Lithospheric Electrical Structure beneath Bayan Obo Region Derived from MT Data

Bo YANG[1], Yanjun WU[3,2], Xiaoling MENG[2], Fei ZHOU[2], Meixia SU[2]
Gang WEN[1], Kongyang ZHU[1], Wencai YANG[1]

[1]School of Earth Sciences, Zhejiang University, Hangzhou, China. bo.yang@zju.edu.cn.
[2]Institute of Geologic Survey and Research of Inner Mongolia, Hohhot, China.
[3]The Surveying and Mapping Geographic Information Center of Inner Mongolia, Hohhot, China.

SUMMARY

We investigated the Bayan Obo REE-Fe-Nb deposit, the world's largest rare earth element deposit, located at the suture zone between the Central Asian Orogenic Belt and the North China Craton. Despite nearly a century of study, its origin remains debated. To gain insights into the regional tectonic regime and mineralization processes, we deployed a dense magnetotelluric (MT) array in the Bayan Obo region in 2022. We employed 51 long-period MT sites and 110 wide-band MT sites to image the three-dimensional electrical resistivity structure of the area. Using the ModEM, we identified a plume-like conductive diapir extending from the asthenosphere to the upper crust, with significant conductive anomalies corresponding to major tectonic features. Our results indicate a complex tectonic history with contributions from multiple magmatic and tectonic events, including the subduction and closure of the Paleo-Asian Ocean. These findings enhance our understanding of the mineralization processes at Bayan Obo and the tectonic evolution of the region, highlighting the importance of deep geophysical structures in unraveling the origins of such giant ore deposits.
Keywords: 3D electrical structure, Magnetotelluric data, Bayan Obo REE deposit, Paleo-Asian Ocean

INTRODUCTION

As the largest rare earth elements (REE) deposit in the world, the Bayan Obo REE-Fe-Nb deposit is located at the suture zone between the Central Asian Orogenic Belt (CAOB) and the North China Craton (NCC), known as the Solonker Suture zone (Fig. 1). Although it was discovered and developed nearly a century ago, the origin of this giant REE ore remains highly debated(She et al, 2023). Given that the regional deep geophysical structure may provide crucial insights into the tectonic regime and mineralization processes, we deployed a relatively dense MT array in the Bayan Obo region in 2022.

To image the three-dimensional electrical resistivity structure, we deployed an MT array consisting of 51 long-period MT sites with periods ranging from 7 to 20,000 seconds and 110 wide-band MT sites with periods ranging from 1/320 to 2,000 seconds (see Fig. 3). The site spacing is approximately 40 km for long-period MT sites and 20 km for wide-band MT sites. The data quality is very good for most sites. We employed the Modular Electromagnetic Data Inversion System (i.e., ModEM, Egbert and Kelbert, 2012) to invert the data. By setting the error floor to 5% of $|Z_{xy}|$ for Z_{xx} and Z_{xy}, 5% of $|Z_{yx}|$ for Z_{yx} and Z_{yy}, and a fixed value of 0.03 for $\mathbf{T}$, we achieved a normalized root-mean-square (nRMS) misfit of 2.79 after 157 iterations using the non-linear conjugate gradient scheme.

RESULTS

As shown in Fig. 3 and Fig. 2, the depth sections and the iso-surface map of the conductors have demonstrate exciting features as following:

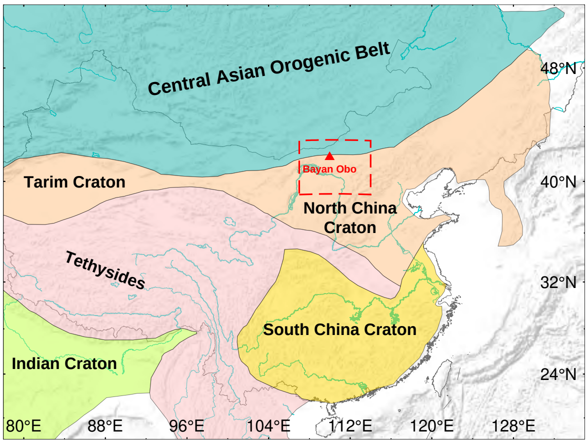
1. A plume-like conductive diapir penetrates nearly vertically from the asthenosphere depth to the upper crust (Fig. 2). At about 100 km depth in the upper mantle, it splits into two branches. One branch continues to rise nearly vertically to the top of the upper mantle at

about 40 km in depth, then extends westward along the North China Craton margin fault to the Bayan Obo REE-Fe-Nb deposit and about 100 km further west, before returning southeastward at lower crust depths. The other branch rises southward and merges with the extensive conductive layer at the top of the upper mantle beneath the Ordos Block in the south.

2. From 150 km depth to 80 km depth, the conductive and resistive anomalies exhibit a horizontal strips feature, extending from north-northwest to south-southeast, possibly indicating regional electrical anisotropy at this depth.

3. In the mid-lower crust (20-40 km depth), the distribution of the conductive anomalies is evidently related to major deep faults in the area (such as the North China Craton margin fault and the Solonker Suture Zone), primarily extending along the fault zones in an east-west direction.

4. At the top of the upper mantle (40-60 km depth), there is a transition in the direction of electrical structure from northwest-southeast to nearly east-west. At this depth, the conductive anomalies of the two aforementioned directions are included.



.

Figure 1: Major tectonic units of mainland China and its adjacent area. The dashed red rectangle indicates the MT data imaging area in the following figures. The location of Bayan Obo REE-Nb-Fe deposit is marked by a red triangle. (Modified after Eizenhofer et al, 2014)

The orientation of regional structures can indicate the era of their formation, providing a geophysical snapshot that reflects tectonic evolution over time. Therefore, the northwest orientation of the upper mantle structures and the nearly east-west orientation of the crustal structures in the study area may preserve relics of different tectonic events from different periods. We can reasonably speculate that the nearly east-west oriented structures in the crust represent conductive belts formed by the subduction and closure event of the Paleo-Asian Ocean. In contrast, the northwest oriented conductive and resistive strips at the top of the upper mantle may be related to older tectonic events or to the remote effects of tectonic events in adjacent areas, such as the ongoing collision between the Indian Plate and the Tibetan Plateau or the subduction of the Pacific Plate under the Eurasian continent(Dong et al, 2014).

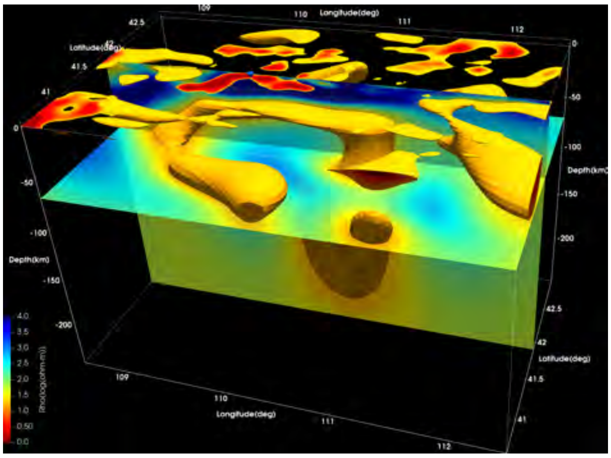


Figure 2: The iso-surface map of the inverted electrical resistivity model, showing distribution of conductors in the study area. We display the conductive anomalies with resistivity lower than 30 ohm-m. Two semi-transparent cross-sections locating at depth=60 km and latitude=41.8°N are plotting as reference.

The Bayan Obo deposit is located on a nearly east-west oriented conductive belt at a depth of 2-3 km. This conductive anomaly is underlain by a continuous resistive layer approximately 20 km thick. Below this resistive layer, at a depth of about 25-40 km, lies the branch of the conductive diapir that intrudes westward.

The shallow conductive anomaly in the Bayan Obo ore does not seem to connect with the branch of the diapir at lower crust depths, suggesting they may not be directly related. Considering most existing studies link the formation of the Bayan Obo giant REE deposit to Mesoproterozoic carbonatite magmatic activity, which was later modified by multiple magmatic events, especially the intense island arc magmatism caused by the subduction of the Paleo-Asian Ocean beneath the North China Craton in the Early Paleozoic, leading to the reactivation of rare earth elements. Therefore, the shallow conductive belt in the upper crust may indicate a favorable area for Fe-Nb-rare earth mineralization at Bayan Obo. The plume-like diapir might be related to mantle upwelling and could represent a mantle source conduit for the area's multiple magmatic events.

The latest major tectonic event in the study area is the Late Permian closure of the Paleo-Asian Ocean. This closure led to the subduction of the Paleo-Asian Ocean's oceanic slab, which carried significant amounts of seafloor carbonatite deposits and rare earth elements into the mantle. The carbon-rich sediments and fluids that entered the mantle with the oceanic slab significantly lowered the melting point of mantle peridotite, resulting in the formation of carbonatite magma. Due to its extremely low viscosity, carbonatite magma can easily migrate and extract rare earth elements. In the Late Permian and Early Triassic, this rare-earth-rich carbonatite magma intruded into the mid-lower crust at the intersections of multiple lithospheric faults, forming the Bayan Obo mantle diapir structure. During its ascent, the carbonatite magma continuously differentiated from the silicate magma, forming large A-type granite intrusions above the diapir and introducing significant heat. This process caused the remelting of Mesoproterozoic carbonatite and sedimentary carbonatite in the original crust(Fan et al, 2016), further enriching and mineralizing the rare earth elements.

CONCLUSIONS

In conclusion, the Bayan Obo REE-Fe-Nb deposit, located at the intersection of the Central Asian Orogenic Belt and the North China Craton, remains a subject of extensive research and debate regarding its origin. Our deployment of a dense magnetotelluric (MT) array in 2022 has provided significant insights into the region's three-dimensional electrical resistivity structure. The data reveal a plume-like conductive diapir extending from the asthenosphere to the upper crust, with distinct branches and conductive anomalies at various depths that correlate with major tectonic features such as deep faults and suture zones. These findings suggest a complex tectonic history involving multiple magmatic and tectonic events, including the subduction and closure of the Paleo-Asian Ocean. The observed conductive anomalies and structural orientations provide evidence for the reactivation and mineralization processes linked to Mesoproterozoic carbonatite magmatic activity and later tectonic events. Thus, our study not only elucidates the deep geophysical structure of the Bayan Obo region but also contributes to the broader understanding of its mineralization processes and tectonic evolution.

ACKNOWLEDGMENTS

This study is funded by NSFC grant (41774079) and the Academician Projects of Inner Mongolia Geological Survey Fund Management Center (2017-YS02, 2020-YS02).

REFERENCES

Dong H, Wei W, Ye G, Jin S, Jones AG, Jing J, Zhang L, Xie C, Zhang F, Wang H (2014) Three-dimensional electrical structure of the crust and upper mantle in Ordos Block and adjacent area: Evidence of regional lithospheric modification. Geochemistry, Geophysics, Geosystems 15(6):2414–2425

Egbert GD, Kelbert A (2012) Computational recipes for electromagnetic inverse problems. Geophysical Journal International 189:251–267

Eizenhofer PR, Zhao G, Zhang J, Sun M (2014) Final closure of the paleo-asian ocean along the solonker suture zone: Constraints from geochronological and geochemical data of permian volcanic and sedimentary rocks. Tectonics 33(4):441–463

Fan HR, Yang KF, Hu FF, Liu S, Wang KY (2016) The giant Bayan Obo REE-Nb-Fe deposit, China: Controversy and ore genesis. Geoscience Frontiers 7(3):335–344

She HD, Fan HR, Santosh M, Li XC, Yang KF, Wang QW, Wei W, Liu YJ, Liu S, Liu SL (2023) Paleozoic remelting of carbonatite in Bayan Obo (China): Further insights into the formation of a giant REE deposit. Gondwana Research 119:172–185

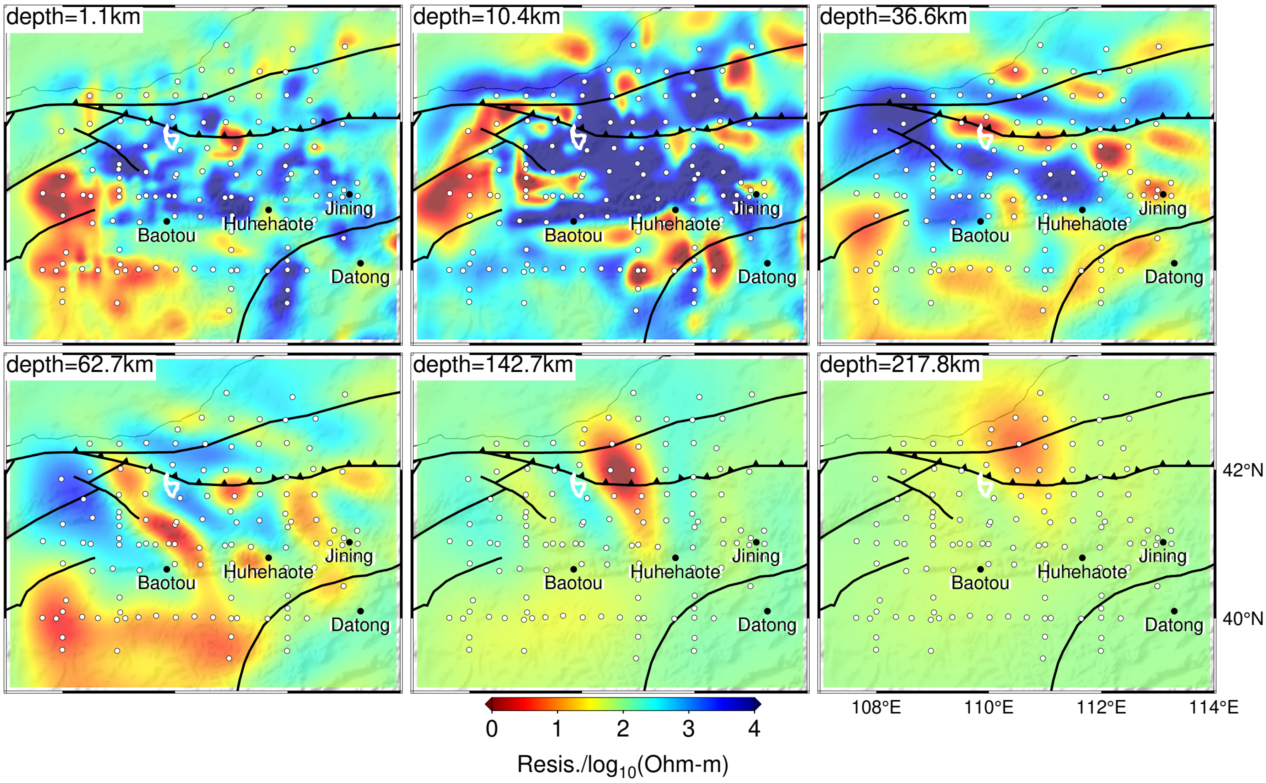


Figure 3: Depth sections of inverted electrical resistivity model, showing depths ranging from shallow crust to upper mantle. We plot the major faults in the study area as black solid lines. The Solonker suture zone has been marked by thrust fault line with jigsaw-like triangles. The white dots denote the MT sites.

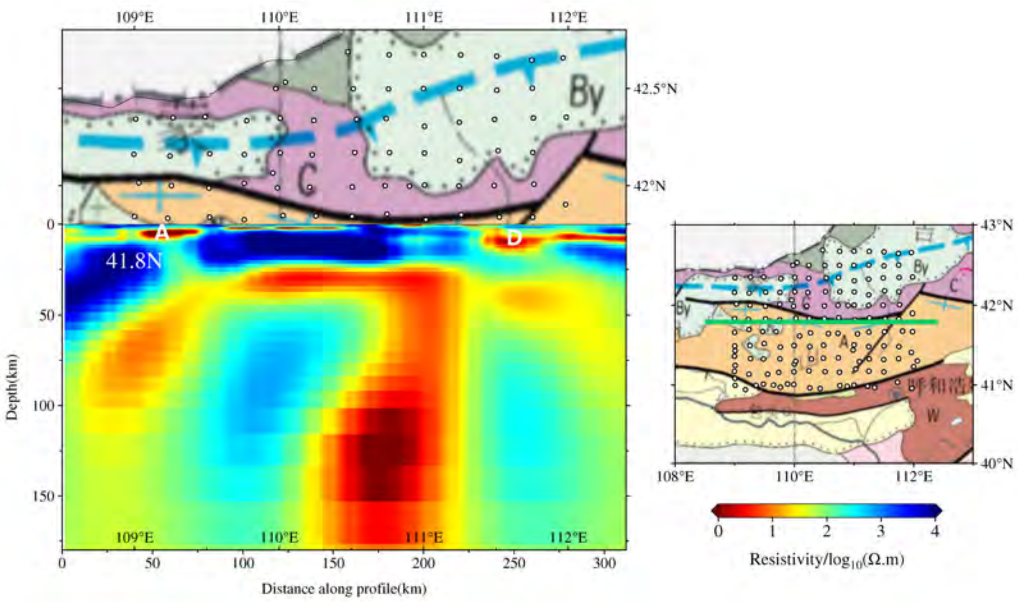


Figure 4: Representative cross section along Latitude 41.8°N. The thick green solid line in the inset map on the right pane indicates the profile position.