Geomagnetic Field Fluctuations over Australia in Relation to Magnetic Surveys

F. E. M. Lilley

Research School of Earth Sciences
Australian National University
P.O. Box 4, Canberra, A.C.T. 2600

Key words: magnetic, fluctuations, survey, induction, geographic uniformity, coast effect, anomaly, Australia

Abstract

Fluctuations of the earth's magnetic field with time can be a source of error of up to tens of nanotesla in magnetic surveying or prospecting. The best defence against possible difficulties such fluctuations may cause lies in understanding their origin, and their geographical uniformity or non-uniformity. The geographical uniformity of magnetic fluctuations has now been measured over several different areas of the Australian continent as part of research projects to examine natural electromagnetic induction taking place in the earth. The present paper shows examples of the results and gives some general description of magnetic fluctuations characteristics at coastlines, inland, and offshore. A major zone of non-uniform magnetic fluctuations has been detected in two places and may run north-south right across the continent.

1. Introduction

It is well-known that the earth's magnetic field as measured at the earth's surface can be regarded as being composed of a major part which is steady and a minor part which fluctuates with time. The steady part arises internal to the earth and may itself change with time (and even reverse) over geologically long times. The fluctuating part has its origin in primary electric currents which flow outside the earth (in the ionosphere and beyond) and in induced secondary currents which flow near the surface and inside the earth. The induced secondary currents flow on global circuits in seawater and in the crust and upper mantle.

The induction of internal electric currents by the external currents and the paths where the internal currents flow are basic research problems in geophysics, giving information on the fundamental structure of the continent. Non-uniform magnetic fluctuations may indicate electrical conductivity contrasts on a regional scale. To study these phenomena a series of magnetometer arrays has been operated over different parts of Australia in 1970, 1971, 1973-74, 1976 and 1977. Together with other (some much earlier) magnetic fluctuation measurements, the observations have clarified patterns of magnetic fluctuation near coastlines and have discovered several major anomalous zones inland. The arrays have thus obtained much data on the patterns of magnetic fluctuations over Australia.

1.1 Relevance to magnetic surveying

The question of the spatial uniformity of transient magnetic fluctuations arises in magnetic surveying due to the desirability of removing the effects of changes with time from data which are intended to show changes of the magnetic field with space. In an early paper on this subject Booth (1936) compared variations in the vertical component of magnetic fluctuations measured near Mittagong, N.S.W. (100 km SW from Sydney) with those recorded simultaneously at the Toolangi Observatory some 570 km away (and 50 km NE from Melbourne). Booth noted differences between the Mittagong and Toolangi data, and concluded that it was not valid to apply as corrections to a magnetic survey the variations measured at an established magnetic station, when station and survey area were as far removed from one another as Toolangi and Mittagong. Example 3 below has direct relevance to Booth's observations, and further discussion of them will be given there.

A modern version of the same question concerns the strategy of reducing oceanographic and aeromagnetic data (which are total field readings) by subtracting from them point by point the simultaneously recorded data from a fixed base station. Clearly the extent to which such a procedure will be satisfactory depends on the extent to which the fluctuations at the base station represent those which occur where the survey ship or aircraft is at the time.

In the present paper some data from Australian magnetometer arrays are examined for information they contain on this basic question. Examples are presented of uniformity and non-uniformity in magnetic fluctuation patterns over Australia. The examples are from magnetic storms where the fluctuations occur over times of minutes and hours, and from the records of a magnetic 'quiet' day.

It is relevant to note also that the converse possibility has been explored in Europe of using regular aeromagnetic survey data to give information on the presence of spatially non-uniform magnetic fluctuations, and thus to detect anomalous electrical conductivity structures in the earth. Two papers in particular inquiring into this problem are by Le Borgne & Le Mouel (1975), and Gregori & Lanzerotti (1979). The former paper uses misfits of the flight-lines and tie-lines of an aeromagnetic survey to deduce magnetic fluctuation data for the western Mediterranean Sea (and thus a conductivity anomaly in Western Europe).

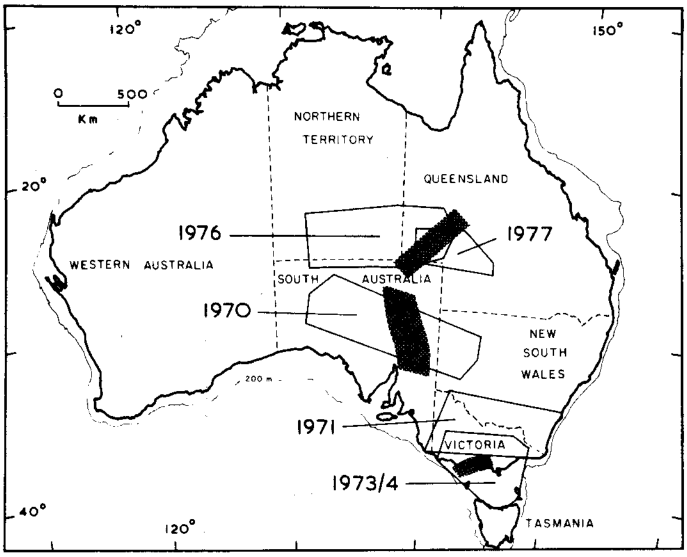

FIGURE 1

Areas covered by magnetometer array studies in Australia. Hatched regions mark the zones of strongest spatial non-uniformity in magnetic fluctuation patterns. In addition a 'coast effect' may be expected to be present everywhere around the edge of the continental shelf. The areas away from the marked zones are not necessarily regions of completely uniform magnetic fluctuation patterns.

The latter paper examines theoretical aspects of some of the data reduction and computational procedures involved.

2. Array areas and instrumentation

The present paper gives examples of data from the magnetometer arrays carried out over the areas shown in Fig. 1. These areas were chosen for study for reasons to do with electromagnetic induction and the tectonic aspects of Australia, rather than to commence a systematic coverage of the continent; however, they have thus sampled continental electromagnetic induction in a number of different places. The results of these array studies have been reported in the scientific literature, in particular the 1970 array by Tammemagi & Lilley (1973) and Gough, McElhinny & Lilley (1974); the 1971 array by Bennett & Lilley (1974); the 1973-74 array by Lilley (1976); the 1976 array by Woods & Lilley (1979a); and the 1977 array by Woods & Lilley (1979b, 1980). Relevant theses are by Tammemagi (1972), Bennett (1972) and Woods (1979).

The array studies have employed some 20 magnetic variometers recording simultaneously. In addition, various other observations have been made in Australia using instruments in smaller numbers, for example Everett & Hyndman (1967), and White & Polatajko (1978). Magnetotelluric observations (e.g. Vozoff *et al.* 1975; Dekker & Hastie 1981) include measurement of fluctuations in the magnetic elements. All the exercises mentioned have been carried out against the framework of basic magnetic observatory work in Australia continued by the Bureau of Mineral Resources, the data from which have been widely used for scientific analysis both in Australia itself (e.g. Parkinson 1959, 1962, 1964; Petersons, Winch & Slaucitajs 1965) and elsewhere around the world (e.g. Banks 1969; Green & Malin 1971). The first observatory magnetic measurements in Australia appear to have been made in Parramatta, New South Wales in 1822 (Rumker 1829) and the first readings of the magnetic elements made with sufficient frequency to record storm fluctuations are likely to have been taken at the 'Rossbank' magnetic observatory established at Hobart, Tasmania in 1840 (see Day 1966; Green 1972).

The instrumentation for the magnetometer arrays shown in Fig. 1 has comprised a network of recording magnetic variometers which act as temporary magnetic observatories. The array studies in question used instruments of the Gough-Reitzel design as described by Gough & Reitzel (1967) and Lilley *et al.* (1975). The instruments record on photographic film at intervals of 10s, 30s or 60s depending on setting, and monitor fluctuations in three Cartesian components of the ambient magnetic field. The notation for the magnetic fluctuation components used in this paper will be D to the magnetic east, H to the magnetic north, and Z positive vertically downwards. A known interaction between the H and Z magnetic sensors in the recorded data is removed during data reduction.

At a station where the steady magnetic declination angle is θ, the fluctuation magnetic field components to the geographic north and east, X and Y respectively, are calculated by:

$$X = H\cos\theta - D\sin\theta$$

$$Y = H\sin\theta + D\cos\theta$$

Previous presentations of array results have generally all been in terms of such traditional component data. Because of the relevance of the present paper to 'total field' magnetic surveying however, characteristics of the temporal fluctuation F of the total magnetic field are here included also, calculated from the X and Z component data according to

$$F = X\cos I + Z\sin I$$

where I is the (steady) inclination angle of the ambient magnetic field. (Although calculation of F from X and Z has been used in the present paper, calculation of F from H and Z would be more direct.)

Two notes may be made concerning this equation for F. The first note follows from the convention that the quantity F is traditionally an amplitude and so is never negative. Thus in the southern magnetic hemisphere, where by convention the value of the vertical magnetic field is negative (as is the value of the magnetic inclination), fluctuations in the vertical field component enter fluctuations of the total field component with changed sign. This effect can be seen in the examples to follow.

The second note is that the contribution of fluctuations in the vertical field to fluctuations in the total field increases with increasing magnetic inclination. Thus Z fluctuations enter F fluctuations minimally at the magnetic equator, and maximally at the magnetic poles.

3. Some notes on the physics involved

The main purpose of this paper is to present examples of observed data which demonstrate the extent to which magnetic fluctuation patterns over Australia may be spatially non-uniform. Quantitative analysis of such data (for both Australia and other continents) has shown the importance of the following three factors in influencing the characteristics of any particular fluctuation pattern, especially in the vertical component of the fluctuating field. The three *factors* are basically properties of the primary source fields which are present external to the solid earth.

3.1 Frequency dependence

Natural magnetic fluctuations occur over a wide frequency range (see for example Campbell 1967). The part of the natural frequency range which is likely to affect magnetic surveying includes magnetic pulsations (which vary over seconds and minutes), magnetic substorms and storms (which vary over minutes, hours and sometimes days), and magnetic quiet days (which vary over hours and tens of hours). Spatial non-uniformity in magnetic fluctuations is generally frequency dependent to some degree so that, to mention one particular possibility, an area with an anomalous substorm pattern may have a smooth daily-variation pattern.

3.2 Horizontal polarization

Especially in areas of anomalous magnetic fluctuations, the strength of the vertical magnetic fluctuation component is usually found to depend on the geographic direction in which the horizontal magnetic fluctuation component is varying: i.e. the direction of 'horizontal polarization' of the magnetic fluctuation. This relationship between vertical fluctuation strength and horizontal fluctuation direction is the basis for the determination of 'Parkinson arrows' (Parkinson 1962) and other similarly determined parameters.

3.3 Source-field uniformity

Non-uniformity can be introduced into observed magnetic fluctuation patterns by electric currents in the overhead source-field which are themselves non-uniform. Whereas non-uniformity due to geology will be geographically consistent (as the geological structure is fixed) many aspects of source-field non-uniformity will be inconsistent from one magnetic event to the next because of the lack of consistent structure in the earth's ionosphere, where the source fields particularly arise.

Source-field non-uniformities for magnetic storms are, however, strongest near where overhead currents are concentrated, which is particularly in the auroral and equatorial regions of the globe. Thus, although in principle source-field non-uniformities might arise as a hazard for magnetic surveying at any time, for Australia there is the fortunate circumstance that the continent lies in mid-latitudes, and non-uniformities in magnetic storm source-fields over Australia are generally very weak, indeed negligible, from the point of view of magnetic surveying.

The case of the quiet daily variation is different for Australia because for this phenomenon, the source fields pass directly over the continent (Matsushita 1967) approximately at the same rate as the sun. Non-uniformity for the daily variation source-field over Australia is then present and observed, most obviously as a phase pattern in which the variation differs from place to place simply as local solar time. In addition to this longitude-dependent phase pattern,

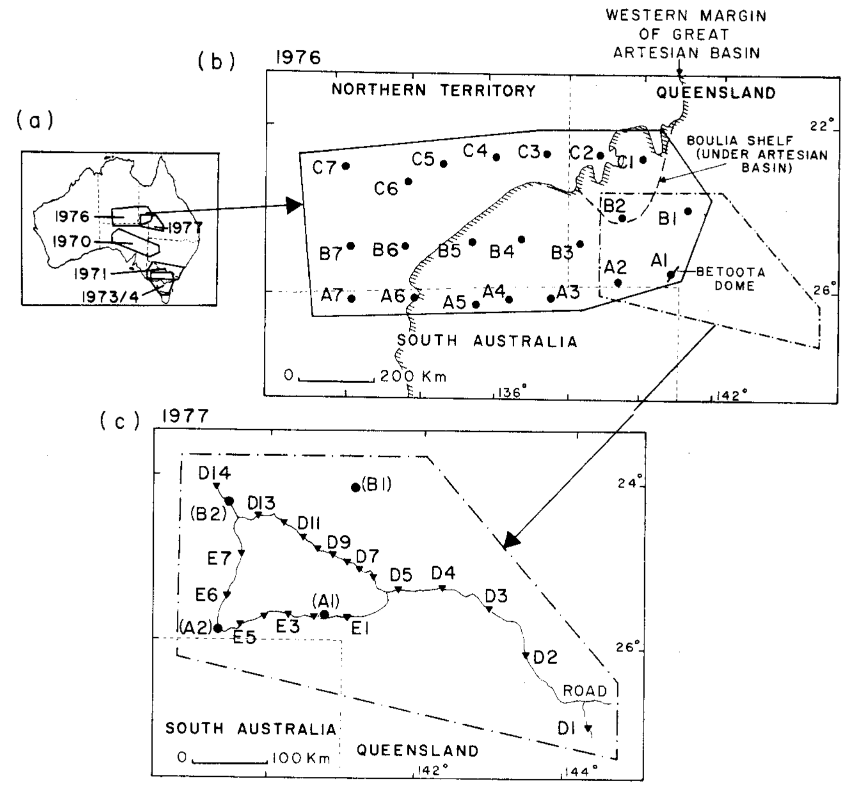

FIGURE 2

Sites of the 1977 magnetometer array study in western Queensland.

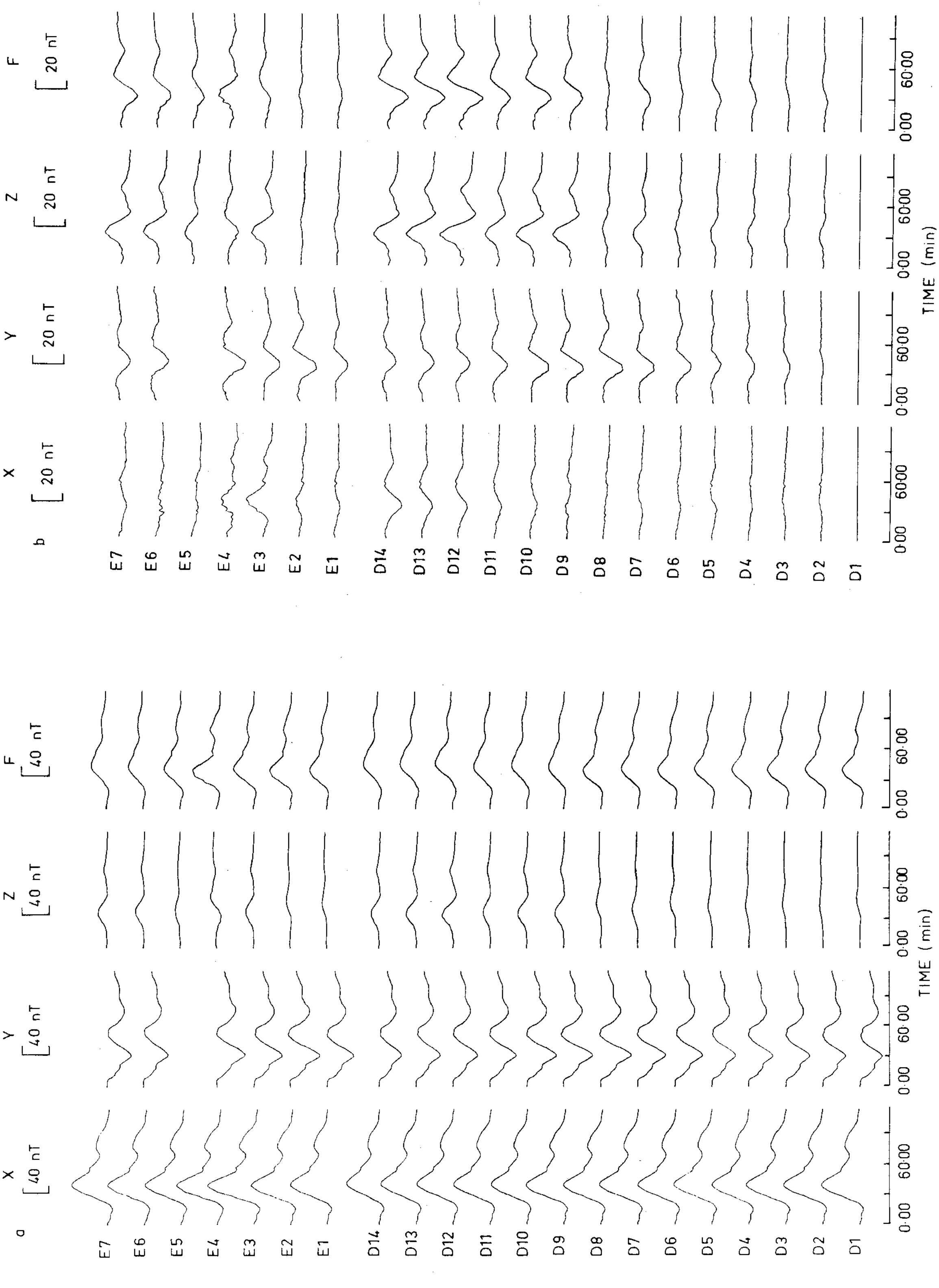

FIGURE 3

(a) Stacked profiles from the observations of the 1977 array of a magnetic substorm event commencing at 1105 h on 13 September 1977 UT and lasting for 115 min. (b) The difference profiles for the same event, obtained by subtracting the records of station D1 from all other station records.

there is a smooth latitude-dependent amplitude pattern (shown for example by Woods & Lilley 1979a). Beyond these known effects, which are quite smooth over the 100 km scales of magnetic surveys, the non-uniformities introduced by the source field of the magnetic quiet daily variation should be negligible for magnetic survey reduction purposes.

4. Examples

Given the variety of physical factors necessary to summarize the magnetic fluctuations response patterns for a particular area, the examples now to be presented must be understood to be samples only of the considerable range of data sets held for the areas shown in Fig. 1.

4.1 Example 1. Profiles from a closely spaced array in south-west Queensland

The 1977 array in south-west Queensland investigated in more detail an anomalous effect discovered by the 1976 array. The recording sites of the 1976 and 1977 arrays are shown in Fig. 2. A set of magnetic fluctuation profiles for a minor substorm event recorded by the 1977 array is shown in Fig. 3a. Note that, generally, the two horizontal components X and Y of the fluctuation are spatially more uniform than the vertical component Z, which varies significantly in this particular area and at some sites shows reversals — compare for example, the Z signals at sites E3 and E4 which are only some 30 km apart. The total field (F) profiles in Fig. 3a show an enhanced fluctuation where the vertical component reverses, for example at site E4.

The differences between the records at the various sites in Fig. 3a are made more apparent in Fig. 3b, where now the signals for one particular station (here chosen to be D1) are subtracted from those recorded at all the other stations, so that Fig. 3b presents on an expanded scale the differences between the fluctuations recorded at the other stations and station D1. That is, if a base station were run at D1 and its signal subtracted from a survey instrument at another station, Fig. 3b shows the incomplete cancellations which would result for survey instruments at the different recording sites of the 1977 array. Note that for some stations (D2, D3, D6, D8, E1 and E2) the process is relatively effective; at other stations (especially D9 to D14, and E3 to E7) cancellation errors remain of the order of 20 nT.

Because of the proximity of some sites which show reversals in the vertical component of the magnetic fluctuations, Woods & Lilley (1979b, 1980) attributed the non-uniformity in the fluctuation fields in south-west Queensland to electrical conductivity structure in the earth's crust, indeed in the basement structure beneath the sediments of the Eromanga Basin. A particularly strong effect is present where the Mt Isa block has its south-east boundary at the Boulia shelf below the Great Artesian Basin.

4.2 Example 2. The coast effect of south-east Australia

The enhancement in the vertical magnetic fluctuation component which occurs near coastlines is one of the best established observed effects in geomagnetism (Parkinson 1959; Parkinson & Jones 1979). The effect is undoubtedly due at least partly to electromagnetic induction in sea water, and also possibly due in part to a contrast between continental and sea-floor geology. Work continues on

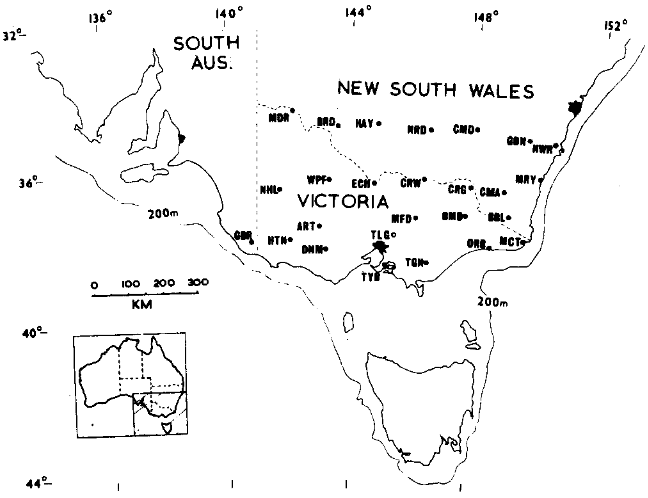

FIGURE 4

Sites of the 1971 magnetometer array study in south-east Australia.

theory and computation to explain the coast effect fully (see for example Cox 1980; Fainberg 1980).

The 1971 array in south-east Australia, recording at sites shown in Fig. 4, demonstrated the coast effect comprehensively for this particular region. A magnetic storm recorded by the array is shown in Fig. 5a, and the vertical fluctuations can be seen to be strongest near the coast, grading smoothly inland. Mildura (MDR) is the most inland station, and in Fig. 5b the records for Mildura are subtracted from all other station records to give difference profiles, which again make more apparent differences actually present in the basic data of Fig. 5a.

The 1971 data also contain anomalous effects for the stations in southern Victoria. These effects were further investigated by the 1973-74 array, which defined more clearly the 'Otway anomaly', detected most strongly near the Otway Ranges.

4.3 Example 3. The magnetic quiet daily variation

The fluctuation fields of the magnetic quiet daily variation penetrate more deeply into the earth (to order 500 km) than those of substorms, and the daily variation patterns though still sometimes anomalous, tend to be smoother than substorm patterns. Often for a shallow crustal induction anomaly, the effect in the magnetic daily variation fluctuation pattern may be barely detectable or not present at all.

However, the coast effect of south-east Australia is apparent in the daily variation, and in Fig. 6a are presented records for a quiet day for the sites of the same 1971 array as show the storm coast-effect in Fig. 5a. For reasons to do with its overhead source-field non-uniformity (mentioned above) the daily variation even inland (such as at Mildura, MDR) has a significant vertical component. This 'normal' vertical component signal undergoes interference by a long-period coast effect, to give resultant profiles at the various stations as shown in Fig. 6a. In Fig. 6b the quiet-day profiles are differenced with respect to Mildura and plotted on an expanded scale, to show more clearly the variation in the pattern across south-east Australia.

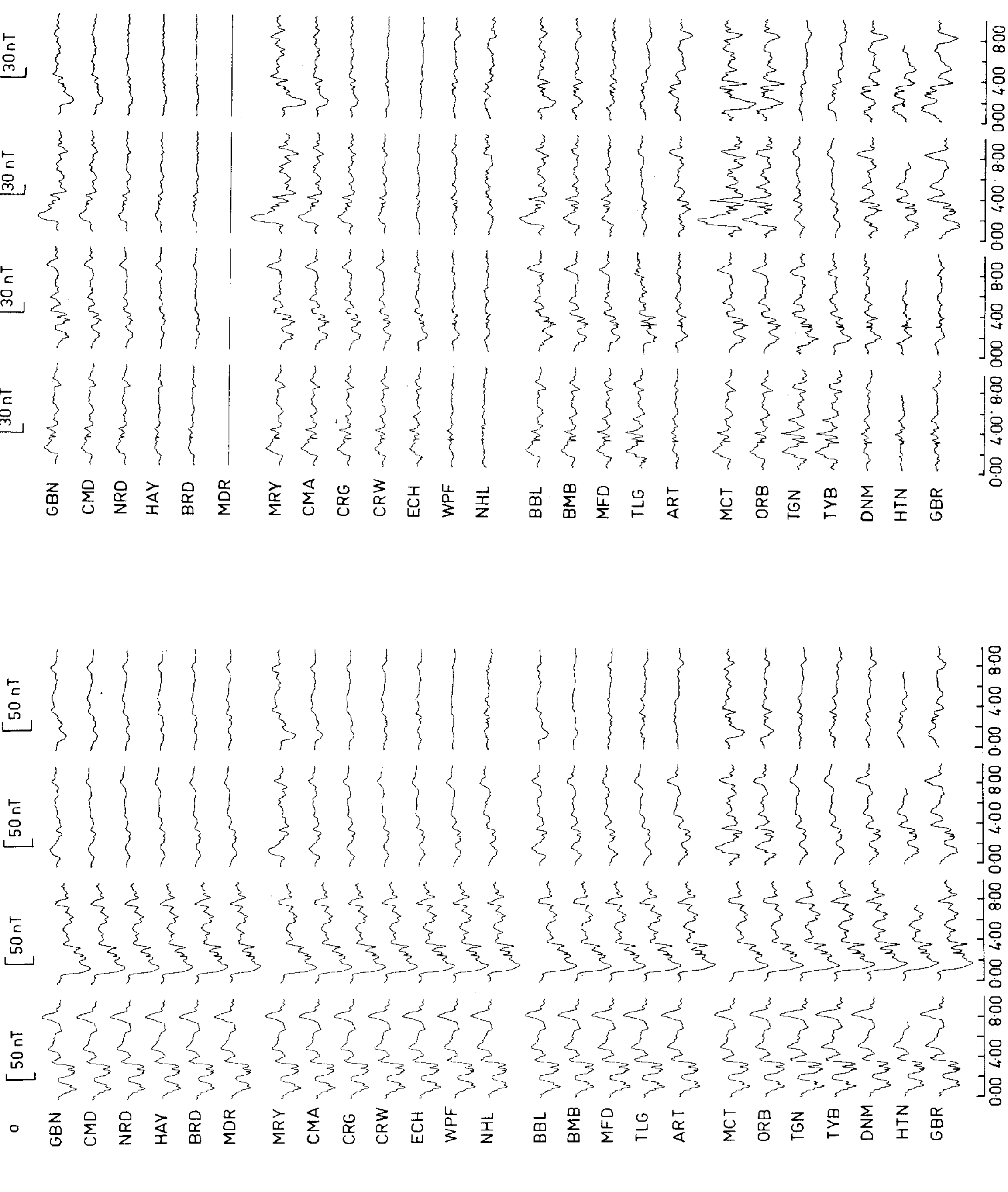

FIGURE 5

(a) Stacked profiles from the observations of the 1971 array of a magnetic storm event commencing at 0800 h on 11 April 1971 UT and lasting for 10 h. (b) The difference profiles for the same event, obtained by subtracting the records of station MDR (Mildura) from all other station records.

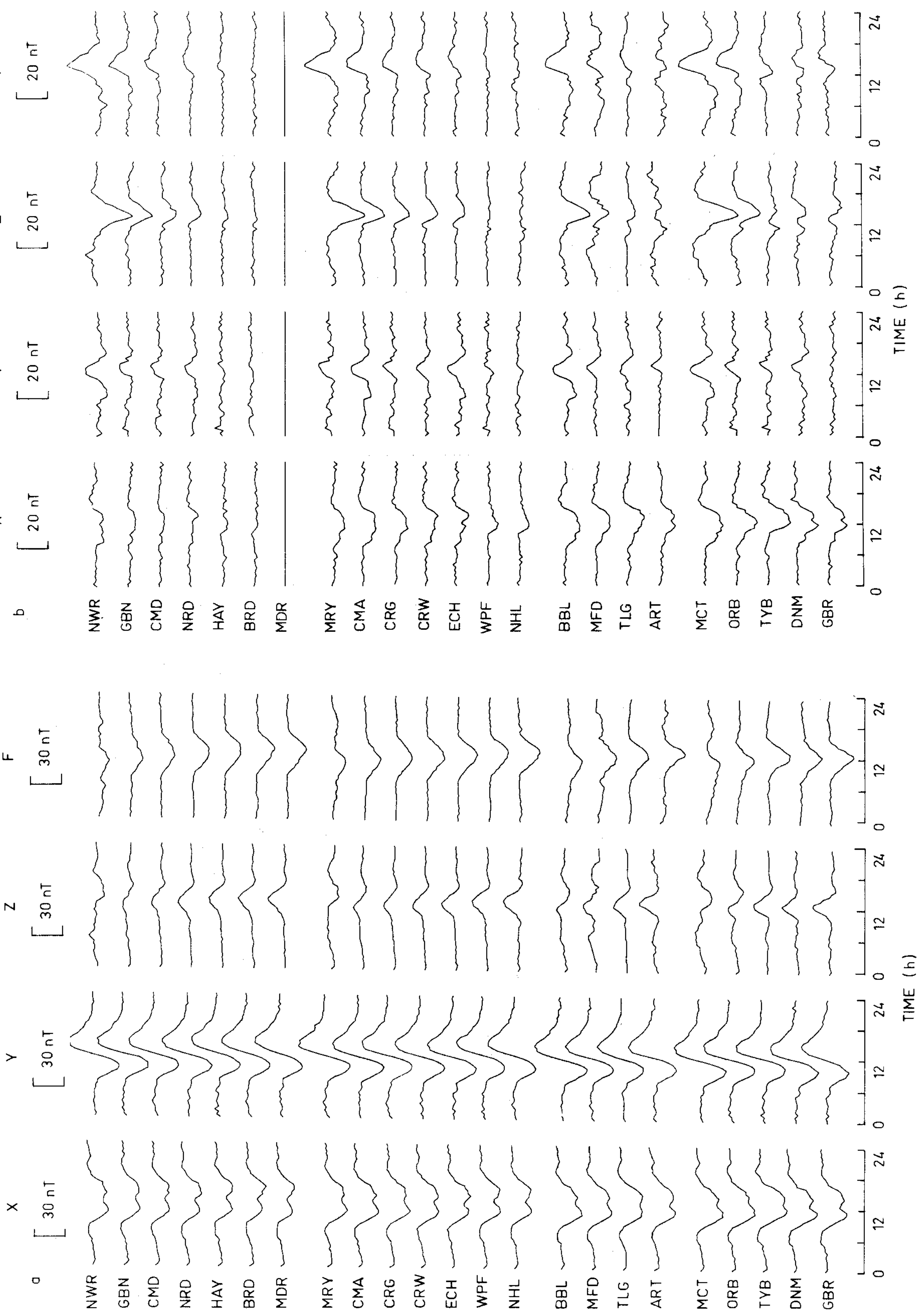

FIGURE 6
(a) Stacked profiles from the observations of the 1971 array of the magnetic 'quiet day' commencing at 1400 h on 24 April 1971 UT (that is at local solar midnight approximately) and lasting for 24 h.
(b) The difference profiles for the same event, obtained by subtracting the records of station MDR (Mildura) from all other station records.

It is now relevant to recall Booth's (1936) observations mentioned in the Introduction above. Figure 6a includes a record from Toolangi (TLG) itself, and also a record from Goulburn (GBN) which is the station of the 1971 array closest to Mittagong (Goulburn being 75 km to the south-east of Mittagong). Inspection of Fig. 6 indicates differences between Toolangi and Goulburn comparable to those observed by Booth between Toolangi and Mittagong, and closer analysis of the 1971 array data (as by Bennett & Lilley 1973) fills in the area between the two stations, interpreting the difference between them essentially as a coast effect (plus possibly at Toolangi a minor contribution from the 'Otway anomaly'). Thus Booth's (1936) observations are qualitatively accounted for without recourse to effects of local static magnetization.

5. Conclusions

The records of the various magnetic observatories and variometers which have operated throughout Australia have defined characteristic magnetic fluctuation patterns for the continent. Examples of the basic data have been given in this paper. The analysis of such data enables Australian magnetic fluctuation patterns to be summarized in three categories.

5.1 The coast effect

At every site where measurements have been made near the sea, a coast effect is present. Parkinson's effect generally holds, that at a coastal station a vertical component fluctuation accompanies, and is in strength proportional to, the component of the horizontal fluctuation which strikes at right-angles across the coastline.

The measure of the strength of a typical coast effect at a coast with a narrow continental shelf might be that for a magnetic fluctuation which is part of a magnetic storm, the vertical fluctuation will be of order 0.7 times the amplitude of the on-shore horizontal fluctuation which it accompanies. This effect reduces going inland and when a distance of order 100 km from the coast the amplitude of the vertical component has dropped to one-half its coastal value. The rate of reduction of the coast effect going inland may differ for some coastlines, apparently with least reduction at shield coasts (see White & Polatajko 1978).

5.2 Inland

Magnetic fluctuation patterns are often smooth inland (for example across northern Victoria and southern New South Wales), indicating that the gross earth electrical conductivity structure is 'one-dimensional' or 'horizontally-layered' in these areas. In some places the magnetic fluctuation patterns are anomalous and non-uniform, indicating the presence of electrical conductivity anomalies in the continental geology. The major zones of non-uniform magnetic fluctuation discovered so far for Australia are marked on Fig. 1, and in these regions as demonstrated in Example 1 above, total-field magnetic fluctuation patterns can change strongly over distances on the scale of hundreds or even tens of km.

5.3 Offshore

For magnetic surveys of the continental shelf the coast effect becomes especially relevant, as it is evidently an effect not so much of the coastline but of the edge of the continental shelf, and may be expected to be at or near maximum strength at this edge.

The character of the effect at the continental edge may be predicted by extrapolating the results of Fig. 5 out to hypothetical continental edge stations. Magnetic fluctuation measurements at sea are technically difficult to make and are few in number. However, White & Polatajko (1978) have made pioneering measurements on the sea floor at the continental edge off South Australia, and have found there a ratio of order unity between the vertical and on-shore horizontal components of magnetic fluctuation, an appropriate increase on the 0.7 quoted above as typical for a coastline station.

There remain, however, substantial areas of the Australian continent for which the magnetic fluctuation patterns are not known. These include much of the Australian shield, some quite long lengths of coastline, and nearly all the continental shelf.

Acknowledgments

This paper is essentially a summary of previous work, much of which has been carried out by and with the colleagues whose names appear as authors of the relevant papers and theses in the reference list. The motivation for writing the paper arose from the stimulation of discussion which took place at the A.S.E.G. Second Biennial Conference in Adelaide in August 1981. A novel feature of the stacked fluctuation profiles in this paper is their inclusion of the total field component, and the production of these data has been arranged by Mrs M. N. Sloane, whose assistance is greatly appreciated.

The author's attention was drawn to the Booth (1936) paper by the history of Australian geophysics published by Day (1966).

Credit for the encouragement of the magnetometer array studies carried out by the Australian National University is due especially to J. C. Jaeger, D. I. Gough, M. W. McElhinny, A. L. Hales and A. E. Ringwood.

Dr W. D. Parkinson is thanked for acting as editor for this paper.

References

Banks, R. J. (1969), 'Geomagnetic variations and the electrical conductivity of the upper mantle', *Geophys. J.R. Astr. Soc.* **17**, 457-487.

Bennett, D. J. (1972), Geomagnetic depth sounding studies in south-eastern Australia. Ph.D. thesis, Australian National University.

Bennett, D. J. & Lilley, F. E. M. (1973), 'An array study of daily magnetic variations in southeast Australia', *J. Geomag. Geoelectr.* **25**, 39-62.

Bennett, D. J. & Lilley, F. E. M. (1974), 'Electrical conductivity structure in the southeast Australian region', *Geophys. J. R. Astr. Soc.* **37**, 191-206.

Booth, E. H. (1936), 'Some observations on zonal discordances in diurnal magnetic variations', *J. Proc. Roy. Soc. N.S.W.* **70**, 338-342.

Campbell, W. H. (1967), 'Geomagnetic pulsations' *in* S. Matsushita and W. H. Campbell (eds), *Physics of Geomagnetic Phenomena*, 821-909, Academic Press, New York.

Cox, C. (1980), 'Electromagnetic induction in the oceans and inferences on the constitution of the earth', *Geophys. Surv.* **4**, 137-156.

Day, A. A. (1966), 'The development of geophysics in Australia', *J. Proc. Roy. Soc. N.S.W.* **100**, 33-60.

Dekker, D. L. & Hastie, L. M. (1981), 'Sources of error and bias in a magnetotelluric depth sounding of the Bowen Basin', *Phys. Earth Planet. Interiors* **25**, 219-225.

Everett, J. E. & Hyndman, R. D. (1967), 'Geomagnetic variations and electrical conductivity structure in south-western Australia', *Phys. Earth Planet. Interiors* **1**, 24-34.

Fainberg, E. B. (1980), 'Electromagnetic induction in the world ocean', *Geophys. Surv.* **4**, 157-171.

Gough, D. I. & Reitzel, J. S. (1967), 'A portable three-component magnetic variometer', *J. Geomag. Geoelectr.* **19**, 203-215.

Gough, D. I., McElhinny, M. W. & Lilley, F. E. M. (1974), 'A magnetometer array study in southern Australia', *Geophys. J.R. Astr. Soc.* **36**, 345-362.

Green, P. & Malin, S. R. C. (1971), 'Lunar and solar daily variations of the geomagnetic field at Watheroo, Western Australia', *J. Atmos. Terr. Phys.* **33**, 305-318.

Green, R. (1972), 'Sponsored research in geomagnetism 130 years ago', *EOS* (Trans. Am. Geophys. Union) **53**, 778-779.

Gregori, G. P. & Lanzerotti, L. J. (1979), 'Geomagnetic depth sounding by means of oceanographic and aeromagnetic surveys', *Proc. I.E.E.E.* **67**, 1029-1034.

Le Borgne, E. & Le Mouel, J. L. (1975), 'A conductivity anomaly in the Western Mediterranean', *Geophys. J.R. Astr. Soc.* **43**, 939-955.

Lilley, F. E. M. (1976), 'A magnetometer array study across southern Victoria and the Bass Strait area, Australia', *Geophys. J.R. Astr. Soc.* **46**, 165-184.

Lilley, F. E. M., Burden, F. R., Boyd, G. W. & Sloane, M. N. (1975), 'Performance tests of a set of Gough-Reitzel magnetic variometers', *J. Geomag. Geoelectr.* **27**, 75-83.

Matsushita, S. (1967), 'Solar quiet and lunar daily variations fields' *in* S. Matsushita and W. H. Campbell (eds), *Physics of Geomagnetic Phenomena*, 301-424, Academic Press, New York.

Parkinson, W. D. (1959), 'Direction of rapid geomagnetic fluctuations', *Geophys. J.R. Astr. Soc.* **2**, 1-14.

Parkinson, W. D. (1962), 'The influence of continents and oceans on geomagnetic variations', *Geophys. J.R. Astr. Soc.* **6**, 441-449.

Parkinson, W. D. (1964), 'Conductivity anomalies in Australia and the ocean effect', *J. Geomagn. Geoelectr.* **15**, 222-226.

Parkinson, W. D. & Jones, F. W. (1979), 'The geomagnetic coast effect', *Rev. Geophys.* **17**, 1999-2015.

Petersons, H. F., Winch, D. E. & Slaucitajs, L. (1965), 'The lunar magnetic variations at Toolangi', *Aust. J. Phys.* **18**, 567-578.

Rumker, C. (1829), 'Magnetic observations made at Parramatta', *Phil. Trans. Roy. Soc. Lond.* **119**, 1-2.

Tammemagi, H. Y. (1972), A magnetotelluric study in south-eastern Australia. Ph.D. thesis, Australian National University.

Tammemagi, H. Y. & Lilley, F. E. M. (1973), 'A magnetotelluric traverse in southern Australia', *Geophys. J. R. Astr. Soc.* **31**, 433-445.

Vozoff, K., Kerr, D., Moore, R. F., Jupp, D. L. B. & Lewis, R. J. G. (1975), 'Murray basin magnetotelluric study', *J. Geol. Soc. Aust.* **22**, 361-375.

White, A. & Polatajko, O. W. (1978), 'The coast effect in geomagnetic variations in South Australia', *J. Geomag. Geoelectr.* **30**, 109-120.

Woods, D. V. (1979), Geomagnetic depth sounding studies, in central Australia. Ph.D. thesis, Australian National University.

Woods, D. V. & Lilley, F. E. M. (1979a), 'Geomagnetic induction in central Australia', *J. Geomag. Geoelectr.* **31**, 449-458.

Woods, D. V. & Lilley, F. E. M. (1979b), 'Concentrations of natural telluric currents and their relation to the basement structure of the Eromanga Basin, southwest Queensland', *Bull. Aust. Soc. Explor. Geophys.* **10**, 212-213.

Woods, D. V. & Lilley, F. E. M. (1980), 'Anomalous geomagnetic variations and the concentration of telluric currents in south-west Queensland, Australia', *Geophys. J.R. Astr. Soc.* **62**, 675-689.

(Received 11 March 1982; revised 14 May 1982)

Note added in proof

Several other papers on subjects connected to the above have recently come to the attention of the author and are relevant to mention here. Thus, for example, Morley (1953) discusses problems of aeromagnetic surveying near the auroral zone in Canada (where the magnetic activity will be both strong, and with non-uniform source fields). Whitham & Niblett (1961) and Riddihough (1971) discuss the general problem of survey diurnal corrections, and Roden & Mason (1964), Whitmarsh & Jones (1969), Goh (1972), and Auld, Law & Currie (1979) discuss the question of removing time fluctuations from marine magnetic surveys.

Auld, D. R., Law, L. K. & Currie, R. G. (1979), 'Cross-over error and reference station location for a marine magnetic survey', *Marine Geophys. Res.* **4**, 167-179.

Goh, R. (1972), A marine magnetic survey in the Mackenzie Bay/Beaufort Sea area, Arctic Canada. M.Sc. thesis, University of British Columbia.

Morley, L. W. (1953), 'The areal distribution of geomagnetic activity as an aeromagnetic survey problem near the auroral zone, *Trans. Am. Geophys. Union* **34**, 836-840.

Riddihough, R. P. (1971), 'Diurnal corrections to magnetic surveys — an assessment of errors', *Geophys. Prospect.* **19**, 551-567.

Roden, R. B. & Mason, C. S. (1964), 'The correction of shipboard magnetic observations', *Geophys. J.R. Astr. Soc.* **9**, 9-13.

Whitham, K. & Niblett, E. R. (1961), 'The diurnal problem in aeromagnetic surveying in Canada', *Geophysics* **26**, 211-228.

Whitmarsh, R. B. & Jones, M. T. (1969), 'Daily variations and secular variations of the geomagnetic field from shipboard observations in the Gulf of Aden', *Geophys. J.R. Astr. Soc.* **18**, 477-483.