Imaging the Whole-Lithosphere Architecture of a Mineral System—Geophysical Signatures of the Sources and Pathways of Ore-Forming Fluids

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Abstract

Mineral systems can be thought of as a combination of several critical elements, including the whole-lithosphere architecture, favorable geodynamic/tectonic events, and fertility. Because they are driven by processes across various scales, exploration benefits from a scale-integrated approach. There are open questions regarding the source of ore-forming fluids, the depth of genesis, and their transportation through the upper crust to discrete emplacement locations. In this study, we investigate an Au–Cu metal belt located at the margin of an Archean-Paleoproterozoic microcontinent. We explore the geophysical signatures by analyzing three-dimensional models of the electrical resistivity and shear-wave velocity throughout the lithosphere. Directly beneath the metal belt, narrow, vertical, finger-like low-resistivity features are imaged within the resistive upper-middle crust and are connected to a large low-resistivity zone in the lower crust. A broad low-resistivity zone is imaged in the lithospheric mantle, which is well aligned with a zone of low shear-wave velocity, examined with a correlation analysis. In the upper-middle crust, the resistivity signatures give evidence for ancient pathways of fluids, constrained by a structure along a tectonic boundary. In the lower lithosphere, the resistivity and velocity signatures are interpreted to represent a fossil fluid source region. We propose that these signatures were caused by a combination of factors related to refertilization and metasomatism of the lithospheric mantle by long-lived subduction at the craton margin, possibly including iron enrichment, F-rich phlogopite, and metallic sulfides. The whole-lithosphere architecture controls the genesis, evolution, and transport of ore-forming fluids and thus the development of the mineral system.

Plain Language Summary

The whole-lithosphere structure of mineral systems, the link between deep and shallow regions, and the nature, origin, and depth of the source fluids that form mineral deposits are open questions. In this study, we investigate a gold and copper metal belt that is located at the margin of an ancient microcontinent and craton with a history of long-lived subduction. We explore the region by examining three-dimensional geophysical images of both the electrical resistivity structure and the shear-wave velocity structure throughout the lithosphere. Narrow, vertical, fingers of low resistivity in the crust give evidence for ancient pathways of fluids beneath the metal belt. Low velocity and low resistivity signatures in the lower lithosphere are interpreted to represent a fossil fluid source region. We suggest that the geophysical signatures observed were caused by a combination of factors related to mantle metasomatism caused by long-lived subduction and magmatism. The possible causes include iron enrichment in a more fertile mantle, the presence of F-rich phlogopite in the lithospheric mantle, and metallic sulfides in the lower lithosphere, including at the base of the crust. The whole-lithosphere structure and favorable geodynamic/tectonic events control the evolution of ore-forming fluids that create metal/mineral deposits.

1. Introduction

The whole-lithosphere architecture, structure and formation, has direct implications for both the genesis of mineral deposits and their discrete emplacement locations. Therefore, knowledge of the deep structural framework of a mineral system can advance understanding of the development and evolution of the system (e.g., Davies et al., 2020; Groves et al., 2018; Huston et al., 2016). Transient tectonic and geodynamic processes occurring at various spatial and temporal scales determine the structure of the lithosphere, and the structure exerts first-order control on the transportation of ore-forming fluids (e.g., along deep-reaching pathways; Huston et al., 2016). Mineral systems can be viewed as a holistic combination of several critical components that overlap in both space and time (e.g., McCuaig et al., 2010; McCuaig & Hronsky, 2014). One description of the components of a...
mineral system (based on Hagemann et al., 2016; see also Dentith et al., 2018) is in terms of: (a) a suitable geodynamic setting, (b) a favorable whole-lithosphere architecture, (c) fertility and sources of fluids and metals (e.g., from geochemical and tectonic processes), (d) drivers of fluid flow, (e) presence of fluid-flow pathways (across all scales), (f) metal concentration and depositional processes, and (g) preservation of the resulting deposit (and its geochemical and geophysical features). However, there are open questions regarding the nature of the source of ore-forming fluids, their origin depth, and the transportation link from the source, through the crust, to emplacement locations (e.g., Groves, Santosh, & Zhang, 2020). For example, whereas metamorphic devolatilization of supracrustal rocks within the continental middle crust and upward migration of the resultant ore-forming fluids have been discussed for some time, recent evidence implicates a lower lithospheric (e.g., subcrustal and/or lower crustal) source for fluids, which, in some cases, may arise from devolatilization of subducted sulfide-rich oceanic sediments or from the lithospheric mantle that has been metasomatized and fertilized from previous subduction and melting events, possibly at craton margins (Groves, Santosh, & Zhang, 2020).

Because mineral systems are influenced by processes across scales (from lithospheric scale to deposit scale), a scale-integrated approach may be required to understand the system (e.g., Blewett et al., 2010; Groves, Santosh, & Zhang, 2020). Furthermore, deep geophysical exploration studies are important for targeting new mineral deposits in unexplored and underexplored regions (e.g., Dentith et al., 2018, and references therein). The lithospheric-scale signatures of many mineral systems are expected to be largely similar, although distinct at the deposit scale, despite differences in age, formation, and style (e.g., whether orogenic gold type deposits, iron oxide copper gold-type deposits, Carlin-type gold deposits, etc.) (Huston et al., 2016; McCuaig & Hronsky, 2014).

The Bayankhongor Au–Cu metal belt, located in central Mongolia, contains significant occurrences of gold and copper mineralization (Figure 1a) (as well as iron and molybdenum). The ages of mineralization in the Bayankhongor zone vary from Early Carboniferous to earliest Triassic (Gerel et al., 2021; Watanabe et al., 1999). Mineral occurrences are expressed as Au-bearing quartz veins, hydrothermal mineralization, placer Au, Cu–Au porphyry, and skarn type deposits, which are associated with Paleozoic oxidized (magnetite-series) granitoid intrusions with sulfide-related mineralization (Buchan et al., 2001; Dejidmaa & Badarch, 1999; Gerel et al., 2021; see also Jargalan et al., 2007; Watanabe et al., 1999). The metal belt is ~200 km long and approximately northwest to southeast striking with the main deposits located from approximately 46.5°N to 45.5°N, 101°E (e.g., Watanabe et al., 1999). It is located ~500 km west of the world-class copper-gold Oyu Tolgoi deposit, one of the largest such deposits in the world (with significant reserves of high-grade mineralization), and ~400 km southwest of both the well-known Boroo gold district and the Erdenet porphyry copper and molybdenum system, one of the largest mines in the world (Figure 1b) (Richards, 2013; Porter, 2016, and references therein). The metal belt lies south of the Hangai Mountains and north of the Gobi-Alta Mountains.

The origin and evolution of this region are complex and are not completely understood. It is believed that the northeastern margin of the Baydrag block, which has basement rocks of Archean–Paleoproterozoic age (Demoux et al., 2009), was an active margin with southward subduction of Bayankhongor oceanic lithosphere occurring over a lengthy period of time (>100 million years), developing in the late Neoproterozoic to early Cambrian (Buchan et al., 2001; Demoux et al., 2009; Zhang et al., 2015). Widespread and intensive magmatism led to the development of regional metamorphic and volcanic belts (Osozawa et al., 2008). Volcanic activity, convergence, pre-existing weaknesses; Walker et al., 2007), which represent a major tectonic boundary at the margin of a some segments of the South Hangai fault system and shear zone pass through this area (likely reactivated from pre-existing weaknesses; Walker et al., 2007), which represent a major tectonic boundary at the margin of a.
Tectonic boundaries have been suggested to be a favorable setting for the migration of fluids (e.g., Griffin et al., 2013), and subduction-related fluids and melts are known to provide critical ore components for several types of (gold-rich) mineral deposits (e.g., Groves, Zhang, & Santosh, 2020). The genesis of the metal belt is closely connected to the unique and complex tectonic history of the local area, which created good metallogenic conditions (see Goldfarb et al., 2014). Some studies have characterized the near-surface structural features of the region (e.g., Buchan et al., 2001); however, the vertical extent of the mineral system is not fully known. Furthermore, its connection to deeper source regions in the lower crust or lithospheric mantle is unknown.

In this study, we analyze data from magnetotelluric (MT) measurements across central Mongolia and explore three-dimensional (3D) models of the electrical resistivity structure throughout the whole lithosphere from the upper crust to the asthenosphere. In addition, we compare shear-wave velocity models and carry out a quantitative correlation analysis. We interpret the geophysical results with the help of geological and geochemical data,

Figure 1. Maps of the study area. (a) The Bayankhongor metal belt, central Mongolia, is located in a region with significant occurrences of gold and copper mineralization (yellow and green symbols) as well as iron (black) (Mineral Resources Authority of Mongolia, 2017; Dejidmaa et al., 2002; Dejidmaa & Badarch, 1999) with the main deposits located from approximately 46.5°N, 99°E to 45.5°N, 101°E (e.g., Watanabe et al., 1999). The metal belt lies at the margin of a craton, an Archean–Paleoproterozoic microcontinent. An ophiolite belt in the Bayankhongor region marks the potential collisional suture between two microcontinents (red-dashed lines; Badarch et al., 2002) and is thus taken as the approximate boundary between the two. Various features are marked: fault traces, including the reactivated South Hangai fault system and shear zone (solid lines; Styron, 2018; Walker et al., 2007); magnetotelluric (MT) measurement sites (circles); profiles analyzed by Comeau et al. (2021) (gray bands); villages for reference (squares; Ba: Bayankhongor; Bu: Bumbugur; Bb: Bayanbulag; Gu: Gurvanbulag). Note that the map is rotated 15° from north. (b) Regional map showing the location of the study area (red box) within Mongolia and the locations of major mining districts (blue triangles; Er: Erdenet; Bo: Boroo; OT: Oyu Tolgoi). Ub is Ulaanbaatar.
with respect to the potential implications for ore-forming fluid generation and transportation, that is, sources and pathways, and discuss the potential causes, or combination of causes, of the geophysical signatures.

2. Methods
The MT method is a geophysical exploration technique that images the subsurface electrical resistivity structure with natural electromagnetic signals. MT data consist of electric and magnetic 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: high-frequency data are sensitive to shallow structures and low-frequency data are sensitive to deep structures. Furthermore, the MT method is a volume sounding method and the electromagnetic fields may be influenced by structures beneath and around the site (e.g., Simpson & Bahr, 2005). The electromagnetic fields are related by a frequency-dependent, complex-valued impedance tensor, from which the apparent resistivity and impedance phase can be determined (e.g., Cagniard, 1953; Unsworth & Rondenay, 2012). MT data are particularly sensitive to the presence of interconnected low-resistivity phases in rock volumes (including aqueous fluids and partial melts). The MT method is well-suited to image large-scale lithospheric structures (e.g., Burd et al., 2013; Comeau et al., 2018; Ostos & Park, 2012; Wannamaker et al., 2008). Additionally, numerous studies have shown that the technique is capable of characterizing the pathways of past fluids and the traces of mineral alteration (e.g., Comeau et al., 2021; Hill et al., 2021; Hübert et al., 2015; Lü et al., 2021; Sheng et al., 2022; Vadoodi et al., 2021; Wise & Thiel, 2020; Yin et al., 2021). Recent works have linked the formation of giant mineral deposits with deep electrical signatures, including the work of Heinson et al. (2018) on the (iron oxide copper gold uranium) Olympic Dam deposit, Australia. The multiscale nature of the MT method allows imaging of the deepest parts of the lithosphere (i.e., lithospheric-scale) as well as the upper part of the crust and directly beneath mineral deposits (i.e., regional-scale and deposit-scale).

An extensive data set of MT measurements has been acquired across central Mongolia since 2016 (total to date of 342 measurement sites) (data described by Becken et al., 2021a, 2021b). The measurements were acquired on an array with a nominal spacing of 50 km by 50 km, as well as along denser profiles, with a spacing of 1–10 km (and a total area of more than 450 km by 700 km). To investigate the upper crustal resistivity structure beneath the metal belt, Comeau et al. (2021) generated high-resolution, crustal-scale 3D models along small segments (∼100 km) of the separate dense profiles in this region (47 measurement sites totally). To investigate the link to deeper structures, in this study, we focus on an area of ∼450 km by ∼200 km across the metal belt (104 measurement sites) by exploring a subset of the 3D model presented by Käufl et al. (2020) (for some details of the modeling, see the Supporting Information S1). Data are shown in Figures S1 and S2 in Supporting Information S1.

3. Results
3.1. Electrical Resistivity Models
A 3D electrical resistivity model, derived from MT data collected across central Mongolia, was presented by Käufl et al. (2020). The part of the model that crosses the study area is shown in Figure 2 as horizontal slices. The upper crust (depths of 0–25 km) is found to be generally highly resistive (~10,000 Ωm). This is attributed to the basement rocks of the continental block, which are Archean–Paleoproterozoic age (McDannell et al., 2018). However, small low-resistivity anomalies (1–100 Ωm; i.e., orders of magnitude lower) are observed and are located beneath the metal belt (labeled C1, C2, and C3) and its eastern edge (labeled C4 and C5). At the southern edge of the model, low-resistivity features are observed at depths <7 km and are associated with fault traces along the flank of the Gobi-Altai mountains (e.g., the feature labeled C6). Due to the irregular site coverage, with large distances between sites on the array compared to the close spacing along the profiles, features at shallow depths (<20 km) distant from MT measurement locations (e.g., between profiles) may not be as well-constrained as others. A direct correspondence between the location of known mineral zones and low-resistivity features is significant. In contrast, the absence of a correspondence can be due to limited information, for example, related to the spatial distribution of MT measurements and to the limited (and possibly biased) mineral exploration coverage. The major low-resistivity features observed appear to correspond well with the metal belt (see Figure 2d). Comeau et al. (2021), using high-resolution models along dense profiles, showed that small-scale low-resistivity features in the shallow upper crust (e.g., <5 km) were coincident with the locations of large deposits of gold and copper and with metamorphic and volcanic belts south of the ophiolite belt.
Figure 2. A three-dimensional electrical resistivity model of the crust and uppermost mantle across the study area, shown as horizontal slices. (a) Map of the study area indicating features of interest. Occurrences of mineralization, the ophiolite belt in the Bayankhongor region, fault traces, villages, and magnetotelluric measurement sites are marked as in Figure 1. Note the model coordinate system is rotated 15° clockwise from north (model coordinates in black; geographic coordinates in blue). (b–h) The model is shown as horizontal slices at depths of 7, 15, 25, 35, 50, 65, and 80 km, respectively. The crust-mantle boundary is at a depth of approximately 50 km. Some low-resistivity features are located beneath the metal belt (C1, C2, C3, C4, and C5, as well as C11 and C12). Others, in the north (C8, C9, and C10), are located near Quaternary volcanism.
The crust across the study region has been determined to be thick, both relative to the surroundings and to the global average of continental crust, with estimates of approximately 50 km (shallowing in the eastern part of the study area, Figure S4 in Supporting Information S1; Feng, 2020; see also Petit et al., 2008; Welkey et al., 2018). Thus, the lower crust is defined as depths of 25–50 km, below the rheological transition from brittle to ductile regime in this region (Déverchère et al., 2001; Welkey et al., 2018). Previous studies reported a sharp transition in resistivity at this boundary, a reduction of orders of magnitude (Comeau et al., 2020; Käufl et al., 2020). A low-resistivity feature (1–10 Ωm; labeled C11) with a size of 100–200 km by 50–100 km, possibly composed of three to four separate parts, is observed in the lower crust and occupies the central part of the study area. It is aligned remarkably well with the location of the metal belt at the surface. To the north, low-resistivity features (10–100 Ωm; labeled C8, C9, and C10) are located near the surface expressions of Quaternary intraplate volcanism (Egiin Davaa, Erdenetsogt, and Orkhon; Ancuta et al., 2018, see also Comeau et al., 2018, 2022), which are outside of or at the edge of the study area (note that the modeling domain goes beyond the study area presented here). Arvaikheer gold district lies northeast of the study area (i.e., beyond C10) and the Altai copper and gold district lies southwest of the study area. A resistive region (∼1,000 Ωm; labeled R1) is observed below the surface trace of the ophiolite belt and the Bayankhongor region in the northwest. To the south, the crust remains highly resistive (∼1,000 Ωm). Toward the southeast, a narrow (50–100 km) highly resistive feature (1,000–10,000 Ωm; labeled R2) is imaged, approximately along longitude 101°E and south of the village of Bayankhongor.

Seismic data point to a relatively thin lithosphere beneath this region with varying thickness estimates of 80–120 km (Petit et al., 2008; Priestley et al., 2006). In the uppermost mantle (depths of 50–80 km), the background resistivity values are ∼100–300 Ωm. In the central region of the study area, a broad low-resistivity zone (30–100 Ωm; C12) is imaged, which is connected to the crustal low-resistivity region above it. Regions to the south and east are relatively resistive (300–1,000 Ωm; labeled R2). At these depths, small-scale structures are not discernible due to the diffusive nature of the MT method.

A perspective view of the 3D model is presented in Figure 3. It displays the whole-lithosphere structure, highlighting the connection between the narrow, finger-like low-resistivity anomalies in the upper crust, the large low-resistivity feature in the lower crust, observed beneath the metal belt, and the broad region of low resistivity.
in the uppermost mantle. Vertical sections are shown in Figures 4 and 5, approximately west-east and north-south, respectively. They show that the low-resistivity features in the uppermost mantle are located slightly farther south than their counterparts in the crust, consistent with a steep, southward dip (see Comeau et al., 2021, and references therein). Furthermore, the tectonic collisional boundary may be marked by a strong contrast from high resistivity to low resistivity near the ophiolite belt location (cf. feature R1 and profile P7). Alternatively, as argued elsewhere by Xu et al. (2020), it is possible that a fossil oceanic plate can be trapped and preserved in the continental lithosphere.

### 3.2. Shear-Wave Velocity Models

A 3D shear-wave velocity (Vs) model, which uses Rayleigh waves and receiver functions, was constructed by Feng (2020) from a local seismic recorder array across central Mongolia (Meltzer et al., 2019; see locations in Figure S5 in Supporting Information S1). The uppermost mantle structure beneath the study area is shown as horizontal slices in Figures 6b and 6c. Within the uppermost mantle (at depths of approximately 57–63 km and 77–83 km), a broad low-velocity zone is imaged (labeled S1). The zone is approximately 100–250 km in size and is located in the central part of the study area, beneath the metal belt. Furthermore, it is coincident with the location of the low-resistivity zone. The low-velocity zone has a velocity of ~4.2–4.25 km/s, which represents a relative change (i.e., \( \Delta V = (V_o - V)/V_o \)) of approximately −1% to −2% compared to the surroundings (4.3 km/s). Toward the southeast, a sharp transition to a small (50–150 km) high-velocity
feature (4.3–4.4 km/s) is imaged (labeled S2), approximately along longitude 101°E and south of the village of Bayankhongor.

Vertical sections in Figures 6d and 6e show the crust and the uppermost mantle structure along profile C (0–10 km north of profile P2) and profile D (within ±10 km of profile P4). The vertical sections show that the low-velocity features described above dominate the lithospheric mantle (e.g., <80 km). The southern profile (D) shows a sharp transition to higher velocity at depths of 80–90 km, whereas the northern profile (C) shows a deeper transition at depths of ∼100 km or more, particularly at longitudes of 99°E to 100°E (beneath the metal belt). On profile D, near longitude 101°E, the sharp transition to high-velocity feature S2 is observed, and the feature appears to be vertically extensive, reaching through the uppermost mantle.

The vertical sections also show the crustal structure. However, there is a lack of information about the fine structure of the crust. This is in part due to resolution differences (in the crust compared to the mantle) and the fact
that a simplified model parameterization in the crust (which constrains the velocity to monotonically increase; Feng, 2020) produces a simplified layered structure that may miss crustal heterogeneity. The northern profile (C) appears to have thicker low velocity layers in the crust at longitudes of 99°E to 100°E (beneath the metal belt) as compared to the surroundings (e.g., the 3.55 km/s contour goes to depths greater than 30 km compared to 15 km to the west or south). This suggests that in the crust below the metal belt, the velocity is reduced and it may indicate a correspondence with the observed low-resistivity anomalies. More information comes from another analysis of the seismic data by Welkey et al. (2018), who reported that large areas in the bottom 10–15 km of the crust showed Vp (p-wave velocity) in the excess of 7 km/s, and determined a high average Vp/Vs ratio across the survey region of ~1.8.
3.3. Comparison and Correlation of Electrical Resistivity and Shear-Wave Velocity

Employing multiple geophysical methods, which are sensitive to distinct physical parameters, can help to reduce uncertainty when interpreting the subsurface structure. Both electrical resistivity and shear-wave velocity are sensitive to rock properties, particularly to composition and mineralogy, and are complementary (e.g., Bedrosian et al., 2004; Unsworth & Rondenay, 2012). There is no theoretical relationship between electrical resistivity and shear-wave velocity, but they are often correlated; however, some variations in rock composition, such as sulfides and minor hydrothermal alteration, may significantly influence the electrical resistivity response but not the velocity (Unsworth & Rondenay, 2012).

A qualitative comparison of the two models reveals broad similarities: the central part of the study area is occupied by a low-resistivity region and a region of low shear-wave velocity, and the southeastern part exhibits high resistivities and high shear-wave velocities. However, some differences are easily seen, for example, in the north, northeast, and southwest parts of the models. Below, we undertake a correlation analysis in order to quantitatively compare the two models. A joint (or constrained) inversion of seismic and resistivity data is possible (e.g., Moorkamp et al., 2007), but is not considered in the current study.

Here, we follow an approach to investigate the (spatial) correlation between two independent geophysical parameters as described by Bedrosian et al. (2004) and others (e.g., Bertrand et al., 2012; Comeau et al., 2016; Cordell et al., 2019). The horizontal slices of both models were interpolated onto a common grid (cell size of 25 km by 25 km). Next, the parameter values were divided into distinct categories (five bins each, 25 total categories; the central region, where most of the interesting parameter variations occur, had bins defined as 0.03 km/s for velocity and 0.33 log units for resistivity). The number of occurrences in each category were then counted. The results are presented as a two-parameter histogram, or correlation plot, in Figure 7a for a depth of 60 km and in Figure S6 in Supporting Information S1 for a depth of 80 km.

Figure 7. Investigation of the correlation between electrical resistivity and shear-wave velocity (V\text{s}) by means of a two-parameter histogram or correlation plot. (a) Resistivity-velocity correlation plot based on horizontal slices at depths of 60–65 km (models show in Figures 2g and 6b). Models were interpolated onto a common grid (cell size of 25 km by 25 km). The grayscale shows the number of occurrences for each combination of parameters (25 total categories; 9 had no occurrences). A trend of increasing resistivity with increasing shear-wave velocity is observed. However, one zone sits outside this trend: Zone 4 represents low resistivity but moderate velocities. There were no occurrences of high resistivity and low velocity. (b) The distinct zones are mapped back to the spatial domain. Zone 1 is located in the central part of the study area, beneath the metal belt, corresponding to features C12 and S1. Zone 3 corresponds to features R2 and S2. Zone 4 indicates the locations where the models are not well-correlated.
By jointly analyzing the parameters in this way, distinct zones can be defined for specific groups of resistivity and shear-wave velocity values. A trend of increasing resistivity with increasing shear-wave velocity is observed with the exception of one zone, which sits outside this trend. Zone 1 represents low velocity and low resistivity, Zone 2 represents intermediate values, Zone 3 represents high velocity and high resistivity, and Zone 4 represents low resistivity but moderate velocities. There were no occurrences of high resistivity and low velocity; similar observations were reported by Bertrand et al. (2012) and Comeau et al. (2016). The distinct zones can then be mapped back to the spatial domain as shown in Figure 7b. Zone 1 is located in the central part of the study area, beneath the metal belt, corresponding to features C12 and S1; Zone 3 corresponds to features R2 and S2; Zone 4 indicates the locations where the models are not well-correlated. For a depth of 60 km, Zone 4 represents ~15% of occurrences, more than half of which are clustered in the northeast (near the locations of Quaternary intraplate volcanism; see Figure S7 in Supporting Information S1 and Figure 2e). For a depth of 80 km, more than half of the occurrences of Zone 4 are clustered in the southwest. The close correlations of both parameters across the majority of the model area are a good indication of the robustness of both model results.

4. Discussion

4.1. Low Electrical Resistivity Features in the Upper-Middle Crust: Evidence for Fluid Pathways

Beneath the metal belt, the electrical resistivity model reveals multiple low-resistivity anomalies (1–100 Ωm) at various spatial scales and depths throughout the crust. In the upper-middle crust, high-contrast anomalies are narrow and vertically extended, resembling finger-like structures. They connect to several large anomalies in the lower crust. Generally, zones of low electrical resistivity are attributed to partial melt, aqueous fluids, interconnected carbon, graphite films, metallic materials, including sulfides, hydrothermal mineral alteration, or a combination of several of the above (e.g., Unsworth & Rondenay, 2012).

In this region, there exists evidence for hydrothermal alteration, including along lamprophyre dikes (potassic mafic igneous intrusives; some of which are 1–10 m wide and several kilometers long) (Jargalan et al., 2007), commonly associated with deep melting and thus deep-reaching (e.g., lithospheric-scale) fluid pathways (e.g., Groves et al., 2018), and fluid inclusions in gold-bearing quartz veins that indicate saline conditions (<7 wt% NaCl; Jargalan & Murao, 1998). These features likely formed due to elevated fluid flow driven by collisional-related or subduction-related metamorphism (Goldfarb & Santosh, 2014; Groves et al., 2018; Müller & Groves, 2016). The past movement of fluids through the crust can be inferred from the electrical resistivity signature (e.g., Comeau et al., 2015; Cordell et al., 2019; Heinson et al., 2018; McGary et al., 2014). This is because fluids flushed through at high temperatures can alter the chemical composition of the surrounding rock and lead to a strong reduction in electrical resistivity (e.g., Harlov & Austrheim, 2013; Pearce et al., 2006).

One potential explanation for the vertically elongated low-resistivity features imaged in the upper crust is that they represent the signatures of hydrothermal alteration along fossil fluid pathways or conduits. Graphite and carbon may play a role here too (e.g., Heinson et al., 2006). The explanation for these features is especially clear given their remarkable correlation with surface gold (and copper) deposits with metal precipitation sites in the uppermost crust located near the top of fluid migration conduits (see Figures 2 and 4). Their locations may be related to crustal weakness from previous magmatic activity (Paleozoic; e.g., Buchan et al., 2002; Osozawa et al., 2008; Zhang et al., 2015). Similar features have been observed elsewhere, notably in the Archean Gawler craton, Australia, where they were inferred to map the paths of metalliferous fluids through the crust and associated with the Olympic Dam mineral complex (Heinson et al., 2018; see; Wise & Thiel, 2020).

At the crustal scale, the favorable structure for the transport and channeling of ore-forming fluids consist of deep-reaching faults, shear zones, crossing faults, and reactivated thrust faults, especially near jogs or bends where structural traps can occur (e.g., Groves, Santosh, & Zhang, 2020). Some large mineral districts are observed to be spaced on the order of the crustal depth (Groves, Santosh, & Zhang, 2020). Examples from Yilgarn and Gawler, Australia, show major faults and/or mineral deposits with spacings of 20–60 km (Dentith et al., 2012; Heinson et al., 2018). At the deposit scale, high fluid flux focused into small volumes is critical for mineral deposit formation.
4.2. Low Electrical Resistivity and Low Shear-Wave Velocity in the Lower Lithosphere: Possible Fossil Source Region for Ore-Forming Fluids

Several large low-resistivity features are imaged in the lower crust. In the uppermost mantle a low-resistivity zone is congruent with a zone of low shear-wave velocity. Any explanation must satisfy both physical parameters. We propose that the features represent the fossil source region of ore-forming fluids for the mineral system. The primary source of metals for the mineral system is inferred to be from the melts of a thermally perturbed, hydrated, and metasomatized lithospheric mantle. The specific chemical composition and mineralogy of the region contribute to the observed low-resistivity and low-velocity anomalies. It is very likely that a combination of effects (several discussed below), some of which may work together synergistically, acts to cause the geophysical signatures observed.

Long-lived subduction processes, which can occur for >100 million years and can affect a large area along tectonic margins, and arc processes result in a large quantity of melt and volatiles (e.g., H2O, CO2, H2S, and SO2) fluxing through the corresponding regions (e.g., see Begg et al., 2009; Hronsky et al., 2012; Xu, Hou, et al., 2021). These processes lead to metasomatism of the lithospheric mantle. Refertilization acts to chemically modify the lithosphere and gradually changes the bulk composition, from the base upward, with enrichment of elements including Fe, Ca, and Al (Griffin et al., 2009, 2013). These processes ultimately lead to enrichment of metals, such as Au and Cu, as well as S. Generally, it is expected that the most intense areas of metasomatism will have reduced electrical resistivity and velocity (see Jessell et al., 2016). The transition from Mg-rich olivine to Fe-rich olivine acts to reduce the shear-wave velocity (Griffin et al., 2009, 2013; Lee, 2003) and thus, a lower shear-wave velocity correlates with a lower Mg# (Mg content, relative to Fe content) and can be used to map mantle compositional variations (in contrast, Vp exhibits little or no correlation with Mg#). Therefore, the lower shear-wave velocity observed can be explained by a more fertile mantle composition (see Begg et al., 2009). Such a composition also causes a reduction in the electrical resistivity, largely because Fe plays an important role as a charge carrier (Dai et al., 2012; see also Thiel & Heinson, 2013; Wang et al., 2012). Furthermore, it can cause a small increase in density (possibly 1%–3%; Fernández et al., 2010; Griffin et al., 2009). The estimated increase in fertility between an Archean age block of subcontinental lithospheric mantle (tectonothermal ages >2.5 Ga) and a younger block (major thermal event or modification <1.0 Ga), or the tectonically reworked area at the margin of a craton, corresponds to a decrease in the shear-wave velocity of ~1–2% (Afonso & Schutt, 2012; Griffin et al., 2009).

Other mantle minerals that can act to reduce electrical resistivity, and which are compatible with a high Vp/Vs ratio, include metasomatism-related F-rich phlogopite and/or hydrous garnet networks (Dai et al., 2012; Li et al., 2016, 2017). Li et al. (2016) showed that the presence of approximately 0.1% phlogopite in peridotite in the continental upper mantle can give a bulk resistivity of 10–100 Ωm at temperatures of 1000–1200°C, which is likely in the study area at depths of 60–80 km (see Comeau et al., 2022) (in contrast, for temperatures <850°C volume fractions more than ~2% are required; see Xu et al., 2020). In central Mongolia, Hunt et al. (2012) determined that the subcontinental lithospheric mantle contained phlogopite based on the analysis of mantle xenoliths and megacrysts. Therefore, F-rich phlogopite can feasibly contribute to the geophysical signatures observed in the lithospheric mantle in the study area. Fluorine can be transported into the upper mantle by altered oceanic crust or brought in from the asthenosphere and seems to be less prone to post-magmatic alteration (Xu et al., 2020, and references therein). A garnet-rich grain-boundary network, which, evidence shows, can be caused by metasomatism within the mantle wedge (Vrijmoed et al., 2013, and references therein), or connected garnet clusters caused by mantle refertilization (Ferrand, 2021), can lower the electrical resistivity (and more so in the presence of iron; Dai et al., 2012), although current experimental studies are limited. Increased upper mantle conductivity elsewhere has been explained by hydrous olivine (Gardès et al., 2014). However, calculations by Comeau et al. (2018) show that it is an inadequate explanation for the observations in central Mongolia because it requires unlikely high water concentrations.

Ducea and Park (2000) showed that accessory sulfide minerals reduce the resistivity considerably, based on a low-resistivity feature (~30 Ωm) in the uppermost mantle beneath the Sierra Nevada, USA, where xenoliths exhibited sulfide concentrations of 0.06%–0.4%. Following their analysis, calculations show that if ≥2% silicate partial melt can explain the observed low-resistivity values, a minimum of 0.155% sulfide melt can alternatively completely explain the observation. This is consistent with the inferred concentration of sulfur in the subcontinental mantle prior to melting (up to a few hundred parts per million; a small amount which cannot explain high
conductivities) and the ratio of sulfur to sulfide (Ducea & Park, 2000; Guo et al., 1999). As the silicate melt is extracted, a higher density residual melt that is more concentrated in sulfides remains (an immiscible sulfide melt; Guo et al., 1999). If the sulfides form an interconnected network, for example, by wetting the grain boundaries of mantle olivine (Gaetani & Grove, 1999), they can substantially contribute to reducing the bulk electrical resistivity. Recent work has demonstrated that Cu–Au-rich sulfide melt likely exists in cumulates near the base of the crust in regions with long-lived magma generation, and investigated mechanisms for the mobilization and ascent of Cu–Au rich fluids upon reheating (Holwell et al., 2022). Metal preconcentration in fluids and/or magmas is thought to be a critical step in the formation of some mineral deposits and is closely related to the segregation of sulfide phases, which have been shown to persist at the base of the crust (Richards, 2011; Xu, Yang, et al., 2021; Zheng et al., 2019). In addition, Holwell et al. (2019) have shown that (metal-rich) sulfides in mantle-derived magmas emplaced at the base of the continental crust play a fundamental role in controlling the abundance of metals in ascending fluids/melts (i.e., their fertility) by acting as a gateway and thus are important in the formation of ore systems. Therefore, sulfide phases likely contribute to the low resistivity observed in the lower crust and in the lithospheric mantle in the study area. However, low volumes of sulfides alone may be difficult to directly reconcile with low-velocity anomalies. Although mantle-derived sources of sulfides may be a major contributor, marine sediments can introduce sulfides to the mantle through subduction, especially if they are rich in pyrite, which occurred in Earth’s past when the chemistry of the oceans was distinct from the present day (Bowles-Martinez, 2019; see Gaboury, 2013, and references therein).

Other explanations for low resistivity in the lithosphere invoke carbon or graphite films. Experimental studies have shown the presence of interconnected graphite as films (possibly in addition to sulfides) along grain boundaries (or in vein networks) can cause a reduction in bulk resistivity of orders of magnitude (Frost et al., 1989; Glover, 1997). However, Yoshino and Noritake (2011) showed that graphite films are not stable under high temperatures conditions, such as those likely present in the upper mantle. Jones et al. (2003) explained low resistivity (≈30 Ωm) in the (cool) lithospheric mantle (75–120 km) of the Archean Slave crater, Canada, as being due to graphite or carbon on grain boundary films. Hill et al. (2021) showed that a low-resistivity zone (≈30–300 Ωm) in the lower crust of the Archean Superior Province, Canada, can be explained by a small amount (order of ≈1%) of interconnected graphite, and suggested that these features are stable and thus may be preserved over geological time. The carbon can be mantle-derived, from magmatic and metamorphic fluids, possibly related to a subduction environment, or a plume. Alternatively, or in addition, organic sources of carbon can be a contributor with transport to the deep lithosphere possible during subduction (e.g., accretionary wedges of marine sediments). In fact, certain periods of Earth’s history (e.g., the Precambrian) have produced exceptionally carbon-rich marine sediments (Heinson et al., 2021; see Gaboury, 2021, and references therein). Heinson et al. (2021) argue that marine sediments buried in the lower crust may be metamorphosed to flake graphite and can produce conductive signatures. Furthermore, some studies (e.g., Gaboury, 2013, 2019, 2021; Large et al., 2011) suggest that carbonaceous oceanic sediments (often pyrite-rich), for example, black shales, may be a potential rich source of gold. The presence of graphite/carbon can contribute to reducing the electrical resistivity in the middle-lower crust, where the temperatures are not elevated (see Zhang & Yoshino, 2017). However, graphite alone may be difficult to directly reconcile with the low-velocity anomaly observed. Thus, ultimately, the results indicate that a combination of factors likely acts to cause the geophysical signatures observed.

### 4.3. Controls on Fluid Evolution and Mineral System Formation

Can models for the geological evolution and tectonic history of the region shed light on the potential origin of the source region or the evolution of ore-forming fluids? The subduction and collision events in this region are estimated to have occurred over a lengthy period of time (>100 million years; Buchan et al., 2001, 2002), as is the volcanic activity, which continued into the early or mid-Paleozoic. The age of the mineralization of large deposits within the Bayankhongor metal belt is inferred to be late Paleozoic or possibly later (many are of late Permian age) (Jargalan et al., 2007; Jargalan & Fujimaki, 2000; Watanabe et al., 1999). Thus, there exists a significant temporal gap between subduction and mantle metasomatism and the emplacement of mineral deposits as observed in other regions (e.g., Locmelis et al., 2015). One explanation for these events, based on the model of Goldfarb and Santosh (2014) (see also Goldfarb & Groves, 2015), hypothesizes that metamorphic fluids produced during one geodynamic event, for example, devolatilization of a subducted slab, migrate upward, for example, along the slab-mantle boundary or tectonic margin, and reside in the lithospheric mantle in metal-rich and volatile-rich zones (e.g., Locmelis et al., 2015) with subsequent releases of ore-forming fluids and upward migration into
the crust triggered by further geodynamic events, possibly far-field stress changes, a switch from compression to transpression, or the cessation of subduction (e.g., Groves, Santosh, & Zhang, 2020). Another explanation for the events is one where ore-forming fluids are generated from the lithospheric mantle that has been fertilized and metasomatized by fluids and melts derived from a much earlier geodynamic event, such as subduction (e.g., Groves, Santosh, & Zhang, 2020; Groves, Zhang, & Santosh, 2020). In such a scenario, former intensive and long-lived arc magmatism may have left abundant sulfide-bearing and metal-rich cumulates near the base of the crust and a subsequent thermal anomaly, such as a mantle upwelling, triggered remelting, which provided abundant metals and S for post-subduction fluid generation and mineral deposit formation (Richards, 2011; Hou et al., 2015; Xu, Hou, et al., 2021; see also Holwell et al., 2022) with a temporal gap suggesting independence of the fluid and mineral formation from the metamorphic and volcanic host rocks. This is consistent with studies that suggest the initial enrichment of metals in fluids and/or magmas is an important step in the formation of mineral deposits (Xu, Yang, et al., 2021; Zheng et al., 2019; see also Heinrich & Connolly, 2022).

Considering the available evidence, and based on conceptual models discussed in various works (see above), we propose the following scenarios. Long-lived subduction along the tectonic margin acted to hydrate the lithospheric mantle and led to metasomatism and widespread magmatism. Refertilization processes acted to chemically modify the lithospheric mantle, causing enrichment and gradually changing the bulk composition. Much later, sulfide and metal-rich cumulates at the base of the crust were remelted, triggered by further tectonic events (such as a local mantle upwelling possibly caused by a slab break-off). Cu–Au-rich fluids/melts were mobilized and driven upward. They moved to the upper crust along pathways, possibly preexisting and reactivated weaknesses, for example, channeled along conduits associated with ancient volcanic activity, up deep faults, shear zones, and shallow thrusts faults, as well as along the paleo-slab interface, constrained by the structure along the major tectonic boundary at the margin of the craton. This was followed by metal concentration, precipitation, and deposition, producing mineral deposits. The geochemical signatures in the upper-middle crust and in the lower lithosphere were preserved due to no further significant tectonic event in which overprinting could occur, resulting in the geophysical anomalies observed today, that is, low-resistivity and low-velocity signatures.

The results of this work serve to illustrate that the whole-lithosphere architecture, inherited from or influenced by earlier tectonic events across multiple spatial and temporal scales, controls the origin, evolution, and transportation of ore-forming fluids and therefore controls the location of potential mineral systems and the discrete emplacement locations of mineral deposits. Thus, from an exploration point-of-view, understanding the whole-lithosphere architecture is crucially important and multiscale investigations are essential.

5. Conclusion

Mineral systems are driven by lithospheric-scale processes, and thus understanding the whole-lithosphere architecture is important. Therefore, modern exploration concepts advocate for a scale-integrated approach with lithospheric-scale, regional-scale, and deposit-scale investigations. The multiscale nature of the MT method enables the imaging of features at multiple spatial scales and depths. Furthermore, wherever possible, employing multiple geophysical methods, which are sensitive to distinct physical parameters, can help to reduce the uncertainty when interpreting the subsurface structure.

In this study, we analyze data from MT measurements across a metal belt in central Mongolia and explore 3D models of the electrical resistivity and shear-wave velocity throughout the whole lithosphere from the upper crust to the asthenosphere. In addition, we carry out a two-parameter correlation analysis to quantitatively compare the models. The electrical resistivity model reveals multiple low-resistivity anomalies. These are observed at various spatial scales and depths throughout the lithosphere, including high-contrast, narrow, vertically extended anomalies within the resistive upper crust, connected to several large features in the lower crust, and a broad low-resistivity zone in the lithospheric mantle. The latter is very well correlated with a zone of low shear-wave velocity. Moreover, these features are located beneath the metal belt.

The low-resistivity features in the upper-middle crust are interpreted to represent the electrical signatures of ancient pathways of fluids and record the location of ascent beneath the metal belt. Within the lower lithosphere, the low-resistivity feature is interpreted to represent the source region of ore-forming fluids. Therefore, the models reveal the complete translithospheric structure of the ancient fluid system, which formed the metal belt, including its deep source region and its pathways. The work highlights the applicability of the MT exploration technique to
image the critical elements of a mineral system using a scale-integrated and whole-lithosphere approach to deep geophysical exploration. Furthermore, the results illustrate that the whole-lithosphere architecture controls the locations of mineral deposits and metal belts.

We propose that the observed geophysical signatures are related to refertilization and metasomatism of the lithospheric mantle by a long-lived subduction event at the margin of the craton that modified the chemical composition and mineralogy of the region. The reduction in shear-wave velocity detected in the lithospheric mantle can be explained by a more fertile melt (e.g., iron enrichment) and is compatible with the presence of phlogopite. The low electrical resistivity observed in the lithospheric mantle can be explained by the presence of F-rich phlogopite and metallic sulfides and is compatible with a fertile mantle. In the lower crust, sulfide phases can explain the reduced electrical resistivity. In addition, the presence of graphite/carbon may possibly play a role in the middle-lower and middle-upper crust. The results indicate that a combination of factors is likely necessary to cause the observed geophysical signatures.

Data Availability Statement

No new data were generated for this study. The seismic waveform data referenced from the Central Mongolia Seismic Experiment, with network name XL, are described by Meltzer et al. (2019) at [https://doi.org/10.1029/2018GL083560](https://doi.org/10.1029/2018GL083560). It is available from the IRIS Data Management Center (e.g., via [https://ds.iris.edu/ds/nodes/dmc/forms/breakfast-request](https://ds.iris.edu/ds/nodes/dmc/forms/breakfast-request)). The MT data referenced are archived by the German Research Centre for Geosciences (GFZ); for a description of the data collection see Becken et al. (2021a) and Becken et al. (2021b) at [https://doi.org/10.5880/GIPP-MT.201613.1](https://doi.org/10.5880/GIPP-MT.201613.1) and [https://doi.org/10.5880/GIPP-MT.201706.1](https://doi.org/10.5880/GIPP-MT.201706.1). A detailed description of the MT modelling and a repository of the MT data are available in Käufl (2020) at [https://doi.org/10.1029/2020gl088455](https://doi.org/10.1029/2020gl088455). It is available from the IRIS Data Management Center (e.g., via [https://ds.iris.edu/ds/nodes/dmc/forms/breakfast-request](https://ds.iris.edu/ds/nodes/dmc/forms/breakfast-request)).

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