Characterization of active fault zones near Ulaanbaatar, Mongolia, from electrical resistivity models: Implications for seismic hazard assessment

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INTRODUCTION

Strong earthquakes have been mapped within the Ulaanbaatar region, Mongolia, near the capital city of Ulaanbaatar. From 1994 to 2016, 120 earthquake events were recorded between 3.4 and 5.6, and 978 earthquake events were recorded with a magnitude between 2.5 and 3.4 (Adiya, 2016; Al-Ashkar et al., 2022). Residents of Ulaanbaatar have felt several of these earthquakes.

Historical records dating back to 1905 show that Mongolia has experienced four major earthquakes with magnitudes greater than eight and numerous moderate earthquakes with magnitudes greater than 5.5 (e.g., Adiya, 2016). However, the seismicity in Mongolia is mainly concentrated along the Mongolian-Altai and Gobi-Altai (south and west of the Khangai mountains), the Bulnay fault (north of the Khangai mountains), and around the Mogod area (east of the Khangai mountains) (e.g., Adiya, 2016), which are remote and sparsely populated areas. In contrast, the region around Ulaanbaatar is home to a large population; it currently has about 1.7 million inhabitants, accounting for half of the country's total population.

In the west of the Ulaanbaatar region, several prominent fault zones exist, some of which have only recently been identified. The majority of the seismic events in this region are associated with three of these: the Khustai, Sharkhai, and Avdar fault zones (Adiya, 2016; Al-Ashkar et al., 2022). Seismicity is typically detected in the upper crust (above ~16 km depth; Ferry et al., 2010; Adiya, 2016). These fault zones are quasi-parallel and are ~100 km long (Figure 1). Historical seismic events are predicted to have produced vertical offsets of up to 10 m, with some sections showing cumulative horizontal offsets of up to 100 m (Al-Ashkar et al., 2022). Based on paleo-seismic surveys, it is estimated that these fault zones could produce earthquakes of magnitude 7+ (Ferry et al., 2010, 2012; Schlupp et al., 2013; Al-Ashkar et al., 2022).

These fault zones pose a serious threat and risk of damage to Ulaanbaatar. Because of this, we aim to characterize the subsurface structure of the active fault zones near Ulaanbaatar to gain a better understanding of them. To do this, we perform magnetotelluric (MT) measurements and generate electrical resistivity models. We aim to provide an integrated interpretation of the electrical resistivity structure of the subsurface incorporating geomorphological and geological knowledge, as well as to geodetic measurements, paleo-seismic trenching, fault mechanical models, and near-surface ground-penetrating radar surveys. Understanding the subsurface structure of the region and characterizing the active faults is an important step for assessing seismic hazards.

Method and data acquisition

The MT method is an electromagnetic technique (e.g., Tikhonov, 1950; Cagniard, 1953) that is sensitive to the subsurface distribution of electrical resistivity (e.g., Unsworth and Rondenay, 2012; Unsworth et al., 2023). It uses natural sources that originate in the atmosphere and ionosphere. At the Earth's surface, electric and magnetic field variations are measured as time series. The broad band of periods of the signals gives sensitivity to a range of spatial scales and depths.

In mid-2024, we carried out measurements across the Khustai, Sharkhai, and Avdar fault zones. The data were collected along a profile with a length of ~110 km. The average measurement site separation was ~600–1,000 m locally around faults and up to 5,000 m away from the faults (top panel in Figure 1). Additionally, data from smaller-scale arrays were acquired where the profile crosses the fault trace in a subsequent follow-up survey campaign. The latter data allow for better characterization of the local fault structure.

The measurements across these fault zones are embedded within a regional array of measurements

collected across Mongolia from 2016-2024 (bottom panel in Figure 1), which have been used to investigate the lithospheric structure, tectonic evolution, and development of Mongolia (Comeau et al., 2018, 2020, 2024; Rigaud et al., 2023a, 2023b; Käufl, et al. 2020) as well as explore its mineral resources (Comeau et al., 2022a) and volcanic-geothermal regions (Comeau et al., 2022b; Batmagnai et al., 2021).
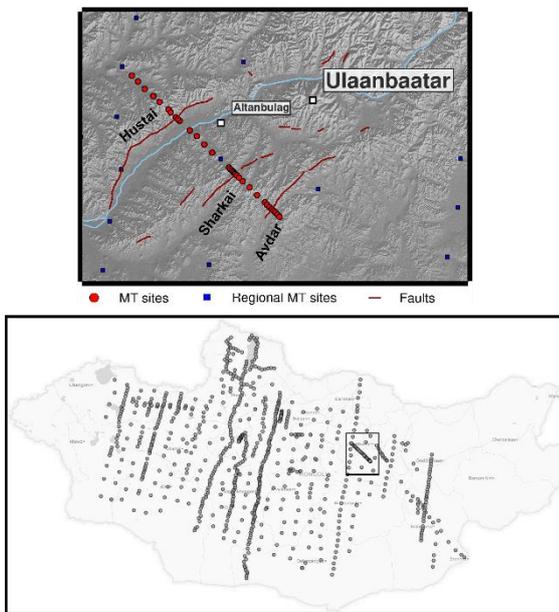

Figure 1 *Top panel: Map of the survey area. Magnetotelluric measurements (red circles) were collected along a profile that crosses the three fault zones (red lines) near the capital city of Ulaanbaatar. Additionally, denser array measurements around the fault zones were carried out (not shown). The profile is embedded within a larger regional array of magnetotelluric measurements collected across Mongolia from 2016 to2024, as shown in the bottom panel; the black square marks the survey area of this study.*

Preliminary two-dimensional electrical resistivity model

To generate an electrical resistivity model from the magnetotelluric data, we used the MARE2DEM algorithm developed by Key (2016). It enables the joint inversion of the transverse electric (TE) mode data and the transverse magnetic (TM) mode data, representing the across-profile and along-profile data in a rotated coordinate system that aligns with the profile. The goal was to minimize the model roughness and find a smooth model that fits the data within an acceptable confidence limit. The smooth model is well suited to the technique because the electromagnetic energy propagates diffusively. This means we may consider the resulting images to be a smoothed version of the true Earth structure.

Data from 36 periods in the range of 128 Hz to 1,500 s were used along with 31 measurement locations, resulting in approximately 4,000 data inputs. The modelling mesh had 18,000 triangular elements. Given the negligible magnitude of real measurement errors, all data points were attributed to an error floor, representing the minimum allowable error value. The error floor on the apparent resistivity was set to 10%, and the error floor on the phase was 1.4°, corresponding to a 2.5% relative error in impedance. The RMS (root-mean-square) misfit value of the model was reduced from 12.6 to 1.9 in 8 iterations.
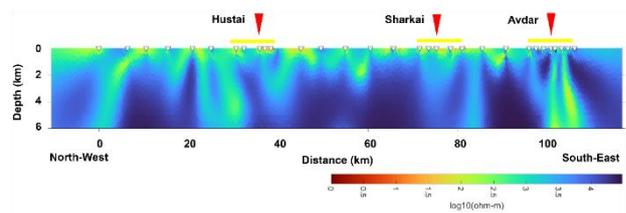

Figure 2 *Preliminary two-dimensional electrical resistivity model. The white triangles mark measurement locations. The red arrows mark the fault zones. The yellow rectangles mark the location of denser array measurements around the fault zones (not shown).*

We modelled the local features near the fault traces (Figure 2) and the regional crustal features of the region. The preliminary model shows several low-resistivity features (approximately <100 Ωm) in the near-surface. The upper crust (0-25 km depth) appears to have a generally high resistivity (~10,000 Ωm) compared to the lower crust (25–50 km depth; 30-300 Ωm).

Summary and conclusions

In the west of the Ulaanbaatar region, Mongolia, there are several prominent fault zones that show signs of seismic activity. These are the Khustai, Sharkhai, and Avdar fault zones. Based on paleo-seismic surveys, it is estimated that these fault zones could produce earthquakes of magnitude 7+. Therefore, these fault zones pose a serious threat and risk of damage to Ulaanbaatar.

In this study, we aimed to characterize the subsurface structure of these fault zones in order to better understand them. We used magnetotelluric data to generate a preliminary two-dimensional electrical resistivity model. Future work will give an integrated interpretation of the electrical resistivity structure of the subsurface with geomorphological and geological knowledge, in addition to geodetic measurements, paleo-seismic trenching, and fault mechanical models. This helps to understand the

subsurface structure of the region and characterize the active faults, which is an important step for assessing the seismic hazard potential.

References

Adiya, M. [2016]. Seismic activity near Ulaanbaatar: Implication for seismic hazard assessment. PhD thesis, Université de Strasbourg. theses.hal.science/tel-01425480

Al-Ashkar, A., Schlupp, A., Ferry, M., Munkhuu, U. [2022]. Tectonic Geomorphology and Paleoseismology of the Sharkhai fault: a new source of seismic hazard for Ulaanbaatar (Mongolia). *Solid Earth*, **13**, 761-777. https://doi.org/10.5194/se-13-761-2022

Batmagnai, E., Samrock, F., Grayver, A., Kuvshinov, A., Saar, M., Demberel, S., Tserendug, S., Tsegmed, B., Dorj, P., Oyuntsetseg, D. [2021]. Deep-rooted geothermal system imaged by magnetotelluric surveys under the Tsenkher hot spring area, Mongolian Hangai. In Proceedings World Geothermal Congress 2020+1. Reykjavik: World Geothermal Congress.

Cagniard, L. [1953]. Basic theory of the magnetotelluric method of geophysical prospecting. *Geophysics*, **18**(3), 605–635. https://doi.org/10.1190/1.1437915

Comeau, M. J., Käufl, J. S., Becken, M., Kuvshinov, A. V., Grayver, A. V., Kamm, J., Dembreel, S., Sukhbaatar, U., Batmagnai, E. [2018]. Evidence for fluid and melt generation in response to an asthenospheric upwelling beneath the Hangai Dome, Mongolia. *Earth and Planetary Science Letters*, **487**, 201–209. https://doi.org/10.1016/j.epsl.2018.02.007

Comeau, M. J., Becken, M., Käufl, J. S., Grayver, A. V., Kuvshinov, A. V., Tserendug, S., et al. [2020]. Evidence for terrane boundaries and suture zones across southern Mongolia detected with a 2-dimensional magnetotelluric transect. *Earth Planets and Space*, **72**(5), 1–13. https://doi.org/10.1186/s40623-020-1131-6

Comeau, M. J., Becken, M., & Kuvshinov, A. [2022a]. Imaging the whole-lithosphere structure of a mineral system—Geophysical signatures of the sources and pathways of ore-forming fluids. *Geochemistry, Geophysics, Geosystems*, **23**(8), e2022GC010379. https://doi.org/10.1029/2022GC010379

Comeau, M.J., Becken, M., Grayver, A., Käufl, J.S., Kuvshinov, A. [2022b]. The geophysical signature of a continental intraplate volcanic system: From surface to mantle source. *Earth and Planetary Science Letters*, **578**, 117307. https://doi.org/10.1016/j.epsl.2021.117307

Comeau, M.J., Rigaud, R., Batmagnai, E., Tserendug, S., Kuvshinov, A., Becken, M., Demberel., S. [2024]. Insights Into the Structure of the Mongol-Okhotsk Suture Zone, Adaatsag Ophiolite, and Tectonic Boundaries of the Central Asian Orogenic Belt (Mongolia) From Electrical Resistivity Imaging and Seismic Velocity Models. *Journal of Geophysical Research: Solid Earth*, **129(4).** https://doi.org/10.1029/2023JB028503

Ferry, M., Schlupp, A., Munkhuur, U., Munschy, M., Fleury, S., Baatarsuren G., Erdenezula, D., Munkhsaikhan, A., Ankhtsetseg, D. [2010]. Tectonic Morphology of the Hustai Fault (Northern Mongolia), A Source of Seismic Hazard for the city of Ulaanbaatar. *In Abstracts for the European Geosciences Union General Assembly, Vienna, Austria*, 2-7 May, 2010, EGU2010-11122.

Ferry, M., Schlupp, A., Munkhuur, U., Munschy, M., Fleury, S. [2012]. Tectonic morphology of the Hustai Fault (Northern Mongolia). *In Abstracts for the European Geosciences Union General Assembly, Vienna, Austria*, 22-27 April, 2012, EGU2012-5803.

Käufl, J. S., Grayver, A. V., Comeau, M. J., Kuvshinov, A. V., Becken, M., Kamm, J., ... & Demberel, S. (2020). Magnetotelluric multiscale 3-D inversion reveals crustal and upper mantle structure beneath the Hangai and Gobi-Altai region in Mongolia. *Geophysical Journal International*, **221(2)**, 1002-1028. https://doi.org/10.1093/gji/ggaa039

Key, K. [2016]. MARE2DEM: A 2D inversion code for controlled-source electromagnetic and magnetotelluric data. *Geophysical Journal International*, 207(1), 571–588. https://doi.org/10.1093/gji/ggw290

Rigaud, R., Comeau, M.J., Becken, M., Kuvshinov, A.V., Tserendug, S., Batmagnai, E., Demberel, S. [2023a]. Magnetotelluric Data Across Mongolia: Implications for Intracontinental Deformation and Intraplate Volcanism — Report on New Measurements. *In Abstracts for the European Geosciences Union General Assembly 2023, Vienna, Austria*, 24–28 April 2023, EGU23-9485 https://doi.org/10.5194/egusphere-egu23-9485

Rigaud, R., Comeau, M.J., Kuvshinov, A.V., Grayver, A., Batmagnai, E., Tserendug, S., Kruglyakov, M., Becken, M., Demberel, S. [2023b]. Extending Magnetotelluric Study from Central to Eastern Mongolia: Preliminary 2-D and 3-D Inversion Results. *In Abstracts for the International Union of*

Geodesy and Geophysics General Assembly 2023, Berlin, Germany, 11–20 July 2023, IUGG23-4312. https://doi.org/10.57757/IUGG23-4312

Schlupp, A., Ferry, M., Munkhuu, U., Demberel, S., Al-Ashkar, A. [2013]. Active faults system and related potential seismic events near Ulaanbaatar, capital of Mongolia. *In Abstracts for the European Geosciences Union General Assembly 2023, Vienna, Austria*, EGU2013-7821.

Tikhonov, A.N. [1950]. On determining electrical characteristics of the deep layers of the Earth's crust. *Doklady Akademii Nauk SSSR*, **73(2)**, 295-297.

Unsworth, M. J., Rondenay, S. [2012]. Mapping the distribution of fluids in the crust and lithospheric mantle utilizing geophysical methods. In D. E. Harlov & H. Austrheim (Eds.), *Metasomatism and the chemical transformation of rock* (pp. 535–598). Springer.

Unsworth, M., et al [2023]. Crustal structure of the Lazufre volcanic complex and the Southern Puna from 3-D inversion of magnetotelluric data: Implications for surface uplift and evidence for melt storage and hydrothermal fluids. *Geosphere*, **19(5)**, 1210–1230. https://doi.org/10.1130/GES02506.1