Regional mineral exploration targeting based on crustal electrical conductivity variations from magnetotelluric data

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SUMMARY

A magnetotelluric survey, comprising 40 stations, has been completed in the southern Yilgarn Craton. The preferred resistivity cross section through the crust and upper mantle shows the local lithosphere comprises three distinct units separated by steep boundaries. The central unit, interpreted as equivalent to the Southern Cross Domain has a resistive crust overlying a more conductive mantle. The two units on either side comprise a conductive lower crust overlying a resistive mantle. Dipping narrow zones of increased conductivity in the crustal part of the model correlate with known surface structures. The eastern margin of the Southern Cross Domain as inferred from deep crustal and mantle resistivity occurs about 50 km to the west of the Ida Fault, the margin of the domain at the surface. The three fold subdivision of the local lithosphere is consistent with the geologically and geochemically defined terranes and domains in this part of the Yilgarn.

Current models for regional mineral exploration targeting emphasize the significance of major geological structures and the edges of cratonic blocks as areas of greatest prospectivity. The South Yilgarn MT dataset demonstrate that such features can be located based on variations in the electrical conductivity of the lower crust and mantle, which can be measured in a cost effective manner using the magnetotelluric method.

Key words: craton margins, Western Australia, Yilgarn Craton.

INTRODUCTION

Funded by the Western Australian Government's Exploration Incentives Scheme, a series of magnetotelluric (MT) surveys have been undertaken in basement terrains in Western Australia. These surveys are part of a project to provide regional exploration targeting datasets for selected terrains in the State being undertaken in the Centre for Exploration Targeting at The University of Western Australia.

Current ideas on regional prospectivity analysis emphasize the importance of major fault structures and in particular the suture zones between cratonic blocks. These zones represent deep penetrating zones of enhanced permeability encouraging the passage of potentially mineralizing brines and melts. Such features have been linked to the occurrence of nickel-sulfide and gold deposits, see for example Begg et al. (2010). The need to map variations in physical properties at lower crustal and mantle depths, and in a cost effective manner, suggests the use of the MT method. Such surveys in the similar geological environment of the Canadian Shield have produced excellent results, e.g. Spratt et al., (2009). Major structures usually, although not necessarily, are apparent as thin dipping conductive zones. Cratonic blocks have generally high resistivity. Variations in the electrical conductivity of the lower crust have been correlated with differences in the age of the Archean crust (Jones and Garcia (2004), potentially allowing major suture zones to be located based on such changes. The passive nature of the MT method means data can be acquired comparatively cheaply; this is an essential requirement given the size of the prospective areas in Western Australia and their geographical isolation.

The MT survey described here is in the southern Yilgarn Craton (Fig.1). The data comprise a single traverse extending from the Southwest Terrane across the Southern Cross Domain (Youanmi Terrane) and on to the Eastern Goldfields Superterrane. These are areas with different geochemical characteristics and which contain significant mineral deposits, notably nickel-sulfide deposits in greenstone belt rocks. The traverse crosses three greenstone belts: the Southern Cross greenstone belt, the Lake Johnston greenstone belt and the Norseman–Wiluna greenstone belt. The greenstone rocks in the Southern Cross and Lake Johnston belts are typically older than those in the Norseman belt. Moreover, a map of variations in granite Nd_{TM} produced by Cassidy and Champion (2004) shows significantly different values in the Eastern Goldfields Superterrane compared to the other terranes crossed by the MT traverse. Also, multi-isotopic analyses of zircons on whole-rock intrusive and volcanic rocks reveal how the lithosphere has evolved through time in the Yilgarn Craton (Mole et al., 2010). These data imply the presence of a palaeo-cratonic boundary in the survey area.

The location of the implied suture zone in the survey area is poorly defined. It is uncertain whether known apparently important structures correspond with the suture or there are major structures yet to be identified. Moreover, the position and geometry at depth of the known major structures in the study area is unknown or poorly constrained, for example the Ida Fault (Fig.1). An improved understanding of the extent and relationships between major crustal domains/terranes and the intervening large-scale structures in the study area was the primary motivation for the MT survey.

METHOD

The MT data were collected by personnel from Moombarriga Geoscience and the Centre for Exploration Targeting. The majority of data were collected in October 2009.

Two (horizontal) components of the electric field and three components of the magnetic field variation were measured at 40 sites, each for approximately 40 hours. Data were recorded using Phoenix Ltd MTU-5A data recorders with MTC-50 magnetic induction coils. Electric dipoles and horizontal coils were installed in magnetic north-south and east-west azimuths and the electric dipoles at all sites were approximately 100 m in length. The electric field was measured using non-polarising (Pb/$PbCl_2$ solution) electrodes. Survey sites were all relatively flat and most sites were remote from any sources of cultural electromagnetic noise. At each site electromagnetic soundings were made using a TerraTEM transmitter and receiver. A 100 m-sided square transmitter loop (Tx area=10000 m^2) was used with sides oriented north-south/east-west. The receiver coil had a 1 m side length (Rx area=105 m^2). The TerraTEM 'intermediate' time series was used (135 channels between 0.0015 and 1900 ms).

Data Processing

In general, data quality is very good, with useful data recorded to periods of about 1000 s. The time-series data were processed using robust remote-reference algorithms supplied by Phoenix Limited and based on the coherence-sorted cascade decimation method of Wight and Bostick (1981) and the heuristic robust approach of Jones and Jödicke (1984). Remote reference processing (Gamble et al., 1979) used a simultaneously recording station within the traverse. Static shifts were estimated using the time-domain (TD) electromagnetic soundings.

The geoelectric strike direction and dimensionality of the MT data was assessed using the phase-tensor method of Caldwell et al. (2004). The strike is undetermined for periods below 0.1s (>10 Hz), but becomes more or less north-south for longer periods. For periods >1 s strike is roughly 10° northnortheast, shifting to >30° degrees for periods >100 s**.** The average strike direction calculated for all data points, with skew <5°, is -2°. If only periods between 1 s and 100 s (where there is a more dominant strike across the profile) are considered the average strike direction is 10°. This is the strike direction used when modelling the data (see below) and corresponds approximately with the stratigraphic and structural strike of the major features in the study area (Fig.1).

The data not significantly affected by 3D conductivity variations were modelled using the 2D non-linear conjugate gradient inversion algorithm of Rodi and Mackie (2001) as implemented in the Winglink™ software package (Geosystem SRL, 2008). This inverse modelling method minimizes an objective function consisting of the data misfit and a measure of model roughness, with the user-specified trade-off parameter, τ, defining the balance between these terms. Both TE and TM modes and the Hz transfer function were modeled over the frequency range 500-0.001 Hz using a uniform grid Laplacian operator and τ=3. Geoelectric strike was taken to be 10° (see above). The misfit between observed and calculated data corresponds to an rms difference of 3.54.

Interpretation

Figure 2 shows the preferred resistivity cross section derived from the MT data, with features of significance labelled and showing aspects of the surface geology. Sub-surface resistivity variations of potential geological significance are labelled and discussed in turn below.

The upper crust is mostly highly resistive (greater than about 10,000 Ω.m). Separating the resistive zones are regions, mostly narrow and dipping either to the east or west, which are more conductive. Based on comparison with equivalent data from the Canadian Shield these zones are interpreted as major fault/shear zones. The data suggest that some of these (e.g. A and E) extend through the entire crust whilst others reach at least mid-crustal levels (e.g. F and G). This is consistent with the interpretation of the seismic reflection data from the region. There is evidence for such structures on both sides of the Southern Cross greenstone belt (A and B), and there are equivalent linears in potential field data. A conductive zone in the upper crust immediately west of the Lake Johnston greenstone belt (C) spatially correlates with a zone of intense NNE-trending magnetic linears. This feature is not shown on geological maps and apparently is a new structure discovered by the MT survey. The Koolyanobbing shear zone, although a major structure in terms of surface geology and magnetic and gravity character, coincides with a subtle geoelectrical anomaly (D). Libby et al. (1991) describe the Koolyanobbing shear zone as a 6 to 15 km wide zone of mylonitic rocks formed from monzogranite to tonalite. This is consistent with the weak conductivity anomaly. The Koolyanobbing shear zone is considered to be predominantly a transcurrent structure, consistent with its steep dip in Figure 2.

At the eastern end of the MT traverse, there are numerous important structures defining terrane and domain boundaries within the Eastern Goldfields Superterrane. One of these (G), coincides with the location of the Ida Fault as shown on Figure 1. However, the position of this feature is not geologically at all well constrained and there is no magnetic or gravity feature coinciding with the Ida Fault as drawn in Figure 1. Feature H appears to be related to major faults at the western margin of the greenstone belts of the Eastern Goldfields superterrane.

The most significant variations in electric resistivity occur between stations STY23-25. There are two zones of lower resistivity (E and F) which are interpreted as major fault structures. For reasons related to the resistivity variations at sub-crustal depths (see below), this region is considered the mostly likely candidate for the position of any major suture zone/palaeocratonic boundary.

Conductivity variations in the lower crust and upper mantle are of particular interest. To the east, feature I is consistent with a conductive lower crust and the depth to its base is in reasonable agreement with the seismic Moho. Note that the apparent position of the electrical Moho is affected by the look up table used to create the figure. MT data cannot discriminate between zones with very high resistivities and if a look up table with maximum values at say 100,000 Ω.m is used the apparent position of the electrical Moho is shallower and in better agreement with the seismic Moho. The westward limit of the conductive lower crust is the E anomaly in the crust. To the west there is no evidence for a conductive lower crust and instead the upper part of the mantle is more conductive (J) than to the east. Feature K is a more conductive zone, when compared with the mantle to the east and the west, at depths of around 100 km. However, it is questionable whether this feature is real as it is close to the maximum depth penetration of the useful data. It is an attractive option to link this feature to alteration of material in the deep mantle but the crust and mantle are quite resistive overall and the skin depth could well be far enough to sense the Southern Ocean, which is only about 150-200 km to the south of the MT traverse.

Based on the above observations, it is proposed that the MT survey has defined 2, or possibly three major 'blocks' of lithosphere: Units 1, 2 and 3 (Fig 2). The distinction between units 2 and 3 is based on their different lower crust and upper mantle electrical properties and the distinct E conductive zone between them. Placing a major lithospheric boundary here is consistent with the isotopic age dates from the greenstone terrains with the Southern Cross and Lake Johnston belts not containing material with the younger ages that are found in the Eastern Goldfields.

The distinction between Units 1 and 2 is made with far less confidence. There are few stations above unit 1 and the lateral changes in crustal and mantle conductivity are less distinct. The boundary between units 2 and 3 may mark the actual location, at least in the deep crust, of the western extent of the Eastern Goldfields Superterrane. This coincides with the Ida Fault to the north of the MT survey area and here the seismic reflection data suggest a coincident change in the nature of the lower crust from the Southern Cross lower crust associated with imbricated fault blocks to the Eastern Goldfields lower crust characterized by flat reflectors. If the Unit 2 and Unit 3 boundary is the equivalent structure then the position of the Ida Fault shown on Figure 1 is too far to the east or else the boundary at the surface does not coincide with the boundary in the deep crust. This is possible given the poor constraints on the location of the Ida Fault in the study area. Also a lack of suitable outcropping lithotypes mean the position of the change in isotopic character between the Eastern Goldfields terranes and those further to the west is poorly constrained.

Jones and Garcia (2004) state, referring to the presence or absence of a conductive lower crust; "… the locations of resistive crust are all Archean in age, and likely Mesoarchean or earlier …. continental crust of ages younger than Mesoarchean predominantly display a conducting lower crust". The implication is that 'Unit 2' on Figure 2 is Mesoarchean (2.8-3.2 Ga) and 'Unit 3' is Neoarchean (2.5-2.8 Ga). This is consistent with the isotopic ages from the greenstone belts at the surface. However, it is common for the position of mantle 'terrane' boundaries to not coincide with surface terrane boundaries (Spratt et al., 2009).

Finally, there is evidence for a correlation between deep electrical structure and the type of komatiites seen at the surface. Barberton- and Munro-type komatiites differ from one another primarily in the depth and degree of partial melting that produces them (Arndt et al., 2008). This is consistent with differences in the electrical properties of the mantle. Munro-type komatiites are the most nickel sulphide endowed globally and in the Eastern Goldfields Superterrane they are the only mineralised komatiites. Conversely, in the Youanmi Terrane all the mineralised komatiites are Barberton-type. Thus, deep electrical structure may provide clues regarding the origin of this type of mineralisation.

CONCLUSIONS

A magnetotelluric survey has allowed electrical conductivity variations in the crust and upper mantle to be determined along a 250 km long traverse in the southern Yilgarn Craton. Based on electrical resistivity variations a 3 fold division of the crust and upper mantle is inferred, which is consistent with geologically based mapping of surface terrane boundaries. A change in electrical properties at the western end of the MT traverse coincides with the boundary between the Southwest Terrain and the Youanmi Terrane (Southern Cross Domain). However, the boundary between the Southern Cross Domain and the Eastern Goldfields Superterrane is 50 km further west than previously thought.

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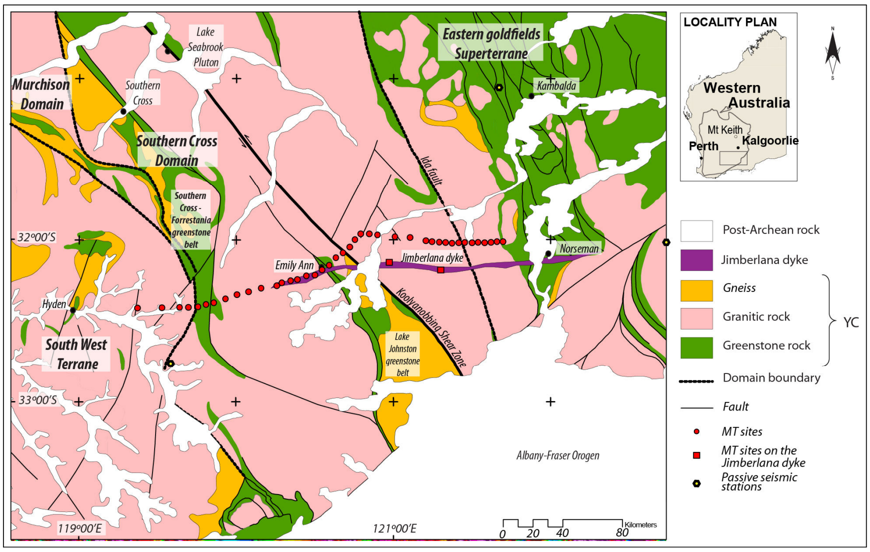

Figure 1. Locations of MT stations overlain on regional geological map of the southern Yilgarn Craton showing major geological/structural boundaries and the various terranes and domains in this part of the Craton. YC – Yilgarn Craton.

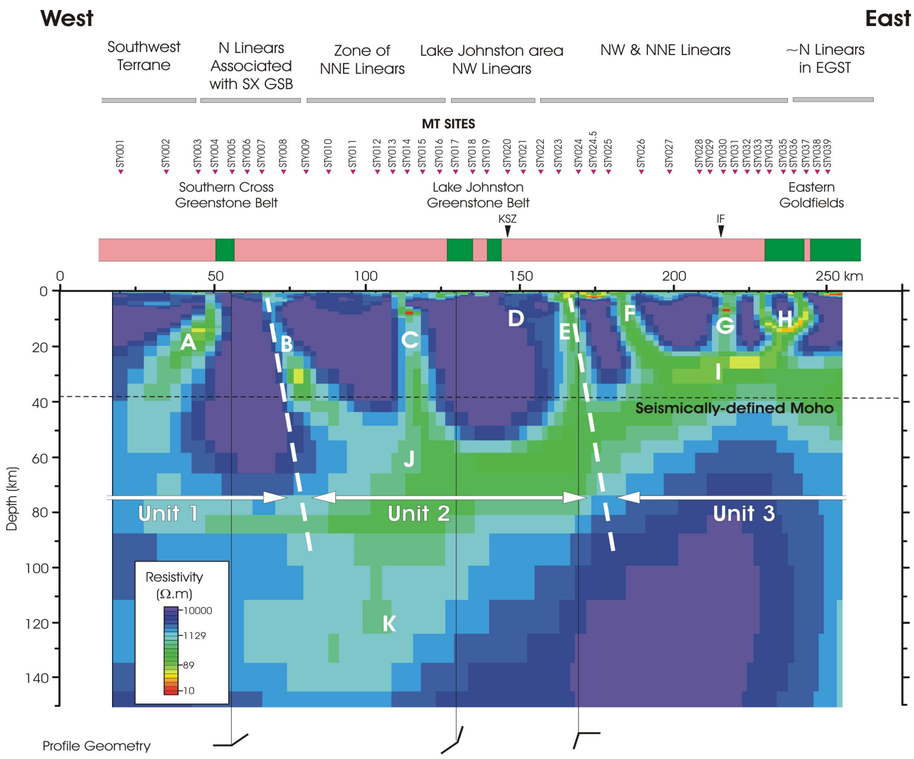

Figure 2 Resistivity cross-section derived from 2D modelling of MT data. KSZ – Koolyanobbing shear zone, IF – Ida Fault. A, B etc are features discussed in the text.