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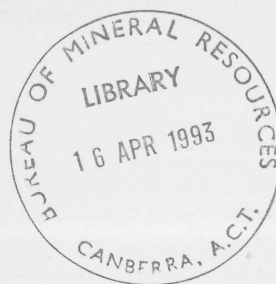
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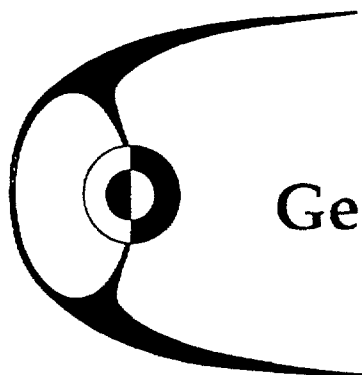
3rd AUSTRALIAN

GEOMAGNETISM WORKSHOP

ABSTRACTS

Charles Barton (editor)

AGSO

AUSTRALIAN GEOLOGICAL
SURVEY ORGANISATION

3rd Australian Geomagnetism Workshop

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ABSTRACTS

Compiled by Charles Barton

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

Minister for Resources: The Hon. Michael Lee
Secretary: Greg Taylor

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Executive Director: Roye Rutland

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FOREWORD

The 3rd Australian Geomagnetism Workshop continues the tradition of previous meetings in this series, held in Canberra in 1985 and 1987, by providing a focus for the wide range of scientists in the Australian region who share a common interest in geomagnetism. The aim of the meeting is to bring together those who use geomagnetic information to take advantage of the many applications of geomagnetic phenomena, those who generate that information, and those who investigate the behaviour and origin of the geomagnetic field. The quality and diversity of the abstracts herein bears testimony to the vigorous state of pure and applied geomagnetism research in Australia.

We wish to thank the speakers who have gone to considerable effort to prepare talks and abstracts for the meeting, and the many persons who have helped with the organization. Support for the meeting has been provided by the Australian Geological Survey Organisation and the Research School of Earth Sciences, Australian National University. The Workshop is sponsored jointly by the Australian Society of Exploration Geophysicists and the Geological Society of Australia, Specialist Group of Solid-Earth Geophysics.

Charlie Barton & F.E.M.(Ted) Lilley (organizers)
Canberra, 7th April, 1993.

APPLICATIONS - SURVEYING & MAPPING THE GEOMAGNETIC FIELD

Australian Magnetic Observatories

P.A. Hopgood

Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601

Magnetic observatories have operated in Australia from when the study of the earth's magnetic field was in its infancy. The first observatory established in the region was that at Hobart in 1840. Since that time the magnetic field has been (all but a few years) continuously monitored in the region. For south eastern Australia there exists an almost continuous magnetic record since 1858, Canberra being the last observatory having been preceded by those at Hobart, Melbourne and Toolangi. Continuous magnetic observations began on the western side of the continent at Watheroo in 1919 and have continued at Gnangara since 1959.

The Bureau of Mineral Resources, Geology and Geophysics was formed in 1946 and both the magnetic observatories operating at that time were soon transferred to its 'Geophysical Observatories' program. The emphasis of the magnetic observatory program at the bureau (renamed the Australian Geological Survey Organisation in August 1992) is placed on solid-earth geophysics and, as such, forms the cornerstone of the 5-yearly epoch charts which detail the secular variation in each of the elements of the magnetic field in the Australian region.

In the 1950s the BMR established a number of observatories in Australian Antarctic Territory and one at Macquarie Island. The latter observatory still operates, as does the one at Mawson. Observatory operations are also maintained at Casey and Davis in collaboration with the Australian Antarctic Division.

Until the Canberra observatory was commissioned in 1978, all BMR's magnetic observatories made analogue recordings on photographic paper which were scaled at 1-hour intervals to produce Mean Hourly Values. An Elsec Automatic Magnetic Observatory (AMO) has always operated at the Canberra observatory. This digitally records variations in D, F & I each minute. All observatories commissioned since 1978 also digitally record variations in three components as well as the total field at 1-minute intervals. This includes the observatories at Charters Towers (est. 1983), Learmonth (est. 1986) and Alice Springs (est. 1992). The observatories at Gnangara, Mawson and Macquarie Island have all now been upgraded to 1-minute digital recording. Each of the observatories maintains a form of telemetry: either a dedicated connection or via dial-up access. In either case, data are available in real-time or very close to it when required. Real-time data from the Canberra observatory were recently transmitted into the GOES-West satellite to the INTERMAGNET global network of geomagnetic observatories. Although this was only an experimental transmission, the intention is for Canberra to become a continuous contributor to this network.

Calibration of the observatories is achieved through the regular performance of

absolute observations using magnetometers which have been extensively intercompared so as to provide a uniform base. In addition, some of the magnetometers are regularly calibrated by the Danish Meteorological Institute. The final results produced are thus consistent across the continent and corrected to the international IAGA standard.

Although the emphasis of AGSO's program in geomagnetism is towards solid-earth geophysics, with a time resolution of 1-minute and observational accuracy of the order of tenths of a nanoTesla, a wealth of information of relevance to upper-atmospheric, magnetospheric and solar physics is available. Data are regularly sent to the World Data Center in Boulder, USA. The K-index is scaled from magnetogram records from four of the observatories. The classical method of scaling is still adhered to, although there is a keenness to switch to a computer based method as soon as an algorithm can be shown to be suitable. To this end an attempt is being made to gather together in a uniform format (FORTRAN) all the available algorithms, and to make these available to the geomagnetism community. Australian observatories contribute towards the global Kp-index and its derivatives, the aa-index and the am-index.

Data from Australian magnetic observatories are reduced by software developed at AGSO which can provide 1-minute value data in the form of computer files in WDC, NGIC or another format, tables or plots; Mean-Hourly-Values, daily, monthly and annual means. The regular means of distributing a summary of observatory data is the 'Australian Geomagnetism Report', a monthly publication until the end of 1992 and annual thereafter.

New Zealand's magnetic observatory instrumentation

Lester A. Tomlinson

Geomagnetic Observatory, Institute of Geological and Nuclear Sciences,
PO Box 29181, Christchurch, New Zealand

New Zealand has been involved in the operation of several magnetic observatories over the last 90 years. The principal ones are Scott Base in the Antarctic, Eyrewell (and its predecessors, Amberley and Christchurch) in New Zealand, and, until the end of the 1980s, Apia in Western Samoa. Maintaining high standards of results from these observatories has not been easy, and each observatory presents its own special problems.

The average life of sets of recording instruments has been about 30 years. Until a few years ago, classical variometers, based on suspended magnets with optical levers and photographic recording, were used at each observatory. These have now been replaced with fluxgate-based digital recording systems developed and built in New Zealand. Careful attention to detail has resulted in instruments which have proved extremely reliable and have a performance at least equal to that from the classical instruments they replaced. Absolute determinations of the magnetic vector are made with a proton magnetometer to measure the magnitude of the vector and a null-detecting fluxgate instrument, the Declination-Inclination Magnetometer (DIM) to measure the direction of the vector.

The Magnetic Repeat Station Network and Estimation of Secular Variation in the Australian Region

Andrew J. McEwin

Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601

A significant program of the Geomagnetism Section of the Australian Geological Survey Organisation is the estimation of secular variation and the production of reference models of the geomagnetic field in the Australian region. This is achieved through analysis of data from the permanent magnetic observatories, which record the magnetic field continuously, and a network of some 83 repeat stations that are occupied on a regular basis. The existing five observatories on continental Australia are too few and too far apart to satisfy the requirements of these functions by themselves. It is simply too expensive to improve the coverage by installing more observatories. The repeat station network, on the other hand, is a relatively inexpensive method of gathering sufficient data for estimation of secular variation and development of geomagnetic reference field models. The network has been designed to supplement the observatories by infilling the gaps between observatories and extending the coverage beyond the observatories.

The network had its beginnings with the Carnegie Institution of Washington in the latter part of last century, and still contains stations that were occupied by them in their first systematic magnetic survey of the globe, e.g. Suva, 1896; Eucla, Hobart, Port Lincoln and Mildura, 1911. Re-occupations were spasmodic until the 1940s. Since 1946, when this work became the responsibility of the Federal Government, regular, approximately five-yearly re-occupations have been undertaken. During this time the network has been modified and improved to provide better coverage of the Australian region, and now extends to Australian offshore islands, Papua New Guinea and south west Pacific islands.

Measurement of the magnetic field, and the subsequent estimation of secular variation by first-differences, is much more exacting than the rapid, relative measurements of the total intensity of the magnetic vector made by industry for exploration purposes. During magnetic repeat station surveys, four vector components of the magnetic field, including total intensity, are measured at each station over a period of three to four days. Methodology is stringent to ensure that measurements are calibrated to absolute levels, that the exact location can be re-occupied in future, and that the immediate magnetic environs remain unchanged for years, even decades. Other considerations are the inherent need to standardise instruments, and to remove diurnal and magnetic storm disturbances to ensure that the estimation of secular variation, a quantity of relatively small magnitude, is accurate.

Five-yearly occupations have, in some cases, proved insufficient for accurate estimation of secular variation in areas of rapid change, and are also becoming increasing difficult to program in terms of available resources. The concept of "super" repeat station has been introduced, where a few selected and strategically located Class A stations will be re-occupied annually within continental Australia. It is expected that these, together with the permanent observatories, will provide adequate and frequent-enough data to show the trend of secular variation at each station and be representative of the general region surrounding each station for the years immediately prior to development of reference models. The remainder of the existing repeat stations will be occupied five-yearly (Class B stations) or ten-yearly (Class C stations), to cover the off shore areas and to provide the necessary in depth detail between the onshore Class A stations.

Analysis of POGS Satellite Data

D.E. Winch

School of Mathematics and Statistics, University of Sydney, F07, Sydney NSW 2006

The US Naval Oceanographic Office has made POGS satellite magnetic data available through File Transfer Protocol (FTP) from the SUN front end of a CRAY computer at the Stennis Space Center. Files consist of approximately 10 days of values from about 160 orbits which are in planes through the geographic axis. Magnetic field components X,Y,Z only are given, relative to the satellite magnetometer which is on a boom whose orientation is changing continually. Total intensity measurements are suitable for analysis, and the IGRF for 1990 provides a suitable starting value. The measurements are made in a 'shell' whose thickness corresponds to the perigee-apogee distance. Unsatisfactory data have been flagged and can be ignored.

There are a number of problems to be solved, for example, the degree and order of the analysis, the effect of Backus sequences, the geographic distribution of satellite altitudes, the diminished number of equatorial as opposed to polar observations. The inclusion of external and non-potential fields in the model, whether or not these fields can be separated using total intensity only, needs to be determined. The available files cover some 200 days and the spherical harmonic coefficients have been examined to see if a significant model of secular variable can be obtained.

Geomagnetic reference fields and direction-finding applications

Charles Barton

Australian Geological Survey Organisation, GPO Box 378, Canberra ACT 2601

Introduction
A geomagnetic reference field is an idealized representation of the Earth's magnetic field, presented either as a numerical model (usually 3-dimensional) or graphically as a contour map or image (usually 2-dimensional). Applications of geomagnetic reference fields range from the sublime, e.g. mapping fluid motions beneath the core-mantle boundary, to the ridiculous, e.g. magnetic compass calibration for the Cuillin Ridge on the Isle of Skye, Scotland. Direction-finding applications generally require a knowledge of the magnetic declination (variation) on a regional, i.e. sub-continental, scale. Such applications include the compass calibration information provided on topographic maps, aeronautical and maritime charts. Some specialized applications also require a knowledge of the inclination of the geomagnetic field, e.g. modelling of the induced magnetization of bodies contributing to magnetic anomalies, or compensating for the vertical field in computer VDU's.

Let the punishment fit the crime

For any particular application it is important to choose a reference field with a level of smoothing (numerical truncation) appropriate for the task in hand. For example, for reducing aeromagnetic survey data to obtain crustal magnetic anomalies it is usual to use a reference field that represents the main (core) field of the Earth, i.e. the International Geomagnetic Reference Field, IGRF, whereas for precise directional drilling using magnetic logging an accurate map of the magnetic field on a local scale is necessary. The compass calibration information supplied on topographic and navigational charts is supplied at an intermediate "regional" level, i.e. it accounts for large-scale crustal magnetic anomalies with wavelength of several hundred kilometres upwards, but smooths out the shorter wavelength effects of local magnetic anomalies.

Mapping the field and the secular variation

Mapping the magnetic field is done via ground, airborne and satellite surveys. Many thousands of stations are required to cover a continental area such as Australia. The aim is to obtain good spatial representation of the field. Thus the primary requirement is for a large number of evenly distributed stations, rather than for accurate measurements/location at each station. For example, during the third-order magnetic field survey carried out by BMR (now the Australian Geological Survey Organisation, AGSO) in the 1960's and 1970's, vector field (3-component) observations were made at more than 6000 stations, to achieve a typically station spacing of 15 km. Helicopters were used to cover the desert areas (grids), elsewhere stations were along roads.

Such detailed magnetic field surveys are costly and are, therefore, undertaken only rarely. Unfortunately the magnetic field changes substantially between (and during) surveys — typically declination may change by many minutes or tens of minutes of arc per year — so survey data rapidly become obsolete despite the high cost of acquisition.

The strategy adopted is, therefore, to measure only the secular change of field on a routine basis. Secular change models of the field are then used to update old survey data, and also to make corrections for surveys that span a long time compared to the rate of change of the field. The secular change originates from a remote source (the Earth's core) and is, therefore, presumed to be a smoothly varying function at the Earth's surface. Hence it need be measured at relatively few stations. Magnetic observatories and repeat stations fulfill this role. The average observatory spacing in our region is about 1800 km for the mainland, and about 1900 km for the entire Australia-Indonesia-Papua New Guinea-New Zealand region. Such a spacing is known to be significantly larger than short wavelength features of the secular variation. Hence the observatories alone lack the spatial resolution required to describe the secular variation, and have to be supplemented by several dozen magnetic repeat stations (as described in an earlier talk). These bring the average spacing of "secular variation" stations down to less than 400 km. The primary requirement at repeat stations is to make very accurate determinations of the undisturbed geomagnetic field at a precisely defined location (i.e. quite distinct from the requirements for a field survey station).

Global reference fields

Global reference fields are generally based on a best fit of a truncated spherical harmonic model of the magnetic potential to world-wide observational data. Individual field

components at any site can then be derived easily from the model. This is done for both the field itself and for the secular variation (used to determine the annual change of each field component). Appropriate algorithms and PC-software packages for evaluating spherical harmonic models are available from leading geomagnetism agencies, including AGSO.

The best known global model is the International Geomagnetic Reference Field, IGRF, which is deliberately truncated at spherical harmonic degree and order 10 (equatorial wavelength 4000 km) so as to remove most of the crustal field and represent the main (core) field. IGRF is made freely available through the International Association of Geomagnetism and Aeronomy, IAGA (IAGA Division V, Working Group 8, R.A. Langel, chairman, 1991 and 1992; Langel et al., 1992). Other agencies that produce global models on a regular basis are the US Geological Survey, NASA's Goddard Space Flight Center, the U.S. Navy (jointly with the British Geological Survey), and the Russian Institute of Terrestrial Magnetism, Ionospheric and Radio Wave Propagation (IZMIRAN).

Global models are convenient to use and are appropriate for applications such as levelling aeromagnetic data and for direction-finding purposes when the higher-resolution information available from regional models is either not necessary or not available.

Free lunches

The data used to generate global models are sent to the World Data Centres by national agencies, such as AGSO, and are made freely available for anyone to use. Agencies producing global models usually provide their model coefficients free of charge, or at the cost of supply only. The U.S.A. is the main provider of both data and global models. This open policy has led to the widespread adoption of global models for many applications, notable IGRF for main field applications, and the joint US Navy/UK "World Magnetic Model" (Quinn et al., 1991) for global direction-finding applications. Clearly, the long-term viability of global model production hinges on continuing international acceptance of the principal of free-interchange of geomagnetic data. This point is well-recognized by the U.S. agencies, and is the reason why they have strongly resisted any moves towards cost-recovery, despite the fact that the U.S.A. is by far the largest source of geomagnetic data.

Regional reference fields

For many direction-finding applications, a higher, regional spatial resolution may be needed. When attempts are made to use global models to represent crustal information at the regional level, we run into two problems. Firstly, there are computational problems because of the very large number of spherical harmonic coefficients required (e.g. 440 coefficients to represent 2000 km wavelengths; 160,800 coefficients for 100 km). Thus the representation of even intermediate wavelength crustal features (~1000 km wavelength) involves handling an unmanageable number of coefficients. Secondly, there are difficulties relating the uneven distribution of survey data over the globe. This is particularly acute for models of the secular variation, that are biased by the high density of observatories in Europe vs. none in large oceanic regions. When such datasets are used to produce a global model, the model is well constrained only where data are plentiful, and can be wildly inaccurate where data are sparse. Thus the model field in a region of sparse data-coverage may by adversely affected by data from remote areas (e.g. the secular variation field modelled over Australia is partly influenced by observations made in Europe). The way around these problems is to produce regional models based exclusively on regional observations.

The Australian Geomagnetic Reference Field

The model produced by AGSO for the Australian region is called the *Australian Geomagnetic Reference Field* (AGRF) and is available both as a PC-software package for generating 3-D point data and as surface magnetic field charts. AGRF is based on a synthesis of all the available vector survey data, suitably updated using estimates of the secular variation. The synthesis takes the form of one numerical (spherical cap harmonic) model that is fitted to field observations updated to a particular epoch, and a second model that is fitted to the secular variation data. Both models are a smoothed fit to the observations, so that they are insensitive to local anomalies (such as produced by outcrops of volcanic rocks or man-made structures), and represent only the broad scale "regional" field and its annual change. AGRF is revised every 5 years in order to keep track of the secular change of the field. The current revision, AGRF90, comprises a field model for 1990.0 and a secular variation model for the interval 1985-1995, and is the preferred source of magnetic declination information for navigational charts, runway bearings and topographic maps.

Difference between global and regional models

The difference in accuracy between global and regional field models is clearly crucial in deciding which model to use. This is illustrated for Australia in Figure 1, which shows for epoch 1990.0 the difference in declination between AGRF and IGRF. Figure 1(a) shows contours of the differences, AGRF-IGRF, in minutes of arc, and Figure 1(b) shows a histogram of the fraction of the area of the 24° spherical cap mapped by AGRF corresponding to successive difference intervals.
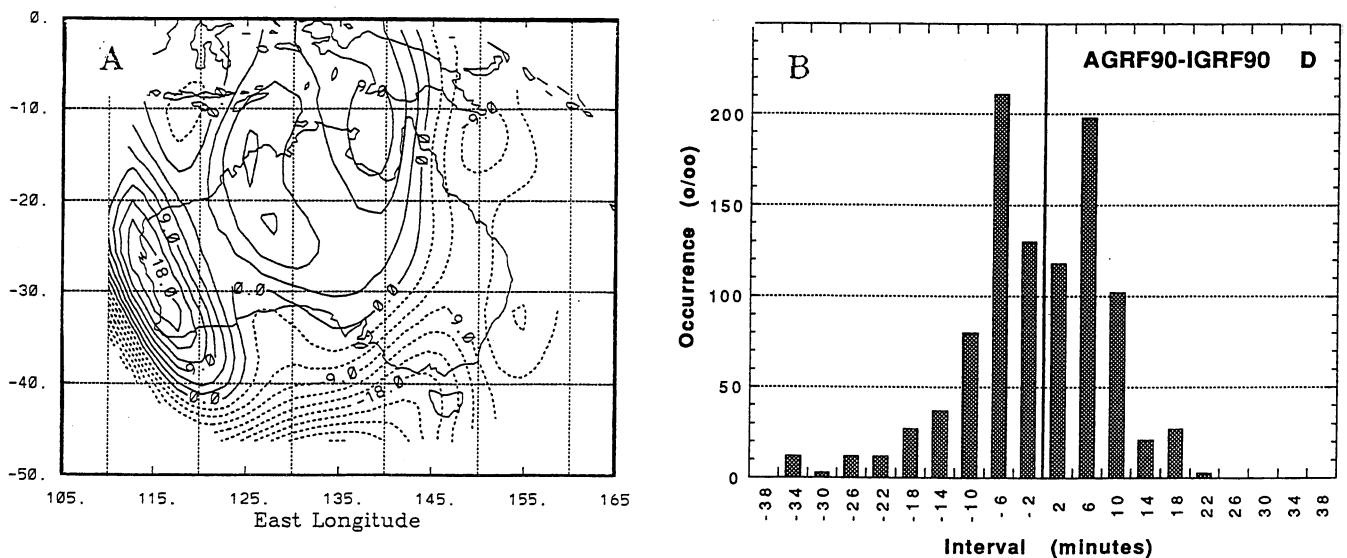
Figure 1. Differences in declination between AGRF and IGRF for epoch 1990.0. **A:** contoured at intervals of 3 minutes of arc; **B:** shown as a spatial distribution histogram. Over most of the region the difference between the two models lies in the range ±10 minutes.

Over most of the region the differences lie within the range ±10 minutes of arc, and are more-or-less uniformly distributed about zero. The skew towards negative AGRF-IGRF differences arises from the prominent difference anomaly in the southwest of the region. These differences are not large compared to the accuracy required of magnetic declination information for most direction-finding applications. However, we must also consider the effect of secular variation estimates.

The difference between the annual change in declination given by AGRF and global field model USGS90 (produced by the U.S. Geological Survey) is illustrated in Figure 2. The vertical scale represents the annual change in declination, range ±0.09°/yr. USGS90 was used as the base reference model in the derivation of AGRF90, and was chosen because it is the IGRF candidate model that best fits the Australian data (it is also very similar to IGRF for 1990). Within the spherical cap containing Australia and near-shore areas (centred near Alice Springs, with spherical radius 24°) the wire-line model shows AGRF90. Outside this cap-shaped region the model is based on USGS90. The prominent step change around the edge of the cap (slightly smoothed in the figure) shows the difference between the regional and global model values for the secular change. Note that the prominent trend in USGS90 from NE to SW is not present in the regional model; and AGRF90 shows shorter wavelength features than are present in the global model. The difference between the two models is greatest in the SW, exceeding 0.05° per year. Thus, in addition the offset between the global and regional models at epoch 1990 (discussed above), there will be an additional difference of up to 0.25° within the 5 year "lifetime" of the models. If the models are used for longer, e.g. 10 - 20 years (as is often the case as people do not always have access to the most recent charts and maps) then the errors will increase proportionally.
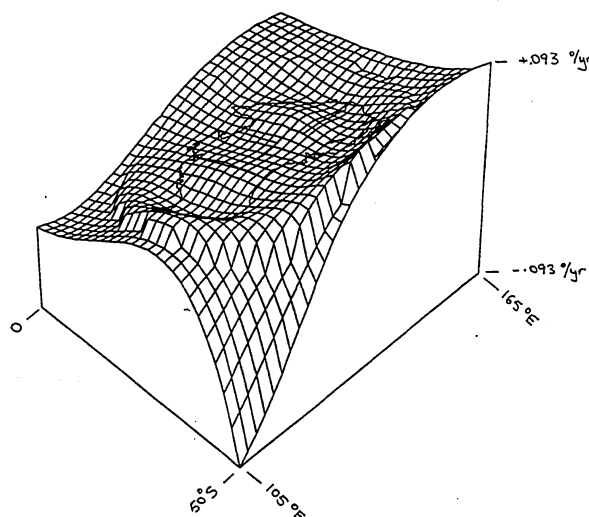
Figure 2. Composite model of the secular change of declination for the interval 1985-1995 for the Australian region, bounded by 0-50°S, 105-165°E. The vertical scale represents the annual change in declination in minutes East per year. Within the spherical cap region of radius 24° centred around Australia the secular variation model of AGRF90 is used; outside this region the USGS90 model is used. The obvious step change around the edge of the 24° cap, within which AGRF90 is defined, reflects the difference between the global and regional models.

Finally, it must be remembered that the secular variation values given by reference field models are nearly always predictive, i.e. they are based on some suitable forward extrapolation of past observations. Unfortunately, the secular variation changes in a non-predictable manner, and not always very smoothly - witness the sudden impulsive changes that have been observed, e.g. the "geomagnetic jerk" of 1970. Thus the accuracy of both regional and global secular variation models at any future epoch is unknown, and, hence, the differences may be better or worse than indicated by the figures calculated for a given epoch.

This discussion has been restricted to the Australian region. Comparisons between global and regional field models for other parts of the globe have been published in a special issue of the Journal of Geomagnetism and Geoelectricity (Volume 44, No.9, p. 677-897, 1992). In general, the comparisons for the Australian region are fairly typical of mid-latitude regions with average data coverage for recent times during which the secular variation has been "well-behaved". In parts of the Western world with much higher densities of data the differences between global and regional models tend to be smaller than here, and for high latitude regions the differences can be very much larger.

Don't throw out the baby with the bath water

It might be concluded from the above discourse that, for many direction-finding applications, a suitable global reference field model would be adequate, provided that it has been updated regularly. Consequently, the effort that goes into regional field surveys and modelling is not warranted. Before making such a conclusion two further considerations must be taken into account.

Firstly, the observational datasets that are obtained in order to produce regional field models are the very datasets upon which the accuracy of global field models depend (regional observatory and survey data are routinely sent to the World Data Centres and contribute to global models). The secular change information from observatories and repeat stations is particularly important in this regard. Consider: the last vector satellite survey of the globe was 13 years ago, so the value of this very costly dataset for field mapping is largely diminished without reliable secular variation information at a regional level.

Secondly, without regional field surveying and modelling activities, the accuracy of global models for various parts of the world would remain largely unknown. Thus the demonstration herein (Figure 1a) that IGRF provides adequate compass calibration data for 1990 for much of central Australia, but not for the west coast or for Tasmania, has only been possible because of the existence of a regional field model.

Conclusion

Regional field surveys and models fulfill a necessary role in providing general-purpose direction-finding information: they provide greater accuracy than can be obtained from global models (although this may not be needed for many applications), they contribute significantly to the accuracy of global field models, and they are important for assessing the accuracy of global models. Only if field surveys can be conducted with sufficient global coverage, be completed sufficiently rapidly, and be repeated at sufficiently regular intervals will traditional regional field monitoring become redundant. There are hopes that regular satellite missions will achieve this, but there are no indications yet that anyone is prepared to fund such an enterprise.

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Geomagnetic Field Based Orientation Systems for Balloon-Borne Astronomy Payloads

Ravi Sood

Department of Physics, University College, University of New South Wales, Australian Defence Force Academy, Canberra ACT 2600.

Very large and complex payloads for x-ray and gamma-ray astronomy, involving multi-national collaborations, are routinely flown on large stratospheric balloons from remote locations in Australia. A prime requirement for these payloads is a pointing system operating to an accuracy of minutes of arc, to enable the x-ray/gamma-ray detector to track the astrophysical source of interest. The geomagnetic field is used for primary aspect acquisition. Details of the operations, and in particular the orientation system, will be described.

Magnetic Effects of Warships

Alan Theobald

Maritime Operations Division, DSTO Materials Research Laboratories, PO Box 44, Pyrmont, NSW 2009

The magnetic signatures of warships have been of interest and concern to navies for many years, not least because this influence is frequently used to trigger mines. The methods of measuring, interpreting and countering these signatures have only been modernised in the last 10 years by the use of increased computer processing power. This is a high priority area for research and continued development within DSTO, on behalf of the RAN, and is one in which Australia is amongst the world leaders.

Warships are generally constructed of steel and hence acquire both a permanent and an

induced component of magnetisation. In water depth approximately equally to the width of the beam of the vessel, the associated magnetic field can be up to 1/5th of the local Earth's field, and is thus readily detectable by an influence mine on the sea-bed, unless countermeasures are taken to minimise this influence. Typical countermeasures are to de-perm the vessel and/or to install a degaussing system.

Mine Countermeasure Vessels (MCMVs) represent a special problem, since their role is to operate in, potentially, mined waters. Hence they are generally constructed of non-ferrous materials (wood or fibre-glass) with special care being taken to minimise the signature of such items as engines and generators etc. Such vessels have extensive Degaussing systems and special ranges are required to ensure that their final signatures are within the appropriate specification.

Submarines also have an additional risk of being detected by the Magnetic Anomaly Detector (MAD) fitted onboard many Maritime Patrol Aircraft. This is used as the final locator prior to weapon release. The principle is similar to that used for detecting ore bodies. A further unique feature of the magnetic signature of submarines is that the interaction of stress within the pressure hull during diving and the local Earth's field can cause the magnetisation of the vessel to change markedly, in which the applied countermeasures may not be as effective as when first applied.

All of the above topics are the subject of current research within Maritime Operations Division of DSTO.

Aviation requirements for magnetic variation information

Tony Gover

Civil Aviation Authority, System Support Group,
GPO Box 367, Canberra ACT 2601

The Civil Aviation Authority (CAA) uses magnetic variation (or declination) data in the following manner. Firstly, as a number painted on each end of a runway. This number is visual to a pilot when he/she is coming in to land. If the pilot sees the number 17, for instance, this means that the runway direction is 170 degrees (magnetic) to the nearest 10 degrees. Secondly, magnetic variation is displayed on aeronautical charts prepared by CAA as isogonals and also as magnetic tracks between points to the nearest whole degree. This information is used by pilots who are not using an Inertial Navigation System (INS) for their navigating. All commercial aircraft use INS, which enables them to fly the shortest distance between points, i.e. great circle tracks.

The Magnetic Compass in Aviation

Harry Hansen and Tony Wilkinson

Aircraft Owners and Pilots Association, PO Box 1065, Fyshwick ACT 2609

Latest developments in satellite navigation systems will accelerate the end of the magnetic compass system as a primary heading reference. By the end of the century it can be expected that the use of magnetic bearing information will be relegated to simple back-up systems with accepted accuracies of degrees rather than minutes of arc.

The Magnetic Anomaly Map of Australia

C. Tarlowski, F. Simonis and P. Milligan

Australian Geological Survey Organisation, GPO Box 378, Canberra

The first detailed magnetic anomaly map of the Australian continent has recently been compiled from individual magnetic survey sheets. The Australian Geological Survey Organisation has been routinely acquiring airborne magnetic surveys over the land area of Australia since 1951 to record and map anomalies in the earth's magnetic field attributable to geological structures and lithologies. In over forty years, more than four million line kilometres of survey data have been flown, while the technology of survey practice has passed through various stages of development.

About 83 per cent of the land has now been covered with so-called reconnaissance surveys flown 150 m above terrain at line spacing between 1.5 and 3.2 km. Located profile data for these surveys have been gridded using a minimum curvature technique, to 15 seconds of arc (approximately 400 m) and where necessary, micro-levelled. Data for many of the remaining areas - particularly the inland sedimentary basins covered by surveys of lower specifications - were obtained from digital data on approximately 2 km grid (72 seconds of arc) published in 1976; these have also been interpolated to 15 seconds of arc.

The data were first assembled for each of over five hundred 1:250 000 map sheets. The 1:250 000 sheets were linked by minimising the discrepancies along their common boundaries and reducing remaining mis-ties through Laplacian smoothing to minimise the visibility of boundaries between surveys acquired separately.

While the data quality varies with instrumentation and survey parameters, it is almost everywhere good enough to provide a useful synoptic view of magnetic anomaly patterns, which can be expected to give important new insights into geology and tectonics at a continental scale, and to provide a regional framework within which to interpret more local magnetic anomalies.

The short-wavelength components of the residual magnetic field are more reliable than long-wavelength components. Therefore, care must be taken when trying to interpret magnetic anomalies with wavelengths exceeding limits of the standard survey covering 1:250 000 map sheet area (typically 90 x 120 km).

GEOMAGNETIC DISTURBANCES, HIGH FREQUENCIES & AEROMAGNETIC EFFECTS

Geomagnetic effects in a high-tech society: forecasting induced geomagnetic effects

David G. Cole and Richard J. Thompson

Radio & Space Services, Ionospheric Prediction Service,
PO Box 5606, West Chatswood, NSW 2057

The effects of solar-induced changes to the earth's magnetic field can have severe repercussions for social and industrial systems. These effects range from the well-documented surges experienced on electricity power lines and long pipelines to the more subtle, but equally damaging, bit errors in satellite digital circuits, increased atmospheric drag on satellites, or manufacturing misalignment in high accuracy automated processes.

Society is affected by such changes through the reduction of quality, or breakdown, of systems that are increasingly seen as everyday expectations. These include routine communications, broadcasting, power supply and navigation.

Industry can be affected by the reduction of accuracy in navigation systems (aviation), poor communications (marine and aviation services), misinterpreted geomagnetic records (geophysical exploration), breakdown in electrical power supplies, and misalignment of finely tuned automatic processes.

Forecasting of geophysical and space conditions can save effort, reduce wastage of resources and improve the quality of social and industrial services. The forecasting of conditions that can give rise to deleterious effects requires the means for the rapid transfer of data and their interpretation along a dedicated chain from observer to end user. Such a rapid data transfer system exists between solar observers and scientists monitoring and interpreting the data, but getting the information to the customer is sometimes less easy. In Australia, the Ionospheric Prediction Service (IPS) prepares forecasts and disseminates warnings to customers that range from geophysical companies to aviation and broadcasting organisations.

Oscillations of Geomagnetic Field Lines at Low Latitudes

F.W. Menk

Department of Physics, University of Newcastle, NSW 2308

Quasi-sinusoidal ULF (1-100 mHz) oscillations of the geomagnetic field are recorded every day by sensitive magnetometers. At low latitudes the signals may be coherent over very wide longitudinal separations, but exhibit latitude-dependent properties, consistent with resonant

oscillations of magnetospheric field lines. These are explained by models of forced, damped transverse oscillations of geomagnetic field lines driven by fast mode waves. Detailed examination of spectral and polarization characteristics with multi-station arrays provides evidence of field line resonance behaviour at geomagnetic latitudes >35°. The recent development of analytical techniques that evaluate the meridional amplitude and phase signatures allows the temporal evolution of magnetospheric properties to be monitored. Parameters which can be evaluated include the effective equatorial plasma density, the latitudinal scale size of the resonance, and the ionospheric damping rate. Examples are shown illustrating these features.

Needs of the mining and petroleum explorers - 1997

Ken McCracken

'Jelore' Technologies, Springhill Road, via Mittagong NSW 2575

No abstract

Limitations Imposed by Geomagnetic Variations on High Quality Aeromagnetic Surveys

Colin V. Reeves

Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601

Abstract
The accuracy and sensitivity with which aeromagnetic anomaly data may be collected and presented as images for those who seek to maximize the representation of the geological information is limited by our ability to remove temporal variations from the recorded total field. Three processes are currently used consecutively to eliminate time-variations: base station subtraction, tie-line levelling and micro-levelling. Of these, the first two involve assumptions that are not entirely justifiable, and the third is essentially an arbitrary process. On profile data with a noise envelope of no more than +/- 0.1 nT, even the third process involves adjustments that are many times larger than other uncertainties in the data.

Introduction
Image presentations of geophysical data are becoming increasingly familiar and images of the latest aeromagnetic surveys routinely display anomalies of sub-nanotesla amplitude. Good images demand good technical data quality; some quite minor data errors become clearly visible under image processing and can easily make an aeromagnetic image appear unattractive and cast suspicions on the quality of the survey.

Helium vapour magnetometers used (by AGSO) in airborne surveys record the scalar

magnitude of the total magnetic field vector. The precision of the measurements is effectively absolute while the sensitivity is limited only by the noise introduced into the signal from a variety of non-geological sources. The 'noise envelope' for modern data, certainly for data acquired with AGSO's own aircraft, has been reduced to about +/- 0.1 nT. That is about two parts per million of the scalar magnitude of the field being measured and four orders of magnitude less than the amplitude of large anomalies in that field. However, from a geological point of view, anomalies of small amplitude may be just as important as large ones. The noise envelope therefore sets one very real limit to the amplitude of geological anomalies we can hope to detect in a survey and portray in an image.

The magnetic effect of the aircraft itself and the accuracy with which magnetometer readings may be positioned in x,y (using differential GPS) are well controlled. More intractable problems are posed by temporal variations in the magnetic field. Micropulsations, diurnal variations and magnetic storms occur on time periods that are short compared with the time taken to carry out a typical aeromagnetic survey.

Base station subtraction.
It is a relatively straightforward matter to run a recording base station magnetometer at a fixed location on the ground while the aircraft is flying and subtract the time-synchronised variations at the base from the profiles recorded in the air to give a residual that is a function of x and y only. Unfortunately, this assumes that base station variations are fully representative of variations over the whole survey area whereas, in fact, it can be shown that such variations are only imperfectly time-synchronous over distances of 50 km or more.

Levelling at line intersections.
Aeromagnetic surveys have always been planned with a network of flight-lines and 'tie-lines' or 'control-lines' to provide a method of eliminating temporal variations from the observed anomalies. The principal is that, since the magnetic (anomaly) field we strive to record is essentially time-invariant, any difference observed in the observed value between two overflights of the same point (i.e. at an intersection) must be due to temporal variations, even though neither of the values is itself strictly correct. The mis-ties at all intersections are then examined and adjusted systematically using low-order polynomials in an attempt to reduce the mis-ties to an amplitude below the noise envelope.

It is assumed that temporal variations are a smooth function of time, i.e. the time taken to fly from one intersection to the next is short compared to the period of any time variations. This is more likely to be true on tie-lines where intersections are encountered more frequently (about every six seconds in National Geoscience Mapping Accord surveys) than on flight lines (about every minute). It is also assumed that intersection points are accurately located in x,y on both flights; mis-location will lead to the unjustified comparison of readings with a different 'geological signal'. To reduce this problem, points are weighted during polynomial fitting with lower weights being assigned to observations made in areas of higher observed magnetic gradients. Rogue points lying outside a few standard deviations of the fitted polynomial line may be rejected completely from the analysis to avoid unjustified distortion of the data.

Creating a grid and imaging the resulting anomaly values after base station subtraction and tie-line levelling usually shows the data to be less than satisfactory in that some line-related noise is still evident. This effect has been described as 'corrugations' and the standard

procedure for removal has been called 'decorrugation' or 'micro-levelling'.

Micro-levelling

The principle of micro-levelling is described by Minty (1991). It has no basis in the physics of geomagnetism and can, with equal justification, be applied to other line-based data such as gamma-ray spectrometry. It is essentially a filtering process which seeks to identify and remove features whose wavelength in the across-line direction is equal to twice the line spacing and in the along-line direction to the spacing between tie-lines. The need for micro-levelling arises from the imperfections in the polynomials applied to 'hang' the flight line data on the tie-lines, and imperfections in the difference values used to calculate those polynomials. The result is that the long-wavelength component of profiles is slightly out of register with neighbouring lines and individual lines of data therefore show up, particularly, for example, when calculating shaded relief effects in directions near normal to the flight line direction. AGSO's micro-levelling routine makes small adjustments to line sections to minimise this effect. The assumption is that the near-DC component of each profile resembles that of its neighbour so that the 'regional' field varies only smoothly from line to line across the whole survey area. The broad warp of this variation is controlled by the tie-lines. The danger is that genuine geological features can also follow flight lines and filtering could remove these too. In practice, a threshold is used to limit removal to low amplitude features which are more likely to be related to problems of imperfect levelling than to geology.

Summary of errors
- Temporal variations recorded on the ground and subtracted from the airborne data may differ from the temporal variations experienced by the airborne magnetometer.
- The assumptions made in the tie-line levelling process may be flawed and lead to long-wavelength distortion of the anomaly field on each profile.
- The process of micro-levelling is essentially arbitrary.

Some numbers derived from the data reduction of a recent aeromagnetic survey in South Australia may help clarify the magnitude of these corrections. Base station subtraction changed the magnetic value recorded on lines by an average of about 35 nT with this value changing by, on average, about 3 nT over the time taken to fly a line. Tie line levelling then changed values by an average (without regard to sign) of 1.7 nT with an average range of 3.1 nT (maximum to minimum) over the length of a line. Micro-levelling adjusted 70% of data points by amounts less than 1.0 nT and 23% of data points by less than 0.1 nT. While the adjustments made in micro-levelling may appear small, it should be noted that about three-quarters of the data points were adjusted by an amount exceeding the nominal noise envelope of the data (0.1 nT).

In addition, the exact relationship between the absolute value of the total field at the ground station and the IGRF at that point is not determined, leading to an uncertainty in the absolute value of data points and hence the absolute value of (observed value) minus (IGRF). (The variations in the IGRF over the survey area are removed separately and amount to a smooth surface subtracted from the data).

The nature of the imperfections in the assumptions made lead to an error in the data set that will have both systematic and random elements. It may be that the time is right to

rethink the whole process of levelling on a more mathematical basis. It will never be possible to take an instant 'snapshot' of the magnetic anomalies over a whole survey area, and deployment of additional ground base stations would add operational costs and difficulties which would buck the welcome trend towards lower and lower survey costs.

Acknowledgment. I acknowledge the help and support of my colleagues in the Geophysical Mapping Section of AGSO for discussions on many aspects of this text.

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Very high-resolution magnetic surveys

John M. Stanley

Geophysical Research Institute, University of New England, Armidale NSW 2351

The objective of magnetic surveys has changed in recent times from one of pure anomaly detection to a new role in providing detailed textural information relating to sub-surface structure. Conventional proton precession magnetometer systems were usually too slow to be logistically practical, or economically viable, for mapping magnetic fields in the detail required to resolve near surface geological and cultural features. As a result, magnetometer surveys have, in the past, been very undersampled, resulting in poorly defined data that were often difficult to interpret. However, advances in microprocessor technology have resulted in the development of a new generation of very sophisticated magnetometers that have revolutionized magnetic exploration. These systems are capable of measuring the magnetic field, processing and storing data at sampling rates of up to 400 per second. Consequently, high resolution surveys and real-time digital processing are now a commercial reality. In addition, portable PC-based imaging systems mean that data can be processed and interpreted on location while a survey is still in progress.

Although they have been developed for hand-carried use, the portability and processing power of the magnetometer systems enable them to be adapted to a variety of survey platforms, including fully compensated vehicle-borne, marine and helicopter surveys. High definition magnetic surveys are finding application in a wide variety of fields, which include geological mapping, archaeological exploration and engineering geophysics.

Instrumentation for airborne magnetic surveys

Zoltan Beldi

Manager, Airborne Division, Geo Instruments, 348 Rocky Point Road, Ramsgate NSW 2219

In recent years, optically pumped magnetometer sensors have provided a means of measuring the total magnetic field vector to previously unobtainable sensitivity levels. The two most commonly used optically pumped sensors are the Cesium Alkali Vapour and the Helium Meta-Stable sensor. Both employ similar principles, involving the measurement of the interference between the spectral lines of their constituent ionised gases in the presence of an ambient magnetic field. Though the Helium sensor has a theoretical sensitivity of 10 times that of the Cesium sensor, both are capable of returning laboratory noise levels in the order of 0.01 nanoTesla (nT) at bandwidths exceeding 10 Hertz. Each sensor has attributes that provide it with advantages over the other under certain circumstances. For example, the Helium sensor has a wider orientation envelope and bandwidth than the Cesium sensor, but draws more power and is more susceptible to vibration-induced noise.

Attention has turned to ensuring that the potential noise performance of the sensor is not degraded by the dynamics of the airborne platform. The following are the most serious causes of "noise" and some of the solutions employed in minimising the influence of the noise sources.

(a) The magnetic influence of the airborne platform

Virtually all aircraft contain components made from ferrous metals, most of which exhibit individual magnetic moments. If the sensor is mounted in close proximity to these components, the total field vector will be influenced by the direction of these components relative to the earth's magnetic field vector. As the components change their relative direction as a result of aircraft manœuvers, a corresponding change of the magnetic field moment, that has no relation to the terrestrial field of interest, will be detected by the sensor.

An additional source of noise is ~generated by the magnetic field from "eddy current" effects. These are minute electrical currents generated by the motion of conductive metals through the magnetic field, and are proportional to the velocity of the platform and the individual volume of the conductive metal components.

The simplest solution to both of these noise sources is to position the sensor sufficiently removed from the offending metallic components. This is often achieved by mounting the sensor in an airfoil "bird", and suspending it from the aircraft by approximately 30 metres of cable. This technique is in common use in Helicopter-borne instrumentation platforms. In the majority of cases this will reduce the influence of the aircraft to less than 0.1 nT.

Unfortunately, there are some drawbacks to this, specifically in the case of fixed-wing aircraft, that are related to practical considerations of installation difficulties. In those cases, the sensor is normally mounted in a "stinger", or pod, usually attached to the tail of the aircraft. Whilst this removes the sensor from the immediate vicinity of most of the offending components, there remain residual moments in the order of tens of nT which must be removed from the measured field. There are two commonly used techniques to achieve this.

*(i) Static compensation:*achieved by the insertion of an opposing magnetic field either by fixed magnets or electromagnetic generating field coils judiciously positioned near the sensor. At best, this approach only reduces three of the vector components out of a much larger number (thirty or so) which influence the measurements. As it is an approximation of the interference effects, the resulting noise level attributable to aircraft manœuvers after compensation may still exceed 0.5 nT. The technique for performing the compensation is very operator-dependent, often time-consuming, and sometimes difficult to achieve as it requires an area of low magnetic horizontal gradient.

*(ii) Dynamic Compensation:*a far more elaborate approach requiring the application of some very advanced modelling techniques using digital processing computers. Modem advances in microcomputers have allowed the Digital Compensator to be carried on board the aircraft, allowing real-time compensation. An example of a successful Dynamic Compensator is the Automatic AeroMagnetic Dynamic Compensator (AADC) produced by RMS Instruments in Canada. The AADC is composed of a high-resolution frequency-counter processing computer and a three-component fluxgate magnetometer. The frequency counter is optimised for the type of magnetometer sensor used, while the fluxgate magnetometer is used solely for the detection of the direction of flight and the manœuver rate of the aircraft.

Compensation is effected by flying the aircraft on the four cardinal headings and performing separate pitch, roll and yaw manœuvers on each heading whilst recording the magnetometer data. The compensation flight must be conducted at an altitude above the ground where the wavelength of any geological magnetic sources is longer than three kilometres. At the conclusion of the compensation flight, the manœuver data are analysed and a set of interference coefficients are derived.

During normal data acquisition, the aircraft manœuvers are sensed by the fluxgate and the derived coefficients are used to provide offsets to the measured field. Noise levels achievable by these means are often better than 0.1 nT.

(b) Position error noise

Traditionally, airborne surveys were preformed using visual navigation and recovery techniques from large scale aerial photography or maps. Visually recovered points were often spaced at one kilometre or more, and intermediate points interpolated assuming constant aircraft speed and track. These techniques could easily result in position error in the order of 50 metres, depending on the accuracy of the maps and the competence of the recovery personnel. Position errors of these magnitudes seriously degrade the effective resolution of existing magnetometers.

Radio-navigation techniques using Ultra High Frequency radio waves improved the situation dramatically, but still caused some errors due to the multi-path and frequency skipping problems experienced by these units under some circumstances.

The Global Positioning System (GPS) using the NavStar satellite constellation has changed all that. By deploying differential measurement techniques (real-time and post-flight), positional accuracies of one metre are being realised. It is possible to install a GPS sensor in the "bird", thus removing one of the uncertainties regarding the true position of the sensor.

The new techniques will ultimately allow positions to be defined with sufficient accuracy to allow the magnetic data to be overlaid with topographic relief maps, thus allowing magnetic modelling of topographic effects to be introduced with greater confidence.

Low amplitude and high frequency aeromagnetic effects - to do diurnal corrections or not?

I.D. Campbell, S. Saul and S.S. Webster

Austirex International Ltd., World Geoscience Corporation
27 Merriwa Street, Gordon NSW 2072

Much time and effort has been expended in airborne geophysics to determine the best method to correct aeromagnetic data for low amplitude and high frequency signals. Clauses exist in most survey contracts to define error tolerances in diurnal records that will force the contractor to re-fly data that exceed these tolerances. However, the contracts do not specify how the contractor will use the diurnal data to correct the airborne data.

Our group's experience over the past few years in conducting surveys around the world leads us to the conclusion that the ground-recorded diurnal field should NOT be used to evaluate airborne magnetic survey data. There is no proof that such ground-based information has any replication in the air. Chamalaun and Cunneen (1990) showed data from the Canning Basin in WA where a subsurface induction anomaly caused non-correlatable data across a large-scale magnetometer array. We will show diurnal data with correlatable large- and micro-pulsations between magnetometers some 1,200 km apart. The regional diurnal stability within survey areas is not predictable when planning a survey, and diurnal data should be used as a guide, not an absolute criterion.

We have experiences in near-polar latitudes (timing: 2nd half of 1991) where we were able to fly 74,000 line km of survey in 3.5 months for a client who trusted our data veracity discretion, whilst another contractor was only able to produce 40,000 line km in 5 months due to severe diurnal limitations. Maps with 1 nT contour interval and enhanced images of excellent quality were produced for this area.

Our procedure for conducting surveys in potentially noisy periods and areas is summarised below:
- tie-lines must be closer spaced than the industry normal of 1/10th ratio, with a 1/5th ratio being acceptable for magnetically active geology, and a 1/3rd ratio being required for quiet geological areas such as sedimentary basins;
- in field processing to enhance images and derivative plots, it is essential for the contractor to evaluate the effects of noisy diurnals on the airborne data; and
- micro-levelling is necessary to remove noise between tie-lines.

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Geomagnetic Pulsations and Their Effects on Airborne Magnetic Surveys

Peter R. Milligan

Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601

Airborne magnetometers now have resolutions of typically less than 0.1 nT, and the location of sub-1 nT crustal anomalies is becoming increasingly important, particularly for the delineation of weak intra-sedimentary magnetic sources in prospective petroleum provinces. Natural time variations of the geomagnetic field, with periods ranging from fractions of a second to diurnal harmonics of several hours, are a source of noise for the accurate delineation of such crustal anomalies. Time variations of period greater than a few minutes are usually successfully removed by the tie-line system employed for aeromagnetic surveys (see Reeves, this volume; Campbell et al., this volume). Hence, micropulsations of the geomagnetic field, which have periods of less than a few minutes and typical amplitudes of a few tens of nT at most, are important likely noise sources in high-resolution aeromagnetic surveys.

The total-field spatial characteristics of micropulsations across Australia are a relatively unknown quantity. With such short periods, micropulsations will induce currents in local subsurface conducting bodies, and also in surface waters. These induced currents will produce their own secondary fields which sum with the inducing fields to produce a complex spatial variation. Highly susceptible rocks will also affect the characteristics of pulsations. The Australian Geological Survey Organisation (AGSO) is currently investigating the morphology of such total-field micropulsations, with the ultimate aim of their accurate removal from total-field aeromagnetic records.

During March 1992, in a collaborative project between AGSO and The Flinders University of South Australia (FUSA), a series of FUSA ring-core fluxgate magnetometers, with a resolution of 0.1 nT, were deployed in an array across Ordovician shales, south of Ballarat. Also deployed were a Narod ring-core magnetometer and a Helium Vapour total-field instrument. The shales were chosen as they have only a small aeromagnetic signature. Long trains of PC4 micropulsations were observed, with a period of 60 s, and peak-to-peak amplitudes up to 3 nT. The micropulsation activity was found to be spatially uniform across the array, which spanned only a small area of width 40 km.

Four instruments were compared at the Canberra Magnetic Observatory during the last week of 1992. They comprised two Helium Vapour magnetometers (from the AGSO aircraft), a Caesium Vapour magnetometer (on loan from Geo Instruments Pty Ltd) and a Narod 3-component ring-core magnetometer (from the Geomagnetism Group, AGSO). Figure 1 shows an example of micropulsations recorded by the aircraft magnetometer. They have an amplitude of approximately 0.16 nT, and a period of 14 s. This would correspond to an interval of 840 metres at the survey velocity of 60 metres per second.

The Airborne Group of AGSO is currently developing a Helium Vapour base-station instrument for accurate sensing of high-frequency geomagnetic variations. This will be capable of measuring the total magnetic intensity at the same sampling interval and resolution as the aircraft magnetometer, and will be deployed at the base airfield during future survey operations. The instrument is PC-based, and data will be transmitted from the

instrument site to the field caravan. Future array studies are also planned to determine the requirements for additional base-stations at more remote localities.
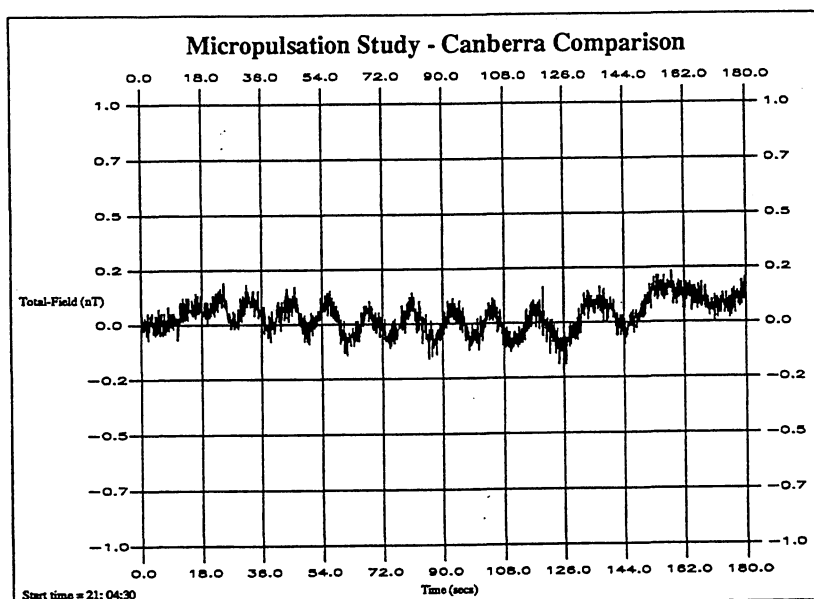
Figure 1. Micropulsations recorded at the Canberra Magnetic Observatory on 24 December, 1992.

Development and Application of Differential Vector Magnetometers

P.W. Schmidt, D.A. Clark, D.A. Coward and M.P. Huddleston

CSIRO Division of Exploration Geoscience, PO Box 136, North Ryde NSW 2113

The amplification of micropulsations in the vicinity of ferromagnetic rock masses has been detected by Ward and Ruddock (1962). In their experiment they used a pair of alkali-vapour scalar magnetometers, one over the source and one removed from the source. Later Goldstein and Ward (1966) showed that it was possible to separate the induced and the remanent parts of magnetic anomalies, and infer a Koenigsberger Ratio (Q) for the source. Micropulsation amplification was detected only over anomalies whose sources were shallow and had low Qs. The diurnal variation was required to detect such changes for deeply-buried sources. The Qs determined in this way using scalar magnetometers are only nominal since, in general, the induced anomaly and the remanent anomaly are not parallel but dependent on orientation and geometry.

Parkinson and Barnes (1985) derived a more general theory that allows for non-parallel induced and remanent anomalies, which requires simultaneous vector measurements. They demonstrated their method over an intense anomaly using three-component fluxgate magnetometers. Clark (1985, in Parkinson and Barnes, 1985) developed the theory further and showed that vector measurements allow the directions of the induced and remanent

magnetisation, and their relative intensities, to be determined. Furthermore, for a compact source it is possible to locate the centre of the source.

Apart from the above application, there are several advantages of vector magnetometer surveys, (i) they provide information on the degree of lineation of geological features, (ii) they enable the strike direction to be determined, and (iii) they define the direction to off-profile sources. These advantages equate to better data for any given line-kilometre or, alternatively, data at lower cost. Moreover, magnetic components are related to potential fields that possess attractive mathematical properties, irrespective of anomaly amplitude. Component anomalies are also simpler to interpret since their form is independent of latitude.

In collaboration with the Geophysical Research Institute (GRI) of the University of New England, we have built two vector magnetometers based on caesium-vapour magnetometers. Although these sensors are fundamentally scalar magnetometers, by using forward and reversed bias fields it is possible to determine component fields. Table 1 shows the sensitivities of the vector measurements required for a meaningful assessment for different conditions. Clearly a widely applicable system must have sub-nanotesla (<1 nT) sensitivity. While the caesium-vapour sensor has an intrinsic sensitivity of 0.01 nT, it has proved difficult to achieve consistent sub-nanotesla vector measurements. Some of the problems encountered include, (i) precise bias field switching, (ii) ironically, field variation during vector measurement (since the differential method ultimately depends on the variations for signal), and (iii) mechanically rigid coil mounts. The alignment of the two magnetometers presents another difficulty that we have yet to address seriously. The required accuracy of alignment also depends on the size of the anomaly, the magnitude of the time-variation and the Q.

TABLE 1   Required magnetometer sensitivity

Anomaly (nT)	$\Delta B(t)$ (nT)	Magnetometer Sensitivity (nT)		
		Q=0	Q=1	Q=9
10,000	100	20	10	1
	10	2	1	0.1
	1	0.2	0.1	0.01
1,000	100	2	1	0.1
	10	0.2	0.1	0.01
100	100	0.2	0.1	0.01
	10	0.02	0.01	0.001

Figure 1 shows a log-log plot of bias field reversibility versus error for a measurement of a component for different bias fields. The bias fields are expressed as fractions of the component magnitude from 0.001 to 0.5. The larger the bias field, the smaller the error. For a component magnitude of 30,000 nT, 0.1 nT accuracy equates to one part in 300,000 or a log10 of - 5.5. This requires a bias field of somewhere between 10% and 25% of the component magnitude (say 3000 nT - 7500 nT) and a reversibility of about 1 ppm (a few pT). With the present coil set this corresponds to a current stability of better than 0.1 μA. So far we have

managed to achieve 0.3 µA stability. The problem of the component varying in magnitude while the measurement is in progress is more insidious, but has a comparable effect as current stability on degrading the signal. For a bias field equal to 10% of the component, i.e. 3000 nT, a variation of more than 3 pT in the component during measurement will produce an error of more than 0.1 nT in the calculated component magnitude.
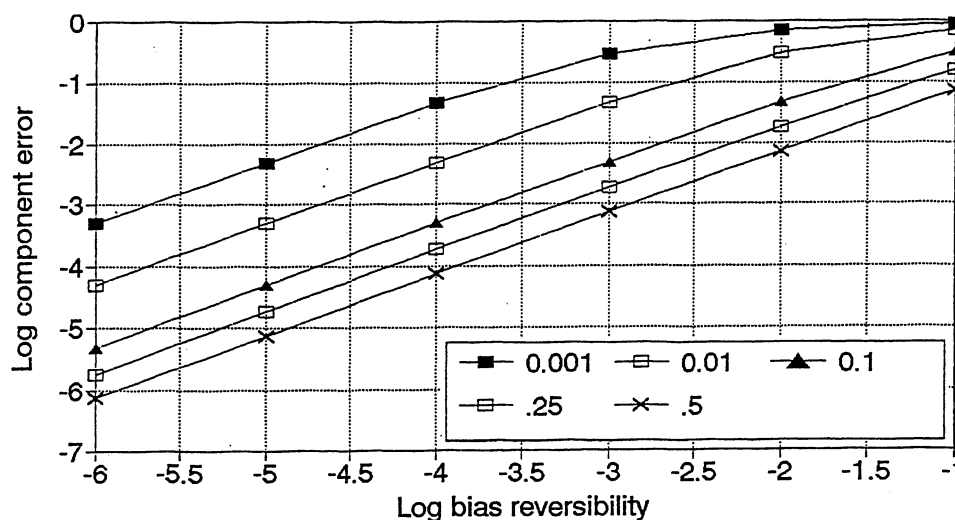
Figure 1. Vector magnetometer error analysis: log-log plot of bias field reversibility versus component error, for different bias field magnitudes expressed as a fraction of the component magnitude. For a component error of one part in 300,000 (0.1 nT in 30,000 nT or log10 of -5.5), requires a bias field of somewhere between 10% and 25% of the component magnitude (say 3000 nT - 7500 nT) and a reversibility of about 1 ppm (a few pT).

To reduce errors of the type discussed above, it is clearly advisable to use as large a bias field as possible. However, there are two constraints on the magnitude of the bias fields, (i) they must not be so large that the orientation of the total field is deflected into the dead-zone of the caesium-vapour sensor, and (ii) power consumption. The first problem could be largely overcome by using the latest caesium-vapour sensors that are not so affected by orientation. The latter problem could be off-set by using more turns for the coils, but this increases inductance effects because of increased measurement time (since there is a wait-time between current switching that depends on the rate of decay). However, it is prudent to make measurements as quickly as possible to reduce the effect of time variations. The optimisation of the system is therefore a trade-off between competing effects. Funding for the two original magnetometers was provided by a Sirotech grant to GRI.

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THE MAIN FIELD

A Personal Check-List of Questions Concerning the Core and the Geomagnetic field and some tentative answers

Frank D. Stacey

Physics Department, The University of Queensland, Brisbane Q 4072

Rather few of the generally accepted views on the properties of the core and the processes by which the geomagnetic field is generated within it are really secure. Some of the unconventional views may yet turn out to be correct. We can examine weak points in our current understanding to find the problems on which new progress is most likely. The following list of questions is intended to help in identifying these weak points. My own opinions, given here as answers to these questions, are intended to stimulate discussion.

Q1: Does the spatial spectrum of the geomagnetic field indicate the scale-depth of current loops in the outer region of the core?

A: Yes. The spectrum suggests a thickness of 160 km for an outermost layer in which the poloidal field is not sheared off by the toroidal field. This coincides with the smallest scale of magnetically maintained current loops if the critical magnetic Reynolds Number is $R_m \approx 10$.

Q2: Is there a stably stratified layer at the top of the core?

A: No. Such a layer would require the core-to-mantle heat flux to be extremely uniform and preclude any mantle control of core processes. Variations in reversal frequency on time scales of order 10^8 years demand mantle control.

Q3: Are reversals triggered by core-mantle boundary phenomena?

A: Mantle effects can hardly be rapid enough to account for individual reversals, but the long-term trend in reversal frequency is almost certainly mantle-controlled.

Q4: Do tidal or precessional torques contribute to dynamo action?

A: No. This has always appeared to be an interesting idea but no way has been found to make it work.

Q5: Do thermo-emf's at the CMB have an influence?

A: No. Even under the most favourable circumstances thermoelectric currents can be only an exceedingly small fraction of the total core currents. Since thermoelectric currents would remove the sign ambiguity in the field generated by the dynamo, they would give an asymmetry to the reversal sequence and this has not been seen. But note that a systematic difference between the dipole/quadruple ratio in normal and reversed states has been reported.

Q6: Are "standing" features of the field due to high conductivity anomalies at the base of the mantle?

A: Yes, but more by default than positive evidence. There is simply no other viable explanation.

Q7: Are the high conductivity anomalies mobile?

A: Yes. The base of the D" layer must be a hot low viscosity region acting as a thermal boundary layer and supplying hot material to mantle plumes. Even dense rafts of high conductivity material not participating in mantle convection would be moved about, as are continents at the Earth's surface.

Q8: Does radioactivity contribute to dynamo power?

A: No. If it did then the gaseous products of radioactivity, helium and/or argon, would be seen in excess in plume basalts, but they are not.

Q9: Is the inner core anisotropic?
A: Yes.

Q9A: Why and how?

A: Compositional convection in the core is rotationally controlled in such a way that inner core material is deposited on the equator. The inner core progressively deforms towards equilibrium ellipticity and the deformation aligns anisotropic crystals. It is, of course, necessary that the inner core be composed of anisotropic material. e-ion is commonly favoured but is not the only possibility.

Q10: What is the dynamo power available from compositional convection?

A: 2×10^{11} W.

Q11: Does the westward drift indicate bodily flow of core material?

A: No. Core-mantle coupling has a time-constant of about 10 years and westward drift has persisted for several centuries. The energy dissipated by differential rotation itself at the

presently observed rate would be about 3×10^8 W and is clearly admissible, but the only way to maintain the motion would be by precessionally misaligned rotational axes requiring very much greater dissipation.

Q12: Is the outer core motion turbulent?

A: Yes, because this is the only way that chemical differences generated at the inner core boundary can be mixed into the outer core. As Braginsky pointed out, this process must be self-adjusted so that the eddy diffusivity is approximately equal to the magnetic diffusivity ($\sim$ 2.4 m^2 s^{-1}). The entropy of mixing may consume as much as 50% of the convective power (reducing the dynamo power to 1×10^{11} W).

Torsional Oscillations and Taylor's Condition

David J. Ivers

School of Mathematics & Statistics, University of Sydney, Sydney NSW 2006

Numerical solutions of the non-steady dynamically-consistent magnetohydrodynamic dynamo problem for the Earth is a difficult, but increasingly more feasible, task. To establish that dynamo regeneration of the magnetic field is actually occurring, the time integration must be over several free-decay times of the Earth's core. (The free-decay time is about 15,000 years.) A major difficulty with such long time integrations are inertial (Rossby) waves, with periods of less than a day, and torsional oscillations, with periods of tens of years, which may be driven by buoyancy. One approach with the Boussinesq equations, initiated by J.B. Taylor (1963), has been to assume that these short period oscillations are unimportant in the dynamo process, and to filter them out by dropping the inertial term in the momentum conservation (Navier-Stokes) equation. However, it is not clear that torsional oscillations can be neglected in this way. In a more conservative approach, it is shown that Taylor's algorithm may be modified to incorporate torsional oscillations and only the inertial oscillations are neglected.

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Geomagnetic Constraints on Core Processes

Ronald T. Merrill

Geophysics Program, University of Washington, Seattle WA 98195, U.S.A.

Magnetohydrodynamic processes acting in the core to produce the geomagnetic field and its secular variation are notoriously sensitive to boundary conditions. Observational evidence, particularly from seismology, suggests that the few hundred kilometre-thick seismic layer (D") at the base of the mantle is a thermal boundary layer in which a chemical boundary layer is embedded. The properties of this layer vary in both space and time. It will be shown that these variations are evidenced in a host of palaeomagnetic and geomagnetic data, including non-stationarities in the reversal chronology, evolution in the ratio of the dynamo families and, possibly, in variations in palaeointensity data.

Geomagnetic reversal transitions and D" Layer

S.K. Runcorn

c/o School of Mathematics and Statistics, Sydney University, Sydney, NSW 2006

The geomagnetic secular variation and non-dipole field have long been recognized to be a factor of about 3 lower over the Pacific hemisphere than elsewhere since 1900. That this was a statistical fluctuation, never plausible, has now been eliminated by the construction of magnetic maps back to 1700. Paleomagnetic data in the Pacific, though scarce, gives evidence that the phenomena has been a feature over the last part of the Cenozoic. Screening by a metallic layer in the lower mantle beneath the Pacific was proposed as an explanation. Seismic studies of the D" layer lend some support to the hypothesis that it has hemispherical asymmetry in its chemical composition. More FeO and FeS in D" below the Pacific distributed in blobs may account for the screening. If correct, the presently used methods of inferring core velocities are unsound.

Recently-acquired data on the transitional VGP paths during some geomagnetic polarity reversals over the last 11 Myr show a strong tendency for two longitude sectors, the Americas and Australia E Asian, to be favoured. The reversal appears to occur through the rotation of the dipole. It is proposed that electromagnetic interaction between the reversing core field and the hemispherically asymmetrical D" layer, with near metallic conductivity beneath the Pacific hemisphere, causes the core to rotate relative to the mantle about the Earth's axis, so that the reversing dipole tends to move along one of the bounding meridians of the conducting shell beneath the Pacific. The dipole tends to diminish in strength during reversals and this explains certain anomalous VGP paths.

Reversals of the Geomagnetic Field

Phil McFadden

Australian Geological Survey Organisation, Canberra ACT 2601

The most recent geomagnetic reversal chronology shows 285 reversals in the past 160 million years. Thus, although on a human time scale the dipole field and the secular variation appear to be the pervasive features of the field, on a geological time scale it is the dipole field and its reversals that emerge in this central role. The fascinating aspect of the reversal process is that it appears to be a non-stationary renewal process with a variable rate and random time intervals between events.

The process is closely approximated by a gamma process, so the probability density p(x) of the interval lengths x is given by

$$p(x)dx = \frac{1}{\Gamma(\kappa)}(\kappa\lambda)^\kappa x^{(\kappa-1)}e^{-\kappa\lambda x}dx$$

where λ is the rate of the process (the inverse of the mean length, μ, of the intervals) and κ, the gamma index, is a measure of the inhibition or encouragement in the process. Inhibition comes about when the occurrence of an event (specifically, in this instance, a reversal) reduces, for some time, the future probability of another event, and is indicated by $\kappa > 1$. Encouragement is the opposite and is indicated by $0 < \kappa < 1$. If $\kappa = 1$ then the process is Poisson and the occurrence of an event has no effect on the future probability of another event.

- Neither κ nor λ is constant - both vary with time, giving us information about processes deep in the earth.
- Because a reversal takes a finite time to occur, the process cannot be truly Poisson; there has to be at least a small amount of inhibition, so $\kappa > 1$ is to be expected. This has a profound effect upon our expectations for the number of very short intervals, even if κ is close to 1.
- κ has remained close to 1 for the past 160 million years, indicating very little inhibition in the process.
- There is no reason to reject the hypothesis of a common stability for the normal and reverse polarity fields at any time during the Cenozoic. This has significant implications for claims that there are several short reverse events during the Brunhes, for that would require that the reverse polarity field has been substantially less stable than the normal polarity field for the past 750,000 years.
- The reversal process actually ceased during the Cretaceous Superchron. This indicates that the reversal process is not always a component of the geodynamo process. This long (approximately 35 million years) interval has been, and sometimes still is, interpreted as an indication of differential stability in the reverse and normal polarity fields. This is inconsistent with the statistics of the process and so we interpret this Superchron quite differently. During the late Mesozoic the inherent rate of the reversal process gradually decreased until it actually reached zero, at which time the reversal process, but not the

dynamo process, effectively ceased. The geodynamo then remained in whichever polarity it happened to have at the time (which, with a probability of 50%, was normal) until the reversal process again became operative. This occurred not because the normal polarity had suddenly become relatively much more stable than the reverse polarity, but because the reversal process itself had ceased. Thus the Cretaceous Superchron should not properly be considered part of the "reversal sequence".

- κ appears to have been driven up as 1 has increased during the Cenozoic. The observed increase in k (the estimate of κ) is consistent with there being an interval of about 45 kyr after a reversal during which the probability for a future reversal recovers to its pre-event value. We have associated this recovery time with the electrical conductivity of the core.

LOW FREQUENCY GEOMAGNETIC VARIATIONS AND INDUCTION STUDIES

Solar and Lunar Daily Geomagnetic Variations

D. E. Winch

School of Mathematics and Statistics, University of Sydney F07, Sydney NSW 2006

Solar and lunar daily geomagnetic variations provide the basic material for electromagnetic sounding of the Earth at frequencies of 1, 2, 3, 4 cycles per solar or lunar day, and also provide information on the upper atmosphere wind movements which provide the dynamo action necessary to give the emf's which drive the current systems.

Solar magnetic variations are driven by solar heating of the ozone layer whilst lunar magnetic variations are driven by tidal movements of the upper atmosphere and are, of necessity, much smaller. Both the principle lunar semi-diurnal tide, M2, and lunar elliptic semi-diurnal tide provide sensible magnetic variations, although with longer runs of magnetic data, many of the smaller tides can also be determined.

Determination of seasonal changes in solar and lunar magnetic effects give some interesting and puzzling results. Seasonal sidebands, which one might expect to be equal, are in fact not, and the reasons and consequences of these differences haven't been explained or followed through.

The oceans are in tidal movement and act as a dynamo in just the same way as the upper atmosphere. Electric potentials on undersea cables show that the potentials produced by ocean movement are likely to be greater than those induced in the ocean by the movement of electric current systems in the upper atmosphere.

A new theory of the solar daily Sq geomagnetic variation

F. H. Hibberd

Physics Dept., University of New England, Armidale, NSW 2351

A new theory for the generation of the Sq solar daily geomagnetic variations is proposed. The distortion by the solar wind of the earth's dipole field results in a non-uniform axially asymmetric field at the earth. The rotation of the earth in this field induces eddy currents in the upper layers of the earth. The force on the earth, transmitted via the Maxwell magnetic stresses in the field, is equal to the force exerted by the solar wind on the magnetopause and must remain constant for a constant solar wind, so that the earth currents are constant for a solar wind. The rotation of the ionosphere and inner magnetosphere in the field of the earth currents induces currents in the ionosphere proportional to the ionospheric conductivity and convection of the flux tubes in the magnetosphere, to maintain the normal component of the field continuous across the ionosphere and zero at the magnetopause. The theory appears able to account for all of the variations and properties of Sq, as well as for the observed super-rotation of the neutral upper atmosphere.

Dependence of Sq on the 10.7 cm Solar Flux

F.H. Hibberd

Physics Dept., University of New England, Armidale, NSW 2351

A remarkably closely linear relation is found to exist over the solar cycle between the annual mean daily range of Sq, largely freed from disturbance, and the 10.7 cm solar flux. Extrapolated to zero solar flux, corresponding to zero ionospheric conductivity, the daily range of Sq remains positive. If the extrapolation is valid, this residual Sq must be due to earth currents and cannot be induced by ionospheric currents as required by the conventional atmospheric dynamo theory.

The annual variation in the nighttime value of the H-component of the geomagnetic field

H. McCreadie and E.C. Butcher

Physics Department, La Trobe University, Bundoora, Vic 3083

Malin and Isikara (1976) proposed that the annual variation in the nighttime values of the geomagnetic field was caused by an annual variation in the latitude of the ring current. Butcher and Schlapp (1992), using longer runs of data, showed that, besides the ring current component, there was also a smaller component of unknown origin. In this paper we model the ring current effect by considering the magnetic effect on a sphere inside a coil of finite length which moves up and down the axis with a period of one year. The latitude variation of the magnitude of the annual (and semi-annual) variation for this case is determined and compared with results obtained at a number of stations.

Butcher, E.C. and D.M. Schlapp (1992). The annual variation of the night-time values of the geomagnetic field. Geophys. J. Int., **111**, 151-158.

Malin, S.R.C. and M. Isikara (1976). Annual variations of the geomagnetic field. Geophys. J. R. astr. Soc., **47**, 445-457.

Electromagnetic induction in earth using long period geomagnetic variations

Haralds F. Petersons

Mathematics Department, Australian National University, Canberra ACT 2601

Earliest studies of the Earth's electrical conductivity assumed, for mathematical simplicity, a radially spherical conductivity model. In more recent times a number of studies have questioned this assumption. In particular, studies of the long period geomagnetic variation response of the Earth suggests departure from radial symmetry. Some of the problems of using long period geomagnetic variations will be discussed as well as the implications of departure from radial symmetry.

Australia-wide Array of Geomagnetic Stations (AWAGS)

François Chamalaun

School of Earth Sciences, Flinders University, Bedford Park SA 5042

Between November 1989 and June 1990, an array of 54 vector magnetic field stations was deployed to record the variations in the Earth's magnetic field across Australia. The array spacing was about 275 km and the data were recorded at 1-minute intervals with nanotesla resolution. Several students are now working with the data. In this presentation, we will present and discuss the results in terms of induction transfer functions covering a wide range of frequencies. Apart from the coast effect, a significant finding is the dominant effect of the principal sedimentary basins, which appear to concentrate current flow, resulting in an almost continuous zone around the Pre-Cambrian craton.

Thin-sheet electromagnetic modelling of the Australian Continental Crust

Robert W. Corkery [1] and F.E.M.(Ted) Lilley [2]

[1] *Department of Geology, Australian National University, Canberra, ACT 0200*
(now at Research School of Physical Sciences and Engineering, ANU)
[2] *Research School of Earth Sciences, Australian National University, Canberra*

A compilation is made of the gross surface geology of the Australian continent. On a grid-scale of 180 km, electrical conductances are estimated down to depth 10 km for both the Australian continent and the surrounding oceans, and used to form a numerical "thin-sheet" model. Within the continent, the greatest contributions to conductance come from the sedimentary basins. Otherwise, the oceans have the strongest effect.

The response of the model to time-varying magnetic fields is computed for a period of 1 hr, as a guide to the electromagnetic induction pattern to be expected regionally from known Australian geology. The coast effect, as observed, is well-modelled given the accuracy of the exercise. Within the continent, strong observed conductivity anomalies are not reproduced unless conductances along their paths are increased substantially. However, such enhancement may not be geologically unrealistic.

The model will benefit from refinement, to be expected in due course both from more field data and advanced computer power. The method appears to be a practical way of establishing the general electromagnetic induction pattern of Australia, set in its surrounding seas.

A Magnetometer Array Experiment in New Zealand

J. D. McKnight

Geomagnetic Observatory, Institute of Geological and Nuclear Sciences,
Wellington, New Zealand

During the 1991/92 summer an array experiment involving 32 three-component magnetometers was run in New Zealand. Simultaneous recordings were made at 1-min intervals at each of 25 sites for four months. These sites cover the whole of New Zealand and Chatham Island, with a typical spacing of 150 km. At the same time a further 12 sites in the South Island were each occupied for two months, these sites being chosen so as to create six lines of magnetometers running roughly east-west across the island, with a typical spacing between the magnetometers of 50 km. Absolute observations, made at each site in the experiment at the beginning and end of deployment, enabled oriented data sets with a resolution of 1 nT to be prepared.

An initial analysis involving the computation of transfer functions at 34 sites has shown that the geomagnetic ocean effect dominates the induction arrows. An attempt to remove the ocean effect by means of a thin sheet numerical model has not produced unambiguous evidence for induction effects associated with the underlying subduction zones.

It is intended to pursue the separation of the ocean effect and induction effects associated with on-shore conductivity contrasts by improving the numerical model and also by using an analogue model. A further objective is the quantification of the diurnal variation occurring over New Zealand in terms of that observed at the Eyrewell magnetic observatory. It is also hoped to combine the New Zealand and Australian (AWAGS) array data sets to study external field variations over the Australasian region.

Earth Potential as Part of an Earthquake and Volcanic Monitoring Programme

Paul T. Finlay

62 Woodside Road, Henderson, Auckland 1208, New Zealand

Structural Setting
The first phase of the South Auckland volcanic eruptions began some 1.4 - 1.8 Ma with the Nga Tutura volcano. The basalt exuded is a fine grained olivine basalt with feldspar, laths, augite, magnetite and spinel. Prior to this, at 1.8 - 2.7 Ma, eruptions occurred 40 km further south, outside the South Auckland region. There is a general migration of the Ngatutura phase with structural control by faults. Some of the volcanoes are aligned on the greywacke basement which is of Jurassic age.

porphyritic fine grained olivine. It covers 240 sq. km and ranges in age from 420 kyr to 810 kyr. The migration of this phase is as equally intriguing as the first. However, there are numerous scattered younger (0.56 Ma) volcanoes with no apparent migration.

In the Auckland region, Rangitoto erupted and emerged from the sea prior to European settlement. The present state and depth of the magma field is unknown. Two tools are available to research the depth, seismology and magnetotelluric methods. Typically type B microearthquakes may occur with magma movement, though not necessarily so, as evidenced on 15 November, 5.25 pm (JST) 1986 at Mt Mihara on Izu Oshima, Japan. The South Auckland region has no seismographs installed though the structural geology is dominated by faults and volcanoes. Mesozoic folding and Cenozoic faulting have occurred and, were it not for an approximately M6.5 earthquake on 23 June 1891 that produced MM7 isoseismals in Auckland and Hamilton, the belief could be held that the region is tectonically inactive.

One fault in particular, the Waikato Fault, has been researched, establishing that it has a calculated downthrow of 2700 m at Port Waikato and 700 m near Tuakau (Hochstein and Nunns, 1976). A further experimental research medium is telluric. It is continuous and freely available.

Earth Potential Site

Four sets of T316 high grade stainless steel rods with three rods to a set, were driven to 600 - 800 mm below the Onewhero volcanic weathered tuff. Each rod is 10 mm diameter and 870 mm in length.

The Onewhero Earth Potential site is on farmland and the earth wires are of high tensile steel stranded insulated wire, buried some 100 - 150 mm below ground level, and originally measured by a YEW 2 pen recorder. This has been upgraded in January 1993 to a data logger which is periodically downloaded to a PC Computer. Measurements are made of rainfall, sunshine, wind, solar flares, geomagnetic disturbances, and so on. The Waikato River is 2 km away to the north east, and the Tasman Sea is but 14 km away, so it is expected that the earth current vector is coastline-dominated. It is hoped to measure microearthquakes with a relatively inexpensive seismometer of a type similar to a prototype being tested at Victoria University, Wellington.

INITIAL TESTS

Line	Geographic Bearing (deg)	Distance (m)	Typical Reading (mV)
A - D	23 - 203	110	200 - 400
B - C	84 - 264	63	100 - 350

Lines AC and BD will form the long term research alignments at 21-201⁻ and 84 - 264⁻ bearing respectively.

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N
W   E
S

Geomagnetic North 1994
ann. inc. +30'
22°

to shearing shed

GULLY (wet)

bush

Cattle drinking Trough

p/pole

B.M.A.
nom. R.L.
100.00

650 976 N
314 520 E

to data logger

olive slip

C   D

2·5 m dia.
dead
stump
(Macrocarpa)

tractor

farmer's

G.L.= 100·60
(Top of earth rods
600 mm below G.L.)

B   84° ~ 264°

V

63 m

102·6

R.L. to top of rods	Depth below G.L.
102·6	600 mm
102·54	650 "
102·4	800 ,

fenceline

No. 8 Wire

+101·9

+103·5

+105·2

106·2 +

Location	North	East	Bearing
Onewhero Site	650 976	314520	B.M.A. —
Mt. Wellington No. 2	698 332	307 310	351° 17'
13 Rangitoto	710 022	308 350	354° 02'
20 Ponui I.	700 622	337 758	25° 05'
Waiatarua T.V. Tower	694 634	282 495	323° 44'

Reference:

| Mt. Eden | 700 000 | 300 000 | 343° 31' |

hillock

A.C. Power lines
6 m above G.L.

phase

109 m

101·6 +

V

230 / 400

hillock

+ highest
point c. 108

23° ~ 203°

G.L.=104·5
Top of earth rods
750 mm below G.L.

A

ONEWHERO
South Auckland. N. Z.
EARTH POTENTIAL SITE

metres

0   10   20   30   40   50

MAGNETOTELLURICS

Magnetotellurics and Regional Tectonics in Australia

Jim Cull

Dept. Earth Sciences, Monash University, Clayton VIC 3168

Resistivity surveys provide one of the few geophysical alternatives to costly seismic profiling for direct mapping of deep structural contacts associated with regional tectonics. Galvanic methods (e.g. DC Schlumberger) are used routinely for mineral exploration and ground water mapping. However, except for a few isolated expanded spreads (e.g. Constable et al 1984), the depth of penetration is less than 1000 m. Normally, long-period EM techniques are required for investigations of the crust and upper mantle. Magnetotelluric data can be analysed for estimates of resistivity at depths from 1-100 km, and magnetometer arrays can be used to extend the results to depths of 500 km (e.g. Woods & Lilley, 1980).

Several deep resistivity surveys have now been completed in Australia. Magnetometer arrays have been deployed for mapping and regional reconnaissance, and magnetotelluric soundings have been obtained over significant geological contacts. However, interpretations have been complicated by anisotropies in the data. Simple 1-D solutions are often inappropriate and several separate anomalies must be identified and eliminated prior to constructing a detailed tectonic model suitable for a regional synthesis. In particular, anisotropies associated with surface perturbations can be readily confused with the response of deep 2-D and 3-D structures.

Major resistivity anomalies have been detected in the Australian crust/mantle by Lilley (1976) and Woods and Lilley (1980). They present an analysis of transient fields observed using magnetometer arrays in Central Australia. Individual substorms were characterised by systematic trends between successive sites in the array. The pattern can be approximated if EM currents are assumed to be confined to a single sheet within the sediments of the Murray basin. Variations in current density were established by Woods and Lilley (1980) using inversion techniques, and the gross features of the distribution were found to be correlated with the 2-D basin structure.

Zones of anomalous resistivity and regional anisotropies detected in other countries have been considered by Porath (1971). He was able to demonstrate a structural mechanism for all reported anisotropies, and variations in mineralogy were rejected. However, Constable et al. (1984) have argued that serpentinization, causing accumulations of magnetite, can provide a mechanism for lowered resistivities near Broken Hill. Concentrations of 1 per cent at the grain boundaries are considered sufficient to generate resistivities as low as 1 ohm-m depending upon the contact configuration.

Magnetotelluric data obtained near Broken Hill are characterised by marked anisotropies, suggesting abrupt lateral changes in resistivity (Cull and Spence,1985). The results are consistent with the concept of a PreCambrian boundary with a semi-vertical contact. This model is based on observations of delayed P-wave travel-time residuals from

west to east across the Willyama Block (Cleary, Simpson and Muirhead 1972). The observed delay times (exceeding 1 s) suggest major lateral density variations in the crust and upper mantle. However, major crystalline anisotropies in the underlying basement can not be dismissed.

Interpretations based on joint inversion of both MT and gravity data obtained in the same area may avoid some complications caused by crystalline anisotropy. Major 2-D structures based on detachment models have been proposed for the Lachlan Fold Belt (e.g. Gray & Cull 1992). Some aspects of these models suggest that significant resistivity variations (arising both from contrasting rock types and from thermal variations) might arise, inspiring the use of deep-probing MT methods. The 2-D framework is punctuated, however, by widespread granite emplacement; gravity methods are a natural choice for mapping the extent of such intrusions. The 2–D/detachment geological models presently favoured imply significant shear-type motions. Consequently, significant anisotropy can be anticipated in the MT data and the nature of the major lateral contacts may remain obscured.

Magnetotelluric inversion algorithms are now emerging with the capacity to generate more sophisticated 3-D models (Wannamaker, 1991), but independent constraints may be vital in selecting adequate error bounds for the critical parameters. Valid 3-D anomalies may be detected in the vertical component of MT data, but additional gravity data can be used to define the geometry and extent of any structure with greater precision. Tensor rotation can then be used to define significant variations in regional strike generated by structural, lithological, or geothermal anomalies. Further improvements in the present algorithms will provide an additional impetus for the investigation of more subtle targets, including mantle plume activity.

Apart from interpretations based on seismic and gravity data, mantle plumes proposed for Eastern Australia (Sutherland, 1991) may be identified directly using resistivity signatures. Semi-conductor mechanisms are expected to dominate the resistivity profile in high temperature zones (e.g. Gray & Cull, 1991) with additional anomalies generated by geochemical zonation, oxygen fugacity, groundwater migration, etc. (e.g. Sato et al., 1989). Consequently, resistivity profiles may provide the most immediate evidence for plume activity while complementing gravity and seismic data for structural analysis.

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Non-stationary Time Series Analysis - MT Applications

Lynn M. Hastie and I.J. Chant

Physics Department, University of Queensland, St Lucia, Brisbane, QLD 4072

In recent studies of MT data it has become obvious that the non-stationarity and non-normal distribution of the natural signals are important contributing factors in producing bias and scatter in the apparent resistivity results that are computed. Using traditional methods based on stationary assumptions, the sorts of biases that occur are large and are unlikely to average out over any reasonable number of data sets.

The recent development of robust methods by Alan Chave and others (Chave & Thomson, 1986: Chave et al, 1987) has produced notable improvements in the stability of results, largely by correcting for the non-normal distribution problems, while the sectioning of records that is involved in these methods has reduced the effect of non-stationarities. However, a recent study by Chant and Hastie (1992) using a different form of spectral estimator, which is expected to cope with non-stationarities better than the Fourier transform, and using very simple robust statistics to estimate the apparent resistivity within each frequency band, appears to have produced comparable results.

In a study of the EMSLAB 1 data set (Jones et al, 1989; Chant & Hastie, 1992), the non-stationary and robust estimators produced results that showed a distinct bias in the estimates of the more poorly-determined apparent resistivity component. The results of the non-stationary method give an apparent resistivity structure which is similar in both orthogonal directions, whereas that shown by the robust method is similar to that for the standard methods and is very different in structure. A further study will have to be undertaken to see if this is a failing or success of the new method.

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Bill Clinton's policy on electromagnetic induction

Michael O. McWilliams

Geophysics Department, Stanford University, Stanford   CA 94305, U.S.A.

No abstract

EM INDUCTION IN THE OCEANS AND SEAFLOOR

Electromagnetic Signals in the Ocean Layer

Anthony White

School of Earth Sciences, Flinders University, Bedford Park SA 5042

Large-scale and transient electromagnetic (EM) signals have been observed in seafloor horizontal electric field (HEF) data collected on the eastern flank of the Cleft Segment of the Juan de Fuca Ridge during the EMRIDGE experiment. From comparison with simultaneous magnetic field observations across the ridge, and to the south of the Blanco Fracture Zone, the origin of these signals is deduced to be largely oceanographic in origin. Harmonic analysis of the ocean tidal signals in the HEF observations shows large O_1 and M_2 components, with estimated seawater conductivity-weighted vertically-averaged velocities of 5.8 and 2.7 cm.s^{-1} respectively. Tidal motions are almost solely aligned with the ridge axis and the coastline of northwest America. Previous HEF measurements made during the EMSLAB experiment further north along the Juan de Fuca Ridge have some similar characteristics to the EMRIDGE HEF data, but estimated tidal velocities are smaller. Power spectra of HEF data from EMRIDGE are considerably larger than similar EMSLAB estimates, particularly for periods greater than 1 hour.

The unusually large oceanographic signals in EMRIDGE HEF data are unique and are

therefore difficult to explain. Electrode potential drift is unlikely to cause such large-scale fluctuations: after initial seafloor environmental settling, electrode potential drift is typically found to be monotonic. Relatively high coherence with magnetic field fluctuations at periods of less than 1 hour are evident throughout the record length, so it is assumed that instrumentation problems, such as variable amplifier gain, did not occur. Another possibility is that the instrument tilted from the horizontal plane, so that in addition to the HEF some component of the vertical electric field (VEF) is also observed; this possibility would imply very active benthic-layer turbulence. No satisfactory explanation for the enhanced oceanographic signals in the EMRIDGE HEF data can be found. However, tidal amplifications over the seafloor topographic discontinuity of the Blanco Fracture Zone and turbulence associated with very rough seafloor topography have been observed at the Juan de Fuca Ridge from current-meter observations, and these may generate a significant motionally-induced EM field.

Progress in Seafloor EM Instrumentation: Observations, Theory and Interpretation

G.S. Heinson

School of Earth Sciences, Flinders University, Bedford Park SA 5042

Tectonically active areas of the ocean floor, such as subduction zones, spreading-ridges and hot-spots, are zones of anomalous electrical conductivity. Molten rock and hydrothermal-fluids have conductivities that are orders of magnitude larger than for cool, dry basalts and peridotites from the crust and mantle. Seafloor measurements of electric and magnetic fields using the magnetotelluric (MT), vertical gradient sounding (VGS) and geomagnetic depth sounding (GDS) methods may be used to infer the sub-seafloor conductivity. They are therefore well suited, perhaps more so than any other geophysical technique, for imaging regions of melt and fluids in the crust and mantle. Seafloor measurements of Earth's EM fields involves novel instrumentation, and the data require new theory and methods of interpretation.

Instrumentation
A new generation of seafloor ring-core fluxgate magnetometers are being built at Flinders University for high-precision magnetic field measurements (0.1 nT). A prototype is currently deployed in 3800 m of sea-water off the coast of California, and will be retrieved at the end of February 1993. An electrometer for the seafloor is also being built, with a 'salt-water chopper' to cancel out electrode noise.

Theory
Seafloor EM observations are complicated by the presence of the highly-conducting ocean layer. Progress is being made in understanding non-uniform EM induction in the oceans due to the geomagnetic coast effect, and from regional and localised changes in seafloor topography.

Interpretation

Two new conductivity interpretations will be discussed. The first is of a two-dimensional section across the coastline of South Australia, using land and sea-floor magnetometer data. The second is a new interpretation of seafloor magnetometer data from the Juan de Fuca Ridge in the northeast Pacific, which suggests the presence of a conductive zone beneath the ridge axis.

Detection and Modelling of ELF Emissions in Sea-Water

Julian Vrbancich

Maritime Operations Division, Materials Research Laboratory,
Defence Science And Technology Organisation, PO Box 44, Pyrmont, NSW, 2009

A portable underwater three-axis electric and magnetic field sensor system with remotely controlled data acquisition has been developed for operation in shallow sea-water. The operational bandwidth is approximately 1 Hz to 1 kHz. Electric field sensors consist of silver/silver chloride electrodes with toroidal step-up transformers and magnetic sensors are based on multi-turn induction coils designed and wound to minimise stray capacitances, thus resulting in higher coil resonant frequencies. A Helmholtz coil system was designed for calibration of the magnetic sensors. All six components of the electric and magnetic fields are sampled simultaneously, multiplexed and transmitted along 1 km of cable to the control station for recording and analysis. This instrumentation enables environmental ELF electric and magnetic fields to be recorded with sensors placed on the sea-bed to minimise motion induced noise.

Experiments have also been performed with a moving horizontal electric dipole representing a controlled source of known dipole strength and frequency. The controlled source is attached to a vessel which is tracked so that the relative geometry between source and sensors is known as a function of time. Tracking is performed with the use of marine GPS receivers and software designed to apply a differential correction from a known reference point to the remote receiver. Comparison with laser tracking confirms the expected ±2 to 5 m tracking accuracy during sea trials conditions. Single frequency or up to twenty harmonically related multiple frequency sinusoidal current waveforms can be applied to the controlled dipole source. The latter are useful for studying the frequency response of detected ELF emissions from a single track of the controlled source.

Theoretical expressions for the quasi-static fields of a horizontal electric dipole in an electrically shallow conducting medium represented by sea-water have been modelled using several numerical techniques. Experimental studies involving the detection of ELF electric and magnetic fields over different sea-bed types give good agreement with predicted theoretical field amplitudes for realistic ranges of sea-bed electrical conductivity. The refinement of such studies may assist in determining sea-bed conductivity.

Dynamo action by an ocean eddy

F.E.M.(Ted) Lilley

Research School of Earth Sciences, Australian National University, Canberra. 0200

The disc dynamo, first envisaged by Faraday, has been discussed widely in physics and geophysics. It has the property of sustaining a magnetic field by motional electromagnetic induction, without the presence of magnetized material; and has thus provided insight into an important aspect of the creation of planetary magnetic fields.

An ocean eddy, rotating in Earth's main magnetic field, causes motional electromagnetic induction similar to one part of the action of a disc dynamo. For an ocean eddy the generated magnetic field is small compared to Earth's ambient field, so that any magnetohydrodynamic effect on the seawater movement is negligible. This circumstance simplifies the mathematical description of the problem, which can be taken as kinematic from the point of view of electromagnetic induction.

An example is shown of motional magnetic fields, generated by a large eddy in the Tasman Sea. The data were recorded on the seafloor, where they were non-zero due to electric currents from the dynamo action leaking into the seafloor sediments.

Natural examples of large-scale motional electromagnetic induction which can be studied are rare. Ocean eddies, which are accessible to the appropriate specialized instrumentation, thus have an added interest.

Geomagnetic observatory data and ocean circulation

D.E. Winch [1] and S.K. Runcorn [2]

[1] *School of Mathematics and Statistics, University of Sydney, Sydney NSW 2006*

[2] *College of Natural Sciences, University of Alaska Fairbanks, AK 99775, U.S.A.*
and Department of Physics, Imperial College, London, U.K.

Spherical harmonic analysis of the annual geomagnetic variation has shown that, unlike the other short period variations, there is a significant part of internal origin that cannot be explained by induction from the external part. From the harmonic coefficients up to the 4th degree, the equivalent electric current distribution over the Earth's surface can be calculated and it is largely within the ocean basins. The potentials are generated by the seasonal variations of the large scale oceanic circulation in the vertical component of the geomagnetic field. Measurements of the electric potential differences between points in the Pacific show an annual variation of the right order of magnitude.
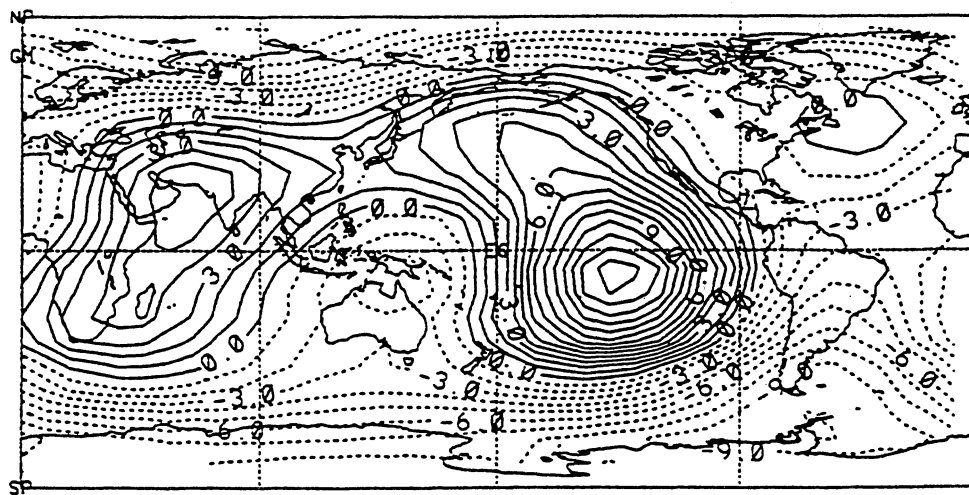
Figure 1. Internal current function for 1 cycle per year B coefficients (kA), computed from midnight values.
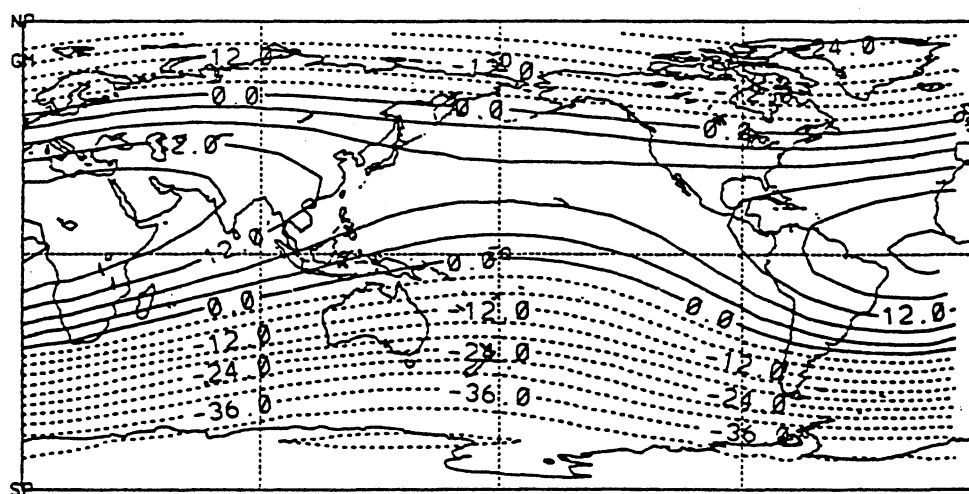

Figure 2. External current function for 1 cycle per year B coefficients (kA), computed from midnight values.

LIST OF REGISTRANTS - GEOMAGNETISM AND PALAEOMAGNETISM

Adelmo Agostini
Chief Geophysicist
NSW Dept. Minerals & Energy
GPO Box 536
SYDNEY   NSW 2001
tel: 02-901 8354, fax: 02-901 8256

Luc Antoine
Dept. Geophysics
University of the Witwatersrand
Private Bag 3
WITS 2050   SOUTH AFRICA
tel: +27-11-716 3521
fax: +27-11-339 7367

Charles Aubourg
Departement de Structures des
Matériaux Géologiques
Université de Cergy Pontoise
47-59 Avenue des Genottes
BP 8428
95806 Cergy   FRANCE
tel: +33-1-30753449
fax: +33-1-34249487

Paul Augustinus
Department of Physical Sciences
University of Tasmania at
Launceston
PO Box 1214
LAUNCESTON TAS 7250
tel: 003-260224, fax: 003-263664

Mike Barbetti
NWG Macintosh Centre
Madsen Building FO9
University of Sydney
SYDNEY   NSW 2006
tel: 02-6923993, fax: 02-6924671

Charles Barton
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9611, fax: 06-249 9986

Zoltan Beldi
Geo Instruments
348 Rocky Point Road
RAMSGATE   NSW 2219
tel: 02-529 2355, fax: 02-529 9726

Jean Besse
Institut de Physique du Globe de
Paris
Université de Paris 6&7,Tour 14-24
4, Place Jussieu
75252 PARIS CEDEX   FRANCE
tel: +33-1-44273273
fax: +33-1-44273373

Marita Bradshaw
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-2499452, fax: 06-2499983

Eric Butcher
Dept Theoretical & Space Physics
La Trobe University
BUNDOORA   VIC 3083
tel: 03-479 2645, fax: 03-479 1552

Gary Caitcheon
CSIRO Division of Water Resources
PO Box 1666
CANBERRA ACT 2601
tel: 06-2465752, fax: 06-2465800

Ian Campbell
Austirex International
27 Merriwa Street
GORDON   NSW 2072
tel: 02-498 2299, fax: 02-418 1292

François H. Chamalaun
School of Earth Sciences
Flinders University of South
Australia
BEDFORD PARK   SA 5042
tel: 08-201 2319, fax: 08-201 2676

Zhong Chen
Department of Geology
University of Western Australia
NEDLANDS   WA 6009
tel: 09-3802652, fax: 09-3801037

Allan Chivas
Research School of Earth Sciences
Australian National University
CANBERRA ACT 0200
tel: 06-2493247, fax: 06-2490738

David A. Clark
CSIRO Div. Exploration Geoscience
PO Box 136
NORTH RYDE   NSW 2113
tel: 02-887 8872, fax: 02-887 8921

David Cole
IPS Radio & Space Services
PO Box 5606
WEST CHATSWOOD NSW 2057
tel: 02-414 8335, fax: 02-414 8340

Eric Colhoun
Department of Geography
University of Newcastle
CALLAGHAN   NSW 2308
tel: 049-215082, fax: 049-215877

Robert Corkery
Research School of Physical Sci &
Engineering
Australian National University
CANBERRA   ACT 0200
tel: 06-249 3326

Ross Costelloe
Geoterrex Pty. Ltd.
7-9 George Place
ARTARMON   NSW 2064
tel: 02-418 8077, fax: 02-418 8581

Mike Craig
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9453, fax: 06-249 9983

Jim Cull
Dept. Earth Sciences
Monash University
CLAYTON VIC 3168
tel: 03-565 4897, fax: 03-565 4903

Peter Davies
Department of Geology and
Geophysics
University of Sydney
SYDNEY NSW 2006
tel: 02-6923244, fax: 02-6920184

David Denham, Chief
Geophysical Observatories &
Mapping
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9267, fax: 06-249 9986

Steward Dennis
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9358, fax: 06-249 9986

Stuart Dodd
Geoterrex Pty. Ltd.
7-9 George Place
ARTARMON   NSW 2064
tel: 02-418 8077, fax: 02-418 8581

James C. Dooley
66 Hawker Street
TORRENS   ACT   2607
tel: 06-286 2145, fax: 06-286 2145

LIST OF REGISTRANTS - GEOMAGNETISM AND PALAEOMAGNETISM

Dr Brian J.J. Embleton
CSIRO Div. Exploration Geoscience
Floreat Park Laboratories
Private Bag
WEMBLEY   WA 6014
tel: 09-387 0729, fax: 09-387 6046

Paul Finlay
62 Woodside Road
Henderson
Aukland 8
NEW ZEALAND
tel: +64-9-832 4375

Sean Fitzsimons
Department of Geography
University of Otago
PO Box 56
Dunedin   NEW ZEALAND
tel: +64-3-4798786
fax: +64-3-4798349

David French
CSIRO Division of Exploration
Geoscience
PO Box 136
NORTH RYDE   NSW 2113
tel: 02-8878666, fax: 02-8878921

Yves Gallet
Inst de Physique du Globe de Paris
Université de Paris 6&7, Tour 14-24
4, Place Jussieu,
75252 Paris CEDEX   FRANCE
tel: +33-1-44273273
fax: +33-1-44273373

John Giddings
Australian Geological Survey Org.
GPO Box 378
CANBERRA   ACT 2601
tel: 06-249 9319, fax: 06-249 9986

Dick Glen
NSW Geological Survey
PO Box 536
ST. LEONARDS   NSW 2065
tel: 02-901 8346, fax: 02-901 8256

Tony F. Gover
Civil Aviation Authority
PO Box 367
CANBERRA   ACT 2601
tel: 06-268 5466, fax: 06-268 4332

Andy Green
CRC for Aust. Mineral Exploration
Technologies
Macquarie University
SYDNEY NSW 2109
tel: 02-805 8365, fax: 02-805 8366

Harry Hansen
Aircraft Owners & Pilots
Association
PO Box 1065
FYSHWICK   ACT 2609
tel: 06-280 4221, fax: 06-280 7341

Larry Harrington
Tasmanian Hardrock Pty. Ltd.
GPO Box 1412
CANBERRA   ACT 2601
tel: 06-248 0323, fax: 06-248 0323

Lynn M. Hastie
Physics Department
University of Queensland
St. LUCIA   QLD 4067
tel: 07-365 3411, fax: 07-365 1242

Chris Heinrich
Australian Geological Survey Org.
GPO Box 378
CANBERRA   ACT 2601
tel: 06-249 9574, fax: 06-249 9983

Paul Hesse
Dept Biogeography and
Geomorphology
Australian National University
PO Box 4
CANBERRA   ACT 2601
tel: 06-2494297, fax: 06-2571893

Graham Heinson
Institute for Atmospheric & Marine
Sciences
Flinders University of S. A.
GPO Box 2100
ADELAIDE   SA 5001
tel: 08-201 2978, fax: 08-201 2676

Prof. Frank H. Hibberd
Physics Department
University of New England
ARMIDALE   NSW 2351
tel: 067-73 2389, fax: 067-72 7414

Ian Hone
Australian Geological Survey Org.
GPO Box 378
CANBERRA   ACT 2601
tel: 06-249 9306, fax: 06-249 9986

Peter Hopgood
Australian Geological Survey Org.
GPO Box 378
CANBERRA   ACT 2601
tel: 06-249 9359, fax: 06-249 9986

Geoff Hunt
Australian Geological Survey Org.
GPO Box 378
CANBERRA   ACT 2601
tel: 06-249 9231, fax: 06-249 9970

Mart Idnurm
Australian Geological Survey Org.
GPO Box 378
CANBERRA   ACT 2601
tel: 06-249 9314, fax: 06-249 9986

David J. Ivers
Department Mathematics &
Statistics
University of Sydney, F07
SYDNEY NSW 2006
tel: 02-692 3561, fax: 02-692 4534

Peter Jacklyn
ABS Radio Science Unit
GPO BOX 9994
SYDNEY NSW 2001
tel: 02-333 1421, fax: 02-333 1414

Lt Cmdr Derek H. James
Hydrographic Projects Office
Department of Defence
PO Box E33
Queen Victoria Terrace
CANBERRA   ACT 2600
tel: 06-266 2587, fax: 06-266 2975

John Jamieson
Australian Geological Survey Org.
GPO Box 378
CANBERRA   ACT 2601
tel: 06-249 9320, fax: 06-249 9986

Chris Jenkins
Ocean Sciences Institute
University of Sydney
SYDNEY   NSW 2006
tel: 02-6922279, fax: 02-6924067

Mel Jones
Pan Continental Mining
Gateway, Level 36
1 Macquarie Place
SYDNEY NSW 2000
tel: 02-256 2041, fax: 02-241 1499

Chris Klootwijk
Australian Geological Survey Org.
GPO Box 378
CANBERRA   ACT 2601
tel: 06-249 9324, fax: 06-249 9986

LIST OF REGISTRANTS - GEOMAGNETISM AND PALAEOMAGNETISM

Lindsay Knight
Knight Industries Pty Ltd
677 Lyne Street
LAVINGTON NSW 2641
tel: 060-251335, fax: 060-258754

Russell Korsch
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9495, fax: 06-249 9972

Leopold Krystyn
Institute for Paleontology
Universitätsstrasse 7
A-1010 Vienna AUSTRIA

Robert Kusi
School of Earth Sciences
Flinders University of South
Australia
BEDFORD PARK SA 5042
tel: 08-201 2978, fax: 08-201 2676

Mark Lackie
CSIRO Div. Exploration Geoscience
PO Box 136
NORTH RYDE NSW 2113
tel: 02-887 8877, fax: 02-887 8909

Frank Lee
Royal Melbourne Institute of
Technology
Flat 38-78 Queens Road
MELBOURNE VIC 3004
tel: 03-5109136

Andrew Lewis
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9764, fax: 06-249 9986

Michael Leys
NSW Geological Survey
PO Box 53
ORANGE NSW 2800
tel: 063-63 8311, fax: 063-63 8344

Zheng-Xiang Li
Geology Department
University of Western Australia
Nedlands WA 6009
tel: 09-380 2652, fax: 09-380 1037

F.E.M. (Ted) Lilley
Research School of Earth Sciences
Australian National University
CANBERRA ACT 0200
tel: 06-249 3406, fax: 06-249 0738

K.G. McCracken
'Jelore' Technologies
Springhill Rd.
Via Mittagong NSW 2575
tel: 048-78 5121, fax: 048-78 5121

Heather McCreadie
Dept Theoretical & Space Physics
La Trobe University
BUNDOORA   VIC 3083
tel: 03-479 2640, fax: 03-479 1552

Michael W McElhinny
Gondwana Consultants Pty Ltd
PO Box 5
HAT HEAD   NSW 2440
tel: 065-65 7604, fax: 065-65 7604

Andrew McEwin
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9392, fax: 06-249 9986

Phil McFadden
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9612, fax: 06-249 9986

James McIntyre
NSW Dept. Minerals & Energy
GPO Box 536
SYDNEY NSW 2001
tel: 02-901 8356, fax: 02-901 8256

Don McKnight
Inst Geological & Nuclear Sciences
32 Salamanca Road
PO Box 1320
Wellington
NEW ZEALAND
tel: +64-4-473 8208
fax: +64-4-471 0977

Michael O. McWilliams
Geophysics Department
Stanford University
STANFORD   CA 94305
U.S.A.
tel: +1-415-723 3718,
fax: +1-415-725 7344

Jean Marcoux
Laboratoire de GÇologie
UniversitÇ de Paris 7
4, Place Jussieu
75252, Paris CEDEX   FRANCE

John Marsh
Domain Defence Systems
PO Box 80
GALSTONE NSW 2159
SYDNEY
tel: 02 6532414, fax:

Fred Menk
Department of Physics
The University of Newcastle
Rankin Drive
NEWCASTLE   NSW 2308
tel: 049-21 5424, fax: 049-21 6907

Prof. Ronald T. Merrill
Geophysics Program AD-50
University of Washington
SEATTLE   WA 98195
U.S.A.
tel: +1-206-543 8020
fax: +1-206-543 0489

Ian Metcalfe
Dept. Geology & Geophysics
University of New England
ARMIDALE NSW 2352
tel: 067-732 860, fax: 067-712 898

Peter Milligan
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9224, fax: 06-249 9986

Brian Minty
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9228, fax: 06-249 9986

Jim Neale
Biogeography & Geomorphology
Research School of Pacific Studies
Australian National University
CANBERRA   ACT 0200
tel: 06-249 2244, fax: 06-257 1893

Bob Nicoll
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-2499415, fax: 06-2499983

Gordon Packham
Ocean Sciences Institute
University of Sydney
SYDNEY NSW 2006
tel: 02-6922279, fax: 02-6924067

LIST OF REGISTRANTS - GEOMAGNETISM AND PALAEOMAGNETISM

Dudley Parkinson
(Univertsity of Tasmania)
68 Risdon Road
NEW TOWN TAS 7009
tel: 002-285 480, fax: 002-284 068

Frank Peerdeman
Research School of Earth Sciences
Australian National University
CANBERRA ACT 0200
tel: 06-2493406, fax: 06-2490738

Peter Percival
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9325, fax: 06-249 9986

Caroline Perkins
Research School of Earth Sciences
Australian National University
CANBERRA   ACT 0200
tel: 06-249 5170, fax: 06-249 0738

Haralds F. Petersons
Department of Mathermatics
The Faculties
Australian National University
CANBERRA   ACT 0200
tel: 06-249 2907, fax: 06-249 5549

Colin Phillips
Department Mathematics &
Statistics
University of Sydney, F07
SYDNEY NSW 2006
tel: 02-692 3561, fax: 02-692 4534

Chris Pigram
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-249 9636, fax: 06-249 9980

Brad Pillans
Geology Department
Victoria University of N.Z.
PO Box 600
Wellington
NEW ZEALAND
tel: +64-4-472-1000
fax: +64-4-495 5186

Ken Plumb
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-249 9311, fax: 06-249 9983

Chris McA. Powell
Geology Department
University of Western Australia
Nedlands   WA 6009
tel: 09-380 2666, fax: 09-380 1037

Pat Quilty
Asst. Director of Research
Antarctic Division
Channel Highway
KINGSTON TAS 7150
tel: 002-323 205, fax: 002-323 351

Shanti Rajagapalan
Geology & Geophysics
University of Adelaide
GPO Box 498
ADELAIDE SA 5005
tel: 08-228 4698, fax: 08-232 0143

Colin Reeves
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9226, fax: 06-249 9986

Prof. Keith Runcorn
Space & Atmospheric Physics
Group
The Blackett Laboratory
Imperial College
LONDON SW7 2BZ   U.K.
tel: +44-71-589 5111
fax: +44-71-823 8250
          and
College of Natural Sciences
University of Alaska Fairbanks
465 Duckering Building
Fairbanks, AK 99775-1240
U.S.A.

Steve Saul
Austirex International
27 Merriwa St
GORDON   NSW 2072
fax: 02-418 1292

Steve Scherl
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-249 9351, fax: 06-249 9986

Phillip W. Schmidt
CSIRO Div. Exploration Geoscience
PO Box 136
NORTH RYDE   NSW 2113
tel: 02-887 8873, fax: 02-887 8921

Martin Schneider
Geoterrex Pty. Ltd.
7-9 George Place
ARTARMON   NSW 2064
tel: 02-418 8077, fax: 02-418 8581

John Shergold
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-249 9410, fax: 06-249 9983

Frank Simonis
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9225, fax: 06-249 9986

Kerry Slater
Dept. Geology & Geophysics
University of Sydney
SYDNEY NSW 2006
tel: 02-519 2311, fax: 02-692 0184

A/Prof. Ravi Sood
Physics Department
Aust. Defence Force Academy
University of New South Wales
Northcotte Drive
CANBERRA   ACT 2600
tel: 06-268 8765, fax: 06-268 8786

Ross Spencer
NSW Dept. Mineral Resources
PO Box 536
St. LEONARDS NSW 2065
tel: 02-901 8364, fax: 02-901 8256

Prof. Frank D. Stacey
Physics Department
University of Queensland
BRISBANE   QLD 4072
tel: 07-374 1053, fax: 07-374 2059

John Stanley
Geophysical Research Institute
University of New England
ARMIDALE   NSW 2351
tel: 067-73 2617, fax: 067-71 1661

John Sumpton
Stockdale Prospecting Ltd
PO Box 126
SOUTH YARRA   VIC 3141
tel: 03-827 7522, fax: 03-826 0974

LIST OF REGISTRANTS - GEOMAGNETISM AND PALAEOMAGNETISM

Shen-Su-Sun
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-249 9484, fax: 06-249 9983

Wayhu Sunata
School of Earth Sciences
Macquarie University
SYDNEY NSW 2109
tel: 02-805 8359, fax: 02-805 8428

Chris Swain
Diamond Exploration Div.
Western Mining Corporation
55 McDonald Street
KALGOORLIE WA 6430
tel: 090-26 5119, fax: 090-21 6776

Ian Sweet
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-249 9307, fax: 06-249 9983

Chris Tarlowski
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9265, fax: 06-249 9986

Prof. Stuart Ross Taylor
Dept. Nuclear Physics
Research School of Physical Sci &
Engineering
Australian National University
CANBERRA ACT 0200
tel: 06-249 2089, fax: 06-249 0748

Alan Theobald
Maritime Operations Division
DSTO Materials Research
Laboratories
PO Box 44
PYRMONT NSW 2009
tel: 02-692 1487, fax: 02-660 0019

Hervé Thévéniaut
Institut de Physique du Globe de
Paris
Université de Paris 6&7, Tour 14-24
4, Place Jussieu
75252 Paris CEDEX   FRANCE
tel: +33-1-44273273
fax: +33-1-44273373

Lester A. Tomlinson
Geomagnetic Observatory
Inst Geological & Nuclear Sciences
PO Box 29181
Christchurch NEW ZEALAND
tel: +64-3-351 6019
fax: +64-3-351 9923

Richard Thompson
IPS Radio & Space Services
PO Box 5606
WEST CHATSWOOD NSW 2057
tel: 02-414 8325, fax: 02-414 8331

Ted Tyne, Chief Geophysicist
NSW Geological Survey
PO Box 536
ST. LEONARDS NSW 2001
tel: 02-231 0922, fax: 02-233 7017

Lisa Vella
Newcrest Mining Ltd.
179 Great Eastern Highway
BELMONT WA 6104
tel: 09-270 7070, fax: 09-479 4104

Khamphira Viravong
Dept. Geology & Geophysics
University of Sydney
SYDNEY NSW 2006
tel: 02-820 9879, fax: 02-692 0184

Julian Vrbancich
Maritime Operations Division
DSTO Materials Research
Laboratories
PO Box 44
PYRMONT NSW 2009
tel: 02-692 1487, fax: 02-660 0019

Steve Webster
Austirex International
27 Merriwa Street
GORDON NSW 2072
tel: 02-498 2299, fax: 02-418 1292

Peter Wellman
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9653, fax: 06-249 9983

Alan Wells
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-249 9408, fax: 06-249 9972

Anthony White
School of Earth Sciences
Flinders University of South
Australia
BEDFORD PARK SA 5042
tel: 08-201 2359, fax: 08-201 2676

Anthony R. Wilkinson, Chief
Executive
Aircraft Owners & Pilots
Association
PO Box 1065
FYSHWICK ACT 2609
tel: 06-280 4221, fax: 06-280 7341

George Williams
Dept. Geology & Geophysics
University of Adelaide
GPO Box 498
ADELAIDE SA 5001
tel: 08-228 5844, fax: 08-232 0143

Joe Williams
School of Geology
Queensland University of
Technology
PO Box 2434
BRISBANE QLD 4001
tel: 07-864 2111, fax: 07-864 1510

A/Prof. Denis E. Winch
Department Mathematics &
Statistics
University of Sydney, F07
SYDNEY NSW 2006
tel: 02-692 3235, fax: 02-692 4534

Bruce Wyatt
Wyatt & Associates
PO Box 705
MAWSON ACT 2607
tel: 06-286 3519, fax: 06-286 3519

Leslie Wyborne
Australian Geological Survey Org.
GPO Box 378
CANBERRA ACT 2601
tel: 06-249 9489, fax: 06-249 9983

Gavin Young
Australian Geological Survey Org.
PO Box 378
CANBERRA ACT 2601
tel: 06-249 9391, fax: 06-249 9983