Imaging the Architecture of Mineral Systems and the Pathways of Ore-forming Fluids across Mongolia with Magnetotellurics

Comeau, Matthew J.; Rigaud, Rafael; Batmagnai, Erdenechimeg; Tserendug, Shoovdor; Demberel, Sodnomsambuu; Becken, Michael; Kuvshinov, Alexey

DOI
10.1111/1755-6724.15225

Publication date
2024

Document Version
Final published version

Published in
Acta Geologica Sinica (English Edition)

Acta Geologica Sinica (English Edition), 2024, 98(supp. 1): 11–13

Imaging the Architecture of Mineral Systems and the Pathways of Ore-forming Fluids across Mongolia with Magnetotellurics

GSC

Matthew J. COMEAU[1, *], Rafael RIGAUD[2], Erdenechimeg BATMAGNAI[3], Shoovdor TSERENDUG[3], Sodnomsambuu DEMBEREL[3], Michael BECKEN[4] and Alexey KUVSHINOV[2]

[1] *Department of Geoscience & Engineering Delft University of Technology, The Netherlands*
[2] *Institute of Geophysics, ETH, Zürich, Switzerland*
[3] *Institute of Astronomy and Geophysics, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia*
[4] *Institut für Geophysik, Universität Münster, Germany*

Citation: Comeau et al., 2024. Imaging the Architecture of Mineral Systems and the Pathways of Ore-forming Fluids across Mongolia with Magnetotellurics. Acta Geologica Sinica (English Edition), 98(supp. 1): 11–13.

In the framework of a mineral system approach, a combination of components is required to develop a mineral system. This includes the whole-lithosphere architecture, which controls the transport of ore-forming fluids, and favorable tectonic and geodynamic processes, occurring at various spatial and temporal scales, that influence the genesis and evolution of ore-forming fluids (Huston et al., 2016; Groves et al., 2018; Davies et al., 2020). Knowledge of the deep structural framework can advance the understanding of the development of a mineral system and the emplacement of mineral deposits. Deep geophysical exploration carried out with this aim is increasingly important for targeting new ore deposits in unexplored and underexplored regions (Dentith et al., 2018; Dentith, 2019).

We analyze data and electrical resistivity models generated from magnetotelluric measurements acquired across Mongolia, part of the Central Asian Orogenic Belt, as part of a regional array (Käufl et al., 2020; Rigaud et al., 2023a, b; Comeau et al., 2024; see Fig. 1) and focus on several metallogenic zones. These zones contain significant resources of copper and gold, as well as rare earth elements. We interpret the results, with the help of geological and geochemical data, in addition to seismic velocity data, and discuss fluid transport pathways and links to the surface expressions of mineral deposits.

The magnetotelluric method: The magnetotelluric method (known as MT) is an electromagnetic geophysical technique used to image the subsurface electrical resistivity distribution (Tikhonov, 1950; Cagniard, 1953). It can make use of passive, natural-source electromagnetic signals that are generated in the atmosphere and ionosphere (Simpson and Bahr, 2005; Unsworth and Rondenay, 2012). These electromagnetic field variations are measured over a broad range of periods at the Earth's surface. This gives sensitivity to multiple spatial scales: long-period data are sensitive to great depths and short-period data are sensitive to shallow depths. The electric and magnetic field variations are related by a complex-valued impedance tensor from which the apparent resistivity and impedance phase can be determined.

MT data are especially sensitive to the quantity and composition of interconnected fluids (Unsworth and Rondenay, 2012). This makes the technique well-suited to image the lithospheric architecture, including fault zones and suture zones, and has been shown to be capable of characterizing fluids and the traces of mineral alteration (Becken et al., 2008; Türkoğlu et al., 2008; Wise and Thiel, 2019; Sheng et al., 2023).

Recent work has drawn links between the surface locations of mineral deposits and narrow conductive features extended through the crust that are attributed to (fossil) fluid pathways or conduits (Heinson et al., 2006, 2018; Jiang et al., 2019; Comeau et al., 2021, 2022; Sheng et al., 2022, 2024), as well as to large conductive features in the deep lithosphere attributed to source regions of ore-forming fluids (Comeau et al., 2022), therefore giving trans-lithospheric images of mineral systems.

Metallogenic zones and Mongolia: The Central Asian Orogenic Belt (CAOB) is a long-lived accretionary orogeny (possibly the largest worldwide) that covers parts of Central and Eastern Asia and includes Mongolia (Yin, 2010). Within the CAOB, the Mongol-Okhotsk suture zone (and the associated ophiolite belts) is related to the closure of the Mongol-Okhotsk paleo-ocean and flanked by volcanic-plutonic belts and metallogenic zones (Tomurtogoo et al., 2005). In southern Mongolia, an accretionary collage of many east-west trending lithostratigraphic domains or terranes has been mapped (Badarch et al., 2002).

The Erdenet copper-molybdenum mine, one of the largest mines in the world, is located at the northern end of the study area (Singer et al., 2008; Porter, 2016, and references therein). Nearby are the well-known Zaamar, Boroo, and Eroo gold belts, part of the North Hentei gold belt (Dejidmaa, 1996; Singer et al., 2008). This region is bounded by large faults that extend for hundreds of kilometres, with the Yeroogol fault to the south and the Bayangol fault to the north (Badarch et al., 2002; Jargalan, 2016).

* Corresponding author. E-mail: m.j.comeau@tudelft.nl

http://www.geojournals.cn/dzxbcn/ch/index.aspx
https://onlinelibrary.wiley.com/journal/17556724

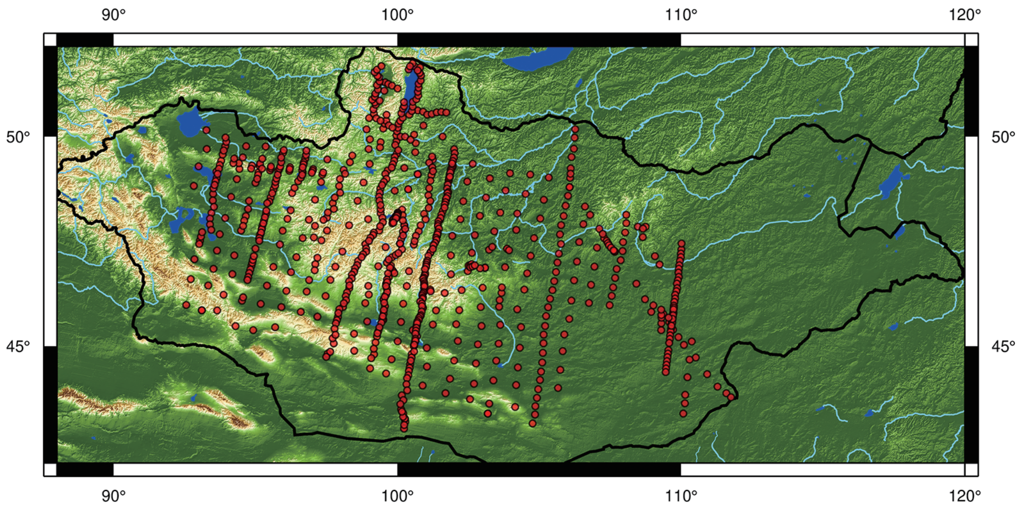

Fig. 1. Map of Mongolia showing the locations of magnetotelluric measurements acquired from summer 2016 to spring 2024.

Far to the south, south of the Middle Gobi Belt, several large porphyry copper-gold-(molybdenum) deposits exist. Including the world-class Oyu Tolgoi, one of the largest such deposits in the world (with significant reserves of high-grade mineralization), Kharmagtai, and Tsagaan Survaga (amongst others; Singer et al., 2008; Porter, 2016). Nearby is the Olon Ovoot gold deposit in the Ulziit gold belt (Jargalan, 2016), as well as the rare earth element mineralization associated with alkaline carbonatite complexes at Mushgai Khudag and Khotgor (Dostal and Gerel, 2023). They are associated with important tectonic boundaries and major approximately east-west trending lineaments.

To the west, the Bayankhongor Metal Belt, which contains significant occurrences of gold and copper mineralization, lies along an ophiolite belt and major tectonic boundary (Buchan et al., 2001; Badarch et al., 2002; Mineral Resources Authority of Mongolia, 2014; Gerel et al., 2021).

Results: Across the area examined, the electrical resistivity models reveal multiple narrow, vertical, low-resistivity features that are spatially associated remarkably well with both a) the proposed boundaries of tectonic domains and b) the surface locations of mineral zones.

In the north, below the projected location of the Eroo, Boroo, and Zaamar gold zones, part of the North Hentei gold belt, as well as below the projected location of the Erdenet copper-molybdenum mine, and below the extensive Yeroogol and Bayangol faults, narrow low-resistivity (1–100 Ωm) anomalies are observed in the upper and middle crust, in contrast to the highly-resistive background (~10,000 Ωm). A detailed follow-up study with dense measurements could elucidate more of the fine structure and ensure these features are well resolved. Although some of the features are quite subtle, it is notable that they can be identified directly in the data.

Similarly, in the south, low-resistivity (1–100 Ωm) anomalies extend below the projected location of the Kharmagtai copper-gold mine, below the Ulziit gold belt, and below the edges of the Gurvansayhan terrane.

To the west, directly beneath the Bayankhongor Metal Belt and the surface expressions of known mineral deposits, including in the Baydrag block, the electrical resistivity model reveals narrow, vertical, finger-like low-resistivity (1–100 Ωm) features within the high-resistivity upper and middle crust. In the lower crust and lithospheric mantle, a broad low-resistivity zone is imaged. In addition to the above, in Bayan-Ölgii, North-Western Mongolia, recent progress has been made acquiring local-scale arrays of measurements across mineralized zones. Here, preliminary results show narrow, vertical, low-resistivity (<50 Ωm) features within the upper crust beneath known molybdenum-tungsten and copper deposits.

The fact that these anomalies are spatially related to the surface locations of large mineral zones and with the proposed locations of tectonic boundaries gives information for their interpretation. One explanation for these small, vertical low-resistivity features is that they may represent the signatures of fossil fluid pathways (possibly from hydrothermal alteration) and record the location of the ascent of ore-forming fluids beneath the metallogenic zones, likely constrained by structure along a tectonic boundary or weaknesses. Furthermore, the results help to confirm ideas about the evolution and development of the CAOB.

The results highlight that mineral systems are driven by lithospheric-scale processes and that understanding the whole-lithosphere architecture, which is influenced by tectonic events, is important. Therefore, modern exploration concepts advocate for a scale-integrated approach (with imaging at multiple spatial scales: e.g., lithospheric-scale, regional-scale, and deposit-scale), for which the MT method is well suited.

Key words: magnetotellurics, electrical resistivity, mineral exploration, mineral emplacement, ore, fluids, fluid transport

Acknowledgements: We thank all those who provided project support and who helped collect field data. We thank our colleagues from the Institute of Astronomy and Geophysics at the Mongolian Academy of Sciences.

References

Badarch, G., Cunningham, W.D., and Windley, B.F., 2002. A new subdivision for Mongolia: implications for the Phanerozoic crustal growth of Central Asia. Journal of Asian Earth Sciences, 21: 87–110.

Becken, M., Ritter, O., Park, S.K., et al., 2008. A deep crustal fluid channel into the San Andreas fault system near Parkfield California. Geophysical Journal International, 173(2): 718–732.

Buchan, C., Cunningham, D., Windley, B.F., et al., 2001. Structural and lithological characteristics of the Bayankhongor Ophiolite Zone, Central Mongolia. Journal of the Geological Society, 158(3): 445–460.

Comeau, M.J., Becken, M., Kuvshinov, A., et al., 2021. Crustal architecture of a metallogenic belt and ophiolite belt: Implications for mineral genesis and emplacement from 3-D electrical resistivity models (Bayankhongor area, Mongolia). Earth, Planets and Space, 73.

Comeau, M.J, Becken, M., and Kuvshinov, A., 2022. 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).

Comeau, M.J., Rigaud, R., Batmagnai, T.S., et al., 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

Davies, S., Groves, D.I., Trench, A., and Dentith, M., 2020. Towards producing mineral resource-potential maps within a mineral systems framework, with emphasis on Australian orogenic gold systems. Ore Geology Reviews, 119: 103369.

Dejidmaa, G., 1996. Gold metallogeny of Mongolia. Mongolian Geoscientist, 1: 6–29.

Dentith, M., 2019. Geophysical Responses from Orogenic Gold Mineral Systems. Acta Geologica Sinica (English Edition), 93 (S1): 239–240.

Dentith, M., Yuan, H., Johnson, S., et al., 2018. Application of deep-penetrating geophysical methods to mineral exploration: Examples from Western Australia. Geophysics, 83(3). https://doi.org/10.1190/geo2017-0482.1

Dostal, J., and Gerel, O., 2023. Rare Earth Element Deposits in Mongolia. Minerals, 13(1): 129.

Gerel, O., Pirajno, F., Batkhishig, B., et al., 2021. Mineral resources of Mongolia. In: Modern Approaches in solid Earth Sciences book series. Springer Nature. https://doi.org/10.1007/978-981-15-5943-3

Groves, D.I., Santosh, M., Goldfarb, R.J., et al., 2018. Structural geometry of orogenic gold deposits: Implications for exploration of world-class and giant deposits. Geoscience Frontiers, 9(14): 1163–1177

Heinson, G.S., Direen, N.G., et al., 2006. Magnetotelluric evidence for a deep-crustal mineralizing system beneath the Olympic Dam iron oxide copper-gold deposit, southern Australia. Geology, 34: 573–576.

Heinson, G S., Didana, Y., Soeffky, P., et al., 2018. The crustal geophysical signature of a world-class magmatic mineral system. Scientific Reports, 8(1): 10608.

Huston, D.L., Mernagh, T.P., Hagemann, S.G., et al., 2016. Tectono-metallogenic systems–The place of mineral systems within tectonic evolution, with an emphasis on Australian examples. Ore Geology Reviews, 76: 168–210.

Jargalan, S., 2016. Gold resources in Mongolia. Shigen-Chishitsu, The Society of Resource Geology, 66(2): 89–94.

Jiang, W., Korsch, R.J., Doublier, M.P., et al., 2019. Mapping deep electrical conductivity structure in the Mount Isa region, Northern Australia: Implications for mineral prospectivity. Journal of Geophysical Research: Solid Earth, 124(11): 10655–10671.

Käufl, J.S., Grayver, A.V., Comeau, M.J., et al., 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.

Mineral Resources Authority of Mongolia, 2014. Present situation of mineral resources of Mongolia. Retrieved from http://www.mram.gov.mn

Porter, T.M., 2016. The geology, structure and mineralisation of the Oyu Tolgoi porphyry copper-gold-molybdenum deposits, Mongolia: A review. Geoscience Frontiers, 7(3): 375–407.

Rigaud, R., Comeau, M.J., Becken, M., et al., 2023a. Magnetotelluric data across Mongolia: Implications for Intracontinental Deformation and Intraplate Volcanism — Report on New Measurements. In Abstracts for the European Geosciences Union (EGU) 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., et al., 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 (IUGG) General Assembly 2023, Berlin, Germany, 11–20 July 2023, IUGG23-4312.

Sheng, Y., et al., 2022. Controls on the metallogenesis of the Lhasa–Mozugongka district, Gangdese Belt, Tibetan Plateau: Constraints on melt distribution and viscosity from the 3-D electrical structure of the lithosphere. Ore Geology Reviews, 145: 104881.

Sheng, Y., et al., 2023. Evidence for partial melting and alkali-rich fluids in the crust from a 3-D electrical resistivity model in the vicinity of the Coqen region, western Lhasa terrane, Tibetan Plateau. Earth and Planetary Science Letters, 619: 118316.

Sheng, Y., et al., 2024. Crustal conductivity footprint of the Miocene porphyry copper polymetallic deposits in the Gangdese metallogenic belt, Tibetan Plateau. Ore Geology Reviews, 168, 106033.

Simpson, F., and Bahr, K., 2005. Practical magnetotellurics. Cambridge University Press.

Singer, D.A., Berger, V.I., and Moring, B.C., 2008. Porphyry copper deposits of the world: Database and grade and tonnage models. U.S. Geological Survey Open-File Report 2008-1155.

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.

Tomurtogoo, O., Windley, B.F., Kroner, A., et al., 2005. Zircon age and occurrence of the Adaatsag ophiolite and Muron shear zone, central Mongolia: Constraints on the evolution of the Mongol-Okhotsk Ocean, suture and orogeny. Journal of the Geological Society. London, 162: 197–229.

Türkoğlu, E., Unsworth, M., Çağlar, İ., et al., 2008. Lithospheric structure of the Arabia-Eurasia collision zone in eastern Anatolia: Magnetotelluric evidence for widespread weakening by fluids? Geology, 36: 619–622.

Unsworth, M.J., and Rondenay, S., 2012. Mapping the distribution of fluids in the crust and lithospheric mantle utilizing geophysical methods. In: Harlov, D.E., and Austrheim, H. (eds.), Metasomatism and the Chemical Transformation of Rock, 535–598 (Springer, Berlin).

Wise, T., and Thiel, S., 2020. Proterozoic tectonothermal processes imaged with magnetotellurics and seismic reflection in southern Australia. Geoscience Frontiers, 11(3): 885–893.

Yin, A., 2010. Cenozoic evolution of Asia: A preliminary synthesis. Tectonophysics, 488(1–4): 293–325.

About the first and corresponding author

Matthew J. COMEAU, Assistant Professor at the Department of Geoscience and Engineering, Delft University of Technology, Delft, The Netherlands. Expertise in applied electromagnetic geophysics and the quantitative interpretation of data. Primarily engaged in acquiring and analysing electromagnetic geophysical data to understand mineral systems and tectonics at various scales, with the integration of other geoscientific data. Other interests include volcanic and geothermal systems and thermo-mechanical modeling to investigate lithospheric dynamics.