai Dome are due to partial melting alone we can estimate the minimum melt fraction required to explain the observed MT data, following Comeau et al. [2016; 2015]. Pure melt resistivity can be calculated with semi-empirical equations, such as SIGMELTS [Pommier and Le Trong, 2011]. Combining this with the rock matrix resistivity using a two-phase mixing law [Glover et al., 2000] we can estimate the minimum melt fraction required to explain the bulk resistivity observed with MT data.

For the low-resistivity anomalies observed in the model we estimate that a minimum melt fraction of 3 - 8% (dependent on the temperature, pressure, and composition assumed) is required to explain the electrical resistivity data of the upper mantle low-resistivity feature C3. This is in agreement with petrological studies that estimated 2 - 12% melting below the Hangai Dome at depths of 70 – 120 km [Hunt et al., 2012; Barry et al., 2003]. Rosenberg and Handy [2005] showed that the largest viscosity decrease and the largest mechanical strength decrease occurs with less than 7% melt. Therefore, the melt connectivity transition may be reached with this amount of melt, potentially initiating intraplate volcanism [e.g., Cashman and Sparks, 2013]. A similar analysis shows that the lower crustal low-resistivity zones of C2 can be explained by a minimum melt fraction of 2 - 5%. Although in the case of the crust, aqueous fluids offer a better explanation.

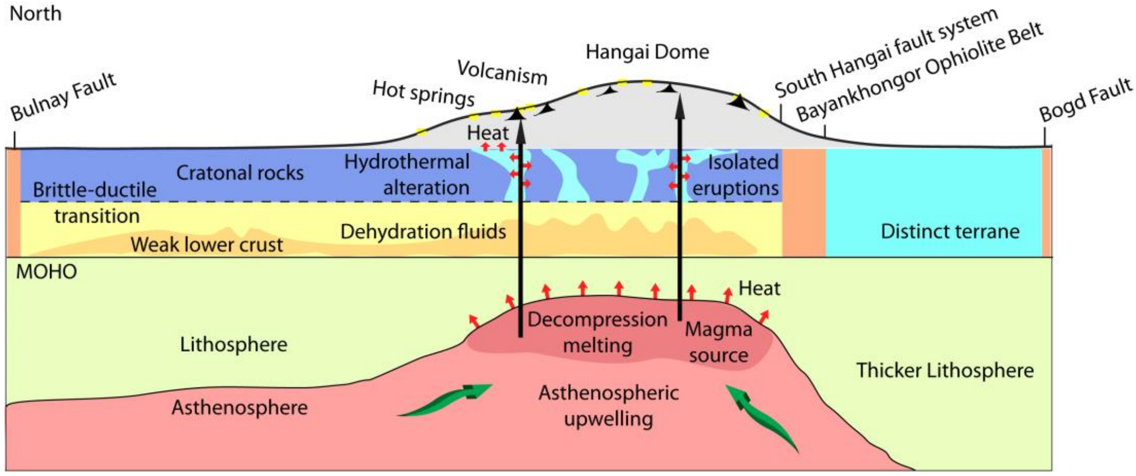

Figure 3. Schematic diagram showing the interpreted structure of central Mongolia and the Hangai Dome.

6. Conclusions

The 2-D electrical resistivity model presented here provides new insights into the electrical resistivity structure of the Hangai Dome, Mongolia. In contrast to the highly resistive upper crust, expected for a cratonal block, the lower crust (30 – 50 km) consists of a low-resistivity zone. This indicates the presence of fluids and implies a weak lower crust. Additionally, the model images a bulging asthenosphere directly below the Hangai Dome that requires the presence of partial melt.

It seems likely that the origin of intra-continental uplift and intraplate volcanism on the Hangai Dome arises from partial melts generated due to decompression melting from an asthenospheric upwelling. Melt migrating within the upper mantle and excess heat can cause thermal modification below the Hangai Dome, thereby supporting uplift. The lower crust, being thermally perturbed, could have underwent metamorphic dehydration reactions that created fluids which are ponding below the brittle-ductile transition (see schematic diagram in Figure 3). However what ultimately initiated the upwelling remains speculative for now.

Acknowledgements

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