

Two-dimensional magnetotelluric inversion with coupled seismic information revealing deep resistive structure in the hinterland of Junggar Basin

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SUMMARY

The Junggar Basin, located between the Tarim Plate, the Kazakhstan Plate, and the Siberian Plate, preserves significant geological records of important tectonic movements and hosts rich oil and gas resources, making it a key area for research. To better understand the deep electrical structure of the Junggar Basin and its formation mechanisms, this study conducts inversions of two magnetotelluric profiles in the hinterland of the basin. The goal is to reveal the deep electrical structure of the basin's hinterland. To achieve a more accurate deep resistivity structure of the study area, this paper introduces a regularization inversion method for two-dimensional magnetotelluric data constrained by seismic information. This is achieved by using regional cosine similarity constraints of model residual vectors or model gradient vectors. The advantages and effectiveness of the new method are demonstrated through complex theoretical models. Subsequently, through the inversion of actual data from two profiles in the study area, we obtained high-resolution deep electrical structures in the hinterland of the Junggar Basin. Based on these results, we inferred the main formation mechanisms of the Junggar Basin.

Keywords: Magnetotelluric, Constraint Inversion, Junggar Basin, Structural Coupling, Deep Structure

INTRODUCTION

Located in northern Xinjiang, the Junggar Basin and its adjacent areas are situated between the Tarim Plate, the Kazakhstan Plate, and the Siberian Plate, belonging to the Paleo-Asian Ocean tectonic domain. The Junggar Basin is also an important large oil-bearing region in western China, preserving significant geological records of tectonic movements and rich oil and gas resources, making it a key area for research. Since the beginning of studies on the Junggar Basin, numerous research efforts have emerged, with previous researchers tirelessly striving to delineate the basin more clearly.

In the past 20 years, there has been substantial research on the deep electrical structure of the Junggar Basin. The Xinjiang Petroleum Administration has conducted magnetotelluric (MT) soundings in the hinterland of the Junggar Basin, completing three MT profiles across the basin. In the late 1990s, the Petroleum Geophysical Exploration Bureau's Geological Survey Institute obtained six MT profiles. They divided the Junggar Basin into six electrical layers, categorized from top to bottom into three parts: the sedimentary cover, the Hercynian basement, and the Precambrian crystalline basement (also known as the Neoproterozoic-Mesoproterozoic basement). Among these, layers 1-4 are sedimentary covers, with the deepest burial depth reaching 12 km; layer 5 is the Hercynian basement of the basin, with the

deepest burial depth reaching 15 km and a resistivity typically between 35 to 45 $\Omega\cdot\text{m}$; layer 6 is the Precambrian crystalline basement, with the deepest burial depth reaching 35 km, and generally located below 15 km depth. From this, it is evident that they consider the Junggar Basin's basement to have a "double-layer" structure. Tian Shao et al. (2014) suggested that the Junggar Basin's crust can be divided into three parts based on electrical structure; they discovered an ultra-high conductivity layer approximately 10 km thick below the crust, determined the position of the Moho interface, and inferred that the lithosphere thickness in the central and eastern regions of the Junggar Basin is around 100 km. Luo et al. (2020) used MT soundings to infer the distribution characteristics of the Carboniferous system in the northern Ulungur depression of the Junggar Basin.

To better understand the deep electrical structure of the Junggar Basin and its formation mechanisms, this study incorporates existing seismic information from the Tertiary to the Permian into the two-dimensional magnetotelluric regularization inversion using a structural coupling approach. This allows for the precise revelation of the deep electrical structure of the Junggar Basin's hinterland by calculating two MT profiles in the basin's hinterland.

METHOD

Based on the new form of model space coupling—regional cosine similarity constraints of model

residual vectors or model gradient vectors (Shi *et al.*, 2018):

We propose a new form of multi-method model space coupling based on regional cosine similarity constraints of model residual vectors or model gradient vectors (Shi *et al.*, 2018):

$$\tau_1(\mathbf{m}_1, \mathbf{m}_2) = \int_V (1 - \cos^2 \theta_{12}) dv \quad (1)$$

This approach constrains the similarity in the direction of physical properties or structural changes using the cosine magnitude obtained from the dot product of normalized dimensionless model residual vectors or model gradient vectors. This serves as a more appropriate and reasonable coupling constraint, which can be extended to three-dimensional multi-method joint inversion. The form of model gradient cosine similarity is:

$$\cos \theta_{12} = \frac{\nabla \mathbf{m}_1 \cdot \nabla \mathbf{m}_2}{|\nabla \mathbf{m}_1| |\nabla \mathbf{m}_2|} \quad (2)$$

$$|\eta_i| = \max\{|\nabla \mathbf{m}_i|, \eta_i^{\min}\}, \eta_i^{\min} > 0, (i=1, 2)$$

Where $\nabla \mathbf{m}$ represents the model gradient change in the specified model coupling region, which can also be expressed as $\mathbf{m} - \mathbf{m}_{\text{apr}}$, i.e., the regional model residual vector. $\cos \theta_{12}$ is the normalized dot product of the model gradients, i.e., the regional cosine similarity, and η_i^{\min} is a small value to avoid singularity in the denominator, which can be determined according to the standard by Molodtsov *et al.* (2013).

For regions with changes in the model gradient, it can constrain areas with large vector angles, indicating inconsistent physical property gradient changes, to be corrected towards similar structures, i.e., consistent model gradient changes. This coupling term will constrain $(1 - \cos^2 \theta_{12}) \rightarrow 0$, thereby highlighting the similarity of two physical property structures. Moreover, this structural coupling method overcomes a series of issues with current mainstream methods, such as the complexity of cross-gradient constraint calculations and the need for prior specification of physical property change directions in gradient dot product constraints, demonstrating more accurate inversion results and coupling capabilities (Shi *et al.*, 2018).

SYNTHETIC TEST

In this section, we designed a representative model (Figure 2) based on the resistivity characteristics of different geological eras in the Junggar Basin, combined with a north-south seismic profile from the central Junggar Basin (Figure 1, He *et al.*, 2018), to verify the effectiveness of the new method.

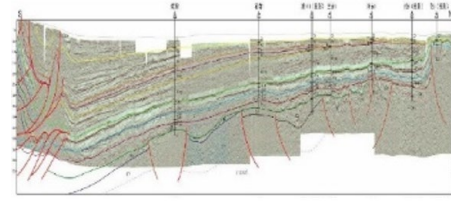


Figure 1. Seismic Profile in the Junggar Basin

We used the seismic profile to obtain the burial depths of the bottom boundaries of various geological eras above the Permian and used this known structural coupling information for the model's inversion calculations. The calculations were performed using the free inversion method based on the OCCAM 2D inversion program (Constable *et al.*, 1987, 1990; Song *et al.*, 2022) and the inversion constrained by "structural" coupling.

The observed sites are distributed on the surface, $\Delta_{\text{receiver}} = 2\text{km}$, the data we used for the inversions both TE and TM mode with 80 frequencies over a range of $320 \sim 3.4 \times 10^{-4}$ Hz, the apparent resistivity and phase data both added with 5% gaussian random noise. RMS misfit decreases to 1.01 within 20 iterations.

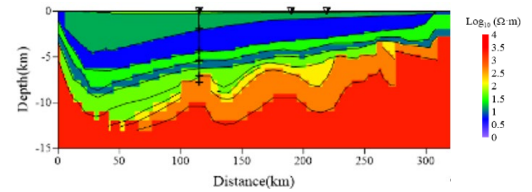


Figure 2. Synthetic resistivity model

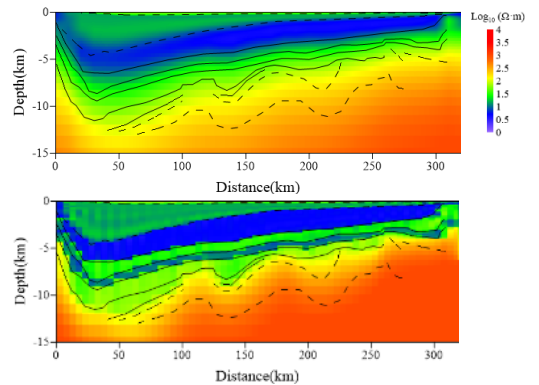


Figure 3. Inversed results by free MT inversion (up) and MT inversion constraint by seismic information (down)

The comparison of inversion results shows that the coupled constraint joint inversion method provides a stronger ability to characterize the deep high-resistivity basement. The position of the top surface of the basement is clearer, with better continuity and layering, and the physical properties of the deep basement are also restored more accurately.

FIELD DATA PROCESSING

Theoretical model tests confirmed the effectiveness of the new method in interpreting deep electrical structures. Therefore, we applied this method to process and calculate the two magnetotelluric profiles (xj9201, xj9202) in the hinterland of the Junggar Basin. The locations of the profiles and the apparent resistivity and phase profiles after preprocessing are shown in Figures 4-6:

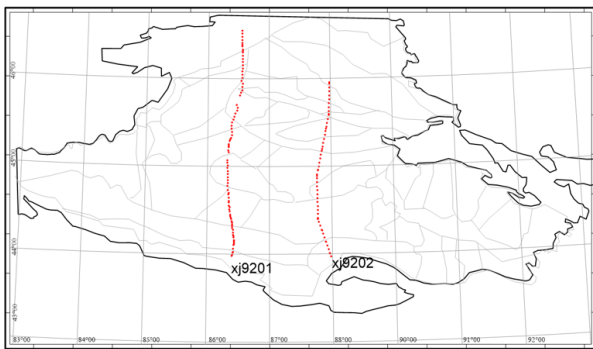


Figure 4 Location of the magnetotelluric data at the Junggar Basin

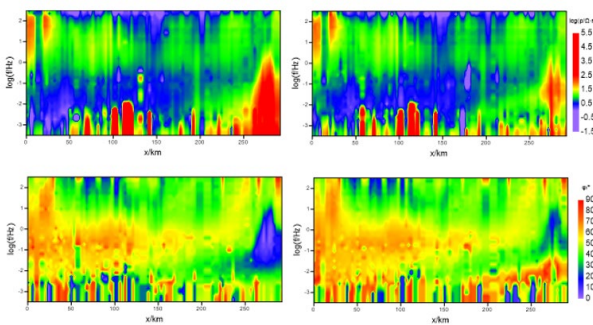


Figure 5 Apparent resistivity and Phase of xj9201 profile

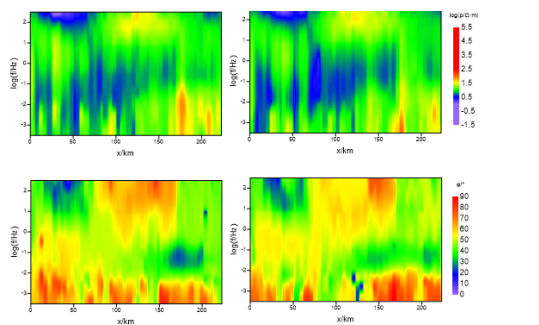


Figure 6 Apparent resistivity and Phase of xj9202 profile

All the inversion parameters and iteration termination conditions are set as demonstrated in synthetic model test, error floor is set to 5%. The inversion result shows in Figure 9, RMS misfit decreases from 35 to 6.7 within 20 iterations.

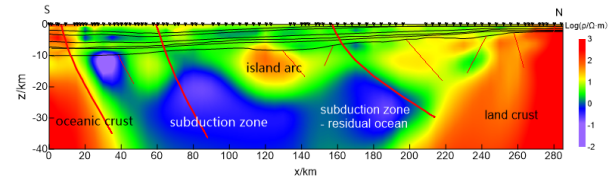


Figure 6. Field data inversion result of xj9201

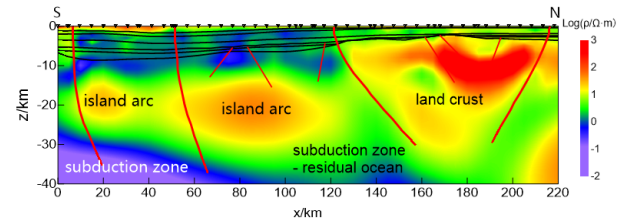


Figure 7. Field data inversion result of xj9202

The resistivity results from the constrained inversion of the magnetotelluric profiles xj9201 and xj9202 (Figures 6-7) reveal that the Carboniferous system in the basin exhibits an oceanic crust-island arc-continental crust structural pattern from south to north. The oceanic crust in the southern part of the basin subducts northward, forming a subduction zone from south to north, with a volcanic island arc at the leading edge of the subduction zone. The northern part of the basin is mainly composed of continental crust and orogenic belts. This indirectly confirms that the formation of the Junggar Basin is due to the collage of multiple island arcs. The intra-basin uplifts, Mosuowan uplift, eastern uplift, and western uplift are all intra-oceanic island arcs formed by the subduction of the Paleo-Asian Ocean. The lateral accretion of island arcs has played an important role in the crustal growth of the Central Asian region. Oceanic subduction is an important mechanism for the compression, infilling, and closure of remnant seas.

CONCLUSIONS

This study introduces a two-dimensional magnetotelluric (MT) regularization inversion method constrained by seismic information, using regional cosine similarity constraints of model residual vectors or model gradient vectors. Complex theoretical models demonstrate that this new method can better restore the true structure and physical properties of the model compared to free inversion. Subsequently, we applied the new method to invert the observed apparent resistivity and phase data from two MT profiles in the hinterland of the Junggar Basin. The resulting resistivity inversion reveals that the Carboniferous system in the basin exhibits an oceanic crust-island arc-continental crust structural pattern from south to north. In the southern part of the basin, the oceanic crust subducts northward, forming a northward subduction zone, with a volcanic island arc at the leading edge. The northern part of the

basin is mainly composed of continental crust and orogenic belts. This confirms that the Junggar Basin was formed by the collage of multiple island arcs.

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REFERENCES

- Constable, S. C., Parker, R. L., & Constable, C. G. (1987). Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data. *Geophysics*, 52(3), 289-300.
- deGroot-Hedlin, C., Constable, S. (1990). Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysics*, 55(12), 1613-1624.
- He, D., Zhang, L., Wu, S., Li, D., Zhen, Y. (2018). Tectonic evolution stages and features of the Junggar Basin. *Oil and Gas Geology*, 39(5), 845-861. (in Chinese with English abstract)
- Luo, W., Hu, Z., Li, G., Yang, X., He, L., Yang, Y., Sun, Q., Zhang, P., Zhang, Q. (2022). Carboniferous strata and their oil and gas prospects from Wulungu depression to the north uplift in the Junggar Basin based on magnetotelluric technology. *Geology in China*, 49(5), 1591-1604. (in Chinese with English abstract)
- Molodtsov, D. M., Troyan, V. N., Roslov, Y. V., et al. (2013). Joint inversion of seismic traveltimes and magnetotelluric data with a directed structural constraint. *Geophysical Prospecting*, 61(6):1218-1228.
- Shi, B., Yu, P., Zhao, C., Zhang, L., Yang, H. (2018). Linear correlation constrained joint inversion using squared cosine similarity of regional residual model vectors. *Geophys. J. Int.*, 215, 1291-1307.
- Song, H., Yu, P., Wang, C., Zhang, L., Zhao, C., Shi, B., Hu, M. (2022). 2D magnetotelluric inversion using hybrid stabilizing functionals: Exponential minimum support and smoothness. *Geophysics*, 87(5), E307-E317.
- Tian, S., Cai, J., Hu, X., Li, J., Zeng, S., Xu, S. (2014). Deep conductivity structure in middle-east Junggar Basin using MT. *Earth Science-Journal of China University of Geoscience*, 39(5), 620-628. (in Chinese with English abstract)