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Detecting the Fingers of God: Optimising magnetotelluric survey design for mineral exploration

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SUMMARY

Magnetotellurics is a versatile exploration technique that can be used for imaging across scale lengths of tens to hundreds of metres, down to tens to hundreds of kilometres. Only in recent years has the potential of MT as an exploration tool been fully realised across varying depth scales. The optimum design of an MT survey for imaging the full mineral system has not yet been studied in detail, leaving questions such as, could the famous 'Fingers of God' conductivity anomalies that point to Olympic Dam, Wirrda Well and Vulcan deposits be resolved with larger site spacing or with a narrower period range? What about with an array instead of a transect? These questions are addressed using synthetic studies that take known conductivity anomalies that lead to mineral deposits, and trialling different survey layouts, period ranges and cover thickness to determine the ideal survey layout to make sure these features are not missed, whilst keeping survey acquisition expenditure and time to a minimum.

Key words: magnetotellurics, mineral exploration, modelling, survey design, Olympic Dam

INTRODUCTION

Almost all of the known mineral deposits to date have been found in areas of outcrop or minimal cover. Given that 70 % of Australia is under cover to some degree, a vast shift in the exploration process within Australia must occur to discover new deposits and keep up with the demand. The Australian Academy of Science's UNCOVER document (Australian Academy of Science, 2012) and the AMIRA roadmap (AMIRA International, 2015) outline the changes that need to occur. Of the four main themes of UNCOVER, arguably the most revolutionary is that of understanding the lithospheric framework beneath Australia.

Shallow electromagnetic (EM) surveys such as airborne EM or audio magnetotellurics (AMT) provide great detail on the resistivity of the shallow upper crust but may not have the power to penetrate conductive cover.
Broadband magnetotelluric (MT) studies usually reveal information on the resistivity structure of the entire crust and perhaps the shallow upper mantle, but whilst usually collecting along a profile are not ideal for exploration targeting over an area, unless many profiles are collected over a region.

Whilst capable of imaging the entire lithosphere (which is up to ~250 km thick in Australia), resolving power decreases with depth thus only broad-scale changes are imaged. A relatively new focus for mineral exploration is that broad scale trans-lithospheric structures provide structural controls for the generation of mineral deposits. Long-period MT may be capable of imaging the fluid delivery pathways and associated compositional variations of the lithosphere from the ascent of mineralising fluids and melts (fossil or present).

MT has gained further validation as a mineral exploration tool from the well-known, so-called, 'Fingers of God' conductivity pathways that point to the Olympic Dam IOCG-U deposit which hosts the world's largest uranium and fourth largest copper deposit, and adjacent 'fingers' pointing to two other IOCG deposits, Wirrda Well and Vulcan (Heinson et al 2018).

But even if we roughly know which MT technique or techniques to use to image the part of the mineral system we are interested in, how do we really know that we would actually be capable of resolving a feature such as the 'Fingers of God' using our chosen survey design (transect? Array? 2 km spaced? 20 km spaced?). Even then, cover thickness varies considerably across Australia and some of the most mineral rich regions such as the Olympic Domain IOCG belt are under cover up to 1000 m or more of sedimentary cover, diminishing the MT signal penetration depth with increasing sedimentary thickness. These are some of the questions and problems we aim to address with this study of optimising MT survey design for mineral exploration, to give the best chance of finding the next 'Fingers of God', without collecting excessively redundant data.

METHOD AND RESULTS

Magnetotellurics is a passive electromagnetic technique measuring natural variations of Earth's magnetic and electric at the surface of Earth (Cagniard, 1953). Interactions of solar wind with Earth's magnetosphere and global lightning activity that traverses the ionosphere, cause magnetic field variations, which act as a source for the induction of electric eddy currents in the Earth.

MT data is generally inverted in 2D or 3D using smooth non-linear inversion schemes, which aim to produce a minimum structure representation of the earth. The models are non-unique, and typically extensive testing of modelling parameters determines the variety of models which can explain the data.
The frequency of the signal as well as the bulk resistivity of the subsurface determines the penetration depth δ of the signal via the skin-depth relationship (in m):

$$\delta = 503\sqrt{\rho \cdot T}$$

Sediment Thickness
Surface sediments are usually conductive due to their high porosity and contained pore fluids. As shown in the skin depth

equation (Equation 1), the depth of signal penetration is dependent on the resistivity of the subsurface. A highly conducting thick sediment layer can significantly reduce the penetration depth. Testing using the Olympic Dam conductor (Heinson et al., 2018) and no sediment cover, through to 800 m of sediment cover, was investigated to better understand the capability of MT to resolve the conductive feature of interest beneath the conductive cover.

Data period range

In field deployments, MT instrumentation is chosen to suit the target. For shallow targets, instruments capable of recording in the high frequency range of audio MT (AMT) may be used. For crustal surveys, broadband MT (BBMT) is normally used. For deeper, whole-of-lithosphere surveys, long period MT data are recorded (LPMT). Some newer magnetometers (that record the time-varying magnetic field) are now capable of recording across the techniques, from AMT through to LPMT, such as the Phoenix ultra-wide band MT (UMT), period range of 0.0001 to 50 000 s, making the issue of which data type to acquire negligible to those who have access to these instruments. For most though, that is not yet the case. Recording more than one technique type requires access to a larger number of instruments (of different types), transportation of more gear in the field, longer time to deploy, and greater difficulty logistically with different MT types requiring different deployment lengths (from minutes to hours with AMT, through to weeks with LPMT) and ultimately greater cost.

An AusLAMP targeted-infill survey, the Olympic Domain survey (Thiel et al., 2019 AEGC) has AMT and BBMT data, with LPMT data available at a couple of locations from the AusLAMP deployments. This array was used to investigate the effects of only collecting the BBMT versus collecting the AMT and the BBMT. The addition of the several AusLAMP sites that fall within the Olympic Domain survey region were also tested.

Site spacing

Often MT transects have variable site spacing, either as a result of access issues, or altering site spacing to suit the complexity of the known geology/geophysics in the region. The distance between site often varies between 1 and 5 km, and several site spacings were tested between these distances, to investigate the decrease in resolution of the Olympic Dam conductor with this change. On completely different scale-lengths are the continental or country wide MT surveys such as AusLAMP (55 km site spacing; Robertson et al 2016) and the USArray (70 km site spacing;). Every second AusLAMP site was removed across the northeast of South Australia to show the difference in inversions of site spacing of 55 km versus 110 km. Whether 3D inversion of the large array that is AusLAMP can detect the conductive fluid pathways beneath a mineral system is investigated by extracting a cross-section from an AusLAMP derived 3D resistivity model along the location of a higher resolution transect. Synthetic testing was also conducted to further investigate this.

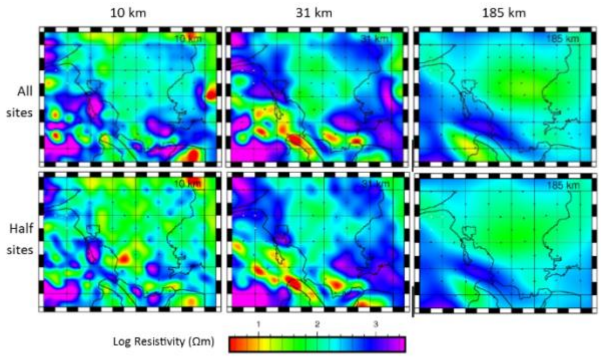

Figure 2- Investigation of site spacing using results of a 3D inversion of AusLAMP MT data across the northeast of South Australia. Site spacing in the top row is ~55 km, and in the bottom row ~110 km.

2D versus 3D inversion

Lastly, the magnetotelluric inversion does not provide a unique solution, and the resultant conductivity structure depends on the inversion code and the inversion technique used. Some of the modelling parameters that affect the results have been tested (Robertson et al 2018, northeast modelling reference), but synthetic modelling of a conductor similar to the one imaged beneath Olympic Dam using both 2D and 3D inversion codes, and using both an array and a transect of data across a replace type structure are tested. A common observation is that 2D inversions produce stronger resistivity contrasts as 3D inversions are able to distribute the conductance (conductivity times thickness) into the third dimension.

CONCLUSIONS

Whilst magnetotellurics is more commonly adopted as a mineral exploration tool in recent years, difficulty still exists in optimising survey design to image different parts of the mineral system, whether it's the deeper source of mineralising fluids, or crustal fluid pathways. Testing both synthetic MT data and real MT data has helped to better determine optimal MT survey design parameters. These include when AMT, BBMT and LPMT are necessary, MT site spacing, and the difference between an array and a transect across conductive fluid pathway type feature, and understanding the effects of sediment thickness when imaging crustal spanning conductive fluid pathways.

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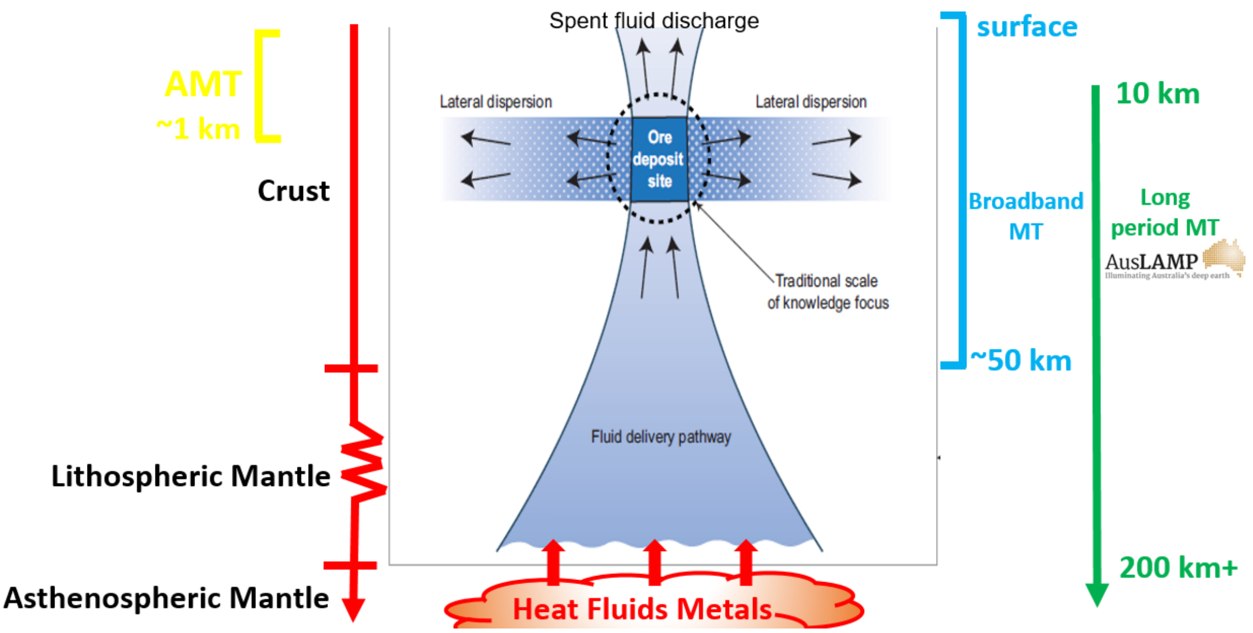

Figure 1: Diagram showing the components of the mineral system, and the depth resolution of AMT, BBMT and LPMT to image them. Adapted from UNCOVER, 2012.