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Editorial: Advances in magnetotelluric imaging

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Editorial on the Research Topic
Advances in magnetotelluric imaging

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Introduction

Geo-electromagnetic methods, especially the magnetotelluric (MT) sounding technique, are irreplaceable geophysical methods used for imaging the Earth's subsurface electrical structure. The establishment of several continent-scale MT arrays, such as EarthScope, SinoProbe, and AusLamp, has underscored the need for advancements in data processing and modeling techniques. Benefiting from rapid developments in three-dimensional inversion algorithms and the release of open-source codes, a substantial volume of continent-scale imaging results has been published in the last few decades. These contributions have offered new, solid evidence that enhances our understanding of geodynamic processes. They also foster a range of novel insights into how the electrical structure can reveal aspects of tectonic evolution and the distribution of mineral resources. Given these developments, we advocate for this Research Topic dedicated to the latest advances in MT imaging, which has published 11 contributions on the new methodologies and findings.

Advances in magnetotelluric imaging

The articles published in this Research Topic presented the latest advances regarding geo-electromagnetic methods, covering numerical modeling, anisotropy, imaging and practical corrections.

Long presents a meshfree numerical approach for forward modelling of geophysical electromagnetic responses, offering a flexible alternative to traditional mesh-based methods like finite element or finite differenceBy using unconnected points and radial basis functions, the method efficiently handles complex geological geometries and irregular topography without the need for structured meshes. The approach is validated through tests on both synthetic and realistic models, including the challenging Dublin Test Model two and the irregular Voisey's Bay deposit, showing strong agreement with analytical and independent numerical solutions. The results demonstrate the meshfree method's accuracy and potential for improving geophysical interpretation in mineral exploration.

Zhang et al. develop a 3D finite element forward modeling algorithm for cross-well induced polarization (IP) in anisotropic media, accounting for directional variations in both conductivity and polarizability. The method is validated using complex isotropic and anisotropic models, confirming its accuracy and effectiveness. Numerical experiments on horizontal and inclined plate models reveal that anisotropy significantly affects the amplitude and shape of apparent polarizability responses, with the most pronounced effects observed in the x-direction for horizontal layers, while y-direction anisotropy shows minimal deviation from isotropic behavior. These findings enhance the understanding of anisotropic influences on cross-well IP data and provide a crucial theoretical basis for more accurate interpretation in practical mineral and resource exploration.

Liu and Sun present a 3D staggered finite difference method for MT forward modeling in axis-anisotropic media, solving the electric field governing equations using the quasi-minimum residual method with validated accuracy against 2D quasi-analytic solutions. Their study demonstrates that MT data can effectively identify horizontal electrical anisotropy, offering valuable insight for characterizing anisotropic geological structures in exploration applications.

Huang et al. propose a new coupling method, minimum cross-gradient support (MCGS), for geophysical inversion that improves the integration of prior information by enhancing constraint strength in regions with weak model gradients. By applying a minimum support function to the cross-gradient, MCGS balances gradient magnitude and direction, allowing for flexible control via focusing factors and reducing reliance on highly accurate prior models. Synthetic tests on a double-blocks and a nappe structure model show that MCGS outperforms traditional cross-gradient and joint minimum gradient support methods in model recovery and constraint effectiveness. Applied to real MT data from the Junggar Basin, MCGS inversion successfully imaged key resistivity structures, including potential Carboniferous remnants and basement distribution, providing new insights into the region's tectonic evolution.

Liu et al. present a physics-informed auto-encoder approach for MT inversion, in which the decoder is replaced with the MT forward operator to ensure physically consistent results and improve data fitting. By embedding the governing physical laws into the network architecture, the method enhances the reliability and interpretability of neural network-based inversions. Scaling laws are introduced to adapt real-world observation systems to the trained model, improving its applicability across diverse survey configurations. Demonstrated on both synthetic and field data, the approach achieves inversion accuracy comparable to classic Occam's inversion with significantly higher computational efficiency, offering a promising path toward fast, robust, and physically grounded MT imaging.

Yu and Han introduce an improved 3D MT forward modeling framework that incorporates a divergence correction procedure for arbitrary anisotropic media, enhancing the convergence of iterative solvers. Originally developed for isotropic conditions, the divergence correction is successfully adapted to anisotropic cases, significantly reducing the number of solver iterations and improving computational efficiency and stability. The method is validated across four numerical examples, including 1D, 2D, and complex 3D anisotropic models, demonstrating robust performance even at long periods and in highly heterogeneous settings. The results highlight the method's effectiveness in accelerating simulations while maintaining accuracy, making it a valuable tool for practical anisotropic MT modeling.

Yang et al. present a high-resolution 3D resistivity model of the Baogutu porphyry copper belt in NW China, derived from a dense natural-source audio-frequency MT (AMT) array of 176 sites. A parallel 3D inversion scheme was applied, and the resulting model was validated through lab-measured rock resistivity and borehole data, revealing prominent east-west conductive zones extending to 600 m depth. The inverted resistivity structure shows strong correlation with shear wave velocity, and their positive relationship helps identify potential mineralized zones. The study demonstrates that dense AMT surveys combined with 3D inversion can reliably image deep mineralized structures and guide future exploration drilling.

Li et al. summarize recent advances in MT studies of the Central Asian Orogenic Belt (CAOB), a complex tectonic zone formed by the closure of the Paleo-Asian Ocean and subsequent crustal collisions and extensions. The authors highlight two recent MT surveys conducted in the Beishan and Bainaimiao segments, revealing detailed crustal and upper mantle electrical structures that shed light on deep deformation mechanisms and continental dynamics. These studies identify key low-resistivity zones, likely associated with fluids, melts, or shear zones, and discuss their implications for lithospheric evolution. The review concludes with an overview of the region's lithospheric electrical characteristics and outlines future directions for MT research to further unravel the geodynamic history of the CAOB.

Ji et al. address the challenge of electrical anisotropy in MT imaging, which can severely distort subsurface models when ignored in standard isotropic inversions. By analyzing phase tensors and induction vectors, the authors identify anisotropic features and estimate anisotropic parameters in 2D models, then apply an equivalence-based approach to convert anisotropic structures into equivalent isotropic anomalies. These equivalent structures are incorporated as prior information in 2D isotropic inversion, significantly improving the recovery of true isotropic features. The proposed method offers a practical and novel strategy for detecting and accounting for electrical anisotropy in MT data interpretation, bridging the gap toward more reliable subsurface imaging in complex geological settings.

Zeng et al. present a robust MT inversion strategy that circumvents the challenges of static shift correction by excluding affected apparent resistivity data and relying solely on phase data during inversion. Leveraging the fact that static shift impacts only amplitude-related measurements, the method preserves inversion accuracy while avoiding error-prone correction procedures. Tests on both synthetic and field data show that the phase-only approach effectively recovers deep subsurface structures with high fidelity. The results demonstrate that accurate MT imaging can be achieved without static shift correction, offering a practical and reliable alternative for data interpretation in geologically complex areas.

Zhang et al. present a MT investigation along a profile from Chazha to Luomai, crossing the northwestern margin of the

Sichuan-Yunnan diamond block—a key region for understanding material escape from the Tibetan Plateau. Using nonlinear conjugate gradient 3D inversion, the research reveals a segmented deep electrical structure. A prominent high-resistivity zone associated with the Dedeng-Batang-Riyu fault acts as a sharp electrical boundary, effectively isolating the Qiangtang block to the southwest from the Sichuan-Yunnan block to the northeast. This finding redefines the northwest boundary of the Sichuan-Yunnan block from a diffuse transitional zone to a distinct, resistive tectonic barrier. Within the block, two major crustal conductive layers at 5–20 km and 10–30 km depths suggest complex internal deformation, challenging the prevailing lower crustal flow model by indicating significant upper-middle crustal weakening and potential localized fluid or partial melt presence. These results provide new insights into the geodynamic evolution and rheological structure of eastern Tibet.

Summary and outlook

MT methods are crucial for probing deep geological structures, particularly in tectonically complex regions like the Central Asian Orogenic Belt and the Sichuan-Yunnan diamond block, where they reveal detailed crustal and mantle electrical structures linked to tectonic evolution and material flow. Electrical anisotropy significantly impacts MT data, and recent advances in forward modeling, inversion techniques, and anisotropy-aware processing—such as divergence correction, minimum cross-gradient support, and physics-informed neural networks—have improved the accuracy and reliability of subsurface imaging. Innovative strategies, including phase-only inversion to avoid static shift and equivalence-based anisotropy compensation, offer practical solutions to long-standing interpretation challenges. Studies integrating MT with seismic and petrophysical data demonstrate strong correlations that enhance the identification of mineralized zones and lithospheric features. Together, these advancements underscore the importance of accounting for anisotropy, static effects, and multi-physics constraints to achieve high-resolution, geologically meaningful models. Overall, modern MT research is moving toward more robust, physically consistent, and integrative approaches that deepen our understanding of Earth's geodynamic processes.

Reference

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