Imprints of tectonic processes imaged with magnetotellurics and seismic reflection

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SUMMARY

Co-located seismic and magnetotelluric (MT) profiles provide fundamental geophysical data sets to image the crust of Australia. Despite their overlapping nature, the data are processed and interpreted separately based on legacy workflows. We qualitatively compare 2D resistivity inversion models derived from MT and uninterpreted seismic reflection profiles across Proterozoic Australia to address the long-standing cross-cutting nature of interpreted seismic faults and low resistivity zones derived from MT. We find that a good correlation exists between high/low reflectivity in seismic sections and low resistivity in MT sections. These relationships elucidate signatures of past magmatic and fluid-related events and constrain zones of weakened rheology in the crust. Depending on their characteristics, these signatures may signify fossil melting of the crust due to underplating or magmatic invasion into the crust or reworking associated with redistribution of fluids along newly developed faults. These findings have implications for constraining mineral deposit genesis and location.
Key words: magnetotellurics, seismic reflection, resistivity, tectonics

INTRODUCTION

Imaging the continental lithosphere is pivotal for our understanding of the state and properties of the lithosphere and the processes that have shaped the continents. Programs focussing on the crustal component of the lithosphere most often use seismic reflection profiles to interrogate the crust (Goleby et al., 1989; Cook et al., 2010). In Australia, deep seismic reflection surveys have been used to provide two-dimensional profiles of the whole crust, informing crustal architecture studies and mineral system settings since 1978 (e.g., Goleby et al. (1989); Drummond et al. (2006); Kennett and Saygin (2015); Kennett et al. (2016)). Surveys continue to be undertaken as part of a collaborative agreement between Geoscience Australia and state and territory organisations in order to address fundamental geodynamic questions, particularly in deeply covered terrain and cratonic margin areas. Increasingly, national and international programs incorporate other geophysical data sets, such as magnetotelluric and potential field data to augment the reflection seismic information. Joint studies performed during the Lithoprobe experiment highlight the complementary nature of magnetotellurics and reflection seismic techniques (Jones, 1998). Several examples of the Lithoprobe program highlighted the coincident nature of low electrical resistivity and high seismic reflectivity in the middle to lower crustal assemblages (Marquis et al., 1995; Cook and Jones, 1995; White et al., 1999). A similar coincidence is postulated from geodynamic considerations of fluid flow in compressive tectonic regimes leading to accumulation of fluids below the brittle-ductile transition (Connolly and Podladchikov, 2004; Thiel et al., 2016b).

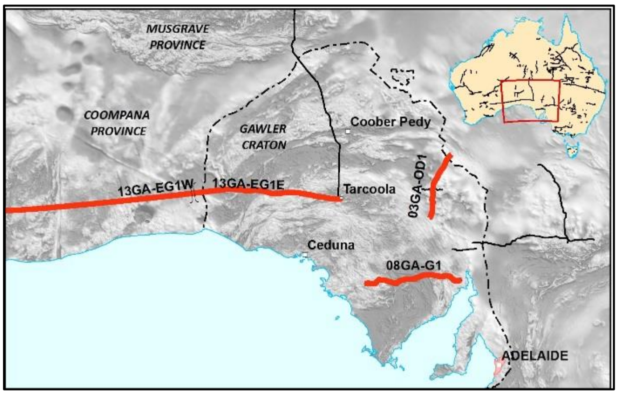

Figure 1: Location of deep seismic reflection profiles across Australia (inset) and co-located deep seismic reflection and magnetotelluric profiles in South Australia. Examples in text are highlighted in red.

However, increasing examples of co-located magnetotelluric and seismic reflection profiles in Australia show that particularly in the mid to lower crust sub-vertical zones of low resistivity cross-cut interpreted faults derived from seismic data. Here, we qualitatively compare 2D resistivity inversion models derived from MT and un-interpreted seismic reflection profiles the Gawler Craton, South Australia (Figure 1) to address the cross-cutting nature of faults interpreted from seismic sections and low resistivity zones derived from MT.

METHOD

While seismic reflection methods image the acoustic impedance as a product of seismic wave speed and density, the magnetotelluric method is sensitive to the electrical resistivity of the subsurface. It is therefore particularly sensitive to fluids (Nover, 2005) in active tectonic settings (Worzewski et al., 2011; Wannamaker et al., 2009; Thiel et al., 2016a), as well as their partial melt sources (Heise et al., 2008; Naif et al., 2013; Didana et al., 2014; Aivazpourporgou et al., 2015). However, lower resistivity anomalies are also found within stable continental interiors and are attributed to graphite (Pous et al., 2004; Thiel et al., 2005; Nover, 2005) and sulphides in the crust (Bedrosian, 2016) or some form of metasomatic imprint at mantle depths, for example in the form of hydrogen impurities in the crystal lattice of mantle constituting minerals (Thiel and Heinson, 2013; Pommier, 2014; Selway, 2014).

A common approach to interpretation of crustal seismic reflection profiles relies on subjective identification of faults, which in most cases are identified as discrete and narrow zones of deformation along which crustal movement is accommodated. These deformation zones are traced through the entire crustal columns often linking known surface faults through the entire crust down to the Moho discontinuity, the crust-mantle boundary. In some cases major faults link up with Moho offsets laterally displaced by tens of kilometers from their surface expression (Goleby et al., 1989). The fault zones accommodate deformation and displacement of lithological blocks. Moreover, they provide pathways for fluids and minor phases further weakening rheology and providing mechanisms for mineral deposit genesis.

However, increasing examples of co-located magnetotelluric and seismic reflection profiles in Australia show that particularly in the mid to lower crust sub-vertical zones of low resistivity cross-cut interpreted faults derived from seismic data. In stable continental lithosphere, zones of low resistivity are typically attributed to minor conducting mineralogy as a result of past fluid precipitation and metasomatic reactions, such as graphite or sulphides, and/or active fluids (Selway, 2014; Thiel et al., 2016a). Seismic profiling has been extensively used in Australia (Goleby et al., 1989; Thybo and Artemieva, 2013; Kennett and Saygin, 2015; Kennett et al., 2016) as well as during the Lithoprobe program in Canada (Cook et al., 2010).

Magnetotelluric measurements were collected along the same profiles as the seismic transects over the last ten years across Australia (Dennis et al., 2011, 2012; Heinson et al., 2006; Selway et al., 2009; Thiel et al., 2010, 2015; Dentith et al., 2012). Data analysis (Caldwell et al., 2004) and 2D modelling codes (Rodi and Mackie, 2001) have since improved and analyses and interpretations matured.

Here, we analyse several examples of co-located seismic and magnetotelluric transects and focus specifically on the correlation between seismic reflectivity and magnetotelluric low resistivity. We illustrate three correlative subsets which describe either fluid-related reworking, magmatic overprints or associated seismic homogenization of lithological fabric due to underplating.

RESULTS

We note several types of correlation between reflection seismic and magnetotelluric data using the following examples surrounding the Gawler Craton, South Australia (Figure 1):

- The Eucla-Gawler collocated seismic and magnetotelluric profile extends from Tarcoola in central South Australia to Haig in Western Australia. Reflection seismic and 5 km-spaced broadband magnetotelluric surveys were acquired along the trans-continental railway, providing in part an east-west transect imaging the crustal architecture across the margins of, and in-between, the Gawler and Yilgarn Cratons. Given competing geo-electric strike directions in magnetotelluric data between broad crustal sections of the c. 800 km long profile (Thiel et al., 2015), 2D modelling was conducted in two suitable sections, which we hereby refer to as Eucla-Gawler East (13GA-EG1E) and Eucla-Gawler West (13GA-EG1W). Reid and Dutch (2015), Spaggiari (2015) and Wise et al. (2015a) review the geology in the vicinity of these profiles, whilst Doublier et al. (2015), Dutch et al. (2015) and Dutch et al. (2016) discuss the seismic interpretation.
- The Olympic Dam profile (03GA-OD1, Figure 1) is a north-south trending transect centred on the Olympic Dam iron oxide-copper-gold±uranium deposit, with the aim of elucidating the crustal architecture constraining the mineralisation setting for this world class deposit (Lyons and Goleby, 2005). Drummond et al. (2006) reviews the crustal architecture and tectonic regime, whilst Wise et al (2015b) details a variation in seismic processing methodology trialled, revealing greater contrasts in the upper crust and permitting interpretation of possible fossil fluid pathways.
  Extensive MT acquisition has also been undertaken in recent years infilling an original site spacing of 5-10 km to approximately 1 km, (Heinson et al. (2006), G. Heinson pers comm.).
- The 08GA-G01 (Eyre Peninsula) collocated seismic and magnetotelluric surveys across the northern Eyre Peninsula were designed to investigate the crustal architecture in the eastern and southern Gawler Craton (Fraser et al., 2010). The east-west oriented Eyre Peninsula profile crosses several north-south trending tectonic domain boundaries (Ferris et al., 2002) as well as the South Australian Heat Flow Anomaly (Neumann et al., 2000).

A correlation is hereby referred to as the spatial coincidence between a region of anomalous conductivity and a sharp or diffuse change in seismic character. Regions of the upper crust in places show correlation between high conductivity and seismic packages of relatively uniform reflectivity. Here we interpret this correlation to be due to conductive phases distributed in lithostratigraphic packages. Causes of conductivity may be: groundwater in porous sediments (Adelaidean strata, north of Olympic Dam), sulphide-bearing shales (Tarcoola Formation, Eucla-Gawler East) or sheared and metamorphosed magnetite-bearing metasedimentary rocks (Moondrah Gneiss, Eucla-Gawler East), (Heinson et al., 2006; Thiel et al., 2015).

Several examples of moderately-dipping conductors aligning with similarly-dipping, reflectors/ or edges of reflective regions are observed in both the Eucla-Gawler East and Eyre Peninsula profiles. Such conductive/reflective regions have variable depth extent, with most examples being confined to the upper crust. This type of correlation is interpreted to represent focusing of crustal fluids or conducting phases during deformation events, producing conductive and reflective shear zones.

Broad regions in the lower-middle crust on the Eucla-Gawler East, Eucla-Gawler West and Olympic Dam profiles display good correlation between weakly reflective zones and conductive pathways, with similar features being observed in other co-located profiles globally (e.g. in the hanging-wall of the Central Metasedimentary Boundary Belt Zone of the Grenville Province, Canada (Adetunji. et al., 2014)). Such conductive zones continue across the Moho, and are assumed to be fed by a pervasive, fertile upper mantle (Thiel et al., 2016a; Heinson et al., 2006). Spatially coincident with such weakly reflective and conductive zones are interpreted Moho offsets, or regions of significant Moho topography. This may imply a causative relationship, ie a Moho offset providing a locus for up-ward

moving conductive phases. Significantly however, structures interpreted from seismics to cross-cut and offset the Moho in such regions are at odds with the conductivity structure. Conductors are generally steep, whilst structures from seismic are interpreted to be shallow-moderately dipping, implying that at lower crustal depths in these regions, conductivity is not controlled by singular structures.
We attempt to distinguish between conductive and seismic character associations caused by stratabound lithostratigraphic packages in sedimentary and metamorphic settings, the topic of previous discussion (e.g. Cook and Jones (1995); Jones (1998); Adetunji. et al. (2014)), and focus on correlations interpreted to be formed by crustal tectono-thermal events.

Two major processes are therefore proposed for bulk modification of the post-formational reflectivity and conductivity structure of the crust:

1. **Crustal re-working**

   The electrical resistivity model of the EW profile across the northern Eyre Peninsula (Figure 2) shows folded high conductivity zones which surface at locations of interpreted NS magnetic anomalies (McAvaney et al., 2016). The conductivity anomalies are not connected to the mantle but reside in the upper to middle crust and extending deeper along the western part of the profile. In the central part of the profile the conductivities are highest and are associated with a seismically reflective zone in the upper crust. A highly resistive crust underlies the folded conductors outcropping in the east, coinciding with known outcrops of the 3.1 GA Cooyerdoo granites. We interpret the resistor to be the Archean nucleus of the Gawler Craton supported by isotope data across the Eyre Peninsula (McAvaney et al., 2016). The upper-mid crustal conductor can be traced NS along the entire Eyre Peninsula through induction arrow studies and has been described as the Eyre Peninsula Conductivity Anomaly (White and Milligan, 1984). A closely-spaced Geomagnetic Depth Sounding profile across the southern tip of the Eyre Peninsula images a similar arcuate shaped structure as the one presented in Figure 2 (Thiel et al., 2005). Given the spatial relationship, we invoke a similar mechanism for the explanation of the upper crust conductivity anomalies to have formed during initial extension and formation of the shallow passive oceanic margin and accumulation of organic material in shallow marine sediments. Subsequent burial of the carbon-rich material in a compressive setting led to thermal metamorphism and precipitation of graphite along grain boundaries. Continued shearing and buckling of the fault zones led to concentration of the precipitates along shear zones (e.g. Willman et al., 2010) which were then subsequently pushed to the surface in some parts as seen today. The high degree of faulting also explains the enhanced seismicity in the seismic reflection profiles.

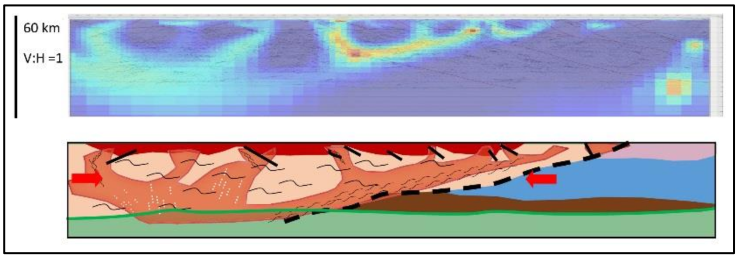

Figure 2: Eyre Peninsula (08GA-G1) east-west profile (see Figure 1 for location). Conductivity model overlain on seismic image (top) and cartoon interpretation of major crustal blocks based on seismic reflectivity and conductivity structure (bottom). Orange polygon shows how the conductivity structure is structurally controlled.

2. **Magmatic/Hydrothermal overprints**

   Despite conductive pathways in the Eucla-Gawler East and Olympic Dam profiles (Figure 3) being similar in nature, to a sub-vertical, conductive and non-reflective pathway in the Eucla-Gawler West profile (Figure 4), we attribute different geological processes to their formation. Commonalities in the lower crust between the two types are: mantle source, a Moho offset providing a locus for upward movement, apparent textural destruction in the lower crust (reduction in reflectivity) and a broad, diffuse signature. Key differences however, reside in the upper mantle and mid-upper crust, where different characteristics are observed in both the reflectivity and resistivity.

   i. **Underplating and mass melt transfer**

      The Eucla-Gawler West profile (Figure 3) displays a highly conductive upper mantle, the top of which correlates in part with the base of the seismic response (the interpreted Moho). At the top of the sub-vertical mantle conductor sits a highly conductive and reflective lower crustal unit which may be an underplate, or the

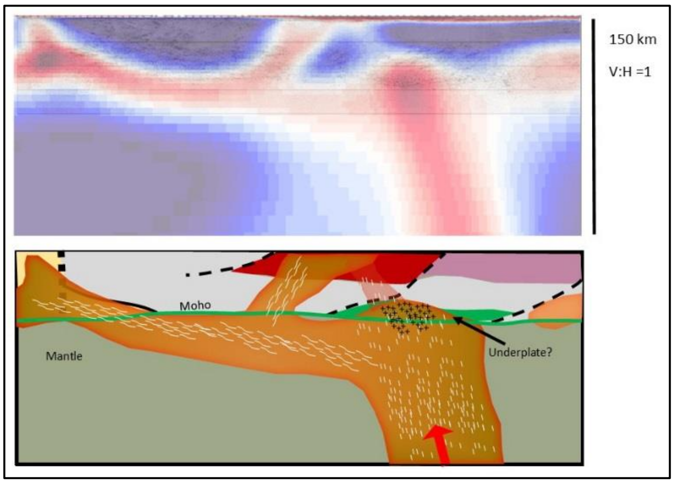

Figure 3: Eucla-Gawler West east-west profile (see Figure 1 for location). Conductivity model overlain on seismic image (top) and cartoon interpretation of major crustal blocks based on seismic reflectivity (bottom). Orange polygon shows how the conductivity structure correlates well with broad changes in seismic reflectivity.

product of a metasomatic reactions between this lower crust and upwelling melts. To the west of the sub-vertical mantle conductor sits a sub-horizontal lower crustal/upper mantle conductor that shallows to the west. This correlates with a region of low reflectivity, with a moderately sharp, perhaps sheared in places, upper margin with a more reflective mid-crust. We interpret this region to be an underplate. Perhaps a rare example of direct geophysical detection of such a feature (Thybo and Artemieva, 2013). In the central Eucla-Gawler West profile, a gradient or offset in the Moho has provided a focus for upward movement of presumed felsic melts, feeding voluminous magmatism at c. 1180 Ma in the Coompana Province (Spaggiari, 2015; Wise et al., 2015a). Due to the broad and diffuse character of this pathway, indicated by low reflectivity and high conductivity, we invoke mass transfer of melts from the base of the crust to the surface, without significant crustal residence times. This is reflected in relatively juvenile isotopic signatures from magmatic rocks of this age in the Coompana Province (Spaggiari, 2015).

ii. Introduction of magmatic volatiles/minor phase movement

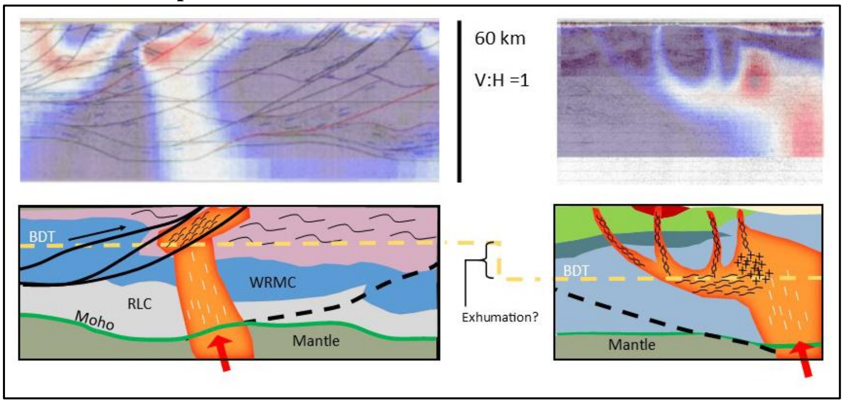

Figure 4: Eucla-Gawler East profile (left) and Olympic Dam profile (right). Mantle sourced conductivity overprinting and destroying earlier fabrics shown. Reduction in reflectivity in lower crust associated with upward-moving conductive phases.

We interpret crustal conductivity anomalies in the Olympic Dam and Eucla-Gawler East profiles (Figure 4) to be due to minor conductive phases, possibly the product of de-volatalization of a metasomatized sub-continental lithospheric mantle (SCLM). Steeply-dipping conductive and non-reflective pathways extend from the upper mantle into the mid crust, possibly controlled by the location of a regions of Moho topography. Ponding, or accumulation, of conductive material occurs in the mid crust at what we interpret to represent the brittle-ductile transition (BDT) at the time of fluid movement. Accumulation of conductive material at this crustal level is also associated with a relative increase in conductivity, as predicted by elementary analysis (Connolly and Podladchikov, 2004). The conductivity and reflectivity structure above the BDT is quite different between the two examples. In the Olympic Dam profile, lateral movement of conductive phases beneath a highly reflective mid-upper crustal layer is inferred, before punching through and producing 3-4 narrow, sub-vertical conductive and non-reflective pathways to the sub-surface. Pre-existing, sub-vertical fault or shear structures in seismic imagery are not obviously controlling such pathways, although this may be a function of their steep nature not being resolved by seismics.

In the Eucla-Gawler East example however, the conductivity and reflectivity structure above the BDT appears to be controlled by active deformation along west-dipping shear zones. Co-incident with inferred pathways of magmatic volatiles are anomalies in potential field imagery. A distinctive linear magnetic anomaly is present at the surface expression of the Karari Shear Zone, likely indicating the (re-)precipitation of magnetite during shearing (Thiel et al., 2015). Density responses are more evident in the case of inferred magmatic volatile pathways in the Olympic Dam profile, in some cases caused by hematite breccias (Skirrow, 2008) associated with iron-oxide copper gold mineralisation.

CONCLUSIONS

1. Changes in reflectivity and resistivity can signify crustal modification processes, of which we have discussed several examples. An interpretation approach using both techniques (seismic and MT) allows for much greater inference on both the tectonic regime at the time of introduction/redistribution of conducting phases, as well as the nature of melt/fluid movement itself.
2. Site spacing and processing methodologies - greater resolving power in mid-upper crust allows for true cross-cutting relations to be defined.
3. Links to mineralisation. There is a spatial coincidence between zones of interpreted magmatic/hydrothermal fluid flow events (imaged by both MT and seismic, as well as having distinctive potential field signatures) and zones of mineralization in the Olympic Dam region. Is this a cause/effect relationship? Can this be used in a targeting sense? Using the case of the Olympic Dam profile, it could be argued that only with an increased MT station spacing and variations in seismic processing that upper crustal features are observed.

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