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The Bayankhongor Metal Belt (Mongolia): Constraints on Crustal Architecture and Implications for Mineral Emplacement from 3-D Electrical Resistivity Models

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Abstract: The Bayankhongor Metal Belt, a narrow metallogenic belt that extends for more than 100 km in central Mongolia, is an economically significant zone that includes sources of gold and copper. Unfortunately, the crustal architecture is poorly understood throughout this region. However, it is known that the crustal structure strongly influences the development and emplacement of mineral zones. Electrical resistivity is a key physical parameter for mineral exploration that can help to locate mineral zones and to determine the regional crustal structure. We use natural-source magnetotelluric data to generate three-dimensional electrical resistivity models of the crust. The results show that anomalous, low-resistivity (conductive) zones in the upper crust are spatially associated with the surface expressions of known mineral occurrences, deposits, and mining projects. We thus infer that the development of the mineralization is closely linked to the low-resistivity signatures and, therefore, to crustal structures, due primarily to their influence on fluid flow. The low-resistivity signatures are possibly related to associated sulfide mineralogy within the host complex and to structures and weaknesses that facilitated fluid movement and contain traces of past hydrothermal alteration. Thus the crustal architecture, including major crustal boundaries that influence fluid distribution, exerts a first-order control on the location of the metallogenic belt. By combining our electrical resistivity results with other geological and petrological data we attempt to gain insights into the emplacement and origin of mineral resources.

Keywords: Metallogenic Belt; Ophiolite Belt; Suture Zone; Mineralization; Mineral Emplacement; Mineral Genesis; Mineral Exploration; Electrical Resistivity; Magnetotellurics; 3-D Inversion

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1. Introduction

The mineral systems concept, whereby mineralized zones are seen as small expressions of a range of Earth processes, is recognized as the key to targeting new deposits and to interpreting ore genesis, through understanding the organizational framework of the system [1]. Links between the location of mineralized zones and their underlying crustal structure have been established for many well-known mineral districts [2]. Furthermore, it has been recognized that major crustal boundaries may be important in the formation of mineralized zones, and that their internal geometry is inherited from earlier tectonic features [3].

A large suture zone in central Mongolia, at the southern margin of the Hangai mountains within the Central Asian Orogenic Belt, is marked by the Bayankhongor Ophiolite Belt [4,5]. It is significant because it gives evidence for the closure of a paleo-ocean, and, therefore, it is believed to represent a major crustal boundary. In addition, segments of the South Hangai fault system pass through this area and they are believed to be part of a reactivated fault system [6]. Immediately to the south of the suture zone, metamorphic and volcanic provinces are identified [7]. Distributed throughout this region are occurrences of gold and copper mineralization [8,9], which make up the Bayankhongor Metal Belt (Figure 1).

Many questions remain about the near-surface framework and crustal structure of these mineral zones. In addition, knowledge of their vertical extent, and possible connection to deeper sources, can provide insights into their formation and development. In this contribution, we analyze three-dimensional (3-D) electrical resistivity models generated from natural-source magnetotelluric (MT) measurements. We investigate and discuss the geometry and extent of the features beneath the metallogenic belt and beneath the adjacent suture zone and ophiolite belt.

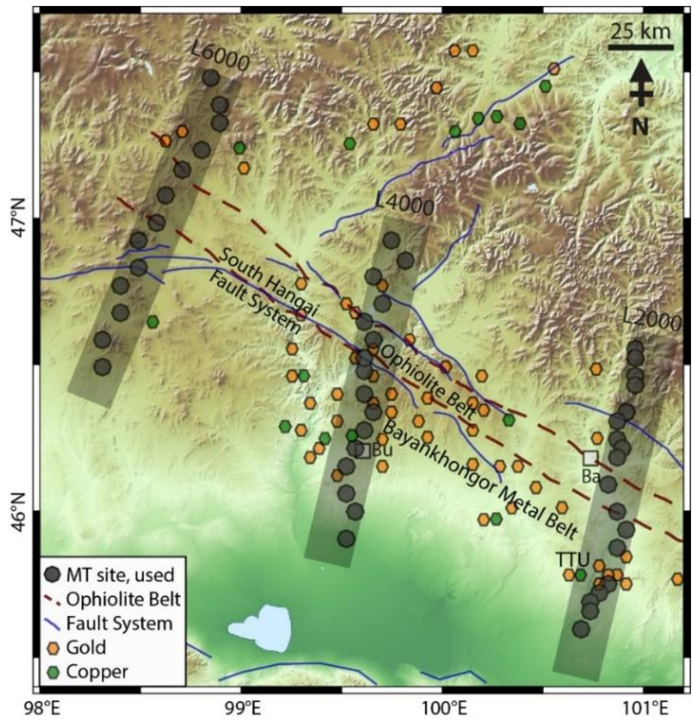

Figure 1. Map of the study area. The locations of MT measurement sites (black) and profiles (grey) are indicated. The approximate location of the Bayankhongor Ophiolite Belt (red) and faults (blue) are marked. This region contains many mineralized zones, which make up the Bayankhongor Metal Belt, that contain significant occurrences of copper and gold (green and yellow, respectively). Villages are labeled: Bu is Bumbugur; Ba is Bayankhongor.

2. Materials and Methods

The MT method is a geophysical technique used to probe the subsurface electrical structure of the Earth using passive electromagnetic signals (over a broad range of periods) generated in the atmosphere and ionosphere. MT data consist of electric and magnetic fields measured at the Earth's surface. These fields are related by a period-dependent impedance tensor that is sensitive to the subsurface electrical resistivity structure; the short period data are sensitive to shallow structures and the long period data to deep structures. The MT technique is especially sensitive to the quantity and composition of crustal fluids, which act to reduce the electrical resistivity. For this reason, numerous studies have shown that the MT technique is ideally suited to image the structure of faults and suture zones at various scales. Subduction zones have been extensively studied with the technique for similar reasons. However, there has been a surprisingly small amount of investigations carried out in obducted environments with ophiolite belts. The MT technique is capable of characterizing the pathways of past fluids and the ancient traces of alteration, and this has been used in some studies to explore the formation and emplacement of mineral ore deposits [2].

An extensive MT dataset exists across Mongolia with several resistivity models produced which investigate multiple features and scales [10-14]. Previous studies have explored the lithospheric-scale regional structure below central Mongolia and have revealed upper-most mantle low-resistivity anomalies attributed to an asthenospheric upwelling [10,11]. The lower crust was also established to have a low-resistivity and was inferred to be a weak, low viscosity region [10,13]. Other work investigated lithospheric removal mechanisms, supported by geochemical data [15,16].

In this contribution we analyze three profile segments in the Bayankhongor region (Line 2000, Line 4000, and Line 6000; longitudes ~100.7°E, 99.7°E, and 98.5°E). The profiles are ~120 km long and separated by ~100 km. They consist of a total of 47 sites (18, 16, and 13 sites, respectively). Data in the period range of 0.01-1,024 s were included. The MT data were inverted with the MODEM inversion algorithm [17,18]. For details of the inversion procedure and model testing please refer to [19].

3. Results

The 3-D resistivity models are shown in Figure 2. In general, the upper crust appears highly resistive (>1,000 Ωm; R1, R2, and R3). This can be explained by ancient microcontinental blocks [4]. The middle crust appears to have a much lower resistivity (<300 Ωm). The most obvious features are the low-resistivity (conductive) anomalies (<100 Ωm). An isolated low-resistivity anomaly (<30 Ωm; M1) appears beneath the eastern end of the Bayankhongor Metal Belt, near the Tsagaan Tsahir Uul and Saran Uul regions that include gold and copper deposits [9,20]. This area is described as a Proterozoic metamorphic unit with granites [20]. Similarly, a low-resistivity feature (<30 Ωm; M2) appears beneath the Bayankhongor Metal Belt near the village of Bumbugur. This area is described as a highly metamorphosed unit [5,7]. The (inferred) location of the Bayankhongor Ophiolite Belt [4,5,7] is congruent with low-resistivity anomalies (<50 Ωm; S1, S2, and S3) that appear to be dipping slightly southwards, consistent with geological estimates [5,7]. Other low-resistivity features (U1 and U2) are observed that do not reach the surface and for which no explanation is available at this time.

4. Discussion

The spatial distribution of mineral zones is known to be strongly influenced by the crustal architecture, which has an impact on the flow of fluids through the crust (i.e., permeability is structurally enhanced). In turn, crustal structure is partly controlled by tectonic and geodynamic processes. Thus the crustal features imaged with geophysical models, such as the resistivity models in this contribution, can give insights into the emplacement of mineral systems. Other geophysical data (such as magnetism and gravity), and their gradients, can also highlight crustal boundaries [21].

The electrical resistivity models show that some low-resistivity anomalies align with the suture zone, and that they extend to great depths. Thus the results show that the ancient suture zone, marked by the Bayankhongor Ophiolite Belt and associated with a paleo-ocean closure, is a deep-reaching structure (crustal or lithospheric scale) and a major crustal boundary [19]. The low-resistivity anomalies may be explained by hydrothermal alteration along fossil fluid pathways, which the MT method is sensitive enough to detect. These fluids may have been sourced through metamorphic dehydration reactions in the crust, and their upwards propagation was controlled by the local permeability within the deformation zone, such as weaknesses that facilitated fluid movement [22].

The locations of other low-resistivity anomalies are spatially coincident with known mineralized zones in the Bayankhongor Metal Belt, which contains copper and gold deposits [5,7,20]. Throughout the area there is evidence of extensive hydrothermal alteration [5,9,20]. In fact, lamprophyre dikes are found within the gold-bearing and copper-bearing zones [20]. Such dikes are often both spatially and temporally correlated with gold mineralization [3]. They were likely formed by fluid flow through the crust during metamorphism and indicate deeply-connected, ore-forming fluid pathways [3]. The observed low-resistivity signature may be explained by hydrothermal alteration along fossil fluid pathways and associated sulfide mineralogy within the host complex related to ore emplacement [19].

We hypothesize that the genesis and emplacement of the minerals within the Bayankhongor Metal Belt is directly connected to the unique and complex tectonic history of the Bayankhongor region. We conclude that the results illustrate that crustal architecture, specifically major crustal boundaries (including crustal/lithospheric scale suture zones) that are inherited from earlier tectonic events, acts as a first-order control on the location of mineral deposits and metallogenic belts, due to its influence on the availability and mobility of (ore-related) fluid.

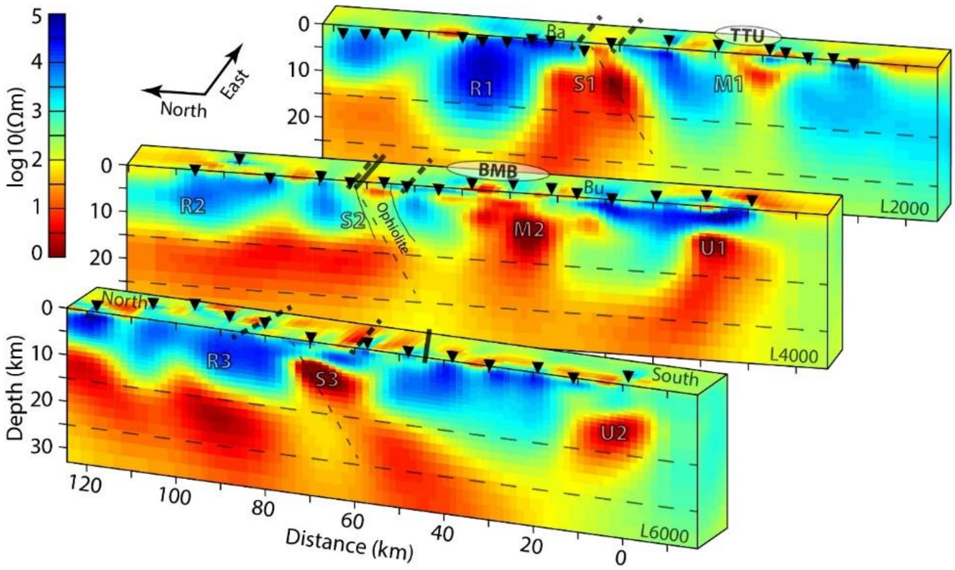

Figure 2. The 3-D electrical resistivity models. The locations of the MT measurement sites are indicated (black). Horizontal lines separate the model into upper, middle, and lower crust. The Bayankhongor Ophiolite Belt (see Figure 1; dashed lines) and the South Hangai fault system (solid lines) are related to a suture zone, revealed to be a major boundary (dashed). Low-resistivity anomalies in the upper crust appear coincident with the boundary (S1; S2; S3). Mineralized zones (BMB: Bayankhongor Metal Belt; TTU: Tsagaan Tsahir Uul and Saran Uul) are coincident with low-resistivity anomalies in the upper crust (M1; M2). Highly resistive features are attributed to an ancient continental block (R1; R2; R3). Other low-resistivity anomalies (U1; U2) have no explanation.

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