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The link between electrical conductivity anomalies and rheological boundaries

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SUMMARY

Interpreting magnetotelluric (MT) models requires solid modelling of the data as well as good knowledge from other geophysical data and geological constraint in the particular tectonic setting of the survey area. MT measurements, relating the natural variations of electric and magnetic field to obtain the electrical resistivity distribution of the crust and mantle appear to show that enhanced electrical conductivity zones are more abundant at certain depths. Models show that frequently enhanced conductivity zones are topping out in the upper crust at depths of about 10-15 km. These features are discrete and extend usually over a few km to tens of km laterally, and can be found across the Delamerian Orogeny, in zones of high heat flow east of the Northern Flinders Ranges and also in the central Eyre Peninsula. We interpret this to be related to recent findings on dynamic interactions between brittle and ductile layers leading to mid- to upper crustal detachment faults. A second zone of higher conductivity occasionally appears in the lower crust, as imaged east of the Flinders Ranges at depths of around 25-35 km. Thirdly, at 80 km depth mantle conductors appear in stable Archean and Proterozoic terranes around the world, such as in the Slave Craton, Kaapvaal Craton and the Gawler Craton. In summary, information from geodynamic modelling helps to understand the processes in the earth in regards to fluid movement and potential mapping of heat flow and corresponding shift in depth of brittle-ductile boundaries.

Key words: magnetotellurics, electrical resistivity, lithological boundaries

INTRODUCTION

Fluids and the consequent chemical alterations in the crust and mantle show a lower electrical resistivity (reciprocal of conductivity) than typical dry rocks (Nover, 2005). In this paper, the focus lies on horizontal features in the lower resistivity distribution, which may represent rheological boundaries in which fluid reside over a limited time before propagating upwards in the lithospheric column.

Laboratory measurements of hydrogen-doped olivine, the main mantle constituent, indicate an increase in conductivity by 1-2 orders of magnitude at mantle temperatures (Yoshino et al., 2009), even at moderately low concentrations of ten per ppm. Magnetotellurics (MT) is therefore the method of choice to detect small amount of fluids in the lithosphere, which are not detectable for seismic methods. Analysis of xenolith data will provide estimates of the fluid content of the mantle, but are sparse and appear biased by the fertilised margins of cratons (Griffin et al., 2009). The MT method has been successfully used in the Kaapvaal Craton, South Africa (Muller et al., 2009), northern Canada and Finland (Eaton et al., 2009) and the Gawler Craton (Thiel and Heinson, 2010) to image the transition from dry harzburgitic to fertilised lherzolitic mantle. The transitions usually occur at the base of the crust. Examples from the St. Peter Suite, South Australia, show a transition at depth of 160 km (Thiel and Heinson, 2010).

Additionally, high conductivities at depths of 80 km in presently stable Achaean cratons have been observed and remain difficult to explain. Suggested conductive agents include graphite in the Slave Craton (Jones et al., 2001) , hydrated minerals in the Kaapvaal Craton (Evans et al., 2011) and compositional changes of mantle minerals in the Dharwar Craton(Patro et al., 2009). New results from the Gawler Craton see a similar feature underlying the surface expressions of the Gawler Range Volcanics and the Hiltaba Suite (Thiel and Heinson, 2013). Hydrogen in the crustal lattice of olivine is held accountable for reducing the resistivity in this case, but iron in the Hiltaba related mineralisation and augites in the Gairdner Dyke Swarm suggests that there may be a contribution to conductivity enhancement from iron as well (Yang et al., 2012).

Recent results across the Gawler Craton indicate two types of horizontal in the crust. Firstly, the lower crust shows a relatively wide-spread resistivity reduction at depth of around 25 km to 40km, i.e. at the eastern margin of the Northern Flinders Ranges. Secondly, conductors extend up to depths of around 10 km in the same area and also in the Southern Delamerian, but are spatially only on the order of a few kilometres wide.

MT METHOD

The MT method records naturally occurring magnetic and electric field at the surface of the earth (Cagniard, 1953). The depth of the induced electromagnetic field is frequency-dependent, i.e. high frequency (short period T) EM waves penetrate less deep than low frequency EM waves. Additionally, the so-called skin-depth is also dependent on the bulk resistivity of the rock, i.e. EM waves penetrate deeper into resistive rock. The resolution decreases with increasing skin-depth, i.e. longer periods signal looses resolution. The

Earth's response is contained in the complex, frequency dependent impedance tensor Z, which relates the measured electric and magnetic field components at the surface, via E = ZB.

The impedance tensor forms the basis of an inverse solution to finding a resistivity model from minimising the misfit between the observed and modelled responses (deGroot-Hedlin and Constable, 1990; Siripunvaraporn et al., 2005). In a 2D inverse code, dimensionality and geoelectric strike constraints must be fulfilled in order to obtain an accurate model. For our models, we used the phase tensor approach to find appropriate subsets where the data shows predominantly 2D characteristics (Caldwell et al., 2004).

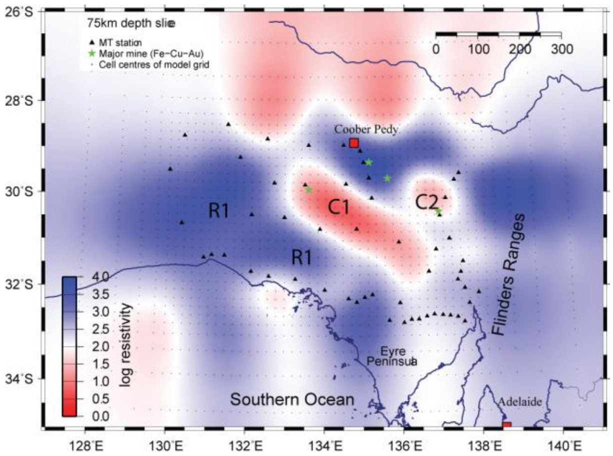

Figure 1: An example of a conductor at 80 km depth (adapted from Thiel and Heinson (2013)) underneath the Gawler Craton.

DISCUSSION

We propose a pattern which appears abundant in the resistivity distribution of stable continental lithosphere. The middle to lower crust and the base of the lithospheric mantle can show elevated conductivities across a wider area and are often bounded by either large-scale lateral shear zones or fault zones in the crust. The feedback mechanisms between fluid migration and rock deformation is poorly understood, but is important for understanding shear-zone-controlled advective flow of fluids in the ductile lower crust (Mack Kennedey et al., 2007). The temperatures in the lower crust are too high to sustain a dynamic fracture-sustained permeability as in the upper crust. Geodynamic modelling of mid-crustal shear zones indicates that permeable porosity is created through viscous grain boundary sliding, creep cavitation and precipitation (Fusseis et al., 2009). Irrespective of active or fossil fluid flow, these ductile shear zones and fluid pathways have a likely electromagnetic response to surface MT measurements.\stanza
The elevated conductivities in the upper and middle crust in discrete pockets likely illustrates zones of fossil fluid flow. It appears that these zones are structurally controlled by the brittle-ductile boundary in the crust (Regenauer-Lieb et al., 2006). Even if fluid propagation has ceased, the precipitation products in form of sulphides or magnetite can significantly reduce the resistivity observed in surface MT measurements.

REFERENCES

Cagniard, L. (1953), Basic theory of the magnetotelluric method of geophysical prospecting, Geophysics, 18, 605–635.

Caldwell, T. G., H. M. Bibby, and C. Brown (2004), The magnetotelluric phase tensor, Geophysical Journal International, 158, 457–469.

deGroot Hedlin, C., and S. Constable (1990), Occam’s inversion to generate smooth, two-dimensional models from magnetotelluric data, Geophysics, 55, 1613–1624.

Eaton, D. W., F. Darbyshire, R. L. Evans, H. Gruetter, A. G. Jones, and X. Yuan (2009), The elusive lithosphere-asthenosphere boundary (LAB) beneath cratons, Lithos, 109(1-2), 1–22.

Evans, R. L., et al. (2011), Electrical lithosphere beneath the Kaapvaal craton, southern Africa, Journal of Geophysical Research, 116(B4), B04,105–.

Fusseis, F., K. Regenauer-Lieb, J. Liu, R. M. Hough, and F. De Carlo (2009), Creep cavitation can establish a dynamic granular fluid pump in ductile shear zones, Nature, 459(7249), 974–977.

Griffin, W. L., S. Y. O’Reilly, J. C. Afonso, and G. C. Begg (2009), The composition and evolution of lithospheric mantle: a re-evaluation and its tectonic implications, J. Petrology, 50(7), 1185–1204.

Jones, A., I. Ferguson, A. Chave, R. L. Evans, and G. McNeice (2001), Electric lithosphere of the Slave craton, Geology, 29, 423–426.

Mack Kennedey, B., and M. van Soest (2007), Flow of mantle fluids through the ductile lower crust, Science, 318, 1433–1436.

Muller, M., et al. (2009), Lithospheric structure, evolution and diamond prospectivity of the Rehoboth Terrane and western Kaapvaal Craton, southern Africa: Constraints from broadband magnetotellurics, Lithos, 112(Supplement 1), 93–105.

Nover, G. (2005), Electrical Properties of Crustal and Mantle Rocks: A Review of Laboratory Measurements and their Explanation, Surveys in Geophysics, 26, 593–651.

Patro, P. K., and S. V. S. Sarma (2009), Lithospheric electrical imaging of the Deccan trap covered region of western India, Journal Of Geophysical Research-Solid Earth, 114, B01,102.

Regenauer-Lieb, K., R. F. Weinberg, and G. Rosenbaum (2006), The effect of energy feedbacks on continental strength, Nature, 442(7098), 67–70.

Siripunvaraporn, W., G. Egbert, Y. Lenbury, and M. Uyeshima (2005), Three-dimensional magnetotelluric inversion: data-space method, Physics of The Earth and Planetary Interiors, 150, 3–14.

Thiel, S., and G. Heinson (2010), Crustal imaging of a mobile belt using magnetotellurics: An example of the Fowler Domain in South Australia, Journal of Geophysical Research, 115(B6), B06,102.

Thiel, S., and G. Heinson (2013), Electrical conductors in Archean mantle - result of plume interaction?, Geophysical Research Letters, accepted, 03/2013.

Yang, X., and C. McCammon (2012), Fe3+-rich augite and high electrical conductivity in the deep lithosphere, Geology, 40(2), 131–134.

Yoshino, T., T. Matsuzaki, A. Shatskiy, and T. Katsura (2009), The effect of water on the electrical conductivity of olivine aggregates and its implications for the electrical structure of the upper mantle, Earth and Planetary Science Letters, 288(1–2), 291 – 300.