The Carpentaria Electrical Conductivity Anomaly, Queensland, as a major structure in the Australian Plate

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The Carpentaria Conductivity Anomaly of western Queensland is a major element in the electrical conductivity structure of the Australian continent. Investigation of it is significant both for its own sake, and as a case history in the general understanding of continental conductivity structure. Following its earlier discovery by reconnaissance magnetometers arrays, detailed magnetotelluric observations were carried out in 1997 along a transect crossing the anomaly, between Cloncurry and Julia Creek. The magnetotelluric results define a good conductor within the crust beneath the sediments of the Eromanga Basin. The conductor extends over a depth range of tens of kilometres. This structure, evidently shown also by aeromagnetic and gravity data, is interpreted as the eastern boundary of the Mt Isa Block at a plate suture, which was later covered by the sediments of the Eromanga Basin. Seismic tomographic results show a major gradient in seismic wave-speed in the region. It appears the potential field, electromagnetic and seismic methods have detected different characteristics of the same geologic structure, with complementary results. The electromagnetic results, new to this paper, define horizontal position well, and give evidence of highly-conducting material from the crust to a depth of tens of km. The seismic results extend the depth of the boundary into the upper mantle. The case history supports the hypothesis that the major conductivity anomalies of the geomagnetic deep-sounding method mark continental sutures, of fundamental significance in recording the creation of continents.

KEY WORDS: electrical conductivity, magnetotelluric method, geomagnetic deep sounding, Mt Isa Block, Eromanga Basin, plate suture.

INTRODUCTION

Electrical conductivity is a physical property of rocks which varies by orders of magnitude both laterally and vertically in the Earth. It can be sensed by observing, and so exploiting, the processes of natural electromagnetic induction which take place in the Earth and its oceans. From the point of view of the structure, evolution and dynamics of a continent, the most interesting features of electrical conductivity are the electrical conductivity anomalies of geomagnetic deep sounding (GDS); these are elongate features which must indicate regions of a continent where the electrical conductivity is unusually high (Parkinson 1983). The present paper will be concerned first with regional GDS, a method in which observations are made with arrays of recording magnetometers which act as temporary magnetic observatories.

Secondarily this paper will be concerned with the detailed investigation of GDS results using magnetotellurics (MT), in a topical example which illustrates the significance of major electrical conductivity structures in the Australian continent. The paper describes the results of a detailed MT study in western Queensland, across the Carpentaria Conductivity Anomaly. The magnetotelluric study followed a regional magnetometer array study (Chamalaun et al. 1999), which in turn had followed a continent-wide magnetometer array study (Chamalaun & Barton 1993), and earlier reconnaissance (Woods & Lilley 1979) and detailed (Woods & Lilley 1980) magnetometer array studies in Queensland. These experiments form successive steps in the detection of an electrical conductivity anomaly, its subsequent delineation, and the investigation of its geological setting.

The work reported in this paper begins with the surface position of the conductivity anomaly known to within 50 km, and its character known to be approximately two-dimensional, and of north-south strike. The conductivity anomaly occurs east of the outcropping part of the Mt Isa Block, in an area where the surface rocks are the sediments of the Eromanga
A motivation of the present study has been the hypothesis that major conductivity anomalies may mark old plate margins (Gough 1983). This idea was a driving reason for the first magnetometer array studies in Australia (Gough et al. 1974), and associated MT studies (Tammemagi & Lilley 1973). The hypothesis is found to be well-supported by the present study.

**CONTINENT-WIDE PATTERN OF CONDUCTIVITY STRUCTURES**

Geomagnetic deep sounding studies have defined six or seven major conductive structures in the Australian continent. These structures, marked on Figure 1, represent the first-order conductivity anomalies of the Australian Plate. In addition, the effects of the highly-conducting sea water are evident around the Australian continent, to a distance inland of some hundreds of km (Corkery & Lilley 1994; Wang & Lilley 1999). The results of Figure 1 have come largely from the interpretation of individual magnetometer array studies, and from the Australia-Wide Array of Geomagnetic Stations, AWAGS, (Chamalaun & Barton 1993). A more integrated interpretation of magnetometer array data has also been obtained by Wang & Lilley (1999) using an inversion process based on thin-sheet modelling. In this latter work the results of multiple GDS studies were fitted simultaneously, by adjusting the parameters of a model which comprised a spatially-variable upper crust, above a layered lower crust and mantle. The result of this inversion is shown in Figure 2. The correspondence between the conductors marked on Figure 1, and the structure shown on Figure 2, is clearly evident.

Major electrical conductivity anomalies of other continents have been interpreted as defining the location of fundamental tectonic boundaries. For example, the North American Central Plains (NACP) Conductivity Anomaly, which runs from Wyoming to Hudson Bay, defines the location of the Trans Hudson Orogen, a Proterozoic Orogenic Belt lying between older, Archean, cratons (Camfield & Gough 1977; Jones 1993). The high conductivity in the NACP and other major conductors has been interpreted as caused by electric conduction in rocks containing either sulphides or graphite, e.g. Jones & Craven (1990); Jones et al. (1997). Such rocks can form when sediments, deposited in oceanic settings, are deformed and metamorphosed during subsequent orogenesis (Boerner et al. 1996).

**ELECTROMAGNETIC METHODS**

**Geomagnetic deep sounding, and induction arrow response**

The geomagnetic deep-sounding method involves the separation of the time-varying magnetic fields of a causative source, external to the Earth, from those associated with induced currents flowing within the Earth. For locations in mid-latitudes, where the source fields are regionally uniform, the vertical component of the magnetic field variations is due almost entirely to the internal currents. An analysis of the relationship between the vertical and horizontal components of the time-varying magnetic field thus provides information on the internal electrical conductivity structure.

An induction arrow, as will be shown in Figure 3 below, is a graphical representation of the transfer function between the horizontal magnetic field components, and the vertical magnetic field component. Arrows are plotted to point towards conductors or more conductive parts of the Earth (Parkinson 1983). Their length is a function of the conductivity contrast, and also decreases with distance from the conductor. Because the
The magnetotelluric method is based on measurements of the time variations of horizontal components of the magnetic field \( H \) and the electric field \( E \). In natural-source MT surveys these signals are caused by magnetospheric and ionospheric sources. Depth information is obtained in MT surveys by analysis of the response as a function of period. Short-period MT signals (10\(^{-4}\) to 10\(^{-3}\) s) penetrate tens to hundreds of metres into the upper crust, whereas long-period signals (10\(^3\) to 10\(^4\) s) penetrate 100 km or more, into the upper mantle. An MT analysis usually commences with calculation of the MT impedance. This quantity is the ratio, in the frequency-domain, of horizontal electric and magnetic field components which are orthogonal:

\[
Z_{xy}(\omega) = \frac{E_x(\omega)}{H_y(\omega)}
\]  

Here \( Z_{xy}(\omega) \) denotes an element of \( Z \) the impedance tensor, \( (x,y) \) denotes the orthogonal components of horizontal direction, and \( \omega \) denotes angular frequency.

In general, the electric and magnetic fields are measured in both horizontal directions, allowing definition of four components of the impedance (now taking frequency dependence as understood):

\[
Z = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix}
\]  

For a one-dimensional (1D) horizontally-layered conductivity structure, the diagonal impedance-matrix terms are zero, \( Z_{xx} = Z_{yy} = 0 \), and off-diagonal terms differ only in sign:

\[
Z_{xy} = -Z_{yx}
\]

For a two-dimensional (2D) structure, in which conductivity is invariant in one horizontal direction, the diagonal terms will be zero if the EM fields are defined in a coordinate system orthogonal to the strike of the structure. In this case the impedance component for the electric field parallel to strike, called the transverse electric (TE) mode, will differ from the component with the electric field perpendicular to strike, the transverse magnetic (TM) mode.

If the impedance is measured at an arbitrary orientation, the angle required to rotate the measurements into TE and TM modes can be determined from the impedance tensor. The impedance data can thus be used to determine the geoelectric strike of a 2D conductivity structure. For a three-dimensional (3D) conductivity structure, the impedance will have a more complex form, but is often presented after rotation to the best-fitting 2D form.

For 2D and 3D data, some form of representative impedance value is often taken as the MT response. Such a value combines the components of an impedance matrix, to provide a response which can be interpreted using 1D methods. The resulting conductivity structure will be an approximation to the true structure. In this paper the central impedance \( Z_c \) of Lilley (1993) is used. Denoting by subscripts \( r \) and \( q \) the real and quadrature parts of a complex quantity, central impedance is defined as

\[
Z_c = Z_{cr} + iZ_{cq}
\]

with the real part \( Z_{cr} \) given by

\[
Z_{cr} = \sqrt{(Z_{xx} + Z_{yy})^2 + (Z_{xy} - Z_{yx})^2}
\]

and the quadrature (or imaginary) part \( Z_{cq} \) given by

\[
Z_{cq} = \sqrt{(Z_{xx} + Z_{yy})^2 + (Z_{xy} - Z_{yx})^2}
\]

**Apparent resistivity**

The magnitude of the MT impedance at frequency \( \omega \) is commonly expressed in terms of the apparent resistivity \( \rho_a \) using the relationship:

\[
\rho_a = \frac{1}{\omega \mu} \left| Z_{xy} \right|^2
\]

where \( \left| Z_{xy} \right| \) is the absolute value of the complex impedance element \( Z_{xy} \).

The apparent resistivity is a weighted average over the penetration depth of the signals. It equals the
resistivity of a uniform half-space which possesses the same response as the observed datum. Magnetotelluric response is commonly specified in terms of the apparent resistivity and the impedance phase. The latter quantity, the phase lead of the measured electric field over the measured magnetic field, also provides important information on the conductivity structure. For MT measurements made over a uniform half-space the phase will equal 45°. For 1D and 2D structures the phase lies between 0° and 90°, and also for most 3D structures it lies in this range. The phase response provides an indication of the gradient of conductivity with depth, at the penetration depth. Phase values exceeding 45° indicate that conductivity is increasing with depth, whereas phase values less than 45° indicate that conductivity is decreasing with depth.

Two-dimensional MT apparent resistivity and phase responses are often presented in the form of pseudosections. These diagrams show site location on the horizontal axis, period on the vertical axis (increasing down the page), and the value of apparent resistivity or phase given by contours. The depth of penetration of MT signals increases with increasing period, so an apparent-resistivity pseudosection will correspond to a smoothed form of the true resistivity-versus-depth section.

Galvanic distortion of the magnetotelluric response

Electric charge accumulation on near-surface (local) heterogeneities can distort the measured MT response, so that it no longer accurately represents the larger-scale (regional) conductivity structure. If the dimensions of the heterogeneity are much smaller than signal penetration into the surrounding material, the distortion will be approximately galvanic, and will affect mainly the electric field response. In the general case, galvanic distortion results in the mixing of impedance tensor terms, a situation commonly referred to as MT tensor distortion. In the case of 2D regional structure with local distortion, if the coordinate system for the data is aligned with the regional strike, the phase of the TE and TM impedance terms will not be distorted.

Over the last decade MT processing methods have advanced considerably and it is now routinely possible to remove, or at least reduce, galvanic tensor distortion. A common tensor-decomposition method is Groom-Bailey (GB) decomposition (Groom & Bailey 1989; Groom et al. 1993). This method involves fitting observed MT data with a model that is based on galvanic electric-field distortion of a 1D or 2D regional MT response. The galvanic distortion at each frequency is characterized by two parameters: the shear, which provides a measure of the local polarization of the electric field response, and the twist, which provides a measure of its local rotation.

The shear angle defined in the GB decomposition provides a useful measure of the degree of distortion (although it will not correctly characterize the distortion in unusual cases involving only rotation and no polarization of the electric field). Shear angles close to zero (< 10°) indicate minimal polarization of the local electric field and very low distortion, whereas angles in the range 10°-30° indicate moderate levels of distortion. For sites with low to moderate distortion, it is usually possible to recover good estimates of the regional TE and TM responses. Shear angles of 30° - 45° characterize strong distortion, and at sites with this level of shear it is commonly difficult to recover the two regional impedance values. A maximum shear angle of 45° means that the local electric field is completely polarized.

Tensor decomposition methods cannot resolve a component of galvanic distortion called static shift. The static shift causes an independent scaling of the TE and TM impedance magnitudes and the corresponding apparent resistivity values. In the GB decomposition model, static shift is parameterized in terms of a site gain, which affects both the TE and TM components, and an anisotropy, which causes a separation of the TE and TM impedance magnitudes.

DETAILED MT STUDY OF THE CARPENTARIA CONDUCTIVITY ANOMALY

Geology and geophysics of the Mt Isa Block and its eastern margin

The position of the Carpentaria Conductivity Anomaly was determined in 1995 by a magnetometer array study covering (in two deployments) a zone across north Queensland (Chamalaun et al. 1999). The results of the 1995 magnetometer array study are summarised in Figure 3. The Carpentaria Conductivity Anomaly is defined over a distance of more than 1000 km by a reversal in the real induction arrow response. It runs north from a location south of the Mt Isa Block, parallel to the eastern margin of the exposed Block, and appears to extend into the Gulf of Carpentaria. The location of the anomaly is defined by magnetometer stations of order 100 km apart so its position is known to an accuracy of about 50 km.

The Mt Isa Block is a major Precambrian element of the Australian continent. It is surrounded by the Mesozoic sedimentary rocks of the Eromanga Basin, the Georgina Basin, and the Carpentaria Basin (Figure 3). Discussions of the regional geological framework of the area may be found in the Denmead et al. (1974) volumes, and subsequent literature on the Tasman Fold Belt. Early studies of the geology of the Mt Isa Block and surrounding areas are synthesised in Blake (1987) and Stewart & Blake (1992). More recent geological studies include that of Southgate (2000), and accompanying papers in a special volume on the Carpentaria - Mt Isa Zinc Belt. Geophysical-based studies of the regional tectonics have included interpretation of the potential field data by Wellman (1992), and seismic reflection and refraction profiling as synthesised by Drummond et al. (1998).

The Mt Isa Block is of Proterozoic age. It is subdivided by major strike-slip faults or fault zones, which strike north-south, into a series of distinct terranes, including (from west to east) the Western Fold Belt, the Kalkadoon Leichhardt Belt, and the Eastern Fold Belt. Further subdivisions of these belts are discussed in Blake & Stewart (1992). The Kalkadoon Leichhardt Belt contains interpreted basement rocks of the belt, which were
deformed and metamorphosed during the 1900-1870 Ma Barramundi Orogeny. The younger Proterozoic rocks, which are subdivided into three cover sequences, are dominated by sediments and volcanics interpreted to have been deposited in rift environments. These rocks were subsequently deformed during the 1620-1520 Ma Isan Orogeny, and shortened by as much as 50% (Blake & Stewart 1992; Drummond et al. 1998). The Mt Isa Block is prospective for base metals and gold, and has important economic significance. The Leichardt River Fault Trough in the Western Fold Belt hosts the majority of the large tonnage lead and zinc deposits in the Mt Isa Block, and the Eastern Fold Belt hosts the most gold and copper occurrences.

The seismic reflection results indicate that the character of the uppermost crust varies between the Western and Eastern Fold Belts, with the Eastern Fold Belt characterized by thin-skinned tectonics and compression-related structures (Drummond et al. 1998). The sedimentary and volcanic rocks are thrust to the west along a series of shallowly east-dipping detachments, which are in turn cut by steeply east-dipping reverse faults. The seismic refraction data resolve a west-dipping high velocity (6.5-7.3 km/s) zone that lies at mid crustal depths beneath the eastern edge of the exposed Mt Isa Block (Goleby et al. 1998). The zone is not defined all the way across the seismic refraction profile, but is co-linear with a second zone at lower crustal depths beneath the Western Fold Belt. The high-velocity zone projects to the surface at a location between 142° and 143°E. Drummond et al. (1998) interpret the deformed upper-crustal units defined by the reflection data, together with the lower crustal high-velocity zone defined by the refraction data, as upper and lower parts of a crustal unit which was delaminated during its westward collision with older Mt Isa Block crust.

The Mt Isa Block extends some distance to the east beneath the Mesozoic sedimentary rocks of the Eromanga Basin (Blake 1987). Potential field data (both aeromagnetic and gravity) were used by Wellman (1992) to define the Mt Isa Geophysical Domain, a region with coherent geophysical responses interpreted to correspond to the Mt Isa Block. In the area of the present study (around latitude 20.75°S) this domain was defined as extending as far east as 141°E, approximately 40 km beyond the margin of the exposed Block. The projected point of intersection of the delaminated crustal units, interpreted from the seismic reflection and refraction data, lie to the east of the margin of the Mt Isa geophysical domain as defined by Wellman (1992). However, the high velocity unit is not defined all the way through the crust, so the projection is somewhat uncertain. Drummond et al. (1998) note that the surface projection of the body is near the mega-element boundary, as based on potential field data (Shaw et al. 1996). The present MT study provides an additional opportunity to examine the geometry of the eastern boundary of the Mt Isa Block, in this case as defined by its electrical conductivity, and to examine the possible coincidence of this boundary with the Carpentaria Conductivity Anomaly.

**MIMIC magnetotelluric survey**

The detailed MT investigation of the Carpentaria Anomaly took place in August 1997, in a field exercise known as MIMIC (the Magnetotelluric Investigation of the Mt Isa Crust). The location of a transect across the anomaly was chosen on the basis of the results from the 1995 magnetometer array study. A good road running east-west between Cloncurry and Julia Creek provided access for the MT sites.

Sixteen MT sites were occupied on a 170 km long transect crossing the anomaly, and three other sites were occupied in different off-transect locations. The geographic coordinates of the sites, and the codes used for them, are listed in Table 1. The relative positions of the sixteen sites forming the MIMIC transect can be seen in several figures below (for example, Figure 5). Sites west of mmc009 are located on the Mt Isa Block and sites east of mmc007 are located on the Eromanga Basin.

Geographically, the ground surface is very flat over the Great Artesian Basin, and hilly over the Mt Isa Block. Settlement in the area is generally sparse. The few sources of cultural electromagnetic noise include some major power lines, and installations at airports.

The equipment used for MT observation was the Flinders University set of EMI MT-1 equipment. Two horizontal wires spread (generally) north and east, with
spans of 100 m or 200 m, were used to observe the natural electric signal at the surface of Earth. Magnetic fluctuations were observed with a three-coil system. Two coils, aligned (generally) north and east respectively, were buried in trenches at the surface of Earth, and a third coil was set up vertically in a hole in the ground, packed with earth, and sheltered from sun and wind by a canvas cover. Measurements were recorded by a laptop computer, and the complete system was powered by car batteries. Sites were typically occupied for one day, and provided estimates of the MT response for the period range 1 ms to 1000 s.

Data processing

The EMI software provided the MT response for each site in the form of auto- and cross-power spectra of the four MT tensor components. These data were first rotated into a geographic north-south coordinate system, and converted into the standard Society of Exploration Geophysicists Electronic Data Interchange (SEG EDI) format.

Examination of the response revealed variable data quality. In general, sites located in the Eromanga Basin showed smooth responses extending over the period range 0.005 s to 1000 s, whereas the response from sites located on the Precambrian Mt Isa Block exhibited higher levels of noise (Figure 4).

Proximity to airports and power lines caused noise at some sites. For this reason, site mmc008 was excluded from further analysis and a broad frequency band was excluded from the response for mmc009. Narrow bands were excluded at other sites, typically at the high or low frequency ends of the available data. Sites mmc017, mmc018, and mmc019 were experimental sites situated some distance from the main profile and are not considered further in this paper. Site mmc005 is situated close to, and has a very similar response to, site mmc013; in fact the latter was occupied as a check on the low apparent resistivities observed at the former. As these two sites are so close geographically (separated by only a few km), site mmc005 has not been included in the analysis, as its data are taken to be represented also by mmc013.

Dimensionality and galvanic distortion

The characteristic dimensionality of the MT response differs between sites in the Eromanga Basin and sites on the Mt Isa Block. At sites within the Eromanga Basin the short-period response is close to 1D. At periods less than 1 s the off-diagonal impedance terms are approximately equal and are much larger (typically by more than a decade) than the diagonal impedance terms. This 1D response is associated with low apparent-resistivity values, and can be attributed to the flat-lying sedimentary rocks of the Eromanga Basin. At longer periods the off-diagonal responses from most sites in the Eromanga Basin (Figure 4) diverge, indicating the presence of 2D or 3D structures.

At Basin sites close to the Mt Isa Block, the divergence from a 1D response occurs at progressively shorter periods. For example at site mmc010, located around 30 km from the Mt Isa Block, the 1D response occurs at periods less than 0.1 s (Figure 4). At sites on the Mt Isa Block, the apparent resistivity observed at the shortest available period is relatively high, and there are significant differences between the off-diagonal elements of the impedance tensor (Figure 4). These results demonstrate the presence of 2D or 3D resistivity structures within the Precambrian material of the Mt Isa Block.

The dimensionality and strike of the MT responses were examined using GB tensor decomposition. GB parameters were fitted to period bands one-decade wide.
in order to both examine the dependence of the response on frequency, and to obtain statistically significant results. Figure 5 shows the regional strike angle determined from the GB decompositions, for period bands 10 s - 100 s and 100 s - 1000 s. These periods correspond to signal penetration through the Eromanga Basin. The results for each site have been obtained independently. Although there is some variation, the results define an overall northerly strike. Averaging the results across different sites and frequency bands gives a mean strike direction of N16°W, which is subparallel to the large-scale geological trends observed in the surface geology (Figure 3).

The GB analysis also provided information on the galvanic distortion of the MT response. For sites on Precambrian rocks, or at the edge of the Basin, the level of distortion was higher, with average shear values for sites mmc007 to mmc014 in the range of 10° to 35°. Table 2 lists the shear values for the different frequency bands for sites in the Eromanga Basin. There is a clear increase in the level of distortion in the period window of 0.1 s to 1 s. This period range corresponds to the significant increase in apparent resistivity at many of the sites in the Eromanga Basin. The distortion at Eromanga Basin sites is therefore interpreted as being associated with localized resistivity structures at, or near, the top of the Precambrian basement, under the sedimentary rocks.

Similar results to those of the GB analysis were obtained following the methods of Weaver et al. (2000), using tensor invariants to classify the dimensionality of the response. As in the GB analysis, the results following Weaver et al. (2000) indicated a 1D response at Eromanga Basin sites, with this response extending to increasingly long period for sites at increasing distance from the edge of the Mt Isa Block. The tensor invariant study indicated that at long periods the response was 3D for most sites. The uniformity of the strike angle obtained in the GB analysis (Figure 5) suggests that the 3D responses represent relatively minor departures from a dominantly 2D case.

The apparent resistivity and phase responses, taken together with the tensor decomposition results, indicate an electrical structure that is approximately 1D at shallow depth (corresponding to periods of less than 0.1 s - 1 s) in the Eromanga Basin, and approximately 2D with a strike of N16°W in the underlying and adjacent Precambrian rocks. For subsequent analysis the data are rotated into the N16°W coordinate system. The MT response corresponding to electric current flow parallel to N16°W then represents the TE mode response, and the orthogonal response, with electric current flow at N74°E, represents the TM mode.

### Apparent resistivity and phase responses

Figure 6 shows the TE and TM pseudosections of the apparent resistivity and phase for the MIMIC traverse. The effect of the more conductive rocks of the Eromanga Basin is clearly visible at sites east of mmc007, in both modes. In the eastern part of the profile the apparent resistivity at periods less than 1 s is typically less than 2 Ω.m, and decreases to less than 1 Ω.m at periods less than 0.01 s. At the edge of the Basin the transition between the low-resistivity response at short periods, and the more resistive response at longer periods, occurs at progressively shorter periods. The results provide an immediate indication of the thinning of the Basin at its western margin.

The phase response also indicates resistivity variations within the Basin and at its base. At sites east of mmc004, the MT response of the base of the Basin is evident at periods between 0.1 s and 1 s. In this period range the phase reaches low values (<20°) indicating a transition to more resistive rocks. The same effect is observed at sites near the edge of the Basin (between mmc013 and mmc007), but with the low phase values occurring at increasingly short period as the edge of the Basin is approached.
The MT response in the Precambrian part of the profile is not as well defined as in the Eromanga Basin, because of the exclusion of noisy data. However, the results for mmc014 and mmc009 show that the apparent resistivity is higher on the Precambrian than on the Basin. The sections suggest a decrease in apparent resistivity at long periods beneath the Precambrian sites; however such an interpretation is based on limited data. There are substantial differences between the responses of the two impedance modes at the sites on, and adjacent to, the Mt Isa Block. These differences are attributed to the 2D structures near the margin of the Block.

Both the apparent resistivity and phase pseudosections reveal a conductivity anomaly in the Precambrian basement beneath the Eromanga Basin. In the apparent resistivity responses this feature is seen as a zone of low resistivity beneath sites mmc013 to mmc015, at periods longer than 1 s. The apparent resistivity decreases to values less than 1 Ω.m, similar to values observed in the sedimentary basin sites at short periods. In the phase response the anomaly is evident as a break in the low phase values, centred on mmc011. This observation again suggests the existence of deep resistivity values which are low, and comparable to those of the shallow rocks. The apparent resistivity data do not clearly define a long-period limit to the conductive response, suggesting there is limited or no signal penetration to depths beneath the conductivity anomaly.

The conductive surface rocks of the Eromanga Basin will reduce the resolution of the underlying Precambrian rocks. As an approximate rule of thumb it is not possible to correctly resolve structures with a conductance (the product of their thickness and conductivity) less than that of overlying structures. The integrated conductance of the Basin rocks in the study area is some 200 S. The observation of a clear anomaly beneath sites mmc013 to mmc015, at periods for which the MT signals are penetrating into the Precambrian crust, indicates the presence of a substantial conductive body (with conductance 200 S or greater) within the crust.

MODELLING AND INVERSION OF THE MT DATA

The MT modelling and inversion were based on three main objectives: defining the resistivity structure of the Eromanga Basin sedimentary rocks using 1D inversion; defining the structure of the underlying crustal rocks, and in particular the conductive anomaly within these rocks, using 2D inversion; and examining the regional induction-arrow response of the crustal anomaly, using 2D forward modelling.

The effect of distortion and static shift on the responses was accommodated by assigning appropriate error floors to the data. The level of tensor distortion at Eromanga Basin sites is relatively small, and the level of static shift is therefore expected to be small in this environment. The error floor assigned to data from Basin sites was 5% uncertainty on impedance (which corresponds to a value of 2.8° on phase), and 10% on apparent resistivity (i.e. 0.0434 on the base-10 logarithm of apparent resistivity). In order to allow for significant distortion and static shift at Precambrian sites, the error floor for the apparent resistivity at sites mmc014, mmc009, and mmc007 was set to a much larger value (typically 80%). This large value will downweight the misfit of these data in the inversions. Galvanic distortion and static shift do not affect the impedance phase if the coordinate system is rotated to the true regional strike, so the error floor for the phase response at Precambrian sites was set to the same value as the Basin sites.

One-dimensional inversion of the Eromanga Basin responses

In order to investigate the shallow resistivity structure at sites on the Eromanga Basin, the MT data were first inverted using 1D algorithms. For each observing site, the inversions provide conductivity profiles with depth. Such profiles can be ‘stitched together’ to give a 2D section across the traverse of sites. The algorithms used were the Fischer inversion (Fischer & Schnegg 1980) which fits the data using models containing a minimum number of layers, and the 1D Occam inversion which fits the data using models containing a minimum amount of structure (Constable et al. 1987). The data sets to which the 1D inversion methods were applied were the TE responses, the TM responses, the determinant impedance responses,
and the central impedance responses (as defined in equation 4 to equation 6 above). The data were inverted across the full observed frequency range.

Figure 7 shows the results for Fischer inversion of the central impedance responses. The section as presented is truncated at depth 300 m, to emphasize the basin structure. The fit of the model responses to the data at individual sites in the Eromanga Basin is very good but, as expected, the fit of 1D models to sites on the Precambrian is relatively poor.

The inversion models obtained share a number of common features, well illustrated by the results in Figure 7. It is shown that the sedimentary rocks of the Eromanga Basin form a region of low resistivity (<3 Ω.m), overlying more resistive rocks, and with more resistive rocks to the west. The thickness of the conductive region increases from near zero at mmc007 to 200–250 m in the east. This conductive region can be further divided into two units; a thin surface unit with thickness <20 m and resistivity <0.5 Ω.m, overlying a thicker and more resistive unit (~1 Ω.m).

Although it is not the focus of the 1D modelling, the results in Figure 7 also define a conductor located at depths beneath the Basin. In the 1D models the conductor lies beneath mmc011 and mmc013. The geometry of this body will be better resolved by 2D inversions of the observed data, now to be described.

Two-dimensional inversion

The 2D inversion procedures followed involve simultaneously fitting both TE and TM responses. The inclusion of both modes provides increased sensitivity to the resistivity structure. For example, the TM mode involving electric current flow parallel to the structure, is sensitive to the presence of conductive features which lie within the structure. The output from a 2D inversion is a cross-sectional image, of resistivity structure along a profile perpendicular to the geoelectric strike (in the present study oriented N74°E).

The algorithms used in 2D inversion were the non-linear conjugate gradient (NLCG) algorithm of Mackie & Rodi (1996) and Rodi & Mackie (2001), and the Occam inversion algorithm of deGroot Hedlin & Constable (1990). Each of these methods determines the 2D model that fits the observed data to a specified tolerance, with minimum roughness. In general a final model will be a smoothed image of Earth resistivity structure, and will be minimalist in the sense of including only those features required to fit the data. The NLCG and Occam algorithms involve different inversion methods. The presence of common features, in the independent results from each, gives increased confidence in the existence of such structures in the Earth.

The NLCG inversions used TE and TM data for 32 frequencies, distributed approximately uniformly in log space between 8.3x10^{-3} s to 147 s. The inversion parameter τ, which defines the trade-off between data misfit and model smoothness, was set to a value of 10. The starting model for all inversions was a uniform half-space, and inversions were run with the resistivity of the half-space set to values of 10, 100 and 1000 Ω.m. The final normalized root-mean-square (rms) misfit for these inversions was 2.1.

Figure 8 compares the model phase responses for the 1000 Ω.m model with the observed data. The NLCG inversion models fit the observed data well, with the model responses including all major features present in the observed data. The misfit is largest at long periods, e.g. in the TM response at site mmc007.

Prominent features in the NLCG inversion models include a very resistive upper crust beneath the exposed Mt Isa Block, a thin near-surface conductor in the Eromanga Basin, and a strong crustal conductor which is centred beneath sites mmc013 to mmc003. The different NLCG inversion models all include the same basic resistivity structures, with variation in some parameters such as the thickness of the resistive crust in the Mt Isa Block. On the basis of other studies in Australia and elsewhere, the background resistivity at crustal depths is expected to be of order 1000 Ω.m, and the optimal inversion model is considered to be that based on the starting halfspace with this resistivity. Figure 9 shows this optimal model.

The Occam inversion was based on 15 periods evenly spaced in log-space between 4.5x10^{-3} s to 263 s, and a 1000 Ω.m half-space starting model. The model obtained from this inversion is shown in Figure 9. Its fit to the observed data, corresponding to an rms misfit of 6.1, is not as good as for the NLCG inversion model (probably because of the more coarse parameterization of the Occam model, and the inclusion of slightly longer-period data in the Occam inversion). Comparison of the NLCG and Occam models (Figure 9) reveals that many structures are present in both models, providing increased confidence in the existence of these features.
The dominant feature of both models is the large crustal conductor, labelled A in Figure 9. Both the Occam and NLG models (as well as the NLG models derived from different starting models) show this major conductor, and show that the resistivity within it reaches values as low as 1 Ω.m. In both models the upper surface of the conductor dips eastward from a depth of ~1 km at mmc011 and mmc013, to a depth of some 5 km at mmc003. The models both show a region of particularly high conductivity (<0.5 Ω.m) at about 3 km depth beneath site mmc004. The NLG models include a second region of high conductivity at <1 km depth beneath sites mmc011 and mmc013, though the Occam model includes a less conductive feature at this location. The MT study by McDougall (1996) was based on relatively sparse site spacing, but did include a site near the location of mmc011. The response at this site, and subsequent 2D modelling by McDougall (1996), indicated the presence of a relatively good conductor (10 Ω.m) in the upper crust. The present study supports and augments that conclusion.

The MT method provides low resolution of the base of conductive zones, and as noted above the MT response in this survey provides no indication of structures beneath the conductor. The different inversion models thus show different resistivity structures beneath the conductor. Although the MT response cannot resolve the base of the conductor, the results do indicate that the vertical thickness of the conductor is of order tens of kilometres, and that the conductor has an integrated conductance of >1000 S.

The 2D inversion models all show that the upper crust of the Mt Isa Block (labelled B on Figure 9) is relatively resistive (>1000 Ω.m). This result is based largely on the data from mmc014, for which both the phase and apparent resistivity responses indicate the presence of a more conductive region at depth (labelled C). Because of the uncertainty, caused by static shift, in the true level of the apparent resistivity values, the depth to the conductive zone is poorly resolved. However, for the inversions based on a 1000 Ω.m starting model, the nal models include a transition to the more conductive zone at ~20 km depth (Figure 9).

The MT models include two additional conductors (labelled D and E). Conductor D includes resistivity values of <5 Ω.m, and forms a sub-vertical body between 5 and 15 km depth beneath sites mmc006 and mmc016. Conductor E forms an east-dipping sub-horizontal body. In the NLG model conductor E is 1 to 2 km thick, occurs beneath sites mmc007 to mmc012, and has similar resistivity to conductor D. The conductor is less well defined in the Occam model, but is clearly present.

Comparison of results with large-scale induction arrow responses

The MT responses and models establish the presence of a discrete conductive body at depth, approximately 50 km east from the surface edge of the Eromanga Basin with the Mt Isa Block. Additional forward modelling has been carried out to examine whether this body adequately explains the original Carpentaria Conductivity Anomaly of Chamalaun et al. (1999) and
Electrical structure of Australia

Wang & Lilley (1999), which was the target of the detailed MIMIC97 magnetotelluric study.

A simplified regional resistivity model was constructed (Figure 10), consisting of the conducting body defined by the MT response and a conductive surface layer corresponding to the sedimentary rocks of the Eromanga and Georgina Basins. These latter features were considered to be appropriate for inclusion in such a forward model, as knowledge of them is reasonably secure. They were embedded in a relatively resistive Precambrian crust. The resistivity between 40 and 60 km depth was set to 100 Ω.m, and beneath 60 km depth it was set to 20 Ω.m.

Figure 10 shows the real induction arrow response of this model. The quadrature component of the induction arrows is much smaller than the real component. The model response includes a clear reversal of arrows over the MT conductivity anomaly. The maximum length of the real arrows is around 0.5 units, and occurs over the period range 1000 s to 10000 s. There are smaller induction arrows in the period range of 0.1 s to 10 s which are associated with edge of the Eromanga Basin. The model response also includes significant arrows at periods less than 100 s, associated with the edge of the Georgina Basin; however this last response depends on the geometry of the margin of the Georgina Basin, which has been assigned arbitrarily in the present model.

Comparison of the model induction-arrow response with the observed arrows (Figure 3) indicates good general agreement between the two data sets. This agreement shows conclusively that the anomaly detected in the MT study is indeed the source of the Carpentaria Conductivity Anomaly. Both the model and the observed data show arrows of significant length (>0.2 units), extending to a distance at least 200 km from the actual conductor. The model arrows are smaller than the observed arrows, suggesting the full conductance of the conductive body is higher than as resolved by the MT data. This result is in accord with the observation that the MT response does not resolve the base of the conductor. The agreement between the model and observed data may also be improved by adjusting the resistivity of the near-surface layers and the mantle layers. Joint inversion of the regional induction arrows and the local MT data responses should provide the optimal resolution of the base of the conductor, but is beyond the scope of the present study.

Figure 10 The model of the Mt Isa Block and neighbouring sedimentary basins, and its real induction arrow response.

GEOLOGICAL INTERPRETATION AND DISCUSSION

Eromanga Basin sediments

The depth of the Eromanga Basin sediments along the MT profile is well-established from wells drilled in the Basin, and is 200–300 m (Senior et al. 1978). The MT results (Figure 9) provide a consistent estimate of the Basin depth, and demonstrate the possible applications of MT to define basement depths in areas without well control.

The resistivity determined for the sedimentary rocks of the Eromanga Basin in this study (<1-10 Ω.m) is consistent with results of earlier studies in the Basin. In previous studies, Whiteley & Pollard (1971) determined values of 1.5 - 55 Ω.m using MT and DC-resistivity methods, Spence & Finlayson (1983) determined values of <5 Ω.m using MT, and McDougall (1996) determined values of 1 - 10 Ω.m using MT and time-domain electromagnetic methods. Following the interpretation of Spence & Finlayson (1983) of resistivity further south in the Eromanga Basin, the low resistivity found in the present study is attributed to high rock porosity, and to a high value of groundwater salinity.

Precambrian basement

The MT results from the MIMIC survey have resolved a number of structures within the Precambrian crust, the most prominent of which is a major crustal-scale conductor. Figure 11 shows the position of the conductivity anomaly with respect to the aeromagnetic image of the area, and the approximate position of crustal structures as interpreted from seismic refraction and reflection results. The region between the edge of the exposed Mt Isa Block and the conductivity anomaly is characterized by a long-wavelength magnetic low. This low has a north-south strike, and extends for several hundred km to the north and south of the MT transect. The conductivity anomaly itself shows some correlation with a long-wavelength magnetic high. In the vicinity of the MT transect, this magnetic high has an approximately north-south strike.

The upper part of the crustal conductor, including the two localized zones of enhanced conductivity (beneath mmc013-mmc011 and mmc004), lies at <5 km depth. Conductor E also occurs within this depth range. These
features lie within the zone of thin-skinned deformation defined by the seismic reflection data. The base of this zone is a sub-horizontal detachment, which occurs at approximately 2 s two-way travel time, i.e. at depth ~6 km. The reflectivity pattern of the overlying rocks extends from the Eromanga Basin onto the exposed Mt Isa Block. On the basis of the reflectivity and observed structures on the exposed Block, the upper crustal unit is interpreted as consisting of the same rocks as the Eastern Fold Belt (Drummond et al. 1998). This geometry would mean that the upper part of conductivity anomaly A, and anomaly E, would lie in rocks of the Eastern Fold Belt.

In contrast to this interpretation, the MT data suggest that a geological contrast exists between the
electrically resistive rocks of the uppermost crust in the exposed Mt. Isa Block, and the upper crustal rocks further to the east beneath the Eromanga Basin. Both the seismic refraction and magnetic data also suggest a geological contrast. The seismic velocity of the uppermost crust (\(<\sim 5\) km depth) is lower beneath the Eromanga Basin (5.7 - 6.1 km/s) than on the Mt. Isa Block (6.1 - 6.5 km/s) (Goleby et al. 1998). The pattern of magnetization over the Eromanga Basin consists of longer-wavelength anomalies than over the Mt. Isa Block. This difference is sufficiently large that it could not be due to the several hundred metres of sedimentary rocks of the Eromanga Basin.

The geometries of the upper-crustal conductive bodies (A, D, and E) suggest that the enhanced conductivity may be caused by deformation or mineralization associated with faulting (Figure 11). With the (approximately) 10 km site spacing of the MT survey, the MT results resolve the location of the subvertical conductive body D to within about 5 km. Given this accuracy the MT results are consistent with the body being caused by enhanced conductivity associated with the Cloncurry and Marimo Faults. These faults extend from the surface to \(>12\) km depth with an eastward dip of 40° - 60° (Drummond et al. 1998). The seismic reflection data indicate that the detachment surface at around 6 km depth, and parallel detachments at more shallow depth, dip gently to the east. The upper surfaces of conductor A and conductor E have a similar dip, suggesting the enhanced conductivity may be associated with these thrust surfaces. The locally-enhanced conductive bodies beneath mmc013-mmc011 and mmc004 occur beyond the end of the seismic reflection profile, but may also be attributed to faulting. McDougall (1996) notes that the former body occurs near the Kevin Downs Fault.

Of several possible causes of enhanced electrical conductivity, it is the view of the authors that the source is likely to be graphite or metallic sulphides and oxides. Elsewhere comparable studies have advocated the interpretation of enhanced conductivity on fault zones in a similar way. For example, Jones (1992) attribute enhanced conductivity on the strike-slip Fraser Fault in British Columbia, Canada as being due to graphite precipitated from fluids moving through the fault zone. In the present study several deposits lie along strike of the seismically-imaged Marimo Fault (Drummond et al. 1998), suggesting fault control on the movement of crustal fluids, and associated mineralization.

The MT results indicate that the enhanced conductivity in conductor A must extend to depths below the upper-crustal detachment surface. The total conductance of the body must be very large, as determined by the MT survey and supported by the regional GDS results, requiring the body to extend through at least the upper crust. Because MT provides poor resolution of resistive regions beneath conductive zones, it is possible that the deeper part of the conductor is discrete from the enhanced conductivity above the detachment zone.

Accordingly, we interpret the enhanced conductivity at depth within conductor A as being associated with the collisional process at the margin of the Mt. Isa Block, and having a different source from the enhanced conductivity at shallow depth. As noted above, a number of collisional plate boundaries have an electrical signature in the form of a major linear conductor. The enhanced conductivity has been attributed to the deformation and metamorphism of graphitic or sulphidic sedimentary rocks, formed in a restricted, reducing, oceanic environment, e.g. Boerner et al. (1996). The high conductivity of conductor A is consistent with the presence of metasedimentary rocks emplaced in the crust during the subduction of oceanic crust at the margin of the Mt. Isa Block.

The seismic refraction data provide supporting evidence of west-dipping high velocity crust beneath the Mt. Isa Block (Goleby et al. 1998). The high-velocity crust projects to the surface well to the east of the conductor. However, the high-velocity block is not defined all the way through mid-crustal depths to the surface. It is therefore possible that the subducted crust dips more steeply at shallow depths (as shown on Figure 11), and is coincident at upper crustal depths with the conductor.

**Implications of MT results for the interpretation of the structure of the Australian Plate**

It is consistent with the purpose of this volume to examine the continental-scale implications of the Carpentaria Conductivity Anomaly, as now revealed.

There are differences in both geological age and tectonic structure between the cratonic areas of central and western Australia, and eastern Australia. Kennett (2002) in this volume reviews evidence from seismic tomography, and shows that 3D shear-wave imaging reveals substantial differences between the cratonic and eastern regions of the continent. Figure 12 of the present paper shows the S-wave velocity for 80 km depth, and Figure 12 of Kennett (2002) shows the result for 140 km depth. Both figures show a 10% variation in S-wave velocity across the Australian Plate. Although some of this variation can be attributed to thermal effects associated with Neogene volcanism in the east, the high shear-wave velocity in the cratonic area requires the existence of chemical variability in the lithosphere (Kennett 2002).

The Tasman Line, taken as defining the eastern limit of exposed Precambrian rocks (Brown et al. 1968), has long been used as an indicator of the transition between the cratonic and eastern regions of the Australian Plate. However, as noted above, this interpretation of the Tasman Line in its traditional position in northern Queensland, shown in the present volume in Figure 1 of Kennett (2002), is not supported by the mega-plate analysis of Shaw et al. (1996), which puts that fundamental boundary west of the traditional position. Neither is the Tasman Line in northern Queensland supported by the seismic tomography results, or the electromagnetic evidence of the present paper. In contrast, in the area of the present study, there is a general correlation between the high shear-wave gradient at the margin of the cratonic region, the interpreted plate boundary defined by the potential field data, and now the electromagnetic data. The combined results suggest the presence of a lithospheric signature associated with the Proteozoic crustal plate margin.

Geological and seismic data suggest that the plate
collision at the eastern margin of the Mt Isa Block occurred during the Proterozoic. The deformation of rocks in the Eastern Fold Belt, interpreted as being due to shortening which occurred during the collision, formed part of the 1620-1520 Ma Isan Orogeny. High-angle faults such as the Marimo Fault, which formed during the orogeny, appear to link with the high-velocity body occurring at mid- to lower-crustal depths. There is no evidence for a plate boundary of Phanerozoic Age in the vicinity of the Mt Isa Block. Although there is some Phanerozoic reactivation of major faults on the Block, the magmatism and peak metamorphism recorded in the Block is of Proterozoic age (Blake & Stewart 1992).

The spatial correlation of the Proterozoic crustal-plate margin to the east of the Mt Isa Block with the seismic velocity gradient in the mantle lithosphere suggests that, at least in northern Queensland, the lithospheric cratonic margin is a Proterozoic rather than a Phanerozoic feature.
Although the cover sequences on the Mt Isa Block are dominated by sedimentary and volcanic rocks formed in a rift setting, the geophysical data suggest the plate margin to the east was more significant than the closing of a relatively narrow rift basin. Firstly, on the basis of the large conductivity anomaly, the plate collision appears to have involved the subduction of a significant volume of oceanic lithosphere. Secondly the change in lithospheric shear-wave properties, in the vicinity of the boundary, suggests a collision involving plates with substantially different lithosphere.

Comparison of the seismic shear-wave images (e.g. Figure 12) with maps of the major conductivity anomalies (e.g. Figure 2 and Figure 3) reveals agreement to exist between the positions of the conductivity anomalies, and gradients in the shear-wave velocity, not only in the area of the present study but also more widely. Other examples may be seen in southern Australia. As the correlation occurs between seismic results for the subcrustal lithosphere, and electromagnetic results for the crust, it implies the presence of significant boundaries extending over a large depth range in the lithosphere. It will therefore be timely to revisit the major continental conductivity anomalies in the Australian Plate, to define the form of the conductors within the crust, and to examine their role as marking cratonic boundaries.

CONCLUSIONS

The MT traverse across the Carpentaria Conductivity Anomaly has been successful in providing detail on the electrical conductivity structure in the Earth which causes the anomaly. The highly conducting zone is in the crust. Its upper surface is close to the base of the Eromanga Basin sediments, which are of thickness some 200 m. From that level the conducting zone extends down some tens of km, to penetrate the mantle.

The geographic coincidence of the conductivity anomaly with a major gradient in seismic wavespeed lends support to the concept that the same tectonic process has caused both. That process was the addition, from the east, of the younger block of continent being joined on to the older block of continent to the west. If a process of subduction was the cause, as happens in present continental accretion, then the wedge, where the subducting slab has sediments which are formed into a geosyncline against the older block, has formed a block of highly conducting material.

More widely, other Australian conductivity anomalies may be viewed in the same light. Thus, with reference to Figure 1 and Figure 2, the Flinders anomaly in southern Australia (marked F in Figure 1) is also in such a region of seismic wavespeed gradient. A similar tectonic history may also thus apply to that part of the Australian Plate.

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