

Australia's Report to the IUGG for the Quadrennium 1999-2003

IAGA – Geomagnetism and Aeronomy

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Preamble

This report covers the scientific activities undertaken in Australia in the area of geomagnetism and aeronomy during the past quadrennium, 1999-2003. A wide spectrum of activities is covered: dynamics of the Earth's core, the tectonic structure of the continent, solar-terrestrial physics, and so on. The report is structured according to areas of activity, although this largely reflects the research interests of individual institutions and organisations. Much of the information about the work that has been undertaken is encapsulated in the list of publications that appears at the end of each section.

The report testifies to the vigour of Australia's scientific research in geomagnetism and aeronomy. This flows from a healthy and resilient economy, the excellent research opportunities in Australia, and a growing recognition and commitment by government to expand Australia's scientific research base to underpin future economic prosperity.

With sadness, we note the loss of two prominent Australian scientists who had a major influence in geomagnetism and aeronomy research. Dr Dudley Parkinson died in Hobart on 12 October, 2001. Dudley was first exposed to the art of geomagnetism as a child while accompanying his father in a bullock-drawn cart on visits to the Watheroo Magnetic Observatory, Western Australia. He will be remembered particularly for his seminal monograph *Introduction to Geomagnetism* published in 1983, and his invention of the so-called 'Parkinson Induction Vector'. Prof. Chris Powell died suddenly on 21 June, 2001 while on a flight from Johannesburg to London. He was a leading authority in tectonics, the first to propose that the Himalayan uplift was due to underplating of Asian by India, the main protagonist of the Rodinia hypothesis, and a strong protagonist of using palaeomagnetic data in combination with regional geology.

Editors

1.1 Space Weather

Dr Phil Wilkinson and Dr David Cole, IPS Radio and Space Services

Space Weather Plan

There has been continued consultation over the development of an Australian space weather plan with science and industry groups involved in space weather. The plan deals with the monitoring, research and outreach aspects of space weather information. The Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering are developing the draft plan further.

Space weather activities in Australia cover a wide range of activities from low to high latitudes. The results of wide-ranging monitoring programs culminate in services offered by the Australian Space Forecasting Center (ASFC) through their webpage (www.ips.gov.au). This section summarises the monitoring work that leads to these services as well as noting a number of current research programs that will extend them.

Ionospheric monitoring

Australia has a widely dispersed ionospheric network complemented by the two solar observatories. IPS radio and Space Services operates these stations. All sites operate at least one vertical incidence ionosonde and some (Vanimo and Townsville) host oblique ionosondes. Recently, the vertical ionosondes have been upgraded at all sites, the aging IPS-4D ionosondes being replaced by either an IPS-5D ionosonde or a Canadian CADI ionosonde. Data are obtained in real time from Vanimo, Pt. Moresby, Darwin, Townsville, Learmonth, Brisbane, Norfolk Is., Mundaring, Canberra, Camden, Christchurch, Hobart, Macquarie Is., Scott Base, Casey, Davis and Mawson. At the Casey and Macquarie Island sites, drift observations are made regularly with the CADI ionosonde. At Davis these observations are made with the Antarctic Division DPS ionosonde. Wide beam riometer observations are collected at Macquarie Island, Casey, Davis and Mawson, in cooperation with Antarctic Division, to support space weather services. Currently, they are used to confirm the presence of polar cap absorption events.

Wherever possible, data are supplied on the ASFC Website to aid validation of space weather forecasts. For instance, all ionograms recorded are scaled automatically and the data are used to generate real-time ionospheric maps that are placed on the IPS Web site (<http://www.ips.gov.au>) and also used as the basis of a variety of real-time services. The real-time ionograms are all made available on the IPS Website as they are obtained. The IPS autoscale software has been further improved and adapted to handle different ionogram formats. Data from the network is currently being used to support modernised HF installations in Australia.

In addition, alternative data driven models have been developed for supporting over-the-horizon radar observations.

Scintillation

The effects of scintillation on GPS have been investigated by making direct observations from Vanimo, equatorward of the equatorial anomaly and several other sites in nearby countries. These observations have been used to validate current scintillation models (e.g., WBMOD) in the local region. In addition, to scintillation work, total electron content (TEC) observations from this and complementary networks have been used to study the effects of ionospheric storms in the region.

Geomagnetic pulsations

The IPS mid-latitude variometer network has been expanded to include Darwin, and will be upgraded with 24-bit A/D converters, low-pass noise filter systems and automated timing checks. The data are sampled at 1-second intervals and used to produce estimated K-indices and "pc3-

indices" for the Australian region. Pc3-indices are the root-mean square values of the component data filtered over the Pc3 pulsation period range (10–45 seconds) and scaled by a factor of 10. Both types of indices are used to generate contour maps, which indicate the levels of geomagnetic activity for the associated period ranges. Magnetograms and time series index plots are also produced from the data, with the indices also used as the basis of several alert systems for space weather conditions. Data from high latitudes is also collected (see High Latitude report) and is subjected to the same analysis. These may be extended to include early warnings for very large geomagnetic field rates of change. All these have been developed as products on the ASFC website.

Solar observations at Culgoora

At the IPS Culgoora Solar Observatory, the principal radio equipment is a radio spectrograph that scans in frequency from 18 MHz to 1.8 GHz. The lower frequency band antennas have recently been rebuilt. All observations are available, through the ASFC Web site (www.ips.gov.au). Data from the spectrograph, together with observations from WIND, have been used to track a coronal mass ejection from the corona out into the solar wind.

The Learmonth Solar Observatory

The Learmonth Solar Observatory (22S, 114E) on North West Cape, Western Australia, is jointly managed with the US Air Force Weather Agency. Continuous automated H-alpha patrol is accomplished with on-site human analysis and digital archive. This is supplemented by photospheric magnetograms (longitudinal component), and daily manual white light sunspot analysis. All data products and a selection of H-alpha images are available from the IPS website (solar section, www.ips.gov.au). Continuous solar radio observations are made on eight discrete frequencies (245, 410, 610, 1415, 2695, 4994, 8800, and 15400 MHz) and from 25 to 180 MHz with a swept frequency solar radio spectrograph. These data are archived digitally at a cadence of one second for the fixed frequencies and every three seconds for the spectrograph scan. The spectrograph data is available on the website at the real-time cadence, and the fixed frequency data at reduced (1-minute) cadence. Radio burst analysis messages are also available in near-real time on the website.

Geomagnetic data are collected from total field (proton precession) and component (fluxgate) magnetometers run in cooperation with Geoscience Australia. These data are available within 5 minutes of collection. Ionospheric data are collected at half hourly intervals from a University of Lowell DGS-256 ionosonde.

Several international research experiments are hosted on-site. These include a station of the GONG helioseismic network (hosted for the US National Solar Observatory), that also provides real-time magnetograms and white-light images. Other monitors include a high time resolution magnetometer (STEL Magnetic Meridian 210 Network) from the Solar Terrestrial Environment Laboratory of Nagoya University, and an ELF (1-100 Hz) monitor from the Geophysics Institute at the University of Alaska. Experiments are underway with a GPS sensor (TEC), and a GLE indicator. In 2003 a small aperture telescope with megapixel CCD camera will commence operations to provide support to the global effort to track Near Earth Objects.

World Data Centre for Solar-Terrestrial Science

The IPS World Data Centre (WDC) has completed a successful installation of a mirror site for the space physics interactive data resource (SPIDR) from the WDC-A for Solar Terrestrial Physics, Boulder. Data are available for on-screen viewing (www.ips.gov.au).

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1.2 Magnetospheric Physics

Associate Professor Fred Menk, Dr Colin Waters, University of Newcastle

There have been several important developments in magnetospheric physics activities in Australia since 1999. A major achievement is the successful launching of the Australian scientific satellite, FedSat, in December 2002 into an 800 km altitude, 98° inclination orbit that is sun-synchronous in the 10:30 – 22:30 LT plane. FedSat was developed by the Cooperative Research Centre for Satellite Systems, a consortium of university groups and industry partners, and carries several experiment payloads. One of these is a fluxgate magnetometer, NewMag, developed and operated by the Space Physics Group at the University of Newcastle. Another payload is a GPS receiver that is providing electron density information through occultation measurements, to the solar terrestrial physics group at La Trobe University.

The NewMag experiment samples the geomagnetic field at 100 or 10 vectors/sec using a triaxial sensor mounted on a 2.5 m long boom of novel design. The magnetometer was constructed at the University of California, Los Angeles, and is based on the design successfully used on the POLAR and FAST missions. FedSat was launched by NASDA, the Japanese National Space Development Agency, and NewMag and the GPS experiment are operating nominally.

Another significant development has been the installation of a SuperDARN HF radar in Tasmania, called TIGER. This radar is ideally located to examine magnetosphere-ionosphere coupling at very high, auroral and sub-auroral latitudes. Further details appear in the ionospheric physics report.

Some recent magnetospheric physics research results include:

- Observations of field aligned currents and waves in the southern auroral zone by NewMag, while flying over instruments at the Australian Antarctic stations, and the TIGER field of view. These data will provide input to space weather modelling and will be used for ground-satellite studies of ULF wave amplitude and phase characteristics, especially in the polar regions.
- In related work, multipoint measurements of the Birkeland currents are obtained from the attitude control magnetometers on the Iridium constellation spacecraft, via a special collaboration with Dr. Brian Anderson at the Johns Hopkins University Applied Physics Laboratory (USA). The current induced, magnetic field perturbation data are obtained for each of the 66 satellites in the constellation as a function of time. Using spherical harmonic data fitting procedures, the global dynamics of the Birkeland currents are determined for both the northern and southern hemisphere auroral regions. Simultaneous electric field data from the SuperDARN radars have provided the first direct estimates of the global scale electromagnetic energy flux ($\mathbf{E} \times \mathbf{b}$) into both ionospheres.
- The Newcastle Group operates ULF magnetometers at several permanent sites and at temporary remote sites in Antarctica and Australia. In one study, ULF wave data gathered from a four-station array at cusp latitudes is providing information on the source regions and propagation of ion-cyclotron waves in the Pc1-2 (0.1 mHz – 5 Hz) and the Pc3-4 (5 – 50 mHz) ranges. In a related study, data from over 20 stations of the IMAGE array in Scandinavia have shown that Pc3-4 waves may exhibit high coherence over extended regions, and propagate poleward at speeds that relate to the Alfvén velocity of waves propagating Earthward through the magnetosphere.
- It has been shown that ULF field line resonance measurements, using techniques developed at Newcastle, can monitor plasma mass density in the inner and outer magnetosphere, and the

position of the plasmopause, on time scales of about an hour. Several international groups are now deploying extensive ground magnetometer arrays for this purpose. The ULF measurements can be combined with other ground and in situ observations and density models. As part of a new collaborative project, VLF Doppler receivers and a 3-station array of solar-powered magnetometers has been established by the British Antarctic Survey near Rothera, Antarctica, to allow the VLF- and ULF-derived electron and mass densities to be compared for the same $L=2.5$ flux tube. In the first study, ground data were compared with in situ He^+ and electron density measurements from the IMAGE satellite EUV and RPI experiments, providing an intercalibration of these different suites. The observations were also compared with density values predicted by the SUPIM plasma model, providing further information on ion concentrations and their variation in the inner magnetosphere.

- In parallel with the experimental programs, there has also been progress on developing theoretical and computer models of ULF wave propagation in the magnetosphere and ionosphere. The Newcastle group has developed both analytic and numerical, 1-D models of these processes and also allow the background magnetic to be at any dip angle. The complex wave reflection and mode conversion matrix has been derived. This matrix describes how the combination of the ionosphere, atmosphere and ground influence the reflection, transmission and mode conversion of the two ULF waves modes incident at the ionosphere. Results from the model indicate that the ionosphere affects the properties of ULF waves in a complicated way which depends on the spatial scale size of the ULF disturbance, the dip angle of the magnetic field (latitude), the ionosphere conductivities (Hall and Pedersen) and ULF wave frequency. The modelling is being extended to 2-D and is being used in a collaborative project with the Defence Science Technology Organization to investigate ULF wave effects in over-the-horizon radar clutter returns and the DOPE instrumentation operated in Scandinavia by the Radio and Space Plasma Physics group at the University of Leicester, UK.
- A related issue is the development of a new technique for extracting small amplitude wave signals from HF radar returns. This indicates that ULF waves are ubiquitous within the F-region and is discussed in the ionospheric physics report.

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1.3 Ionospheric Physics

Professor Peter Dyson, La Trobe University

A major development has been the installation of the first Tasman International Geospace Environment Radar (TIGER) in Tasmania. This is a SuperDARN radar that began operations in December 1999. The plan is to locate a second TIGER radar in NZ with a beam that intersects that of the Tasmania radar. Construction of the second radar has begun, depending on funding, should be operational early in 2005. TIGER is operated by a consortium led by Prof P. Dyson, La Trobe University. The consortium members are La Trobe University, University of Newcastle, Monash University, Australian Antarctic Division, IPS Radio & Space Services, DSTO ISR, and RLM Systems. TIGER is located more equatorward than most of the other existing SuperDARN radars and is therefore able to routinely observe sub-auroral processes and open up new areas of research.

Other experimental ionospheric research programs utilise digital ionosondes and GPS receivers at sites in Antarctica and Australia. The IPS Radio & Space Services ionosonde network continues to be upgraded with new ionosondes and increased web access for users, including researchers.

A current initiative being pursued through national science and engineering academies is the development of a Space Weather Plan as proposed by Dr D. Cole of IPS Radio & Space Services.

Some recent research results:

- The influence of the IMF on the occurrence of sporadic E (Es)-layers in the southern polar cap ionosphere has been investigated. The main results are: the IMF B_y component mainly controls the occurrence of the midnight Es-layers through its influence on the corresponding southwest electric field; the IMF B_z component mainly controls the occurrence of the evening Es-layers; and the total occurrence of Es-layers depended more on B_y than on B_z .
- The TIGER and Halley SuperDARN radars have been used to investigate the response time of the high-latitude convection pattern to IMF changes that first impact on the noon-sector ionosphere. Unlike previous studies, the results suggest that the majority of IMF-driven convection changes proceed on finite time scales (~ 6 mins), although there is some evidence for very rapid but weaker responses, especially in the noon-afternoon sector.
- TIGER observations of a boundary in the line-of-sight (LOS) velocity spread were compared with satellite observations in the midnight sector. The results suggest the boundary is a reasonable proxy for the open-closed magnetic field line boundary (OCB), fluctuating in response to discrete events occurring in the outermost regions of the magnetosphere.
- Detailed study of high time resolution sea scatter returns from TIGER has shown that small ($\sim 10 \text{ m s}^{-1}$) Doppler oscillations are very frequently present for up to several hours per day. These appear to be coherent and in phase across the entire field of view, and are correlated with ULF pulsations recorded by ground magnetometers. Using a new technique to remove background convective flows, such oscillations can be imaged over the entire field of view. This opens up the exciting new possibility of using SuperDARN radars to probe ULF wave signatures simultaneously over very large spatial extents, while at the same time providing improved understanding of phenomena that lead to clutter in HF and over-the-horizon radar returns.
- GPS observations have been used to map the total electron content variations and the occurrences of amplitude and phase scintillation activity. These data are being used to

investigate the formation of high latitude irregularity patches and auroral blobs as well as the associated scintillation activity and gravity wave activity. In the low latitude regions of Northern Australia, the detailed morphology of GPS scintillation activity has been investigated.

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1.4 Atmospheric Physics

Professor Robert Vincent, University of Adelaide

The focus of middle atmosphere research in the past four years has been on studying the mechanisms that couple the lower and upper atmosphere, with an emphasis on small-scale atmospheric gravity waves. A major development for the Atmospheric Physics group at the University of Adelaide is the installation of new MF radar system on the geographic equator at Pontianak, Indonesia. The radar uses a cross-antenna with arms approximately 800 m in length to generate a narrow beam for Doppler studies of gravity wave momentum fluxes. Construction and operation of the radar is a joint initiative with Kyoto University and the Indonesian Agency for Space and Aeronautics. This radar is being used to study gravity waves generated by convection in the troposphere.

Gravity waves generated by convection and their propagation through the middle atmosphere to the ionosphere were the focus of a field experiment in Northern Australia in late 2001. The Darwin Wave Experiment (DAWEX) brought together scientists from Australia, Japan and the United States who used a variety of atmospheric and meteorological radars, balloon-borne radiosondes, airglow imagers, ionospheric radars and numerical models to study gravity waves generated by the large convective storms that occur in the vicinity of Darwin, and especially the Hector phenomenon over the Tiwi Islands north of Darwin.

Experimental research programs are ongoing using MF radars in northern Australia, Adelaide and Davis to study the dynamics of the mesosphere and lower thermosphere over a range of latitudes. Meteor radar techniques have recently undergone a resurgence and a 31 MHz VHF meteor radars is now located in Adelaide. Another VHF radar operating at 55 MHz was recently installed at Davis, Antarctica. Meteor wind observations are underway and observations of PMSE and MLT temperatures derived from meteor observations are planned.

The analysis of seven years of hydroxyl temperature data from Davis has provided the best determination of winter temperature variations in the upper mesosphere (~87 km) at high southern latitudes. Inter-year trends at this site fit best with a solar-cycle variation of order ~7K. Our experimentally determined OH (6-2) band relative transition probabilities have reduced uncertainties in absolute rotational temperatures from this band to ~2K. The comparison of Davis hydroxyl temperatures with sodium lidar temperature measurements at Syowa has yielded average winter temperatures in absolute agreement to within 4 K and demonstrated a strong correlation of temperature variations over separation distances of ~1500 km (correlation coefficient ~0.6).

A major development in understanding of the stratospheric temperatures and structure began in February 2001 with the commencement of observations with a Rayleigh/Doppler middle-atmosphere lidar at Davis. The observational program has concentrated on three areas;

- Middle atmosphere climatology: Vertical Rayleigh soundings have been made 2-3 times per week to characterise the temperature profile in the stratosphere and lower mesosphere. The measurements have been validated using coincident radiosonde soundings to 35km, and satellite soundings to 65km. The monthly average lidar temperatures obtained so far agree reasonably well with the MSIS empirical climatology, except during winter and spring in the lower mesosphere, where the observations have been up to 20K warmer than the model. This discrepancy appears to be related to gravity wave filtering effects associated with the influence of planetary wave activity. Small vertical scale (<10km) wave-like temperature perturbations with downward phase progression were observed in the winter and spring of 2001 and 2002.

The most significant of these events were observed during the early spring of 2002 prior to the unprecedented Antarctic stratospheric warming, and included temperature inversions of 10K amplitude in the lower mesosphere in August and a warm advection event of 20K amplitude in the mid-stratosphere in mid-September. Analysis of these events is continuing.

- Polar Stratospheric Clouds (PSCs): A climatology of PSCs at Davis is being developed. Significant differences in the temporal and altitude extent of the clouds was observed between 2001 and 2002, and this relates to differences in stratospheric temperatures over this time. High-resolution Rayleigh observations have provided evidence that small-scale inertial gravity waves are intimately associated with structures in the clouds. Work is in progress examining the influence of gravity waves on cloud microphysics using high-resolution depolarisation measurements and ozonesonde soundings. The ozone measurements are also being used in assessment of the stratospheric temperature climatology, and are contributing the Antarctic MATCH program.
- Polar Mesospheric Clouds (PMCs): Observations during the summer of 2001/02 revealed detection of at least one PMC. The characteristics of this event, and several other possible detections, are being compared with South Pole observations during 2000 and 2001, which represent the only other Southern Hemisphere ground-based lidar measurements reported to date.

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1.5 High Latitude Space and Atmospheric Sciences (SAS)

Dr Marc Duldig, Australian Antarctic Division

The Australian Antarctic (Mawson, Davis and Casey) and sub-Antarctic (Macquarie Island) stations continue to provide a platform for the projects listed in Table 1. This work supports research programs of the Australian Antarctic Division (part of the Federal Department of Environment and Heritage), Australian Government agencies and Universities and the international community. The SAS program, formerly known as the Atmospheric and Space Physics (ASP) program, conducts research and monitoring studies in 'middle atmosphere' and 'space weather' in line with Australia's Antarctic Science Program Strategic Plan 2000-2005 (<http://www.aad.gov.au/default.asp?casid=920>).

The Australian Antarctic Program has a long and proud history of research in upper atmosphere and cosmic radiation physics. This research has continued with the thrust aimed at understanding space weather phenomena better and to contribute toward usable forecasting models. Much of the observational component of this program has been automated and the responsibility for the data and its archiving has been passed to the Ionospheric Prediction Service (IPS), both for predictive use and as a world data centre, and to Geoscience Australia.

Specific Results

The program of automation of data collection at all bases continued including a new logging system which logs data from the Standard Riometer, Fluxgate Magnetometer and Magnetic Pulsations experiments with daily data files being transferred back to IPS Radio and Space Services in Sydney who receive the data in their capacity as a World Data Centre. These systems also send back smaller amounts of data every five minutes, which are used by IPS for ionospheric forecasting. A new data collection system recording digital all sky camera images was also installed at all stations. All of the new systems can be controlled and interrogated from the Australian Antarctic Division Head Office in Kingston with minimal interaction from station personnel. Instruments operated were: Fluxgate Magnetometers at Casey and Davis; Induction Magnetometers at all stations; Wide Angle Photometers at Casey (decommissioned at the end of 2001 because it requires skilled operators that would no longer be available) and Davis; 30 MHz Riometers at all stations; All Sky Imaging Systems operated at all stations except Mawson and the Mawson system was upgraded during the summer 2001/2 for subsequent automated operation. Casey magnetometer data is now collected remotely and processed by the Geomagnetism Section of Geoscience Australia.

Studies of cusp wave phenomena have been undertaken including field line resonances and ionospheric waveguide attenuation. Conjugate studies between Longyearbyen and Davis indicate systematic changes in the frequency response of the "Pc5 arch" with magnetic activity. These are predictable and may lead to the development of diagnostic techniques. The analysis of three years of ULF Pc3 hydromagnetic wave data has shown that some diurnal characteristics of these waves are controlled by the geomagnetic field geometry while others are controlled by the Sun Earth connection.

Eight years (1993-2001) of Casey ionospheric drift measurements form a unique data set that can be reliably used to test various convection models. A local Casey convection model has been constructed with these data. Comparison with the widely used Weimer 96 (W96) model shows good agreement with predicted velocities. The Casey observations have confirmed the existence of multiple convection cells for certain orientations of the interplanetary magnetic field. When compared with a previous study, Casey observations confirm the superiority of the Weimer model over the pioneering Heppner-Maynard model.

The influence of the IMF on the occurrence of sporadic E (Es)-layers in the southern polar cap ionosphere has been investigated. The main results are: the IMF By component mainly controls the occurrence of the midnight Es-layers through its influence on the corresponding southwest electric field; the IMF Bz component mainly controls the occurrence of the evening Es-layers; and the total occurrence of Es-layers depended more on By than on Bz.

In October 2001 the DPS-4 digital ionosonde, located at Casey since 1993, was relocated to Davis station. Of great concern however is the amount of RF interference generated. Mitigation strategies have been put in place to minimize the communications interference to acceptable levels but this is not a long-term solution and does not address the problems still encountered by the SHIRE experiment. AAD researchers involved in the digital ionosonde project are currently investigating filtering and other techniques to remove the interference

The Southern Hemisphere Imaging Riometer (SHIRE) was utilized to study riometer signatures associated with magnetic impulse events (MIEs) detected in co-located fluxgate magnetometer data. SHIRE allows two-dimensional imaging of localized regions of enhanced cosmic noise absorption (CNA) as they evolve over time, facilitating study of the morphology and dynamics of MIE-associated absorption events. Another type of impulsive event, which covers the complete 200 x 200 km square field of view of SHIRE, forms at the northern boundary of the instrument field of view and expand in 2 minutes over the entire field of view. It then convects west and south (poleward) out of the field of view. The total duration is about 4 minutes. The velocity is about 1-2 km/s westward and 4 km poleward. Davis is on closed field lines equatorward of the cusp during these events and the relationship to transient magnetic reconnection and impulsive penetration phenomena are being studied.

Equipment for measuring the total electron content located at Casey was transferred to Davis over the 2001-2 summer in line with the focus of the SAS program at that base. Results from the Casey data collected around sunspot maximum indicate that the total electron content, as measured by GPS, is generally lower than predicted by the International Reference Ionosphere (IRI) Model. Patches and auroral activity have also been observed in the total electron content measurements. Scintillation activity is not always associated with the patches. This may result from the geometry of the ray path from GPS through the ionospheric patch. Diagnostic tools such as optical imaging should assist in determining the spatial and temporal motion of the patches now that the equipment is located at Davis. Comparisons of the scintillation activity with the model WBMOD show significant differences.

The [Tasman International Geospace Environment Radar \(TIGER\)](#) SuperDARN radar has been operating at Bruny Island, south of Hobart, since November 1999. Periodic visits to the radar site for data retrieval, maintenance and upgrading of equipment are undertaken. The radar scans south over Macquarie Island to coastal Antarctica and is operational for well over 90% of the available time. An evaluation of the International Reference Ionosphere (IRI) as a tool for predicting HF propagation at high latitudes by comparing predictions of sea-scatter with TIGER observations was made. It was found that the IRI predicted properties of propagation via the standard F2-layer mode quite well. However modes not predicted by the IRI become very important at night when the sea-echo occurrence is often 20% or higher. A new technique, based on the Fourier transform and cross-spectral analysis techniques, to determine propagation characteristics of medium-scale travelling ionospheric disturbances (MSTIDs) observed by TIGER was developed. Data obtained in winter were studied in detail and it was found the propagation direction changes of MSTIDs changes during the day from northeast to northwest at about 0500 UT (~1500 Magnetic Local Time).

Geoelectric field measurements have been made at Vostok, Antarctica, from Dec 1998 in association with Russian and American colleagues. Significant progress has been made in the

development of an air-earth current meter. Independent confirmation that a global geoelectric field signal is present in ground-based geoelectric field data from Vostok was achieved. Similarly confirmed was a near instantaneous (coincident within an hour) influence of the By component of the Interplanetary Magnetic Field (IMF By) on the ground-based geoelectric field measured at Vostok, when Vostok is on the dayside of the magnetosphere. The results of an expanded analysis showing the details of the association between the Interplanetary Magnetic Field components, By and Bz, and the geoelectric field measured on the dayside at Vostok have been published.

Cosmic radiation bi-hemisphere studies have revealed possible evidence for precursor signatures to geomagnetic storms in the high-energy cosmic ray records. Further analyses are needed but the work is encouraging. The most advanced study of a GLE was undertaken. For the first time an analysis with fine time resolution was achieved and showed that the temporal development of the event, previously only guessed, has greater variability than expected. This indicates that understanding of the cosmic ray scattering in the dynamic heliomagnetic field is not as well developed as had been thought. The annual cosmic radiation latitude survey was conducted aboard the US Coast Guard icebreakers. Two new containers were commissioned with upgraded electronics and were transferred onto the icebreakers at Hobart. The Mawson Cosmic Ray Laboratory building was extended and the IQSY neutron monitor was enlarged from 6 to 18 counters in October 2002. Advanced electronics have been added to the system in preparation for real time data transfer as a component of the Space Ship Earth international consortium.

Table 1: Experiments in the Australian Antarctic Program showing location and collaborating agencies.

Current Experiments

Experiment	Casey	Davis	Mawson	Macquarie Island	Other	Research Agency
Cosmic Ray Neutron Monitor			X		Kingston Tasmania	AAD
Cosmic Ray Surface Muon Telescope			X		Kingston Tasmania	AAD, Shinshu U, Nagoya U
Cosmic Ray Underground Muon Telescope			X		Liapootah Tasmania	AAD, Shinshu U, Nagoya U
30 MHz Riometer	X	X	X	X		AAD, IPS
Fluxgate Magnetometer	X	X				AAD, GA, IPS
Magnetic Absolutes	X	X	X	X		GA
Induction Magnetometer	X	X	X	X		AAD, La Trobe U, Newcastle U
Digital All-sky Imagers	X	X	X	X (2002)		AAD
Ionosonde	X	X	X	X		IPS
Digital Portable Sounder	X (2001)	X (2002)				AAD, La Trobe U, IPS
Satellite Scintillations	X (2001)	X (2002)		X		AAD, La Trobe U
Total Electron Content	X	X	X	X		AAD, GA, La Trobe U
VLF/ELF Radio Receiver	X					BAS
SHIRE Imaging Riometer		X				AAD, Newcastle U, U Maryland
Electric Field Mill		X			Vostok	AAD
TIGER SuperDARN Radar		X			Bruny Is Tasmania	La Trobe U, AAD, IPS, BAS, Newcastle U, Monash U, DSTO, RLM

AAD – Australian Antarctic Division, IPS – Ionospheric Prediction Service, GA – Geoscience Australia, BAS – British Antarctic Survey, ARL – Australian Radiation Laboratories, RLM – RLM Systems Pty. Ltd., BoM – Bureau of Meteorology, U – University

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2.1 Geomagnetic Observatories, Surveys, and Field Models

Dr Peter Hopgood and Mr Andrew Lewis, Geoscience Australia

Geomagnetic Observatories

The Australian network of permanent geomagnetic observatories is operated by Geoscience Australia (formerly AGSO). The network comprises six observatories on the Australian continent (CNB-Canberra, CTA-Charters Towers, ASP-Alice Springs, KDU-Kakadu, GNA-Gnangara, and LRM-Learmonth), two in Antarctica (MAW-Mawson and CSY-Casey) and one in the sub-Antarctic (MCQ-Macquarie Island). The Australian Antarctic Division provides support for the Antarctic and sub-Antarctic observatories.

Several changes have been made to the observatory network during the past four years. In 1999, the Antarctic station at Casey was upgraded to observatory status through the more stringent control on absolute observations and consistency with the Australian Magnetic Standard held at Canberra. Processing of data from Davis station in Antarctica ceased in 2001, although variation data are still acquired by the Australian Antarctic Division. Residential developments in the vicinity of the Gnangara observatory appears to have led to an increasing incidence of vandalism and security breaches there. Negotiations are presently in progress to move the observatory from Gnangara to a site 70km north at Gingin.

With funding from the Australian overseas aid organisation, AusAID, Geoscience Australia provides support to the Indonesian geomagnetism program. The observatories at Tangerang (TNG) and Tondano (TND) were upgraded to digital status in 1999 and 2001. On-going support is provided for maintenance, processing, and data dissemination.

The Australian observatories that have been accepted as INTERMAGNET observatories are presently: Canberra, Gnangara, Alice Springs, Kakadu, Charters Towers, and Macquarie Island. Most of these were accepted during the past four years.

Accuracy of data produced by the Australian network has recently been enhanced by the establishment of a magnetometer calibration facility at the Canberra Magnetic Observatory. Funding was provided by the Defence Department. The facility has been in operation since 2001 and has provided highly accurate scale-values, relative sensor orientations, and temperature sensitivities of 3-component observatory variometers. The facility was used in the calibration of the magnetometers for the FedSat satellite.

In addition to providing data and indices of magnetic disturbance to the World Data Centers, observatory data are now stored routinely in Geoscience Australia's Oracle database. Gradual population of this database with historical geomagnetic data as well as with current data in near real-time has enabled a previously unknown level of data accessibility and timeliness to be achieved. Data are available via the internet at Geoscience Australia's website www.ga.gov.au.

Geomagnetic Surveys, Field Models and Charts

Geoscience Australia's Geomagnetism program includes repeat station surveys at 15 super-repeat stations that cover Australia, south-west Pacific islands, and Papua New Guinea. Each station in the network was occupied approximately every two years, with three to four days of magnetic data recorded using a portable on-site variometer. Over the period 1999 to 2003, a total of 26 station occupations were made (7 in 1999, 8 in 2000, and 11 in 2002). The aim is to improve the spatial resolution of the available observatory data used for modelling the secular variation. Our experience has shown that, given limited resources, better data are obtained by operating a smaller number of repeat stations with a higher frequency of occupation. The present network of 15 super-repeat stations replaces the 85 stations that used to be occupied every 5 years.

Data from the Australian observatories and repeat stations were an important component of the global data set used for the year 2000 revision of the International Geomagnetic Reference Field.

The epoch 2000 revision of the Australian Geomagnetic Reference Field (AGRF) was completed. The AGRF is a spherical cap harmonic model of the geomagnetic field in the Australian region that is presented as a software package and a set of iso-magnetic contour maps. The main field model comprises a “regional residual field” (RRF) to which is added the IGRF 2000. The RRF is derived from ground, high altitude airborne, and satellite vector magnetic data over the Australian region. The secular variation model in the AGRF is derived from repeat station and regional observatory data. The model is valid for the interval 1995 to 2005 over a spherical cap shaped region centred on latitude 24 degrees south, longitude 135 degrees east with a radius of 24 degrees. AGRF is the basis for providing magnetic compass calibration information for the region.

A new spherical harmonic secular variation model for use in the Australian region was developed in 2002 in collaboration with Denis Winch and Jon Turner, University of Sydney using the GA repeat station and observatory data set. The model is valid over the interval 1960 to 2005, and can be used to update magnetic survey data from one epoch to another within the modelled period and region.

The South Magnetic Pole

A survey to relocate the South Magnetic Pole was undertaken in December 2000 during a privately-funded expedition aboard the *Sir Hubert Wilkins* to Commonwealth Bay supported by Don McIntyre of Ocean Frontiers and Dick Smith. A sequence of direct observations of the instantaneous pole position were made at sea using a ship-board technique for determining the magnitude and direction of the horizontal field, H. The mean of the observed positions of the magnetic pole under quiet conditions was 64.67 deg S, 138.12 deg E, only 11 km from the position of the dip pole predicted by the International Geomagnetic reference Field, and the closest directly-measured approach to either of the Earth’s magnetic poles of 1.6 km was recorded. Using data from the French observatory at Dumont D’Urville as a reference, the effective annual mean (undisturbed) position of the South Magnetic Pole for epoch 2001.0 was estimated to be 64.617 deg S, 138.150 deg E. This is only 7.2 km from the IGRF prediction, which demonstrates the accuracy of the IGRF in the south polar region.

The present set of ship-board observations, together with earlier attempts using the same technique in 1986 are the culmination of long history of attempts to reach the South Magnetic Pole: James Clark Ross in 1841, David, Mawson, and Mackay in 1909, Bage, Webb and Hurley in 1912, and Pierre Mayaud in 1954. The South Magnetic Pole has drifted some 1300 km from the position calculated by Ross in 1841, at an average speed of 8.2 km/year. The pole is presently drifting in a northwesterly direction at 4 km/year, which is about ten times slower than the drift rate of the North Magnetic Pole.

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2.2 Analyses of the Geomagnetic Main Field

Associate Professor Denis Winch, University of Sydney

Analysis of Satellite data

Main field analyses had languished since the launch of Magsat in 1979 at an altitude of 430 km in a Sun-synchronous orbit on the dawn-dusk terminator. The POGS satellite was launched in 1990, but provided only a relatively small amount of data. After a series of postponements, the satellite Ørsted was launched on 23 February 1999 at an altitude of 760 km. The data provided from Ørsted confirmed the lithospheric anomalies inferred from Magsat data. Two general-purpose mini-satellites have been launched since then. The first was Champ, launched in mid 2000 at an altitude of 430 km, which has provided data for main field, secular variation and lithospheric field studies.

The second was the Australian general-purpose mini-satellite, FEDSAT, successfully launched on 14 December 2002 at an altitude of 800 km, for which preliminary magnetic data recorded has been made available.

Analysis of satellite vector data and satellite total intensity data have been done by direct spherical harmonic analysis, by along track filtering, and by reduction of data to a common altitude, and collecting in 1 degree by 1 degree bins. Removal of the main magnetic field, using spherical harmonics to degree and order 14, leaves the lithospheric anomaly field of degree higher than 14, and the lithospheric fields from the various satellites show many anomalies over land areas, and smaller anomaly field over the ocean areas. Attention has been given particularly to the Australian region.

Analysis of 1 cpy and 2 cpy magnetic variations

Analysis of midnight values of observatory magnetic data for semi-annual variations of the main field yielded a result consistent with the model of axial displacement of the ring current, and induction in the Earth. A similar analysis for an annual variation yielded a strong internal field, with an equivalent current system showing strong circulation in the ocean areas, and internal components in advance of the corresponding external component. Efforts to interpret the internal annual variation using standard induction theory for uniform spherical conductors could not explain these results, and the annual variation results could not be used for conductivity studies. However, it seems likely that the midnight values of the magnetic field include an alias of the magnetic field variation originating in the sidereal time tide K1. Observed only at midnight over a year at a particular observatory, the tide K1 will appear to be a one cycle per year term. This work provides the first evidence of a K1 ocean dynamo,

Analysis of solar and lunar daily variations

Work is continuing on the analysis of solar and lunar daily variation contributions to observations of the main field made at satellite altitudes, above the ionosphere. It appears that the internal and the external components of the variation field tend to reduce the variation field on passing through the ionosphere to only a fraction of its ground based level.

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2.3 Core Processes and Geomagnetism

Dr David Ivers, University of Sydney

Numerical Dynamical Models of the Geodynamo

A prototype physical model for the geodynamo in spherical geometries is being modelled numerically. The prototype model consists of a uniformly electrically-conducting spherical solid-inner and spherical-shell fluid-outer cores, and an insulating mantle. The magnetic field, the velocity, the pressure and the temperature in the outer core of the model are governed by the Navier-Stokes momentum equation in a uniformly rotating reference frame with Coriolis, viscous and magnetic Lorentz forces, the magnetic induction equation, and the heat equation. The magnetic field and the velocity are solenoidal. The inner-core is electrically-conducting and free to rotate about the geographic axis. Rotation of the inner core about other axes is excluded, since ellipticity constrains such rotation in the real Earth. The inner-core rotation is governed by the axial viscous and magnetic torque balance at the inner-core boundary. The magnetic field and the temperature in the inner-core are governed by the magnetic induction equation and the heat equation. The motion may be driven by heat sources or temperature differences between the interior and the core-mantle boundary. The gravitational field may be asymmetric to allow for lateral inhomogeneities in the lower mantle.

Codes have been developed for various forms of the rotating Boussinesq/anelastic non-linear and linearised magnetohydrodynamic (mass, momentum, induction and heat) equations. The numerical modelling of various extensions of the prototype model are being investigated, including no inner-core, an insulating or perfectly-conducting inner-core, stress-free and various thermal boundary conditions, a non-uniformly electrically-conducting mantle, anisotropic turbulent viscous or thermal diffusion, pressure buoyancy, non-spherically-symmetric gravitation, inviscid spherical dynamos, inner-core translation, and departures from spherical boundaries due to ellipticity or topography. Problems of interest include topographic effects on the convection, locking of convection to a non-spherically-symmetric gravitation varying in colatitude and/or azimuth and turbulent viscous and thermal diffusivities due to the effects of the magnetic field and rotation. The equations are discretised using spherical harmonic expansions and toroidal-poloidal representations of the magnetic field and the velocity in angle, and Chebychev collocation in radius. The equations are time-stepped with the linear terms treated implicitly, and the product or non-linear terms treated explicitly. All products are evaluated in physical space for efficiency. The codes have been benchmarked.

Linearised Magnetohydrodynamics of the Earth's Core (D.Ivers, C.Phillips)

Linear stability models of the Earth's core complement and offer some advantages over fully-dynamical dynamo models. In particular, they provide information about the time-behaviour and strength of the magnetic field, and allow investigation of parameter regimes inaccessible to time-stepping dynamical codes. Computer codes have been developed for core models consisting of the linearised rotating Boussinesq induction, momentum and heat equations for a uniformly-conducting spherical-shell fluid outer core with a conducting or non-conducting inner-core, non-conducting exterior, and no-slip or stress-free boundary conditions. The basic state is steady and possibly three-dimensional, and may include both meridional and azimuthal velocity components. Vector and tensor spherical harmonic spectral equations, together with poloidal-toroidal representations of the velocity and magnetic fields, are used in angle. Second- or fourth-order finite-differences on a variable grid or Chebychev collocation methods are used for the radial discretisation method. Eigen- and critical-value methods are used to solve the equations.

Modelling Core Turbulence (D.Ivers, C.Phillips)

Anisotropic turbulence in the Earth's core has been modelled by viscous and thermal diffusion

tensors. Spectral equations for rapidly-rotating and strong magnetic field anisotropic turbulence have been derived using computer algebra to incorporate turbulence models that are more realistic than enhanced molecular diffusion into existing dynamically-consistent angular-spectral geodynamo codes.

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2.4 Electromagnetic Induction in the Earth by Natural Source Fields

Dr Ted Lilley, Australian National University

The magnetic field of the Earth changes on a very wide range of time-scales. Almost all reflect processes of electromagnetic induction taking place. These processes may be due either to electromagnetic induction in a stationary Earth due to external source fields, which vary with time; or to motional electromagnetic induction, as in the oceans, and (on a much stronger scale) in Earth's core.

As the appended publication list demonstrates, in any four-year period new observational experiments may be commenced, whilst analysis and interpretation of observations during the previous four-year period will be continued and may be brought to completion. Also, new work may be planned for the years ahead; for example, a present experiment contemplated is seeking an Antarctic limb (as suggested by Gondwanaland reconstructions) of the South Australian Eyre Peninsula conductivity structure.

Electromagnetic Induction in the Earth by Natural Source Fields will be reported in three general sections. The individuals responsible for the research are best identified by their authorship of the associated publications in the publication list. This report does not aim to fully cover developments which have occurred in Australia in the application of the magnetotelluric method in mineral exploration. Similarly it does not cover extensive developments in controlled-source electromagnetic methods in mineral exploration, and in environmental applications such as regolith and soil-salinity studies.

2.4.1 *Electromagnetic Studies of Continental Structure*

(i) Carpentaria conductor

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

(ii) Electromagnetic induction information from aeromagnetic crossover points

The availability of a great deal of high resolution aeromagnetic data, with accurate navigation and magnetic readings, has stimulated research into the use of cross-over misfits as data for studying electromagnetic induction in the Earth. Aeromagnetic surveys consist both of survey lines and more widely-spaced ties, flown at right angles to the lines. This practice gives rise to crossover points where lines and ties intersect and two separate measurements of the total magnetic field have

been made. Differences between such points contains information on electromagnetic induction in the Earth.

Methods have been developed to use such data to gain reconnaissance information on regional electrical conductivity structure for an area where an aeromagnetic survey has been carried out. The methods have been tested for a range of Australian aeromagnetic data-sets. The aircraft results give a clear indication of the presence of known electrical conductivity structures.

(iii) Electromagnetic induction studies of the Eyre Peninsula Anomaly

Long-period natural-source electromagnetic (EM) data have been recorded using portable three-component magnetometers at forty sites in 1998 and 2002 across the southern Eyre Peninsula, South Australia that forms part of the Gawler Craton. Site spacing was of order 5 km, but reduced to 1 km or less near known geological boundaries, with a total survey-length of approximately 50 km. Two profiles trending east-west were inverted for two-dimensional (2D) electrical resistivity models to a depth of 50 km across the southern Eyre Peninsula. The main features from the models are (a) on the eastern side of the Gawler Craton, the Donington granitoid suite to the east of the Kalinjala shear zone are resistive (>1000 Ohm.m); (b) the boundary between the Donington granitoid suite and the Archaean Sleaford complex, which has much lower resistivity of (<10 Ohm.m), dips at about 45° to the west; (c) two very low resistivity (< 1 Ohm.m) zones in the top 5 km Hutchison group sediments correlate with banded iron formations, and are probably related to biogenic-origin graphite deposits concentrated in fold hinges; and (d) a second zone of higher resistivity (>100 W.m) is coincident with the Hall suite volcanics on the western side of the Eyre Peninsula. Such features suggest an extensional regime during the time period 2.00 - 1.85 Ga.

(iv) A magnetotelluric profile across the Broken Hill and Olary Domains.

Seventeen magnetotelluric survey sites were occupied across the Olary and Broken Hill Domains in the Curnamona Province, Australia. Two-dimensional modelling along the magnetotelluric profile identifies the Broken Hill Domain as a zone of high electrical resistivity to a depth of 15km. Gravity modelling along a coincident profile has also shown the Broken Hill Domain to be significantly denser than its surrounds. Seismic data have provided evidence of numerous faults and shear zones within the Pre-Cambrian Broken Hill Domain basement, and is indicative of compression during the Delamarian Orogeny. It is proposed that the majority of crustal fluids were removed from these rocks by granulite facies metamorphism and tectonic compression. The boundary of the Olary Domain appears to be delineated by the Mundi Mundi Fault with an order of magnitude increase in resistivity on the Broken Hill side. The location of the Flinders Conductivity Anomaly was also observed and a number of conducting mechanisms considered, including crustal fluids and graphite films.

(v) Mantle anisotropy beneath Australia

Olivine crystals are anisotropic in electrical conductivity, particularly if hydrogen diffusivity plays a role in the conduction mechanism, with the a-axis being most conductive. Because MT tensor-decomposition techniques provide conductivity strike and orientation information as a function of depth, long-period MT observations can detect olivine preferred-orientations in the Earth below the lithosphere. In 2000, Professor Karsten Bahr and Dr Fiona Simpson from the University of Göttingen, Germany collaborated with University of Adelaide and ANU. During a nine-month sabbatical, they obtained long-period MT responses from four stations 150-300 km apart on the North Central Proterozoic craton of Australia. These stations were intentionally remote from known tectonic boundaries and coastlines. All sites indicate a consistent conductivity strike of 38 ± 6 dg. This can be related to a significant drop in electrical resistivity to less than 200 ohm.m, which is most pronounced in the direction of strike, at depths greater than 150 km. Such resistivities can be explained by olivine if hydrogen diffusivity plays a role. In the lithospheric mantle, the strike can also be influenced by macroscopic structures (such as shear zones) preserved from palaeo-orogenic deformation. At the temperatures expected below 150 km depth, macroscopic structural

lineaments are unlikely to be preserved. The strike of maximum conductivity below 150 km is close to but does not match exactly the present-day direction of absolute plate motion, which is N9.6°E. Directions of seismic and electrical anisotropy imply that strains associated with present-day plate motion do not dominate present mantle deformation below the North Central Australian Craton. This observation raises an intriguing paradox given that, moving with a speed of 8.4 cm year⁻¹, the Australian plate is one of the fastest moving plates on Earth, and should impart a high strain. The phenomenon may indicate recent resistance to mantle flow caused by a cold, high viscosity layer in the sub-lithospheric mantle below central Australia.

2.4.2 Marine Investigations

(i) SWAGGIE (Southern Waters of Australia Geomagnetic and Geoelectric Induction Experiment)

Reduction and analysis of the large data-set obtained during the SWAGGIE experiment of 1998 has been advanced. The purpose of the marine electromagnetic investigation is to investigate the conjectured extension offshore of the Eyre Peninsula Conductivity Anomaly (EPA), which is a major linear electrical conductivity structure found in the Eyre Peninsula, South Australia. The marine investigation was supported by two cruises of the research vessel Franklin, and was notable for involving, through both national and international collaboration, the largest array of seafloor EM instrumentation yet assembled for an experiment in Australian waters. On land, recording magnetometers were deployed in an array across the southernmost part of Eyre Peninsula.

Induction arrows computed from data observed on seafloor, seafloor, and nearby land show the conductivity anomaly continuing from the South Australian coast-line across the continental shelf as far as the continental slope. This result is pleasing, as examples of such electrical conductivity structures being mapped in the presence of an overlying sheet of seawater of depth of order 100 m are rare. Modelling and inversion of the observed data so far indicate that the conductive structure, in section, must have a near-vertical orientation, and lie in the middle to lower crust.

(ii) CAMEL (Carpentaria Marine Electromagnetic Experiment)

Twelve MT deployments were made in the Gulf of Carpentaria in northern Australia along a single transect, in late 1999. The region studied was chosen to be along strike northwards, under the waters of the Gulf, of the Carpentaria electrical conductivity structure, as earlier found by land studies in western Queensland. The Carpentaria Conductivity Anomaly is a major element in the electrical conductivity structure of the Australian continent. The magnetotelluric results on shore define a good conductor within the crust beneath the sediments of the Eromanga Basin. The conductor extends over a depth range of tens of kilometres. Seismic tomographic results show a major gradient in seismic wave-speed in the region. The case history supports the hypothesis that the major conductivity anomalies of the geomagnetic deep-sounding method mark continental sutures, of fundamental significance in recording the creation of continents. Evidence that the conductivity structure continues north into the Gulf of Carpentaria is currently being assessed.

(iii) OCELOT (Ocean-Continent Electromagnetic Transect)

The OCELOT experiment was conducted in year 2000, across the continental shelf and Exmouth Plateau of northwest Australia. This area is an important source of hydrocarbons, and has been well prospected seismically. Sixteen seafloor MT instruments were deployed in two arrays. Twelve of the instruments were deployed in a linear array across the continental shelf and slope, offshore from the Archaean shield of the Pilbara Block. Another eight sites were occupied by deploying four instruments twice each on the continental shelf, in a line across the predicted Canning Basin anomaly position. These latter instruments have special high-frequency capability. The first results obtained are induction arrows from seafloor magnetometers, and these show the presence of the Dampier sub-basin, with sediments to depth 10 000 m, lying on the coastal side of the Carnarvon Basin.

(iv) Data from floating magnetometers

Novel data were obtained during 1998 by releasing a total-field magnetometer to float on the surface of the deep ocean for several days, tracking its position by satellite technology. In an associated experiment, in the more shallow water of the continental shelf, a magnetometer was moored for several days at each of a number of sites. Analysis of these data has proceeded with several objectives in view. Firstly, it has proved possible to combine the sea-surface total-field data with nearby land data to give induction arrows for the sea-surface sites, thus introducing a new technique to marine electromagnetic methods. The induction arrows thus obtained augment the information available for the conductivity structure of the continental shelf.

Secondly, the area is one predicted to be of low magnetic amphidrome value (see section 3.3 below), and the opportunity was taken to check this prediction. In the event, amphidrome values calculated from the sea-surface magnetometer data were indeed typically 3 (a low value), in agreement with the predictions of the model for the whole of Australia.

(v) The magnetic fields of ocean waves and swell

Ocean swells have a magnetic signal, caused by the motional induction of sea water moving in the steady main magnetic field of Earth. To check the character of such signals at the sea surface, data have been analysed from a magnetometer set free from a ship to float unrestricted on the surface of the ocean for periods of several days. The path of the floating magnetometer was tracked by satellite; this procedure enabled also the eventual recovery of the magnetometer by the ship.

Superimposed upon a background of slow change of magnetic field, as the magnetometer drifted across different patterns of crustal magnetisation, are high-frequency signals generated by the strong ocean swell present at the time. These wave-generated signals are typically up to 5 nT trough-to-peak, consistent with theory for their generation by ocean swells several metre trough-to-peak in height. The power spectra of the magnetic signals show a consistent peak at period 13 s, appropriate for the known characteristics of ocean swell in the area. The power spectra then exhibit a strong (-7 power) fall-off as period decreases below 13 s. This strong fall-off is consistent with oceanographic observations of the spectra of surface swell, combined with motional induction theory.

(vi) Magnetic fields generated by motional induction: ocean current contributions to vertical profiles in deep oceans

The Earth's main magnetic field should have a uniform gradient with depth in the ocean. Superimposed upon this gradient may be signals arising from the motional induction of seawater moving in the steady main magnetic field of Earth. There are circumstances where theory predicts such motionally-induced magnetic fields to be of order 100 nT, and to vary with depth in a way which is directly related to the velocity profile. Exploratory soundings of the magnetic field have been made in the oceans around Australia to test these predictions. The magnetic field parameter observed has been that of the 'total field', which should sense the component of the ocean velocity which lies in the magnetic meridian. The magnetometer has been both lowered by cable from a ship, and also operated free-fall to the seafloor (and return).

The observations confirm the theoretical gradient of the main field where there is no ocean current, and where ocean currents exist give profiles of their magnetic north component. Observations taken in an eddy of the East Australian Current show the correct contrast in sign for north and south flowing streams.

(vii) Magnetometer records from the floor of the Southern Ocean

In the Southern Ocean Magnetometer EXperiment (SOMEX), four instruments were deployed on the floor of the Southern Ocean in April 1996. To provide simultaneous magnetic records for reference purposes, a land station was operated at Kingston, Tasmania, to the north of the seafloor sites. Also the magnetic observatory at Macquarie Island, southeast of the seafloor sites, provided simultaneous reference data. The intentions of the experiment were several: (i) to establish the feasibility of deployment and recovery of the magnetometer package in the hostile environment of the Southern Ocean, (ii) to make initial seafloor measurements in the latitude of the Southern auroral zone, (iii) to analyse the fluctuation data for ocean-floor conductivity structure in the vicinity of the Antarctic-Australia Spreading Ridge, and (iv) to examine the data for evidence of a magnetic signal caused by the motional induction of the Antarctic Circumpolar Current, especially in the context of a major experiment in physical oceanography taking place there at that time.

The seafloor observations were planned to coincide with a major oceanographic experiment, the Sub-Antarctic Flux and Dynamics Experiment (SAFDE) of Luther and colleagues. This experiment, part of the larger World Ocean Circulation Experiment (WOCE), thoroughly instrumented the ACC south of Tasmania for two years, 1995 - 1996. The results of the SAFDE experiment provide valuable information for assessing the results of the present magnetometer experiment.

Of the four magnetometers deployed, two were recovered a year later in 1997, and two in 1998. Two failed to record any data, and one of the instruments which did record data suffered intermittent faults. Within these limitations, present work addresses particularly the third and fourth of the objectives listed above (the first and second regarded as having been achieved).

2.4.3 Theory

(i) Two-dimensional magnetotelluric responses of three-dimensional bodies.

Magnetotelluric (MT) tensors have significantly different forms depending on whether the subsurface is one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D). In subsurface geological structures that are not 1D, two-dimensionality is often assumed, as inversion routines for 2D earth models are computationally more tractable than those for full 3D media. In 2D, the MT tensor decouples into two independent modes, the transverse electric (TE) mode and the transverse magnetic (TM) mode. Often only one of these modes is acquired during commercial operations. Field data were collected with the Mount Isa Mines Distributed Acquisition System (MIMDAS) in the Deep Well prospect of the Curnamona Province in South Australia. The target for the survey was an elongate magnetic anomaly of a type that would normally be approximated as 2D but which has a finite strike length and is therefore a 3D body.

(ii) The invariants of the magnetotelluric impedance tensor

For a particular frequency, a magnetotelluric impedance tensor is complex and consists of eight numbers. It is of great value to be able to cast these numbers into one value which refers to the geographic direction of measurement, and seven values which are independent of the direction of measurement and are termed rotational invariants.

The seven invariants then summarise the electromagnetic response of the Earth, and, as a set, may be specified in various different ways. With the first two invariants containing the 1-dimensional scale of the tensor, and the next two invariants its 2-dimensional characteristics, three invariants are left to express the 3-dimensional characteristics of the tensor (and thus of the Earth). Collaborative work has continued on the best specification of the invariants, especially with a view to clarifying the frequently-encountered case in actual data of "galvanic distortion".

(iii) Magnetic amphidrome

A magnetic amphidrome is defined as a place where changes of the magnetic field over time, as measured by a total-field magnetometer, are negligible. The phenomenon is caused by destructive interference between the vertical and horizontal components of the time-varying field, due to particular circumstances of electromagnetic induction. A simple condition for an amphidrome is that the direction of Earth's main magnetic field be aligned with the normal to the Parkinson "preferred plane" in which the small vector changes of rapid fluctuations tend to lie.

A wide band across the southern coast of Australia is predicted to be near-amphidromic by numerical models, the effect being due to the ocean-continent electrical conductivity contrast. Various examples of recorded magnetic fluctuation data confirm this prediction. A consequence of amphidromic conditions is that magnetic surveys are less vulnerable to contamination by magnetic storms.

(iv) Measurement of the horizontal electric field

In surface impedance measurements, traditionally, the horizontal electric field has been measured using a staked voltage probe. Previous publications suggested that an insulated wire dipole without the stakes was a more reliable measurement technique, leading to a series of communications in the literature by the late Professor James R. Wait. In the final analysis, it was determined that both the staked probe and the insulated dipole yield reliable measurements of the horizontal electric field. The principle difference between the two results under ideal circumstances lies in a simple factor of two; the staked probe will yield twice the voltage compared to an insulated wire of the same length.

(v) Analytical and numerical modelling of surface impedance

There is considerable interest in the development of numerical modelling codes capable of simulating the response of arbitrary two- and three-dimensional structures. One development has been the impedance method for two-dimensional modelling, including non-reflecting and infinite boundary conditions for surface impedance modelling.

Electrical anisotropy is a well-known phenomenon in electromagnetic geophysics, and is now gaining significant attention in the multi-dimensional modelling and inversion. As various numerical modelling codes are developed, it is important to co-develop benchmark solutions to which the family of modelling codes can be compared to. A set of one-, two- and three-dimensional analytical solutions have been derived for inclined uniaxial electrically anisotropic and inhomogeneous media for surface impedance problems.

It has been demonstrated that in two-dimensional TM-type problems, the inclined uniaxial anisotropy problem can be equally cast as a biaxial anisotropy problem, simplifying numerical modelling algorithms.

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2.5 Aeromagnetism (Acquisition, Processing & Interpretation)

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Aeromagnetic Surveys

1999 was a landmark year in the acquisition of airborne magnetic and gamma-ray spectrometric data by Geoscience Australia, the national agency for geoscience research and geospatial information. The first-pass magnetic coverage of the Australian continent was completed, after nearly 50 years of surveying (airborne surveying commenced in 1951 by the forerunner of Geoscience Australia, the Bureau of Mineral Resources, Geology and Geophysics, or BMR). The occasion was marked by publication of the first complete colour pixel-image map of Australia, the Magnetic Anomaly Map of Australia (Milligan and Tarlowski, 1999).

1999 also marked the end of national airborne geophysical surveying using government-owned aircraft. Geoscience Australia has continued acquisition, in collaboration with State, Territory and industry partners, by using the services of geophysical contractors. Areas selected for surveys have been targeted to enable geophysics to help in the solution of specific geological problems. State and Territory government geological surveys have also increased their acquisition of airborne geophysical data, with specific initiatives aimed at providing incentives for exploration companies to expand their activities.

All publicly available data are collected in the National Geophysical Database of Geoscience Australia. From 1999 to 2003 ~2 000 000 line-km of data have been added to the database. An index of the holdings is published annually (Richardson, 2002), and may also be viewed on-line by following the appropriate links through the Geoscience Australia web site (<http://www.ga.gov.au/>).

Aeromagnetic Data Processing

During the last few years research in processing methods has continued to improve the quality of final data, along with improvements in the accuracy and resolution of data acquisition. For example, there is growing interest in low altitude, close line-spacing, high-resolution surveys, and acquisition of gradient information.

A major innovation during 1999 to 2002 has been the development of a new method of merging separate magnetic survey grids into a seamless composite grid at a specific resolution (Minty, Milligan, Luyendyk & Mackey, 2003; Milligan, Minty, Luyendyk & Lewis, 2001). This method treats the matching process as an inverse problem, whereby the overlap differences of the grids are globally minimised. It also enables grids to be adjusted by a surface higher than degree 0, although this should be used with caution. Final short-wavelength mismatches along the boundary overlaps are smoothed out using a convolution filter. A further feature enables the incorporation of independent information, to which the grids may be levelled, into the matching process. An example of such information is airborne magnetic data acquired in 1990 around two circuits of Australia, with diurnal control using an array of 50 three-component magnetic variometers. Known as the Australia Wide Array of Geomagnetic Stations (AWAGS) experiment (Chamalaun and Barton, 1990), the associated airborne data are an important test resource.

Program *Gridmerge*, which incorporates the method described above, is now available as part of a commercial geophysical processing system.

Magnetic Anomaly Grid Database of Australia (MAGDA)

Geoscience Australia is now developing a definitive database of the highest quality matched Airborne total magnetic intensity grids publicly available for Australia. From this database, using

Gridmerge, composite grids of any area at any appropriate resolution will be available to clients, including some delivery by the world-wide web.

Over the last few years, considerable effort has been put into quality grid generation for data covering all the State and Territory geological surveys, either by Geoscience Australia or by the appropriate geological surveys. Poor-quality data from old surveys have been reprocessed, using modern techniques of levelling, gridding, filtering and micro-levelling. It is aimed to complete this production for the remainder of Australia by the end of 2004.

One of the remaining areas for research in the generation of large-area composite grids is quantifying the accuracy of intermediate to long wavelength components, and how this accuracy may be improved. Such research will be commenced during 2003-2004, including investigations of the possible use of other datasets, such as those available from satellite missions.

Aeromagnetic Interpretation

The focus for airborne geophysical interpretation within Geoscience Australia is the challenge of finding major mineral deposits that are under cover material. Several projects, in collaboration with State and Territory government surveys, have concentrated on this problem over the last few years. Mineral provinces investigated are; the Mt Isa Block and McArthur Basin in Queensland and the Northern Territory; the Curnamona Province (including Broken Hill) in New South Wales and South Australia; the Southern Lachlan Fold Belt in eastern Australia; the Gawler Craton in South Australia; the North Australia Craton; the Yilgarn Craton of Western Australia; and TASMAR, a study of northern Tasmania.

These studies use a multidisciplinary team approach with concentration on development of integrated, predictive models of ore forming systems and an understanding of ore signatures through and within the cover material. Innovative methods of interpreting the potential field data, such as constrained inversion and “worming” technologies, are of vital importance in helping understand the crustal architecture which forms the framework of such ore systems. A wide range of data, maps and information has been produced within these projects to assist companies undertaking mineral exploration within Australia. Products range from craton-wide interpretations to localised map sheets covering discrete mineral fields. Outputs include both hardcopy map and digital map files for use in GIS, and more recently three-dimensional models which include a variety of data and interpretations, released as vrml files.

Aeromagnetic Risk Map of Australia

Lateral heterogeneity in magnetic induction properties of the crust contributes to errors in aeromagnetic survey data when one or more base stations are used to remove the diurnal (temporal) variation of the field. The dispersion of the magnetic induction (Parkinson) vectors in a particular region provides a measure of this heterogeneity, and has been incorporated into an aeromagnetic risk factor (ARF). This has been computed for a grid of points over the Australian mainland using the available magnetic induction data. As aeromagnetic surveys normally record only total field, the ARF has to be modulated to reflect the angle between the ambient field vector and the induction vector (a notion akin to the amphidrome situation reported in the section *Electromagnetic Induction in the Earth by Natural Source Fields*). The resulting contour map of Australia provides a qualitative measure of how accurately a base station in any part of the country represents the temporal fluctuations of the field at an aircraft undertaking survey work in the general vicinity of that base station.

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2.6 Marine Magnetism

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Geoscience Australia conducted a limited program of marine magnetic data acquisition during 1999-2002. Nine surveys were conducted in cooperation with other institutions, concentrating mainly on Australia's Pacific Ocean and Antarctic margins. These surveys added to Geoscience Australia's database of one million line km of marine magnetic total field measurements. Also during this period Geoscience Australia undertook a compilation of these data (Petkovic, et al, 2001) to produce a 1 km gridded dataset extending 8°-52°S, 106°-172°E and incorporating the aeromagnetic data to provide onshore coverage (Petkovic & Milligan, 2002).

Through the research contract between Geoscience Australia and two Russian institutions (VNIIOK, PMGRE, St-Petersburg) the broadest compilation and re-processing of magnetism data ever undertaken on the Antarctic margin was carried out. The new high-quality magnetism grid resulting from this work incorporates all Australian, all Russian and most of other foreign data. It covers the Antarctic sector 40 – 160° E up to 60° S. The next step in this research will be rotation of points with TMI attributed to each point to create a set of reconstructed magnetic field images corresponding to major episodes of Australia/Antarctica separation and subsequent drift. Such reconstructions will have an impact on the accuracy of plate tectonic reconstructions.

The need to upgrade the marine magnetism acquisition system has been identified as a result of cooperation with international marine magnetism community. Geoscience Australia is now targeting differential recording, enabling effective removal of diurnal variations, and deep water recording capability.

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2.7 Palaeomagnetism and Rock Magnetism

Dr Phil Schmidt (CSIRO, North Ryde) and Chris Klootwijk (ANU, Canberra)

Three main palaeomagnetic laboratories were active in Australia during the period 1999 to 2003: (i) the Black Mountain Laboratory in Canberra, operated jointly by the Australian Geological Survey Organisation (AGSO, now Geoscience Australia) and the Australian National University, (ii) the CSIRO laboratory at North Ryde in Sydney, run by the Commonwealth Scientific and Industrial Research Organisation, and (iii) the UWA Laboratory in Perth, run by the University of Western Australia. Responsibility for running the Black Mountain Laboratory reverted solely to ANU in 2000. A smaller laboratory at La Trobe University in Melbourne which continues to operate despite closure of the Earth Sciences department there.

The ANU/AGSO Group

The ANU/AGSO laboratory continued to work on dating of Australia's ancient regolith, definition of the Proterozoic polepath, and definition of the Middle to Late Palaeozoic polepath from studies in the New England and Lachlan Orogens. Activities became more focused on regolith dating after ANU resumed control of the laboratory.

The CSIRO Group

Activities at CSIRO revolved around industry related problems associated with the interpretation of magnetic (and gravity) signatures and developing new instrumentation, notably using high-temperature SQUIDS for a magnetic tensor gradiometer and also for a spinner magnetometer where the specimen is rotated about two axes (like an AF demagnetiser) and all three components are deconvolved from a single spin. In principle, bulk susceptibility and AMS can also be extracted if an appropriate magnetic field is applied. This feature will be developed in the future.

Other research at CSIRO concentrated on palaeogeographies and palaeolatitudes of Precambrian glacial deposits and iron-formations (in collaboration with Dr George Williams of Adelaide University). Collaboration with Dr Mark Lackie and Kari Anderson of Macquarie University produced important Palaeozoic results from north Queensland, some of which bear on topical subjects such as Inertial Interchange TPW. Dr Tim Rolph and students from the University of Newcastle have also made use of the CSIRO laboratory for environmental studies of fly-ash fall-out near power stations in the Hunter Valley and palaeoclimatic implications of loess. Studies of the New England Foldbelt were also conducted by CSIRO (in collaboration with Professor John Roberts, Richard Geeve, and Xiang Wang of the University of New South Wales).

The La Trobe laboratory focused on the rock magnetic signature of bacterial activity associated with gas hydrates in marine sediments on palaeosecular variation recorded in glacial sediments from the Kiaman Superchron, on magnetostrigraphy (with Ray Cas of Monash University) and secular variation (with Neil Opdyke of the University of Florida) in the Newer Volcanics province of Victoria, and on paleomagnetic studies of south-west Pacific tectonics.

The UWA group

The UWA group, as a key part of the Tectonic Special Research Centre funded by the Australian Research Council (1997-2005), has mainly concentrated on combined Precambrian palaeomagnetic and geochronological investigations and the testing of supercontinent hypothesis. Major field regions were Central and Western Australian cratons (Drs David Evans, Zheng-Xiang Li, Sergei Pisarevsky, Michael Wingate, late Professor Chris Powell, and visiting scientists Professor Henry Halls and Dr Mireille Perrin), China (Li, Evans and collaborator Professor Shihong Zhang), Africa and India (Evans and Wingate), and East Antarctica (visiting scientist Professor Dai Jones). In addition, the group worked on the timing and genesis of the iron ore deposits in the Hamersley Province (Li, Powell, Dr Nadir Halim, and student Wanwu Guo), palaeoenvironment of Western Australia and China (Dr Hongbo Zheng, Powell, Li and collaborating Chinese groups) as well as

issues like true polar wander, snowball Earth, and mantle superplumes. Dr Pisarevsky took over the job of maintaining the Global Palaeomagnetic Database from Professor Michael W. McElhinny from 2001.

The untimely death of Professor Chris Powell was a great loss to Australia, and particularly for UWA and the Tectonics Special Research Centre. Despite this loss, the centre has continued to function productively with many contributions focused on the Neoproterozoic, a period in Earth's history increasingly being seen as crucial for the 'Cambrian explosion', when life on Earth suddenly became profuse.

Quaternary Palaeomagnetism

The "Palaeoclimatic and vegetation record from Tasmania Lakes" project was completed in 2001. The project was undertaken by Prof. Eric Colhoun of the University of Newcastle in collaboration with Geoscience Australia, the University of Tasmania, and the University of Sydney. Logistic support was provided by the Australian Antarctic Division. The project provided for the first time a high-resolution record from lake sediments of the climate history of Tasmania going back to oxygen isotope Stage 5. Little, and in some locations nothing, was known about lake sediment records in Tasmania prior to this project. Palaeomagnetic and rock magnetic data were used for stratigraphic correlation and dating, and for rapid characterisation of climate-controlled sediment properties.

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