Mapping the Carpentaria conductivity anomaly in northern Australia

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Abstract

A band across northern Queensland, Australia, was studied in 1995 by a magnetometer array experiment in two parts: a western part (Q1), and an eastern part (Q2). Forty-three sites were occupied in all, by Flinders University magnetometers which recorded in three components at intervals of 1 min. A major purpose of the study was to further clarify the position and indeed the existence of a major electrical conductivity anomaly, suspected to exist in the area from earlier reconnaissance observations. The arrays were successful in clearly delineating the path of the conductivity anomaly, here termed the Carpentaria conductor. It is seen to continue up the eastern side of the Mt Isa Inlier, from where it was mapped in detail previously in southern Queensland. The results show the anomaly to be offset from the ‘Tasman Line’, which is thought to indicate a major structural boundary in the Australian Continent, and which possibly has a conductivity anomaly associated with it further south. Elsewhere the array results give a clear measure of the coast effect of northeast Australia, and they set the magnetic variations recorded at Charters Towers Observatory in the context of the coast effect. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Electrical conductivity anomaly; Carpentaria; Magnetometer arrays

1. Introduction

Magnetometer array studies are a basic geophysical mapping tool, using natural fluctuations of Earth’s magnetic field, and the electrical currents these induce in Earth, to study the Earth’s electrical conductivity structure. The method exploits the long wave length source fields which are present naturally, due to electric currents in Earth’s upper atmosphere, ionosphere and magnetosphere. It is well suited to a mid-latitude continent like Australia, where overhead source fields are relatively uniform. A recording magnetometer, in essence a temporary magnetic observatory, records the geomagnetic field variations unattended for a period of weeks or months.

The method has been used in Australia for some 40 years, since the observations by Parkinson (1959; 1962) and others of the correlation in the variation of the vertical and horizontal field components at certain magnetic observatories, and the setting up of temporary observatories (for example, Everett and

2. Setting of the 1995 Queensland arrays

The 1976 magnetometer array experiment of Woods and Lilley (1979) covered the southwestern part of Queensland (Fig. 5). That array discovered a major anomaly near its southeast corner, which the 1977 array of Woods and Lilley (1980) followed up in detail. The present study area was covered by recording magnetometers at 250 km spacing during the Australia Wide Array of Geomagnetic Stations (AWAGS) experiment of 1989–1990 (Chamalaun and Barton, 1993a,b). Since 1983 there has been a magnetic observatory at Charters Towers (Barton and Lilley, 1986; Milligan, 1988).

Fig. 1. Sites of the Q1 and Q2 magnetometer array studies in Queensland in 1995. Also shown are the major elements of the geological structure of that part of Australia. The dashed thick line is the approximate location of the postulated ‘Tasman Line’. FB denotes Fold Belt, and I denotes Inlier. Charters Towers Magnetic Observatory (CHA) is sited in an abandoned gold mine and records the magnetic field elements at 1-min intervals using an EDA fluxgate magnetometer.
The results of the AWAGS observations were that the western Queensland anomaly was suspected to continue north from Birdsville, but could still possibly head northeast, taking a significantly different path across major elements of Australian geology. The 1995 arrays thus were designed to answer the primary question of the existence and position of the western Queensland electrical conductivity anomaly, and its relationship to fundamental Australian geology.

The 1995 arrays were set up at sites as shown in Fig. 1, which also shows the major geological elements of the studied area. Due to logistic considerations, the sites were occupied in two consecutive arrays, of 21 and 22 instruments, respectively, which will be termed Q1 and Q2. One site (Trenton (TRE)) was common for both arrays, as was the Charters Towers observatory (CHA). The sites can be seen to be typically 100 km apart; a spacing that has proved effective in earlier array studies in Australia (Lilley and Bennett, 1972; Woods and Lilley, 1979; Chamalaun, 1985), as a balance between area investigated and density of data obtained.

The Q1 array operated from June to August 1995, and the Q2 array from September to November 1995. During these periods, a variety of natural geomagnetic activity occurred. Details of site position and name are given in Table 1. The instruments used were the current version, with solid-state recording, of the Flinders University three-component fluxgate magnetometers described by Chamalaun and Walker (1982). The instruments were set to record at 1-min intervals, and the typical sensor resolution was 1 nT.

Each instrument was set level when installed, and so recorded the vertical component \( z(t) \) of the magnetic field directly, as a function of time. However, an instrument when installed was given no particular azimuthal alignment, as the field strengths recorded by the two horizontal sensors give the instrument orientation relative to magnetic north (at some magnetically undisturbed epoch, which in this case was

Table 1
Names, codes, and geographic co-ordinates of the observation sites of the Q1 and Q2 magnetometer arrays in 1995 in Queensland, Australia

<table>
<thead>
<tr>
<th>Name of site</th>
<th>Code</th>
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<th>Longitude</th>
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Q1 Array (June 1995–August 1995)

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<td>Corinda</td>
<td>COR</td>
<td>22.15°S</td>
<td>145.15°E</td>
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<td>Rimbaanda</td>
<td>RIM</td>
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<td>BAR</td>
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<td>SUB</td>
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<td>MOR</td>
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<td>149.46°E</td>
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<td>148.65°E</td>
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<td>Collinsville</td>
<td>COL</td>
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<td>Pentland</td>
<td>PEN</td>
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<td>Greenvale</td>
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<td>TRE</td>
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<td>Charters Towers</td>
<td>CHA</td>
<td>20.08°S</td>
<td>146.25°E</td>
</tr>
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</table>
midnight of the first recording day). Then, using the values for Australian magnetic declination given by McEwin (1993), signals $x(t)$ and $y(t)$ in the horizontal directions of geographic north and east are obtained.

3. Regional geology

The part of Australia in Fig. 1 covered by the Q1 and Q2 arrays includes the northern part of a most fundamental boundary of the continent: that of older Precambrian structures to the west with younger Paleozoic basins to the east (Veevers, 1984). The eastern part of the continent is generally described as the Tasman Fold Belt (e.g., the papers by Scheibner, 1974, and Harrington, 1974, in the work of Denmead et al., 1974). The Tasman Fold Belt is Palaeozoic to Early Mesozoic in age and comprises the Lachlan Fold Belt, the New England Fold Belt (in the east), and the Hodgkinson Fold Belt (in the north). To the west are older structures, Proterozoic and Archean.

The boundary between east and west is termed the ‘Tasman Line’, a name attributed to Hill (1951). The significance of the Tasman Line is that it holds the key to the history of the eastern part of the continent, which is thought to have accreted against the western shield following the breakup of the early supercontinent named Rodinia (see Powell et al., 1993; Li et al., 1996; Metcalfe, 1996). Because of this significance, the ‘Tasman Line’ is a frequent marker for large-scale geological divisions of Australia (see for example Powell et al., 1994; Van der Hilst et al., 1998). However, what forms the Tasman Line takes at depth, and even its exact position in places where it is obscured by sediments, are matters yet to be determined.

Returning to the units named in Fig. 1, the Georgetown Inlier is of Precambrian age and the Tasman Line is placed to the east of it. The Mt Isa Inlier, west of the Georgetown Inlier, consists of Early and Middle Proterozoic rocks. Fig. 1 shows the outcrop of the Mt Isa Inlier, and around this outcrop the Inlier is overlain by the following sedimentary basins:

1. The Georgina Basin, of Late Proterozoic to Devonian age, to the west.
2. The Eromanga Basin, of Mesozoic age, to the south and southeast, and
3. The Carpentaria Basin, of Mesozoic age, to the northeast.

The resistivity of sedimentary rocks is generally dominated by the conducting pore fluids (Keller, 1998; Palacky, 1998) and increases with age due to the closure of pore spaces. On this basis the Georgina Basin would be expected to be less conductive than either the Eromanga Basin or the Carpentaria Basin. On the basis of such a lithology–resistivity linkage, both these latter units would be expected to be relatively conductive.

In Fig. 1, generally in an area bounded by the sites SUR, GAR, PEN and HUG, lie Cainozoic basaltic provinces, where Pliocene to Recent basalts have been extruded (Stephenson and Griffin, 1976).

4. Examples of recorded data

As is often the case for magnetometer arrays, the prime results are evident from an inspection of the recorded data. Thus, Fig. 2 shows stacked profiles for the Q1 array, for a typical substorm event of variable horizontal polarisation. The stations are arranged from east to west down the page. Anomalous $z(t)$ responses can be seen immediately in Fig. 2, where the figure shows a very clear example of a reversal in the vertical component of the fluctuating magnetic field. The stations where the strong positive $z(t)$ signals occur are on the western side of the Q1 array. The phenomenon, consistent as it is in successive magnetic disturbance events, indicates a concentration of induced electric current in the ground, running approximately north–south through the array area.

Fig. 3 shows similar stacked profiles for the Q2 array, for a comparable magnetic substorm event. Now the prime cause of signal in the $z(t)$ data can be traced to the proximity of the Coral Sea (see Fig. 1), indicating a coast effect.

In both Figs. 2 and 3, in addition to the traditional $x(t)$, $y(t)$ and $z(t)$ data, information is included, in the right-hand column of each figure, on the spatial variation of the total-field $f(t)$. From each $f(t)$ profile, the simultaneous record of station TRE (the more central of the two common stations for the two arrays) has then been subtracted, to give ‘difference’ profiles, $\Delta f(t)$, in the tradition of Lilley (1982) and Chamalaun and Cunneen (1990).
Fig. 2. An example of recorded data from the Q1 array at a time of disturbed magnetic activity. The observed data are shown as three traditional components, $x(t)$, $y(t)$ and $z(t)$. Also shown are differences ($\delta f(t)$) in the total-field component between each station and station TRE (taken as a 'base'). Note the different scales for $z(t)$ and $\delta f(t)$. The length of each record is 24 h. The stations are arranged from east to west down the page. The vertical scale is shown to the left of the time scale.
Fig. 3. An example of recorded data from the Q2 array at a time of disturbed magnetic activity. Same legend as for Fig. 2.
These difference profiles are included because of their relevance to aeromagnetic mapping, as they demonstrate the typical spatial inhomogeneity of the total field variations in this area and in particular, if base-station records are used to correct aeromagnetic records, Fig. 2 shows how sensitive this process is to the position of the base station.

5. Data reduction and induction arrows

The full data-set has been edited for obvious noise spikes, and then plotted as a further check on data quality, before its use in the calculation of magnetic response functions (Hobbs, 1992). In this latter task, the robust technique described by Chave et al. (1987) has been employed. The period range covered is from 6 to 114 min, and a time-dependence of the form $e^{-i\omega t}$ has been assumed (Lilley and Arora, 1982). Of the two possible common stations for the Q1 and Q2 arrays, TRE and CHA Towers Magnetic Observatory, the latter has been used as a remote reference site, for both arrays. While the Trenton site is more central, data from an established observatory were thought to be preferable, given their availability. Also Charters Towers is remote from the main anomaly evident in Fig. 2 which was taken to be an advantage in its favour. The slight coast effect at Charters Towers was not thought to be important, especially as it is the horizontal fluctuation components which are used in the remote reference calculations.

The magnetic response functions thus obtained are listed in Appendix A for period 66 min, and for other periods are given by Wang (1998). The response function errors are generally small: less than 1% (Chave et al., 1987).

Denoting the transforms of the time series $x(t)$, $y(t)$ and $z(t)$ into the frequency domain as $X(\omega)$, $Y(\omega)$ and $Z(\omega)$, respectively, the magnetic response functions are the values $A$ and $B$ in the best-fit (Schmucker, 1970; Chave et al., 1987) equation to the data

$$Z(\omega) = A(\omega)X(\omega) + B(\omega)Y(\omega)$$

and are thus complex functions of frequency, $\omega$. To form an induction arrow they are plotted with the real parts of $A$ and $B$ to the south and west, respectively, according to the Parkinson convention (Hobbs, 1992); such arrows will then generally point to the high conductivity side of a nearby conductivity contrast.

The real (or in-phase) induction arrows are plotted in Fig. 4, for the periods of 6, 18 and 66 min. They are a most effective way of combining together the data from both the Q1 and Q2 arrays.

6. Interpretation of the real induction arrows

6.1. Period 66 min

The longer-period data are less influenced by local near surface effects, and show the primary electrical conductivity structure directly. In fact the pattern shown at 66 min period is simple. It may be summarised as follows.

(a) The conductivity anomaly to the west, approximately along the meridian of longitude 141° in Fig. 4.

(b) The coast effect in the east. These data complement studies of the coast effect for other parts of the Australian continent, and clearly provide a set of observations, unperturbed by other conductors, for the contrast of the east Australian continent with the electrically conducting ocean water of the Coral Sea. To the north, the Gulf of Carpentaria is relatively shallow (it is everywhere less than 70 m deep) and, in contrast to the Coral Sea, the Gulf is an insufficient electrical conductor to cause a coast effect at long periods.

(c) No major anomalous response in the area of the recent volcanics.

(d) No obvious anomaly in the region accepted to be that of the ‘Tasman Line’.

6.2. Shorter periods

At shorter periods, data bring out more detailed structure and respond to shallower conductivity contrasts. However, the station spacing is now not sufficiently dense to delineate the finer-scale patterns in detail. Nevertheless the induction arrows generally point in the same direction down to a period of 6
min. The main conductor is evident in the shorter periods as well.

The shorter period arrows are shown in Fig. 4 to illustrate a point of some interest. Consider the rotation of the induction arrow from its direction at 66 min to that at 6 min. Most stations in the west (between CAC and ADE) rotate anticlockwise (when viewed from above), whereas the stations near the Gulf such as HEL, DOO and ALE rotate clockwise. On the assumption that at the shorter period the induction arrows point to a second and shallower conductor this characteristic may be interpreted as an indication that the anomalous conductor bifurcates to the north of the Mt Isa Inlier, with a shallower branch curving west.

7. Geological interpretation

The long-period (66 min) arrows are now transferred to a map of geological structure and ocean bathymetry in Fig. 5, with relevant previous arrow determinations also included. The continuity of the induction arrow pattern between the earlier stations to the south and the Q1 and Q2 arrays is clearly established, showing the conductivity anomaly to lie along the path shown in the figure.

The major conclusion of the 1995 Queensland arrays can be stated to be the demonstration of the anomaly, now called the Carpentaria anomaly, at the eastern edge of the Mt. Isa Inlier, where it has continued north from the Birdsville area. The interpretation of the AWAGS data by Chamalaun and Barton (1993b) for this part of Australia is strongly supported.

It is notable, with reference to Fig. 5, that there is no similar effect at the edge of the Georgetown Inlier, which from surface geology should be similar to the Mt Isa Inlier. Similarly, there are no comparable effects at the edges of the other conductive basins; no resistive contrast is seen at any of the boundaries of the Drummond Basin.

The simple association of the Tasman Line with the conductivity structure of northern Australia is left in doubt by the results of the Q1 and Q2 arrays. An objective of more detailed work must be to subject this postulate to closer examination. An outcome
Fig. 5. Diagram combining real induction arrows for period 66 min, major geological boundaries, and position of conductivity anomaly as determined by the Q1 and Q2 magnetometer arrays (labelled arrows), together with other relevant previous results (unlabelled arrows) from Woods and Lilley (1979; 1980) and Chamalaun and Barton (1993a). The conductivity anomaly is schematically shown by the thick line between longitudes 140° and 142°. The actual width of the conductor is poorly determined.
may be a clearer understanding of the position of the Tasman Line, as the eastern limit of Precambrian basement, beneath the extensive sedimentary basins of inland Australia.

8. Conclusion

The 1995 arrays have again demonstrated the effectiveness of a set of recording magnetometers as a reconnaissance method, for determining the presence of major contrasts in electrical conductivity structure. The horizontal resolution of the method is good, being limited in the present case by how close the stations themselves are installed. The Q1 and Q2 arrays provide an excellent demonstration of how analysis at longer periods allows a greater horizontal spacing of observing sites, before correlation between adjacent sites becomes weak, and the danger of aliasing between sites arises. The arrays have improved the overall coverage of Australia and were used in the recent thin-sheet inversion of Australian data by Wang and Lilley (1999).

Acknowledgements

Exercises of the logistic scope of those described involve many people, and we are grateful for assistance in the field, in many ways. In particular we thank Bob Walker and Penny Lilley. We also thank two referees for their thoughtful comments. The 1995 Queensland array studies were run under the ANU Institute of Advanced Studies — Australian Universities Collaboration Scheme. Liejun Wang is the recipient of an Overseas Postgraduate Research Scholarship and an ANU PhD Scholarship.

Appendix A. Magnetic response function values for period 66 min, for the Q1 and Q2 magnetometer arrays

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<th>Q2 Array (September 1995–November 1995)</th>
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