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Investigating the Whole-lithosphere Structure of a Mineral System — Pathways and Source of Ore-forming Fluids Imaged with Magnetotelluric Modeling

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Whole-lithosphere structure has direct implications for both the genesis of minerals and the locations of mineral emplacement; thus knowledge of the deep structural framework of the lithosphere can advance understanding of the development and evolution of mineral systems (e.g., Huston et al., 2016; Groves et al., 2018; Davies et al., 2020). Transient tectonic and geodynamic processes — occurring at various spatial and temporal scales — control the structure of the lithosphere. In turn, this structure influences the transportation of fluids (including ore-forming fluids) through the crust, largely by controlling permeability (e.g., Huston et al., 2016).

These concepts are widely seen as the key to gaining an understanding of deep ore genesis, with a focus on the critical processes of ore-forming fluid generation and transportation as well as concentration and preservation (e.g., Davies et al., 2020, and references therein). Moreover, deep (geophysical) exploration studies carried out with these concepts in mind may be crucially important for targeting new ore deposits in unexplored and underexplored regions (e.g., Dentith et al., 2018, and references therein; Dentith, 2019).

We analyze data from magnetotelluric (MT) measurements across southern Mongolia (data described in Becken et al., 2021a, b) and explore three dimensional (3-D) models of the electrical resistivity structure throughout the whole lithosphere, from the upper crust to the asthenosphere (see Comeau et al., 2021; see also Käufl et al., 2020). This region has notable occurrences of gold and copper mineralization over an extended area and is located near the edge of a micro-continental block. We interpret the geophysical results, with the help of available geological and geochemical data, with respect to the potential implications for fluid generation and transportation and discuss links to the surface expressions of known mineral deposits.

Methods: Magnetotelluric exploration

The MT method is a geophysical exploration technique that uses natural electromagnetic signals to image the subsurface electrical resistivity structure. MT data consists of natural electromagnetic fields measured at the Earth's surface over a broad range of frequencies, with signals generated in the atmosphere and ionosphere. This allows the exploration of multiple spatial scales: short-period data are sensitive to shallow structures and long-period data are sensitive to deep structures (e.g., Unsworth and Rondenay, 2012).

MT data is particularly sensitive to the amount and composition of fluids, which tend to reduce electrical resistivity. This makes the technique well-suited to image the internal structure of fault zones, magmatic systems, and deep lithospheric structures (e.g., Becken et al., 2008, 2011; Comeau et al., 2015, 2018, 2020; Käufl et al., 2020). In addition, numerous studies have shown that the MT exploration technique is capable of characterizing the pathways of past fluids and the traces of mineral alteration (e.g., Hübert et al., 2015; Wise and Thiel, 2019).

Recent work has linked the formation of mineral ore deposits with deep electrical signatures — including the work of Heinson et al. (2018) on the Olympic Dam deposit, Australia; Comeau et al. (2021) on mineralization in the Bayankhongor belt, Mongolia; and Yin et al. (2021) on ore zones in Nanling, China, amongst others. The multi -scale nature of the MT exploration technique enables imaging of the fluid source region in the deepest parts of the lithosphere or crust as well as fluid pathways or conduits in the upper part of the crust.

Results and discussion: Origin and transportation of ore-forming fluids

Electrical resistivity models reveal multiple conductive (low resistivity) features of interest at different spatial scales and depths throughout the lithosphere, including: a) expansive, deep-seated conductive zones, attributed to the fluid source region and to thermal anomalies; b) conductive anomalies within the resistive upper crust, which give evidence for the ancient pathways of ore-

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forming fluids; c) near-surface conductors that aligned with deep-reaching suture zones and faults adjacent to mineralization zones and ore deposits, explained by the fact that they occur in weakened deformation zones along a major tectonic boundary.

The structure of the lithosphere and crust, which is mainly controlled by tectonic and geodynamic processes, has a direct impact on the formation and evolution of ore-forming fluids and on fluid transportation to shallow near-surface depths. Thus the structural framework inferred in this study, from electrical resistivity data, can shed light on the formation and development of the mineral system.

In the upper crust, the conductivity signatures associated with the downward-extension of the mineral deposits may be due to hydrothermal alteration from fluid-rock interactions, which ultimately leads to ore emplacement. These processes are greatly enhanced by crustal deformation events, and may be fault-controlled (e.g., Goldfarb and Groves, 2015); thus the complex tectonic history of the specific region likely controls the formation of the mineral system (see details in Comeau et al., 2021). Note that care must be taken to consider overprinting from subsequent events.

Considering the available evidence, we favor a model that hypothesizes: 1) fluids were generated by devolatilization within a subducting slab during paleo-ocean closure, prior to the suturing of micro-continental blocks; 2) fluids migrated upwards along the plate boundary to the mantle wedge and hydrated the lithosphere; 3) later, enriched ore-forming fluids moved to the upper crust along pre-existing weaknesses and pathways, including crustal-scale suture zones between micro-continental blocks and shallow thrusts faults (see Goldfarb and Groves, 2015; Comeau et al., 2021).

The results of this work illustrate that crustal architecture inherited from earlier tectonic events exerts a strong control on the formation and evolution of mineral deposits due to its impact on ore-forming fluid genesis and transportation. Furthermore, the work highlights the applicability of the magnetotelluric exploration technique to image the critical elements of a mineral system using the whole-lithosphere approach to deep geophysical exploration.

Key words: magnetotellurics, electrical resistivity, lithosphere structure, mineral exploration, metal belt, ore-forming fluids, mineral emplacement, fluid transport

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