Mapping Deep Electrical Conductivity Structure 

in the Mount Isa region, Northern Australia:

Implications for Mineral Prospectivity

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Abstract The Mount Isa Province in northern Australia is one of the world’s most strongly endowed regions for base metals and host to major iron–oxide–copper–gold (IOCG) deposits. The Carpentaria conductivity anomaly at the eastern margin of the province is a major electrical conductivity structure of the Australian continent. We use magnetotelluric data to image the crustal architecture in this highly mineralized region. The resistivity models reveal a number of prominent crustal-scale conductors, suggesting that the Carpentaria conductivity anomaly is likely caused by a series of isolated or interconnected bodies. These conductors confirm the position and geometry of the ancient Gidyea Suture zone, the eastern boundary of the Mount Isa Province, interpreted as a west-dipping subduction zone. The Carpentaria conductivity anomaly may record the activity of fluid dehydration involved during a subduction event, with the enhanced conductivity likely being caused by deformation or mineralization of graphitic or sulfidic rocks during orogenesis. The major iron oxide in the Ernest Henry IOCG deposit located in the hanging wall of the Gidyea Suture zone is magnetite, suggesting another possible conductive source. The distribution of known gold and copper deposits shows a close spatial correlation with the suture zone, suggesting that this structure is potentially a fundamental control on IOCG deposits in its vicinity. The implication is that crustal-penetrating structures act as potential pathways for fluid movement to form mineral deposits in the upper crust. The significance of mapping such structures using geophysics is highlighted for mineral exploration.

1. Introduction

The Mount Isa Province in northern Australia (Figure 1) is one of the world’s most prospective regions for minerals. It hosts three of the ten largest Zn–Pb deposits in the world (e.g., Huston et al., 2006), the world-class sediment-hosted Mount Isa copper deposit (Lilly et al., 2017), and the Ernest Henry iron–oxide–copper–gold (IOCG) deposit (Williams et al., 2005). The hypothesis that major electrical conductivity anomalies may define the location of fundamental tectonic boundaries (Gough, 1983; Gough et al., 1974; Tammemagi & Lilley, 1973) has led to numerous studies that aim to map the first-order conductivity structure of the Australian continent (see Wang et al., 1997, for a summary). The Carpentaria conductivity anomaly has been identified as one of the major conductivity structures of the Australian continent and was observed initially by a continent-wide magnetometer array study (Woods & Lilley, 1979), followed by further studies to explore its position and causative structures (Chamalaun et al., 1999; Lilley et al., 2003; Wang et al., 2014). These studies characterized the anomaly as a crustal-scale conductor with a north–south orientation, extending over a distance of more than 1,000 km southwards from the Gulf of Carpentaria. In its northern and central part it runs parallel to and largely coincides with the eastern margin of the exposed Mount Isa Province (Figure 2 inset). This margin, named the Gidyea Suture zone by Korsch et al. (2012), is a major crustal boundary separating the Mount Isa Province in the west from the Kowanyama Seismic Province in the east. Korsch et al. (2012) interpreted this zone to be an ancient (Paleoproterozoic or older), crustal-scale suture zone. Previous work suggested that the Gidyea Suture zone may broadly correspond to part of the Carpentaria conductivity anomaly mapped by Lilley et al. (2003). Here we investigate the spatial relationship between the conductivity anomaly and the crustal suture zone in greater detail.

Geophysical data, including Magnetotelluric (MT) data and deep seismic reflection data, were acquired over several years in the Mount Isa region by Geoscience Australia, in collaboration with the Geological Survey of...
Queensland. The most recent seismic and MT survey forms part of Geological Survey of Queensland's Mount Isa Geophysics Initiative Program, shown in Figure 2 (Donchak, 2014). Here, we discuss 2-D and 3-D resistivity models derived from the MT data to investigate the crustal architecture of this highly mineralized region. Particular attention is paid to characterization of the Carpentaria conductivity anomaly and the Gidyea Suture zone in the context of mineral prospectivity.

This latter point is of particular interest as crustal-penetrating structures and deep faults are potential pathways for metalliferous fluids to travel into upper crustal levels where mineralization occurs (e.g. Begg et al., 2010; Drummond et al., 2000; Heinson et al., 2018; Johnson et al., 2013; Willman et al., 2010). This has, for example, been recognized for the giant Olympic dam IOCG deposit in the Gawler Craton in South Australia, where the Elizabeth Creek Fault is imaged in seismic reflection data as a crustal-scale structure beneath the

Figure 1. Map showing the major provinces and basins in northwest Queensland and the location of deep seismic reflection lines collected since 1994. Location of the map is shown in the inset. NT = Northern Territory; NSW = New South Wales; QLD = Queensland; SA = South Australia; TAS = Tasmania; VIC = Victoria; WA = Western Australia.
deposit (Drummond et al., 2006; Neumann et al., 2010). Similarly, in the Archean Yilgarn Craton of Western Australia, the major gold, nickel, and iron deposits concentrate along major intracratonic boundaries (Dentith et al., 2018; Mole et al., 2015). In the Northern Territory of Australia, there is potential for Tennant Creek–Rover IOCG-U type deposits to be found in the general vicinity of the Atuckera Fault (Huston et al., 2011), interpreted as a deeply dipping crustal-scale fault (Korsch, Struckmeyer, et al., 2011). The inset shows the national conductivity model at a depth of 36 km by Wang et al. (2014), with the position of the Carpentaria conductivity anomaly and the location of the MT survey area. The red star marks the position of the Ernest Henry iron–oxide–copper–gold deposit.

Following these examples, a possible genetic link between the Gidyea Suture zone and the Ernest Henry IOCG deposit in its hanging wall (Figure 2a) warrants further investigation.

2. Geological Setting

The Mount Isa Province underwent a complex evolution from about 1,800 Ma to about 1,520 Ma, consisting of crustal thinning, continental rifting, and sedimentary basin formation, accompanied by magmatic intrusion and the formation of mid-crustal extensional shear zones at depth, along with significant intervals of crustal shortening (Gibson et al., 2008; Holcombe et al., 1991; Passchier, 1986; Passchier & Williams, 1989; Withnall & Hutton, 2013). Three periods of continental rifting of crystalline basement led to the formation of three vertically stacked sedimentary basins (1,790–1,740 Ma Leichhardt Basin, 1,730–1,640 Ma Calvert Basin, and 1,635–1,575 Ma Isa Basin; Jackson & Rawlings, 2000). The province is segmented by major, broadly north-south striking fault zones, which define a series of terranes including the Western Fold Belt and the Eastern Fold Belt, separated by older basement rocks of the Kalkadoon–Leichhardt Belt (Betts et al., 2006; Blake, 1987). Sedimentary and volcanic rocks in both fold belts were deposited in crustal-scale rifts, which were subject to deformation during the 1,740–1,710 Ma Leichhardt Event (Blaikie et al., 2017) and the 1,620–1,520 Ma Isan Orogeny, which shortened the province by up to 50% (Blake & Stewart, 1992; Drummond et al., 1998). For more details on the regional geology of the Mount

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Figure 2. Magnetotelluric (MT) surveys in the Mount Isa region (same area as in Figure 1) overlain on (a) the total magnetic intensity anomaly map of Australia, sixth edition (Nakamura & Milligan, 2015), with warm colors indicating magnetic highs and colder colors indicating magnetic lows and (b) Bouguer gravity anomaly map (Nakamura, 2016). Green triangles show the MT sites used in Lilley et al. (2003). The extent of the subsurface Millungera Basin is outlined (Korsch, Struckmeyer, et al., 2011). The inset shows the national conductivity model at a depth of 36 km by Wang et al. (2014), with the position of the Carpentaria conductivity anomaly and the location of the MT survey area. The red star marks the position of the Ernest Henry iron–oxide–copper–gold deposit.
Isa Province and basin history and evolution, see Blake (1987), Betts et al. (2006), Withnall and Hutton (2013), Gibson et al. (2016), and other references cited therein.

3. Materials and Methods

3.1. MT Data

In 2014, MT data and deep seismic reflection data were acquired along a 670-km transect in the southeastern Mount Isa region (Line 14GA-CF1, Figure 2). The transect extends from the eastern margin of Mount Isa Province to the Thomson Orogen, intersecting at least two known major crustal boundaries, namely, the Gidyea Suture zone (Korsch et al., 2012) and the Cork Fault (Hawkins & Harrison, 1978; Senior et al., 1978; Spampinato et al., 2015). Audio-MT (AMT) and Broadband MT (BBMT) data covering periods of 0.0001 to 3000 s were acquired at 138 stations with a site spacing between 2.5 and 5.0 km. Details of data acquisition and processing can be found in the released data package. Except in the dead bands (0.001–0.002 s for AMT and ~10 s for BBMT) and long periods data (>1,000 s), the soundings of the MT data show smooth continuous curves indicating reasonable quality (Figure 3).

In addition, a number of supplementary MT data sets have been reexamined here (Figure 2). In 2007, BBMT data (250 to 0.001 Hz) along the 07GA-IG1 deep seismic line were acquired at 42 sites spaced approximately 10 km apart (Henson et al., 2009). In 2009, BBMT data along Lines 06GA-M4, 06GA-M6, and Line M5 were collected from 153 stations with site spacings varying between ~1 and ~4 km. These data provide complementary information for characterizing the Carpentaria conductivity anomaly and Gidyea Suture zone.

3.2. Dimensionality Analysis

Dimensionality analyses of the MT response were undertaken using the phase tensor (Booker, 2014; Caldwell et al., 2004) and the ellipticity criterion (Becken & Burkhardt, 2004). The phase tensor can be graphically depicted as an ellipse. The phase tensor ellipticity indicates a 1-D structure when its value is less than 0.1. The skew angle (β) measuring the degree of asymmetry of the phase tensor is an indication of the three-dimensionality of the subsurface. Although strictly 2-D resistivity structure requires β be zero, a threshold of 3° is recommended by Caldwell et al. (2004). However, in case of real data, a threshold of 5° has been used as an acceptable approximation to the assumption of 2-D or quasi-2-D structure in prior and recent publications (e.g., Dentith et al., 2018; Heinson et al., 2018; Thiel et al., 2009). For this particular data set, we also use a threshold of 5°, in order to include more data for 2-D modeling. The potential 3-D effect in the data is examined by comparing with the 3-D model.

The phase tensor pseudosections for the MT responses along the main profile (14GA-CF1) are given in Figure 4, in which the phase tensor ellipses are colored by their ellipticities and skew angles, respectively. At short periods (<1 s) the phase ellipses at all stations are close to circular with low ellipticity, suggesting that shallow resistivity structures are approximately 1-D. Generally, the resistivity structure becomes 2-D or quasi-2-D at periods of 1–100 s, and up to 1,000 s with some sites showing 3-D effects at long periods. In particular, larger skew angles are observed between site 10540 and 10420 and some discrete sites. Data at periods greater than 1,000 s show predominantly 3-D structures.

The complementary data along Lines 07GA-IG1, 06GA-M4, 06GA-M6, and M5 indicate the MT responses in the broadband range are more affected by 3-D resistivity structures. The phase tensor sections for these lines are shown in the Supporting Information (Figures S1–S4). Therefore, the emphasis here is on the 3-D modeling approach and interpretation of the results. However, we have performed 2-D inversions for the main profile (14GA-CF1), which are briefly described below. Further details of directionality analysis and 2-D inversions are provided in the supporting information (Text S1–S3).

3.3. 2-D Data Inversion

Data inversion of the main profile (14GA-CF1) was firstly undertaken using the 2-D nonlinear conjugate gradient algorithm of Rodi and Mackie (2001, 2012) implemented in the WinGLink® software package. Based on the directionality analysis (Text S1), we divided the transect into three segments for 2-D inversion and interpretation, that is, NW, Central, and SE sections, separated by Site 11120 and Site 10550, respectively. The MT data were projected onto straight profiles perpendicular to the geoelectric strike (Figure 4), with data rotated to represent the transverse electric and the transverse magnetic mode.
A series of models were generated using various combinations of parameters and data subsets (transverse electric, transverse magnetic, and vertical magnetic transfer function [tipper]). Data of periods in the range of 0.001–1,000 s were inverted using a uniform 100 Ω m half space as the starting model, excluding data with 3-D effect at sites between 10540 and 10420. An optimal τ-value of 5 was chosen to control the balance between model roughness and model-data misfit. The final preferred models achieved root mean square misfits of 2.2 (NW), 2.8 (Central), and 2.9 (SE) with an error floor of 10% for apparent resistivity, 4% (~1°) for phase, and 2% for tipper where data are available (note, tipper data were not collected at some of the sites).

In the preferred resistivity models (Figure 5), the conductive near-surface layer ($\rho < 20 \Omega m$) representing the sedimentary basins is resolved by the AMT data. The NW model reveals a crustal-scale diamond-shaped...
Figure 4. Phase tensor sections of the magnetotelluric data along the main profile (14GA-CF1) plotted for every third site. Phase tensor ellipses are colored by (a) ellipticity and (b) skew value, indicating dimensionality. Rose diagrams show the dominant strike derived from the phase tensor and regional geology, plotted for the NW (left), Central (middle) and SE (right) sections. Data with larger skew angles at sites between 10540 and 10420 are excluded from the 2-D inversion.
Conductor ($\rho$ < 5 $\Omega$ m) labeled C1 extending to a depth of ~40 km. The Central model indicates two conductive bodies in the upper and middle crust, labeled C2 and C3. The most prominent feature is the Conductor C2 ($\rho$ < 5 $\Omega$ m) extending over a depth from 2–5 km to ~25 km. The SE model reveals a few discrete Conductors C5, C6, and probably C7 adjacent to the Cork Fault. Resistive areas ($\rho$ > ~1,000 $\Omega$ m) in the models include discrete small-scale zones (R1, R2, and R3) immediately beneath the near-surface conductive layer and large-scale resistive blocks, for example, R4 and R5.

### 3.4. 3-D Data Inversion

Dimensionality analysis shows the influence of 3-D structures reflected in the MT responses, particularly in the broadband frequency range of 10–1,000 s. It has been demonstrated by previous studies (e.g., Patro & Egbert, 2011; Siripunvaraporn et al., 2005) that more realistic results can be achieved using a 3-D inversion algorithm to interpret MT profile data. Therefore, 3-D data inversion was undertaken using the ModEM code (Egbert & Kelbert, 2012; Kelbert et al., 2014). We applied the standard minimum-structure nonlinear conjugate gradient algorithm for this study.

To improve 3-D modeling efficiency, the sites array was rotated 48° clockwise to align with the model grid, and the data were rotated counterclockwise according to the grid axis. This resulted in a significantly reduced number of cells. In the NW-SE direction, the model consisted of 260 cells with a size of 2 km and 9 padding cells (increases by a factor of 1.5) on both sides (total length of 1,030 km). In the NE-SW direction, the model consisted of 45 cells with a size of 2 km and 9 padding cells (increases by a factor of 1.5) on both sides (total length of 524 km). In the vertical direction, the first layer thickness was set as 10 m, and subsequent layer thickness was increased by a factor of 1.2 until the depth of the model reaches 345 km (greater than two times of the max skin depth). For consistency with the 2-D model parameterization, data of 30 periods in the range of 0.001–1,000 s were inverted using a uniform 100 $\Omega$ m half space as the starting model. The covariance factor of 0.2 was applied in all directions, which controls the model smoothness. We ran a number of sensitivity tests using various subsets of the data (e.g., impedance only, tipper only, and combined impedance and tipper). Error floors of 5% of $\sqrt{|Z_{xy}Z_{yx}|}$ were applied to each impedance tensor component, and an absolute value of 0.02 was specified for tipper where data are available.

The preferred 3-D model achieved a root mean square misfit value of 1.34 after 102 iterations. The result was extracted and projected onto a 60-km deep planar vertical surface generated from the MT sites along the transect (Figure 6). In comparison to the 2-D models, the 3-D model captures the major structural features, that is, conductive zones C1, C2, C3, C6 and resistive zones R1–R5, at similar locations where they were detected by the 2-D models. In addition, the 3-D model reveals a weak conductive zone (C4) at the transition zone of Mount Isa Province and Thomson Orogen (between Sites 10540 and 10420).

The same modeling procedure was applied to the data sets collected along seismic lines 07GA-IG1, 06GA-M6, and 06GA-M4, and MT Line M5, and the planar vertical surfaces to a depth of 60 km were extracted from the 3-D models (Figures 6 and 7). Most models detect a pronounced conductor dipping to the west, that is, Conductor C8 in the model for 07GA-IG1, Conductor C10 in the model for 06GA-M4, and Conductor C11 in the model for M5. These conductors essentially form part of the same conductor zone considering their position and proximity.

### 4. Interpretation and Discussion

#### 4.1. Robustness of Resistivity Structure Derived From 2-D and 3-D models

In practice, 2-D and 3-D inversion techniques can be used to complement each other for MT interpretation. 2-D inversion allows a much finer discretization of the subsurface and therefore better resolution of small-scale structures, whereas 3-D inversion is often used to interpret large-scale and complex 3-D subsurface structures (Tietze & Ritter, 2013). In the present study, the 2-D and 3-D models of the main profile (14GA-CF1) agree well in terms of recovery of major resistivity features, although differences can be observed in the size, position and shape of individual features (compare Figures 5 and 6). The two prominent conductors (C1 and C2) are evident in both models, as well as the conductor in the vicinity of the Cork Fault zone (C6). Another conductor (C3) around Site 10600 is also resolved in both models. Nevertheless, the Conductors C5 and C7 present in the 2-D models are vague in the 3-D model, with slightly higher conductivity values observed at the approximate locations. With respect to resistors, the 2-D and 3-D models agree...
remarkably well except for the location of R3. These agreements suggest that these features are robust in terms of representing the true earth resistivity structure.

Discrepancies between 2-D and 3-D results are usually attributed to the limitations of either 2-D or 3-D inversions. First, 2-D interpretation of MT data may be affected by 3-D electrical structures, as shown in dimensionality analysis. Second, the 2-D model sections are projected profiles perpendicular to the geoelectric strike; thus, the locations of the MT sites have shifted. For example, the location of R3 is different in the 2-D and 3-D models. Finally, there might be artifacts produced by 2-D models due to unreliable...
regional strike used for 2-D inversion. This is related to the fact that determination of a single dominant strike can be problematic due to local distortion and noise in the data (Jones & Groom, 1993) and also due to variations in different sites and periods of a data set. Within a complex 3-D medium, electric and magnetic fields are elliptically polarized and non-orthogonal (Becken et al., 2008), and, hence, a standard 3-D inversion utilizes the four impedance tensor components, all of which contain information about the subsurface.

Note that the inversion algorithms of both 2-D and 3-D applied in this study do not account for electrical anisotropy in the MT responses (Heise & Pous, 2001; Wannamaker, 2005), and therefore, the resistivity models may contain artefacts if high anisotropy in electrical conductivity is present in the structure (Jones et al., 1997; Meqbel et al., 2014; Patro & Egbert, 2011), for example, due to faulting or fracturing associated with conductive material (Kirkby et al., 2017). Identification of anisotropy in the MT data is difficult, and inversion of anisotropic data is beyond the scope of this study.

4.2. Sedimentary Successions Represented in the MT Models

At the surface, the Mount Isa Province is surrounded by the Mesozoic Eromanga and Carpentaria basins and the Neoproterozoic-Paleozoic Georgina Basin (Figure 1). The near-surface conductive layer in the MT models represents the sedimentary basins reasonably well in terms of resistivity and thickness (Figure 5). The resistivity is in the range of 1–20 Ω m, which agrees well with the estimates of sedimentary basins (Hermance, 1995). The sedimentary succession northwest of Site 10980 is about 300–500 m deep in the Carpentaria Basin, and thickens to the southeast reaching a depth of ~1,000 m in the Eromanga Basin. This is consistent with the depth extent compiled from drill hole data and estimates from other geophysical data (Brown et al., 2012; Meixner, 2009; Munson et al., 2013; Senior et al., 1978; Spence & Finlayson, 1983).
The Millungera Basin was recently discovered in the area beneath the shallow cover of the Carpentaria Basin and above the Kowanyama Seismic Province (Figure 2, Korsch, Struckmeyer, et al., 2011). The resistivity of rocks in the Millungera Basin is expected to be higher than that of the younger sedimentary basins because drillhole samples show that the rocks lack porosity and are predominantly pink to red, quartzose sandstones to quartzites with minor micaeous siltstones, and clay bands. Korsch, Struckmeyer, et al. (2011) also interpreted several granites immediately below the Millungera Basin, which may coincide with the discrete resistive zones detected in the MT models (R1, R2, and R3; Figures 5 and 6).

4.3. Spatial Correlation Between the Gidyea Suture Zone and the Carpentaria Conductivity Anomaly

The position of the Gidyea Suture zone was previously defined using potential field data (gravity and magnetics) and seismic data (Korsch et al., 2012; Korsch & Doublier, 2016; Shaw et al., 1995). The suture zone is characterized by low-amplitude magnetic and gravity anomalies with an approximately north–south strike (Figure 2). It is imaged by seismic reflection data along Line 07GA-IG1 as a broad zone of low reflectivity approximately 10 km across, dipping about 40° to the southwest (Figure 3b, Korsch et al., 2012). Results from the present study further confirm the position and geometry of this suture. Conductors C8, C11, and C10 dip to the west, and their eastern limit approximately coincides with the position of the Gidyea Suture zone on the surface (Figure 6). The cross section of the conductive zone is about 10–15 km wide and the marked resistivity contrast extends to the lower crust, which agrees with the seismic expression.

Continental scale magnetometer array studies (site spacing of ~275 km) suggest that the Carpentaria conductivity anomaly runs parallel to the eastern margin of the exposed Mount Isa Province, possibly extending to the north over a distance of more than 1,000 km (Chamalaun & Barton, 1993; Wang et al., 2014; Wang & Lilley, 1999). The high-resolution MT models, presented here (Figures 6 and 7), reveal the presence of several conductors, with Conductors C1, C8, C11, and C10 forming one prominent conductive zone and Conductors C2, C9, C12, and C16 forming another prominent conductive zone. These two conductive zones are interconnected in the north (models of 14GA-CF1 and 07GA-IG1), but are separated by a resistive zone in the south (models of M5 and 06GA-M4). This is why they are labeled separately. These conductors essentially form part of the Carpentaria conductivity anomaly, indicating that the anomaly is unlikely caused by a single continuous body but by a series of isolated or interconnected bodies, whose combined responses result in the large-scale conductive zone mapped by the continental scale magnetometer array studies.

4.4. Interpretation of the Carpentaria Conductivity Anomaly

Crustal conductivity anomalies must be interpreted with care due to a variety of possible sources such as aqueous fluids, partial melts, or metallic compounds (Becken et al., 2011; Ferguson et al., 1999; Jones, 1992; Myer et al., 2013). Nevertheless, the presence of fluids or partial melts is unlikely to explain the crustal-scale Carpentaria conductivity anomaly (which extends to at least 45 km depth on Line 14GA-CF1, Figure 6) because the porosity and brine conductivity would have to be unreasonably high at mid-crustal depths (Archie, 1942; Heinson et al., 2005; Storvoll et al., 2005) and because present-day conductive slab dehydration fluids or magmatism related to an ancient suture zone of Paleoproterozoic age or older would not be expected to still exist. Previously, it has been proposed that the cause of enhanced conductivity in tectonically stable lithosphere is likely to be related to interconnected conductive minerals (Bedrosian, 2007; Selway, 2014; Yardley & Valley, 1997). Some possible sources include iron sulfides (such as pyrite and pyrrhotite), iron oxides (magnetite), and graphite (e.g., Corseri et al., 2017; Robertson et al., 2015; Selway, 2019).

For the Carpentaria conductivity anomaly, Boerner et al. (1996) and Lilley et al. (2003) attributed enhanced conductivity to deformation or mineralization of graphitic or sulfidic sedimentary rocks associated with the collisional process during orogenesis. The westward dip of the Gidyea Suture zone infers that plate convergence on a west-dipping subduction zone resulted in collision between the Mount Isa Province and the Numil Seismic Province (which occurs in the middle to lower crust beneath the Kowanyama Seismic Province; Korsch et al., 2012). Magmatic arc-like geochemical signatures identified in the Kalkadoon–Leichhardt Belt of the Mount Isa Province (McDonald et al., 1997) support this interpretation. Therefore, we speculate that this conductive zone may record the activity of dehydration fluids or magmatism involved during a Proterozoic subduction event, when fluids rising off the subducting slab and its overlying mantle wedge entered the crust. The conductivity anomaly likely preserves a signature of refertilization of the lithosphere during subduction-related metasomatism and may have been enhanced during the subsequent Isan
Orogeny, which is recognized throughout wide parts of the province, and shows a complex history involving both north–south and east–west shortening (Betts et al., 2006; Korsch et al., 2012; O’Dea et al., 1997). Since the Carpentaria Conductivity Anomaly is crustal scale and associated with a fossil subduction zone in a now tectonically stable environment, we prefer an interpretation of grain-boundary graphite films, as suggested by Selway (2019) for strong conductors (less than \( \sim 10 \, \Omega \, \text{m} \)) in stable lithosphere. The favorable pressure–temperature conditions for graphite films to stay interconnected to form a conductor is mainly within the crust, but not at shallow depths nor at depths greater than the uppermost mantle. Sulfides are unlikely to form significant crustal conductors because of their insufficient volume in Earth composition (Allègre et al., 1995). Therefore, such minerals may only contribute to discrete, localized features in the upper crust. Another potential source could be the presence of magnetite as the conductive mineral, given the spatial relationship between the Gidyea Suture zone and the Ernest Henry IOCG deposit in its hanging wall (Figure 2a). The major iron oxide in the breccia-hosted Ernest Henry IOCG is magnetite, with associated hydrothermal K-feldspar, biotite, and carbonate, and copper mineralization at Ernest Henry is primarily in the form of chalcopyrite (Williams et al., 2005). It is compatible with the potential field magnetic data, where the area as a whole is characterized by a high magnetic response (Figure 2a).

Similar interpretations of conductivity anomalies can be found in other case studies. For example, Robertson et al. (2015) interpreted low-resistivity pathways to be serpentinite with magnetite in mafic–ultramafic rocks created by fluids released from the upper mantle during a Cambrian subduction in southeast Australia. In another example, Heinson et al. (2018) attributed the conductive region along the margin of the Mesoarchean to Mesoproterozoic Gawler Craton (South Australia) to grain-boundary sulfides, which coincide with the IOCG-U Olympic Dam deposit. Elsewhere, Jones (1992) attributed enhanced conductivity to graphite precipitated from fluids moving through the fault zone on the strike-slip Fraser Fault in British Columbia, Canada. Likewise, the North American Central Plains conductivity anomaly consists of a series of discrete conductors associated with sulfides concentrating along fold hinges, and the conductive bodies were emplaced as part of Paleoproterozoic subduction and collision-related processes (Camfield & Gough, 1977; Jones et al., 1997; Jones et al., 2005).

4.5. Implications of Other Conductors for Regional Tectonics

In the Mount Isa Province, the Pilgrim Fault is a major north–south striking structure, that appears to define the western limit of the conductive zone on Line 06GA-M4 (Conductor C10), although the anomaly on Line 07GA-IG1 (Conductor C8, Figure 6) appears to extend to the west of the fault. On Line 06GA-M6, Conductor C13 occurs in the hanging wall of the Pilgrim Fault, but does not have the horizontal extent of the conductive zone farther to the north, implying that this conductive zone diminishes rapidly to the south (Figures 6 and 7).

C14 is a small conductor on Line 06GA-M6 located approximately midway between the Pilgrim Fault and the Gidyea Suture zone (Figure 6). This conductor appears to be associated with a braided network of unnamed faults (lower right inset in Figure 6). In this vicinity, Korsch et al. (2008) interpreted a network of faults to be east dipping. The locations of the Broken Hill-type Pegmont mineral deposit and the IOCG Osborne mineral deposit appear to be closely aligned with the eastern limit of the conductor and the easternmost fault in this system and occur in the hanging wall of this fault.

At the eastern end of deep seismic reflection Line 07GA-IG1, a series of seismic reflectors that extended into the mantle was interpreted by Korsch et al. (2012) as the Rowe Fossil subduction zone (Figure 7). The 3-D resistivity model derived from the MT data shows the presence of a strong conductive zone (Conductor C15), which coincides with part of the Rowe Fossil subduction zone that occurs within the middle to lower crust (Figures 6 and 7). Therefore, it is possible that this conductive zone also may record the activity of dehydration fluids or magmatism involved during a subduction event, where fluids rising off the subducting slab migrated into the lower to middle crust. Korsch et al. (2012) considered that this fossil subduction zone was older than 1,700 Ma, whereas Nordsvan et al. (2018) put it at 1,650–1,600 Ma. Nevertheless, the strong conductive anomalies at both the Gidyea Suture zone and the Rowe Fossil subduction zone suggest that MT signatures of fossil subduction zones may be characterized by strong conductive anomalies.

Historically, the Cork Fault marks the tectonic boundary between the cratonicized Proterozoic Mount Isa Province (Betts et al., 2006) and the Phanerozoic Thomson Orogen (Murray & Kirkegaard, 1978; Spampinato et al., 2015). The Cork Fault dips to the southeast, and its surface position on Figure 8 is...
based on field mapping and interpretation of potential field data and shallow seismic reflection data (Hawkins & Harrison, 1978; Senior et al., 1978; Spampinato et al., 2015). The fault is considered a major lithospheric structure that possibly developed during initial N-S to NNW-SSE extension in the Mesoproterozoic and may have penetrated the entire crust during the Neoproterozoic Rodinia breakup and also during the Phanerozoic evolution of the Tasmanides (Finlayson & Leven, 1987; Passmore & Sexton, 1984). The MT data along Line 14GA-CF1 image the deep crustal architecture of the Cork Fault and suggests that it is a crustal-scale fault dipping steeply to the southeast (Figure 8). A large resistive anomaly (R4), approximately 50 km across, occurs immediately to the north of the fault and extends to the base of the crust. It also appears to extend to the south for approximately 10 km beyond the fault, and this could be a result of the spacing of the MT stations of ~5 km. The conductive zone (C6) to the south of the Cork Fault and the resistive crust of the Thomson Orogen (R5) farther south suggest the possibility of a major crustal boundary, with an apparent dip to the southeast within the Thomson Orogen (labeled D on Figure 8).

Although the previously known structures, Gidyea Suture zone and Cork Fault, on Line 14GA-CF1 are related to MT anomalies, the MT model in Figure 8 can also be used to subdivide the crust into several discrete structural blocks. Korsch et al. (2012) divided the crust to the east of the Mount Isa Province into the Kowanyama Seismic Province in the upper crust and the Numil Seismic Province in the middle and lower crust. Based on the interpretation of Korsch and Doublier (2016), we infer that these seismic provinces extend from the Gidyea Suture zone to the Cork Fault (Figure 8). The 3-D resistivity model of Line 14GA-CF1 shows significant variations in conductivity of the crust between the Gidyea Suture zone and the Cork Fault. Thus, based on the MT model, it is possible to subdivide the crust into at least four discrete units, separated by boundaries labeled A, B, and C in Figure 8. Boundaries A and C appear to have apparent dips to the southeast, whereas the orientation of boundary B is ambiguous and could have a dip to the northwest.

5. Implications for Mineral Exploration

Crustal-penetrating structures, including major crustal boundaries and deep faults, represent important conduits by facilitating transport of metalliferous fluids from the lower crust/upper mantle into the upper crust to form major mineral systems (e.g., Drummond et al., 2000; Johnson et al., 2013; Willman et al., 2010). Conductive crustal pathways may mark the prevailing alteration from mineralizing fluid migration through zones of weakness and often show a spatial correlation with mineral occurrences in the upper crust (e.g., Dennis et al., 2011; Heinson et al., 2006; Robertson et al., 2015). A close spatial relationship between major crustal boundaries (Korsch & Doublier, 2016) and certain types of mineral systems, such as lode gold deposits (Groves et al., 1989), IOCG (Groves et al., 2010), and orthomagmatic Ni-Cu deposits (Begg et al., 2010), has been observed. In fact, the majority of these types of deposits appear to form during periods when collisions, basin inversions, and regional contraction are dominant (Begg et al., 2010).
The Mount Isa Province is one of the major Precambrian elements of the Australian continent. Precambrian deposits are found to be the dominant members of the IOCG group, in terms of both copper and gold resources (Groves et al., 2010). Shown in Figure 9, the distribution of most of the gold and copper deposits in the Eastern Fold Belt appears to be in a close proximity to the Gidyea Suture zone and other internal major faults (Quamby Fault, Pilgrim Fault, and Cloncurry Fault). As suggested by Huston et al. (2009), the Gidyea Suture zone has the potential to be a fundamental control on the Ernest Henry IOCG and other IOCG deposits in its vicinity. A recent 3-D resistivity model derived from MT data collected in the same area detected two prominent conductors in the upper crust of the Mount Isa Province that are associated with mineral deposits in the Ernest Henry mining complex (Wang et al., 2018). We speculate that there is further potential for the

Figure 9. The major mineral deposits and Ernest Henry IOCG deposit (red star) overlain on the regional Bouguer gravity anomaly map (Nakamura, 2016) marked with the major crustal boundaries (Gidyea Suture zone and Cork Fault) and major faults (Quamby Fault, Pilgrim Fault, and Cloncurry Fault) in the Eastern Fold Belt.
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6. Conclusions

New geophysical data, including MT data and seismic reflection data, were acquired in the Mount Isa region. The MT data are used to image the crustal architecture, and the results provide important insights into the correlation between crustal-scale fluid pathways and possible mineral occurrences.

2-D and 3-D resistivity models derived from the MT data reveal a number of prominent crustal-scale conductors, suggesting that the Carpentaria conductivity anomaly is unlikely caused by a single continuous body but by a series of isolated or interconnected bodies. The conductors confirm the position and geometry of the ancient Gidyea Suture zone, which is a major crustal boundary approximately 10 km wide, interpreted as a west-dipping subduction zone. The Carpentaria conductivity anomaly may record the activity of fluid dehydration involved during a subduction event, with the enhanced conductivity being likely caused by deformation or mineralization of graphitic or sulfidic rocks during orogenesis. The major iron oxide in the Ernest Henry IOCG deposit located in the hanging wall of the Gidyea Suture zone is magnetite, suggesting another possible conductive source. The distribution of known gold and copper deposits in the Mount Isa Province appears to be related to the Gidyea Suture zone and other significant faults within the eastern part of the province, suggesting that this suture has the potential to be a fundamental control on IOCG deposits in its vicinity. Our results support the scenario that conductive crustal structures including major crustal boundaries and deep faults represent important conduits that facilitate fluid transport from the lower crust/upper mantle into the upper crust to form major mineral systems. Therefore, mapping such structures in the subsurface, using geophysical data such as MT and deep seismic reflection methods, provides critical information for undiscovered mineral systems in greenfield areas.

discovery of mineral deposits in the hanging walls of the major structures, such as the Gidyea Suture zone, the Pilgrim Fault, Quamby Fault, and Cloncurry Fault. From a mineral exploration perspective, the importance of mapping deeply penetrating structures is highlighted because such structures may provide an effective pathway by linking the lower, fertile source regions with depositional sites in the upper crust. Therefore, they help focus the search for undiscovered mineral systems in greenfield areas (Korsch & Doublier, 2016). In contrast to the Mount Isa Province and Gidyea Suture zone, no major mineral deposits associated with Cork Fault have been found to date. As Groves et al. (2010) pointed out, smaller and rarer Phanerozoic IOCG deposits are thought to have formed in tectonic settings similar to those in the Precambrian where conditions favor the generation of giant IOCG deposits. A wide range of settings have been proposed, including intracontinental settings (Hitzman et al., 1992), orogenic and subduction-related continental margin settings (Hitzman, 2000; Sillitoe, 2003), and plume-modified orogenic setting (Betts et al., 2009).
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