Exploration Geophysics (2000) ***31****, 052-057*

The total-field geomagnetic coast effect: The CICADA97 line from deep Tasman Sea to inland New South Wales

Adrian P. Hitchman[1] Peter R. Milligan[2] F.E.M. (Ted) Lilley[3] Antony White[4] Graham S. Heinson[5]

Key Words: Aeromagnetics, coast effect, electromagnetic induction, micropulsations, total magnetic field

ABSTRACT

In the CICADA97 experiment a line of simultaneously-recording stationary vector magnetometers was deployed from inland NSW, across the east Australian coast, and into the Tasman Sea. The purpose of the experiment was to investigate the effect of electrical conductivity structure near a coastline on natural time-variations in Earth's magnetic field. Aeromagnetic surveys regularly take place in such coastal areas, and removal of time-variations of the magnetic field is a prime task of data reduction. CICADA97 data show that long-period variations of the total field are systematically enhanced near the NSW coast, while spatial patterns of short-period variations (such as pulsations) may be strongly influenced by electrical conductivity structures on a smaller scale, such as bays and inlets.

INTRODUCTION

Removal of temporal magnetic-field variations from aeromagnetic data is an essential part of the derivation of the crustal anomaly field (Bhattacharyya, 1971; Reeves, 1993). The process of removal is complicated when temporal variations are spatially non-uniform across a survey area. Such spatial non-uniformity commonly results from the secondary magnetic fields associated with electrical currents induced in geological structures (Lilley, 1982; 1984). These currents are non-uniform where heterogeneous electrical conductivity structure exists.

Electromagnetic (EM) induction studies have established major locations of heterogeneous conductivity structure for the Australian continent. Wang (1998) summarises these studies and shows the locations of known intra-continental conductivity anomalies. However, the strongest and most consistent heterogeneities in electrical conductivity are associated with coastlines.

The conductivity structure near coastlines results from the juxtaposition of seawater and oceanic lithosphere, with continental lithosphere. Non-uniform electrical currents induced here, by the time-varying external magnetic field, primarily modify the vertical component of the magnetic field (Parkinson, 1959). At mid to high latitudes, the vertical field makes a significant contribution to the total field, as shown in Figure 1. Consequently, the coast effect has important implications for magnetic mapping.

The CICADA project (Clarifying Induction Contributions to Aeromagnetic DAta) has investigated interactions between electromagnetic induction in the Earth and total-field magnetic mapping data. In particular, the CICADA97 experiment, located in southeast Australia, investigated the implications of EM induction near the coast, for short-period variations of the total field.

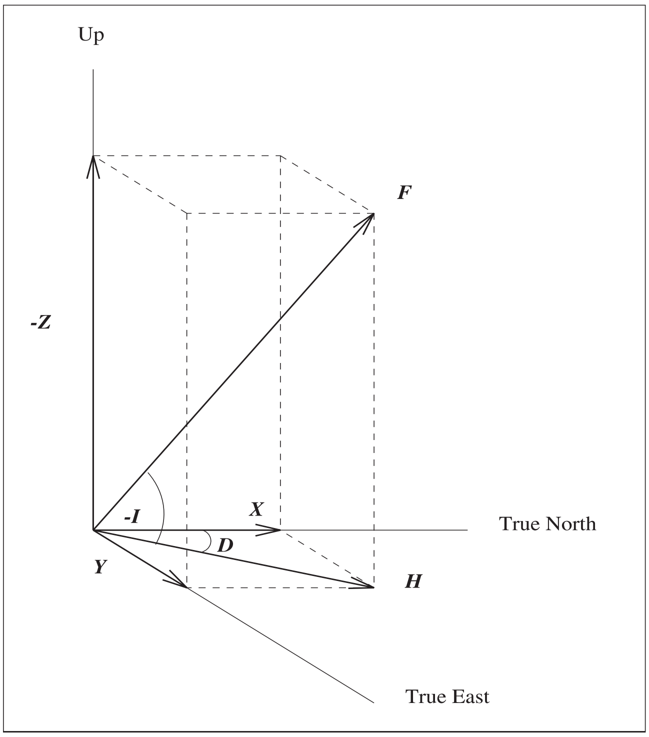

Fig. 1. Components of Earth's magnetic field (total field *F*, horizontal component *H*, vertical component *Z*, north component *X*, east component *Y*, declination *D*, inclination *I*). The orientation of the vertical component, which results in both *Z* and *I* having negative values, describes the southern-hemisphere magnetic field direction.

[1] *Research School of Earth Sciences*
The Australian National University
Canberra ACT 0200
Phone: (02) 6249 3424
Facsimile: (02) 6249 0738
E-mail: adrian@rses.anu.edu.au

[2] *Australian Geological Survey Organisation*
GPO Box 378
Canberra ACT 2601
Phone: (02) 6249 9224
Facsimile: (02) 6249 9913
E-mail: peter.milligan@agso.gov.au

[3] *Research School of Earth Sciences*
The Australian National University
Canberra ACT 0200
Phone: (02) 6249 4174
Facsimile: (02) 6249 0738
E-mail: ted.lilley@anu.edu.au

[4] *School of Earth Sciences*
The Flinders University of South Australia
GPO Box 2100
Adelaide SA 5001
Phone: (08) 8201 2359
Facsimile: (08) 8201 2676
E-mail: antony.white@es.flinders.edu.au

[5] *School of Earth Sciences*
The Flinders University of South Australia
GPO Box 2100
Adelaide SA 5001
Phone: (08) 8201 2607
Facsimile: (08) 8201 2676
E-mail: graham.heinson@es.flinders.edu.au

Earlier studies, for example, Bennett and Lilley (1971), Lilley and Bennett (1972), Kellett et al. (1991), have documented the coast effect in this region for magnetic-field variations with period ranging from tens of minutes up to 24 hr. CICADA97 develops this earlier work by extending the period range down to 10 s, and by specifically considering the total-field ramifications of EM induction effects at coastlines.

THE CICADA97 EXPERIMENT

A line of ten 3-component magnetometers, extending from inland NSW, across the coast, to the deep Tasman Sea, was deployed in September 1997 (Figure 2 and Table 1). The instruments were fluxgate magnetometers based on those reported by Chamalaun and Walker (1982), with enhancements by A. White and G. Heinson of The Flinders University of South Australia, to incorporate ringcore sensors and solid-state memory. All magnetometers had a least-count resolution of 0.1 nT (Milligan, 1995); the land instruments and Solo (on the continental slope) sampled the field every 5 s, and the deep-sea instruments every 10 s.

The seafloor magnetometers were deployed and retrieved using the RV *Franklin*, operated by the Commonwealth Scientific Industrial Research Organisation (CSIRO). Solo was deployed specifically as part of the CICADA97 line. The deep-sea deployments, SODA3 and SODA4 had, by design, the dual function of both contributing to CICADA97, and also providing seafloor observatory data for a simultaneous experiment studying motional electromagnetic induction by the movement of seawater in the East Australian Current. This latter experiment was named Study of Ocean Dynamo Action (SODA).

CNB is the Canberra magnetic observatory, operated by the Australian Geological Survey Organisation (AGSO). CNB data were recorded using a 3-component *Narod* ringcore fluxgate magnetometer. This instrument has a sample interval of 1 s and a least-count resolution of 0.025 nT (Hopgood and McEwin, 1997).

TIME SERIES DATA

Figure 3 shows three days (274 to 276) of recording for stations from CLC to SODA4. The inland station, BLN, recorded insufficient data during the selected period to be included in this figure. In addition to the field components H, D and Z, variations of the total field (F) are shown in the figure. The total-field variations, $f(t)$, have been computed from

$$f(t) = h(t) \cos I + z(t) \sin I \ , \qquad (1)$$

where $h(t)$ and $z(t)$ are the time variations of H and Z, respectively, and I is the main-field inclination in degrees (see Figure 1).

The similarity of $h(t)$ and $d(t)$ variations, for the land stations and Solo, indicates that relatively uniform source fields existed during this period of recording. The SODA3 and SODA4 data have been recorded below almost 5 km of ocean. The attenuation of these variations, particularly evident at short periods, is due to this overlying seawater.

The first 24 hours displayed in Figure 3 are relatively active. Vertical variations with period approximately 1 hr are progressively enhanced as the coastline is approached. This enhancement is a typical response to a coastal conductivity structure that is essentially two-dimensional (Parkinson, 1962). At these periods, similar enhancement is evident in the total-field variations. This enhancement is exemplified by the negative excursion of the total field, which occurs at approximately 12:00 UT on day 274. It is recorded as a 9 nT excursion at the inland station CLC, and increases progressively to be 87 nT at Solo, on the continental shelf.

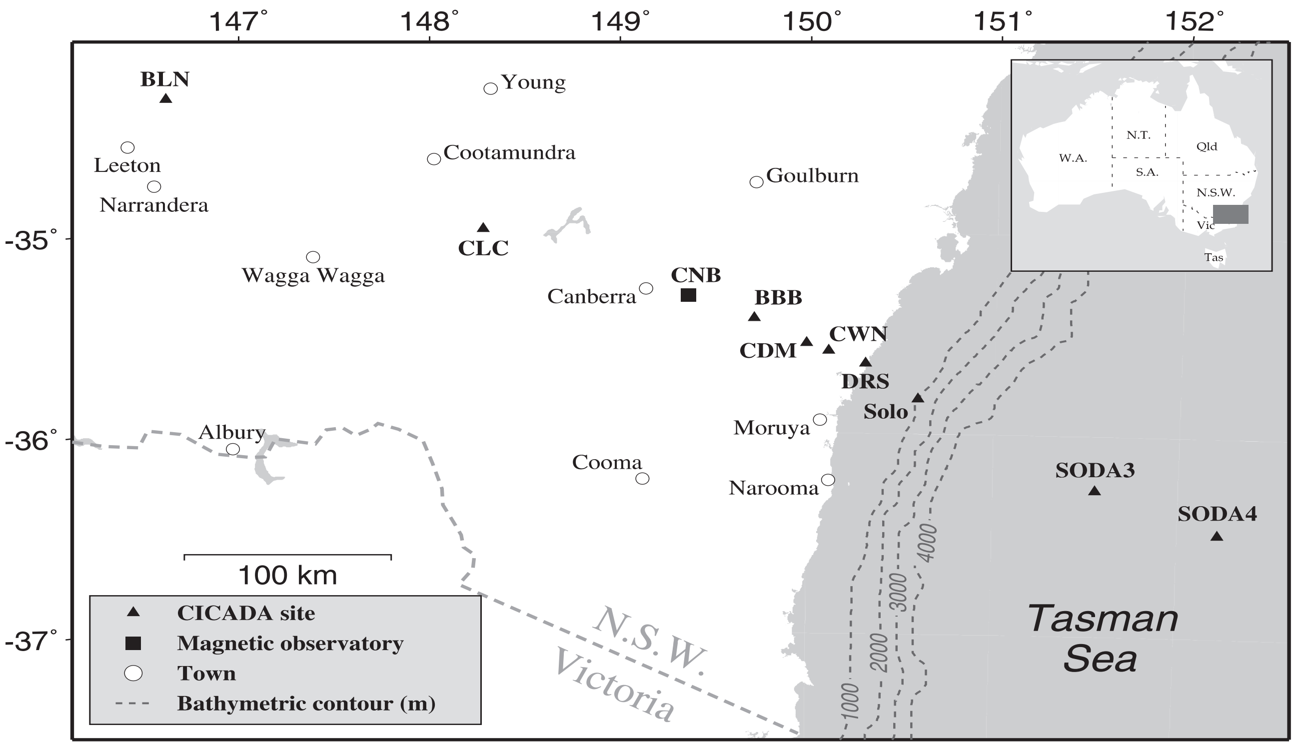

Fig. 2. Locations of CICADA97 stations used to investigate the total-field implications of the geomagnetic coast effect. CNB is the Canberra magnetic observatory operated by AGSO. The 'D' of DRS marks the position of Batemans Bay, referred to in the text.

Of additional interest is the difference between the total-field variations recorded at DRS and Solo. DRS, and locations like it, could conceivably be used as a base-station site for aeromagnetic surveys over the continental shelf. However, it is evident from Figure 3 that such coastal locations may be inadequate monitors of offshore temporal variations. For example, the negative field excursion previously described is almost three times larger at Solo than at DRS.

The data contain evidence of additional effects at shorter periods. Figure 4 shows in greater detail the sudden commencement (SC) which occurred at 01:00 UT on day 274. This event, and the ensuing short-period activity, has consistent amplitude at stations between CLC and CWN, but is significantly enhanced and modified at both DRS and Solo. (The higher frequency content in the BBB record, evident in this and the following figure, is the result of instrumental noise.)

Figure 5 shows a train of micropulsations that began at 11:00 UT on day 276. Again, the stations CLC to CWN display a relatively uniform record of this activity, however DRS and Solo exhibit significant departures from this pattern. At DRS, micropulsation variations are substantially attenuated and there is a suggestion of a reversal in orientation. This reversal is very apparent in the Solo data, in conjunction with strong enhancement of the micropulsations. Milligan et al. (1993) report relatively uniform micropulsations measured over a 40 x 40 km inland area. In a subsequent study, Milligan (1995) found micropulsations tended to possess similar phase, but varying amplitude, over a 1:250 000 map sheet. As shown in Figure 5, over short distances, patterns of micropulsation amplitude and phase can be strongly influenced by coastal conductivity patterns.

TRANSFER FUNCTIONS

The tendency for short-period vertical variations (Z) to result from induction by H and D is expressed in the relationship

$$Z(w) = A(w)\,H(w) + B(w)\,D(w)\ , \qquad (2)$$

in which all parameters are complex, having real and quadrature parts, and are frequency dependent (Parkinson and Jones, 1979). The transfer functions A and B are influenced by the underlying electrical conductivity structure.

It is common to represent the transfer functions diagrammatically as real and quadrature ‘induction arrows’. These arrows are derived by vectorially adding the eastward-directed B to the northward-directed A. By reversing the direction of the real transfer functions before addition, a real induction arrow is obtained which points toward a nearby good conductor. Whether quadrature transfer functions are reversed prior to addition is dependent on the time dependence used in transforming the data to the frequency domain (Lilley and Arora, 1982). The orientation of the induction arrow also shows the orientation, or polarisation, of the horizontal variations which results in the strongest induction of vertical variations (Parkinson, 1962). The length of the induction arrow is related both to the proximity of the conductor and to its conductivity contrast with the background structure.

In deriving induction arrows for the CICADA97 stations, the variations in H and D recorded at CNB have been taken as representative of those occurring at each station in the line, or, in the case of the marine stations, at the sea-surface above the station (Ferguson et al., 1990). That is to say, local vertical variations have been used in equation (2) with CNB horizontal variations to obtain transfer functions, and hence induction arrows, for each station. For land stations, this approach ensures that local peculiarities, such as instrumental effects, do not adversely perturb the transfer functions, and Figure 3 indicates that CNB horizontal variations are indeed representative of those recorded at each site. For marine stations, this approach results in arrows which are representative of the sea-surface, rather than the seafloor (Ferguson, 1988; Ferguson et al., 1990). The RRRMT software package (Chave et al., 1987; Chave and Thomson, 1989) was used to solve equation (2), to find A and B.

Figure 6 shows the real induction arrows obtained for each station by first reversing, then vectorially adding, the transfer functions A and B. The BLN arrows were derived using CNB horizontal variations and BLN vertical variations recorded on day 273.

A feature of Figure 6 is that induction arrows are generally oriented toward the coastline, and suggest an essentially two-dimensional conductivity structure. This orientation indicates that the strong conductivity contrast between highly conductive seawater and continental crust is an important influence on the generation, by induction, of variations in the vertical component of the magnetic field. The orientation of the induction arrows also indicates the

Station	Code	Longitude	Latitude	Elevation
Barellen	BLN	146°36.5'E	34°19.0'E	208m
Coolac	CLC	148°16.2'E	34°58.9'E	313m
Canberra	CNB	149°21.8'E	35°18.9'E	859m
Bombay Bridge	BBB	149°42.8'E	35°25.6'E	667m
Clyde Mtn.	CDM	149°59.6'E	35°33.0'E	213m
Currowan	CWN	150°08.9'E	35°35.7'E	50m
Durras	DRS	150°17.2'E	35°39.4'E	10m
Solo	Solo	150°34.9'E	35°49.3'E	-523m
SODA3	SODA3	151°33.2'E	36°16.3'E	-4807m
SODA4	SODA4	152°13.2'E	36°29.1'E	-4772m

Table 1. Details of the location of CICADA97 stations. Longitudes and latitudes are in geographic coordinates. All data are derived from GPS measurements; with the exception of CNB, obtained from Hopgood and McEwin (1997); ocean depths for the three seafloor magnetometers, obtained from the RV *Franklin* depth sounder; and data for CWN and DRS, estimated from the Ulladulla 1:250 000 topographic map.

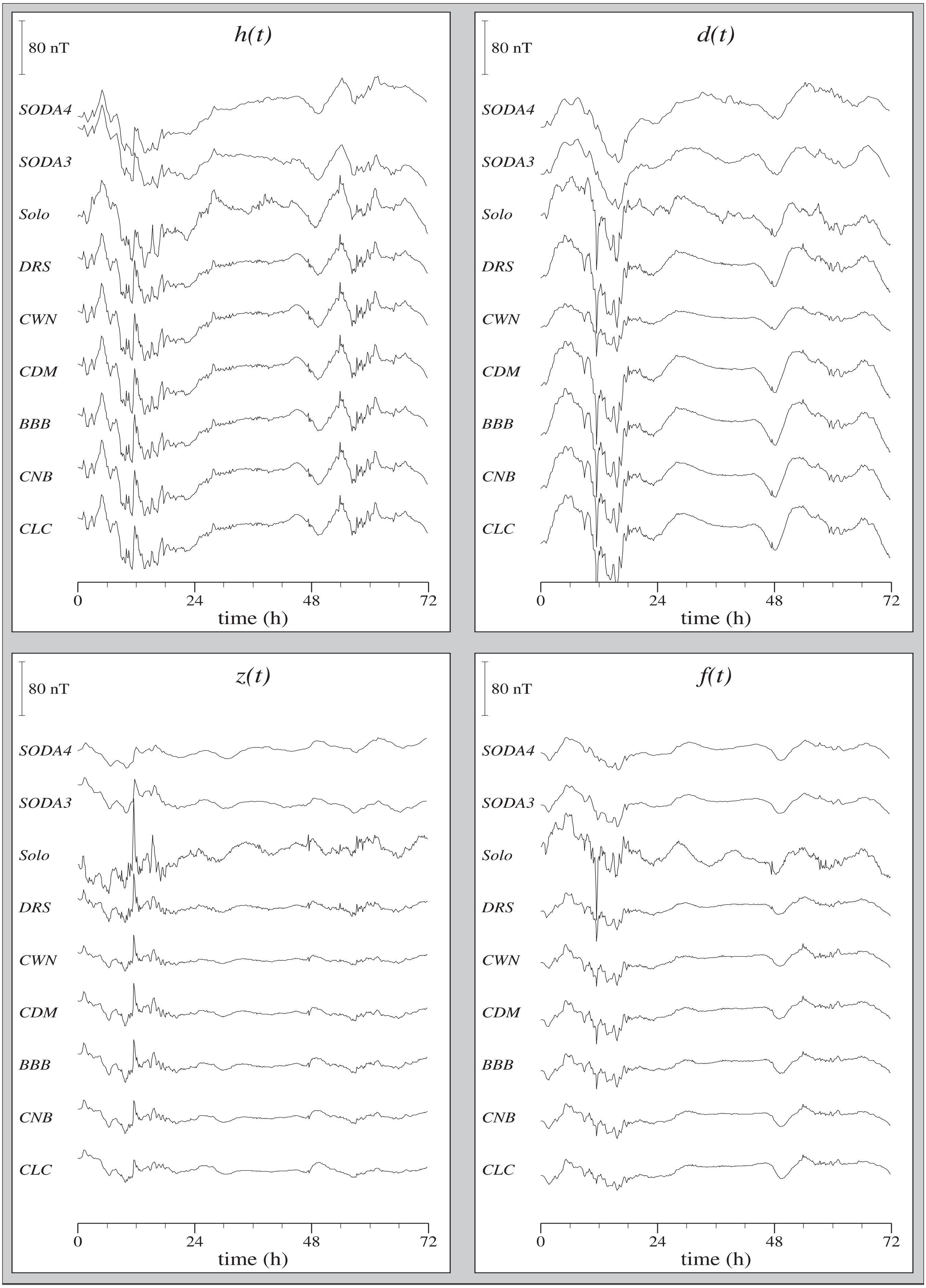

Fig. 3. Variations of the horizontal component, declination, vertical component and total-field (*h(t)*, *d(t)*, *z(t)* and *f(t)*, respectively) recorded at the CICADA97 sites. Data are for a 72 hr period consisting of day 274 to 276 (1 October to 3 October), 1997.

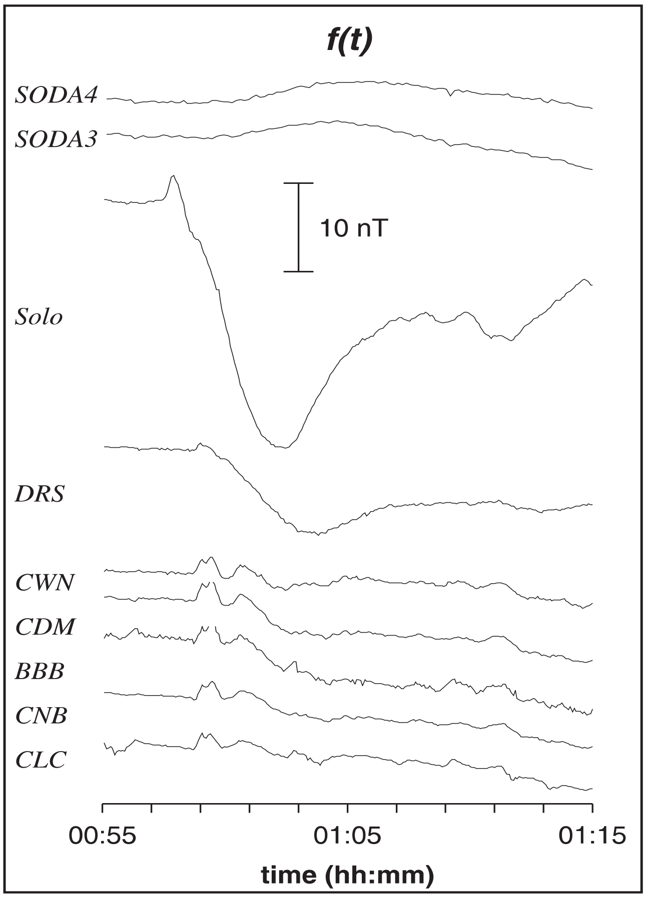

Fig. 4. Expanded total-field record of the sudden commencement that occurred at 01:00 UT on day 274.

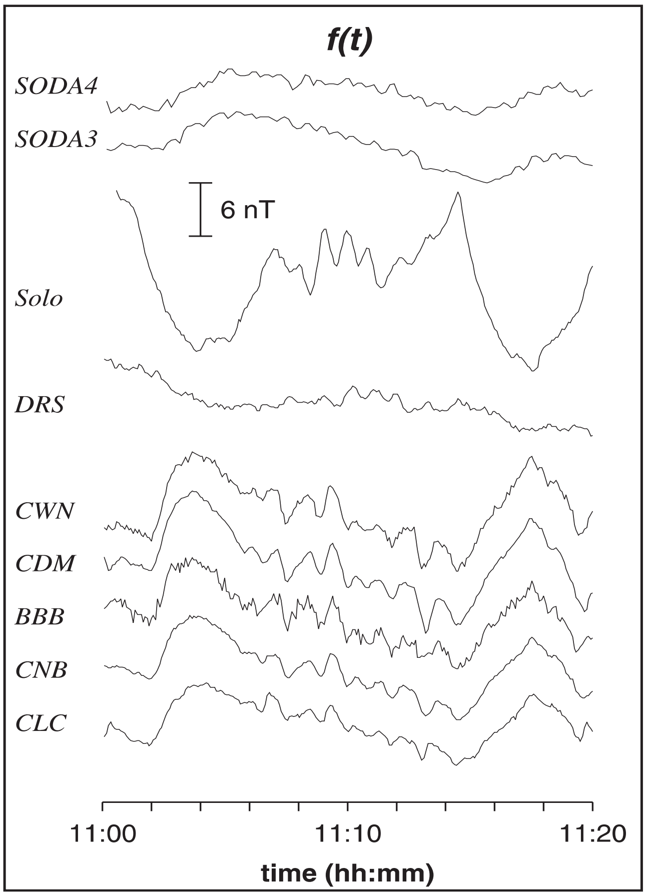

Fig. 5. Expanded total-field record of micropulsations that began at 11:00 UT on day 276.

polarisation of horizontal variations which results in the strongest induction effect. The induced vertical fields are a significant contributor to the time-varying total field at mid to high latitudes, as shown in equation (1).

It is evident from Figure 6 that even at BLN, the most inland station, magnetic-field variations with period greater than 1000 s (about 15 min) are influenced by the coast effect. At stations nearer the coastline, induction arrows have two general features. First, the coast effect influences variations with progressively shorter period at stations progressively nearer the coastline. Second, the increasing length of the arrows indicates that the induced vertical field is stronger near the coast.

The induction arrows at DRS and Solo are exceptions to this pattern, and depart markedly from the general southeast orientation of the other arrows. This departure indicates the existence of more complex, three-dimensional, conductivity structure in the vicinity of these stations, and suggests a complexity of short-period induction patterns which is not observed at other stations. This suggestion of complexity is also evident in the abruptness with which the short-period arrow pattern changes between CWN and DRS, two stations that are only 15 km apart.

The DRS induction arrows indicate the presence of a strong conductivity contrast located to the south of the station. It is possible that Batemans Bay, a relatively small coastal indentation that extends 10 km inland (Figure 2), is the feature causing the reorientation of the DRS arrows.

There is an additional consequence of the southward orientation of the DRS arrows. Lilley et al. (1999) describe the circumstances under which total-field variations may be suppressed owing to the effect of electromagnetic induction in the Earth, and have termed locations where this occurs 'magnetic amphidromes'. This suppression is related to the electrical conductivity structure, represented by the induction arrows, and the inclination of the main field. In the southern hemisphere, amphidromic conditions exist where induction arrows are oriented southward and have a length equal to -cot I.

At DRS, the inclination is approximately -66° (Lewis and McEwin, 1996), so that -cot $I = 0.45$. In the period range 26.7 s to 106.7 s, the DRS induction arrows have lengths ranging from 0.32 to 0.61, and a southerly orientation (see Hitchman (1999) for tabulations of these quantities). Hence, at these periods, amphidromic conditions are approached at DRS, and suppression of total-field variations in this period range is expected, as has been observed in Figure 5.

CONCLUSIONS

The coast effect causes significant enhancement of variations of the vertical magnetic field. At mid to high latitudes, these vertical fields are an important component of total-field variations.

At long periods, the influence of the coast effect on total-field variations can extend hundreds of kilometres inland. At these distances this influence is usually relatively small and spatially uniform. As proximity to the coast increases, however, the coast effect exerts a progressively stronger influence on total-field variations, and this influence extends to progressively shorter periods.

Associated with the influence of the coast effect on short-period variations is the increased likelihood of non-uniform spatial patterns of induction. This greater propensity for spatial non-uniformity can result from induction in relatively small, near-surface features such as bays and inlets.

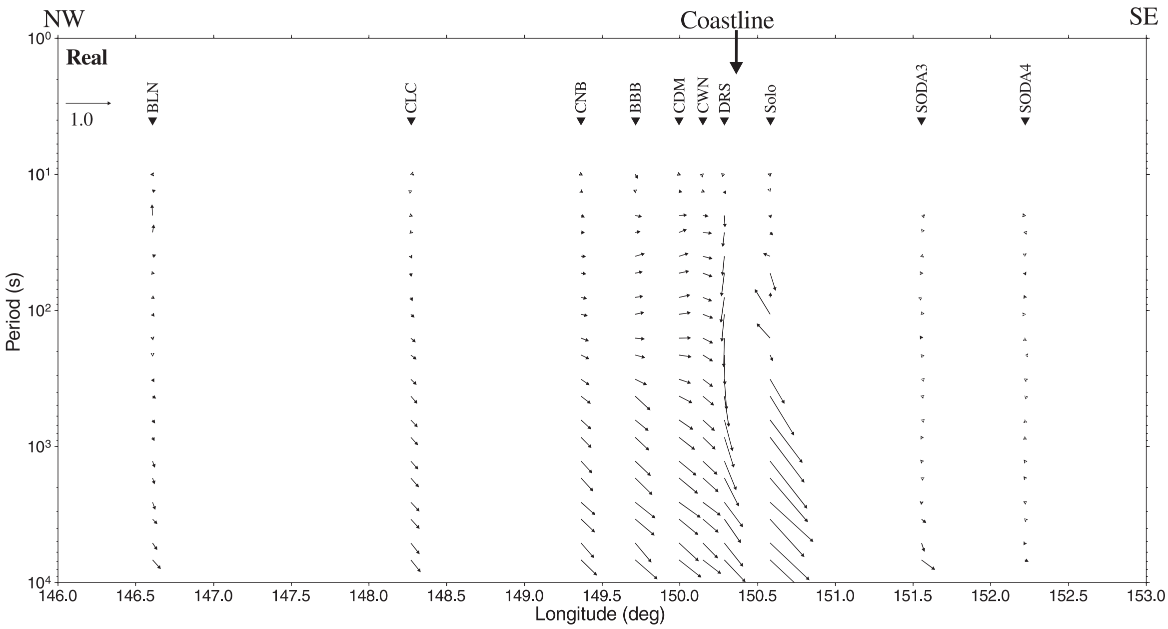

Fig. 6. Real induction arrows for the CICADA97 sites, derived using CNB as a reference site for horizontal variations. Data from days 274 to 276 were used for all stations, except BLN, where day 273 was used.

For an airborne survey with a tie spacing of 4 km and an aircraft speed of 60 m/s, the time required to traverse from one tie to the next is 67 s. Tie-line levelling is capable of removing temporal variations with period greater than the time taken to traverse two tie spaces. Hence, periods of several minutes and less cannot be removed. The coastal data presented here show a marked spatial non-uniformity at these periods, with amplitudes varying by several nanoTesla. These data indicate the problematic nature of attempting to remove such short-period variations using either tie-line levelling or solitary base stations.

This study has highlighted the potential for significant heterogeneity in spatial patterns of total-field variations near coastlines. It sheds more light on the difficulties associated with attempting to obtain a single record of temporal field variations that adequately represents variations across a coastal survey area, and suggests the value of base-station arrays in such situations.

ACKNOWLEDGEMENTS

The authors wish to thank Satoru Yamaguchi, Kobe University, Japan, for assistance with fieldwork. The Geomagnetism Group, AGSO, has provided data from CNB. During the course of this research APH was the recipient of an ANU PhD scholarship. PRM publishes with the permission of the Executive Director, AGSO.

The authors are grateful to two anonymous referees for comments, which have resulted in improvements to this paper.

REFERENCES

Bhattacharyya, B. K., 1971, An automatic method of compilation and mapping of high-resolution aeromagnetic data: Geophysics, 36, 695-716.

Bennett, D. J. and Lilley, F. E. M., 1971, The effect of the south-east coast of Australia on transient magnetic variations: Earth and Planet. Sci. Lett., 12, 392-398.

Chamalaun, F. H. and Walker, R., 1982, A microprocessor based digital fluxgate magnetometer for geomagnetic deep sounding studies: J. Geomag. Geoelectr., 34, 491-507.

Chave, A. D. and Thomson, D. J., 1989, Some comments on magnetotelluric response function estimation: J. Geophys. Res., 94, 14215-14225.

Chave, A. D., Thomson, D. J. and Ander, M. E., 1987, On the robust estimation of power spectra, coherences and transfer functions: J. Geophys. Res., 92, 633-648.

Ferguson, I. J., 1988, The Tasman Project of Seafloor Magnetotelluric Exploration: PhD thesis, The Australian National Univ.

Ferguson, I. J., Lilley, F. E. M., and Filloux, J. H., 1990, Geomagnetic induction in the Tasman Sea and electrical conductivity structure beneath the Tasman seafloor: Geophys. J. Internat., 102, 299-312.

Hitchman, A. P., 1999, Interactions Between Aeromagnetic Data and Electromagnetic Induction in the Earth: PhD thesis, The Australian National Univ.

Hopgood, P. A. and McEwin, A. J., 1997, Australian Geomagnetism Report 1994, Report 42, Australian Geological Survey Organisation.

Kellett, R. L., Lilley, F. E. M. and White, A., 1991, A two-dimensional interpretation of the geomagnetic coast effect of southeast Australia, observed on land and seafloor: Tectonophysics, 192, 367-382.

Lewis, A. M. and McEwin, A. J., 1996, The geomagnetic field in the Australian region, Epoch 1995.0, Australian Geological Survey Organisation.

Lilley, F. E. M., 1982, Geomagnetic field fluctuations over Australia in relation to magnetic surveys: Bull. Austral. Soc. Expl. Geophys., 13, 68-76.

Lilley, F. E. M., 1984, On the spatial pattern of magnetic fluctuations in the Cobar area, NSW: Expl. Geophys., 15, 79-83.

Lilley, F. E. M. and Arora, B. R., 1982, The sign convention for quadrature Parkinson arrows in geomagnetic induction studies: Rev. Geophys. and Space Phys., 20, 513-518.

Lilley, F. E. M. and Bennett, D. J., 1972, An array experiment with magnetic variometers near the coasts of southeast Australia: Geophys. J. Roy. Astr. Soc., 29, 49-64.

Lilley, F. E. M., Hitchman, A. P. and Wang, L. J., 1999, Time-varying effects in magnetic mapping: amphidromes, doldrums and induction hazard: Geophysics, 64, 1720-1729.

Milligan, P. R., 1995, Short-period geomagnetic variations recorded concurrently with an aeromagnetic survey across the Bendigo area, Victoria: Expl. Geophys. 26, 527-534.

Milligan, P. R., White, A., Heinson, G. and Brodie, R., 1993, Micropulsation and induction array study near Ballarat, Victoria: Expl. Geophys. 24, 117-122.

Parkinson, W. D., 1959, Directions of rapid geomagnetic fluctuations: Geophys. J. Roy. Astr. Soc., 2, 1-14.

Parkinson, W. D., 1962, The influence of continents and oceans on geomagnetic variations: Geophys. J. Roy. Astr. Soc., 6, 441-449.

Parkinson, W. D. and Jones, F. W., 1979, The geomagnetic coast effect: Rev. Geophys. and Space Phys., 17, 1999-2015.

Reeves, C. V., 1993, Limitations imposed by geomagnetic variations on high quality aeromagnetic surveys: Expl. Geophys., 24, 115-116.

Wang, L. J., 1998, Electrical Conductivity Structure of the Australian Continent: PhD thesis, The Australian National Univ.