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Multi-scale magnetotelluric surveys – mapping from the lithosphere to the near surface for mineral systems

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SUMMARY

Geoscience Australia has undertaken a series of integrated studies to map the footprint of mineral systems at multiple scales. We have used long-period data from the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) to resolve large-scale lithospheric architecture in northern Australia. A 3D resistivity model reveals a broad conductivity anomaly in the lower crust and upper mantle that extends from the Tennant Region to the Murphy Province. This anomaly represents a potential fertile source region for mineral systems. We then undertook a higher-resolution infill magnetotelluric survey to refine the geometry of major structures and to investigate if the deep conductive structure is connected to the near surface. Resistivity models reveal two prominent conductors in the resistive host whose combined responses represent the lithospheric-scale conductivity anomaly mapped in the AusLAMP model. The resistivity contrasts coincide with major structures interpreted from seismic reflection and potential field data. Most importantly, conductive structures coinciding with major faults in this region extend from the lower crust to the near surface. This observation strongly suggests that the major faults are deep-penetrating structures that potentially acted as pathways for transporting metalliferous fluids to the upper crust where they could form mineral deposits. This result indicates high prospectivity for major mineral deposits in the vicinity of these major faults. In addition, we used high-frequency data to estimate cover thickness to assist with stratigraphic drill targeting which, in turn, will validate models and improve our understanding of basement geology, cover sequences and mineral potential. This study demonstrates that integration of geophysical data from multiscale surveys is an effective approach to scale reduction during mineral exploration in covered terranes.

Key words: Magnetotellurics; AusLAMP; resistivity; Exploring for the Future; northern Australia.

INTRODUCTION

Conceptually, four components are essential for mineral deposit formation (Skirrow et al., 2019; Wyborn et al., 1994): (1) constituent sources, e.g. ore metals, sulphur, fluids and ligands; (2) energy drivers that facilitate fluid flow and transfer of mass and energy; (3) favourable lithospheric architecture that allows energy transfer and fluid propagation; (4) deposition mechanisms representing chemical, physical, barometric and/or thermal change that denatures ligands and facilitates mineral precipitation. If the four core components coexist spatially and temporally, a source is conveyed to a deposition site by an energy driver via architecture connections to form a mineral deposit. Within this conceptual framework, the footprint of a mineral system is potentially detectable at a variety of scales, from ore deposits to the Earth's lithosphere. Magnetotellurics (MT) is one of few techniques that can provide multi-scale datasets to map the footprint of mineral systems. It has been successfully used to detect key mineral system components at a range of scales, in conjunction with other geoscientific datasets.

The Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) aims to acquire long-period MT data on a half-degree grid spacing (~55 km) across the entire Australian continent. As part of the Exploring for the Future (EFTF) program, Geoscience Australia has significantly progressed AusLAMP data coverage throughout the Northern Territory and western Queensland, including many covered regions. A resistivity model derived from the newly-acquired AusLAMP data (Figure 1) has mapped large-scale conductivity anomalies in highly endowed mineralised regions and in greenfields regoins where mineralisation has not previously been recognised (Duan, 2019; Duan et al., 2020). In particular, the model reveals a conductivity anomaly extending from the Tennant Region to the Murphy Province, representing a potentially fertile source region for mineral systems. This conductive feature coincides with a broadly east-northeast-trending corridor marked by a series of large-scale structures identified from interpretation of seismic reflection and potential field data.

Infill surveys were conducted to acquire higher-resolution gravity and MT data in the East Tennant region to better constrain geological architecture and to improve understanding of mineral potential. In particular, we used broadband MT (BBMT) data from the infill survey to image crustal architecture and to characterise the geometry of major structures. The main question to answer is whether the deep conductivity anomaly detected by the AusLAMP data is connected to features in the near-surface. We then used audio MT (AMT) data to constrain cover thickness to select drilling targets for the first MinEx CRC stratigraphic drilling program which, in turn, will test models and develop better understanding of basement geology, cover sequences and mineral potential.

In this paper, we present 3D inversion of the infill MT data and preliminary interpretation of the resistivity models. We also present 1D probabilistic inversion of the AMT data for cover thickness estimation, using a trans-dimensional Markov chain Monte Carlo algorithm.

METHOD AND RESULTS

In July and August 2019, BBMT and AMT data were acquired at 131 stations with site spacings of ~2–10 km (Figure 3). We designed the MT survey to include three transects perpendicular to the geological strike, supplemented by a ~10 km-spaced array between the transects. Additional data were acquired at the proposed drill sites. Generally, impedance data were of good quality over periods of 0.0001–1000 s, except data in the dead-bands (0.001–0.002 s for AMT and ~10 s for BBMT) in which natural signals are typically weak. Details of data acquisition and processing can be found in the survey logistics report as part of the data release (Jiang & Duan, 2019).

Dimensionality analyses using the phase tensor (Booker, 2014; Caldwell et al., 2004) showed at longer periods (>100 s) the geoelectric structure is a mixture of 2D and 3D responses. Therefore, we undertook data inversion using the 3D ModEM code (Egbert & Kelbert, 2012; Kelbert et al., 2014). We applied the standard minimum-structure non-linear conjugate gradient algorithm. To improve computational efficiency, the NW-SE profiles were rotated 45° clockwise to align with the N-E model grid. Data were then rotated 45° counter-clockwise to keep the same geological strike angle with reference to the source field polarisation directions. This manipulation significantly reduced the number of cells in our inversion. The model consisted of, horizontally, 180 × 140 cells with 800 m cell size and 11 padding cells with dimensions increasing outwards by a factor of 1.4. In the vertical direction, the first layer thickness was set as 10 m and subsequent layer thicknesses were increased by a factor of 1.1 until the model depth reached 855 km (i.e. two times greater than the maximum skin depth). Data at 47 periods in the range 0.0001–1000 s were inverted using a uniform 100 Ωm half space as the starting model. Error floors of 5% of SQRT(|ZxyZyx|) (where Zxy and Zyx are the two off-diagonal impedance tensor components) were applied to each impedance tensor component. To smooth the model, a covariance value of 0.2 was applied twice in all directions across the model cells, following sensitivity tests of multiple covariance factors. We also used different subsets of the data to test the robustness of major features in the models. Our preferred 3D model converged to a normalised root-mean-square misfit value of 1.6 after 196 iterations, which is considered to be a reasonably good fit to the data.

To estimate cover thickness for drill site planning, we applied a probabilistic approach to invert AMT data using the 1D Rj-McMCMT code developed at Geoscience Australia (https://github.com/GeoscienceAustralia/rjmcmcmt). The code is built on the open-source rj-McMC library (Hawkins, 2013). The algorithm uses trans-dimensional Markov chain Monte Carlo techniques to solve for a probabilistic resistivity-depth model. The inversion of each station employs multiple Markov chains in parallel to generate an ensemble of millions of resistivity models that adequately fit the data given the assigned noise levels. Once the ensemble of models is generated, its statistics are analysed to assess the posterior probability distribution (PPD) of the resistivity at any particular depth. This probabilistic approach gives a thorough exploration of the model space and a more robust estimation of uncertainty than deterministic methods allow. For details of the algorithm, refer to Brodie and Jiang (2018).

INTERPRETATION AND CONCLUSION

We have used long-period AusLAMP data as a first-order reconnaissance survey to resolve large-scale lithospheric architecture for mapping areas of mineral potential in northern Australia. The 3D resistivity model reveals a broad conductivity anomaly extending from the Tennant Region to the Murphy Province in the lower crust and upper mantle, representing a potential fertile source region for mineral systems. Results from the higher-resolution infill magnetotelluric survey reveal two prominent conductors (Figure 2, C1 and C2) in the resistive host whose combined responses result in the lithospheric-scale conductivity anomaly mapped in the AusLAMP model. Most importantly, conductive structures indicate a “favourable” crustal architecture linking the lower, fertile source regions with depositional sites in the upper crust approximately at the location of the major faults (Figure 2). This observation strongly suggests that the major faults are deep-penetrating structures that potentially acted as pathways for transporting metalliferous fluids to the upper crust where they could form mineral deposits.

Elsewhere, similar structural controls have been observed in mineralised terranes and associated with IOCG discoveries (Skirrow et al., 2018). Examples include Olympic Dam in South Australia (Heinson et al., 2018; Heinson et al., 2006) and Mt Isa in northern Australia (Jiang et al., 2019; Wang et al., 2018). In the East Tennant region, there is potential for IOCG-type deposits to be found in the general vicinity of the major structures. Preliminary petrological studies from an historic drill hole (DDH005) indicate the presence of IOCG-type hydrothermal alteration including magnetite-rich, potassic, and later hematite-sericite-chlorite alteration (Schofield et al., 2020; Skirrow et al., 2019). As shown in Figure 2, there is a close spatial relationship between this drill hole, a major fault and the C2 conductive zone.

Results from probabilistic inversion of high-frequency AMT data (Figure 3) provide cover thickness estimates at proposed drill sites that have assisted with stratigraphic drill targeting which, in turn, will also validate models and improve our understanding of basement geology, cover sequences and mineral potential.

This study demonstrates that the integration of geophysical data from multi-scale surveys is an effective approach to scale reduction during mineral exploration in covered terranes with limited geological knowledge.

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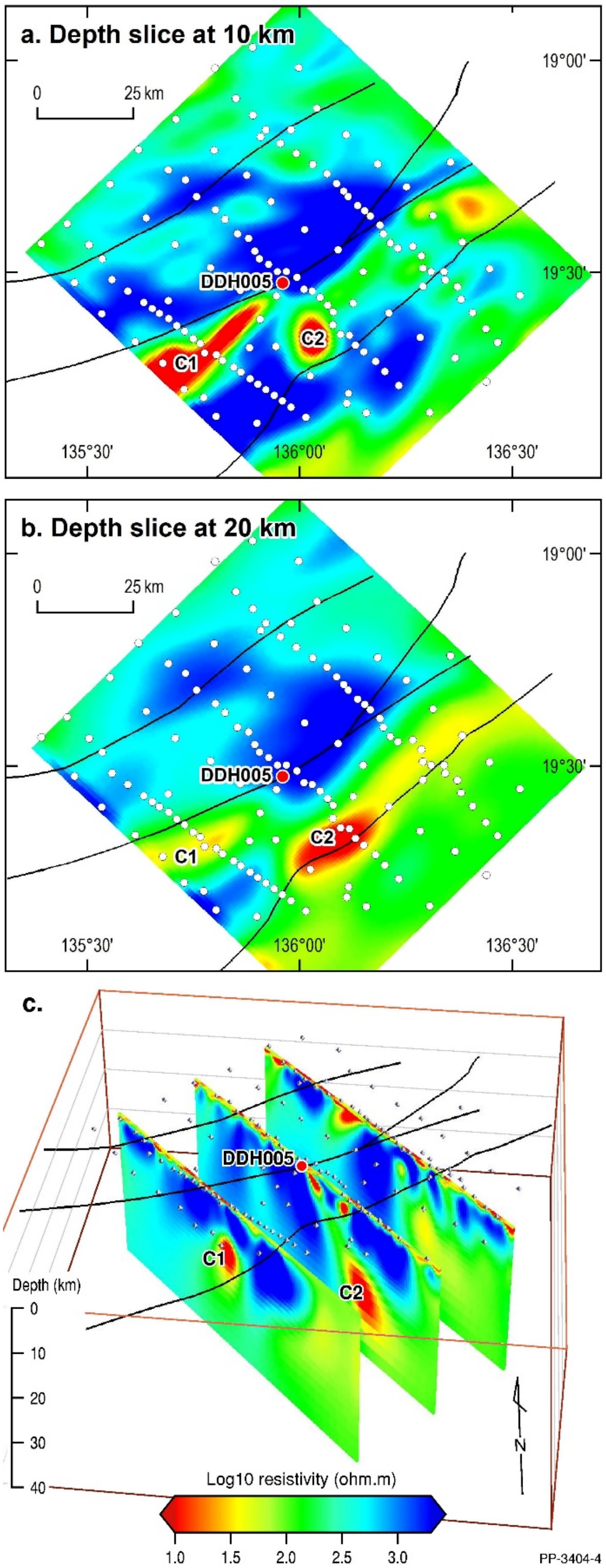

Figure 2. (a) and (b) Depth slices at ~10 km and ~20 km, respectively, from the 3D conductivity model. (c) Vertical sections to a depth of 40 km along the three transects showing conductors extend from the lower crust to the near-surface. Black lines = major faults interpreted from seismic and potential field data; White dots = MT stations; Red dot = location of drillhole DDH005; C1 = conductor 1; C2 = conductor 2.

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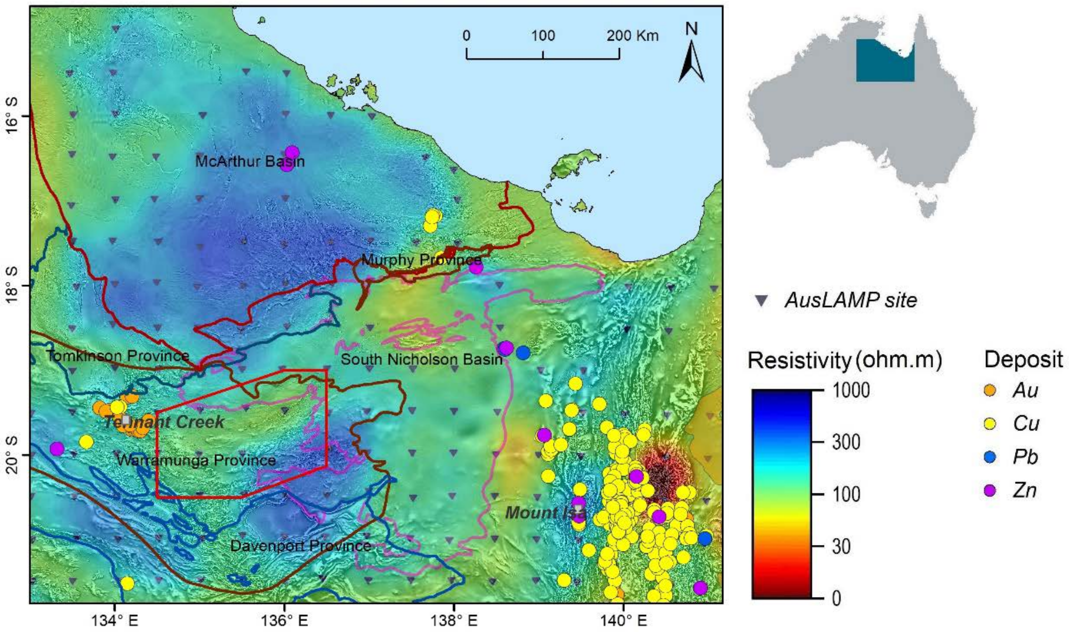

Figure 1. 3D conductivity model derived from the Exploring for the Future AusLAMP dataset shown at a depth of ~35 km (Duan, 2019; Duan et al., 2020) overlain on the total magnetic intensity anomaly map in grey scale (Nakamura & Milligan, 2015). The red line shows the outline of the East Tennant region.

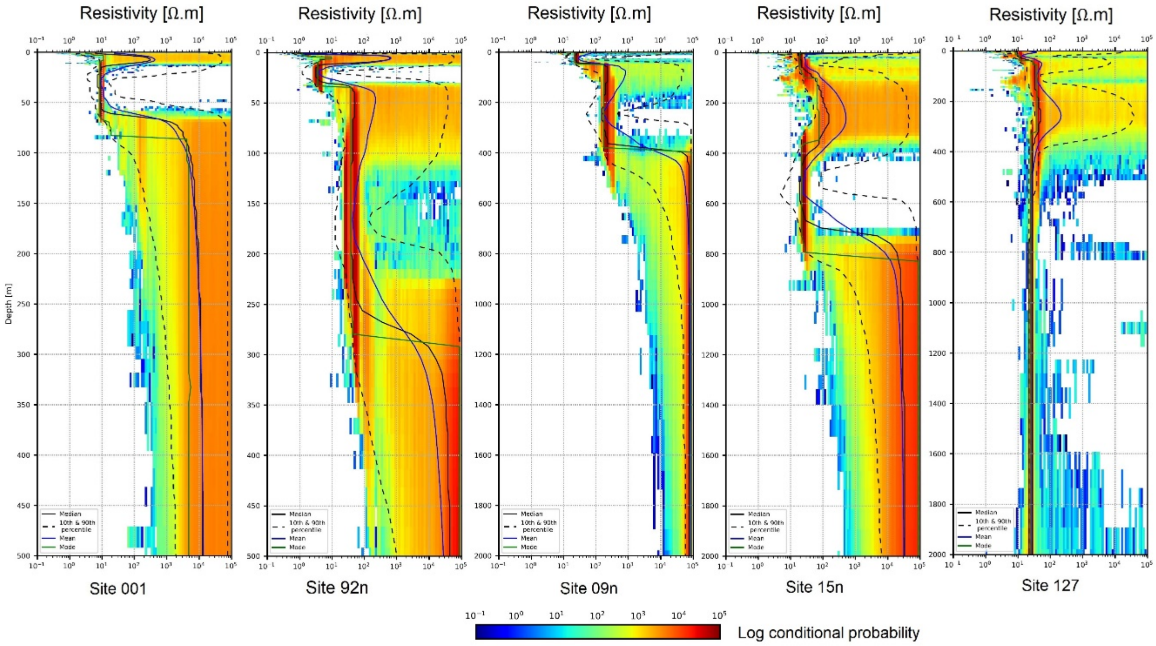

Figure 3. Examples of the 1D probabilistic inversion results at a few proposed drill sites: the summary median, 10th and 90th percentile, mean and mode models overlie the pseudo-coloured shaded image of the 2D log-PPD histogram.