Research School of Earth Sciences

Annual Report 2001

Evening sun over the geodetic monitoring GPS site at Landing Bluff, Australian Antarctic Territory.

One of three sites established by the Geodynamics group to monitor post-glacial crustal rebound around the Lambert Glacier. Paul Tregoning and RSES Electronics have designed an innovative automated system where GPS, meteorological and system diagnostic data are downloaded daily and transmitted by satellite phone link back to RSES for analysis. The equipment (including batteries), hibernates through the Antarctic winter night and automatically reactivates when the spring sun is sufficient to provide power to the system.

Photo: R.Stanaway

Introduction - 2001 in review

The Research School of Earth Sciences (RSES) is engaged in basic research in the physics, chemistry, material properties and environmental conditions of the Earth. As a component of the Australian National University's (ANU) Institute of Advanced Studies (IAS), RSES is expected to both conduct research at the highest international level and take a leadership role in defining new directions of research in geophysics and geochemistry - particularly those which have relevance to the needs and geologic setting of Australia.

During 2001, Professor David Green stepped down after seven distinguished years as Director of RSES. David's tenure as Director was notable for the move towards the study of the Earth's environment, particularly with regard to establishing a geologic baseline for climate change. This initiative is now fully integrated into the School's scientific culture and has substantially reshaped our view of what constitutes the study of the solid Earth. David retired at the end of 2001 to return to the high pressure lab and undertake many long overdue experiments. I greatly admire both what he accomplished during a period of declining support for higher education and the gracious manner with which his goals were realized.

In addition to my transition to the Directorship, several other changes to the School's operation occurred during 2001. Among the most significant was the IAS "buy-in" into the Australian Research Council (ARC) grants scheme, in which a portion of our block grant is transferred permanently to the ARC in return for our scientific staff becoming eligible to complete for ARC funds. Our first foray into contesting ARC funds was highly successful, with 40% of our application receiving support. Our goal is to eventually derive approximately 20% of our total support from both ARC competitions and from Department of Education, Science and Technology (DEST) funds, distributed on the basis of our performance against key research and research training indicators. Because these changes to our funding structure significantly limit our ability to centrally manage the School's research budget, we addressed whether a different model for managing our research enterprise was more appropriate to our new circumstances.

The School chose to devolve budgetary control of most non-infrastructure support with the view that managing those funds as close as practicable to the level of the individual investigator minimizes potential mismatches between research expenditures and grant income. We utilized the four research themes identified in the 1999 Strategic Planning process (see 2000 Annual Report) as umbrella structures to facilitate local budget planning. These four broad disciplinary fields are:

> *Earth Physics* (including geodynamics, seismology and geomagnetism, and geophysical fluid dynamics): physical measurements and mathematical analysis of the structure of the Earth and of the physical processes operating within the Earth system.
>
> *Earth Chemistry* (including geochronology and isotope geochemistry, ore genesis, and thermochronology): investigation of the chemical structure and evolution of the Earth and the nature and timing of terrestrial processes.
>
> *Earth Materials* (including petrophysics, petrochemistry and experimental petrology): study of the chemical and physical properties of earth materials under the conditions of temperature, pressure and stress of the Earth's interior.

Earth Environment (including environmental processes, environmental geochemistry and geochronology and posts funded by IPC environment): elucidation of the chemical and physical processes that operate within and between the Earth's hydrosphere, atmosphere and upper crust, and the establishment of the palaeoclimatic and longer term environmental record.

Each research area will be led from 2002 by a Coordinator who, within the school-wide framework, leads local efforts to plan the research program and coordinate funding from both block grant and external sources. This new structure was implemented at the end of 2001 with Prof. Brian Kennett (*Earth Physics*), Dr. Trevor Ireland (*Earth Chemistry*), Dr. Ian Jackson (*Earth Materials*), and Prof. Rainer Grun (*Earth Environment*) initially taking on the Coordinators role. With the exception of Earth Physics, group structures within areas have been essentially abandoned.

It is to our clear advantage that we take these immediate steps to take maximum advantage of the opportunities that exist in the new funding environment. While the need to devolve budget authority within the School has been dictated to us by outside events, I anticipated these actions having the effect of further empowering individual investigators to not let the limitations of internal resources suppress their scientific ambitions. My role remains to provide overall academic leadership to the School and undertake strategic planning to maintain the School's position among the world leaders in geophysics and geochemistry research. In that regard, additional reorganization is required.

RSES has a distinguished history of leading the development of experimental and analytical devices in geophysics and geochemistry. While the success of the vast majority of those endeavours reflects the foresight and ingenuity of our scientists, the environment within which those advances took place was to a great degree made possible by our block funding. This system permitted us to undertake high risk endeavours that intrinsically cautious federal grants schemes are generally less able to support. However, erosion of the purchasing power of the block grant through unfunded salary increases and the declining Australian dollar threatens our ability to remain at the forefront of instrument and technique development. Thus, simultaneous with the creation of the four research theme areas, we have chosen to sequester a portion of block grant funding for planning purposes, including seeding of new scientific initiatives, to use as matching funds for external grants, and support original, on-going research efforts that are outside the funding priorities of federal grant schemes. This fund, which will eventually grow to $750k/year will be derived from savings largely realized by external support of technical and fixed term academic posts. Our first initiative is an effort with the Research School of Astronomy and Astrophysics to create a joint institute to study the fundamental nature of planetary systems.

Our academic staff continue to receive international recognition for their outstanding research achievements. Among the many honours bestowed last year (see Major Prizes, Honours and Awards), I note that Professor Ross Griffiths was elected a Fellow of both the Australian Academy of Sciences and the American Geophysical Union. Professor Kurt Lambeck was awarded the Prix International George Lemaître by Louvain University, Belgium. Professors David Green and Malcolm McCulloch both received ISI Citation Laureate Awards for authoring multiple high impact papers. Malcolm has also just learned of his election to AGU Fellowship. Many notable research achievements are described in the body of this report. In describing the research themes of the School, I highlight below just a few of them.

The **Environmental Geochemistry and Geochronology** Group investigates the long-term interaction between mankind and its environment with a view to guiding our understanding of the past, present and future environments. Of note, they dated the remains of a giant kangaroo at Lake Mungo to be no more than 35,000 years old, whereas nearby aboriginal hearths are at least 41,000 years old. The preliminary conclusion is that at least one giant marsupial appears to have survived long after the arrival of humans on this continent. The implication of this result to the "blitzkrieg" model of human impact on megafaunal extinction is under consideration.

The **Environmental Processes** Group seek to understand the response of the Earth's surface to physical environments. This past year, they discovered that brief climatic excursions occurred periodically throughout the last 8000 years, suggesting greater global climate instability following the end of the last ice age than previously appreciated.

The **Geochronology and Isotope Geochemistry** Group focuses on isotopic variations that can be used for dating purposes as well as tracers of large-scale evolutionary processes affecting the Earth. Within that group, two sub-themes have emerged. The Origins subgroup is involved in investigations ranging from the evolution of the Australian continent to the origin of life on Earth. We are following up our recent discovery of evidence of a terrestrial hydrosphere 500 Ma earlier than previously documented. The Thermochronology subgroup recognizes that all significant geophysical processes involve heat flow disturbances and thus seek to understand the tectono-thermal evolution of the lithosphere through use of radiometric systems.

Research in the **Geodynamics** Group includes the large scale crustal deformation and modelling of tectonic processes, including linkage to surface processes and climate. Among results reported in 2001, the puzzling nature of intracratonic deformation of the Australian continent was successfully modelled as a consequence of horizontal stresses originating at plate boundaries and transmitted into areas of decreased lithospheric strength. This recognition has potentially important implications to our understanding of the effect of the Indo-Asian collision on the Cainozoic evolution of Australia and is the focus of a major consortium of Australian tectonic researchers.

Geophysical Fluid Dynamics is the study of fluid flows and their roles in transporting heat, mass and momentum in the Earth's atmosphere, oceans, crust and deep interior. This past year, laboratory experiments using our rotating table have demonstrated the strong influence of sloping bottom topography on the pattern of upper ocean circulation driven by the atmospheric winds, and we have developed computational methods to study the effect of wind variability on instabilities in ocean currents. We have also discovered new mechanisms by which fresh water input to the oceans at high latitudes can cause oscillations and transitions in the thermohaline circulation that may strongly influence climate variation.

Understanding how orebodies form is vital to the development of mineral exploration models. Research into ore systems is conducted within the Ore Genesis Group, Petrochemistry and Experimental Petrology Group, and the Petrophysics Group. Our efforts are linked with the Department of Geology under the aegis of the **Centre for Advanced Studies of Ore Systems**. Our experimental work has shown for the first time that the sulfide ores of Broken Hill - the largest known lead-zinc deposit on the planet - must have been partially molten during peak formation. Implications of this discovery could transform our understanding of how giant ore deposits form and lead to refinements in the tools we use to discover them.

The **Petrochemistry and Experimental Petrology** (P&EP) Group experimentally investigates the physical conditions under which the Earth formed and evolved. This past year, they extended their study of the properties of sulfur in silicate melts by examining very oxidizing conditions, under which the sulfur dissolves as sulfate not sulfide. Implications of this work include understanding sulfur degassing from magmas during major volcanic eruptions, a known cause of global climate modification.

The **Petrophysics** group research centres on investigation of the physical behaviour of geological materials under controlled laboratory conditions and application of the resulting insights to the structure and processes of the Earth. Using a unique experimental apparatus, we have learned that the partial melting expected beneath mid-ocean ridges results not only in very low seismic velocities, but produces an unusual frequency dependence that could fingerprint molten parts of the overturning upper mantle and thus help us better understand the nature of the Earth's deep interior.

The **Seismology and Geomagnetism** Group is engaged in investigations of the internal structure of the Earth. This past year saw the development of a new approach to surface wave tomography which permits data from a wide variety of sources to be incorporated resulting in more refined estimates of the Earth's internal structure.

The report that follows describes the results of the School's research programs and publications during 2001 in detail. For this and subsequent years we have abandoned the traditional publication of the Annual Report and instead provide it from the world-wide web base. An abbreviated brochure containing highlights of the full Annual Report will still be published and sent to interested colleagues.

Seismology & Geomagnetism

Report not accessible

Geodynamics

Research in the Geodynamics Group of RSES covers a number of inter-related areas including: (i) the study of the Earth's deformation during glacial cycles and the associated glacial history and sea level change, (ii) the geodetic monitoring and analysis of recent crustal deformation as part of the study of the kinematics and dynamics of tectonic processes and glacial rebound, (iii) the modelling of tectonic processes, including surface processes. The first area, of glacial rebound and sea level change, is aimed at understanding and developing predictive models for the interactions between the ice sheets, the oceans and the solid earth during glacial cycles. These are global interactions and their study requires a global approach. Field studies in 2001 have included targets in Antarctica, Greenland, Sweden and Barbados. The second area, of geodetic monitoring of crustal deformation, includes two long-term projects; the kinematics of the deformation of Papua New Guinea and the crustal rebound in East Antarctica. The first aims to delineate the major active tectonic boundaries in PNG through repeat GPS surveys and the detailed analysis of motion on some boundaries. The second aims to determine the slow movements of the rock surface in the Lambert Glacier area of East Antarctica in response to past and present changes in ice distribution as well as any internal tectonic deformations of the Antarctic Plate. The third area, includes the study of landscape evolution under combined tectonic and climatic processes. Emphasis in 2001 has been on understanding the coupling between erosion and tectonics but work has also continued on understanding lithospheric-scale tectonic processes. The ability to quantify rates of surface erosion and tectonic uplift has been strengthened in the group by the appointment, jointly with the environmental Processes Group, of Dr Derek Fabel, who will expand upon the School's capabilities in cosmogenic exposure age dating.

Some highlights from each of these three research areas include:

- *Quantification of Sea level oscillations after the end of the Last Interglacial*. Sea level oscillations during the last glacial cycle have been substantial in amplitude and rapid in time, reaching tens of meters in periods possibly as short as 1000 years. This implies that large ice sheets can grow and decay rapidly. One of the most significant pieces of evidence for this comes from the age-height relationship of coral reefs growing in a uplifting environment, as in the Huon Peninsula, Papua New Guinea, and in Barbados. Earlier work focussed on these fluctuations during the marine isotope stage 3 (OIS 3) and new work was started on the substages of OIS 5. New results by E.K. Potter from Barbados include the ages and the sea levels corresponding to the substages 5c and 5a, respectively about 102,000 and 83,000 years ago. Considerable variation in the sea levels for these times have been reported across the Caribbean and along the US east coast but these apparently conflicting results have been shown to be the result of the isostatic rebound of the North American ice sheet and the concomitant spatial variability in sea level change. The results have yielded new estimates for ice volumes and, along with the identification and dating of other sea level features, they are providing new constraints on ice volumes during the OIS 5 interval.

- *Successful installation and operation by P. Tregoning of the long-term GPS crustal deformation monitoring networks in two very contrasting environments - Papua New Guinea and Antarctica.* Both pre- and post-earthquake crustal deformation associated with the November 2000 earthquakes in southern New Ireland were successfully recorded on a network setup by RSES to investigate the unusual deformation pattern detected in earlier surveys. Post-seismic deformation is continuing and the combination of quasi-continuous monitoring at some sites and episodic monitoring at others, is providing important new insight into the fault geometry and into the tectonic stress regime for the Rabaul and New Ireland regions. The Antarctic installations are able to survive winter conditions and to transmit data back to ANU until the onset of darkness. Preliminary results of several years of data indicate that there is no significant horizontal deformation of East Antarctica within the Lambert Glacier and adjacent areas.

- *Deformation of the Australian Continent.* Many examples of intracratonic deformation of the Australian continent are recorded in the geology, a number of which have been examined individually or regionally. These features are important for developing a broad understanding of the evolution of the continent because of their potential for reactivation when regional stress fields change, although the continent does not appear to be subject to large-scale deformation today, as attested to by stability of the GPS network at the < 1 mm/year level, but its past record is otherwise. A comprehensive review by J.Braun provides a more global perspective of deformations for the Palaeozoic period in Australia through the development of thin-plate models in which deformation is driven by forces acting on the plate boundaries. Then it has been possible to model successfully the tectonic history of the continent for this 200 million year period as a consequence of horizontal stresses originating at plate boundaries and transmitted into areas of decreased lithospheric strength. These zones of weakness may themselves be the result of repeated deformation episodes that leads to strain localisation because of non-linear effects.

Timing and Magnitude of OIS 5a and 5c Sea-Level Oscillations

E-K. Potter, K. Lambeck and T. Esat

The timing and magnitude of sea level oscillations during the last glacial cycle can be calculated from uplifted coral reefs such as those found on the island of Barbados. Using Radtke and Schellmann’s (2001) revised morphostratigraphic analyses of the Barbados coral terraces, as well as a new set of over 80 U-Th coral age measurements, we have re-calculated paleo-sealevels for the oxygen isotope stage (OIS) 5c and 5a sea level maxima. The sea levels associated with the “classic” stage 5c (102 ka B.P.) and 5a (83 ka B.P.) maxima are both calculated to be around 22 m below present. We have also identified a third, previously poorly described, sea level feature with an age of around 76 ka B.P. at a paleo-sealevel of around 24 m below present.

A comparison of the OIS 5a paleo-sealevels calculated for Barbados with estimates of stage 5a sea level at other sites in the Caribbean region show an apparent disagreement. In the Bahamas and Florida stage 5a sea-level estimates range between 5 and 10 m below present. At Bermuda and on the US East Coast, stage 5a age marine deposits can be found above present day sea level. These apparently conflicting observations can be reconciled by taking into account the deformation of the earth in response to changing ice and water surface loads, a process termed glacio-hydro-isostasy. The sites mentioned lie in the “intermediate zone” of the Laurentide Ice Sheet, and so a gradient of stage 5a relative sea level observations is expected. The gradient in stage 5a sea level across this region is sensitive to the rheology of the earth and the melting history of the Laurentide during the time leading up to the peak of stage 5a and during the last deglaciation (stage 2-1).

Sea Level Change from Mid Holocene to Recent Time: An Australian Example with Global Implications

K. Lambeck

Observed relative sea-level change reflects changes in ocean volume, glaciohydro-isostasy, vertical tectonics and redistribution of water within ocean basins by climatological and oceanographic factors. Together these factors produce a complex spatial and temporal sea-level signal. For the tectonically stable Australian margin, geological evidence indicates that sea-levels at 7000-6000 years ago were between 0 and 3 m above present level, due primarily to glacio-hydro-isostatic effects of the last deglaciation. The spatial variability of this signal determines the mantle response to the surface loading and leads to an effective lithospheric thickness of 75-90 km and an effective upper mantle viscosity of (1.5-2.5) x 10^{20}Pa s. Compared with results for other regions this is indicative of regional variation in upper-mantle response. Also, ocean volumes continued to increase after 7000 years ago by enough to raise global mean sea level by about 3 m. Much of this increase occurred between 7000 and 3000 years ago. Because of the spatial variability in mantle response, isostatic corrections to tide-gauge records of recent change should be based on regional model-parameters rather than on global parameters. The two longest records from the Australian margin give an isostatically corrected rate of regional sea-level rise of 1.40±0.25 mm/year. Comparisons of this rate with rates from other regions indicates that the spatial variability in secular sea-level is likely to be significant, with estimates of regional rates ranging from about 1mm/year to 2 mm/year. These rates of secular change cannot have persisted further back in time than a few hundred years without becoming detectable in high-resolution geological and archaeological indicators of sea-level change.

The November 16, 2000 M_w=8.0 New Ireland earthquake, Papua New Guinea

P. Tregoning, H. McQueen, R. Stanaway, S. Saunders[1], R. Curley[2], and K. Lambeck

GPS fieldwork has continued during 2001 to monitor the post-seismic deformation of the Gazelle Peninsula and southern New Ireland in Papua New Guinea after the sequence of three major earthquakes which occurred in November 2000. To date, up to 300 mm post-seismic motion has occurred at the continuously-observing GPS sites operated by the Rabaul Volcano Observatory. Quasi-continuous observations have been made on a bi-weekly basis at several sites near Rabaul while two campaign-style occupations have been carried out on the New Ireland sites.

The information obtained from the GPS monitoring of the post-seismic deformation shows clearly that the region has not yet returned to its pre-earthquake stress state. (Figure 1). Numerical modelling techniques are being applied to extract material parameters and fault geometry from the observations on deformation proceeds. At this stage it is not known how long it will take for this to occur; however, continued monitoring of this lithospheric relaxation/stress cycle will provide considerable insight into the tectonic stress regime that affects the Rabaul and New Ireland regions.

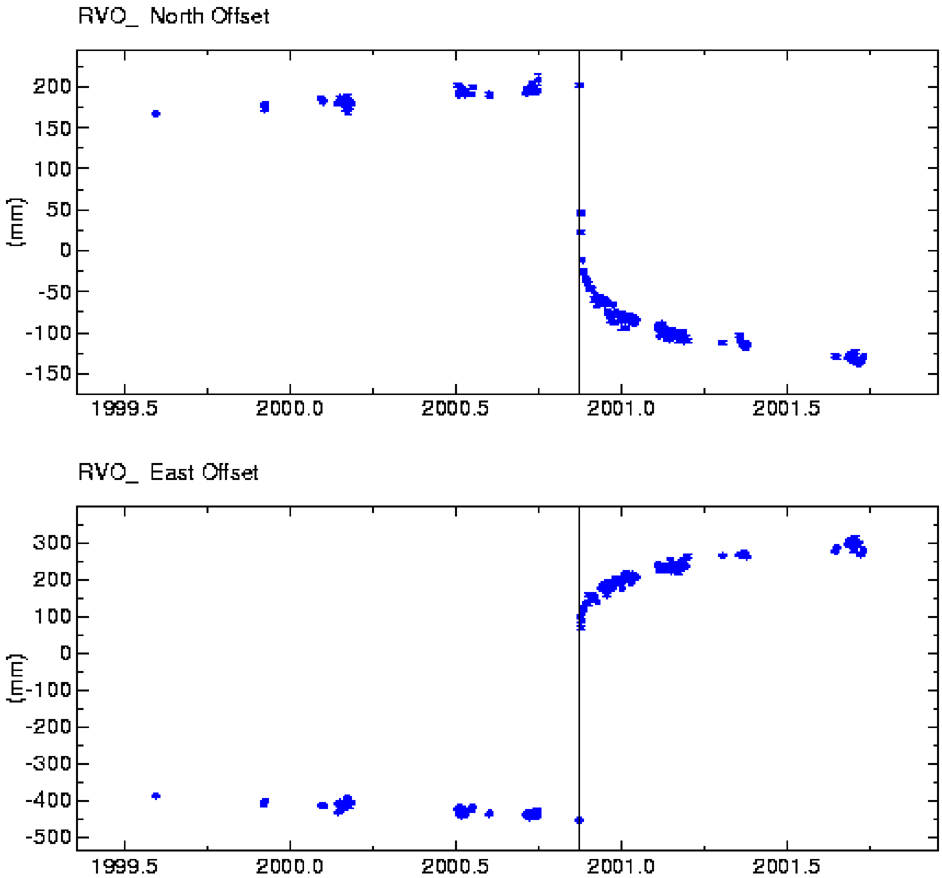

Figure 1: Time series of in local north and east coordinates of the position estimates at the Rabaul Volcano Observatory continuous GPS site with respect to the rigid South Bismarck Plate. Co-seismic offsets and the post-seismic relaxation are clearly evident.

Measuring postglacial rebound near the Lambert Glacier, Antarctica

P. Tregoning, H. McQueen and K. Lambeck

The Antarctic GPS program to monitor glacial isostatic adjustment near the Lambert Glacier continued in 2001. In November 2000 our field party returned to the Prince Charles Mountains to check the operation of the Beaver Lake system, install a new suite of equipment at Landing Bluff (at the Amery Ice Shelf coast) and upgrade the installation at Dalton Corner. The Landing Bluff installation was completed successfully and data from this site were transmitted to Canberra on a daily basis from December 2000 to May 2001. Figure 2 shows the calculated daily position estimates of the Landing Bluff GPS site.

At this stage this project still requires additional data before being able to produce accurate estimates of vertical uplift rates at the remote sites. Horizontal velocity estimates at Mawson, Davis and Beaver Lake and show no significant horizontal motion with respect to a rigid Antarctic Plate.

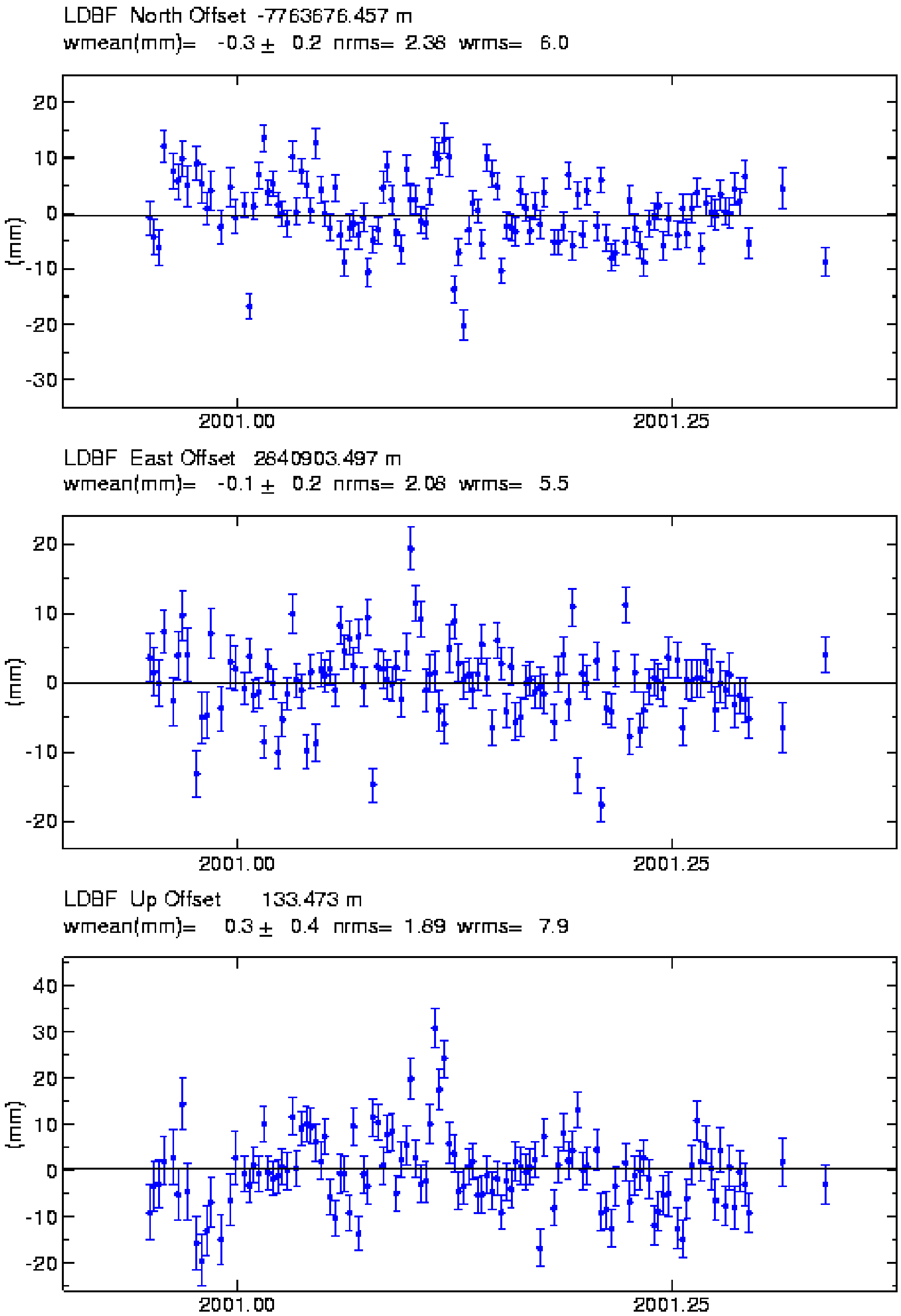

Figure 2: Daily position estimates of the Landing Bluff benchmark during the summer of 2000-2001.

GEOPHYSICAL FLUID DYNAMICS

PDF available

Geochronology and Isotope Geochemistry

Introduction

The isotopic compositions of the elements are not constant. The transmutation of nuclides during radioactive decay changes the abundance of both parent and daughter nuclides. Given the rate of nuclear decay of the parent, the age of a given sample can be calculated from parent daughter ratios and this forms the basis of geochronology. Fractionation of isotopes in chemical reactions occurs because of the mass difference between isotopes. An understanding of the physical processes involved can therefore be ascertained by measuring isotopic abundances. Spallation induced isotopic shifts form the basis of cosmogenic dating and are also evident in extraterrestrial samples exposed to cosmic rays. Finally, the elements themselves may retain a memory of their nucleosynthesis in stars. Our group carries out measurements of a variety of elements that show the effects of one or more of these processes.

The noble gases, helium, neon, argon, krypton and xenon, are very useful geochemical tracers. Studies of their abundances and isotopic compositions in geological samples provide important constraints on hypotheses concerned with the origin and evolution of the Earth's atmosphere, crust, mantle and core. The identification of the primordial noble gas composition of the Earth is critically important for understanding how and when the Earth acquired its volatiles and how its atmosphere evolved. We have found a remarkable correlation between helium and neon isotope systematics in mantle-derived samples. These results have provided strong evidence for primordial helium and neon of solar composition within the Earth. It is very important to ascertain whether the heavier noble gases, argon, krypton and xenon in the Earth are also solar in composition. To better constrain the evolution of noble gas compositions in the mantle we have started undertaking noble gas studies on old mantle-derived materials, including diamonds and early Archaean materials from Greenland. We have also started research projects on cosmogenically-produced noble gases in rocks at the Earth's surface in relation to exposure ages.

The GIG Group is involved in a wide range of study areas from the formation of the Earth from its primordial constituents through to the history of the Earth as a dynamically evolving planetary body. Our research techniques are primarily focused on variations in isotopic abundances that can be used for radiometric age dating as well as tracers of processes affecting the Earth. Additional information is derived from geochemical characteristics of rocks as well as their mineralogy and petrology, and when appropriate, field geology.

The thematic areas are exemplified by some of the specialties of the group members. Dr Ireland is interested in the nature of material that makes up the Early Solar System and the processing of that material into planetary bodies. Dr Bennett is working on the origin and chemical evolution of the earth as well as applications of isotope geochemistry to problems in the Earth Sciences. Dr Nutman specializes in early Archaean geology and Precambrian tectonics. Dr Williams is focused on SHRIMP zircon geochronology and its application to the development of the Australian continent and once contiguous areas of Gondwana. Dr Honda is involved in the application of terrestrial noble-gas studies to the origin and evolution of the Earth's atmosphere, crust, mantle, and core.

Analytical facilities within the group include the SHRIMP ion microprobes and the noble gas mass spectrometers. The facilities are available to outside researchers through PRISE. We also collaborate with Geoscience Australia in optimizing the SHRIMP facilities for geochronology.

SHRIMP Development

S. W. Clement, J. J. Foster, T. R. Ireland, B. Jenkins, P. Lanc, N. Shram, R. Waterford, A. Welsh, I. S. Williams

SHRIMP RG:

The design of the reverse geometry SHRIMP RG should produce approximately four times the mass resolution of the forward geometry SHRIMP II design at the same sensitivity level. This year saw us take a major advance in the performance of the SHRIMP RG with a redesign and refitting of the mass analyzer. The main problem in the original design was an assumed fringe field distribution of the electrostatic quadrupole lenses that was based on a magnetic quadrupole. The electrostatic lenses were modeled in 3D with SIMION resulting in significant changes to both the lens structures and the chambers, effectively allowing the electrostatic field to expand without truncation by ground potential. The recommissioning of the SHRIMP RG immediately revealed a dramatic improvement in image quality with mass resolution at close to design specification (Figure). In terms of sensitivity, SHRIMP RG can run at or above SHRIMP II levels at 6,000 R. There remains a vestige of aberration from wide divergence into the mass analyzer but at this stage it is unclear whether this is due to residual problems with the electrostatic lenses, or a known discrepancy between the theoretical fringe field of the magnet and that measured. We are continuing a study on the modeling of the magnet design through simulations produced by the OPERA program. The results of these studies will also have implications for our future designs of the SHRIMP II instruments.

SHRIMP RG has been successfully used for U-Pb analysis in the standard SHRIMP configuration, measurement of trace elements at ca. 12,000 R, as well as higher resolution measurements for Sr and Ti isotopes. The main limitation for high mass resolution measurements at ca. 20,000 R and above is the limited field step size available. A redesigned field controller with effectively unlimited steps is being produced and should be fitted to the SHRIMP RG in early 2002.

SHRIMP I:

A catastrophic blow out of an oil seal resulted in the contamination of the source chamber. Following an heroic refurbishment of the source chamber by Dr John Foster, SHRIMP I is performing better than ever. SHRIMP I is currently only being used for U-Pb geochronology.

SHRIMP II:

This year has seen the testing of the prototype multiple collector and Cs gun/negative ion configuration. Testing of the multiple collector during the year indicated general agreement with expectation, but there were problems in the control of individual counters that had not been expected, and some stray ions causing cross talk in the individual counting systems. Based on the experience gained from testing of the prototype, a series of modifications have been proposed and fabrication is underway of the modified counting system.

SHRIMP II was also tested in negative ion mode during early 2001. The Kimball Physics Cs ion gun was attached to the primary column and a stable negative ion beam from Si metal was produced at the collector. The coming year will be busy with the final refinements for the multiple collector and an extended push for a stable isotope capability for SHRIMP II.

Some traumatic changes have been made to SHRIMP II that have clearly affected our ability to keep it in a stable configuration for routine analysis this year. The multiple collector requires a new transfer lens in order to make use of the single ETP multiplier on the central beam trajectory. Specific conditions for tuning the transfer lens to obtain optimal peak-shape have been more painstaking than for the single collector and tuning appears to be variable from day to day. Operation of SHRIMP II was also affected by arc discharges in the primary column and required several extensive cleaning episodes to return to stability.

Computing and Control:

SHRIMPs are controlled by the National Instruments LabVIEW platform. This year we have moved the SHRIMPs from the Macintosh platform to Windows with a clear increase in performance in terms of stability and response time. Both SHRIMP RG and SHRIMP II are now operating under Windows LabVIEW. It is expected that we will transfer SHRIMP I from its remarkably robust Macintosh II computer control of ca. 1990 to LabVIEW in the coming year. In addition, we are in the process of moving SHRIMP RG off GPIB/optical fiber communication to direct optical fiber communication. This will increase communication speed as well as reliability. Developments in the control programs are ongoing. This year has seen the development of an automatic tuning facility for SHRIMP analysis further reducing the impact of human variability in analysis. We are working on the development of an automatic mode of operation where stored points can be revisited for unattended analysis.

Noble Gas Development

M. Honda, I. Iatsevitch

During the year we have successfully modified the noble gas extraction system for the automation of gas handling procedures, and programming for automating much of the operation of the gas extraction system and the VG5400 mass spectrometer has been completed principally through the efforts of Dr I. Iatsevitch. For the next phase of the automation, the tasks we plan to undertake include: (1) automatic tune-up of the mass spectrometer source conditions to maximize ion beam intensities, (2) automatic adjustment of the mass spectrometer magnet pole piece position, required to optimize measurement of each of the five noble gases, and (3) automatic cooling of the activated charcoal trap with liquid nitrogen during neon analysis.

Early solar system processes and chronology

T. R. Ireland

The solar system formed approximately 4,560 million years ago. The solar nebula evolved from a cold cloud of dust and gas with high-temperature processing of the dust into a variety of macroscopic solid objects now found in meteorites. Chondrules, composed predominantly of Mg silicates, are by far the most abundant of these, and their origins remain enigmatic. No less enigmatic are calcium aluminium-rich inclusions CAI, that preserve an inconsistent picture of a number of high-temperature processes. CAI are the oldest materials known to have formed from the earliest solar system at 4568 ± 1 Ma. Chondrules likely formed at a similar time. Planet building processes are also recorded as differentiated meteorites (e.g. eucrites) and well-dated examples of these have an age of 4558 ± 1 Myr. These two time markers represent the best absolute age constraints of the early solar system.

Relative time scales can be addressed through short-lived radionuclides with half lives of order 10 Myr or less. One of these short-lived nuclides, ^{182}Hf that decays to ^{182}W with a half life of 9 Ma, has attracted attention of the past few years because of the possibility of dating metal-silicate fractionation (specifically core formation) of large planetary bodies. The presence of a ^{182}W deficit in iron meteorites (relative to bulk chondrite meteorites) suggests that Fe meteorites formed, that is Hf was fractionated away from W, prior to the complete decay of ^{182}Hf. The equivalence of chondritic and terrestrial W isotopic compositions therefore indicates that terrestrial core formation, which causes Hf-W fractionation, can only take place after all ^{182}Hf has decayed to suitably low levels, approximately 60 Ma.

Of fundamental importance in the Hf-W system is the initial $^{182}Hf/^{180}Hf$. The low level of Hf and W in meteorites requires the analysis of rather large samples and in fact only whole-rock isochrons have been produced through ICP-MS analysis. In this regard there is a question over the absolute age of a meteorite or suite of meteorites that affects the calculated initial of the $^{182}Hf/^{180}Hf$. Specifically, is the W isotopic composition affected by the formation of the Fe meteorite or is it a signature of earlier processing.

To address these issues, the W isotopic composition of meteoritic zircons has been addressed through analysis with the SHRIMP RG. Zircon has high concentrations of Hf (typically 1-2 wt%) and has low levels of W making it ideal for the determination of initial $^{182}Hf/^{180}Hf$. The zircons clearly show elevated ^{182}W at high Hf/W. The relative difference between the inferred $^{182}Hf/^{180}Hf$ in the chondritic and eucritic zircons is consistent with the 10 Myr age difference between these different formation events. However, a specific calibration of Hf/W has proved difficult because of the absence of W in terrestrial (and meteoritic) zircon. This calibration is fundamental to the interpretation of the mineral isochrons in the meteorites and the interpretation of the whole-rock isochrons.

The significance of impacts on the early (3.8-4.0 Ga) Earth: Constraints from studies of coeval lunar (Serenetatis Basin) and terrestrial (West Greenland) samples

Vickie Bennett, Marc Norman and Allen Nutman

Much speculation exists as to the role of impacts in the development of early life. They have been variously accused of sterilizing the planet, promoting suitable environments for life development, or of providing the transport mechanism from other planetary bodies. The large impact basins on the Moon (Figure 1) are now generally considered to have been formed by a terminal cataclysmic bombardment at ca. 3.8-4.0 Ga. Coincidentally or not, the large nearside lunar basins are almost identical in age with the oldest terrestrial rocks, and are therefore relevant for consideration of the possible role of impacts in shaping the terrestrial continents and early life environments. Consideration of the higher cross section and greater gravitational focussing of the Earth requires that during this time period, the Earth as well as the Moon underwent significant meteorite bombardment. Owing to limited preservation and the pervasive tectonic overprinting and metamorphism which has affected all >3.6 Ga terrestrial samples, however, the record for the early Earth is difficult to decipher. In contrast lunar samples may represent a much more straightforward record of impact events and have much to tell us about events affecting the early Earth. What is not known, in both cases, are the numbers and compositions of the various impactors.

This past year, as an alternative approach to understanding the role of impacts in the early Earth as while as providing new data on lunar processes, we have initiated studies on lunar impact samples. This is a logical extension of our on-going program of integrated geochemical and geologic investigations of well-preserved, extensive 3.6 Ga->3.9 Ga terranes of south West Greenland.

Some of the clearest indicators of the presence and type of meteorite impactors are the amounts and relative proportions of the highly siderophile ("metal-loving") elements, most notably Re, Pt, Pd Os, Rh, Ru and Ir. Here at RSES, we have developed low blank, high precision methods for measurement of these analytically difficult elements even in low concentration (parts per trillion level) samples. The chemistry is based on isotope dilution combined with carius tube digestion and ion exchange separation of the HSE conducted in a purpose built, HEPA filtered clean laboratory. The resulting solutions are then analysed using an HP 7500 ICP-MS. At present we are one of the few labs in the world, and the only Australian laboratory to have this capability. Through the use of these techniques, we are able to obtain precise HSE signatures from both >3.8 Ga lunar and terrestrial samples. The goal of the lunar work is to use the recently recognized, distinctive signatures of different meteorite classes (representing potential impact materials) to determine the number and types of impactors represented in the lunar cratering record as represented by impact breccias collected during the Apollo 16 and 17 missions.

Our first lunar results are from Apollo 17 impact melt samples that all likely represent ejecta from the Serenitatis basin. Ar-Ar ages are consistent with the formation of these breccias in a single impact event at 3893 ± 9 Ma. HSE from 11 representative samples have W-shaped patterns on CI chondrite -normalized diagrams, with enrichments in Re, Ru and Pd relative to Ir and Pt, and absolute abundances ranging from ~0.5 to 4% of CI chondrite reference values. Stronger depletions of Ir and Pt relative to Re, Ru, and Pd are correlated with decreasing HSE concentrations. The samples with the highest HSE concentrations have patterns that are identical to those of EH chondrites, but the patterns become increasingly less diagnostic of meteorite group with decreasing concentrations. An additional sample (77035) has a distinctly different HSE pattern and is more consistent with an impactor of ordinary or EL-type chondrite composition. It likely represents a discrete impact event that was sampled at the Apollo 17 site These data demonstrate that lunar impact melts contain signatures that link them to specific types of meteorite impactors that hit the Moon and provide new constraints on the types of materials that must have reached the Earth as well.

Figure 1: Lunar impact crater. The highly siderophile element characteristics of melts from similar craters are being studied to determine the characteristics of the meteorite flux on the ancient Earth and Moon.

The second aspect of this project is the analysis of samples from >3.8 Ga well preserved terranes of southern West Greenland. This area includes, but is not limited to the Isua Supracrustal Belt and the Akilia Island "early life" locality. In contrast to a previous studies our early terrestrial work is focussing on the HSE compositions of the oldest preserved (>3.8 Ga) mantle materials rather than on metasediments. Whilst early Archean metasediments can potentially record meteoritic fluxes, it would be extremely fortuitous for the key layers to be preserved and sampled in these rare and highly altered sequences. The HSE component within the Earth's upper mantle must have been added subsequent to core formation and thereby provides a time integrated average of late meteoritic additions to the Earth. The HSE compositions of the oldest mantle samples therefore could provide a monitor of meteoritic contributions.

Rhenium Systematics in Lau Backarc Basin Basalts from in situ Laser Ablation ICP-MS Analysis of Glasses

W. Sun, V.C. Bennett, S. Eggins, T. Falloon

Recent results from the long-lived ^{187}Re-^{187}Os isotopic system are providing new insights into the chemical evolution of the Earth. However, the fuller application of this system is strongly limited by the lack of knowledge of the global budgets of the parent element Re. For example studies on eclogites and blueschists show that large amounts of Re may be lost from the oceanic slab during subduction. The most straightforward destination of the "lost Re" should be the mantle wedge and subsequently, arc and/or back arc volcanics. This is not supported by the published Re contents of arc volcanic rocks which are much lower than expected. In order to further understand the behavior of Re in the arc environment we have undertaken a study of Lau Backarc Basin basalts.

The approach used here differs from prior work in two important ways. Firstly we analysed only submarine basaltic glasses obtained by shipboard dredging, rather than samples that had been erupted sub-aerially. Previous work on Hawaiian samples (Bennett et al. 2000) suggests that Re may be lost during degassing on eruption leading to an underestimate of Re concentrations. This is likely to an even more significant problem for volatile rich arc basalts. Secondly, Re concentrations were determined in the glasses *in situ* using an excimer laser coupled to a HP 7500 quadrapole ICP-MS. This ensured that only fresh glassy material without micro-phenocrysts was analysed. Submarine MORB glasses were also analyzed for comparison. The Re contents of samples from the Lau Basin spreading centers (1.2 to 1.6 ppb) are higher than published concentrations for both MORB and arc basalts. This suggests that literature averages do significantly underestimate the Re contents in arcs. The high Re contents however cannot be explained by simple addition of slab components. For example Re abundances do not correlate with other fluid mobile elements such as Pb. Additionally the systematic correlations between Re and other moderately compatible elements such as Yb (Figure 2), suggest that Re was not controlled directly by subduction released materials. Rather, it is likely controlled by melting processes.

The systematic behavior of Re with Yb as well as other heavy REE during melting has been well documented for many sample suites (Figure 2). However the Lau Basin basalts show a much steeper correlation than MORB and with a slope similar to that of the komatiite trend. The difference between MORB and komatiite has been previously explained by the presence and absence of residual sulphide, respectively. This results from Re being a chalcophile element whereas Yb is lithophile such that when there is no sulphide in the residue, Re behaves more incompatibly. It is thus likely that conditions in the arc mantle wedge such as higher oxygen fugacity coupled with the involvement of hydrous fluids led to smaller amounts of residual sulphide during melting.

The Lau Basin samples also exhibit regional differences with the Re contents of Eastern Lau Spreading center basalts systematically higher than those from the other areas. As the Eastern Lau Spreading center is closer to the Tonga arc, the higher Re contents could reflect a complex enrichment of the local mantle source by subduction released materials, or that larger amounts of S are dissolved in the melts as the result of the greater involvement of hydrous fluids derived from the nearby slab.

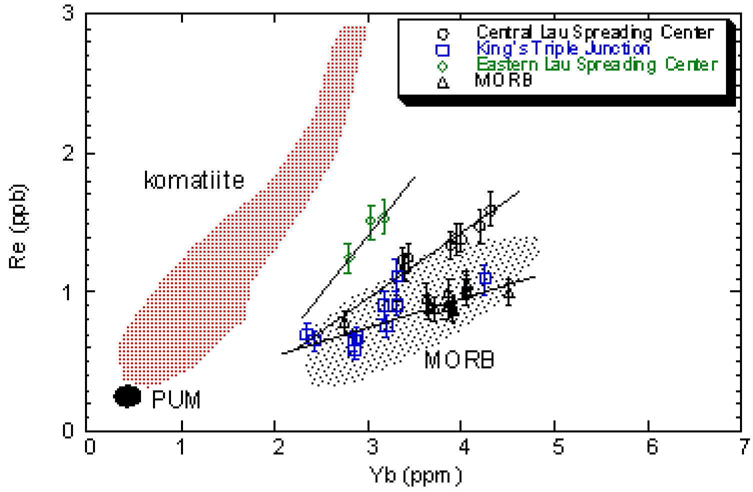

Figure 2: Re versus Yb diagram for the Lau Backarc Basin and MORB submarine basaltic glass samples. The Lau Basin samples define a much steeper slope than do mid-ocean ridge basalts. This steep slope is more komatiites arrays suggesting derivation from a source with low residual sulphide.

Searching for an Archaean Alps in Greenland: An ancient continent-continent collision

Nutman A.P. and Friend C.R.L.

Plate tectonics is geology's unifying theory, providing the framework for understanding the modern Earth. Notably, many geologically recent (past ~1 Ga, billion years) mountain belts are recognised to be collision zones between once distant parts of Earth's crust. Archaean (pre-2.5 Ga) belts of deformed and metamorphosed rocks might be the sites of continental-continental and/or volcanic island arc collisions developed under an ancient regime resembling modern plate tectonics, or might have formed by different processes. Whether or not there is evidence of Archaean plate tectonic processes is important for understanding both crustal evolution and the ancient mineralisations that are of great economic significance for Australia.

In plate tectonics, collision and accretion at convergent plate boundaries produces regions of crustal blocks (terranes) of different age and history bounded by faults/mylonites. At Archaean higher crustal levels, prime evidence for collisional/accretionary tectonics has come from collages of tectonically-bounded packages of unrelated rocks in low to medium metamorphic grade granite-greenstone terranes, particularly the Superior Province of Canada, and parts of the Yilgarn Craton of Western Australia. Archaean high grade gneiss complexes, with upper amphibolite to granulite facies metamorphism at medium to high pressures (6 to 10 kbar) contain a record of deeper Archaean crust. The superbly exposed high grade gneiss complex in Godthåbsfjord, West Greenland with 1.5 km of topography, shows juxtaposition of unrelated amphibolite-granulite facies gneiss complexes (terranes) along high grade mylonites. Such discoveries make it the world's best candidate for a well-exposed, deep section through an Archaean (at ~2.7 Ga) continent-continent collision zone. However the case for plate tectonic style collisions to explain the Archaean evolution of areas such a Godthåbsfjord is weakened by the lack of convincing evidence of suture zones (junction between unrelated parts of the crust once far apart). From Alpine analogies, the most diagnostic would be finding that unrelated terranes of crustal rocks are separated by a tectonic panel with lenses of upper mantle ± exhumed crustal rocks with relicts of high pressure metamorphism. Panels of such rocks represent vestiges of oceanic lithosphere and sediments, trapped between colliding blocks of continental crust.

In 2000 in Godthåbsfjord, we discovered of <200 m thick tectonic panel, containing late Archaean massive ultramafic rocks, lenses of gabbro, metabasalt and metasediment. This panel is bounded on its top and bottom by folded, metamorphosed mylonites. The mylonites separate the panel from extensive blocks of gneiss structurally above and below of different ages, and which did not have a common metamorphic history until the late Archaean. A deformed, but non-mylonitic pegmatite intruded along a mylonite has yielded a SHRIMP U/Pb zircon date of 2.7 Ga. In 2001, we found similar ultramafic rocks in the panel's likely extension up to 20 km away. So far, the panel seems to form an extensive sheet no more than a couple of hundred metres thick, between the two different gneiss blocks. Preliminary geochemical data (Mg/Si versus Al/Si) suggest the ultramafic rocks are candidates for abyssal peridotites. This panel is the best candidate yet for the suture zone in the Godthåbsfjord region, making it more promising that this region contains a late Archaean collisional orogen, formed like the European Alps.

This panel will be the focus of further planned research, such as geochemical studies to confirm or deny the abyssal peridotite affinity of the ultramafic rocks. Another key indicator of a suture panel would be to find relicts of high pressure metamorphism, because, as in the Alpine model, the rocks in it would have been exhumed from greater depth. Even in modern collisional settings, high pressure assembles are rare, because of large-scale re-equilibration at lower pressures during their exhumation. In Godthåbsfjord, the difficulty of finding relict high pressure assemblages will be compounded by recrystallisation during further ductile deformation and amphibolite facies metamorphism in the period 2.7-2.5 Ga. Therefore we hold-out very little hope of actually finding relict eclogites. Instead we will employ a novel zircon geochemical method developed by Dr D. Rubatto which will allow us to determine if any metamorphic zircons in the mafic rocks in this panel formed as part of plagioclase-free (eclogitic) assemblages. Both the ultramafic geochemistry and metamorphic investigations are to address criticism over lack of undeniable evidence of sutures in Archaean orogens and to understand the nature of Archaean tectonic processes.

Zircon formation during fluid circulation in eclogites (Monviso, Western Alps): implications for Zr and Hf budget in subduction zones

D. Rubatto, J. Hermann

Recent studies demonstrated that metamorphic zircon can form by recrystallisation, metamorphic reactions, dissolution/precipitation or even aqueous fluid circulation at variable pressure and temperature conditions. During high-pressure metamorphism, i.e. subduction, metamorphic zircon can form in a variety of rock types: it is commonly found in metasediments and in eclogites derived from ophiolitic gabbros, especially highly differentiated Fe-Ti gabbros and leucogabbros. In addition to dating, the study of zircon in these rocks bears important information for recycling of Zr, Hf and U in subduction zone processes. Subduction zone magmas are characterised by a depletion of HFSE (Zr, Nb, Hf, Ta) with respect to REE of similar incompatibility. These features can be explained either by processes dominated by the mantle wedge or by fractionation during liquid extraction from the subducted oceanic crust. Based on experimental partitioning between rutile and aqueous fluids/melts, it has been proposed that residual rutile in eclogites might be responsible for limited release of HFSE from the subduction zone. Up to now, the possible influence of residual zircon on the Zr and Hf budget in subducted crust are not well known. We address this issue using isotope and trace element data from zircon and associated minerals from eclogite-facies rocks.

The zircons from an eclogite and an enclosed eclogite-facies vein from the Monviso ophiolite (Western Alps) display contrasting chemical and morphological features and document different stages of the evolution of the ophiolite. The zircons from the eclogite, which was metamorphosed at 600°C and 20 kbar, are inherited from the protolith and do not display significant metamorphic recrystallisation. They have a typical magmatic zoning and trace element composition with strong enrichment of heavy rare earth elements (HREE) over middle rare earth elements (MREE), and an accentuated negative Eu-anomaly indicating formation in the presence of plagioclase. The age of these magmatic zircons documents the formation of oceanic crust at 163±2 Ma. Zircons from the eclogite-facies vein contain garnet, omphacite and rutile inclusions demonstrating that they precipitated under eclogite-facies conditions. These zircons are rather homogeneous in composition: they have Th/U ratios < 0.09, are generally depleted in trace elements, display no Eu-anomalies and only weak enrichment of HREE with respect to MREE, consistent with a garnet-bearing, plagioclase-free, i.e. eclogite-facies, paragenesis. Metamorphic vein zircons yield an age of 45.0±1.0 Ma providing evidence for Eocene subduction of the Monviso ophiolite.

In the vein, the contemporaneous formation of metamorphic zircon with eclogite-facies omphacite and garnet permits determination of a set of trace element distribution coefficients between these minerals at high pressure. This set of partitioning can be used to identify chemical equilibrium among these phases in high-pressure rocks where the textural relationships are less clear than in the studied vein. This is especially important to relate zircon formation, and hence age, to sensors of metamorphic conditions such as garnet and omphacite.

The presence of zircon and rutile in the vein demonstrates that high field strength elements (HFSE) are mobile at least over a short distance in aqueous fluids at eclogite-facies conditions. However, the concentrations of Zr and Hf in the aqueous fluid are estimated to be at least a factor 10 lower than primitive mantle values.

Mass balance calculations demonstrate that zircon hosts more than 90% of the bulk Zr and Hf and about 70% of U in the vein. Our new data combined with available literature data indicates that zircon is a residual phase in subducted basalts and sediments up to at least 800-900°C. Therefore, residual zircon in subducted crust together with rutile completely buffer the HFSE in liberated subduction zone fluids/melts and might be partly responsible for negative Zr and Hf anomalies in subduction zone magmas. However, the extremely low Zr and Hf contents of the eclogite-facies aqueous fluid, from which the vein minerals precipitated, indicate that aqueous fluids are not capable of enriching a mantle source in these elements. Thus, subduction zone magmas showing a slab HFSE component require metasomatism of the mantle wedge by hydrous melts, which are able to transport significant amounts of such trace elements.

Further evidence that eastern Australian S-type granites are derived from early Paleozoic sediments

I.S. Williams

Geochemical studies over many years have demonstrated that the S-type granites of southeastern Australia are derived predominantly from source rocks that have been chemically fractionated by weathering, namely sediments. Initially it was suggested that those sediments were deeply-buried Proterozoic continental crust, but as more work was done on zircon from the granites and their host rocks, it became evident that both the granites and the extensive Paleozoic flysch into which they were intruded share a common provenance. The question is now whether the granites might be the product of partial melting of the flysch itself.

Inherited zircon, namely zircon that is significantly older than its igneous host rock, is common in the granites of southeastern Australia. It usually occurs, not as discrete grains, but as cores surrounded by an overgrowth of younger zircon precipitated from the melt phase of the magma, and varies widely in its relative abundance. Inherited zircon is extremely rare in the more mafic metaluminous rocks, such as gabbros and diorites, and generally scarce but ubiquitous in the more felsic metaluminous rocks such as the majority of the I-type tonalites, granodiorites and monzogranites. In contrast, it constitutes a major fraction of the total zircon content of the S-type granites, particularly the mafic S-type granites, in which virtually every zircon grain contains a large inherited core.

These differences in abundance are governed by several factors, for example the abundance of zircon in the magma protolith, the capacity of the magma to incorporate zircon-bearing country rock during its ascent, and the solubility of such assimilated zircon in the magma. High-temperature metaluminous magmas have the greatest power to assimilate, but it is just such magmas in which assimilated zircon is most likely to dissolve. In contrast, zircon is relatively insoluble in low-temperature peraluminous melts with little assimilation power, so zircon from the magma protolith has a greater chance of being preserved uncontaminated as inheritance in the resulting granite.

Detrital zircon in sedimentary rocks commonly survives high grade metamorphism, simply being overgrown by new zircon precipitated during the metamorphic event. If sufficient partial melt develops for a magma to mobilise, then the former detrital zircon is preserved in that magma as zircon inheritance. Case studies of progressive metamorphism indicate that incorporation of detrital zircon into an S-type magma has a negligible effect on the zircon U-Pb isotopic systems. Once it is recognised that the inheritance in S-type granites is predominantly source-derived, then the inheritance pattern in those granites becomes a direct guide to their possible source rocks.

A feature of the S-type granites in southeastern Australia is the close similarity between their inheritance age patterns and the detrital zircon age patterns in the enclosing early Paleozoic flysch. If part of the flysch sequence itself was the source of the magmas, then the age of the youngest inherited component is of particular interest because it places an upper limit on the deposition age of the source metasediment. Young inherited zircon is relatively rare, however, and there is always the question of whether the apparent ages of such cores have been reduced by partial loss of radiogenic Pb. By combining cathodoluminescence imaging of the zircon internal structures with the observation that inherited zircon in S-type granites commonly preserves the external morphology and growth zoning of the original detrital grains, it has recently been possible to identify, and use SHRIMP to date, several very young inherited zircon cores in one of the most inheritance-rich S-type granites in the region, the Jillamatong Granodiorite. The ages, most confirmed by replicate analysis, extend to just below the age of the Cambro-Ordovician boundary, indicating not only that the granite was derived from Paleozoic, not Proterozoic sediment, but also that that sediment was deposited after the Cambrian sediments that in places can be seen to form the base of the flysch pile. The inherited zircon is readily explained without invoking the presence of Proterozoic continental crust beneath southeastern Australia.

The Svecofennian Province of southern Finland— accretionary arc complex or marginal basin?

R.W.R. Rutland and I.S. Williams

The extensive mid-Proterozoic Svecofennian Province covers over 300,000 km^2 of southwestern Finland and eastern Sweden. In recent decades this vast region, dominated by migmatised greywackes and volcanic rocks intruded by voluminous Proterozoic granites, has been interpreted to represent a sequence of juvenile island arcs and subduction zones that were successively accreted to the margin of the Archean Baltic Shield to the north. This concept is now being called into question, however. Firstly, the greywackes contain zircon much older than the associated volcanic rocks, and secondly, the igneous rocks themselves are much more evolved chemically and isotopically than would be expected had they been produced in a primitive arc environment. The alternative suggestion is that the greywackes of the Svecofennian Province are in fact remnants of the fill of a large basin developed at a continental margin, akin to the Paleozoic Lachlan Fold Belt in eastern Australia. The volcanic rocks would thereby be the preserved remains of extensional volcanism which followed closure of that basin.

A premise of this alternative view is that the greywacke sequence predates, rather than is contemporaneous with, the volcanic succession. This is not a novel idea—Sederholm, as early as 1897, proposed that the two sequences were separated by a great unconformity. The difficulty in testing the hypothesis, however, is that the sequences have been extensively metamorphosed, commonly to granulite facies, so structural and isotopic evidence of their earlier history is extremely difficult to recover.

An experiment is currently in progress to try and establish the deposition age and thermal history of the Svecofennian greywackes using SHRIMP ion microprobe analysis of individual zircon and monazite grains. The work is being done on a small number of samples carefully selected on structural criteria to be as free as possible of the effects of the late metamorphic overprint. Early results are encouraging. Consistent with earlier work, preserved detrital zircon shows that the greywackes are derived from sources dominated by rocks up to 100 million years older than the overlying volcanic sequence. More importantly, there is evidence in the tiny overgrowths on individual zircon grains, that not only were the source rocks in places metamorphosed to high grade before erosion, but some of the greywackes were metamorphosed to the point of partial melting about 60 million years before being metamorphosed again by the thermal overprint associated with the late igneous activity. So pervasive is the late overprint that in most cases evidence of the early metamorphism is preserved only by zircon, but in one case, evidence for this main metamorphism is also preserved by monazite (Figure 3). These results strongly support the proposition that the migmatitic basement was deformed and metamorphosed before the overlying volcanic sequence was deposited, and suggest that the Svecofennian Province formed in a tectonic setting very different from that commonly assumed.

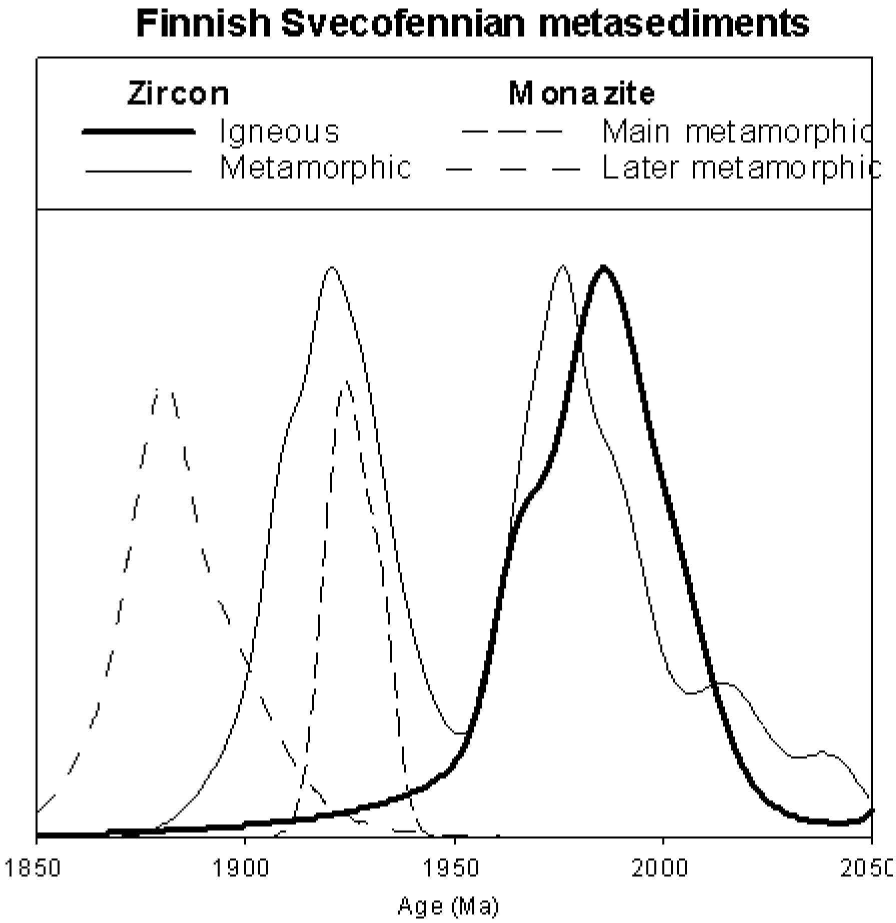

Figure 3: Relative probability histograms of the Proterozoic zircon and monazite ages from selected Finnish Svecofennian metasediments showing the presence of minerals recording three thermal episodes. The oldest (c.1980 Ma) is represented by detrital grains, the younger two (c.1920 and c. 1880 Ma) are represented by post-deposition metamorphic mineral growth.

Carboniferous and Triassic eclogites in the western Dabie Mountains, east-central China: evidence for protracted convergence of the North and South China Blocks

Weidong Sun, Ian S. Williams, Shuguang Li

SHRIMP U-Pb dating and laser ablation ICP-MS trace element analyses of zircon from four eclogite samples from the northwestern Dabie Mountains, central China, provide evidence for two eclogite facies metamorphic events. Three samples from the Huwan shear zone yield indistinguishable late Carboniferous metamorphic ages of 312 ± 5, 307 ± 4 and 311 ± 17 Ma, with a mean age of 309 ± 3 Ma (e.g. Figure 4). One sample from the Hong'an Group 1 km south of the shear zone yields a late Triassic age of 232 ± 10 Ma, similar to the age of ultra-high pressure (UHP) metamorphism in the east Qinling-Dabie orogenic belt. REE and other trace element compositions of the zircon from two of the Huwan samples indicate metamorphic zircon growth in the presence of garnet but not plagioclase, namely in the eclogite facies, an interpretation supported by the presence of garnet, omphacite and phengite inclusions. Zircon also grew during later retrogression. Zircon cores from the Huwan shear zone have Ordovician to Devonian (350-440 Ma) ages, flat to steep heavy-REE patterns, negative Eu anomalies, and in some cases plagioclase inclusions, indicative of derivation from North China Block igneous and low pressure metamorphic source rocks (Figure 4). Cores from the Hong'an Group zircons are Neoproterozoic (610-780 Ma), consistent with derivation from the South China Block. In the western Dabie Mountains, the first stage of the collision between the North and South China Blocks took place in the Carboniferous along a suture north of the Huwan shear zone. The major Triassic continent-continent collision occurred along a suture at the southern boundary of the shear zone. The first collision produced local eclogite facies metamorphism in the Huwan shear zone. The second produced widespread eclogite facies metamorphism throughout the Dabie Mountains – Sulu terrane and a lower grade overprint in the shear zone.

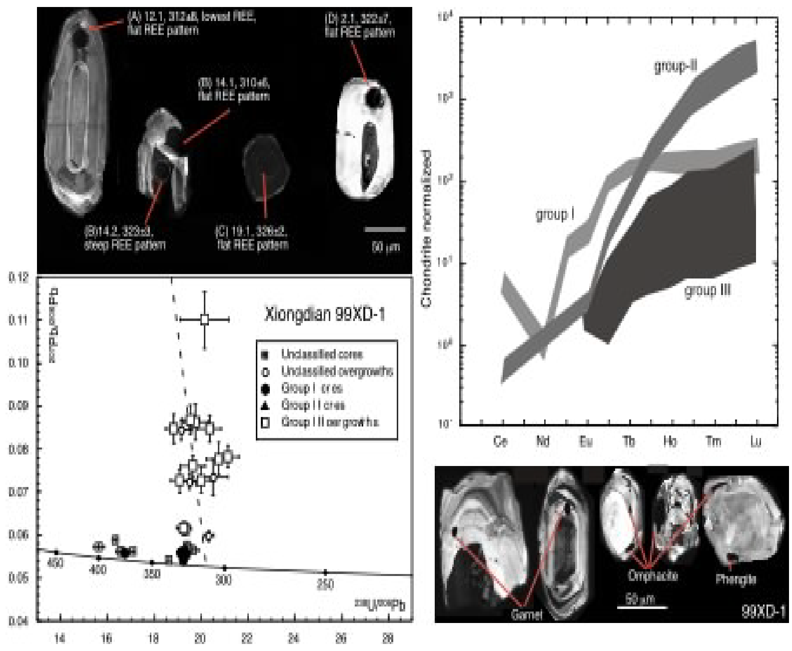

Figure 4: Zircon U-Pb isotopic analyses, chondrite-normalised REE patterns, representative CL images of zircon structures and inclusions of high pressure minerals (garnet, omphacite and

phengite) restricted to the overgrowths, indicative of late zircon growth under eclogite facies conditions from Xiongdian eclogite 99XD-1 (garnet quartzite) from the Huwan shear zone. Analytical uncertainties 1s .

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Geochronological correlation within the Curnamona Province of southern Australia, and links to Mount Isa and other north Australian Pb-Zn bearing successions

R.W. Page

The advent of a more robust temporal framework (reported in RSES Annual Report 2000) for the Palaeoproterozoic history of the southern Curnamona Province provides the basis for scrutinising lithostratigraphic and sequence stratigraphic correlations on a regional and inter-basin scale. The Willyama Supergroup sequence in the Curnamona Province is host to Broken Hill's Ag-Pb-Zn orebody. Improved correlation across the Province, from the Olary Domain (eastern South Australia) to the Broken Hill Domain (western NSW) allows comparisons in this sequence that generally affirm earlier lithostratigraphic correlation. This includes the equivalence of 1710-1720 Ma Curnamona and Thackaringa Groups, and the recognition of a coeval 1700-1710 Ma felsic magmatic event in the Olary and Broken Hill Domains.

New SHRIMP U-Pb ages from several tuffaceous sediments immediately above the calcareous and gossanous, base-metal enriched Bimba Formation in the Olary Domain are remarkably consistent on a regional scale. They define the depositional age of this horizon at 1693±3 Ma. This helps resolve a longstanding question as to which part of Olary sequence is correlated with the ~1690 Ma-Broken Hill Group. The base, middle, and upper part of the latter are defined by ages in the Ettlewood Calc-Silicate Member (1693±4 Ma), Parnell Formation (1693±5 Ma), and Hores Gneiss (1685±3 Ma). The new ages reported here and elsewhere thus substantiate earlier lithostratigraphic correlations between the lower Broken Hill Group and the lower Strathearn Group.

These correlations, together with the potential importance of syn-depositional base-metal ore formation, call for closer comparison with other Palaeoproterozoic Pb-Zn mineralised sequences — especially the 'Carpentaria Zinc Belt' of northern Australia. The gross lithostratigraphy, depositional ages, and possible hiatuses within the Curnamona Province have parallels and provide a quantitative basis for correlation with basin development in Mount Isa and McArthur Basin. The paucity of rocks equivalent in age to Broken Hill Group is possibly linked to the widespread 'Gun' erosional event in northern Australia between 1690 Ma and 1665 Ma ago. However, in the upper Willyama Supergroup, a clear age correlation with northern Australian sequences emerges. This derives from (a) close comparison of middle Paragon Group ages with tuff ages associated with the Mount Isa and Hilton orebodies at ca. 1655 Ma, and (b) similarly comparable ages of ca. 1640 Ma for the upper Paragon Group and Isan Superbasin hosts of the HYC deposit of the McArthur Basin, the Walford deposit, and other mineralised sequences of Lawn Hill Platform. Revisions and improvements to the age and stratigraphic framework of the Willyama Supergroup, and links that emerge with northern Australia sequences might provide a fresh basis and refocus of exploration efforts in the Curnamona Province.

Age and stratigraphic placement of new hominid genus from Kenya

I. McDougall, F.H. Brown, P.N. Gathogo[5], M.G. Leakey, and F. Spoor

In March, 2001, Leakey et al. reported in Nature the finding of fossils assigned to a new genus of hominid, *Kenyanthropus platyops*, with important implications for our understanding of early human ancestry. The fossils were found in near flat-lying sediments of the Nachukui Formation in the Turkana Basin, northern Kenya, just to the west of Lake Turkana in the Lomekwi drainage. The stratigraphic placement of the fossils was undertaken by F.H. Brown and P.N. Gathogo and most of the numerical age measurements on associated tuffaceous horizons were made at ANU. The type specimen of the new genus, a nearly complete cranium, is from a horizon 3.5 Ma old, and additional jaws and teeth, assigned to the same genus, are from sediments deposited between about 3.5 and 3.3 Ma ago. The new fossils are distinctly different from those of *Australopithecus afarensis*, which are of similar age and from the Hadar region in Ethiopia. The new finds indicate that as far back as 3.5 Ma ago there were at least two lineages that could have ultimately given rise to modern humans, so that the early stages of human evolution are more complex than previously thought.

Stratigraphic sections shown in Figure 5 also indicate the level from which the hominid fossils were recovered. Sample 4000 refers to the type specimen of *Kenyanthropus platyops* within the sequence comprised mainly of sands, salts and clays deposited in fluvial and lake-margin environments. Interbedded with the normal detrital sediments are several tuffaceous horizons. These tuffs are the key to the stratigraphy as their identification through chemical fingerprinting and their widespread distribution throughout the Turkana Basin has enabled a robust relative time framework to be established. In addition, isotopic age measurements on alkali feldspar crystals in small pumice clasts in some of the tuffs, has provided numerical ages for the explosive eruptions that produced the tuffs. Deposition of the tuffs is considered to have occurred very soon after their explosive eruption, so that the age of eruption in most cases approximates closely that of deposition also. The $^{40}Ar/^{39}Ar$ dating of single crystals of feldspar from pumice clasts in the Topernawi and Moiti tuffs yielded precise and concordant ages for each of the two horizons, actually indistinguishable in age at 3.96 ± 0.03 and 3.94 ± 0.03 Ma, respectively (Figure 5). The Lokochot Tuff has not been directly dated, but an age of 3.57 Ma is derived by stratigraphic interpolation, and the estimated age of the Tulu Bor Tuff of 3.40 ± 0.03 Ma is derived from earlier measurements by other workers on a correlative of the tuff in Ethiopia. Together these results provide good control, with an interpolated age of 3.5 Ma for the type specimen of the new hominid. From the stratigraphy and the age of tuffs higher in the sequence in the Turkana Basin, the fossils found above the Tulu Bor Tuff in the area are regarded as no younger than about 3.3 Ma.

This study is a further excellent example of the value of an integrated interdisciplinary approach involving detailed stratigraphic mapping and geochronology done in conjunction with the palaeontological exploration. This has lead to remarkably tight relative and numerical age control, facilitating discussion of the evolution of hominids toward modern humans relatively free of some of the dating problems associated with hominid finds of decades past.

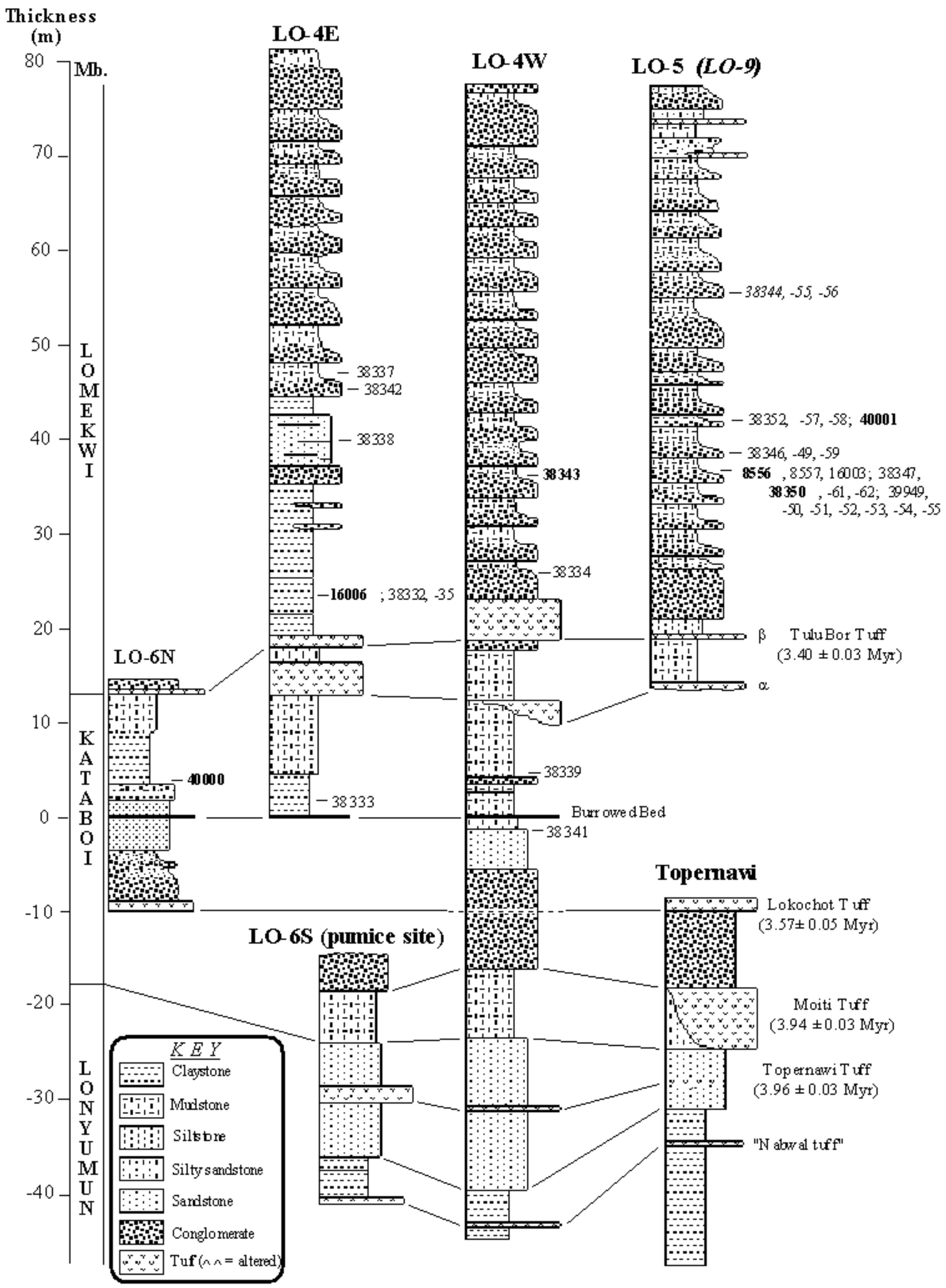

Figure 5: Stratigraphic sections and placement of hominid specimens in the Lomekwi drainage, west of Lake Turkana, northern Kenya. Reproduced from Leakey et al. (*Nature*, 410, 433-440, 2001)

Exposure dating in young lava flows using cosmogenic neon-21

D. Gillen, M. Honda and A. Chivas[3]

A study was designed to further develop the relatively new method of cosmogenic exposure dating with noble-gas isotopes, particularly neon-21. The motivation for the study was the need for a reliable way of dating exposed surfaces in relation to a variety of geomorphological problems, and possibly measurement of minimum eruption ages for young volcanic rocks that have never been covered.

Cosmogenic neon-21 was used to determine exposure ages of young basaltic lava flows from the Newer Volcanic Province, southwestern Victoria. Ages determined from neon-21 analyses in olivine showed correlation with exposure ages previously determined by radiocarbon dating and cosmogenic chlorine-36 exposure dating. An age of about 20 ka for the Tyrendarra flow agreed with C-14 results; the Harman Valley flow from Mount Napier returned ages of 20 and 27 ka which show agreement within uncertainties with both Cl-36 and conventional C-14 ages; ages of 22 and 26 ka determined for Mount Porndon were much younger than the corresponding Cl-36 age of 59 ka, indicating some uncertainty over this age. Helium-3 analyses were also attempted but low concentrations relative to detection limits of the VG5400 noble gas mass spectrometer caused large uncertainties in the measurements, so the resulting exposure ages were considered to be less reliable.

The achievements of this study include the obtaining of meaningful exposure ages for such young basalts, and the reasonable agreement of these ages with C-14 and Cl-36 ages. These outcomes help to validate this dating technique, and continuing study in this area is important to further develop this approach.

Noble Gases in black bort diamonds from Jwaneng, Botswana

M. Honda, D. Phillips and J. W. Harris[2]

Research goals in noble gas geochemistry include understanding the structure of the Earth's mantle and the creation of a coherent model of its evolution. In this regard, noble gas compositions in mid-ocean-ridge basalts (MORBs) and in ocean island basalts (OIBs) such as from Loihi Seamount, Hawaii, and Iceland, have provided very useful information on the mantle. However, virtually all these data are from samples that are effectively of zero-age, and therefore, they only give information about the present composition of mantle noble gases. It is critically important to determine if there is any systematic variation of mantle noble gas composition with time. In particular, in relation to the current debate about mantle structure and evolution (e.g. two layered convection vs. whole mantle convection), information on noble gas compositions in ancient mantle can provide very strong constraints. If noble gas measurements are made on mantle-derived samples of different ages, these can be used to evaluate as to what degree, if any, the upper mantle had interacted with the lower mantle, and allow further refinement of models concerning mass transport, including volatiles, in the mantle. However, attempts to determine the noble gas composition of ancient mantle by analysis of older geological samples have, with few exceptions, been unsuccessful, in part owing to the lack of suitable samples.

Diamonds have unique characteristics that make them potentially very useful as sources of noble gases from the mantle. This is because: (1) diamonds have been demonstrated to retain significant amounts of mantle-derived noble gases, (2) most diamonds appear to be derived from 150 km to 200 km depth in the Earth, (3) diamonds cover a wide range of crystallization ages of between 0.6 and 3.5 billion years, (4) diamonds have been shown to have low diffusivities for noble gases so that they are highly retentive of noble gases, and (5) diamonds typically have suffered little interaction with crust or atmosphere, owing to their great crystallization depths and extremely rapid emplacement to shallow crustal levels in kimberlite and lamproite pipes. Thus, diamonds form under a wide range of conditions and compositions and provide a direct window into the ancient mantle. As such they are unique as sources of mantle-derived noble gases.

As a pilot study, this year we have undertaken noble gas analysis of four black bort diamonds from the Jwaneng kimberlite pipe, Botswana, by stepwise heating and vacuum crushing. From these diamond samples we found xenon isotope anomalies, relative to atmospheric, and the xenon data lie on the MORB correlation line when they are plotted on the $^{129}Xe/^{130}$ vs. $^{136}Xe/^{130}Xe$ diagram (Figure 6). In contrast, $^{40}Ar/^{36}Ar$ ratios in the samples are much lower than the MORB value of > 60,000. Neon isotopic ratios are close to atmospheric; there is no evidence for existence of MORB-like neon in the samples. These observations indicate that the MORB-like noble gas composition in the mantle source where the diamonds crystallized was overwhelmed by the lighter-gas enriched atmospheric noble gases. If this is correct, the question as to why elementally fractionated atmospheric noble gases have been introduced into the mantle source remains to be answered.

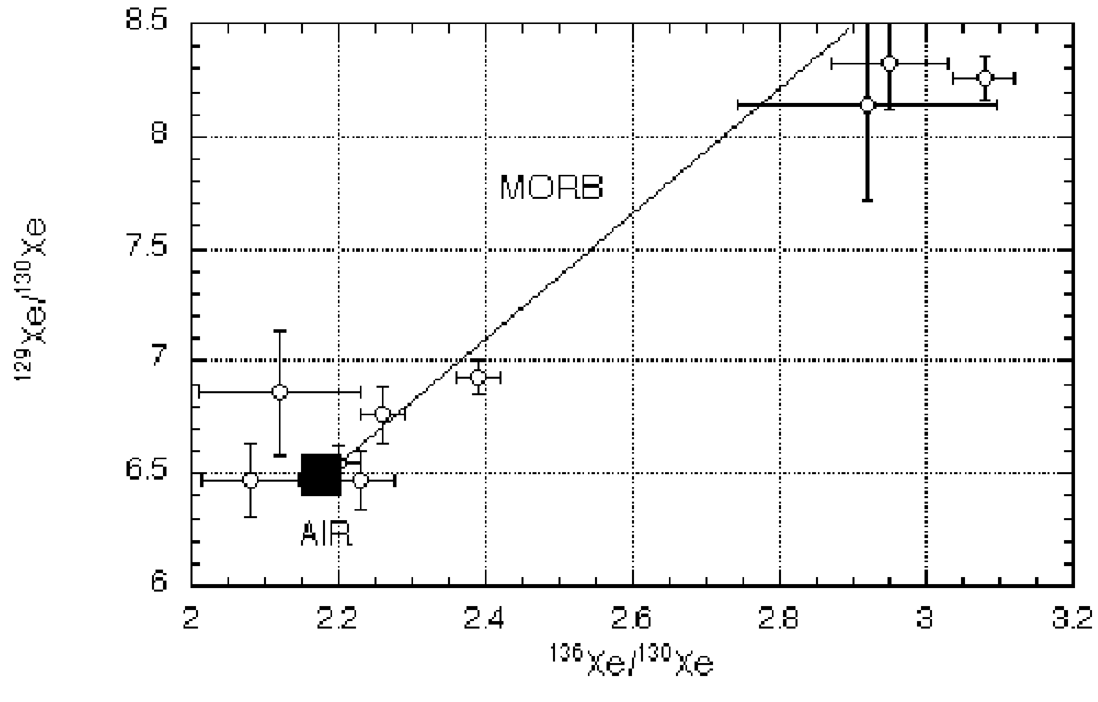

Figure 6: Plot of $^{129}Xe/^{130}$ versus $^{136}Xe/^{130}Xe$ observed in bort diamonds from the Jwaneng kimberlite, Botswana. The xenon data from the Jwaneng diamonds lie on the MORB correlation line determined by Kunz et al. (1998). Some of the Jwaneng diamonds show the highest xenon isotope anomalies, relative to atmospheric, so far observed from mantle-derived samples.

Thermal evidence for Early Cretaceous metamorphism in the Shyok suture zone and age of the Khardung volcanic rocks, Ladakh, India

W.J. Dunlap and R. Wysoczanski

The Dras island arc (NW India) is intruded by the Ladakh Batholith and rimmed along its southern margin by the Indus suture zone (Figure 7), which developed ca. 50 Ma at the start of the India-Asia collision. Along its northern margin the Ladakh Batholith intrudes the Shyok Formation, a series of folded and faulted metasedimentary and metavolcanic rocks that are thought to mark an older suture of Cretaceous age. Restoration of Miocene and younger strike-slip movement of ~150 km on the Karakoram fault suggests that the Shiquanhe suture in China was once continuous with the Shyok suture in Kohistan, but no geochronologic evidence for this connection has been demonstrated in the intervening region in Ladakh.

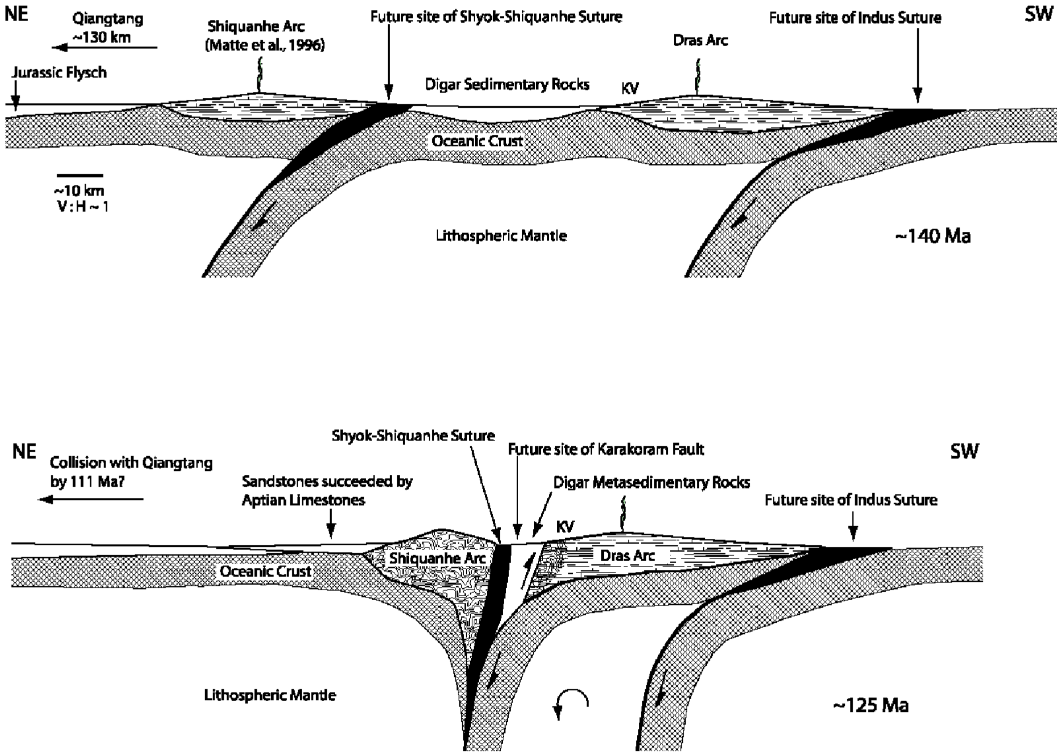

Figure 7: Tectonic cartoons, in cross-sectional form, of the region where the Karakoram fault zone has formed, in the vicinity of the Shyok-Shiquanhe and Indus suture zones. The figure is centred on the Ladakh sector of the Dras island arc. Schematic interpretive cross-sections of the region shown at ca. 140 Ma and 120 Ma (partially after Matte et al., 1996): acretionary prisms shown in black, KV is future site of deposition of Khardung Volcanic rocks from about 67.4 Ma to 60.5 Ma.

The Khardung calc-alkaline volcanic rocks were deposited unconformably on the Shyok Formation and are thought to be of Late Cretaceous age on the basis of fossils and regional correlations, yet no reliable radiometric ages have been published. New SHRIMP U/Pb ages on single zircon grains from Khardung volcanic rocks have confirmed that a ~7 km thick section was deposited between 67.4 Ma and 60.5 Ma. The underlying Shyok Formation has been difficult to date due to strong thermal overprinting related to both intrusion by the ca. 102-50 Ma Ladakh granites and movement on the younger Karakoram fault. Near Digar a series of metasedimentary and metavolcanic rocks in structural and metamorphic continuity with the Shyok Formation has experienced less thermal overprinting and a muscovite from a marble unit yields a $^{40}Ar/^{39}Ar$ maximum age ca. 124 Ma, which indicates that greenschist facies metamorphism took place prior to this time. The geochronological evidence is consistent with an Early Cretaceous age for the Shyok Formation, but it further suggests an Early Cretaceous metamorphic and deformational event related to convergence in an oceanic arc setting between the Dras island arc and the Shiquanhe island arc. This metamorphism was followed in the Late Cretaceous by suturing of the Dras island arc to the continental rocks of the Qiangtang block in westernmost Tibet along the Bangong suture.

GEOSCIENCE AUSTRALIA

Research staff from Geoscience Australia (GA, formerly Australian Geological Survey Organisation) currently work within RSES mostly on U-Pb SHRIMP geochronology. This capability was recently enhanced and diversified by expanding into Ar-Ar geochronology. The geochronologists principally work in the Minerals Division within a variety of regional projects spread over several provinces across Australia (Yilgarn, Gawler, Tanami-Arunta, Broken Hill, Mt Isa, and Tasmania). Andrew Cross has recently been appointed to GA as a SHRIMP geochronologist.

GA research is based on the longstanding relationship with the Research School, in particular within the Geochronology and Isotope Geochemistry Group. The scientific outcomes address GA's role in Minerals Promotions under the National Geoscience Agreement (NGA), Petroleum Promotions, and the Predictive Minerals Discovery Cooperative Research Centre (pmd*CRC). A selected range of research activities from these projects is described below.

$^{40}Ar/^{39}Ar$ geochronology

Geoff Fraser

In mid 2000, Geoscience Australia and the Northern Territory Geological Survey commenced a joint project investigating gold mineralisation in the Tanami Region in the context of the geological development of the North Australian Craton. The Tanami Region, located 600 km northwest of Alice Springs, is one of the most important new gold provinces in Australia. It straddles the Northern Territory-Western Australia borders along the southern margin of the Palaeoproterozoic North Australian Craton. The Tanami Region contains over 50 gold occurrences, including three established goldfields (Dead Bullock Soak, The Granites and

Tanami), as well as several significant gold prospects (Groundrush, Titania, Crusade, Coyote, Kookaburra). The region has produced 4.1 Moz Au and the remaining resource is ~8.4 Moz (260 t) Au. This figure is steadily growing as a result of extensive exploration.

Considerable uncertainty surrounds the age of gold mineralisation in the Tanami Region. Prior to the current study, understanding of its geological history held that a phase of major tectonism, referred to as the Tanami Event, occurred between ~1848 and 1825 Ma, immediately followed by rifting, volcanism and granite intrusion in the period 1825 to 1815 Ma. Several of the Tanami gold deposits exhibit a spatial relationship between mineralisation and granitoids, which has led to the proposal of a genetic link between granitoid intrusion and mineralisation; this proposal is currently being tested with both U-Pb and $^{40}Ar/^{39}Ar$ geochronology. In contrast, the Callie deposit does not appear to be spatially related to intrusives, raising questions about the role of granitoids in gold mineralising events.

Two samples of biotite from gold-bearing quartz veins in the Callie deposit yield $^{40}Ar/^{39}Ar$ age spectra in which the majority of the gas has apparent ages in the range ~1670 to 1720 Ma. Textural evidence clearly suggests that these biotites crystallised synchronously with the quartz veins in which they are hosted, which in turn are interpreted as synchronous with ore mineralisation. Evidence from fluid inclusions suggests vein formation temperatures were likely in the range 310 to 330°C, similar to typical biotite closure temperatures for Ar diffusion. It is, therefore, likely that the $^{40}Ar/^{39}Ar$ ages preserved in vein-biotite closely approximate the timing of vein crystallisation and associated ore formation.

The limited amount of $^{40}Ar/^{39}Ar$ data currently available is consistent with at least some of the gold mineralisation in the Tanami Region significantly post-dating the Tanami Event. In the case of the Callie Deposit the data are suggestive of a link with the Strangways Event, (1720 – 1730 Ma, Collins and Shaw, 1995) responsible for widespread deformation and metamorphism in the Arunta Province several hundred kilometres south-west of the Tanami Region. Work is currently in progress to further evaluate the possible influence of Strangways age tectonic activity in the Tanami region, and the extent to which this younger event may have been responsible for gold mineralisation.

The major building blocks of Tasmania, as identified by SHRIMP U-Pb zircon dating

L.P. Black[11, 12]

This study is part of Geoscience Australia's TASmanian Mapping Accord Project (TASMAP). Based on geological mapping and aeromagnetic images, pre-Late Carboniferous Tasmania has been divided into seven different strato-tectonic elements – King Island, Rocky Cape, Dundas, Sheffield, Tyennan, Adamsfield-Jubilee and Northeast Tasmania. Each of these is believed to have a geological history and internal structure that is at least partly different from those of the other elements. SHRIMP U-Pb dating is being used to better define the geological histories of these elements, in an attempt to understand the significance of their inter-relationships. It is hoped that this information will allow us to determine whether the elements have always been in their present juxtaposition, whether they are reassembled components of what was a single terrane, or whether they represent the aggregation of originally unrelated terranes.

Recent and current geochronological effort is largely concentrating on the dating of zircon from Devonian-Carboniferous granites, which occur in six of the seven elements. One facet of this exercise is to establish from comagmatic zircon the emplacement ages of those granites, and their inter-relationships. In addition, the zircon that these granites have brought up from depth provides evidence of the age of components within the underlying crust. Each of these datasets therefore helps better constrain different temporal and spatial aspects of the geological evolution of the individual elements.

The new emplacement ages readily demonstrate the relative resistance of the U-Pb system in zircon to isotopic resetting. Thus, previously obtained Rb-Sr and K-Ar mineral ages tend to be somewhat younger, even though emplacement was at a high crustal level where subsequent geological effects had been interpreted as being insignificant. There was a general westward progression of igneous activity over about 50 million years (from the Early Devonian to the earliest Carboniferous). The youngest granites in the Northeast Tasmania element are essentially coeval with the oldest granites in the western elements. Both I-and S-type granites (including Heemskirk red and Heemskirk white varieties) in the latter elements share a common age of about 360 Ma (though I-type granites also formed both earlier and later than this). Coeval I- and S-type activity also appears to have occurred in northeast Tasmania about 25 million years previously. A small pluton on King Island yields a relatively complex array of individual zircon ages, consistent with it representing a second attempt at granite formation at 350 Ma. Whereas elevated temperatures about 10 million years earlier had generated substantial granite production in what is now west coast Tasmania, that event is interpreted to have been insufficiently intense to have produced more than localised partial melting in the King Island element.

Magmatic activity within the Blue Tier Batholith (BTB) of Northeast Tasmania lasted for about 23 million years. Unlike some of the previously reported Rb-Sr ages, all of the U-Pb zircon ages are consistent with field observations, which reveal that the hornblende-biotite granodiorites are older than the biotite granites, which predate the alkali-feldspar granites. The new data support a previous Rb-Sr-based conclusion that the mineralised Lottah Granite is distinctly younger than the Poimena Granite, and that the two are genetically unrelated to each other. Much of the zircon in a mafic enclave from The Gardens Granodiorite is of the same age as the host intrusive, an important but not necessarily diagnostic observation for deciding between the competing models currently being used for magma genesis in the Lachlan Fold Belt. Igneous activity within the adjacent Scottsdale batholith commenced about 10 million years after granite emplacement was initiated in the BTB, and lasted for less than 10 million years.

A quantitative correlation between U-Pb zircon age and the presence or absence of regional foliation within Northeast Tasmania granites, allows that deformation to be dated at about 390 Ma.

To properly understand the significance of inherited zircon components within the Devonian – Carboniferous granites, it is important to know just what zircon components are present in the enclosing metasedimentary sequences. Consequently, representative samples (often of quartzitic composition) of those sequences were collected from each of the seven different strato-tectonic elements. All six of the westerly elements have strikingly similar zircon age arrays. Only the Tyennan sample, which yields no zircon younger than about 1680 Ma, has a signature that appears to be slightly different from the others; zircon at least as young as about 1400 Ma is present in the other westerly elements. This could signify that the Tyennan element is older than the others, although it might merely reflect a sampling bias. There is no other chronological evidence to potentially distinguish between the six more westerly units. A dominance of 1700-1800 Ma zircon indicates that all of these rocks were primarily derived from Palaeoproterozoic source terranes. For all but the Tyennan sample, deposition clearly occurred after about 1400 Ma, and the presence of ~1200 Ma zircon at some locations suggests an even younger limit.

The early Palaeozoic Mathinna Group of Northeast Tasmania yields a very different age pattern, one that is typical of the Lachlan Fold Belt on the Australian mainland. 500-600 Ma zircon is dominant, 800-1400 Ma zircon is less common, and minor quantities of older (including Archaean) zircon are also present.

Several useful observations can be made on the inherited zircon within the Devonian-Carboniferous granites. First, there is no evidence of different age components in the I- and S-type granites, though the former generally contain less inheritance. Neither is there any obvious difference between the inheritance in the granites from any of the 6 western elements, once again suggesting these elements are at least broadly comparable. In contrast, there is a most pronounced difference between that array and the inheritance within the Northeast Tasmania granites.

Importantly, the inheritance patterns for all the granites were found to closely mirror those of the rocks they intrude, to the extent that it is possible to tell whether or not a granite sample derives from Northeast Tasmania purely on its inherited zircon signature. Previously dated Neoproterozoic granites in western Tasmania have similar inheritance to their Devonian-Carboniferous counterparts, suggesting that the sources of the granites in that region did not significantly change over a 400 million year period. The data also indicate that those deep crustal source rocks in western Tasmania are considerably older than those in the northeast.

Terrane recognition in the southern Arunta Province, central Australia

J.C. Claoué-Long[11,12] and A. Cross[11,]

Geochronology effort in northern Australia has been strengthened this year by the Northern Territory Geological Survey (NTGS) funding the appointment of Andrew Cross to join Geoscience Australia's geochronology group. NTGS is remapping the fundamental geology of northern Australia and is using SHRIMP U-Pb geochronology intensively to identify and correlate major rock packages over very wide areas.

This year a major focus has been an area west of Alice Springs where NTGS geoscientists have been mapping Proterozoic rocks which are well exposed in a series of ranges in the southern Arunta Province. Extrapolation from existing mapping to the east had inferred that the Proterozoic units in the area are divided about a major east-west discontinuity, the Redbank Deformed Zone, thought to juxtapose the northern (older) and southern (younger) Arunta terranes. However, the extensive new dating coverage shows that the region is dominated by gneisses and granites formed in the period ca. 1680 – 1640 Ma, long after the ca. 1870-1770 Ma crust-forming events that created the Arunta terranes and the North Australian Craton to the north. Clearly this package of rocks developed independently from the main Arunta terrane, and the location of the structural junction with the North Australian Craton is yet to be determined.

Rich information about the evolution of the south Arunta terrane has come from the age spectra of detrital zircon grains in metasediments, which preserve the event histories of the source regions from which the sediments were derived. A quartzite in the north of the region contains detritus with a wide range of formation ages from the late Archaean to ca. 1765 Ma, clearly sourced from the North Australian Craton to the north. In contrast, another sediment near the southern limit of the exposed region appears to be the product of a sediment dispersal system off the craton, because its detrital zircons have a very different age spectrum lacking the Archaean and earlier Proterozoic components. The main correspondence with the North Australian Craton lies in the development of thin zircon overgrowths in rocks throughout the region at ca. 1590 Ma, the age of the major Chewings thermal event documented in the Reynolds Range to the north; this cryptic evidence provides a clue to the time when the south and north Arunta terranes became juxtaposed.

Three features distinguish this program of geochronology. First is the intensive use of modern isotopic dating in a relatively small region of Proterozoic rocks, enabling detailed correlations and event chronologies to be developed for the whole range of magmatic, metamorphic and sedimentary units. Second, the essential nature of microbeam sampling with SHRIMP in zircons that preserve 3 or even 4 stages of growth reflecting the prolonged episodic crystallisation of a complex magmatic and metamorphic terrane. Thirdly, close integration with the field and geophysical mapping process has converted structural observations into a dynamic interpretation of terrane evolution, and enabled mappers to enter their second field season armed with factual age correlations as a guide.

Ore Systems studies

Earthquakes, aftershocks and gold deposits

Stephen Cox

Mesothermal lode gold systems are a major global gold resource. This deposit type is particularly well-developed in Archaean greenstone sequences such as the Yilgarn Craton in Western Australia, the Superior Province in Canada, and in Zimbabwe. They also occur in some Phanerozoic terrains, such as the Bendigo zone of the Lachlan Fold Belt in Australia, the Meguma region of the Appalachian fold belt, and in Mesozoic to Tertiary circum-Pacific orogens. In these terrains, the deposits tend to form at depths of 8 km to 20 km in post-peak metamorphic regimes in fold and thrust belts.

Mesothermal gold deposits are typically located in low displacement faults and shear zones. Gold deposition within these structures requires large fluid fluxes to be loclised within them while they were deforming, typically at depths within the continental seismogenic regime, or just below the seismic-aseismic transition.

The large-scale factors controlling localisation of fluid flow to restricted parts of crustal-scale shear systems are not well understood. Two intriguing aspects of the development of mesothermal gold systems are:

- they tend to develop predominantly in low displacement faults and shear zones adjacent to to much larger shear zones, rather than in the major, crustal-scale shears;
- mesothermal gold deposits tend to form in clusters of deposits in localised domains along small segments of volumetrically more extensive shear systems.

By analogy with the distribution of slip in modern seismogenic systems, the low displacement faults which host mesothermal gold deposits are interpreted as aftershock structures whose development is related to stress changes driven by repeated large slip events on the nearby, crustal-scale shear systems. Local permeability enhancement in low displacement aftershock networks seems to play a key role in controlling the architecture of fluid flow and related gold deposition in crustal-scale hydrothermal systems.

Analysis of aftershock distributions in modern seismogenic systems indicate that aftershocks cluster in restricted regions around mainshock ruptures, and that this distribution is influenced by mainshock rupture geometry, slip directions and magnitude, and the orientations of the regional stress field. 3D finite element modelling (Coulomb stress transfer modelling, or STM) of stress changes associated with large earthquake rupture events indicate that aftershocks occur preferentially in domains where stress changes due to the mainshock have moved the stress state closer to failure.

ST modelling is being tested in the WA goldfields for its potential as a tool to predict the distribution of low displacement faults and shear zones, and associated domains of high fluid flux in ancient, gold-hosting shear systems. A more robust understanding of the factors which may lead to localisation of fluid flow and fluid-rock reaction within crustal-scale shear networks has application in the development of more advanced area selection strategies in exploration programs targetting mesothermal gold systems. A basic understanding of these processes will also find application for understanding the evolution of other epigenetic mineralisation styles whose development is also influenced by growth of fault and fracture systems (eg. some epithermal systems, magmatic-related systems, and Carlin systems).

The distribution of gold deposits near Kambalda, in Western Australia, is being used to examine potential relationships between slip on the crustal-scale Boulder-Lefroy fault system and the localisation of gold deposits in the St Ives goldfield. The distribution of aftershock domains is particularly sensitive to the location of rupture arrest sites on mainshock structures. Static stress changes have been modelled on the basis that mainshock arrest was repeatedly localised on a kilometre-scale contractional jog on the Playa Fault the St Ives area. The modelling indicates that strike-slip, reverse and normal faults located immediately north-west of the Victory jog are all brought closer to failure by sinistral mainshock on the Boulder-Lefroy-Playa system. A remarkable correlation exists between the modelled domain of increased Coulomb faulure stress and the distribution of gold deposits in the St Ives goldfield (Figure 1). Proximity to failure

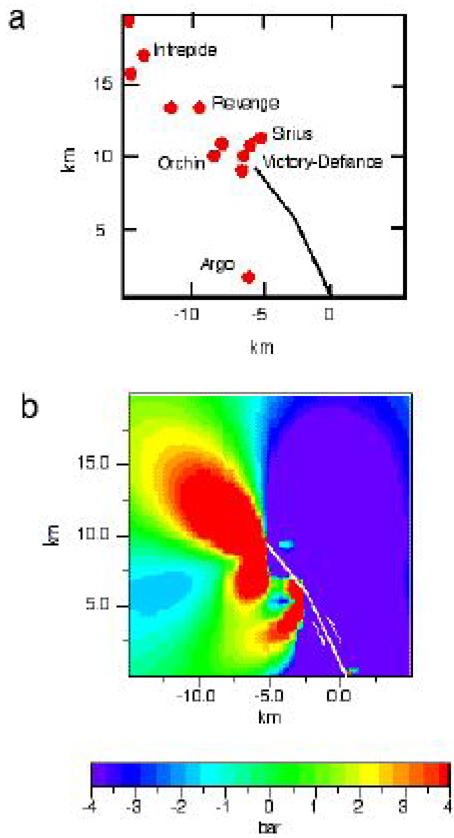

Figure 1. a. Map illustrating part of the area covered by stress transfer modelling in the St Ives goldfield, WA. Position of the modelled slip patch on the Boulder-Lefroy-Playa fault (BLPF) is indicated, together with locations of gold deposits and prospects. The modelled sinistral slip patch on the BLPF has a northern termination at the Victory complex, an imbricate thrust array in a contractional jog on the BLPF. b. Distribution of modelled Coulomb stress changes for strike-slip aftershock structures in the St Ives Goldfield. There is a strong correlation between gold occurrence and lobes of increase of Coulomb failure stress.

is significantly increased for distances up to 10 km north-west of the Victory jog.

Significantly, STM indicates that deposits hosted by low displacement "aftershock" faults can form in domains of Coulomb stress increase which are up to 15 km away from the structures which localise mainshock arrest. So stress transfer modelling indicates that exploration should not just focus on the immediate vicinity of jogs or bends on large displacement structures.

With the support of an ARC-Linkage grant, and in collaboration with a number of minerals industry partners, including The Australian Minerals Industry Research Association (AMIRA), the project will be expanded in 2002-2003 to undertake further detailed case studies elsewhere in the Yilgarn Craton in WA and in the Abitibi Belt in Canada.

Detrital Zircons in Appalachian rivers: a Record of the Grenvills Superorogeny?

Kenneth Eriksson, Ian Campbell, Michael Palin and Charlotte Allen

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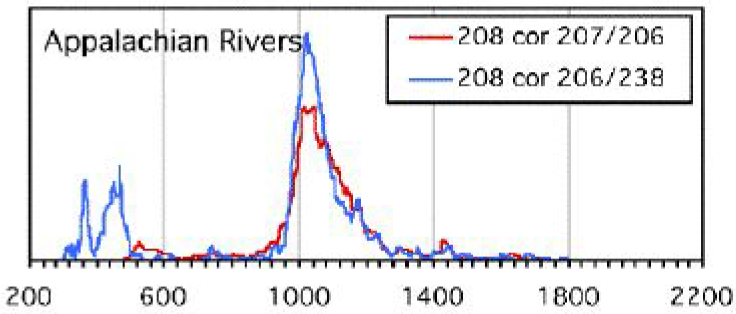
Detrital zircons from six rivers draining the Appalachian Mountains were dated using U-Pb isotopes measured by excimer laser ablation (ELA)-ICP-MS. Of the 905 grains analyzed, 726 (80%) yielded ages that were more than 90% concordant. The ages for 72% of the concordant zircons are between 950 and 1250 Ma and define a continuous Grenville tectono-magmatic event that peaked around 1030 Ma. Of the remaining zircons, 19% have Paleozoic ages corresponding with the Taconic (480-420 Ma) and Acadian (400-350 Ma) orogenies. The overwhelming dominance of Grenville-age zircons in rivers draining the Appalachian Mountains implies the former existence of a mountain belt whose detritus has dominated the sedimentary record for the past 1.0 billion years in eastern North America and beyond. In the zircon age spectra, which is a measure of the intensity of crustal melting associated with a tectono-magmatic event, the Grenville dwarfs the collective Paleozoic orogenies in the Appalachians by four times and therefore is called a "superorogeny".



New ELA-ICP-MS U-Pb zircon ages of the Alumbrera magmatic-hydrothermal system in the Farallon Negro district, NW Argentina

Anthony C. Harris , Charlotte M. Allen Rodney J. Holcombe2, Ian H. Campbell,
Scott E. Bryan2 and J. Michael Palin

The Late Miocene volcanic rocks of the Farallon Negro district, NW Argentina host a large porphyry Cu-Au deposit, Bajo de la Alumbrera (644.7Mt @ 0.5% Cu and 0.58g/t Au). ELA-ICP-MS U-Pb zircon ages have shown that the exposed magmatism in the volcanic complex lasted only 2.5. m.y. Cu-Au mineralisation occurred throughout this period, but the bulk of the mineralisation at Alumbrera was emplaced towards the end of magmatism. This differs from other porphyry districts where ore is emplaced at the culmination of a protracted history of tens of millions of years (e.g. El Salvador and Potrerillos districts, Chile).

Intrusions within the Alumbrera porphyry Cu-Au deposit are multiphased occurring at two discrete intervals. The earliest at 8 Ma (7.99±0.12 Ma) is believed to be associated with minor Cu-Au disseminations while the later intrusions at 7 Ma (7.12±0.04 Ma) are emplaced synchronously with the bulk of the mineralisation. Comparison of these intrusion ages with previously published $^{40}Ar/^{39}Ar$ ages for potassic and phyllic alteration (Sasso and Clark, 1998, Society of Economic Geologists Newsletter, v. 34) shows that the magmatic-hydrothermal system was possibly sustained for as much as 2 to 3 m.y. Thermal collapse of the system may have occurred as much as a million years after the final intrusion. It is commonly reported that porphyry-related hydrothermal systems should cool in less than 100,000 yr. These results redirect attention away from the porphyritic intrusions being the principal heat source and focuses on the possible role of the much larger underlying pluton in driving the magmatic-hydrothermal system.

Origin and composition of ore-forming fluids in the giant Golden Mile gold deposit, Kalgoorlie Western Australia

C.J.Heath, I.H. Campbell, M.Palin and W.J. Dunlap

Australia is the worldÕs third largest gold producer, and the Golden Mile AustraliaÕs most significant gold deposit. Despite producing more gold both historically and currently than any other deposit in the country, the Golden Mile remains geologically poorly understood. Located in the Archaean Yilgarn craton of Western Australia, the Golden Mile is fundamentally different in size, metal budget, structure and mineralogy from the many other lode gold deposits in this highly mineralised region. The aim of this study is to investigate the origin and composition of the ore bearing fluids responsible for producing this unique gold deposit.

Recent work at the Research School of Earth Sciences has focused on stable isotope and geochronology studies of the Golden Mile. Fifteen key samples spatially distributed throughout the deposit were selected for this purpose. Ten of the samples consist of vanadium sericite from tellurian rich ores, and 5 consist of sericite from sulphurous auriferous rich ores. Prior to mineral separation thin sections were cut and analysed by Electron Microprobe to determine major element geochemistry. Vanadium content of the V-sericites varied from 0.78 - 5.32 Wt %, and potassium from 6.75 - 8.41Wt %. Mineral separation was undertaken using a centrifuge heavy liquid technique. Average grainsize of the sericite separates obtained from the 15 samples was 26 mm ± 11 mm 1s, with purity at approximately 98% sericite. Quartz and pyrite were also separated from the whole rock samples at the same time as the sericite.

Previous geochronology at the Golden Mile remains ambiguous. Kent and McDougall (1995) dated two muscovite samples using the $^{40}Ar/^{39}Ar$ method, giving ages of 2628 ± 13 Ma, and 2630 ± 13 Ma for auriferous mineralisation. Kent and McDougall (1995) suggested that the Golden Mile samples should be considered minimum estimates due to evidence of hydrothermal activity post Au mineralisation, and that two samples cannot be considered truly representative of such a huge mineral deposit. Witt et al., (1996) proposed that the muscovite dated by Kent and McDougall (1995) may not represent the mineralisation event, and that the muscovite is potentially reset. For this reason the V-sericite samples analysed by this study are ideal candidates for $^{40}Ar/^{39}Ar$ geochronology, as they are directly related to the gold mineralisation event at the Golden Mile. Prior to $^{40}Ar/^{39}Ar$ analysis the samples were analysed using the K/Ar method to test for sample recoil during the 48 day irradiation period.

The fifteen sericite samples used for $^{40}Ar/^{39}Ar$ geochronology were also analysed for stable isotopes. Stable isotope analysis was employed to determine the source of the ore bearing fluid. Preliminary deuterium / hydrogen stable isotope analysis were undertaken on a subset of the 15 samples at the United States Geological Survey in Denver, Colorado. It is expected that the remaining D/H analysis will be completed in early 2002. Likewise, the 15 samples will be analysed for oxygen stable isotopes in early 2002. Quartz - sericite mineral pair $d^{18}O$ data will be used to provide temperature constraints on lode formation. When coupled with the D/H data, the oxygen data will also be used to help predict the source of the ore bearing fluid.

The final component of this study of the ore bearing fluid in the Golden Mile will consist of fluid inclusion analysis. Fluid inclusions plates have been constructed from the 15 key samples, as well as others. Proposed fluid inclusion studies include paragenetic, microthermometric, geobarometric and compositional analysis. As well as conventional analytical techniques, such as heating freezing, it is proposed that an infra-red and laser raman microprobe study be undertaken on the fluid inclusions.

Major and trace element geochemistry of the Los Picos-Fortuna/Pajonal-El Abra batholith: implications for magma evolution associated with porphyry copper mineralization

Julian Ballard, Ian Campbell, Joerg Hermann and Alejandro Faunes

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The Los Picos-Fortuna/Pajonal-El Abra batholith is a composite system of Eocene calc-alkaline intrusions that is associated with porphyry copper mineralization at El Abra in northern Chile. Major and trace element data from the intrusions have been used to identify the principal controls on the magmatic evolution of the batholith. Linear major element variations show that differentiation was driven principally by fractional crystallisation of plagioclase and variable amounts of a mafic phase such as pyroxene and/or amphibole. Trace element data support this hypothesis but also provide evidence for two end-member differentiation trends, a high water (HW) trend in which amphibole replaces pyroxene early in the fractionation sequence, and a low water (LW) trend in which the replacement of pyroxene occurs late.

A study of Ce(IV)/Ce(III) in zircon has shown that intrusions belonging to the HW trend crystallised from more oxidised magmas than those belonging to the LW trend. The early appearance of amphibole in the HW intrusions results in the progressive depletion of the HREE with increased fractionation. The LW intrusions crystallised from drier, more reduced magmas, with plagioclase crystallisation being more important and amphibole crystallisation being less important. As a consequence, the evolving LW magma developed a strong negative Eu-anomaly, not seen in the HW trend, but only minor HREE depletion. Porphyry copper mineralization is associated with the El Abra mine porphyry, the youngest, most oxidised and most fractionated member of the HW trend. The HW and LW magmas are thought to have evolved together in a deep, long-lived, zoned magma chamber that underlay the Los Picos-Fortuna/Pajonal-El Abra batholith, as shown schematically in figure 1.

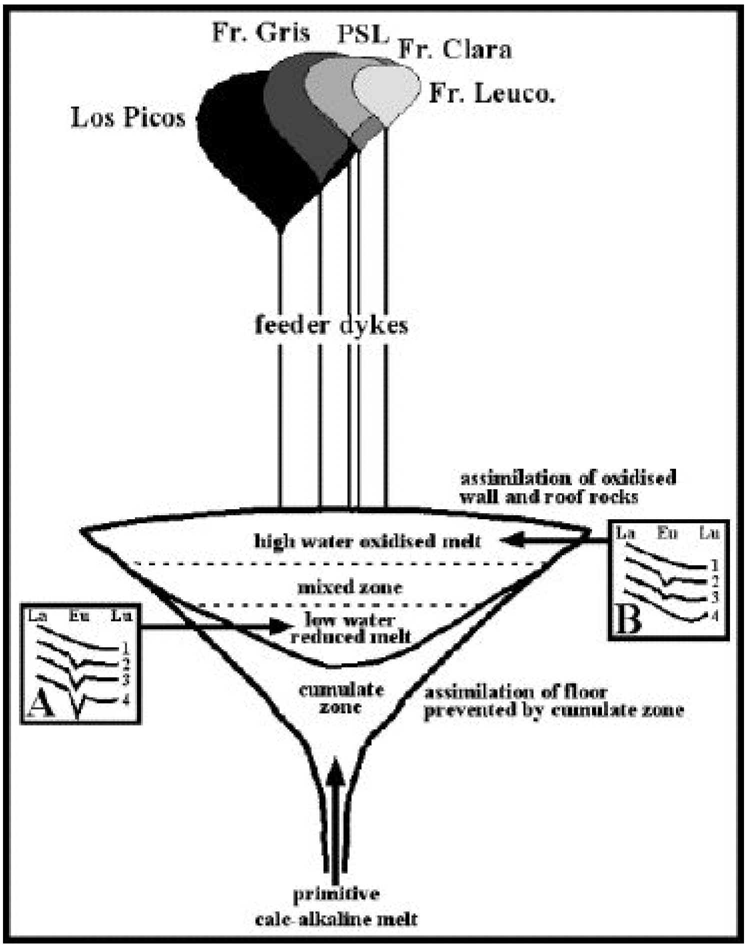

Figure 1: A schematic cross-section of the Los Picos-Fortuna section of the Los Picos-Fortuna/Pajonal-El Abra batholith, showing a zoned magma chamber deep in the crust that is believed to underlie the batholith and to be responsible for the developments of the HW and LW trends. The high water/low density (HW) magma overlies the drier/high density (LW) magma. The LW magmas develop a pronounced negative Eu-anomaly during differentiation and a weak concave HREE pattern, whereas the HW magmas lose their weak negative Eu-anomaly and develop a strong Er-centred HREE concave pattern.

Mafic Underplating in Compressive Volcanic Arc Segments and Cyclic Ramping of Volatile Concentrations in Long-lived (3-8 Myr) Magmatic Reservoirs : Drivers of Metallogenic Fertility

Bruce Rohrlack, Robert Loucks and Michael Palin

Magmatic volatiles such as water, sulphur and chlorine are essential components of ore-forming fluids in porphyry copper and high-sulphidation epithermal copper-gold deposits in volcanic arcs. A spatial and temporal association of magmatic-hydrothermal Cu-Au deposits and compressive stress is evident in many subduction-related volcanic arcs. The clustering of ore-forming episodes in time and space is a broader expression of the effect of tectonic stress on depth of magma chamber entrapment and depth-related chemical trends of magmatic differentiation. We use tectonic/palinspastic reconstructions to constrain the average rate of crustal shortening (~ 18-19 mm year) during the past 7 Myr in southern Mindanao, in the vicinity of the Tampakan stratovolcano complex. The high Al content of hornblende phenocrysts in the Tampakan dacites constrains most of the magmatic differentiation to occur at ~ 5-6 kbars and 18.6-22.3 km depth in a magma chamber near the base of the crust. Volcanic-hosted metamorphic xenoliths from monogenetic volcanoes which have sampled thermally undisturbed country-rock from the base of the crust in other arcs, indicate that average temperatures at the base of the arc crust are typically 750 ± 75°C (hotter than the wet granite solidus). Hence magma chambers trapped in the lower crustal regime tend to cool slowly and to last long enough to undergo multiple replenishments of mantle-derived magma during the course of cooling, differentiation by fractional crystallisation, and intermittent tapping of residual melts from the top of the chamber to feed shallower chambers or volcanic eruptions.

We have used zircon geochronology to parameterise time series in chemical compositions of volcanic whole-rocks and of phenocrysts. The latter are, in turn, used to obtain time series in calculated temperature, oxygen fugacity, and wt% H_2O dissolved in the magma, as described by Rohrlach and Loucks (RSES Annual Report, 2000). The time series reveal several major cycles of magma replenishment and differentiation over a period of ~ 8 Myr, as shown in the accompanying figure. This reservoir longevity and continuity in magmatic evolution over several million years, afforded by the hot, deep environment of entrapment, facilitates cyclic build-up of incompatible magmatic volatile components in residual melt fractions over time intervals which are an order of magnitude longer than those in shallow upper-crustal sub-volcanic magma chambers.

Ratios of incompatible on compatible elements in detrital zircons of Late Miocene to Recent age on the flanks of the Tampakan stratovolcano reveal cyclical increases in incompatible element concentrations within the melts from which the zircons crystallised (Figure 4b). The cyclic advancement and retreat of these element ratios is superimposed on a long-term trend to highly evolved incompatible-element-rich compositions. During this 8 million year period, erupted magmas progressively became more fractionated, as defined by increasing silica content of the melts (Figure 4a). They became increasingly water-rich as melts progressed from ~ 2.9 wt/% H_2O to ~ 7.3 wt/% H_2O (Figure 4c), and became progressively more chlorine-rich as defined by chlorine contents recorded in apatite phenocrysts. Modelling of major-, trace- and rare-earth-element trends in Late Miocene to Recent igneous rock samples from the Tampakan district reveal several magmatic cycles wherein hornblende became increasingly dominant within each fractionating sequence, with hornblende supplanting pyroxene in the crystallisation sequence at progressively earlier intervals in successive magmatic cycles. This Late Miocene to Recent period of increasing volatile contents in the long-lived, Moho-level magma reservoir, sampled by successive stratovolcanoes via a series of small and transient upper crustal chambers, is coeval with a 7 million year episode in which the amount of plate convergence in excess of that not accommodated by subduction was partitioned into compressive intra-crustal folding, thrusting and thickening (Figure 4d).

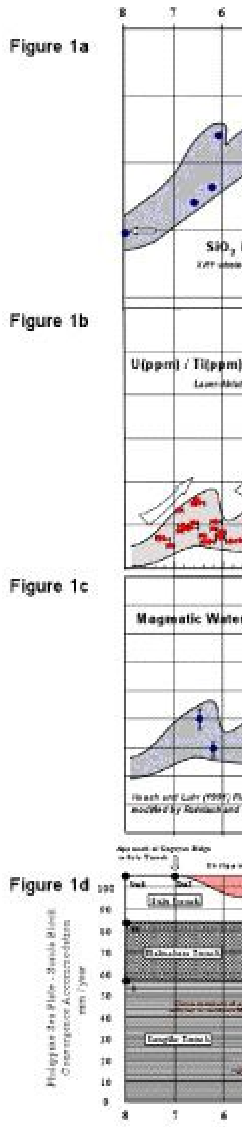

Figure 4: (a) Time series ev
from the Tampakan stratov

These geochemical data are interpreted to reflect a long-term build-up of magmatic volatile components within a sub-crustal magma chamber over several million years. Multiple replenishments of primitive magma from the mantle added successive aliquots of volatile components such as water, sulphur and chlorine, to a long-lived magmatic reservoir in which the horizontal compressive stress in the lower crust inhibits escape of buoyant volatile-enriched residual melt fractions by sub-vertical dyke propagation from the deep reservoir. In that case, the residual melt fraction from a cycle of magmatic differentiation can pass on its accumulation of incompatible components (H_2O, Cl, SO_3) to the next generation of replenishing mantle-derived magma. Through a succession of such differentiation and replenishment cycles, the residual melts may eventually ramp up to exceptional concentrations of incompatibles. High metallogenic fertility is strongly facilitated by high concentrations in magmatic chlorine and water. Because H_2O solubility in silicate melts is chiefly a function of pressure, the more H_2O-rich a magma is, the deeper it starts exsolving a magmatic hydrothermal fluid. Aqueous fluids exsolved deeper are denser and have much higher partition coefficients of metal-chloride salts into the exsolving fluid, so the metal scavenging efficiency of fluids from parental melt is expected to increase with depth of exsolution.

whole-rock XRF analyses.
^{206}Pb using LA-ICPMS on
hornblende and biotite. (b)
in detrital zircons from the
ablation ICP-MS. (c) Magn
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Zircon chronochemistry by excimer laser ablation ICP-MS

Michael Palin, Ian Campbell and Charlotte Allen

The accessory mineral zircon ($ZrSiO_4$) contains a wealth of petrogenetic information for igneous rocks of intermediate to felsic composition and provenance constraints for siliciclastic sediments. Excimer laser ablation (ELA)-ICP-MS permits in situ (³15 micrometer spot) measurement of U-Th-Pb isotopes and selected major and trace elements in zircon. Instrumental mass bias in the quadrupole ICP-MS and elemental fractionation induced during ablation are corrected for by reference to zircon and glass standards, a robust procedure because of reproducible ablation by the ArF excimer laser.

The capability of ELA-ICP-MS for simultaneous collection of U-Th-Pb isotope and major and trace element data has been used to examine evolution of Cenozoic igneous suites associated with major Cu±Au deposits in Chile, the Philippines, and Indonesia. Using a lattice-strain model of mineral-melt trace element partitioning, the REE contents of zircon can provide estimates of relative magmatic oxidation state. Shallow intrusions spatially associated with ore display exhibit anomalously high oxidation states and in some cases are preceded by oxidation trends in older units. These patterns can be explained by the interdependent relations of oxidation state, sulfur speciation and solubility, and metal partitioning in silicate magmas.

Rapid analysis by ELA-ICP-MS (2 min/spot) enables studies of detrital zircons on scales previously unrealized. These capabilities have been used in studies of modern and ancient detrital zircons from a variety of geologic settings including: large rivers in North and South America, India and China; Neogene volcanics in the Asia-Pacific region; Neoproterozoic through Paleozoic sandstones of the Appalachians; and Proterozoic conglomerate and Archean quartzite in Brazil. By analyzing large numbers of grains (minimum n = 60, typical n = 100) for both their age and chemical composition, tighter constraints can be placed on the provenance of these siliciclastic materials.

Detrital zircon record of Paleozoic orogeny in eastern North America

Michael Palin, Ian Campbell, Kenneth Eriksson , and Charlotte Allen

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Zircon grows mainly from melts of intermediate to felsic composition derived from the crust. In general, the more heat supplied to the crust during an orogenic event, the greater the amount of melting and the more zircon produced. Although crustal melting behavior can be influenced by previous thermal history, zircon productivity is a first-order measure of the thermal perturbation associated with an orogeny. Detrital zircons provide a robust record of past orogenic events, in some cases preserving samples of crystalline rock no longer present or exposed.

In the central and southern Appalachian Mountains of eastern North America, the vast majority of detrital zircons from modern river sands and Neoproterozoic through late Paleozoic sandstones yield Grenville ages (1250-950 Ma). Although detrital zircons with Paleozoic ages are rare (<1%) in the sandstones, they comprise about 17% of those in the river sands. These grains display age peaks at 420-500 Ma and 350-380 Ma which correspond well with the Taconic and Acadian orogenies (Fig. 5). The low Th/U ratios and narrow age distribution of the Acadian zircons may reflect a metamorphic origin in contrast to the magmatic character of Taconic zircons. The scarcity of detrital zircons with Alleghenian ages is unexpected in light of the widespread occurrence of late Paleozoic plutons in the southern Appalachians and indicates a possible sampling bias related to erosional base level. Nonetheless, the Alleghenian orogeny must have involved much less new zircon production than the Grenville suggesting that the two collisional events were fundamentally different with respect to the extent of crustal melting. The lack of Paleoproterozoic zircons of South American or African heritage is equally surprising considering that the accreted Carolina terrane originated from margin of the Amazonian Craton and that Alleghenian collision took place with Africa.

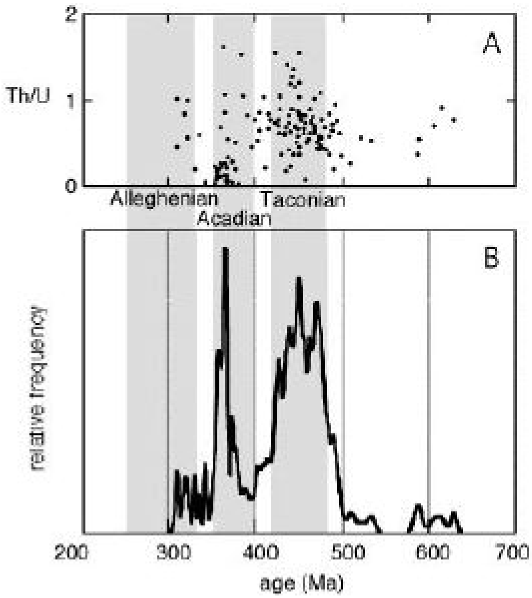

Figure 5: Th/U ratios (A) and age spectra (B) of modern detrital zircons with Neoproterozoic/Paleozoic ages collected from rivers draining the central and southern Appalachian Mountains. Also shown are age ranges of the 3 Paleozic orogenies in the Appalachains: Taconic (480-420 Ma), Acadian (400-350 Ma), and Alleghenian (330-250 Ma).

Platinum group element geochemistry of the intrusive andesite of the Kelian Region, East Kalimantan, Indonesia: implications for the genesis of the Kelian Gold Deposit

Bambang Setiabudi, Ian Campbell, Candace Martin and Charlotte Allen

The Late Miocene volcanic rocks of the Farallon Negro district, NW Argentina host a large porphyry Cu-Au deposit, Bajo de la Alumbrera (644.7Mt @ 0.5% Cu and 0.58g/t Au). ELA-ICP-MS U-Pb zircon ages have shown that the exposed magmatism in the volcanic complex lasted only 2.5. m.y. Cu-Au mineralisation occurred throughout this period, but the bulk of the mineralisation at Alumbrera was emplaced towards the end of magmatism. This differs from other porphyry districts where ore is emplaced at the culmination of a protracted history of tens of millions of years (e.g. El Salvador and Potrerillos districts, Chile).

Intrusions within the Alumbrera porphyry Cu-Au deposit are multiphased occurring at two discrete intervals. The earliest at 8 Ma (7.99±0.12 Ma) is believed to be associated with minor Cu-Au disseminations while the later intrusions at 7 Ma (7.12±0.04 Ma) are emplaced synchronously with the bulk of the mineralisation. Comparison of these intrusion ages with previously published 40Ar/39Ar ages for potassic and phyllic alteration (Sasso and Clark, 1998, Society of Economic Geologists Newsletter, v. 34) shows that the magmatic-hydrothermal system was possibly sustained for as much as 2 to 3 m.y. Thermal collapse of the system may have occurred as much as a million years after the final intrusion. It is commonly reported that porphyry-related hydrothermal systems should cool in less than 100,000 yr. These results redirect attention away from the porphyritic intrusions being the principal heat source and focuses on the possible role of the much larger underlying pluton in driving the magmatic-hydrothermal system.

Coupled andesitic and rhyolitic magmatism in the Kelian gold deposit, Indonesia

Bambang Setiabudi, Michael Palin and Ian Campbell

The Kelian gold deposit is located within the central volcanic arc of the island of Kalimantan in Indonesia. Hydrothermal activity produced extensive brecciation, alteration and gold and base metal mineralisation predominantly hosted by a body of andesite porphyry. The absolute ages of igneous rocks in the mine area are not known, nor has it been established whether the gold mineralisation was formed by a hydrothermal system driven by the andesitic magmatism or by processes related to phreatomagmatic activity associated with a nearby maar-diatreme complex .

The andesite porphyry at Kelian displays 3 zircon age populations as measured by ELA-ICP-MS: 21.2 ± 0.3 Ma, 20.5 ± 0.1 Ma and 19.7 ± 0.1 Ma. The youngest of these is interpreted to be the emplacement age and the older ages to represent earlier episodes of zircon crystallisation in the andesite source region. The maar-diatreme complex is intruded by rhyolite porphyry that also yielded 3 age populations that are shifted slightly relative to those of the andesite: 20.8 ± 0.1 Ma, 20.0 ± 0.2 Ma and 19.3 ± 0.1 Ma (Fig. 6a). By the same line of reasoning, the youngest zircon population is interpreted as the emplacement age of the rhyolite and the older two populations to represent prior episodes of zircon growth. Taken together, the zircon dates indicate alternating cycles of andesitic and rhyolitic magmatism. Trace element compositions of the andesitic and rhyolitic zircons do not overlap (Fig. 6b), limiting mixing during 2+ m.y. of magmatic activity. These observations, combined with the spatial proximity of the volcanic centers, require physically distinct long-lived andesite and rhyolite magma source regions, perhaps coupled in their responses to periodic emplacement of primitive magma into the underlying arc crust.

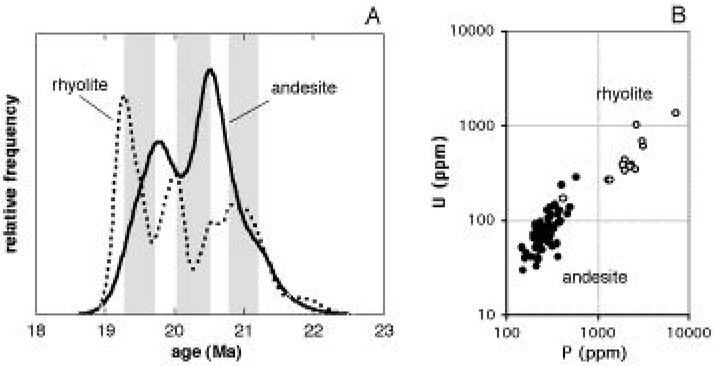

Figure 6: Age spectra (A) and trace element compositions (B) of zircons in andesite and rhyolite porphyries from the Kelian gold deposit.

Ore forming fluids of the Laverton District, Yilgarn Craton, Westen Australia: source, gold precipitation mechanism(s) and extent of alteration

Amanda Stoltze and Ian Campbell

Greenstone-hosted mesothermal gold deposits of the Archaean Yilgarn Craton, Western Australia, have yielded the majority of AustraliaÕs gold. The Laverton region, within the Yilgarn Craton, is Australia's second largest gold producing district and host to the Sunrise Dam, Granny Smith and Wallaby deposits. The gold deposits are structurally controlled, but are hosted by a variety of lithologies; granodiorite at Granny Smith, conglomerate of dominantly basaltic composition at Wallaby, and andesitic volcaniclastic and banded iron formation at Sunrise Dam. Mineralisation in banded iron formation can be explained due to the interaction of ore fluids with the iron-rich wall rock causing precipitation of gold, but this process can not be responsible for mineralisation in iron-poor lithologies. Another possible gold precipitation mechanism is the mixing of two fluids (ore fluid with a second fluid from a different source), which will be investigated using stable isotopes.

The emphasis of this study will be the recently developed Wallaby deposit. Here a suit of monzonite-syenite-carbonatite dykes is concentrated in the centre of a steeply plunging pipe of magnetite-actinolite alteration that hosts the majority of the cross-cutting mineralisation. The relationship between the intrusive suite, the magnetite-actinolite alteration pipe and the overprinting ore alteration will be investigated using stable isotopes and trace element geochemistry. Ore fluid characteristics and the fluid source (metamorphic, magmatic, connate, seawater or mantle source) will also be determined using fluid inclusions and stable isotopes (H, O, C, N, B). The extent and composition of geochemical changes associated with alteration events will be identified by trace element geochemistry using laser ablation ICP-MS analysis.

Experimental Petrology Group

Annual Report 2001

Introduction

The Petrochemistry and Experimental Petrology (P&EP) Group uses a laboratory-based experimental approach combined with field observations to study the Earth, its origin, evolution and mineral wealth. The group operates a wide range of experimental apparatuses for generating the high temperatures and pressures that are needed to reproduce the natural conditions within the Earth. The equipment includes: high temperature furnaces capable of reaching 1800ºC, several of which are equipped for precise control of oxygen and sulfur fugacities by gas mixing; ten solid-media piston-cylinder devices for generating pressures to 6 GPa and temperatures in excess of 2000ºC, some of which are large-capacity devices capable of synthesising relatively large volumes of high pressure phases for detailed mineralogical studies; a multi-anvil apparatus, which can achieve pressures of 26 GPa; and, through collaboration with the Department of Geology, the Faculties, a well-equipped hydrothermal laboratory. These high-temperature, high-pressure apparatuses are complimented by an array of microbeam analytical techniques, including electron microprobe, ion microprobe, laser-ablation ICP-MS, FTIR spectroscopy and visible-UV spectroscopy. The group has just taken delivery of a new electron microprobe, a Cameca SX100, which will be operated in collaboration with a consortium of other Canberra users. It is expected that this new instrument will become operational in February 2002. As well as providing better imaging capabilities and more stable operation (hence accuracy), the new instrument will enable quantitative element mapping. It will replace our ageing Cameca Camebax, which is now entering its nineteenth year of operation, having obtained over 300,000 quantitative analyses – an incontrovertible testament to the importance of the electron microprobe to the group's activities over the years.

Most of the group's activities are concentrated into five areas: 1) Origin of the Earth and core formation; 2) Phase equilibria, including melting relations, in mantle systems; 3) Phase equilibria related to crustal evolution and ore deposits; 4) Physics of melting and melt extraction; and 5) Spectroscopic and thermodynamic property measurements on minerals and silicate melts. The latter area of research is undertaken in the belief that better understanding of large-scale geological processes often requires detailed, fundamental knowledge of the behaviour of minerals at the atomic scale.

This year saw the formal retirement of Professor D. Green, who will continue with the group in an emeritus role. Much of the strength of the group derives from its Visiting Fellows, who bring an immense amount of intellectual diversity to the group's activities. This year, the group has benefitted from extended stays by Dr G. Witt-Eickschen of the University of Cologne, who used the laser-ablation ICP-MS to study mantle xenoliths of the Eifel graben; Dr A. Glikson, formerly of AGSO, whose interests centre around asteroid and comet impacts and early crustal evolution; Dr J.-P. Li, of the Chinese Academy of Sciences, Guangzhou, who is investigating the origin of the high-K magmas of the Tibetan Plateau; and Dr S. Redfern of Cambridge University, who is working on the relationships between the crystal structure of minerals and their physical and thermodynamic properties. During the year Dr Taylor resigned his Research Fellowship to concentrate on his diamond exploration activities.

The group continues to develop its use of X-ray absorption spectroscopy (XANES) at the Australian National Beamline Facility at Tsukuba, Japan, to characterise the chemical environment and oxidation states of trace elements in minerals and silicate melts. Drs Berry and O'Neill extended their previous work on Cr oxidation states in Fe-free systems by studying the effect of Fe. This necessitated developments in two directions: firstly, the XANES spectra of a series of glasses with variable Fe^{2+}/Fe^{3+} ratios have been studied, in order to develop XANES as a general analytical method for Fe oxidation states in silicate glasses. The calibration glasses were previously characterized by Mössbauer spectroscopy in collaboration with Dr Jayasuriya and Prof Campbell of the School of Physics, ADFA. Secondly, in-situ measurements of both Cr and Fe XANES spectra have been obtained at temperatures to 1500ºC and controlled oxygen fugacity, using a furnace designed and built by Mr M. Shelley.

This spectroscopic work on silicate melts compliments the thermodynamic and phase equilibrium studies carried out by the group. Dr H. O'Neill and co-workers have measured the solubilities of several siderophile elements (Fe, Ni, Co, Mo, and W) in silicate melts as a function of melt composition, and are now using these data to work out generalised models for the activity coefficients of different groups of trace elements in silicate melts. Mr A. Hack and Dr J. Mavrogenes are investigating Cu solubilities in supercritical fluids to high temperatures and pressures, necessitating the development of several new experimental techniques.

Dr J. Hermann and Prof D. Green continue their investigation of phase relations applicable to ultra-high-pressure metamorphic terrains. Drs J. Mavrogenes and H. O'Neill have extended their experimental work on the properties of sulfur in silicate melts by studying very oxidizing conditions, under which the sulfur dissolves as sulfate not sulfide. The effects of fO_2, fSO_2, melt composition and temperature have been quantified in this regime from experiments at atmospheric pressure; and these have been complimented by experiments at high pressure on the solubility of anhydrite ($CaSO_4$). Dr U. Faul has been investigating the constraints from U-series data on melt transport beneath mid-ocean ridges and ocean island basalts. Dr S. Kesson continues to develop expertise for the group in the field of powder X-ray diffraction using the Rietveld method, which technique is becoming an increasingly important part of the group's activities.

The group contains four PhD students, Messrs Hack, Xi and Sommacal, and Ms L. Glass. Earlier in the year, Dr C. Magee successfully completed and defended his thesis on the origin of carbonado. Mr Hack is studying metal solubility in high temperature fluids, using synthetic fluid inclusions analysed by the LA-ICP-MS. Ms L. Glass is writing up her study of what were formerly named the Antrim Plateau basalts of the Northern Territory and other related basalts of northern Australia; the stratigraphic part of her work has led her to suggest a new name, the Kalkarinji flood basalt province. Mr Sommacal, in conjunction with Dr M. Sambridge, is developing new computational ways to handle the thermodynamics of compositionally complex, multisite solid solutions, with the immediate aim of developing a thermodynamic model for phase relations in the upper mantle. Mr X. Liu has almost completed an experimental investigation of the effects of Cr_2O_3, K_2O and H_2O on mantle melting in the simplified model mantle system CaO-MgO-Al_2O_3-SiO_2 at 1.1 GPa.

Of the technical staff, Mr M. Shelley has constructed a high-temperature furnace for X-ray absorption spectroscopy in silicate melts under controlled CO/CO_2 atmosphere to 1500ºC, and has built a new sample cell for the laser-ablation ICP-MS apparatus. Mr W. Hibberson and Mr D. Scott have continued the development of the 6-7 GPa piston-cylinder apparatus, and have been extensively engaged in sample synthesis for many of the group's activities. Mr N. Ware maintains and operates the group's present aging electron microprobe and has been busy preparing the ground for the new Cameca SX100. Sadly, Mr J. Derlacki was forced to resign through ill health this year, and died shortly after. His quiet competence will be greatly missed.

Research Activities

Free energy of formation of zircon, hafnon and fayalite (revisited)

H.StC. O'Neill

The free energy of formation of zircon ($ZrSiO_4$) from its oxides was determined between 1100 and 1300 K by an electrochemical method, in which values of μO_2 defined by the two assemblages Fe_2SiO_4-Fe-SiO_2(qz) and Fe_2SiO_4-Fe-ZrO_2-$ZrSiO_4$ were measured using oxygen concentration cells with calcia-stabilized zirconia solid electrolytes. The difference in μO_2 corresponds to the reaction ZrO_2+SiO_2(qz)=$ZrSiO_4$. The results, when analysed using calorimetric data for the entropies and high-temperature heat capacities of $ZrSiO_4$, ZrO_2 and SiO_2(qz), yields $\mathrm{Delta}_{f,ox}\,H°_{298K}$ =—24.0±0.2 kJ/mol for $ZrSiO_4$, in good agreement with the calorimetric value of Ellison and Navrotsky (1992). Assuming a temperature of 1430 K for the martensitic phase transition between the monoclinic and tetragonal forms of ZrO_2 (baddeleyite), with an enthalpy of transition of 8.67 kJ/mol, $ZrSiO_4$ is predicted to decompose to ZrO_2 plus SiO_2 (cristobalite) at 1940 K. For hafnon ($HfSiO_4$), the results show that its entropy of formation is similar to that for zircon, implying $S°_{298K}$ = 93.6 J/mol.K, but with $\mathrm{Delta}_{f,ox}\,H°_{298K}$ = -25.0±0.2 kJ/mol.

Cells with both $ZrSiO_4$ + ZrO_2 and $HfSiO_4$ + HfO_2 show an anomalous excursion in EMF when the temperature of the a-g transition in Fe metal at 1184 K is traversed; this excursion takes >12 hours to decay back to the equilibrium value. This behaviour is presumably related to strain caused by the volume change of the a-g transition.

Redetermination of the μO_2 of the Fe_2SiO_4-Fe-SiO_2(qz) equilibrium (the quartz-fayalite-iron or QFI oxygen buffer) gave results in reasonable agreement with previous work, but with a different slope versus temperature, implying a slightly higher value of $S°_{298K}$ for Fe_2SiO_4 than the currently accepted calorimetric datum.

The magnesiowüstite — iron equilibrium and its implications for the activity-composition relations of $(Mg,Fe)_2SiO_4$ olivine solid solutions

H.StC. O'Neill, M.I. Pownceby and C.A. McCammon

The chemical potential of oxygen (μO_2) in equilibrium with magnesiowüstite solid solution (Mg, Fe)O and metallic Fe has been determined by gas-mixing experiments at 1473 K supplemented by solid cell EMF experiments at lower temperatures. The results give:

$$\mu O_2\ (\mathrm{kJ/mole}) = \mu O_2\ (\mathrm{IW}) + 2\,(X_{MgO})^2\,[(5.76+3.47\mathrm{x}10^{-3}T)+0.41(3-4X_{MgO})]$$

where IW refers to the Fe-"FeO" equilibrium.

The previous work of Srecec et al. (1987) and Wiser and Wood (1991) agree well with this equation, as does that of Hahn and Muan (1962) when their reported compositions are corrected to a new calibration curve for lattice parameter vs. composition.

The amount of Fe^{3+} in the magnesiowüstite solid solution in equilibrium with Fe metal was determined by Mössbauer spectroscopy on selected samples. These data were combined with literature data from gravimetric studies and fitted to a semi-empirical equation:

$$X_{FeO1.5} = (1-X_{MgO})^{3/2} [0.103 - 0.203 X_{MgO} + 0.213 (X_{MgO})^2]$$

These results were then used to reassess the activity-composition relations in $(Mg,Fe)_2SiO_4$ olivine solid solutions at 1400 K, from the partitioning of Mg and Fe^{2+} between olivine and magnesiowüstite in equilibrium with metallic Fe experimentally determined by Wiser and Wood (1991). The olivine solid solution is constrained to be nearly symmetric with $W_{Mg-Fe}(ol)$ = 2.6 kJ/mol, with a probable uncertainty of less than ±0.5 kJ/mol (one standard deviation). The results also provide a useful constraint on the free energy of formation of Mg_2SiO_4.

An experimental investigation of the effect of melt composition on the activity coefficients of FeO, NiO, CoO, MoO_2 and MoO_3 in silicate melts, and its implications for trace element partitioning

H.StC. O'Neill and S.M. Eggins

The thermodynamic theory describing the partitioning of trace elements between crystals and silicate melt implies that partition coefficients should depend on the major-element composition of the melt from two different causes, namely 1) the activity coefficient of the trace-element oxide component in the melt, and 2) the activities of all the major-element components needed to balance the trace-element substitution in the crystal (the "stoichiometric control"). Partition coefficients are also expected to vary with the composition of the crystal, and temperature and pressure. Because these variables cannot be controlled independently in direct crystal/melt partitioning studies, it has not been possible to disentangle their effects, or to determine their relative importance.

In order to explore the effects of melt composition on activity coefficients of trace-element oxide components, the activity coefficients of five such components, MoO_2, MoO_3, FeO, NiO and CoO, were measured in 18 different melt compositions in the system CaO-MgO-Al_2O_3-SiO_2 plus one composition in CaO-MgO-Al_2O_3-SiO_2-TiO_2 at 1400ºC, by equilibration with the metal under controlled oxygen fugacity. MoO_2 and MoO_3 are expected to have geochemical properties similar to the High Field Strength Elements (HFSEs). The activity coefficients of MoO_2 and MoO_3 vary by factors of 20 and 60 respectively over the range of compositions investigated. Their variation is highly correlated, and mainly depends on the amount of CaO in the melt, suggesting the influence of $CaMoO_3$ and $CaMoO_4$ complexes. The analogy between Mo and HFSEs implies that melt composition can be expected to have an important influence on HFSE partition coefficients.

The activity coefficients of FeO, NiO and CoO vary by a factor of two over the same range of melt compositions, but show no simple dependence on any particular major-element oxide component. However, the activity coefficients of all three components are very highly correlated with each other. This means that the effect of melt composition can be largely eliminated if the ratios of two activity coefficients are taken, as, for example, when two-element distribution coefficients are used.

The oxidation state of iron in silicate melts

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Although iron oxidation states can be accurately determined by Mössbauer spectroscopy, the technique does not have the spatial resolution important for many geological problems. X-ray absorption near edge structure (XANES) spectroscopy can be used to determine and quantify iron oxidation states with micron resolution. We have recorded Mössbauer and XANES spectra for a glass of anorthite-diopside eutectic composition containing 0-7 wt% ^{57}Fe prepared over a range of oxygen fugacities. The Mössbauer results confirm that the iron oxidation state ratio is related to the oxygen fugacity by a factor of 0.25 ($\log[Fe^{3+}/Fe^{2+}]$ μ $0.25\log fO_2$) as expected from the reaction $FeO + 1/4O_2 = 1/2Fe_2O_3$. This result is in agreement with theory but differs from a literature value of 0.2185 determined empirically for natural compositions. The discrepancy is attributed to non-Henry's Law behaviour at high Fe_2O_3 concentrations. The energy centroid of the iron 1s-3d transition in the XANES spectrum was found to be linearly correlated with the oxidation state determined by Mössbauer spectroscopy. This provides a calibration for extracting oxidation state ratios for a silicate glass. Further work will determine the generality of this calibration for a range of glass compositions.

Partitioning of iron between magnesian silicate perovskite and magnesiowüstite at about 1 Mbar

The two major phases in the Earth's lower mantle are magnesian silicate perovskite $(Mg,Fe)SiO_3$ and magnesiowüstite (= ferropericlase) $(Mg,Fe)O$. Allocation of ferrous iron and magnesium between them is described by a parameter called a "distribution coefficient" (or "partition coefficient") K_D such that

$$K_D = \frac{X^{mw}_{Mg^{2+}}}{X^{mw}_{Fe^{2+}}} \frac{X^{pvsk}_{FeSiO_3}}{X^{pvsk}_{MgSiO_3}}$$

where X means mole fraction. Over the past two decades, substantial effort has been directed towards experimental measurements of perovskite-magnesiowüstite distribution coefficients, with the objective of understanding the effects of pressure, temperature and system chemistry. These goals are important because that distribution relationship describes the essential phase chemistry of the lower mantle, and also offers a valuable independent constraint on geophysical and geochemical models of the Earth's interior. However a review of the scientific literature soon reveals that, whilst it is agreed that iron is preferentially-concentrated in magnesiowüstite, preferred values for the distribution coefficient range from as low as 0.1 to near unity!

Some of the dispersion amongst distribution coefficient values arises from the inadvertent – often unavoidable – oxidation of some ferrous iron to the trivalent state during experiments. Unfortunately in many cases this process has been unrecognised or unacknowledged. And this ferric iron, we now know, is concentrated in magnesian silicate perovskite in preference to magnesiowüstite, which results in distribution coefficients with seemingly elevated values. There has also been considerable debate as to whether distribution coefficients measured in the widely-studied experimental system MgO-FeO-SiO_2 are applicable to the real Earth. The argument hinges on the role of Al_2O_3, which under lower mantle conditions is accommodated in magnesian silicate perovskite. The results of some classes of high-pressure experiments imply that incorporation of Al^{3+} in perovskite requires coupled substitution with ferric iron: $Mg^{2+} + Si^{4+} = Fe^{3+} + Al^{3+}$. And the presence of iron in both valence states leads to predictable confusion over what thereby constitutes an appropriate value for the distribution coefficient.

Our objective has been to determine Mg^{2+}-Fe^{2+} distribution coefficients for perovskite-magnesiowüstite pairs produced by disproportionation of olivine Fo_{90}, at pressures relevant to the deeper part of the lower mantle (~ 1 Mbar), for which data are minimal. We then examined our data critically from the perspective of the various issues raised above, and from thermodynamic fundamentals.

The disproportionation products of olivine Fo_{90} in our diamond anvil cell experiments at pressures of about 1 Mbar are found to be magnesian silicate perovskite Mg# ~94 and a series of magnesiowüstites Mg# 85—90, yielding a recommended value of 0.4 ± 0.1 for the distribution coefficient that defines the exchange of Mg^{2+} and Fe^{2+} between the two phases (K_D). The distinctive compositional trends which would signify that new ferric iron had been stabilised during experiments are lacking. We cannot measure the temperature of our experiments, so Wood's multi-anvil study (Earth Planet. Sci. Lett. (2000) 174, p.341) was used to link our K_D values to temperature. Our recommended value of 0.4 ± 0.1 is thereby equated with temperatures of 2000 ± 300 K. We compared our data with the results of an analogous experimental campaign that we had earlier conducted at much lower pressures of 25—50 GPa, and found them to be much the same. However, the implication that pressure accordingly has minimal effect on distribution behaviour is not in accordance with our thermodynamic calculations, which predict that K_D should fall by about 40% if pressure increases from 50 GPa to 1 Mbar. An explanation for this discrepancy is required. The most likely culprit is the molar volume for the hypothetical end-member perovskite $FeSiO_3$. If this were in error by only -0.5%, the volume change for the exchange reaction, and hence the pressure-dependency of K_D, would be effectively zero.

We were also able to demonstrate that the presence of Al^{3+} in magnesian silicate perovskite in amounts appropriate for the lower mantle (about 5 mole %) does not modify distribution behaviour, provided the oxygen content of the system remains essentially constant – a situation that would necessarily prevail in the real Earth. The above considerations allow us to predict that magnesian silicate perovskite Mg# 93.0 ± 0.6 would coexist with magnesiowüstite Mg# 82.6 ± 0.9 just beyond the 660 km discontinuity (1800 K), whilst at the core-mantle boundary (2650 K) the corresponding values would be 91.9 ± 0.4 and 84.9 ± 0.8.

The partial melting of a phlogopite-bearing garnet lherzolite in the model mantle system SiO_2-Al_2O_3-MgO-FeO-CaO-K_2O-H_2O

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Phlogopite is a potential host for K_2O and H_2O in the metasomatized portions of the upper mantle. Many petrological and geochemical studies suggested that the phlogopite-bearing mantle lherzolite might be the source material of high-K basalts. For example, the shoshonitic rocks on the Tibetan plateau revealed that K_2O appears to be buffered at about 4% over a wide range of SiO_2 (46-60%). A possible explanation for this apparent buffering behaviour is that the shoshonites were derived from a low degree partial melting, leaving a phlogopite-bearing garnet lherzolite as residual material. To test this possible hypothesis, it is necessary to determine precisely the melt composition in equilibrium with Ph-Ol-Gt-Opx-Cpx. For this purpose, experiments have been carried out in the system SiO_2-Al_2O_3-MgO-FeO-CaO-K_2O-H_2O at a pressure of 28 kb in the piston-cylinder apparatus.

Experiments were carried out using $Au_{80}Pd_{20}$ as capsule, which avoided Fe loss from the charge. The sandwich method was used, in which an upper and lower phlogopite-bearing garnet lherzolite layers sandwich a middle layer of glass of the composition estimated to be in equilibrium with phlogopite-bearing gt-lherzolite. This geometrical arrangement results in pool of melt large enough to be analyzed directly by electron microprobe. The composition of the initial melt is adjusted by successive approximations until the appropriate composition is found. Starting phlogopite was synthesized at 28 kb and 850°C and the garnet lherzolite (the assemblage ol+opx+cpx+gt with mg#=90) at 28 kb and 1250°C. A phlogopite-bearing garnet lherzolite was then obtained by adding 12 wt% phlogopite. Glass was made by melting oxide mixture at 1550°C under argon in an atmospheric furnace. To ensure a molar K_2O/H_2O ratio of unity as in phlogopite, necessary H_2O was added as $Mg(OH)_2$.

The preliminary results show that the melt in equilibrium with a phlogopite-bearing garnet lherzolite at 1220°C and 28 kb is very rich in SiO_2(50%), K_2O(18%) and Al_2O_3(17%), and poor in MgO(3.5%), FeO(3.6%) and CaO(2.1%). Phlogopite appears to be stable to within about 30°C above the solidus. Elimination of the phlogopite with temperature initially results in only a small change in melt composition, i.e. K_2O decreases to about 17%, Al_2O_3 remains almost the same (17%), and SiO_2, MgO, FeO and CaO increase to 50.5%, 4.5%, 4.0% and 2.8%, respectively, at 1240°C. The melt should be rich in H_2O, but the precise amount needs to be obtained by IR spectroscopy.

The above results imply that mantle phlogopite-bearing garnet lherzolite would not produce shoshonitic magma by low degree partial; rather, such melts would be extremely rich in Al_2O_3, K_2O and H_2O. For confirming the suggestions above, the experiments in Na_2O-containing system are being conducted.

Subsolidus phase relations in the system MgO-ZnO-SiO_2 and Mg-Zn partitioning between olivine, pyroxene and spinel

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The subsolidus phase relations in the system MgO-ZnO-SiO_2 at 10 kb and 1200°C has been determined (Figure 1).

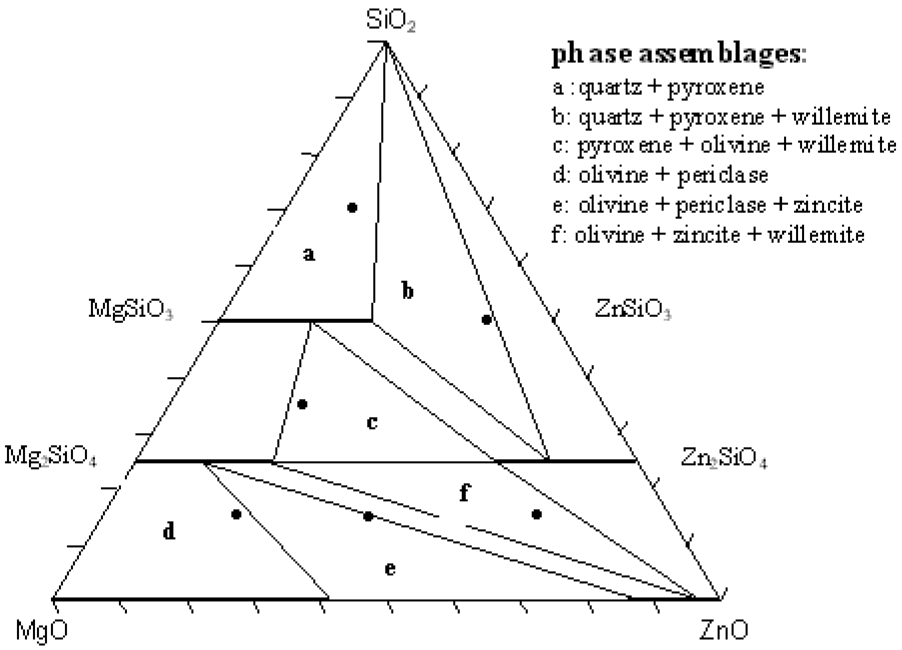

Figure 1: Subsolidus phase relations in the system MgO-ZnO-SiO_2 at 10 kb and 1200°C. Filled circles represent the starting compositions.

The Mg-Zn distribution coefficient (Kd) between Ol, Px and Sp have been experimentally measured as a function of temperature and pressure. The results show that (1) $Kd_{ol\text{-}sp}$ and

Technical advances in partial melting experiments

X. Liu, H.StC. O'Neill and W.O. Hibberson

Water is well known to have a large effect on the solidus temperature of mantle peridotite. It is therefore essential to exclude water as completely as possible from the experimental charge during investigation of mantle melting under anhydrous conditions. Historically, many melting experiments in the piston-cylinder apparatus have used traditional experimental pressure assemblies consisting of salt-pyrex or even talc-pyrex sleeves. Water from the incompletely dried assembly or other sources may react with the graphite heater to produce hydrogen. Diffusion of this hydrogen through the Pt capsule may reduce the experimental charge, and produce water at the same time.

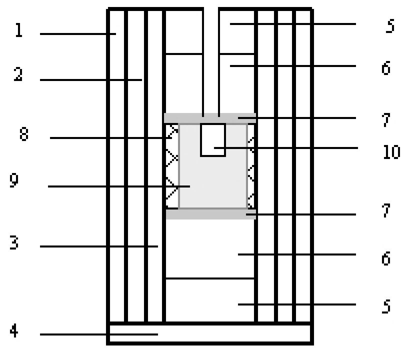

Figure 1: New experimental assembly arrangement (salt-pyrex-Fe_2O_3). 1. salt sleeve; 2. pyrex tube; 3. graphite heater; 4. graphite; 5. MgO spacer; 6. Al_2O_3 spacer; 7. ruby disc; 8. Al_2O_3 sleeve; 9. Fe_2O_3 sleeve; 10. Capsule.In addition, even carefully dried experimental charges may possibly absorb some moisture from the air during the capsule-welding process.In order to solve these problems, a new experimental protocol has been developed: 1. New welding process. The Pt capsule is held in a steel block that is heated to ~700ºC during welding. Previously, the open capsule plus charge is dried at 150ºC for several hours.2. New experimental assembly arrangement (salt-pyrex-Fe_2O_3) –

Figure 1. The basic structure of the new assembly is the same as the old salt-pyrex assembly: a central part surrounded by a graphite heater, a pyrex tube and an outermost salt sleeve. The difference lies in the central part. In the central part of the new assembly, the Pt capsule is enclosed by a Fe_2O_3 sleeve, which is in turn surrounded by an alumina sleeve. At each end of the alumina sleeve, there is a ruby disc which completely separates the Fe_2O_3 sleeve from the rest of the assembly. This prevents reduction of the Fe_2O_3 sleeve by the graphite heater, or contamination of the thermocouple. Composite spacers of alumina and magnesia are positioned next to the ruby discs. This enhances the mechanical stability of the assembly. The Fe_2O_3 sleeve is made by cold pressing in a steel die and sintering at 850°C, 1 atm for 3 hours.Using these new experimental techniques, the water content of experimental charges is

kept to insignificant levels. Another advantage of using the new cell assembly is that the hydrogen fugacity surrounding the capsule is kept extremely low by the Fe_2O_3 sleeve.

Accurate determination of the solidus of simplified spinel lherzolite in the system CaO-MgO-Al_2O_3-SiO_2 (CMAS) at 11 kbar: forward and reversal experiments

X. Liu and H.StC. O'Neill

The simple system CaO-MgO-Al_2O_3-SiO_2 (CMAS) is widely recognised as a good analogue for the Earth's mantle, since, under the appropriate pressure-temperature conditions, the major mineral phases of the mantle all occur in this system. In the upper mantle, there are four such phases, namely, olivine, orthopyroxene, clinopyroxene, and an aluminous phase, plagioclase, spinel or garnet, depending on pressure. Accurate determination of melt compositions multiply saturated with four mineral phases at the solidus of the system CMAS are particularly desirable in order to understand how melt compositions change with pressure (i.e., the depth interval over which melting occurs), and to constrain the thermodynamic properties of silicate melts. However, the determination of such compositions is difficult experimentally, as the five phases (melt plus four crystalline phases) constitute an isobarically invariant assemblage in the component CMAS system, and therefore only coexist over an infinitely narrow temperature interval.

We have determined the solidus of simplified spinel lherzolite in the system CMAS at 11 kbar using three different experimental methods: 1. Normal forward partial melting experiments; 2. Sandwich forward partial melting experiments; 3. Reversal experiments.

Preliminary normal forward partial melting experiments were first undertaken using the typical salt-pyrex assembly. We bracketed the solidus between 1300°C (ol+opx+cpx+sp) and 1310°C (melt+ol+opx+sp). However, the solidus temperature in these preliminary experiments may be slightly low because of contamination by water. We were unable to obtain the full 5 phase assemblage due to the univariant nature of the melting reaction.

In the sandwich experimental technique, a layer of glass was put between two layers of the crystalline assemblage. The aim is to produce a relatively large volume of melt in equilibrium with crystals of the appropriate composition; this should eliminate problems caused by quench modification of the melt composition. The composition of the initial glass and the crystalline mixture containing Fo, Sp, Opx, Cpx came from the literature. In order to ensure near-anhydrous conditions, new salt-pyrex-Fe_2O_3 sleeve assembly was used.

As the solution to the problem of obtaining all five phases, we conceived the following strategy. Adding a highly incompatible component to the system (i.e., one that enters only the melt phase) turns the system into a divariant one, allowing the four crystalline phases plus melt to coexist over a finite temperature interval. The amount of the incompatible component and the temperature (the two are completely correlated) are varied, and the results so obtained are extrapolated to zero concentration of the incompatible component.

For the incompatible component we chose K_2O, since this component can be important in other contexts in igneous petrogenesis; consequently, the information obtained on the effects

Two initial melt compositions were synthesised, with 1% or 3% K_2O. Extrapolating the K_2O content of the melt in those experiments displaying Fo+Sp+Opx+Cpx+Melt back to zero K_2O gives a solidus temperature for isobarically invariant melting in the system CMAS at 11 kbar of 1320°C. The same principle allows a very accurate determination of the melt composition at the solidus.

Computational Petrology and Pyroxene Thermodynamics

A new way to represent the Gibbs free energy (**G**) for any multi-phase system has been formulated for silicate/oxide systems. The chemical composition of each phase has been unambiguously expressed by the number of cations per formula unit ('constituents', symbol 'N'), which are subject to constraints by both stoichiometry and charge balance. Related to the *constituents* are the site occupancies for each element *i* in phase f . For each *constituent* we can write an expression of the type

$$N_i^{\phi} = \sum_{j=1}^{n} X_{ij}^{\phi} \quad \text{where} \quad X_{ij}^{\phi}$$

represents the site occupancies of element i in site j, the summation to be extended to all sites n in phase f . As a result for every phase f in the system the molar Gibbs free energy (Gf) assumes the form of

$$G^{\phi} = G(T, P, X_{ij}^{\phi})$$

with respectively i = 1, …, c number of element and j = 1,.., n number of sites present in phase f . The total G of a system will be then given by

$$G = \sum_{\phi=1}^{p} n^{\phi} G^{\phi}$$

where n^f = number of moles of phase f,G^f = free energy per mole of phase f , and p = number of phases f in the system.

For each phase, the molar free energy (Gf) is given by the sum of contributions from 1) the Gibbs free energy of the end-members, 2) ideal mixing on sites, and 3) excess mixing terms. The principle underlying the formulation of the term due to the Gibbs free energy of the end-members has been elucidated. As an example, the expression of this term for a general (Na-Ca-Mg-Fe^{2+}-Al-Cr-Fe^{3+}-Si-Ti) pyroxene system (32 end-members) has been derived.

The Gibbs Free Energy Minimum Principle states that the equilibrium value of any unconstrained parameter in a system in contact with a temperature and pressure reservoir minimizes the Gibbs free energy (**G**) at constant temperature and pressure. It follows that at any given temperature and pressure a closed multi-phase system is at its equilibrium condition when the chemical composition of the phases present in the system and the number of moles of each are such that the Gibbs free energy of the system reaches its minimum value.

In order to compute phase equilibria in pressure-temperature-compositional space a computer program (Gib) has been written to find the minimum in the Gibbs free energy. In the program the unknowns sought are the constituents of each phase together with the numbers of moles of that phase. The system's Gibbs free energy is minimized under mass balance, stoichiometry, charge balance and positivity constraints. The minimization is carried out by making use of a '*Feasible iterate sequential quadratic programming*' method (FFSQP) which is specifically designed for general constrained optimization problems of this kind.

Initial application of the program is to a system of coexisting pyroxenes (orthopyroxene, and low Ca- and high Ca clinopyroxene). Future work will focus on extending the calculations to the subsolidus upper-mantle systems consisting of olivine, plagioclase, spinel and garnet in addition to pyroxenes. This will provide the basis for a more comprehensive thermodynamic modeling tool for investigating phase/melting relationships in the Earth's mantle at high pressure and temperature.

^{17}O multiple-quantum MAS NMR study of silicate minerals

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Two-dimensional triple-quantum ^{17}O (I = 5/2) MAS NMR powder spectra were obtained for hydroxyl-chondrodite, hydroxyl-clinohumite, orthoenstatite, clinoenstatite, protoenstatite, and diopside. The spectra were analysed to yield the ^{17}O isotropic chemical shifts and quadrupolar coupling parameters of the oxygen sites in each sample. The values obtained were compared with those found previously for forsterite. The ^{17}O resonances of the hydroxyl sites were identified using ^{17}O {^{1}H} cross-polarisation and assigned by comparison with the spectrum of ^{17}O-enriched brucite. For the pyroxenes, bridging and non-bridging oxygens were distinguished by their characteristic quadrupolar parameters. Using all this data, complete assignments of the five crystallographically-inequivalent oxygen sites in hydroxyl-chondrodite, the nine such sites in hydroxyl-clinohumite, the three sites in protoenstatite and diopside, and of the six sites in orthoenstatite and clinoenstatite, have been suggested. The validity of these assignments are supported by the observation of a correlation between ^{17}O isotropic chemical shift and Si-O bond length. It is hoped that the present work will serve as a model for future NMR studies aimed at determining the hydroxyl site in nominally anhydrous mantle minerals.

Copper speciation in vapor phase fluid inclusions from the Mole Granite, Australia

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X-ray fluorescence elemental maps and copper K-edge X-ray absorption spectra were recorded for single vapour and brine phase fluid inclusions from the Mole Granite, NSW, Australia. The maps indicate that copper is concentrated in the vapour inclusions and at room temperature uniformly distributed in the condensed fluid. Opaque precipitates in these inclusions do not contain copper. The absorption spectra identify the stable complexes as $[Cu(OH_2)_6]^{2+}$ at 25°C, $[CuCl_2]$- at 200°C, and $[CuCl(OH_2)]$ at the homogenisation temperature of around 400°C. This change in copper coordination and oxidation state is fully reversible. The results suggest that copper is transported in the vapour phase as a neutral chloride complex. We aim to identify the factors that control copper partitioning between a vapour phase and high density brine. This work has implications for understanding the metal distribution between epithermal and porphyry type environments in hydrothermal systems.

Mid-Ocean Ridges and Ocean Islands: Comparing the constraints on melt segregation from U-series data

U. Faul

The isotopes in the Uranium decay series have half-lives from 1600 years (^{226}Ra), 33,000 years (^{231}Pa) to 75,000 years (^{230}Th). This range in half-lives is assumed to cover the time scale from the first generation of melt at depth beneath mid-ocean ridges or ocean islands to the eruption at the surface. U series data from mid-ocean ridges and ocean islands shows ubiquitous Th excess (activity ratio (^{230}Th/^{238}U) >1), indicating that the parent ^{238}U is slightly more compatible and therefore has a slightly longer residence time in the melting column. For mid-ocean ridge basalts (MORBs), plots of the activity ratio of (^{230}Th/^{238}U) versus the ratio of the absolute abundances of Th and U indicate a correlation with more enriched basalts (higher Th/U wt ratio) having larger Th excess. This correlation can be explained with more enriched source material having a lower solidus temperature and beginning melting deeper in the garnet stability field. Since garnet most strongly fractionates Th from U, the more melt is produced in the garnet stability filed the larger the excess. For the much shorter lived ^{226}Ra the opposite correlation is observed: the most depleted basalts have the highest Ra excesses. ^{231}Pa excess appears uncorrelated with enrichment. Since the partition coefficients between melt and matrix of all U-series isotopes, but particularly Ra, are small this is taken to imply that porous flow up to the last stages of melting takes place at very low porosities (of order of 0.1%).In comparison with MORBs, ocean island basalts (OIBs) have much smaller Ra and Pa excesses, even though the source material is generally more enriched and fast transport through the lithosphere is indicated by the presence of xenoliths in the erupted lavas. The available data from OIBs show a better correlation between enrichment and ^{230}Th excess than MORBs and a good correlation between Pa excess and enrichment is apparent whereas there is none for MORBs.OIB disequilibrium data can be modelled by porous flow of the melt with reasonable permeabilities and melt properties, whereas modelling the MORB data by porous flow requires unreasonably high permeability or low melt viscosity. This and the scatter of the data for individual ridge segments possibly indicates that processes in the shallow mantle, such as flow through veined, previously depleted and cooled mantle could play an important role in determining some of the U-series characteristics of MORBs.

Experimental evidence for diamond facies metamorphism in the Dora Maira massif

J. Hermann

The peak metamorphic conditions of subducted continental crust in the Dora Maira Massif (Western Alps) have been revised by combining experimental results in the KCMASH system with petrographic observations in whiteschists. Textural observations in whiteschists suggest that the peak metamorphic assemblage consisting of garnet + phengite + kyanite + coesite ± talc originates from the reaction kyanite + talc <-> garnet + coesite + liquid. In the experimentally determined petrogenetic grid, this reaction occurs above 45 kbar at ~730°C. At lower pressures talc reacts either to orthopyroxene and coesite or, together with phengite, to biotite, coesite and kyanite. The liberated liquid is probably supercritical in nature with equal amounts of H_2O and dissolved granitic components. Experimentally determined Si-isopleths in the talc-phengite-kyanite-coesite field as well as in the garnet-phengite-kyanite-coesite filed further constrain peak pressures to ~42 kbar for the measured Si = 3.59 of phengite in the natural whiteschists. All these data provide evidence that the whiteschists reached diamond facies conditions.

The fluid absent equilibrium 4 kyanite + 3 celadonite = 4 coesite + 3 muscovite + pyrope has been empirically calibrated on the basis of garnet and phengite compositions in the experiments. Garnet-phengite thermometry in graphite bearing metapelites and kyanite-phengite eclogites, forming the country rocks of the whiteschists, yield temperatures of ~750°C. At this temperature, peak metamorphic pressures were calculated to 44 ± 3 kbar using the calibrated equilibrium. Therefore, the whole ultrahigh-pressure unit of the Dora Maira massif most likely experienced peak metamorphic conditions in the diamond stability field. The absence of metamorphic micro diamonds might be explained by kinetic problems of graphite to convert to diamond.

Interaction of hydrous granitic melts with carbonates at 4.5 GPa: Implications for metamorphic diamond formation and devolatilisation in subduction zones

J. Hermann and D.H. Green

Interlayered pelites and carbonates (marls) are common in subducted continental crust and oceanic sediments. The interaction of hydrous granitic melts produced in metapelites with carbonates has been investigated by piston cylinder sandwich experiments at 4.5 GPa. The carbonate layer consists of natural dolomite and a synthetic simplified pelite composition (KCMASH) with additional 1.2 wt% H_2O was used for the pelite layer. At 1000°C, 4.5 GPa the paragenesis in the carbonate-free system consists of phengite + garnet + clinopyroxene + kyanite + coesite + hydrous granitic melt. Dolomite embedded in the pelite reacts with the hydrous silicate melt and produces the paragenesis garnet + clinopyroxene + dolomite + liquid. Qualitative mass-balance constraints the liquid composition to 60 wt% CO_2, about 10 wt% of H_2O, K_2O and CaO and very small amounts of SiO_2, MgO and Al_2O_3. It is likely that significant amounts of the carbon are dissolved as $(CO_3)^{2-}$. This liquid therefore reflects rather a carbonatite-like liquid than an aqueous CO_2-H_2O fluid.

In the pelite adjacent to the dolomite layer, an increasing abundance of garnet, kyanite and melt and a decreasing amount of clinopyroxene, phengite and coesite has been observed. This suggests that the presence of carbonate enhances melt production in the pelite. No clear separation between the hydrous granitic melt and the carbonatite-like liquid has been observed indicating that they are most probably completely mixable at the experimental conditions. The presence of a carbonatite-like liquid in the carbonate layer and a hydrous granitic melt in the pelite domain could be a clue to understanding formation of metamorphic diamond in subducted crust. The interaction of the hydrous granitic melt with dolomite produces CO_2 and/or $(CO_3)^{2-}$. It is likely that a hydrous granitic melt is more reduced than carbonates. Because of the curvature of the carbon saturation surface in a $f(O_2)$ vs liquid composition diagram, the liberated $CO_2/(CO_3)^{2-}$ drives the hydrous granitic melt into the "liquid+diamond" field, leading to the precipitation of diamond. Another way of diamond formation could include the reaction of the carbonatite-like liquid with the hydrous granitic melt. Because the carbonate—like liquid is likely to retain a much higher solubility of carbon than a hydrous granitic melt, diamond could precipitate during mixing of the two different liquids.Further carbonate solubility experiments were carried out in a natural pelite composition with addition of different amounts of carbonate.

At 900°C, 4.5 GPa, 10, 20, and 30% of a carbonate mix consisting of 20% calcite and 80% dolomite were run together with a pelite containing 6.8% H_2O. All runs contained phengite + garnet + onphacite + coesite + liquid ± kyanite. The 10% of carbonate was completely dissolved in the liquid. In the runs with 20% and 30% of carbonate added, dolomite but no aragonite was found. This indicates that the whole $CaCO_3$ component of the carbonate was dissolved in the liquid. The liquid is characterised by a quenched hydrous granitic glass containing numerous bubbles, probably exsolved CO_2, and small quench carbonates. This further supports the hypothesis, that a carbonatite-like liquid and a hydrous silicate melt are mixable at 4.5 GPa and 900-1000°C. The melting reaction in marls can be summarised asphengite + omphacite + coesite + aragonite + H_2O -> garnet + liquidMass balance indicates that 1.5-2 times more CO_2 than H_2O can be dissolved in hydrous granitic melts. We therefore propose that hydrous granitic melts are capable of transferring not only H_2O but also significant amounts of CO_2 from subducted sediments to the mantle wedge. The physical properties, the ability to transport trace elements and the interaction with the mantle wedge of such melts are yet to be determined.

A precise Ar-Ar age for the Kalkarinji low-Ti Continental Flood Basalt Province of northern Australia

L.M. Glass and D. Phillips[1] [1] *School of Earth Sciences, The University of Melbourne, Victoria*

The Antrim Plateau Volcanics and their stratigraphic equivalents (Helen Springs, Nutwood Downs, Peaker Piker and Colless Volcanics) comprise Australia's largest Phanerozoic age flood basalt province. However, the eruption age of the province has not been precisely determined to date. Stratigraphic constraints suggest the province is Early Cambrian in age (545 - 508 Ma) consistent with a recently determined SHRIMP U-Pb zircon age of 513 ± 12

Ma and older K-Ar measurements giving ages of ca 510 Ma. In order to obtain more precise eruptive ages for basalts over the geographical province, petrographically least altered rocks from the Limbunya (western NT), Helen Springs, Daly River and Katherine regions were selected for plagioclase separation. The freshest feldspar grains were carefully handpicked from the mineral separates. Of the four samples analysed by stepwise degassing, two samples yielded well-defined plateau ages (Figure 1). The others (Daly River and Katherine) had discordant saddle-shaped spectra, suggestive of excess argon and/or alteration.

Table 1: Isochron data for the Antrim Plateau and Helen Springs basalts

^{40}Ar-^{39}Ar plateau ages

Region	*Sample No.*	*Age*	*%^{39}Ar included*	*MSWD*
Helen Springs	HS002(1)	508±2 (1 sigma)	99.2	0.89
Helen Spring	HS002(2)	508±2 (1 sigma)	52.8	1.30
Limbunya	LB011(1)	504±2 (1 sigma)	74.9	1.80

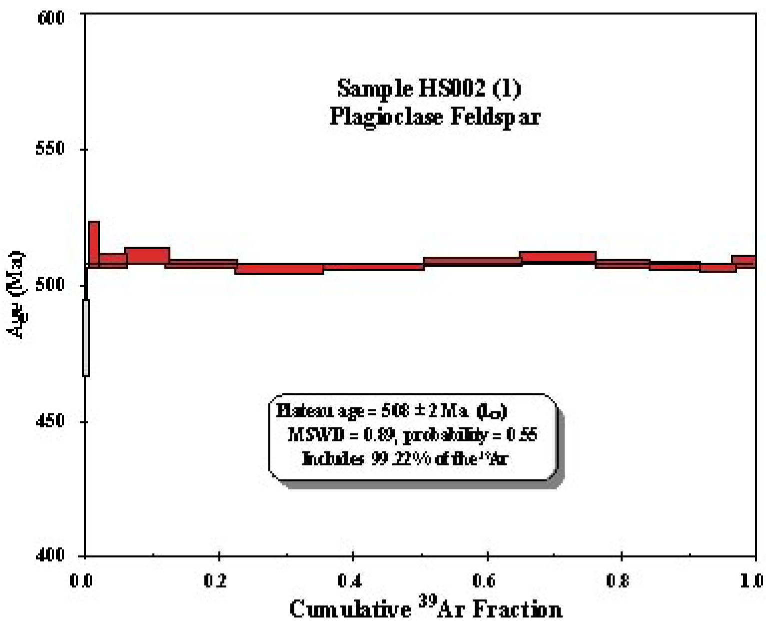


Figure 1: ^{40}Ar-^{39}Ar step heating age spectrum for Antrim sample HS002 (1) plagioclase separate.

The new high-precision Ar-Ar age is younger than previously obtained and indicates the eruptive event occurred at the Lower Cambrian - Middle Cambrian boundary. In view of the new ages, we now have geochronological evidence that definitively links the Antrim Plateau Volcanics and their stratigraphic equivalent, the Helens Springs Volcanics. Because the Antrim Plateau Volcanics and their stratigraphic equivalents are geochemically, isotopically and geochronologically indistinguishable we introduce a new name for the province: the Kalkarinji Continental Flood Basalt Province. The name has been chosen firstly to minimise confusion with the more well known northern hemisphere Antrim basalts in northern Ireland and also to provide an all encompassing name to embrace the north Australian Cambrian flood basalt event. It is possible that coeval basalts in the Officer (Table Hill Volcanics) and Savory Basins (M Wingate, *pers. comm*. 2001) may also be part of the eruptive event and warrants further investigation.

Determination of clinopyroxene-liquid and plagioclase-liquid trace element partition coefficients from the low-Ti Kalkarinji flood basalts and their application to geochemical modelling

L.M. Glass

Partition coefficients are widely used for modelling igneous crystal-melt processes such as partial melting, crystal fractionation and assimilation. In trace element modelling, it is essential to choose an appropriate set of partition coefficients relevant to the pressure-temperature conditions and rock composition of interest. However, partition coefficient data from the literature is of variable quality and often incomplete so that data from different authors using different methods have to be combined. With the advent of laser-ablation ICPMS (Inductively Coupled Plasma Mass Spectrometry) methods, it has become possible to measure a full range of trace elements in natural mineral-melt samples with high sensitivity and precision.The Kalkarinji basalts of northern Australia are characterised by pronounced upper-crust-like geochemical signatures and show well defined geochemical evolution trends on Harker diagrams. It has been suggested that the crustal signatures of low-Ti basalts of this kind are due to shallow-level assimilation-fractional crystallisation (AFC) processes occurring as a result of turbulent flow in magma conduits. In order to test this hypothesis by geochemical modelling it is necessary to have an accurate and appropriate set of mineral-melt partition coefficients.The Kalkarinji basalts are typically aphanitic in texture with rare microphenocrysts of clinopyroxene and plagioclase so that whole-rock compositions effectively represent liquid compositions. Trace element contents of clinopyroxene and plagioclase microphenocrysts were measured directly from thin sections of selected Kalkarinji basalts in order to determine a comprehensive set of partition coefficients. Analyses were undertaken using an UV excimer laser system (193nm wavelength) coupled to an Agilent 7500s quadrupole ICPMS. Only data from inclusion-free crystals showing internal geochemical homogeneity were considered.**Table 1: Selected Preferred Mineral Melt Partition Coefficients for Tholeiitic Compositions**

	Clinopyroxene	*Calcic Plagioclase*
P	0.039	0.025
Rb	0.003	0.022
Sr	0.069	1.86

Y	0.515	0.007
Zr	0.076	<0.001
Nb	0.010	<0.001
Ba	0.004	0.237
Nd	0.186	0.030
Ta	0.005	0.004
Th	0.005	<0.001

The above values have been used to model FC and AFC geochemical evolution of the Kalkarinji basalts. Applying least-squares regressed data for parent-daughter fractionation steps over a range of 9 to 3wt% MgO, it can be demonstrated (Figure 1) that the observed geochemical evolution trends of the Kalkarinji basalts are consistent with crystal fractionation-only, i.e. no crustal assimilation is required to explain the trends. This result is consistent with Sr and Nd isotopic results obtained last year (Annual Report 2000) and implies that the crustal signature of the basalts was either acquired by crustal assimilation of picritic melts with >10wt% MgO or is a source-related feature.

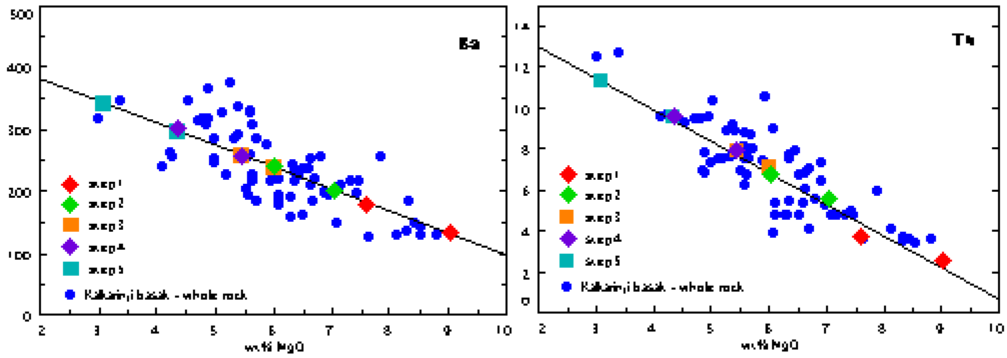


Figure 1: Trace element (ppm) - MgO (wt%) modelled parent-daughter evolution steps for purely crystal fractionation, calculated using the new partition coefficients. These results demonstrate that assimilation of crustal material is not required to explain the trends in the 9 to 3 wt% MgO range.

Fluid inclusion analysis by laser-ablation ICPMS and comparison with proton induced x-ray emission

A. Hack and J. Mavrogenes

Fluid inclusion analysis by excimer laser-ablation ICPMS (LA—ICPMS) has received much attention in the literature recently as it shows great potential for delivering detailed information on mass fluxes and processes in crust and mantle hydrothermal regimes. However, until now no data was available on which to judge the accuracy of the laser-ablation technique and thus its ability to provide true quantitative fluid compositions. This

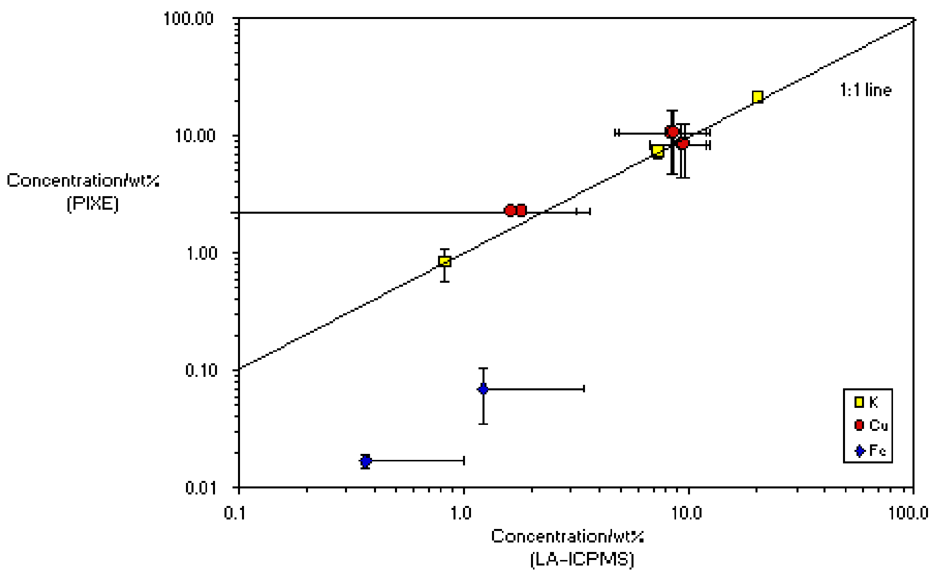


Figure 1: Comparison of LA—ICPMS and PIXE synthetic fluid inclusion data from three experiments at different run conditions for Cu, K, and Fe. LA—ICPMS data were quantified by using the K concentration determined by PIXE as an internal standard and NIST 612 silicate glass as the external analytical standard. Errors = 1s.

The work confirms that LA—ICPMS provides a ready means of measuring fluid inclusion element ratios and its ability to quantify individual element concentrations provided that an internal standard is reliably known. Trace element doping of experimental starting fluids, as a means of internal standardisation is not as robust as previously believed. Further work will investigate the accuracy of the freezing point depression model as a technique for estimating internal standards for LA—ICPMS fluid inclusion quantification.

Copper solubility in mineral-buffered supercritical fluids — some preliminary results from fluid inclusion synthesis experiments

A. Hack and J. Mavrogenes

In the present study copper solubility has been measured in supercritical fluids as a function of salinity at 700°C and 300MPa under mineral-buffered conditions in the system H_2O-Cu-Fe-K-H-Cl (Figure 1).

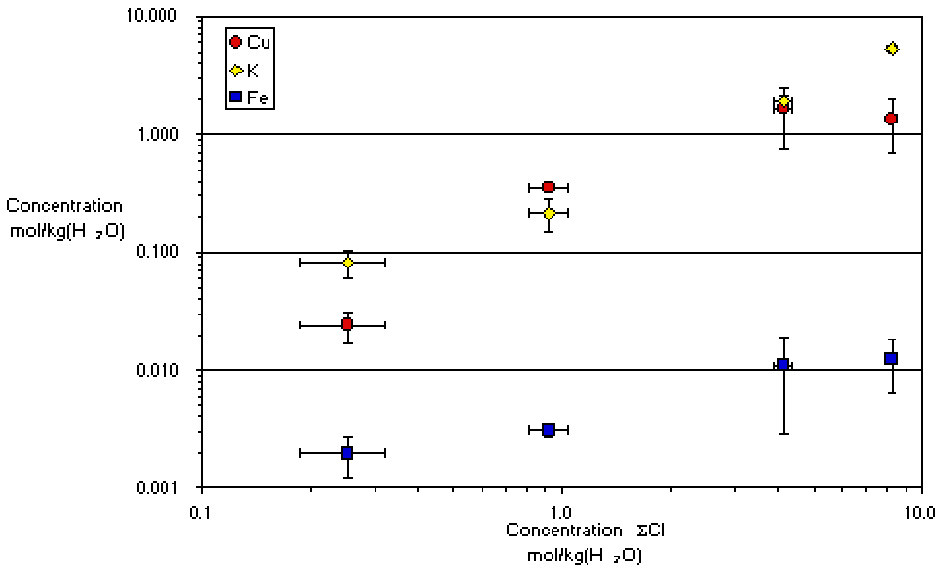


Figure 1: Solubility data for Cu, K, Fe in moles per kilogram H_2O at 700°C and 300MPa as a function of total chlorine measured in individual quartz-hosted fluid inclusions by LA—ICPMS and PIXE. Fluid was buffered by the mineral assemblage quartz-sillimanite-K—feldpar-magnetite-hematite. Errors = 1s

The experimental design allows the solubility data to be interpreted thermodynamically thereby allowing information on copper complexation and its speciation to be derived. For instance the data can be treated by way of a general dissolution reaction (1).

$$Cu^0_{(metal)} + nHCl^0_{(aq)} = CuCl(HCl)^0_{n-1(aq)} + \frac{1}{2}H_{2(gas)} \quad (1)$$

This involved simultaneously solving a system of equations relating mass action, charge balance, and potassium mass balance. Fe data could not be fit to the speciation model but since it is a minor component in these fluids can probably be neglected without significant effect. For simplicity activity coefficients for ionised aqueous species were calculated using the Davies revision of the extended Debye-Hückel expression and neutral species were assigned a value of unity. The standard states were defined as the pure mineral and liquid at the temperature and pressure of interest for solid phases and H_2O. For aqueous species a hypothetical ideal 1 molal solution referenced at infinite dilution at the temperature and pressure of interest, and the pure gas taken at 1 bar and the temperature of interest for gases.

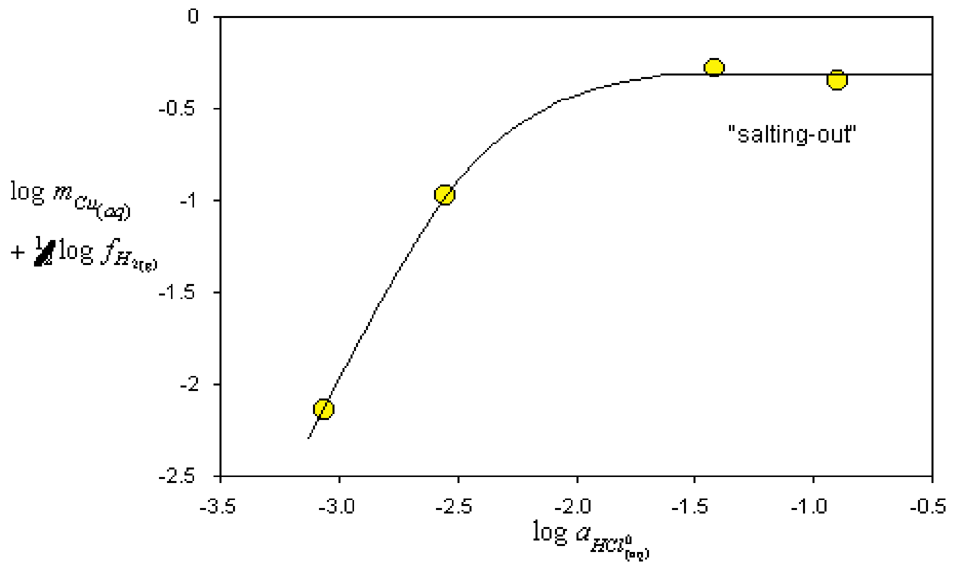


Figure 2: Thermodynamic representation of the copper solubility data with respect to reaction 1. Curve fit by eye.

The preliminary solubility data are not detailed enough to allow derivation of the copper chloride speciation, but a simple thermodynamic treatment indicates a significant 'salting out' (or saturation) effect for copper in the most saline experiments (Figure 2). Further experiments to constrain copper speciation and investigate solubility as a function of salinity, temperature and pressure are continuing.

Structure-property relations of minerals

S.A.T. Redfern

My work is focussed on developing and testing models that relate the properties of solids across many length scales. It ranges from investigating the influence of microstructure in minerals (at a scale of millionths of a metre) on the anelastic properties of the deep mantle (at a scale of millions of metres), through understanding crystal chemical controls on the atomic structure and stability of minerals and biominerals, to exploring routes to determine chemical activities in solid solutions.

This may be considered under the following themes:

a) **Structural physics and chemistry of mesoscopic materials**

How do domain walls generated below symmetry-breaking phase transitions influence the elastic properties of minerals? Using novel apparatus designed and constructed in house we are able to follow the anelastic response of minerals below phase transitions, using experimentally observed critical behaviour in elastic loss and moduli to develop new models for the real behaviour of microstructured minerals in the Earth. This has led to the first observations of superelastic behaviour in mantle-relevant perovskites at seismic frequencies. A related theme is the investigation of chemical transport along domain walls by direct experimental observation, measuring Li diffusion in microstructured quartz (Figure 1).

b) **Structural controls on stabilities at high P/T**

What are the processes that control the phase stabilities of minerals under the conditions of the geotherm? In many cases these depend upon the behaviour of hydrogen, and changes in hydrogen bonding. In a larger collaborative programme I am involved in the development of new apparatus to allow neutron diffraction of minerals at high-P/T in situ, providing a way forward for the direct observation of the nature of hydrogen in solids at the conditions of the upper mantle.

c) **Novel routes to new materials**

Nature is able to provide several clues as to the synthesis and exploration of technologically useful materials. Biominerals display physical properties far in excess of the constituent parts, with control of structure exercised principally during growth at the surface. We have begun an exploration of the nature of the surface control of carbonates in the formation of biominerals, with the potential to apply these controls in the synthesis of new structures. On the other hand, the potential of high-P/T synthesis via metastable precursors provides a route for the development of novel refractory oxides relevant to the problems of chemical and nuclear waste disposal, as well as structures of interest in materials chemistry more widely.

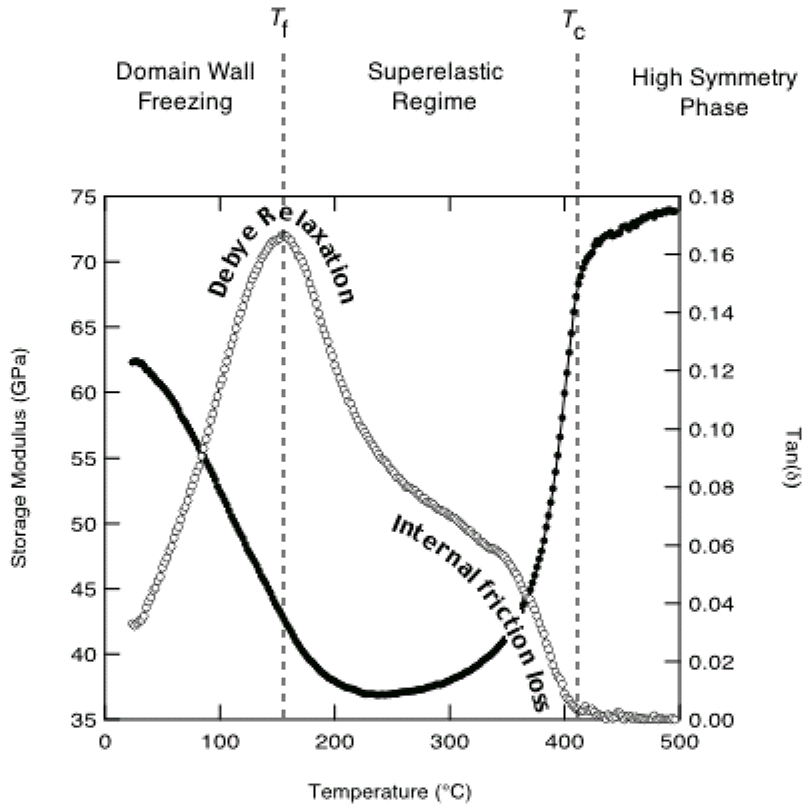


Figure 1: The behaviour of the elastic storage modulus and elastic loss modulus of a strontium-calcium titanate perovskite as a function of temperature through the cubic-tetragonal phase transition. The large elastic loss ("tan delta") arises from the movement of domain walls under applied stress in the three-point bend geometry of the experiment, and their interaction with pinning centres and grain boundaries. The dynamics of domain movement and relaxation behave according to a Debye model, with a peak in tan delta below which domain wall movement freezes.

Asteroid/Comet impacts and archaean crustal evolution

No article available

SEM/EDS and laser ICPMS study of c. 3.24—3.225 Ga Barberton impact spherules

A.Y. Glikson, G. Byerly[1], C. Allen, W. Taylor and I.H. Campbell [1] University of Louisiana

Least-altered samples of Barberton impact spherules (microkrystites) were studied by optical microscopy, scanning electron microscopy, electron probe EDS spectrometry, and laser-ICPMS mass spectrometry. The spherules are dominated by chlorite and are set in heterogeneous siliceous matrix. Some spherules contain partly resorbed octahedral nickel-rich chrome spinel concentrated in annular zones. EDS analyses of chromites indicate high levels of Ni, Co, V and Zn identified earlier by Byerly and Lowe (1994, Geochim. Cosmochim. Acta, 58, 3469-3486). Laser-ICPMS Analyses of micron-scale PGE nuggets indicate about an order of magnitude enrichment in Pt and Rh relative to the other PGEs

(RSES-2000, p. 124—125). Geochemical evidence for a meteoritic component in the spherules includes: (1) the spherules display PGE patterns depleted in the volatile Pd and Au (Kyte et al., 1992, Geochim. Cosmochim. Acta, 56, 1365-1372) consistent with their suggested condensation from impact-released vapor; (2) the spherules contain high Ni, Co and Cr levels (Ni and Cr up to about 3000 ppm), Ni/Co ratios (~40—80) higher than Barberton komatiites (<10) and C1 chondrites (21), and Ni/Cr ratios (~0.5—1.0) higher than Barberton komatiites (0.1—0.6) and lower than C1 chondrites (~4.0) (Figure 1). These relations allow mass balance mixing estimates of the proportion of meteoritic component (MC) admixed in the impact released vapor, showing that the MC varies between spherules, which range from compositions akin to komatiites and high-Mg basalts to compositions including a high meteoritic component of about 30 percent. Rare Earth element patterns in the spherules display marked relative depletion in the light REE (La/Sm)N ~ 0.4—0.8 as compared to Barberton komatiites with ratios of about unity or higher, potentially related to loss attendant with vapor condensation.

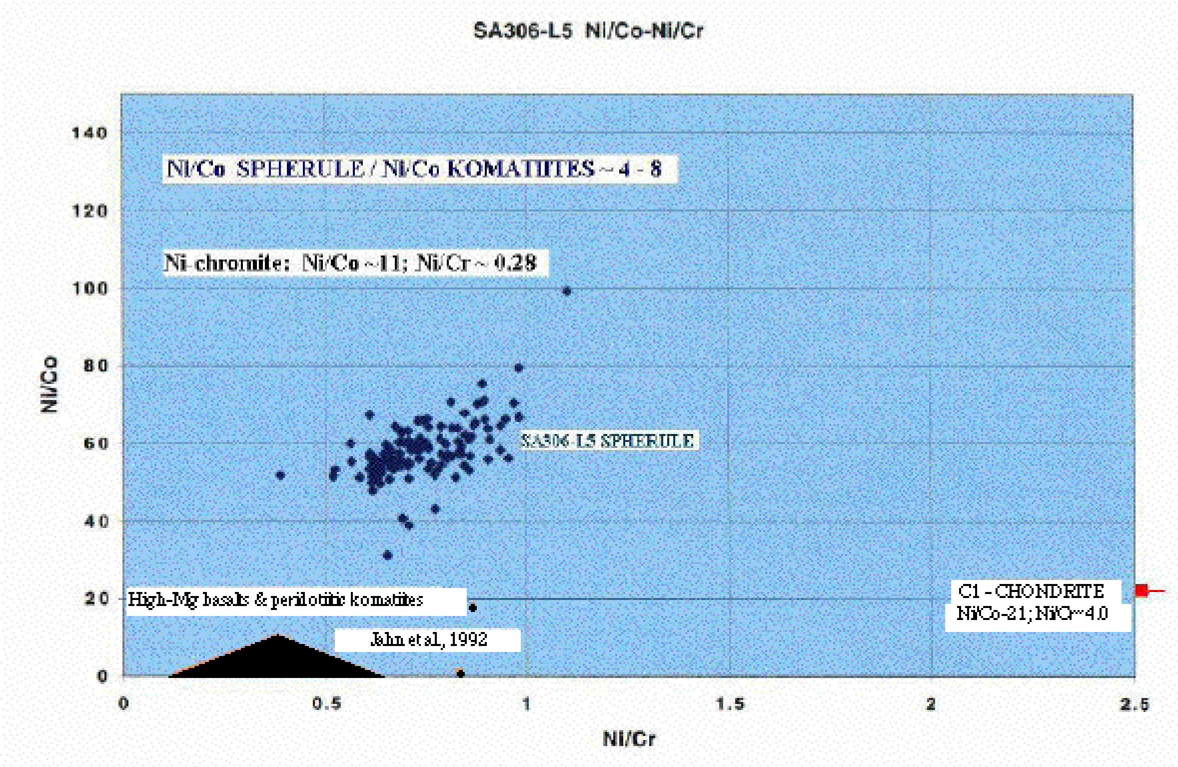


Figure 1: Ni-Co-Cr relations in Barberton spherules, indicating meteoritic signatures in impact condensate spherule SA306-L5, with distinct high Ni/Co (40—80) and high Ni/Cr (0.5—1.0) as compared to Barberton komatiites and high-Mg basalts.

SEM/EDS analyses of late Archaean — early Proterozoic Hamersley Basin impact spherules

A.Y. Glikson, B.M. Simonson[1] and S. Hassler[2] [1] Oberlin College, Ohio [2] State University of California, Hayward

Since 1992 several impact fallout units have been identified in the Hamersley Basin and Oakover syncline, including (with increasing age): Dales Gorge Member, Brockman Iron Formation, 2470+/-4 Ma; Bee Gorge Member, Wittenoom Formation, 2561+/-8 Ma; top Jeerinah Formation below Marra Mamba Iron Formation, pre-2630 Ma post-2687 Ma; lower Carawine Dolomite; top Lewin Shale (Simonson, 1992, Geol. Soc. Am. Bull., 104, 829-839); Simonson and Hassler, 1997, Aust. J. Earth. Sci., 44, 37-48). A field trip was undertaken by AYG during July-September, 2001, visiting impact fallout localities in the Hamersley Basin and Rippon Hills, followed by field work in the central and western Hamersley Basin aimed at extending the search for these units in other parts of the Basin. The thickness of impact spherule units generally increases eastward, where impact spherule-bearing debris flows reach a thickness of near 25 meters. Impacts on the scale indicated by the Hamersley fallout deposits trigger high energy seismicity and earthquakes, perhaps up to a magnitude of 9 on the Richter scale. The occurrence of boulder-scale rip-up clasts at the bottom of impact fallout units represents the effects of earthquakes and/or powerful tsunami waves effecting the sea floor. Impact spherules in the Hamersley Basin typically contain inward-radiating crystals of K-feldspar, surrounding off-center central cavities filled with carbonate, quartz and iron oxides. Other spherules are dominated by hydrous Mg-rich silicates – chlorite and stilpnomelane. The lack of shocked quartz grains in these deposits suggests that the spherules originated from impacts impinging on basaltic oceanic crust and not on quartz-bearing continental crust. PGE studies of Hamersley spherules indicate Iridium anomalies of up to about 1.7 ppb, with mean values of about 0.5—0.6 ppb – about an order of magnitude higher than background sediments (Simonson et al., 1999, Geol. Soc. Am. sp. Pap., 339, 249-261). Hydrous alteration resulted in obliteration of other PGE and trace metal signatures.
SEM/EDS studies of the Dales Gorge spherules identify cores of stilpnomelane enveloped by shells of K-feldspar which contain euhedral ilmenite blades and micro-scale Ni, NiO, NiS and Co-bearing NiAs particles (Figure 1a, 1b). Due to their micron-scale size no pure probe analyses were obtained of the Ni particles and ilmenites. SEM/EDS analyses of zoned spherules from the top Jeerinah spherule layer indicate abundance of Ni-rich (up to 0.9% NiO) hydrous iron oxides, whichoccur both as veins through the spherules and in the inter-spherule matrix.

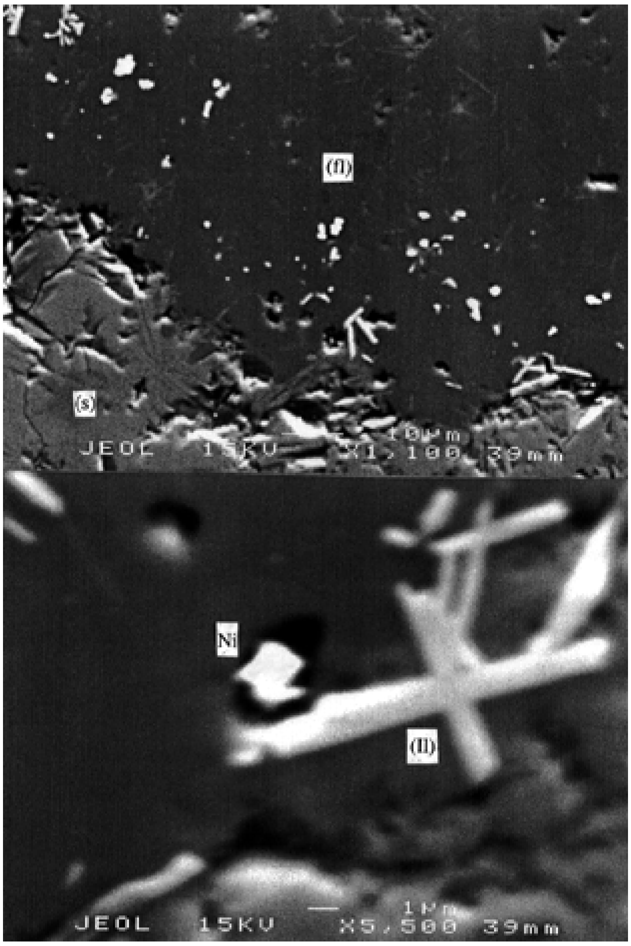


Figure 1: (1) SEM Backscattered Electron (BSE) image of Ilmenite (Il) and Ni particles (Ni) in feldspar shell (fl) and surrounding stilpnomelane (s), Dales Gorge Member spherules; (2) detailed BSE image of Ilmenite blades and Ni-particle.

Siderophile enrichment of basement uplift granitoids, Woodleigh impact structure: shock metamorphism and vapor-mediated chemical alteration

A.Y. Glikson, S. Eggins, F. Pirajno[1], R. Iasky[1], A. Mory[1] and T.P. Mernagh[2] [1] Geological Survey of Western Australia[2] Australian Geological Survey Organization

Scanning electron microscopy, electron microprobe energy dispersive spectrometry, laser ICPMS spectrometry, Laser Raman spectroscopy (LRS), and whole-rock major and trace element XRF and ICPMS analyses allow resolution of shock-related micron-scale heterogeneities in granitoid core samples from the central uplift of the recently confirmed 120 km-diameter Woodleigh impact structure, Western Australia. The samples consist of interleaved zones dominated by quartz showing planar deformation features (PDF), feldspar with PDF, diaplectic feldspar showing fusion along and across PDFs which results in honeycomb-like textures, and microbrecciated pseudotachylite veins enriched in vapor-transferred components and classified as S-type pseudotachylites (Spray, 1998, Geol. Soc. London Sp. Publ., 140, 195—204). The pseudotachylite and amorphous intra-feldspar zones are enriched in refractory Al, Mg, Ca and siderophile elements and depleted in the volatile Si and K relative to whole rock compositions, which approximate adamellite. However the rocks are enriched in Mg, Fe, Ca, Ni, Co and Cr relative to low-Ca granites. High Ni/Co and

Ni/Cr ratios militate for the importance of a meteoritic component. The bulk of the metals occur in penetrative pseudotachylite veins and in amorphous diaplectic zones within desegregated and resorbed feldspar. The origin and mode of transport of the trace metals require that melt and vapor originated from the exploding projectile. Evidence for a vapor phase is yielded by occurrence of texturally isolated micron-scale metal-enriched amorphous spots within feldspars. The enrichment in metals suggest the shocked granitoids were located either at high levels of the central uplift or, alternatively, represent subcrater breccia injected by impact melt and vapor.

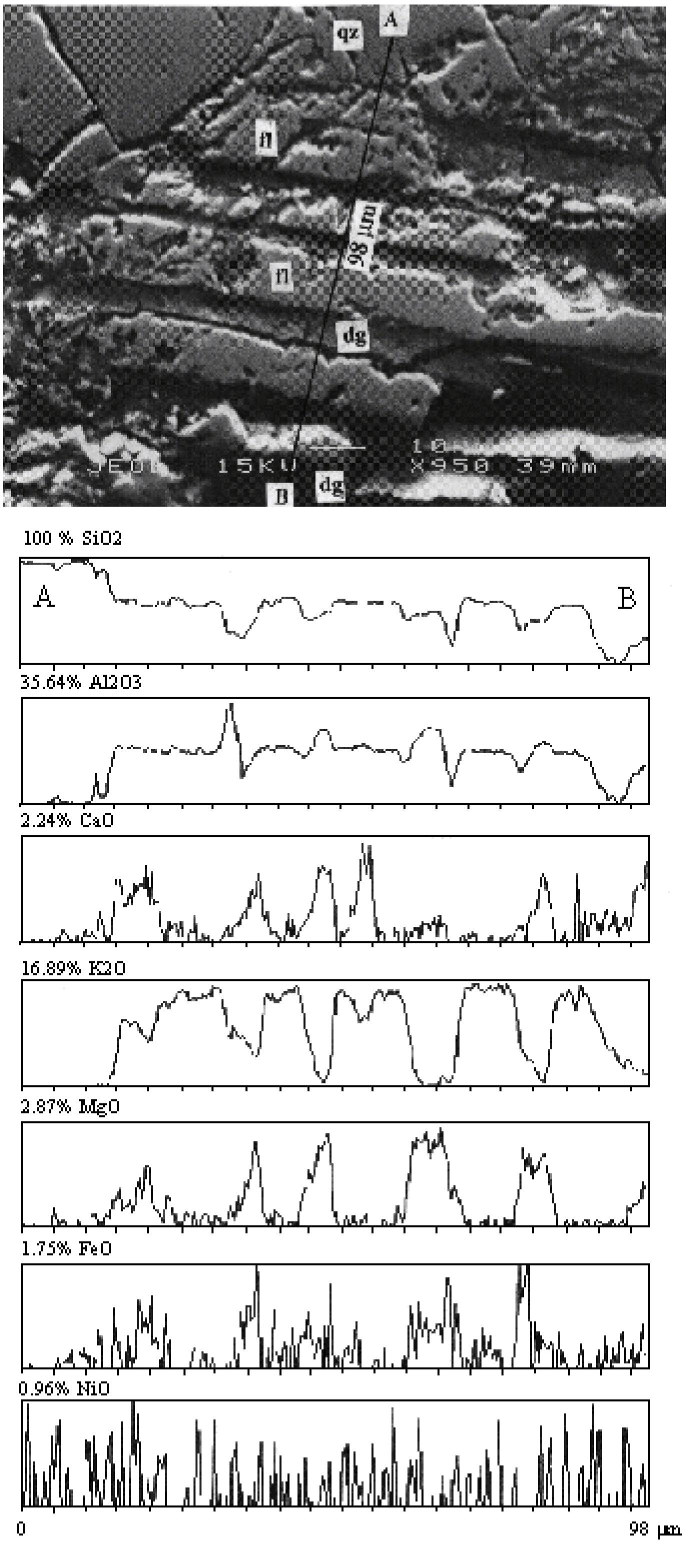


Figure 1: SEM BSE image marking an EDS (Energy Dispersion Spectrometry) chemical profiles along a 98 micron-long traverse through a shock metamorphosed feldspar grain. The K-feldspar shows diaplectic shock-amorphisation along PDF (planar deformation features). The traverse starts in quartz (qz) at point A, passing through alternations of feldspar with diaplectic spots (fl) and parallel amorphous zones (dg) marking solid-state transformation of feldspar to glass along PDF planes. The chemical profiles indicate depletion of the amorphous material in volatile oxides (SiO_2, K_2O) relative

to feldspar and enrichment of the amorphous material in more refractory oxides (CaO, MgO, FeO). Note the high levels of NiO, interpreted in terms of metal-volatile transfer from the impacting projectile.

Petrophysics Annual Report 2001 - Introduction

The Group's research centres on investigation of the physical behaviour of geological materials under controlled laboratory conditions and application of the resulting insights to the structure and processes of the Earth.

Measurements of macroscopic physical properties such as strength, permeability or seismic wave speeds and attenuation, are interpreted through microstructural studies centred around light and electron microscopy. Often it is necessary to prepare, from either natural or synthetic precursors, simpler synthetic materials whose properties are amenable to more detailed interpretation than those of complex natural rocks. Our interest in Earth materials is shared by members of the School's Petrochemistry and Experimental Petrology Group, who focus primarily upon the chemical aspects of their behaviour.

Geological and geophysical observations of the response of the Earth to naturally applied stresses, which vary widely in intensity and timescale, provide much of the motivation for the Group's work. In the laboratory, ultrasonic wave propagation and lower frequency forced-oscillation methods are used to probe the elastic/anelastic behaviour which determines seismic wave speeds and attenuation. On longer time scales and at higher stresses, the mechanical behaviour of synthetic faults and fault gouge is studied with particular interest in the complex interaction between chemical reaction, crustal deformation and fluid flow. The fact that all but the simplest elastic behaviour of geological materials is controlled by microscopic defects such as dislocations and processes operative at grain boundaries, places a premium on the complementary microstructural studies involving light and electron microscopy.

Major achievements for 2001 include

- Demonstration of the capability for accurate high-temperature (to 1600 K) measurement of elastic wave speeds by ultrasonic interferometry
- Identification of a melt-related dissipation peak in an exploratory study of the influence of partial melting on seismic wave attenuation in fine-grained polycrystalline olivine.

Members of the group collaborate widely within the School and beyond. Natural links with the Seismology Group are based on a common interest in the interpretation of seismological models for the Earth's interior. Preparation of synthetic rock specimens and their precursors and investigations of melt distribution within partially molten upper mantle rocks involve intensive collaboration between the Petrophysics and Petrochemistry and Experimental Petrology Groups. The field-based observations of the structures and microstructures in naturally deformed rocks, and fluid-chemical studies by members of the Centre for Advanced Studies of Ore Systems (RSES and Geology Department, Faculty of Science), complement the experimental program in rock deformation.

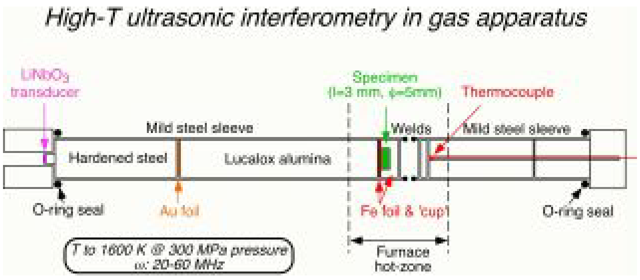
Within the wider ANU community, the influence of the Petrophysics Group is felt in a variety of forums. The ANU's flagship TEM serving the needs of the campus materials science community, is housed within the School and operated by Dr. Fitz Gerald and Mr. D. Llewellyn on behalf of the ANU Electron Microscope Unit. In this capacity, Dr Fitz Gerald collaborates intensively in microstructural aspects of various materials science programs particularly those of the Research School of Physical Sciences and Engineering. Maintaining the group's longstanding commitment to the enrichment of undergraduate teaching, Dr.

The successful operation of novel equipment, and the further development and timely exploitation of associated experimental techniques, depend heavily'upon the skill and commitment of research support staff Messrs H. Kokkonen and J. Carr and Ms. L. Weston along with the staff of the School's Mechanical and Electronics Workshops. Mrs K. Provins provides invaluable administrative support for the activities of the Petrophysics and Ore Genesis Groups, including responsibility for website development and maintenance. With the arrival of School-funded post-doc Eric Tenthorey from Columbia University, New York and the funding this year of two new ARC proposals, the Group is well positioned to pursue the ambitious research agenda outlined below. It is with regret that we farewell Joshua Carr after just two productive years with the Group as a trainee technical officer and wish his well in his new career.

Temperature dependence of elastic wave speeds by ultrasonic interferometry

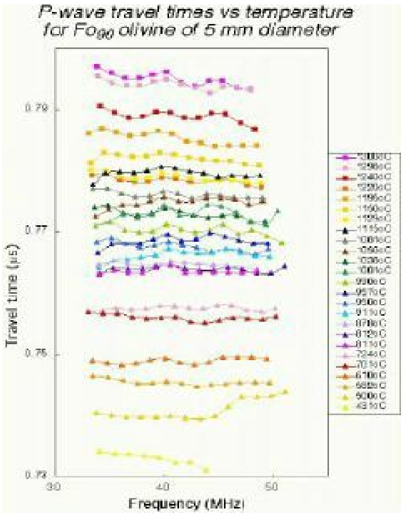
I. Jackson, L.J. Weston and S.L. Webb

For several years we have been working on the development of experimental methods for measurement of elastic wave speeds by ultrasonic interferometry within the high-temperature, moderate pressure environment (to 1600 K, 300 MPa) of an internally heated gas-charged pressure vessel. Last year we described preliminary measurements made with an assembly, comprising a compound hardened steel/polycrystalline alumina acoustic buffer rod in contact via Fe foil with a specimen of 7 mm diameter otherwise surrounded by soft-iron pressure-transmitting medium, all enclosed within a thin-walled mild steel sleeve (Figure 1). Our ultimate objective is to perform measurements on specimens of high-pressure silicate minerals typically < 3 mm in diameter. In preparation for such measurements we have this year performed measurements on a series of cylindrical specimens of progressively smaller diameter machined from the same boule of fine-grained (~3µm) synthetic polycrystalline Fo_{90} olivine.



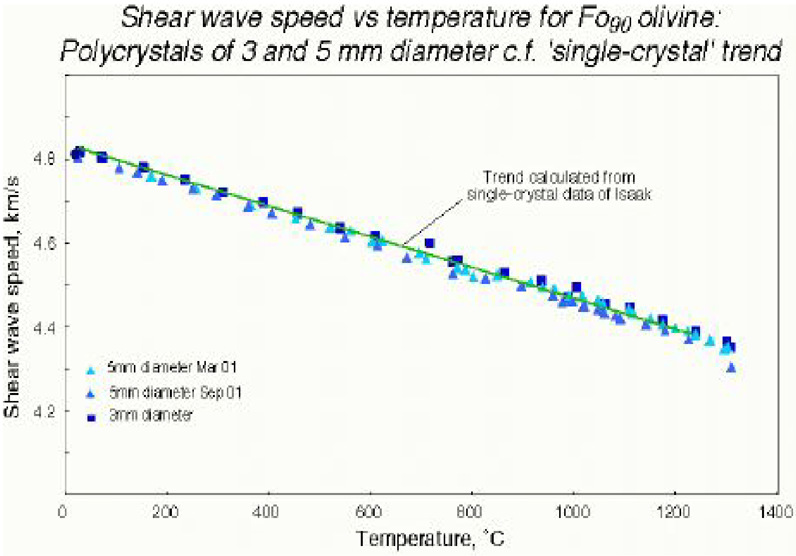
Experimental assembly for measurement of the temperature dependence of elastic wave speeds in an internally heated gas-charged pressure vessel by ultrasonic interferometry.

With appropriate spacing between a pair of phase-coherent RF pulses applied to the transducer, interference between the echoes returning to the transducer following reflection from the near and far ends of the specimen gives rise to a series of alternate maxima and minima in the amplitude of the overlapping echoes as the carrier frequency is varied. Each of these interference extrema corresponds to a situation in which the two-way path through the specimen contains either an integral or half-integral number p of wavelengths. Consequently the traveltime $t = p/f$ is estimated with considerable redundancy by the determination of the carrier frequencies f for a series of successive interference extrema. A representative set of traveltimes inferred in this way is shown in Figure 2. Mean traveltimes determined as averages over a fixed frequency interval are combined with the temperature-adjusted specimen length to calculate the compressional (V_P) or shear (V_S) wave speed.



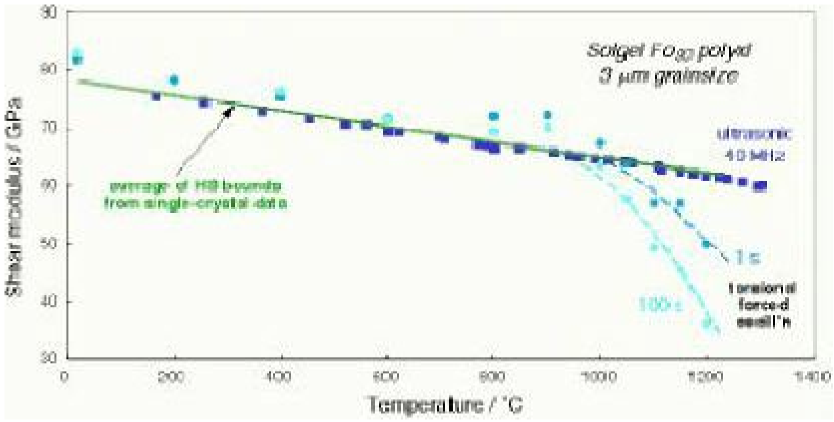
Representative data from ultrasonic interferometry illustrating the redundancy provided by traveltime determination from multiple interference minima.

Compressional and shear wave speeds thus determined for cylindrical Fo_{90} olivine polycrystals of 5 and 3 mm diameter and 3 mm length are compared in Figure 3 with the temperature-dependent wave speeds expected from single-crystal elasticity data. The agreement is excellent indicating the considerable robustness of the technique. The temperature-dependent shear wave speed thus inferred from measurements at frequencies near 40 MHz is compared in Figure 4 with the results of torsional forced oscillation measurements at seismic frequencies (10 mHz - 1 Hz, see below). For temperatures ≤ 1200 K, there is a broad consistency within experimental error between the results obtained at these vastly different frequencies indicative of essentially elastic behaviour. At higher temperatures, the G(T) trends for the two frequency ranges diverge markedly reflecting frequency-dependent (dispersive) behaviour associated with viscoelastic relaxation. This comparison highlights the dangers inherent in the traditional direct seismological application of wave speeds measured in the laboratory with ultrasonic and opto-acoustic techniques. The temperature sensitivity of the shear modulus and hence wave speed may be seriously underestimated (Figure 4).



Comparison of measurements performed on Fo_{90} specimens of two different diameters (5 and 3 mm) indicating the insensitivity of the results to the size of the specimen and also the close approach to the temperature dependent modulus calculated from single-crystal elasticity data.

Comparison of shear moduli measured on fine grained Fo_{90} olivine by ultrasonic interferometry (specimen of 5 mm diameter, average frequency ~40 MHz), and by seismic-frequency (≤ 1 Hz) forced-oscillation techniques, with expectations from single-crystal elasticity data (line). The markedly lower values of modulus and stronger temperature sensitivity observed at seismic frequencies and sufficiently high temperature (≥ 1300 K) are associated with substantial viscoelastic relaxation and have important implications for the interpretation of tomographic models of wave speed variability for the upper mantle.



The quality of the ultrasonic measurements is maximised for an echo amplitude ratio near unity. However, as the specimen diameter is reduced there is a systematic reduction in the amplitude of the echo returning from the far end of the specimen. We are seeking to improve this situation by tapering the end of the buffer rod to better match the specimen diameter. In addition we plan soon to explore the use of dual-mode transducers in making simultaneous measurements of both compressional and shear wave speeds. With these further improvements to the technique we expect to commence measurements on a suite of specimens of high-pressure silicate minerals during the coming year. This work, to be performed in collaboration with colleagues from the State University of New York at Stony Brook and Delaware State University, will address key unresolved issues concerning the elasticity of the transition zone of the Earth's mantle.

Seismic wave attenuation in polycrystalline olivine: the influence of grain size and partial melting

Ian Jackson, John Fitz Gerald, Uli Faul, Harri Kokkonen and Joshua Carr

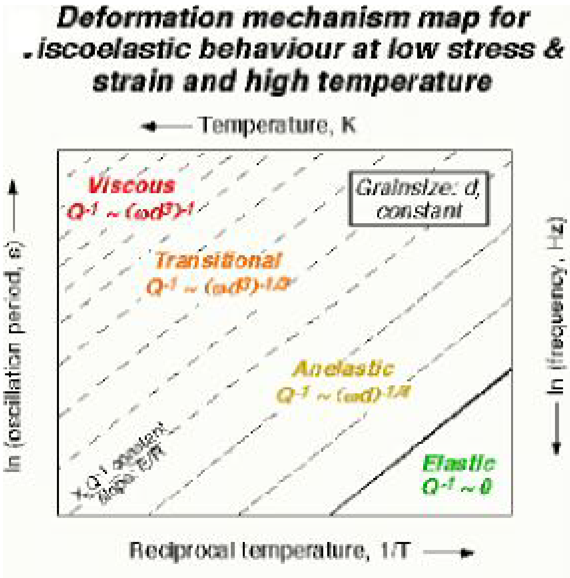


Figure 6. A schematic deformation mechanism map for the linear viscoelastic behaviour encountered at very low stress and strain levels in fine-grained polycrystalline materials, illustrating the expected frequency, temperature and grainsize sensitivity of the strain energy dissipation. The parallel lines trending from lower left to upper right (of slope E/R) are

contours of constant Q^{-1} associated with constant values of X µ T_o exp(-E/RT). As X increases from its value at the elastic threshold (i.e. moving towards the upper left of the figure by increasing temperature T or period T_o) the frequency and grain-size sensitivity of the dissipation steadily strengthen.

During 2001 the focus has shifted increasingly to the behaviour of partially molten ultramafic materials. To this end pellets have been cold-pressed from mixtures of Fo_{90} olivine ($[Mg_{0.9}Fe_{0.1}]_2SiO_4$ - either natural or synthetic) and synthetic basaltic glass powders containing either 2 or 4% of the basaltic component. These pellets have been converted into dense polycrystalline aggregates by hot-isostatic pressing within $Ni_{70}Fe_{30}$ foil-lined mild steel sleeves in an internally heated gas-medium apparatus typically for 25 hr at temperatures of 1200-1300°C and pressures of 200-300 MPa. Firing of some of the precursor powders and in some cases also the hot-pressed specimens has resulted in substantial variation of the water content (~20-250 wt ppm H_2O) of the resulting specimens.

Both shear modulus and strain energy dissipation Q^{-1} have been inferred from torsional forced oscillation measurements performed during slow staged cooling to room temperature following a protracted annealing period at the highest temperature Ð identical in most cases to that of the prior hot-pressing experiment. Exploratory experiments have revealed a variation of dissipation with oscillation period and temperature that is qualitatively different from the monotonic variation characteristic of the melt-free materials. For the melt-bearing specimens a well-defined Q^{-1} plateau at temperatures of 1400-1500 K separates more markedly frequency and temperature dependent dissipation at both lower and higher temperatures (Figure 7(a)). That this perturbation is associated with a melt-related dissipation peak superimposed upon the monotonic background characteristic of melt-free materials is seen most clearly in the plot of log Q^{-1} versus 1/T (Figure 7(b)). The peak enters the observational window from periods longer than 100 s contributing to a steepened dependence of Q^{-1} upon period at 1270-1320 K. Its systematic displacement to shorter period with increasing temperature results in reduced frequency sensitivity first at long periods and ultimately across the entire observational window. The nearly frequency-independent behaviour at 1420 and 1470 K evidently results from the near cancellation of the contrasting frequency dependences associated with the background and the long-period side of the dissipation peak. At sufficiently high temperatures, the melt-related dissipation peak moves to periods significantly shorter than 1 s and the monotonic frequency and temperature dependence associated with the background dissipation is progressively restored.

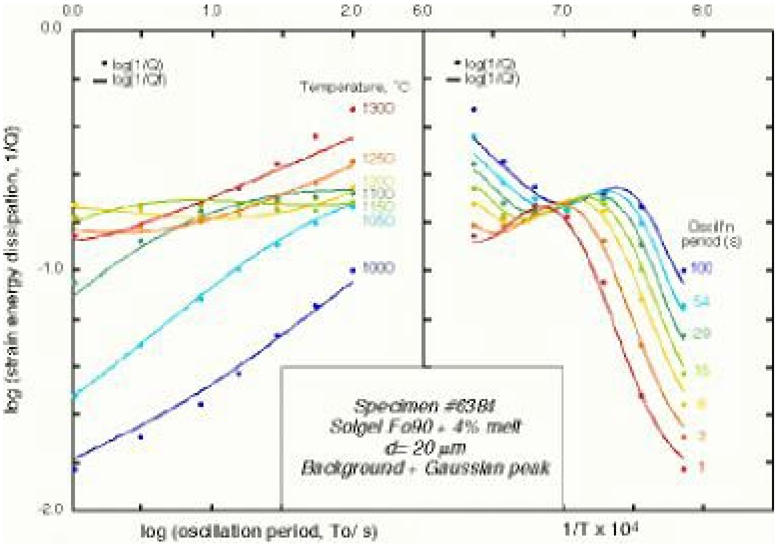


Figure 7 The variation of strain energy dissipation with oscillation period and temperature for specimen #6384 (sol-gel Fo_{90} + 4% basaltic melt). Data are indicated by the plotting symbols, whereas the curves represent a fit to the data involving superposition of a Gaussian dissipation peak upon the monotonic background characteristic of melt-free materials.

In work in progress, the methods of light microscopy and scanning and transmission electron microscopy are being combined to determine the temperature-dependent melt fraction in such specimens and the nature of the grain-scale melt distribution (Figure 8). This additional information is expected to help identify the cause at the microscopic scale of the observed melt-related dissipation. The stress induced local redistribution of melt ('melt squirt') is a serious contender.

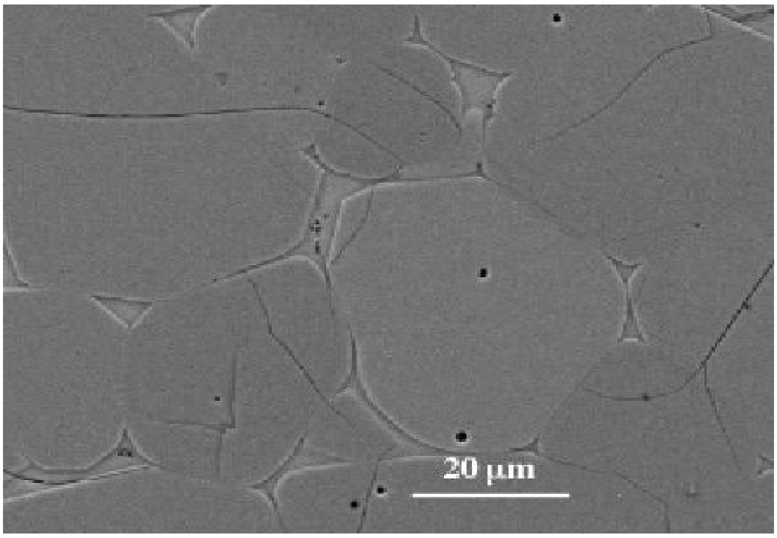


Figure 8 A suitable micrograph showing melt distribution -possible from one of the recent cook-quench-look experiments on AT6384. The unusual frequency dependence of dissipation seen in these exploratory experiments, if confirmed more generally, might prove to be a seismologically observable characteristic of partially molten regions of the Earth's upper mantle.

A test of an alternative finite-strain equation-of-state for the lower mantle

I. Jackson

It has long been recognised that there is no unique choice of the strain measure to be used in finite-strain equations of state. However, experimentally determined compression curves for standard materials such as MgO provide an opportunity to test the performance of equations of state based on the alternative Eulerian, Lagrangian and Hencky (or natural) strain measures. In this way it was demonstrated conclusively in the early 1970's that the Eulerian strain measure is to be preferred over the Lagrangian if the Taylor expansion of Helmholz free energy in powers of strain is to be truncated at third order. The natural strain measure $e_H = (1/3) \ln (V/V_0)$ recently proposed by Poirier and Tarantola needs to be tested in the same way. Accordingly, shock compression curves (Hugoniots) for MgO were calculated from 3rd-order Eulerian (Birch-Murnaghan) and Poirier-Tarantola isentropes with ultrasonically determined K_0 and K'_0 along with a common Mie-Grüneisen-Debye treatment of the additional thermal pressure. The Hugoniot based on the Birch-Murnaghan isentrope accurately reproduces the shock compression data whereas the Hugoniot based on the 3rd-order Poirier-Tarantola isentrope is clearly systematically too compressible at very high pressure (Figure 9). Pending further testing, the Eulerian strain measure is therefore preferred.

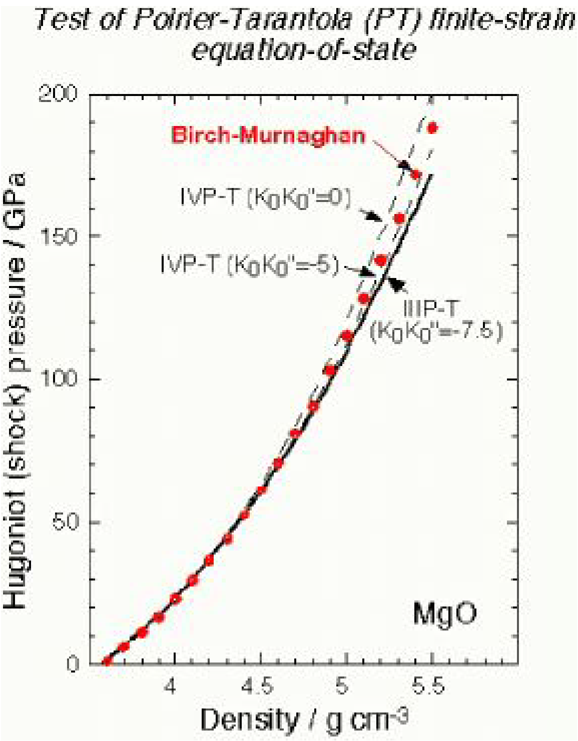


Figure 9 Comparison of calculated Hugoniots for MgO based on the alternative Eulerian and Poirier-Tarantola isentropes. The Hugoniot based on the 3rd-order Poirier-Tarantola isentrope is clearly too compressible at very high pressure.

Nevertheless, the implications have been explored of fitting the Poirier-Tarantola equation of state (at either 3rd or 4th order) to the prem model of Dziewonski and Anderson for the pressure dependence of the seismic parameter f and the density r. The curves labelled 'IIIP' and 'III&phi' in the uppermost panel of Figure 10 define the values of the zero-pressure bulk modulus K_0, that for each trial value of the zero-pressure density r_0, provide optimal fits to $P(e_H)$ and $f(e_H)$, respectively. The intersection of these curves defines a unique ($_0$, K_0) combination that simultaneously fits both datasets very well. The associated values of the higher derivatives K'_0 and $K_0K''_0$ can be read off the lower panels. The optimal 3rd-order Poirier-Tarantola fit to the prem lower mantle is given by (r_0, K_0, K'_0, $K_0K''_0$) = (3.965, 193.5, 4.79, -11.6), where $K_0K_0'' = - 3 - K'_0(K'_0 - 3)$. Relative to the corresponding 3rd-order Eulerian fit, $_0$ is marginally (0.5%) lower. K_0 is substantially (9%) lower resulting in more compressible behaviour at low P offset at higher P through a markedly higher (+23%) value for K'_0. The consequences of such a high value of K'_0 are tempered by a ~3-fold increase relative to the Eulerian fit in the magnitude of $K_0K''_0$. Such differences would have profound implications for interpretation of the elasticity of the lower mantle in terms of chemical composition and temperature.

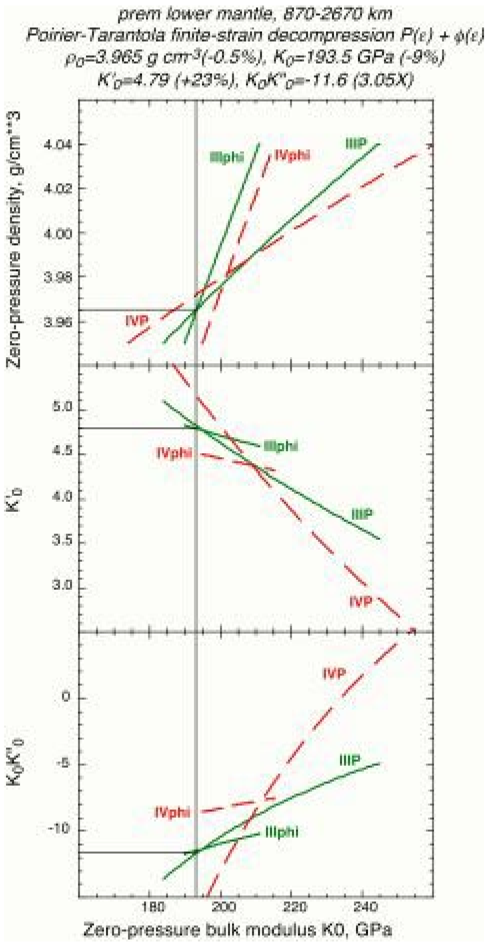


Figure 10. Adiabatic decompression of the prem lower mantle model with the Poirier-Tarantola finite-strain equation of state. The vertical line spanning all three panels links the intersections of the IIIP and IIIf covariance curves, thereby serving to identify the parameters of the optimal fit to both $P(e_H)$ and $r(e_H)$.

Fluid Rock Interaction Fluid flow, vein formation and permeability evolution in the Earth's Crust

Eric Tenthorey, Stephen Cox and Christoph Hilgers

Chemical reactions in the Earth's crust can profoundly influence various mechanical and hydraulic properties of the host rock. One such property, permeability, can be altered dramatically as reactants dissolve and metamorphic products form within fractures or intergranular pore space. In addition to the obvious importance of permeability in the formation of certain ore deposits and for hydrocarbon migration, rock permeability can also have an important role in controlling pore pressures and lithologic strength. In the case where permeability reduction is accompanied by deformation, pore pressures may rise and induce mechanical failure of the rock, thus creating new fracture conduits for fluid flow and reaction. If such a process is repeated over time, extensive vein networks can form, potentially containing significant precious metal concentrations. Although such ideas are generally accepted among the scientific community, the incorporation of chemical fluid-rock reaction processes into understanding linkages between fluid transport properties and deformation processes is relatively new. As a result, these processes are very poorly understood in terms of how pore and fracture topology evolve, the magnitudes of permeability change involved and the role of temperature and pore pressure on chemical reactivity and mechanical behaviour. We are investigating these questions with the aim of understanding large scale issues such as hydration and fluid flow in the lower crust, mechanics of faulting and the formation of economically valuable mineral deposits. The first phase of this project is exploring hydrothermal sealing in fractured quartzite. These experiments are being performed in a Paterson high pressure rig. The fractured specimens are subjected to temperature gradients of up to 25°C/cm with the high temperature end of the sample at temperatures ranging from 500-900° C. As fluids diffuse from the high T/high solubility end of the specimen to the lower T end, precipitation of quartz occurs. We are exploring the temperature dependence of fracture closure processes and rates. Previous studies on reactive flow have shown that such topologic changes in sealing fractures have drastic effects on flow properties, namely permeability. Experiments, currently in preparation, will combine diffusion driven vein formation with permeability and porosity measurements, so that the link between various vein morphologies and flow properties may be quantified. The next step in this program will investigate fracture sealing and permeability evolution in a dynamic environment, where episodic shear failure and associated permeability enhancement competes with fracture healing and sealing processes which destroy permeability between slip events. These experiments are providing a quantitative understanding of processes controlling fluid-driven nucleation of earthquakes.

Environmental Processes group

Holocene Records of the Indian Ocean Dipole

N.J. Abram and M.K. Gagan

The Indian Ocean Dipole is a recently discovered mode of inter-annual climate variability, which results in anomalous winds, sea surface temperatures and rainfall throughout the Indian Ocean region, bringing drought to Indonesia and Australia and floods to eastern Africa. Developing a better understanding of the natural dynamics and effects of the Indian Ocean Dipole is essential for improved long-range forecasts of droughts and floods in the Indian Ocean region.

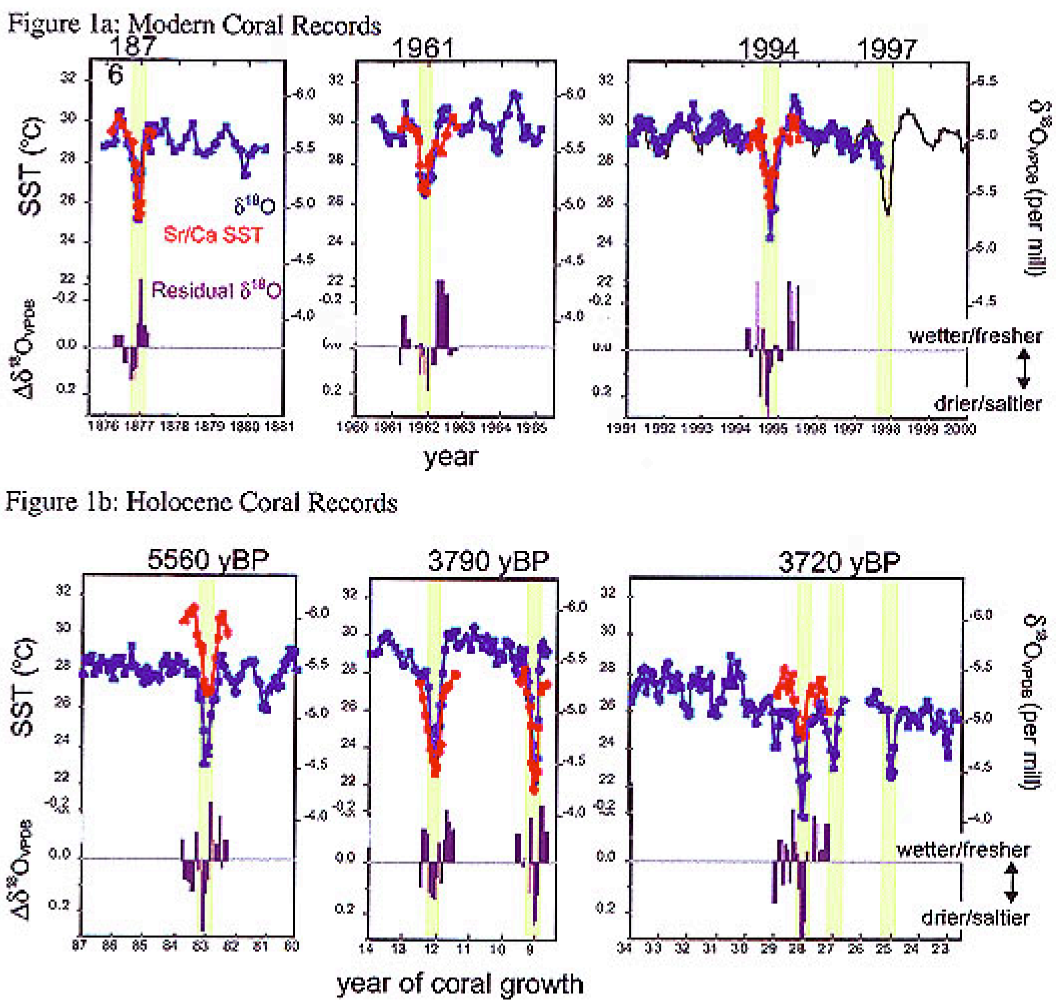


Figure 1: (A) Modern and (B) Holocene coral records of the Indian Ocean Dipole. Dipole events are marked by shaded yellow bars. Dipole events are characterised in the coral records by strong cooling in coral Sr/Ca (red symbols) and $\delta^{18}O$ (blue trace) as well as drying in residual $\delta^{18}O$. The modern coral records identify a previously unrecognised Indian Ocean Dipole event during 1876, while the Holocene corals provide the first evidence that the Indian Ocean Dipole has operated since at least the mid-Holocene.

Corals from the Mentawai Islands (south-west Sumatra, Indonesia) provide an excellent opportunity to reconstruct the dynamics of the Indian Ocean Dipole. This area lies in the eastern Indian Ocean and experiences upwelling, strong sea surface cooling and drought during Indian Ocean Dipole events. The delta18O and Sr/Ca composition of modern corals from the Mentawai Island clearly preserve the 1994 and 1961 Indian Ocean Dipole events (Figure 1a). A previously unrecognised dipole event is also identified during 1876. Dipole events in the modern coral records are characterised by distinct cooling signals in coral Sr/Ca and delta18O as well as low rainfall in residual delta18O records. These modern coral records confirm that corals from the Mentawai Islands can be used to reconstruct Indian Ocean Dipole events.

The Holocene coral records preserve similar signals (Figure 1b) and provide the first evidence that the Indian Ocean Dipole has operated since at least the mid-Holocene. These dipole events also occurred during times when the Mentawai Island corals indicate that mean sea surface temperature and/or rainfall conditions were different to present day, showing that the Indian Ocean Dipole is a robust climatic feature that persists in a range of mean climatic states. The fossil coral records also provide evidence that the Indian Ocean Dipole system can operate independently of the El Niño-Southern Oscillation (ENSO), with dipole events continuing in the mid-Holocene when ENSO is thought to have been substantially weaker than present day.

Abrupt tropical cooling ~8,000 years ago

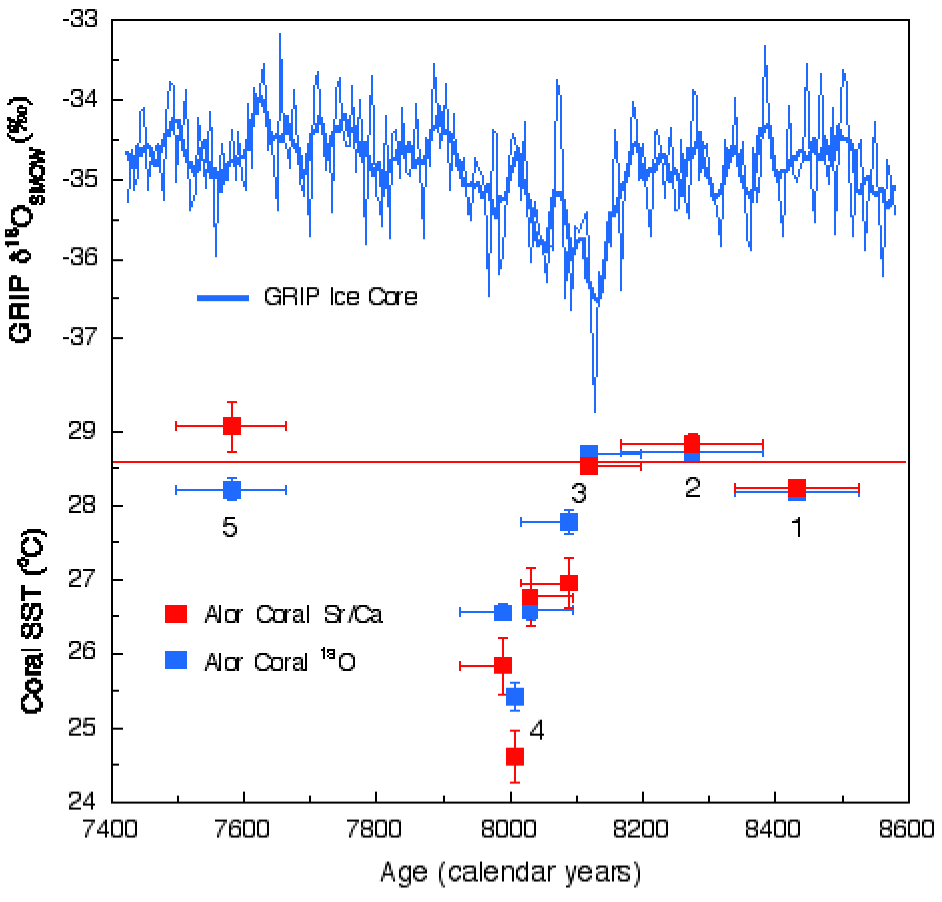
M.K. Gagan, L.K. Ayliffe*, H. Scott-Gagan, W.S. Hantoro, B.W. Suwargadi, D. Prayudi, M.T. McCulloch

Understanding the sensitivity of tropical temperatures to climate change is a fundamental goal in climate change research. Establishing the relative timing and magnitude of abrupt climate change in the tropics and polar regions provides an important means for evaluating the potential role of the tropics in global climate change. The largest abrupt climate change in the Holocene occurred between 8200 and 8000 calendar years ago, when the temperature dropped by 4-8 C in central Greenland and 1.5-3 C around the North Atlantic region. However, little is known about the nature of the so-called 8.2 ka cold event in the tropics.

We drilled a sequence of exceptionally large, well-preserved *Porites* corals within an uplifted palaeo-reef in Alor, Indonesia, with Th-230 ages spanning the period 8400 to 7600 calendar years before present (Figure 2). The corals lie within the Western Pacific Warm Pool, which at present has the highest mean annual temperature in the world's ocean. Measurements of coral Sr/Ca and oxygen 18 isotopes at 5-year sampling increments for five of the fossil corals (310 annual growth increments) have yielded a semi-continuous record spanning the 8.2 ka event. The measurements (Figure 2) show that sea-surface temperatures were essentially the same as today from 8400 to 8100 years ago, followed by an abrupt ~3°C cooling over a period of ~100 years, reaching a minimum ~8000 years ago. The cooling calculated from coral oxygen 18 isotopes is similar to that derived from Sr/Ca. The exact timing of the termination of the cooling event is not yet known, but a coral dated as 7600 years shows sea-surface temperatures similar to those of today.

The cooling of ~3°C was very rapid (~0.3°C per decade) and is nearly synchronous with abrupt cooling in the North Atlantic region, as indicated by the decrease in oxygen 18 isotope values of ice from the GISP2 ice core (Figure 2). This new finding supports the hypothesis that abrupt climate change at high latitudes can propagate rapidly to the tropics. Initial cooling at high latitudes could serve to enhance the equator-to-pole temperature gradient and strengthen both the meridional atmospheric circulation and the tropical tradewinds. Today, strong tradewinds in the vicinity of Alor, and elsewhere in the tropics, drive upwelling that locally cools the ocean surface. Our results indicate that the Warm Pool region is unexpectedly sensitive to climate change at high latitudes, suggesting that ocean-atmosphere feedbacks involving the tropics may play a role in propagating abrupt climate changes between the northern and southern hemispheres.

Figure 2: (A) Summary of decadal-average coral Sr/Ca (red symbols) and delta 18OPDB (blue) temperatures calculated for Holocene (Th230 ages) Porites from Alor, southern Indonesia (8°17'S, 124°25'E). For comparison, the upper blue curve shows the 5-year average delta 18OSMOW values (smoothed with 25-year running mean) of ice in the GISP2 ice core, interpreted to reflect the temperature of precipitation over Summit, Greenland (Stuiver et al., 1995). Horizontal bars for coral Sr/Ca and delta 18O indicate time-span of coral cores (40-75 years) plus the 2 sigma uncertainty in the Th230 age determinations. Vertical bars indicate standard error of temperature estimate. Records for cores 3 and 4 have been divided into sections to show timing of cooling event relative to that observed in the GISP2 ice core. Red line shows modern mean sea-surface temperature (28.6°C)



at Alor.

Non-stationary ENSO teleconnections in northeast Australia Since 1650 AD

E. Hendy, M.K. Gagan and J. Lough

A 373-year chronology for eight, multi-century, *Porites* coral cores was developed using cross-dating techniques adapted from dendrochronology. Characteristic patterns of distinct fluorescent lines within the coral skeletons were matched between coral cores from inshore and mid-shelf reefs in the central Great Barrier Reef, Australia. Skeleton-plots of fluorescent banding were produced for each core and combined into a master chronology back to AD 1615, which overcame dating difficulties caused by core and discontinuities. The master record provides a proxy for Burdekin River discharge and Queensland summer rainfall.

Climatic patterns in NE Australia associated with El Niño Southern Oscillation (ENSO) events varied during the 20th century. Instrumental records show that the links were strong prior to the 1920s and since the 1960s, but were non-existent from the 1920s to 1950s, when interannual rainfall variability was reduced. Using the fluorescence master record, we have examined links between climatic variation in NE Queensland since the mid-17th century and a published reconstruction of ENSO for the same period (NINO3, 1650-1980). Correlations between the two series mimic the periods of fluctuating links during the 20th century. Furthermore, the master record is significantly correlated with the NINO3 series from the mid-17th to late 18th centuries, suggesting that ENSO-related patterns were as dominant then as in recent decades. However, the relationship between ENSO activity and Queensland rainfall is weak from the 1800s to the 1870s, when both inter-decadal and interannual variability are low in the fluorescence master record. In summary, these results show that recent increases in ENSO variability and the strength of the effect of ENSO on NE Queensland rainfall are not confined to the modern period, but instead occurred regularly over the past several centuries. Such variability must, therefore, be a mode of 'natural' climate behaviour that needs to be understood.

Diagenesis and Geochemistry of Late Quaternary Porites Corals: Implications for Palaeoenvironmental Reconstructions

H.V. McGregor and M.K.Gagan

Coral proxy records of hydrological balance and sea surface temperature, using Sr/Ca and oxygen-isotope ratios, have become important tools in palaeoclimate reconstruction. However, there have been few systematic investigations of the potential impact of post-depositional alteration of coral skeletons on geochemical tracers commonly used in such reconstructions. In order to address this, we analysed Sr/Ca, oxygen (delta18O), and carbon (delta13C) isotope ratios in sub-aerially exposed, diagenetically altered mid-Holocene *Porites* corals from Muschu Island, Papua New Guinea. Thin-section analysis of the coral skeletons reveals a predictable sequence of vadose-zone diagenesis, which progresses from initial leaching of coralline aragonite with fine calcite overgrowths, to calcite void filling and calcitic neomorphic replacement of the coral skeleton. Calcite percentages were determined by X-ray diffraction.

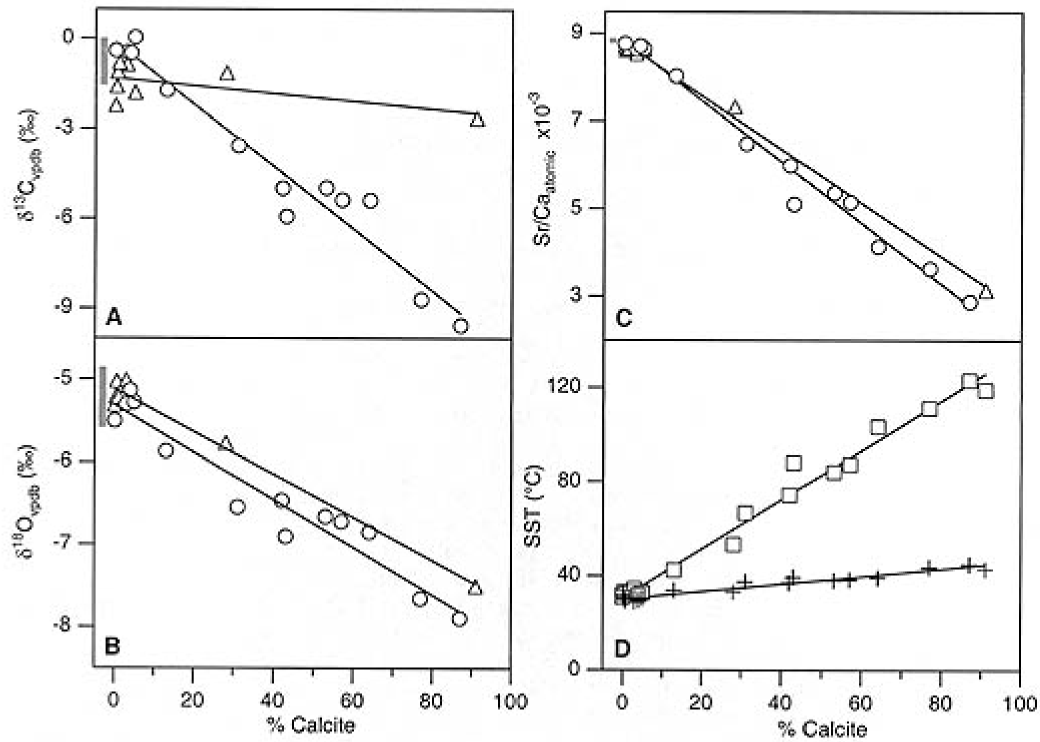


Figure 3: Comparison of (a) $\delta^{13}C$, (b) $\delta^{18}O$, and (c) Sr/Ca results for aragonite to calcite transects. Δ, results from coral FM08 and O, results from FM19. Solid lines show least squares regressions for FM08 and FM19. Stippled bars represent the range of values for aragonitic modern and fossils coral samples from PNG. (d) Combined FM08 and FM19 $\delta^{18}O$ (+) and Sr/Ca (□) data converted to apparent SST. Solid lines show least squares regressions for $\delta^{18}O$ and Sr/Ca SSTs.

The results show that coral Sr/Ca ratios are particularly sensitive to calcite diagenesis (Figure 3). Pure diagenetic calcite yields a very low Sr/Ca ratio of 0.0021 (Figure 3C), reflecting the Sr/Ca ratio of dissolving carbonate phases and the low Sr/Ca partition coefficient for calcite. The delta18O value of 8.1 (Figure 3B) for pure calcite is also much lower than that for coral aragonite precipitated from seawater, due to calcite precipitation from 18O-depleted equatorial rainfall in the vadose zone. Decreases in delta13C values are more variable among secondary calcite samples (1.4 to 10.5, Figure 3A) and reflect the concentration of 13C-depleted organic material in the soil cover adjacent to each location.

These results indicate that secondary calcite contamination of fossil coral skeletons will have a much greater impact on palaeotemperature reconstructions derived from coral Sr/Ca, compared to those derived from delta18O (Figure 3D). Using conventional Sr/Ca-temperature relations, coral palaeotemperature reconstructions may be consistently biased toward warmer apparent temperatures at the rate of ~1°C per 1% calcite added to the skeleton. On the other hand, calcite diagenesis does not cause large shifts in apparent temperature based on delta18O. Although diagenesis of coralline aragonite could severely alter palaeoclimate proxies, fine-scale sampling, textural analysis, and geochemical screening techniques can be imposed to ensure that it does not impede the reconstruction of tropical palaeoclimates.

Comparison of Diploastrea heliopora and Porites Corals for Palaeoclimate Reconstruction

T. Watanabe*, M.K. Gagan, W.S. Hantoro

Understanding climate variability in the tropical ocean over the last several hundred years is a high priority in climate change research. Recent instrumental advances and improved sampling techniques have shown that annual climatic cycles can accurately be determined from high-precision, analyses of chemical and isotopic tracers in coral skeletons. Paleoclimate studies using coral records generally are focussed on year to year variability, such as that produced by the El Niño Southern Oscillation (ENSO) and Asian-Australian Monsoon.

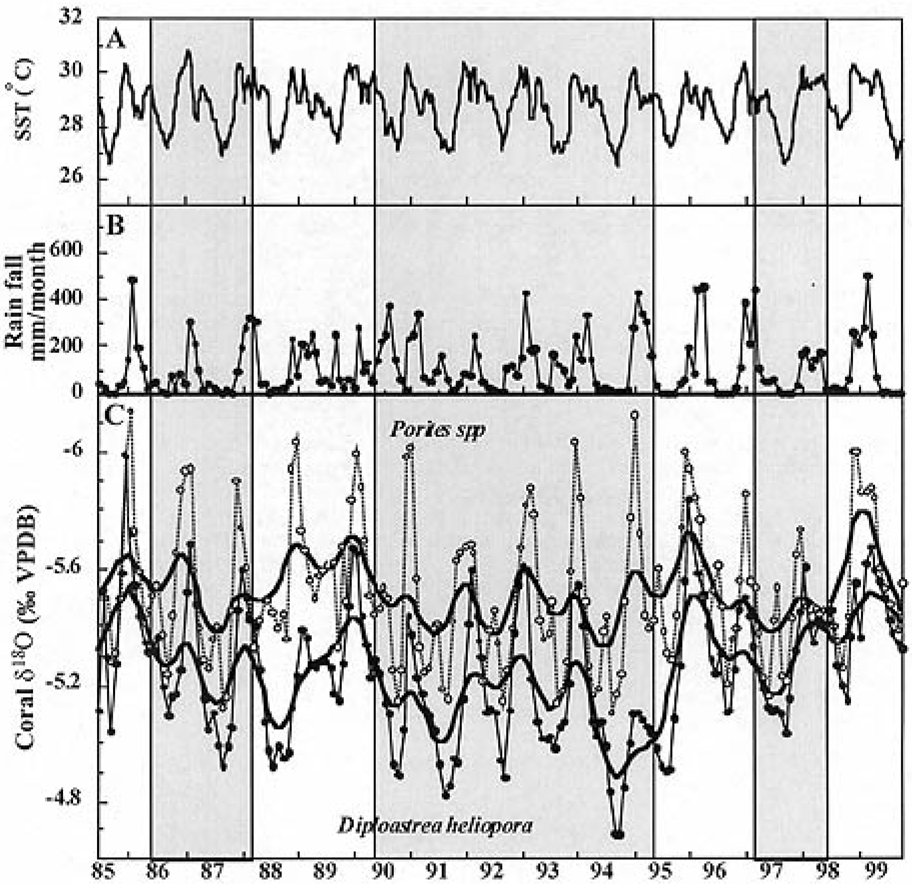


Figure 4: (A) Monthly sea surface temperature record of IGOSS nmc blended ship and satellite data for the 1° x1° box centred at 124.2°E, 8.1°S. (B) Monthly precipitation record from CDIAC (Carbon Dioxide Information Analysis Center) during 1985 and 1999. (C) Coral skeletal $\delta^{18}O$ records for *Diploastrea heliopora* (solid line and circles) and *Porites spp* (dashed line and open circles). The coral records are interpolated to a resolution of 12 samples per year. Data have been smoothed with a 30 running average to remove the seasonal trend (thick line). ENSO events are shown by shading.

We have studied the coral *Diploastrea heliopora* as recorder of interannual climate variability. This species grows slowly (35 mm per year), has long lifespan up to 700 years, and is widely distributed throughout the tropical regions in the Indo-Pacific Ocean. This coral also can survive in bad water quality. Figure 4 shows carbon and oxygen isotopic records for coral *Diploastrea heliopora* using a new sampling technique designed to minimize any smoothing or distortion of the isotopic record. Our samples come from Alor Island, Indonesia, and are compared with results from the coral *Porites,* which has been widely used for palaeoclimatic reconstruction (Figure 4). The mean value of the oxygen isotope ratios for the *Diploastrea* specimen is 0.25 higher than that for *Porites*, suggesting some difference in fractionation of 18O and 16O for the two corals, but oxygen isotopic profiles for the *Diploastrea* from Alor record well the variation of precipitation/evaporation in this region. The results suggest that *Diploastrea* could yield a dependable palaeo-ENSO signal and that it has good potential as a new long-lived archive for reconstructing palaeoclimate in tropical Indo-Pacific region.

Speleothem oxygen isotopic records from the Last Glacial Maximum

P. Treble

Speleothems (cave stalagmites and flowstones) have the potential to provide the terrestrial equivalent of the detailed multi-proxy palaeoclimate records derived from deep-sea sediment cores and corals. Speleothems are usually continuous, well-dateable by U-series and preserve stable isotopes and trace elements which may serve as first order climate proxies for temperature and rainfall variations.

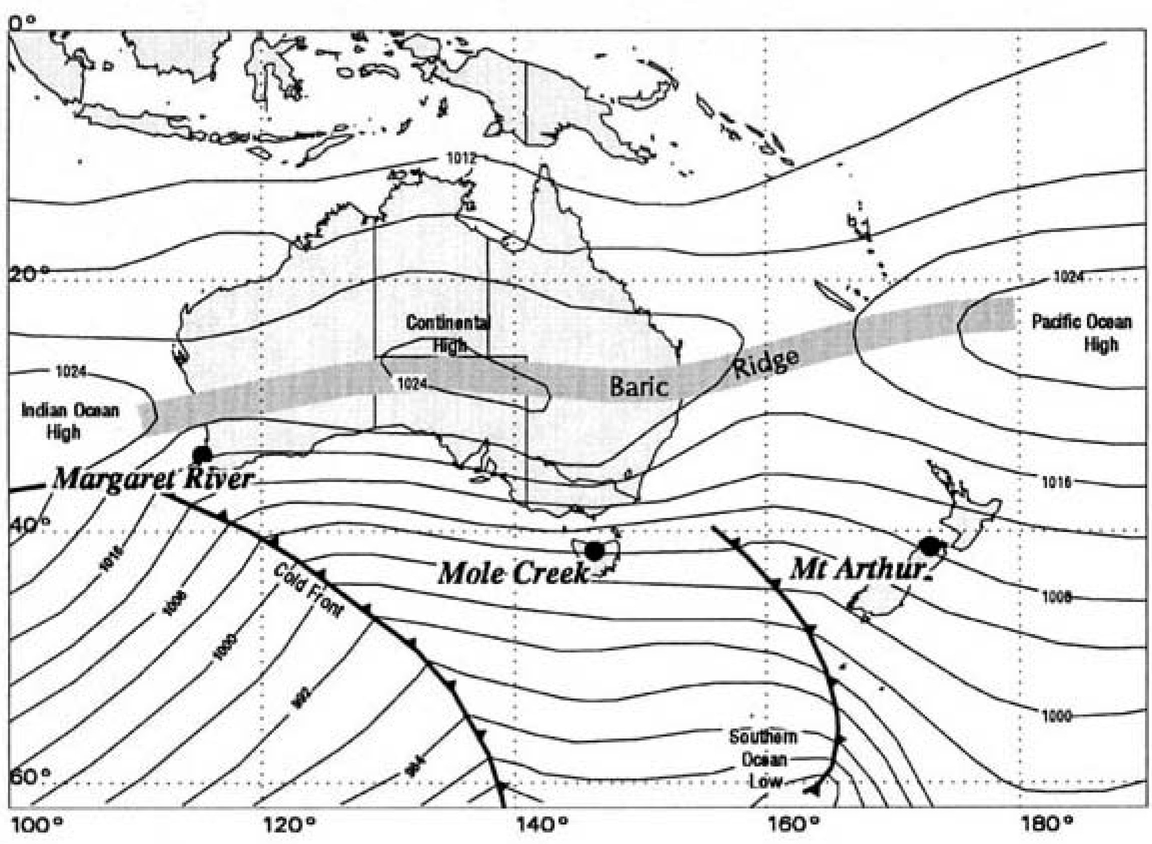


Figure1 Site locations of speleothem flowstone c records; Margaret River (southwest Western Australia), Mole Creek (Tasmania) and Mt Arthur(South Island New Zealand). Average Synoptic features for Southern Hemisphereare shown.

Oxygen isotopes are the key for palaeoclimate reconstruction from speleothems. The isotopic composition in speleothem calcite (delta18Oc) is dependent on the isotopic composition of its meteoric rainfall source (delta18Ow) and also the cave temperature. Changes of global ice volume also can affect the net composition. Thus, speleothems are potentially a record of both temperature and rainfall variations, which may be expressed in a simple equation as follows:

$$\Delta\delta 18Oc = \Delta\delta 18O_{cave\text{-}temperature} + \Delta\delta 18Ow \ \ [+ \Delta\delta 18O]_{ice\text{-}volume}$$

This study compares oxygen isotope records from cave flowstones from southwest Western Australia and Tasmania with records previously published from South Island New Zealand. These sites (Figure 5) were chosen in order to compare the speleothem records from sites that are climatically similar today and also known to have experienced similar temperature depressions at the Last Glacial Maximum. Furthermore, these sites are sensitive to the north-south migration of the rain-bearing low pressure systems and fronts of the southern hemisphere westerlies.

Comparing the results of the speleothem c records reveals an unexpected anomaly: those from Tasmania move *positively* with post-glacial warming, while those of southwest Western Australia and New Zealand move *negatively*. The difference suggests that either these sites were climatically less similar at the LGM than previously thought, or that an additional process overshadows the rainfall isotopic shift, but is not controlled by temperature, nor does it affect the speleothem sites uniformly. It is clear that records of rainfall isotopes independent of cave temperature are required to resolve this. It is proposed to reconstruct the LGM rainfall isotopes by direct isotopic analysis of the trapped water (fluid inclusions) in the speleothem calcite, in the expectation that this technique will resolve the divergence between New Zealand and Tasmanian speleothem records, and may also resolve a longer-standing question of Australian Quaternary science concerning the behaviour of the southern hemisphere westerly wind and frontal systems during the Glacial Maximum.

Rapid changes of sea level, ice sheets and deep-sea temperatures during the last glacial period

J. Chappell, T. Esat and Y. Yokoyama

All major components of the global climate system were in play during large, rapid climate changes that occurred in the last glacial cycle: continental ice sheets, ocean circulation, and the circulation and composition of the atmosphere. In order to understand the system it is necessary to know the timing of events for each component, so as to know which factors may be the triggers of other processes.

Ongoing research based on coral terraces at Huon Peninsula (HP), Papua New Guinea, has produced a new and more detailed analysis of the sea level, derived with the help of a computer model which simulates reef growth on uplifting terrain under varying sea level. The analysis uses the inverse method of searching for a sea level curve that leads to simulations closely matching observed topographic and stratigraphic sections, which also are controlled by precise U-series ages from the coral terraces. A restricted envelope of sea level curves was found that yield simulations that closely match the observed sequences at HP. The limit of resolution of sea level changes is a few metres and is limited by "noise" in the processes of uplift and reef growth at HP, arising from repeated metre-scale uplift events.

In addition to sea level cycles with the orbital precession period of ~20 ka, identified previously, the new sea level envelope shows shorter cycles within the later part of the last glacial cycle, with peaks at 33, 38, 44.5, 52 and 58-60 ka. The timing is fixed by precise U-series dates. Each cycle of 6-7000 years ended with a sea level rise of 10-15 m lasting at 1-2000 years, following a longer period of falling sea level. Except for the short cycle terminating at 33 ka, each sea level rise corresponds to a Heinrich episode marked by ice-rafted detritus (IRD) in the north Atlantic Ocean, signalling massive ice outbreak from the north American ice sheet. The sea level rise events may also have triggered ice breakouts from Antarctica. Furthermore, the sea level cycles terminating at 38, 44.5, 52 and 58-60 ka coincide with similar cycles in benthic oxygen isotope reported from north Atlantic sediment cores, indicating that the temperature in the north Atlantic deep ocean varied by 1-2 C, in phase with the sea level cycles.

Palaeoenvironmental records and radiocarbon dating at Niah Caves in north-eastern Sarawak

M. Bird, C. Hunt and G. Barker

The Niah caves are located on the edge of the Gunong Subis, a limestone massif on the coastal plain of northeastern Sarawak. Deposits in the caves contain a remarkable record of human occupation dating back into the Pleistocene. The caves were first excavated in the 1950s and the most notable discovery at that time was a human skull (the so-called "Deep Skull"), together with charcoal that yielded a radiocarbon date of *c*.40,000 years BP. The skull provides the earliest evidence for human settlement on Borneo, but both the stratigraphic context of the skull and the validity of the radiocarbon dates are uncertain, due to a poor understanding of the stratigraphy during the initial excavations and to the fact that radiocarbon dating was in its infancy at the time the samples were dated.

The Niah Caves Project is re-investigating the archaeology of these sites in an effort to establish a coherent stratigraphy and chronology for the deposits. Another aim of the project is to situate the archaeological findings within a regional palaeo-environmental framework. Work at the Australian National University has focused on the use of carbon-isotopes and radiocarbon dating in support of the aims of the larger multidisciplinary and multi-institution project. Samples of charcoal have been dated from positions stratigraphically above the putative location of the Deep Skull. The two samples closest to the skull returned ages of

42,600 ± 670 BP and 41,800 ± 620 BP. These samples were single fragments of charcoal, deposited on the surface of brown silt deposit immediately prior to the covering of both the brown silt deposits and the skull by a debris flow of guano, originating from further inside the cave. The ages of these samples therefore date the debris flow, and provide an upper age limit for the Deep Skull.

Organic carbon from the terminal portions of two speleothems from the cave were dated and returned ages of 4,800 ± 50 and 16,200 ± 120 BP. Two samples from the thick stratified sequence of guano in the cave interior were also dated. A sample from one metre's depth yielded an age of 13,700 ± 90 BP and another from four metres depth returned an age of 29,500 ± 250 BP. The isotopic composition of both speleothem and guano samples suggest a dominance of C3 (forest-derived) carbon in the area of the cave at all these times. The deposit of guano in the interior of the cave is around 10 metres thick and may therefore yield a long record of environmental change in the cave area. Coring of this deposit is planned in 2002.

Sediment cores immediately outside the cave penetrated a mangrove peat relating to a mid-Holocene sea-level highstand, confirming that the caves were situated on an island during the mid-Holocene. The carbon-isotope record of another core from a freshwater lake 50 km east of the caves at 240 m a.s.l., suggests a dominance of forest vegetation in the region back to at least 8,000 BP. Taken together, the sparse isotopic evidence available at the present time suggests a continuity of forest cover in the area since before theLast Glacial Maximum.

Global-scale climate-related variations in the carbon isotope composition of soil organic carbon in coarse-textured soils

M. Bird, Y. Zhou, L. Vellen, J. Cowley, J.O. Carter and G.D. Farquhar

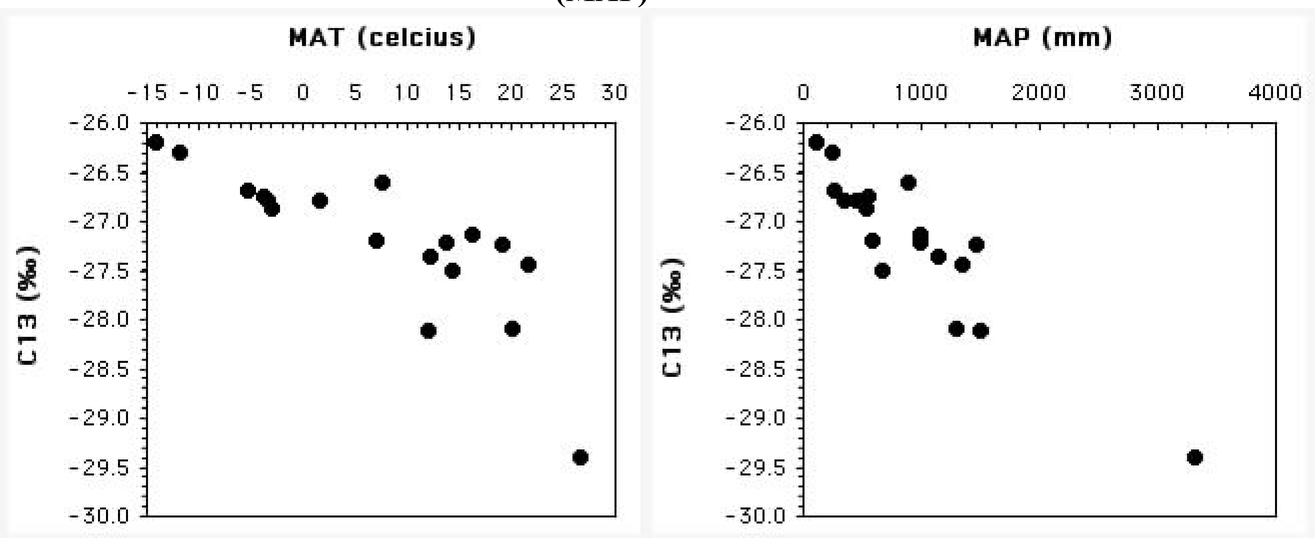
Soil organic carbon (SOC) is the major terrestrial reservoir of carbon and contributes substantially to the flux of CO2 between the terrestrial biosphere and the atmosphere. Carbon isotopes in the SOC pool are effected by several processes, including isotopic fractionation effects that accompany microbial degradation of SOC. Furthermore, the SOC pool is not in isotopic equilibrium with the modern atmosphere, but is subject to a 'lag' between photosynthetic uptake of CO2 respired from SOC and microbial respiration that is a function of decomposition rate.

Owing to the mixed C3/C4 biomes in the tropics and sub-tropics, the delta13C value of SOC is affected by a highly heterogeneous distribution of C3 and C4 vegetation. Hence, this study utilizes stratified sampling to provide weighted delta13C values for SOC. About 8,000 cores from coarse-textured soils were collected since 1997 from 41 regions of widely different climate, mostly in Australia but also in Botswana (4), Siberia (3), Canada (5), the Czech Republic (1) and Sarawak (1). Mean annual temperature for these regions range from -14 to +28°C and precipitation from 120 to 3,300 mm. Samples were collected at each locality from beneath trees and away from trees. Multiple cores were collected in sealed bags from 0-5 cm depth and 0-30 cm. A visual estimate of crown cover was made at each location. Five localities over several kilometres comprises a transect, and five transects represent a *region* (200 cores in total).

Soil bulk densities ranged from 0.19 to 1.73 g/cc for the 0-5 cm interval and 0.58 to 1.54 g/cc for the 0-30 cm interval. Weighted carbon inventories over the full 0-30 cm interval ranged from 36 mg/sq cm in hot, dry regions to a maximum of 960 mg/sq cm in wet, cool temperate locations. In pure C3 biomes, delta13C values for SOC in the 0-5 cm interval ranged from -29.4permil in wet tropical forests to -26.2permil in arctic tundra regions, and the values from beneath trees and grass agreed to ± 0.07permil. Figure 6 shows the variation with temperature and rainfall. The pattern is different where C4 plants are a significant fraction of the total biomass. Here, theweighted delta13C values increases rapidly in hot, drier environments characterized by tropical and sub-tropical savannas and desert, owing to increased proportions of C4 plants in the total biomass. To a lesser extent, the increase also reflects the tendency for isotope fractionation during C3 photosynthesis to decrease under water-limited conditions, with a resultant increase in the delta13C value of C3-derived carbon.

Finally, the weighted delta13C value of the 5-30 cm interval is enriched by 0.9 ± 0.6 permil compared to the 0-5 cm interval. This may result from several factors: (i) SOC age generally increases with depth, and older SOC will have been formed in equilibrium with the higher delta13C atmosphere that existed prior to industrialization, (ii) the effect of microbial degradation is to increase the delta13C value of the remaining SOC, and (iii) the relative contribution of carbon from woody roots increases with depth.

Figure : **(a) Relationship between the weighted delta13C value of SOC from exclusively C3 biomes and mean annual temperature (MAT), and (b) for mean annual precipitation (MAP)**



Anomalies in the Production of Australia's soil

J. Chappell

Soil generally is comprised of mineral particles produced by weathering of the underlying bedrock or sediments, and organic compounds derived from vegetation and soil fauna. The rate at which rock converts to soil is considered to be broadly affected by climate, with the properties and availability of soil water, together with the activity of soil microbes, governing the process in detail.

The rate of soil production from rock weathering has recently been determined by measuring concentrations of radionuclides produced *in situ* by cosmic rays passing through quartz particles (see Annual Report 2000). This work found that the rate of soil production decreases as the soil thickness increases, which is consistent with the concept that soil water availabilty and chemical activity decreases with soil depth. Analyses from soil-mantled granite lanscapes in humid temperate southeastern Australia found that the rate under thin soil reaches a maximum of about 50 metres per million years. However, reconnaissance samples from similar granite terrain the West Australian wheat belt failed to reproduce these results: the maximum production rate was found to be only 2-3 metres per million years, and no depth-dependence was detected. The explanation seems to lie with the impact of Quaternary climatic changes, which led to repeated episodes of aridity, soil loss and the mixing of wind-driven sand with the residual soil. The implication that the West Australian arable soils may have a quite different history from their counterparts in southeastern Australia is now being examined.

Understanding historical channel change: Channel stability and instability in south eastern Australia and their causes

P. Rustomji

This project is concerned with the characterisation of the variety of river settings in south eastern Australia, in an attempt to better understand and interpret changes in river channel morphology over historical times. Digital terrain models are used to analyse catchment morphology of some fifty river basins. Similarly, analyses of stream flow records have revealed differences in the hydrological behaviour of the same rivers including measures of flood variability and runoff generation rates. Results indicate that there exists a previously unrecognised degree of variability in the hydrologic behaviour of different river basins, which influence channel morphology and its sensitivity to extreme events. A fieldwork program has commenced, where surveys of channel morphology, collection of river bed and bank sediments plus assessment of riparian vegetation levels is being undertaken. Linked with historical and geomorphologic evidence for channel instability and change, this program aims to determine the catchment variables that control sensitivity of a river to extreme events.

Paleomagnetic dating of weathered regolith at Cobar, NSW

B. Pillans, M. Smith and K. McQueen

The success of geochemical exploration in areas of thick regolith depends on knowledge of the nature, and history and timing of geochemical dispersion in complex weathered materials.

Paleomagnetic dating of weathered regolith at four sites near Cobar, western NSW, has helped establish a framework for the weathering history of this region. Oriented samples of oxidised saprolite from each site were subjected to stepwise thermal demagnetisation in the laboratory, and remanences were measured on an ScT 2-axis cryogenic magnetometer.

Well-defined, stable magnetic remanences were isolated as follows (see Table 1): At Wilga Tank, a deep weathering profile with a ferruginous mottled zone and underlying bleached saprolite, is preserved beneath a dissected basalt flow. A nearby volcanic plug and lava flow yielded K/Ar ages of ca. 15 Ma. The upper part of the sub-basaltic weathering profile yield a pole position that lies close to the 12 Ma (middle Miocene) pole, suggesting a similar age to that of the basalts. Samples from saprolite from a quarry just north of Elura mine indicate two periods of iron mobilisation, one of Middle Miocene (12 Ma) age and the other of Latest Cretaceous to Early Paleocene (60 ± 10 Ma) age. Similar ages were obtained from another site (McKinnons open pit), while at the New Cobar open pit, oxidised saprolite (after Early Devonian shales and siltstones) gives a pole of apparent Jurassic age (ca. 180 Ma).

Similar weathering ages have been determined in the Yilgarn Craton of Western Australia, and also in northern South Australia and southern Queensland. The wide distribution and broad range of geologic and geomorphic settings of these sites are consistent with a paleoclimate-driven weathering episode across southern Australia. Finally, the dispersion patterns for base metals and gold are different for the McKinnons and New Cobar settings. This reflects different chemical and ferruginisation conditions, which probably relate to the different histories of the regolith profiles.

TABLE 1: Summary of paleomagnetic results from weathered saprolite.

LOCATION	N(+)(1)	REMINENCE DIRECTIONS (2)				SOUTH POLE			
		o Decl.	o Incl.	k	o alpha 95	o Long.	o Lat.	K	o A95
Elura mine									
Ferruginous nodules	35(35)	206.6	74.4	117	2.25	123.4E	55.3S	43.8	3.71
	31(0)	6.3	-59.1	96.2	2.65	118.6E	79.4S	65.3	3.22
New Cobar mine									
Oxidised saprolite	42(21)	325.2	-72.2	41.9	3.45	176.5E	54.1S	18.8	5.22
McKinnons mine									
Pink saprolite	82(38)	11.9	-61.4	73.2	1.84	109.6E	75.2S	40.2	2.5
Red saprolite	35(35)	205.3	70	297	1.41	114.6E	61.3S	128	2.15
Wilga Tank									
Ferruginous mottles	35(15)	2.3	-63.3	52.7	3.37	141.8E	75.4S	25.9	4.86
Perth Basin									

Weathering overprint		128(?)					109.9E	82.7S			2.4
Morney profile, Qld											
Deep weathering profile		37(17)	17.8	-68.3		2.4	118.5E	59.8S			3.8

Notes: (1) N = number of specimens; (+) = number of specimens with positive inclination
(2) k and K are Fisher precision parameters; a _95 and A95 are semi-angles of 95% confidence.

Earth's Early Atmosphere and Biosphere

J.F. Lindsay and M.D. Brasier

How ancient is oxygenic photosynthesis? This is a question with considerable relevance to the origins of life and the evolution of the atmosphere. If earth's atmosphere had not become significantly enriched in oxygen, the biosphere would have evolved in an entirely different direction.

The evolution of earth's early biosphere and atmosphere may be examined through analysis of the stable isotopes of carbon. Over the past several years, in a cooperative program with the Earth Sciences Department at Oxford University, we have assembled a large set of carbonate carbon isotopic data from dolostones preserved in the Hamersley and related basins, which lie along or either side of the Capricorn Orogen in Western Australia. Fom this work, we have a carbon isotope curve for carbonates from 2.6 to 1.9 Ga, a period in earth history when the earth's atmosphere was oxygenating rapidly. The curve is complex but suggests that active plate tectonics around 2.2 Ga played a major role in driving the isotope balance of both the atmosphere and biosphere.

Prior to 2.6 Ga relatively little is known of oxygenic photosynthesis. Given the paucity of platform carbonates prior to this time and the fact that nonphotosynthetic means of isotopic fractionation are possible, an isotopic approach by itself seems unlikely to be fruitful. The best opportunity appears to come from the identification of microfossil assemblages. Relatively few Archaean microfossil assemblages have been described to date, of which those from c. 3.46 Ga chert in the Apex Basalt, Warrawoona Group in Western Australia hold a key position because of their supposedly excellent state of preservation and general acceptance by the scientific community. Recently, we have re-examined both the geological setting and biogenicity of these very early microfossil-like structures, which have been taken to support an early beginning for oxygen-producing photosynthesis. Recent field mapping and sampling reveals that the 'fossiliferous' cherts occur in a hydrothermal complex.

Micro-Raman and thin section petrography of the 'microfossil' filaments suggest that their septate appearance is largely created by microcrystalline quartz grains (c. 1 µm) interspersed with darker amorphous graphite that makes up the bulk of the filament and suggests that these structures may be pseudofossils. However, high-resolution stable isotope analyses from freshly cut rock slices reveal delta13Cpdb values of -30 to -26permil for reduced carbon, comparable with results from earlier studies and consistent with biogenic fractionation. The evidence is consistent with a hydrothermal setting for this deposit, but raises questions about the presence of cyanobacteria. The isotope values imply a significant biological contribution to the carbon cycle, perhaps from hyperthermophile methanogenic bacteria, which have been claimed on the basis of bacterial rRNA sequencing to be an early branch of the tree of life, and are arguably of much greater antiquity than cyanobacteria. If so, then oxygenic photosynthesis was a relative late development in the evolving biosphere and the earliest life perhaps evolved in high temperature hydrothermal settings independent of sunlight. Thus, life may have evolved independently many times throughout the universe, on any planetary body where surface conditions were suitable for the development of a sustained hydrothermal system, independent of the distance of the planet from its star, the magnitude of the star or even whether the planet is in orbit around a star. As long as the planet has sufficient endogenic energy resources at least primitive life could be sustained.

PRISE

Link to report no longer available.

RESEARCH SUPPORT

ELECTRONICS GROUP

Demand for Electronics support remained strong during the year, despite the unexpectedly low requirement for SHRIMP MultiCollector development. Maintenance activities accounted for 22.3% of human resources, administration and group support 14.5%, ASI support 0.96%, with the remaining 62.2% devoted to development activity.

Notable developments undertaken included:

- Design of a precision, evacuated "Input Node Switch Box" to facilitate evaluation and development of low level 'Electrometers' for the NG61 instrument and the Finnigan company. (D. Corrigan).
- Four user configurable Data Acquisition interface systems for geophysical Fluid Dynamics (A. Welsh and others).
- Three integrated high performance Ion Pulse Counting System (IPCS) for use on SHRIMP instruments and the NG61 mass spectrometer (A. Latimore, J. Lanc and N. Schram).
- Ongoing refinement, safety interlocking and Data Acquisition development for various high pressure apparati within the Petrophysics group. (A. Forster and J. Lanc).
- Fabrication, testing and calibration of four 'tesla tamer' © magnetic field probes for sale to ASI, and progress towards completion of a further 4 probes. (J. Arnold).

- Development and manufacture of a 4 channel Salimeter for GFD. (J. Arnold).
- Considerable progress towards completion of three 'FC3' Field Controller Units, for application to SHRIMP II, SHRIMP RG, and the NG61 Mass Spectrometer. (J. Lanc).
- Design, manufacture and testing of five Sublimator Pump Controllers for the NG61 instrument (N. Schram).
- Design, manufacture and testing of two Filament Supplies for the EG&G Filament Degasser project. (N. Schram).
- The completion of a range of smaller development projects, including evaluation of Keithley 6430 electrometers (N. Schram), modifications and upgrading of AntPAC hardware (A. Welsh), Noble gas extraction line automation (N. Schram), and the fabrication of two Getter Pump supplies for GIG (J. Arnold) .

Staffing

The group comprises 7 permanent Technical Officers, including D. Corrigan who remained seconded to the group for the year, whilst engaged in electro-mechanical design for the NG61 Mass Spectrometer project. The group anticipates appointment of two Trainee Technical Officers during 2002, as part of the school's succession planning strategy.

Outlook

2002 promises to be an interesting year, as we return our attention to the SHRIMP MultiCollector, and further development for the NG61 Mass Spectrometer project. The profound changes to costing and accounting envisaged from 2002 will present a challenge to the group. We anticipate an initial period of adjustment, followed by a long term, unpredictable effect on the scope and nature of operations.

RSES ENGINEERING WORKSHOP

We have had no large exciting projects this year but have never the less been very busy. The year started with a complete rebuild of Shrimp 1's source chamber due to a massive oil dump in the works. Valther Baek-Hansen assisted John Foster in this rebuild resulting in a much-improved machine.

We have lost Chris Morgan to Geophysical Fluid Dynamics and he will not be replaced as we were one staff member over strength due to the appointment of Andrew Wilson when he completed his fitting and machining apprenticeship. We hope to appoint another apprentice when circumstances permit.

The requests for workshop time from campus users is still being met although with the joint RSES, RSPhysS&E computer controlled Electrical Discharge Machine situated in RSPhysSE workshop the work is being shared and because of the expertise developed, drawing complex work from interstate.

We have had some success quoting for external work and fitting it in with our school commitments and priorities. This work is generally of an unusual or demanding nature. This is in line with the school's new approach to funding.

Geoff Woodward built Jim Dunlap's new helium line with Xiadong Zhang supervising and assembling. Geoff also built the solar cell supports for Paul Tregoning's Antarctic project.

David Thompson built a new chiller for Malcolm McCulloch with Les Kinsley designing and testing.

Andrew Wilson is building an optically-stimulated luminescence lens and camera system for Nigel Spooner and is working with Iain McCulloch on this project.

Roger Willison built the supplementary coring equipment for the trip to Indonesia sampling corals. This was for Nerilie Abram and Mike Gagan. The trip went well with few problems.

Chris Morgan completed the heat exchanger parts for Geophysical Fluid Dynamics before moving onto his new position in the GFD laboratory.

We are building a new larger and improved filament degasser for Environmental Geochemistry and Geochronology to a concept by Malcolm McCulloch designed by the workshop.

All of this is happening around the usual emergencies, consumables, minor jobs and Shrimp multiple collector development.

STAFF AND STUDENTS

ACADEMIC STAFF

Director and Professor:

- D.H. Green, BSc MSc DSc, DLitt (Hon) *Tas*, PhD *Camb*, FAA, FRS (until 1 August 2001)
- T.M. Harrison, BSc *British Columbia,* PhD *ANU* (from 2 August 2001)

Professor of Seismology:

- B.L.N. Kennett, MA PhD ScD *Camb,* FRAS, FAA

Professor of Geophysics:

- K. Lambeck, BSurv *NSW*, DPhil DSc *Oxf*, FAA, FRS

Professors:

- J.M.A. Chappell, BSc NZ, MSc *Auck*, PhD *ANU*, FAAS
- S.F. Cox, BSc *Tas*, PhD *Monash*
- R.W. Griffiths, BSc PhD *ANU*, FAIP, FAA
- R. Grün, DiplGeol, Dr rer nat habil *Köln*, DSc *ANU*
- M.T. McCulloch, MAppSc *WAIT*, PhD *CalTech*

Senior Fellows:

- J. Braun, LicSc *Liège*, PhD *Dalhousie*
- I.H. Campbell, BSc *WAust*, PhD DIC *Lond*
- G.F. Davies, MSc *Monash*, PhD *CalTech*
- M. Honda, MSc PhD *Tokyo*
- I.N.S. Jackson, BSc *Qld*, PhD *ANU*
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- B.J. Pillans, BSc PhD *ANU*
- M.S. Sambridge, BSc *Loughborough*, PhD *ANU*

Fellows:

- R. Armstrong, BSc MSc PhD *Witwatersrand*
- V.C. Bennett, BSc PhD *CalifLosAngeles*
- M.I. Bird, BSc *Syd*, PhD *ANU*
- C.M. Fanning, BSc *Adel*
- M.K. Gagan, BA *CalifSantaBarbara*, PhD *JamesCook*
- T.R. Ireland, BSc *Otago*, PhD *ANU*
- R.R. Loucks, BS *Colorado*, PhD *Harvard*
- M. Norman, BSc *TTU*, MSc *UT*, DPhil *Rice*, FGSAm
- A.P. Nutman, BSc PhD *Exeter*
- N. Spooner, BSc MSc *Adel*, PhD *Oxon*

- I.S. Williams, BSc PhD *ANU*

Research Fellows:

- A.J. Berry, BSc *Syd*, DPhil *Oxf*
- W.J. Dunlap, BA *CarletonColl*, MS PhD *Minn*
- S. Eggins, BSc (Hons) MSc *Melb* PhD *Tas*
- F.G. Fabel, BSc PhD *Melb*
- H.U. Faul, Vordiplom Ulm, PhD *UOregon*
- G. Hughes, BE ME *Auck*, PhD *Camb*
- J.A. Mavrogenes, BS *Beloit*, MS *Missouri-Rolla*, PhD *VirginiaPolyTech*
- C. Meriaux, BPhys Paris XI, PhD Paris VII
- J.M. Palin, BA CalifState, MS *NewMexicoInstMin&Tech*, PhD *Yale* [†]
- A. Reading, BSc Edin, PhD Leeds
- W.R. Taylor, BSc *Auck*, PhD *Tas*
- P. Tregoning, BSurv, PhD *NSW*
- G. Yaxley, BSc PhD *Tas*

Postdoctoral Fellows:

- C. Bryant, BSc *UNE*, PhD *ANU*[y]
- A. Gorbatov, BSc *Moscow,* BSc PhD *UNAM*
- J. Hermann, Diplom PhD *ETH Zürich*[y]
- A. Kiss, BSc PhD *ANU*[y]
- N. Rawlinson, BS *Monash*
- D. Rubatto, BSc MSc *Turin*, PhD *ETH*
- E. Tenthorey, BSc *McGill* MSc *Florida* PhD *Columbia*

VISITING FELLOWS ON FACULTY DURING 2001:

- Dr C. Alibert (RSES)
- Dr A. Bidokhti (Tehran University)
- Dr L.P. Black (AGSO)
- Dr E. Calvo (ICER-CSIS Spain)
- Dr J. Claoué-Long (AGSO)
- Dr S. Clement (Consultant, PEI)
- Professor W. Compston (Emeritus)
- Professor D. DePaolo (University of California, Berkley)
- Dr G.L. Fraser (AGSO)
- Dr A. Glikson (GeoSpectral Research, ACT)
- Professor A.L. Hales (Emeritus)
- Dr M. Idnurm
- Dr L. Ingram (University of California, Berkley)
- Dr J.-P. Li (Chinese Academy of Sciences)
- Dr J. Lindsay (AGSO)
- I. McDougall (RSES)
- Dr P.L. McFadden (AGSO)
- Dr C. Martin (RSES)
- Dr W. Müller (ETH Zurich)

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- Dr C. Pelejero (ICER-CSIC Spain)
- Dr D. Phillips (DeBeers Geoscience)
- Dr S. Redfern (Cambridge)
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- Dr M.W. Schmidt (CRNS)
- Dr S.-S.Sun (AGSO)
- Dr O Titov (St Petersburg State Univ)
- Professor J.S. Turner (Emeritus)
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- J.M. Evans, BSc *ANU*
- S. Fishwick, BSc *Edin*
- L.M. Glass, BSc *WA*
- R. Gresham, BTech BSc *Flin*
- A.C. Hack, AssocDi AppSc CIT, BSc *ANU*
- C.J. Heath, BSc *Monash*
- E.J. Hendy, DipSc *Otago*, BSc *Waikato*
- Y. Hiyoshi, BSc
- T.-K. Hong, BSc MSc, *Seoul National*
- J. Kemp, BSc *ANU*
- X. Liu, MS, *ChineseAcSci*, BSc *ChinaUnivGeosci*
- W. Lus, BSc *PNG*
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- K. Marson-Pidgeon, BCA BSc *Vic Well*
- J. Mullarney, BA *Cambridge* MSc *Bristol*
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- D.I. Osmond, BSc *ANU*
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- B.D. Rohrlach, BSc *Adel*
- P. Rustomji, BSc *ANU*
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- S. Sommacal, Laurea in Science Geologiche (BSc)*Univ Degli Studi Di Padova*
- A. Stoltze, BSc *Curtin*
- W. Sun, BSc MSc *USTC*
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- K. Worden, BSc *ANU*

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Assistant Executive Officer:

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- G. Kretschmer, BSc *Flind* (from 16 July 2001)

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- V. Baek-Hansen

- Biggs, Mr P.J.
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- J.A. Cowley, BSc *ANU*
- Z.J. Derlacki AssocDipMath, AssocDipAppSc, *CCAE*[#]
- A.W. Forster
- J.J. Foster, BSc *Syd*, MSc PhD *ANU*
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- R.E. Willison
- A. Wilson
- G.F. Woodward
- R. Wylde-Browne
- X. Zhang, PhD *LaTrobe*

Trainee Technical Officer:

- J. Carr[†]

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- C. Harney, DipLibInfStud *CIT*

Stores Supervisor:

- W.A. Hampton

Administration:

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- T. Coombes
- J.A. Delhaize
- P.A. Gillard
- V.M. Gleeson
- M. Hooper
- D.H. Kelly
- M. Lukatela, BAMod Lang, GradDipLib, *CCAE*
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- R. MacPherson
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- Professor David H. Green. (ex officio) Director RSES (until 1 August 2001)
- Professor T. Mark Harrison. (ex officio) Director RSES (from 2 August 2001)
- Professor S. Greenhalgh. University of Adelaide
- Dr Neil Williams. Chief Executive Officer, AGSO
- One external membership vacant (vice Powell)
- Professor R.J. Wasson. Director CRES
- Professor B.L.N. Kennett. RSES
- Dr H. StC. O’Neill. RSES

[y] Funded by the Australian Research Council

[†] Left during 2001

RSES Publications 2001

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ACADEMIC STAFF MATTERS

The following personnel joined the academic staff of the School during 2001 or took up new appointments in 2001:

Dr C. Bryant	ARC Postdoctoral Fellow – Geochronology and Isotope Geochemistry
Dr T. Esat	Senior Fellow – IPC Environment Projects
Dr F.S. Fabel	Research Fellow – Geodynamics
Professor T.M. Harrison	Director, RSES
Dr R. Kerr	Fellow to Senior Fellow – Geophysical Fluid Dynamics
Dr A. Kiss	ARC Postdoctoral Fellow – Geophysical Fluid Dynamics
Dr M. Palin	Research Officer – Ore Genesis
Dr N. Rawlinson	Postdoctoral Fellow (from Monash University) – Seismology and Geomagnetism
Dr M. Sambridge	Fellow to Senior Fellow – Seismology and Geomagnetism
Dr N. Spooner	Research Fellow to Fellow – IPC Environment Projects
Dr E. Tenthorey	Postdoctoral Fellow – Petrophysics

The following personnel left the academic staff of the School during 2001:

Dr J. Hermann	Relinquished his position as ARC Postdoctoral Fellow in the Petrochemistry and Experimental Petrology Group to take up a new 3-year fellowship for "advanced scientists" funded by the Swiss National Science Foundation. Dr Hermann remains in the Petrochemistry and Experimental Petrology Group as a Visiting Fellow.
Dr M. Palin	Left his position as Research Officer in the Ore Genesis Group to take up a faculty appointment in the Department of Geology, University of Otago, Dunedin, New Zealand.
Dr W. Taylor	Left his position as Research Fellow, Petrochemistry and Experimental Petrology to take up a position as Exploration Manager, Elkedra Diamonds NL in WA.

THESES SUBMITTED IN 2001

PHD

Name	Thesis Title	Supervisor/Advisor

Mr J. Ballard	A comparative study between the geochemistry of ore-bearing and barren calc-alkaline instructions	*Supervisor:* Dr I Campbell (RSES) *Advisors:* Dr J. Mavrogenes and Dr M. Palin (RSES)
Mr H.-X. Cheng	Seismic body-wave attenuation in the Upper Mantle beneath the Australian continent.	*Supervisor:* Professor B.L.N. Kennett (RSES) *Advisors:* Dr I. Jackson and Dr M Sambridge (RSES) [submitted in 2000]
Ms P.M. English	Cainozoic evolution and hydrogeology of Lake Lewis Basin, Central Australia	*Supervisors:* Professor J. Chappell and Dr B. Pillans (RSES) *Advisor:* Professor R.A. Eggleton (Geology, Faculty of Sciences ANU)
Ms J.M. Evans	Calibration of the production rates of cosmogenic 36^{Cl} from potassium	*Supervisors:* Dr K. Fifield (RSPHYSSE) and Dr J. Stone (Washington State) *Advisor:* Professor A. Chivas (Newcastle)
Mr Y. Hiyoshi	Regional surface waveform inversion for Australian paths	*Supervisor:* Professor B.L.N. Kennett (RSES) *Advisors:* Dr E. Debayle (University of Strasbourg) and Dr M. Sambridge (RSES)
Ms J. Kemp	Palaeohydrology and geomorphology of the Lachlan Valley, New South Wales	*Supervisor:* Professor J. Chappell (RSES) *Advisors:* Professor G.S. Hope (RSPAS) and Dr J. Croke CSIRO)
Mr C.W.J. Magee	Geologic, microstructural and spectroscopic constraints on the origin and history of carbonado diamond	*Supervisor:* Dr H. O'Neill (RSES) *Advisors:* Dr I.S. Williams, Dr A. Berry, Dr W. Taylor and Dr M. Palin (RSES)
Ms K.A.. Marson-Pidgeon	Seismogram synthesis for teleseismic events with application to source and structural studies	*Supervisor:* Professor B.L.N. Kennett (RSES) *Advisors:* Dr M.S. Sambridge and Dr A. Gorbatov (RSES)

Mr B.T. Setiabudi	Geochemistry and geochronology of the igneous suite associated with the Kelian epithermal gold deposit, Indonesia	*Supervisor:* Dr I.H. Campbell (RSES) *Advisors:* Dr J. Mavrogenes and Dr M. Palin (RSES)
Mr M.G. Wells	Convection, turbulent mixing and salt fingers	*Supervisor:* Professor R.W. Griffiths (RSES) *Advisors:* Dr G. Hughes (RSES) and Dr J.R. Taylor (ADFA)

POSTGRADUATE AWARDS AND SCHOLARSHIPS

Australian National University Scholarship

- Mr S. Fishwick
- Ms J. Mullarney
- Mr Y. Zhou

Australian Postgraduate Award:

- Ms R. Gresham

A.L. Hales Honours Year Scholarship:

Mr R. O'Leary - Australian National University

- *Project:* Dolerite hosted gold mineralisation at Argo Deposit, St Ives Gold Operations, WA
- *Supervisor:* Professor S.F. Cox (RSES)

Ms A. Kalinowski - Australian National University

- *Project:* An experimental investigation into the causes and effects of sulfide partial melting at Broken Hill NSW, Australia
- *Supervisor:* Dr J. Mavrogenes (RSES)

Mr K. Worden - Australian National University

- *Project:* Petrology of the Takitimu Mountains, Southland New Zealand
- *Supervisor:* Professor R. Arculus (Geology, ANU) and Dr I. Campbell (RSES)

SUMMER RESEARCH SCHOLARSHIPS

Michelle Baker - University of Waikato

- *Project:* Geochemical analysis of basalt soil from North Queensland, Australia

- *Supervisors:* Professor M McCulloch and Dr C. Martin (Environmental Geochemistry and Geomagnetism)

Jennifer Eccles - University of Auckland

- *Project:* 3-D structure of Australia
- *Supervisors:* Professor B. Kennett and Dr M. Sambridge (Seismology and Geomagnetism)

Benjamin Garden - University of Otago

- *Project:* Experimental phase equilibria and megacryst chemistry of the Kakanui nephelinite.
- *Supervisor:* Dr S. Eggins (Petrochemistry and Experimental Petrology)

Kate Procko - University of Adelaide

- *Project:* OCELOT2000: Preliminary analysis and investigation.
- *Supervisor:* Dr F.E.M. Lilley (Seismology and Geomagnetism)

Michelle Salmon - Victoria University of Wellington

- *Project:* Modelling crustal deformation patterns after the M8.0 New Ireland earthquake of November 2000
- *Supervisor:* Dr J. Braun (Geodynamics)

Martin Smith - University of New South Wales

- *Project:* A palaeomagnetic study of weathering profiles in the Cobar Basin, NSW
- *Supervisor:* Dr B. Pillans (Environmental Processes)

Marion Walls - Victoria University of Wellington

- *Project:* Seismic tomographic imaging of the NW Pacific, proximal to Japan
- *Supervisors:* Professor B. Kennett, Dr A. Gorbatov and Dr M. Sambridge (Seismology and Geomagnetism)

Briar Wait - University of Auckland

- *Project:* Geochemistry of soils from the Johnstone River, Queensland
- *Supervisor:* Professor M. McCulloch

HONOURS AND AWARDS

(Academic Staff)

Dr Campbell was awarded a Centre of Excellence Fellowship from the Japanese Government to work in Japan for up to twelve months. Dr Campbell has also been included in the Science Citation Index list of Highly Cited Researchers (top 0.5% of cited authors).

Professor R.W. Griffiths was elected a Fellow of the Australian Academy of Science and also elected a Fellow of the American Geophysical Union.

Professor R. Grün was elected visiting fellow at St Catherine's College, Oxford, during his overseas study leave.

Dr R.C. Kerr was elected a Fellow of the Australian Institute of Physics.

Professor K Lambeck was awarded the Prix International Georges Lemaître 2001prize, a prize awarded by Louvain University in Belgium for research in astrophysics and geophysics. Professor K Lambeck was also awarded the 2001 Tage Erlander prize by the Swedish Research Council to carry out research into the glacial history, sea-level change and crustal rebound in Sweden. The second stage of this Erlander Professorship is to be taken up in 2002.

Professor M.T. McCulloch received the ISI Citation Laureate Award for authoring multiple high-impact papers from the period 1981-1998.

(Students)

Mr Wilfred Lus, from the Petrochemistry and Experimental Petrology Group, received an Outstanding Student Paper award at the AGU Fall Meeting held in San Franscisco from December 10 to 14, 2001. His paper was entitled "*Papuan Ultramafic Belt Ophiolite: Field Mapping, Petrology, Mineral Chemistry Geochemistry, Geochronology, and Experimental Studies of the Metamorphic sole*".

VISITORS

Dr Martine Amalvict of the Université Louis Pasteur in Strasbourg visited for two weeks in June to collect and analyse gravity and geodetic data at the Superconducting Gravimeter site at Mt Stromlo.

Dr A.A. Bidokhti, Geophysics Department, University of Tehran, was a Visiting Fellow in the Geophysical Fluid Dynamics Group from October 2000 to June 2001 and carried out experiments modeling ocean outflows from marginal seas and gulfs.

Professor K. Bahr, of the University of Gottingen, Germany, visited the Seismology and Geomagnetism Group in March. He presented a group seminar, and discussed recent magnetotelluric studies of the Australian crust and upper mantle with Dr F.E.M. Lilley.

Ms I.P. Buxbom, PhD student at the Hydrodynamics Laboratory, Denmark Technical University, visited the Geophysical Fluid Dynamics Group 14–25 May and gave a seminar on wave-induced flow through sediments.

Dr J. Bye and Mr J. Vladusic of the Mathematics Department, Melbourne University, were School Visitors 24–28 March and 4–8 June. They carried out experiments in the Geophysical Fluid Dynamics laboratory to investigate surface wind-wave interactions.

Professor K.V. Cashman of the Department of Geological Sciences, University of Oregon, was a Visiting Fellow in the Geophysical Fluid Dynamics Group, 30 April–18 May, to continue a collaborative project with Professor R.W. Griffiths and Dr R.C. Kerr on solidification in channellised basaltic lava flows.

Dr S.W.J. Clement, Ion Optical Consulting, Prince Edward Island, visited the Ion Probe group for a month in November-December to work with members of the group on the ion optics of the SHRIMP II multiple collector.

Bénédicte Duffait of the University Joseph Fourier in Grenoble visited for 6 months as a PhD student under joint supervision between Peter Van der Beek and Jean Braun

Professor Kenneth Eriksson from Virginia Polytechnic Institute and State University visited the Ore Genesis Group for six months to work with Drs Campbell, Palin and Allen dating detrital zircons from North American rivers and Appalatian sandstones.

Associate Professor I. Ferguson of the Department of Geological Sciences, University of Manitoba, Canada, visited the Seismology and Geomagnetism Group in July, and worked on the interpretation of the Carpentaria conductivity anomaly. He gave a group seminar on "The electrical resistivity structure of a major fault: the Great Slave Lake Shear Zone, NW Territories, Canada".

Dr Susan Frederiksen of the Harhus University, Denmark, visited for one year to do research in collaboration with Jean Braun

Dr A. Glikson, ANU, has been a Visiting Fellow with the Petrochemistry and Experimental Petrology group from 19 July, in view of his interests in early crustal evolution.

Dr J. Goodge, Southern Methodist University, departed in January after spending a 6-month sabbatical in the Ion Probe group, during which he worked with Dr I.S. Williams and Mr M. Fanning in a collaborative study of the record of the history of the Antarctic craton and Neoproterozoic to early Paleozoic sedimentation as exposed in the Transantarctic Mountains.

Mr Anthony Harris, a PhD student from University of Queensland worked with Drs Campbell, Palin and Allen to date igneous intrusions associated with the Alumbrera magmatic-hydrothermal system in the Farallon Negro district, NW Argentina.

Dr C. Hilgers, RWTH-Aachen (Germany) visited Professor S.F. Cox and Dr E. Tenthorey for three months from October to undertake high pressure experiments on crack sealing.

Professor A. Hofmann, Max-Planck-Institute, Mainz, Germany was a Visiting Fellow from 26 March to 2 April and held discussions with the Petrochemistry, Environmental Geochemistry and Isotope Geochemistry groups and also gave a school seminar.

Mr A. Hogg, PhD student in the Centre for Water Research, University of Western Australia, visited the Geophysical Fluid Dynamics Group, 19–20 February, in order to discuss the effects of mixing on buoyancy-driven exchange flows between ocean basins and marginal seas.

Dr J. Hollis, N. Daczko, and G. Clarke, University of Sydney visited RSES to carry out SHRIMP age determinations on rocks from Fiordland, New Zealand.

Dr J.R. Holloway of the Arizona State University, USA, was a visiting Fellow from 4-10 January.

Dr M. Hutchison, University of Arizona, USA, has started a Visiting Fellowship with the Petrochemistry and Experimental Petrology group from 1 November 2000, to work on the geochemistry of diamond indicators and major and trace element partitioning between high pressure phases.

Ms P. Lavery and Ms A. Storkey, graduate students from La Trobe University, Melbourne, visited the Ion Probe group for 10 days in November-December to work with Dr I.S. Williams on the history of partial melting, deformation and fluid flow in the Harts Range region, central Australia, as recorded by the U-Pb systems in titanite, monazite and zircon.

Dr J.-P. Li, Chinese Academy of Sciences, has been a Visiting Fellow from 1 November 2000 with the Petrochemistry and Experimental Petrology group to study experimentally the genesis of shoshonites from the Tibetan plateau.

Professor P.F. Linden, Department of Mechanical and Aerospace Engineering, University of California at San Diego, visited the Geophysical Fluid Dynamics Group, 17–19 December.

Dr J.R. Lister, Institute of Theoretical Geophysics, University of Cambridge, visited the Geophysical Fluid Dynamics Group, 16 December 2001–5 January 2002.

Dr T. Matsumoto of Osaka University visited the Geochronology and Isotope Geochemistry group for five weeks in February to work with Dr M. Honda on nitrogen analysis on a suite of alpine-type peridotites from the Horoman ultramafic complex, Hokkaido, Japan.

Dr K. Misawa, Japanese National Institute of Polar Research, visited the Ion Probe group for a week in March for consultations with Dr I.S. Williams on ion probe analytical procedures.

Professor P. Myrow, The Colorado College, visited the Ion Probe group for two weeks in April to work with Dr I.S. Williams on a study of the provenance of late Neoproterozoic and early Paleozoic marine sediments from northern India to test alternative scenarios for the assembly of Gondwana.

Dr T. Nakajima, Geological Survey of Japan, visited the Ion Probe group for three weeks in June to work with Dr I.S. Williams dating plutonic rocks from Pakistan and Japan.

Dr M. Rattenbury of the Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand visited RSES to use the SHRIMP for geochronological studies of high-grade gneisses from the West Coast, South Island, New Zealand.

Dr J.W. Rottman, University of California at San Diego, visited the Geophysical Fluid Dynamics Group, 15–20 December, and gave a lecture on the modelling of turbulent mixing in stratified flows.

Dr F. Simpson, University of Adelaide, visited the Seismology and Geomagnetism Group in March. She discussed recent magnetotelluric studies of the Australian Upper Mantle with Dr F.E.M. Lilley, and presented a School seminar.

Dr S. Redfern, Cambridge University, UK, has been a Visiting Fellow with the Petrochemistry and Experimental Petrology group from August 2001 to collaborate with Dr H. O'Neill on a number of projects centring on order-disorder phenomena in minerals.

Professor T. Sato of the National Astronomical Observatory of Japan visited the Geodynamics group in November to work with the superconducting gravimeter at Mt Stromlo and discuss analysis of observations.

Dr M. Schmidt, CNRS, Clermont-Ferrand, France, visited the Petrochemistry and Experimental Petrology group for six months to work on an experimental investigation of ankaramites.

Dr Keith Sircombe, University of Western Australia worked with Drs Campbell and Palin, dating detrital zircons using the laser ICP-MS.

Dr Song Biao, Dr Wan Yusheng and Dr Jian Ping, Chinese Ministry of Land and Resources, visited the Ion Probe group for a month in February-March to be trained by Dr I.S. Williams in ion probe sample preparation and analysis techniques as part of the terms of sale of a SHRIMP II to the Ministry of Land and Resources, Beijing

Dr J.R. Taylor, Physics Department, University of New South Wales at the Australian Defence Force Academy, was a Visiting Fellow in the Geophysical Fluid Dynamics Group for 4 months, September–December, while on sabbatical leave. He carried out laboratory experiments with frontogenesis and gravity current flows to model phenomena observed in the atmospheric boundary layer of Southeast Australia.

Dr Kentaro Terada, Hiroshima University, departed in mid January after a 5-week visit to the Ion Probe group to work with Dr I.S. Williams on negative ion stable isotope analysis using the SHRIMP II ion probe. The visit was funded by the Australian Academy of Science as part of its exchange program with the Japan Society for the Promotion of Science.

Professor Nico Vlaar of the University of Utrecht visited for 3 months, working on Archaean Tectonics.

Dr S.D. Weaver and Ms V. Tappenden, Dept of Geological Sciences Canterbury University, New Zealand visited RSES to use the SHRIMP for geochronology of New Zealand and Western Antarctica.

Ms C. Zhao from the Seismological Bureau of Urumqi, China is visiting the Seismology and Geomagnetism Group for one year.

Dr G. Witt-Eikschen, University of Köln, Germany, visited the Petrochemistry and Experimental Petrology Group from 26 April to 17 July to undertake a collaborative study with Dr H. O'Neill and other members of the P&EP group on trace element partitioning among the minerals of spinel lherzolite xenoliths from the Eifel, Germany, using the laser-ablation ICP-MS.

Professor J.S. Turner was an Emeritus Professor and a Visiting Fellow in the Geophysical Fluid Dynamics Group.

CONFERENCES AND OUTSIDE STUDIES

Dr C. Allen attended the 2001: A Hydrothermal Odyssey, in Townsville and presented a paper, 16–20 May.

Dr R. Armstrong attended the European Union of Geosciences (EUG XI) meeting in Strasbourg, France where he co-authored several research papers. He also participated in a field/technical meeting of the IGCP 418 Working Group in South Africa, where aspects of the Kibaran geology of southern Africa were studied.

Dr V. Bennett attended the Lunar and Planetary Science Conference, Houston in March and presented a co-authored paper on the "Highly siderophile element characteristics of Apollo 17 lunar impact breccias". She was a visiting scientist at the Department of Terrestrial Magnetism, Carnegie Institution, Washington, D.C. during March-April. In December she convened a special session on "Highly Siderophile Elements in the Earth, Moon and Planets" at the American Geophysical Union meeting (San Francisco, Ca.) and presented two papers as part of session.

Mr J.P. Bernal attended the 7th Australasian Conference on Isotopes in the Environment, Robertson, NSW, 24-27 September, 2001, where he presented a co-authored paper entitled "U-decay series in weathering minerals, can we make them tell the time?"

Dr A.J. Berry attended the Goldschmidt conference in Virginia, USA, from 20–24 May where he presented work on the oxidation states of chromium and iron in silicate melts. He also presented seminars to the School of Chemistry, University of Sydney, and the School of Physics, Australian Defence Force Academy.

Dr I. Campbell attended the European Union of Geosciences Meeting in Strasbourg, where he presented a paper and represented Australia at the Annual Meeting of the Council of the International Mineralogical Association. After the meeting he gave talks at the universities of Cambridge, Bristol and Cardiff. Dr I. Campbell was also awarded a Centre of Excellence Fellowship by the Japanese Government to work with Professor Nakamura at the Institute for Study of the Earth's Interior, Okayama University. While in Japan he attended a workshop on "Transport of Materials in the Dynamic Earth", where he presented a paper. He also gave talks at the universities of Tokyo and Tohoku and at the Tokyo Institute of Technology. Dr I. Campbell attended the 2001: A Hydrothermal Odyssey, in Townsville, 16–20 May and presented a paper.

Professor S.F. Cox gave an invited keynote presentation at "2001: A Structural Odyssey", the conference of the Geological Society of Australia's Specialist Group in Tectonics and Structural Geology, held at Ulverstone, Tasmania, in February. Professor Cox gave an oral presentation at "2001: A Hydrothermal Odyssey", in Townsville in June. Professor S.F. Cox also provided an invited presentation at the "International Symposium on Slip and Flow Processes Near the Base of the Seismogenic Region", held in Sendai, Japan, between 4 and 8 November.

Dr S. Eggins attended the 7th Australasian Conference on Isotopes in the Environment, Robertson, NSW, 24–26 September 2001.

Mr C.M. Fanning presented papers at the European Union of Geosciences XI meeting in Strasbourg in April and at the III South American Symposium on Isotope Geology in Pucon, Chile, during October. Mr Fanning also presented talks on the application of SHRIMP to dating metamorphic rocks at Southern Methodist University in Texas in March and the University of Granada in Spain in April. Mr Fanning was involved with the collection of further Duluth Gabbro samples for use as a zircon reference with staff of the National Institute for Polar Research, Tokyo, and the Geological Survey of Japan during October. Mr Fanning was an invited speaker at the "International Geoscience Symposium on Tectono-metamorphic history of East Gondwana: geochronological and petrological approach" held during January at the Research Institute of Natural Sciences, Okayama University of Science, Japan.

Dr U. Faul attended the 6th meeting of the Australian Microbeam Analysis Society in Sydney from 12–16 February to participate in an EBSD workshop and give a presentation entitled "EBSD mapping of silicates". He also gave a seminar at Macquarie University and participated in the "Exploring the Earth" symposium at the Australian National University. Dr U. Faul further attended the 11th Annual Goldschmidt Conference in Hot Springs, Virginia, USA from 20–24 May where he presented a paper on "Constraints on Porosity in Partially Molten Regions in the Upper Mantle from Permeability Measurements and U-series Modeling". Dr Faul subsequently visited the Earth Sciences Department, University of California, Santa Cruz were he presented a seminar. He further attended the conference "Transport of Material in the Dynamic Earth" Kurayoshi, Japan, from 2–6 October where he presented a poster entitled "High-T viscoelasticity in synthetic olivine aggregates: role of grain size and melt fraction".

Dr J. Fitz Gerald visited the Department of Earth Sciences at the University of Liverpool in March-April for familiarisation with a new field-emission electron microscope recently installed. From there, he attended the conference Deformation Mechanisms, Rheology and Tectonics at Noordwijkerhout, The Netherlands and presented a paper "Seismic wave attenuation in olivine: quantification of grainsize sensitivity and the influence of partial melting" and a poster "Slip systems, dislocation generation and dynamic recrystallization of plagioclase in single crystal experiments". In May he attended the Australian Workshop on Nanotubes and Fullerenes in Canberra to present a paper "Effects of annealing times on formation and growth of BN nanotubes".

Professor R.W. Griffiths attended the 8th National Conference of the Australian Meteorological and Oceanographic Society held at the University of Tasmania in February. He also attended the Fall Meeting of the American Geophysical Union in San Francisco in December, where he presented an invited paper on "Solidification in channel flows: lava tubes or a'a' flows?". While on two weeks Outside Studies Leave he visited Arizona State University and the University of Oregon to continue collaborative research on lava flow dynamics. In April he spent two weeks Outside Studies Leave taking field observations of lava flows in Hawaii.

Professor Rainer Grün was on overseas study leave from the beginning of April to the end of October at the Research Laboratory for Archaeology and the History of Art. He worked with Dr Alistair Pike on the problem of uranium migration into teeth. Together with Professor

Chris Stringer from the Natural History Museum, London (palaeoanthropology), Dr Martin Richards, University of Huddersfield (genetics), and Dr William Davies, Cambridge (archaeology), Professor Grün initiated and discussed the concept for a major review paper on the timing of modern human evolution. It is anticipated that the paper will be finished by the beginning of 2002. Professor Grün carried out fieldwork in South Africa, with Dr J. Brink, Bloemfontein, to work on the newly discovered human remains from Cornelia. He gave a seminar at the National Museum, Bloemfontein. Professor Grün carried out fieldwork in Spain in collaboration with Professor Trinidad de Torres, Escuela Tecnica Superior de Ingenieros de Minas de Madrid, to work on cave bear evolution. In the UK, he gave seminars at the Department of Geography, University of Oxford, the Research Laboratory for Archaeology and the History of Art, University of Oxford, Department of Archaeology, University of Bristol and the Medial School, University College of London. He was invited to give a seminar at the Institut für Geochemie, Mineralogie und Lagerstättenkunde, Universität Frankfurt. He met with Professor Ulrich Radtke, Universität zu Köln, Professor Helene Valladas, CNRS, Gif-sur-Yvette, and Professor Martin Aitken, Augerolles, for the discussion of collaborative projects and progress in the field of Quaternary geochronology. Together with Professor Helmut Wopfner and Dr Alexandra Hilgers, Universität zu Köln, Professor Grün collected samples in the Stretzlecki desert for the dating of the onset of dune formation. Professor Grün was invited to the International Symposium on New Prospects of ESR Dosimetry and Dating, 25–27 October 2001, Osaka, where he gave a talk on non-destructive ESR dating of tooth enamel. He chaired session B: Dating. He was also invited to the 3rd Asia-Pacific EPR/ESR Symposium, 29 October to 1 November 2001, Kobe, Japan, where he presented a plenary seminar on ESR dating applications in archaeology and earth sciences and chaired Session S1: Geology and EPR Dosimetry.

Miss E. Hendy was awarded ‘Best student poster’ for ‘Coral evidence for abrupt changes in ocean-atmosphee dynamics in the western Pacific since 1565 AD’ presented at the EuroConference on ‘Abrupt Climate Change Dynamics: Achieving climate predictability using paleoclimate data’, held at Castelvecchio Pascoli, Italy, 10–15 November 2001. Miss Hendy was also an invited speaker for the ‘Young Scientists Plenary’ at the Geological Society of New Zealand Conference (November 26–29) held at Waikato University, Hamilton, New Zealand. Her talk was entitled ‘The Great Barrier Reef since 1565 AD from a coral’s perspective’, and she also presented a poster of ‘Historical die-offs in massive *Porites* cores’. She gave two presentations at the AUSCORE meeting on South Stradbroke Island, 16–19 February 2001, the talks were ‘Multi-proxy reproducibility of decadal-centennial scale SST variation on the GBR’ and ‘A snapshot of isotope and trace element ratios in GBR *Porites* colonies from 12°S to 22°S’.

Dr J. Hermann attended a conference on "Fluid/Slab/Mantle Interactions and Ultrahigh-P Minerals", Waseda University, Tokyo, Japan, 30–31 August 2001 and the "6th International Eclogite Conference", Niihama, Japan, 1–7 September 2001.

Dr M. Honda was invited to Japan under the "FY2000 JSPS (the Japan Society for the Promotion of Science) Invitation Fellowship Program for Research in Japan, and gave lectures at several universities. He also attended the AGU Fall meeting in San Francisco where he presented a paper entitled "Xenon compositions of magmatic zircons in 3.63 and 3.81 Ga meta granitoids from Greenland – a search for a record of extinct ^{244}Pu in ancient terrestrial rocks".

Dr G.O. Hughes visited the Department of Civil Engineering, University of Canterbury, in April and gave a seminar on "The mixing due to a turbulent patch in a density-stratified fluid". He also attended the 14th Australasian Fluid Mechanics Conference held at the University of Adelaide in December, where he presented a paper on the "Damping of internal gravity waves in stratified fluids".

Dr Ireland attended the Goldschmidt 2001 Conference, Hot Springs, Virginia, and presented an invited paper on SHRIMP geochronology at the Krogh Symposium and presented another paper on the chronology of the early solar system. Dr Ireland also participated in the National Space Science Association’s annual meeting in Sydney and presented a paper on upcoming sample-return missions.

Dr I. Jackson presented invited lectures at the Goldschmidt conference in Virginia in May and at the Gordon conference on the Earth’s Interior in New Hampshire in June. During this trip to the USA, he also lectured at UCLA, the Carnegie Institution of Washington, Princeton University, and the State University of New York at Stony Brook. In August he attended and presented papers at the IASPEI/IAGA joint assembly in Hanoi, Vietnam. Dr Jackson also chaired the organising committee for the conference *Exploring the Earth: a Celebration of Four Journeys* in Canberra in February.

Dr R.C. Kerr attended the 14th Australasian Fluid Mechanics Conference held at the University of Adelaide in December. He presented papers on "Theoretical and experimental modelling of thermal erosion by laminar lava flows" and on "Surface solidification in open channel flow". He also acted as chairman for the Invited Review Lecture on "Oceanography and Geophysical Flows".

Professor B.L.N. Kennett attended the Ocean Hemisphere Project Symposium at Mt Fuji in Japan in January giving a paper on the nature of heterogeneity in the Earth’s Interior. In March he travelled to Europe on Outside Studies Leave. He spent some weeks at EOST, Université Louis Pasteur in Strasbourg working with Dr E. Debayle on surface wave tomography and attended the European Union of Geosciences meeting, presenting a paper on the development of tomographic methods. He then moved to Norway and worked for nearly two months at the Norwegian Seismic Array (NORSAR) including studies of location of seismic events at regional distances and in 3-D structures. He presented seminars at NORSAR, the University of Oslo and the University of Bergen and a presentation to a Workshop on Calibration of Seismic Locations. Professor Kennett attended the IUGG Executive Committee meeting in Sapporo at the beginning of August; later in the month he travelled to Hanoi for the Joint General Assembly of IAGA and IASPEI. In addition to his duties as President of IASPEI, he gave two papers, one on regionalised travel times and the other on surface wave velocities and anisotropy under Australia. He gave a presentation on mantle structure at the Australian Crustal Research Centre Symposium in Melbourne in November. In December he attended the Fall AGU meeting in San Francisco with an invited paper on deep slab structure and a further presentation on surface wave velocities and anisotropy under Australia.

Dr A.E. Kiss attended the 14th Australasian Fluid Mechanics Conference held at the University of Adelaide in December. He presented a paper entitled "Potential vorticity ‘crises’ and western boundary current separation".

Professor K Lambeck gave invited lectures at the Academia Europaea Conference in Rotterdam, at the Conference on 'Climate Change 2001' at Utrecht University, at the University of Stockholm, the Lemaître lecture in Belgium, the Inceptions Workshop in Idre, Sweden, and the Conference on Recent Crustal Motion in Helsinki. He also attended the Inter-Academy Panel Executive Committee meeting in Paris and the Global Change Open Science Conference in Amsterdam

Dr F.E.M. Lilley attended the four-day meeting "Exploring the Earth" held at ANU from 20–23 February 2001, and chaired the third day, which comprised papers present in honour of Professor Anton L. Hales on the occasion of his 90th birthday. Dr Lilley attended the joint meeting of the two IUGG associations, IAGA and IASPEI, held in Hanoi, Vietnam in August. He presented four papers at the meeting, co-authored with collaborators at RSES and more widely in Australia.

Professor M.T. McCulloch attended the AUSCORE Meeting at the University of Queensland, 16–20 February 2001. He also attended the Australian Coral Reef Society annual meeting Magnetic Island, Townsville, the 2nd National Conference on Aquatic Environments, 20–23 November 2001, Townsville and the GEOTROP 2001 4th International Conference on Environmental Chemistry and Geochemistry in the Tropics, also in Townsville. Professor McCulloch was invited speaker at the Earth System Processes Conference, Edinburgh, Scotland.

Dr J. Marshall attended the AUSCORE meeting on North Stradbroke Island from 17–19 February 2001, and presented a paper entitled "An assessment of the Sr/Ca ratio in shallow water hermatypic corals as a proxy for sea surface temperature." He also attended the Australian Coral Reef Society Conference on Magnetic Island from 6–8 July and delivered an address on "Sr/Ca derived sea surface temperatures from Myrmidon Reef and temperature impacts on coral bleaching." From 4–7 November he attended the First ARTS Open Sciences Meeting in Noumea and gave a paper on "Decadal-scale, high resolution records of sea surface temperature in the eastern Indian Ocean from proxy records of the Sr/Ca ratio of massive *Porites* corals".

Dr C.E. Martin presented invited seminars at the Georgia Institute of Technology in March and at the University of Otago in April. In June, Dr Martin did field work in the Orange area with PhD student Alma Joglekar (University of Sydney, Orange). She was first author on a talk entitled "Particulate and dissolved Os supply to the ocean from Papua New Guinea" that was given at a TROPICS special session at the Australian Marine Sciences Association-New Zealand Marine Sciences Society joint meeting held in Townsville in July. Dr Martin attended the Seventh Australasian Conference on Isotopes in the Environment that was held in Robertson, NSW in September. At that conference she presented a talk on "Investigating the contribution of dust to Australian soils".

Dr J. Mavrogenes attended the Goldschmidt conference in Virginia, USA, from 20–24 May.

Dr W. Müller gave a presentation entitled "Excimer-Laser-ablation ICP-MS analyses of teeth: Implications for U-series dating and isotopic tracing" at ICP-MS Conference Series, Vienna, 10–15 September 2001. He also gave an invited talk "Isotopic composition of the Iceman's tooth enamel – clues to his origin?" at The Iceman – Congress to celebrate the 10th anniversary of the discovery of the Iceman, Bolzano, Italy, 20–22 September 2001.

Ms J. Mullarney attended the 14th Australasian Fluid Mechanics Conference held at the University of Adelaide in December. She presented a paper on "Convective circulation driven by a non-uniform bottom heat flux and a localised salinity flux".

Dr H. O'Neill attended the Goldschmidt conference in Virginia, USA, from 20–24 May where he gave the keynote talk in the session on "Mafic Magma-ore deposit links".

Dr J.M. Palin attended "2001: A Hydrothermal Odyssey, New Developments in Metalliferous Hydrothermal Systems Research" in Townsville in May. He presented two talks: "Zircon U-Th-Pb geochronology of the Chuquicamata, Fortuna, and El Abra igneous complexes in northern Chile, by excimer laser ablation ICP-MS" and "Wall rock carbonation and large gold deposits: Coincidence or cause?". In October, Dr Palin attended the Annual Meeting of the Geological Society of America in Boston where he chaired a theme session on the geochemistry of siliciclastic sediments and gave two talks: "More than dates – Provenance determination of detrital zircon by excimer laser ablation ICP-MS" and "The Grenville superorogeny revealed by detrital zircons in Appalachian rivers". He also visited the University of Michigan and Yale University and gave departmental seminars at both institutions.

Ms E.K. Potter attended the AGU Fall Meeting in San Francisco.

Dr A. Reading attended a workshop on Antarctic Neotectonics from 11–15 July 2001 in Siena, Italy. She convened one of the five main programs and contributed an oral presentation and a review paper to the workshop volume. Afterwards she visited Dr K. Gohl, Bremerhaven, Germany, and Dr K. Priestley, Cambridge, United Kingdom, to discuss proposed and current seismic deployments.

In September 2001, Dr D. Rubatto was invited as key note speaker at the VI International Eclogite Conference in Niihama, Japan, where she presented two papers on dating of eclogitic rocks via U-Pb and the formation of metamorphic zircon during subduction-zone fluid circulation. Dr D. Rubatto also gave a lecture at the Geology Department at Monash University on SHRIMP U-Pb dating of metamorphism.

In August Dr M. Sambridge attended the 1st joint IASPEI/IAGA Meeting in Vietnam, where he presented three papers. Afterwards he visited the Colorado School of Mines (CSM) and gave a seminar on aspect of nonlinear inversion. While at CSM he began a new collaboration with Professor R. Snieder on multiple scattered seismic waves. In October he also visited The Department of Terrestrial Magnetism, in Washington DC and gave a seminar on the ensemble inference techniques.

Dr N. Spooner gave an oral presentation on "Optical dating at the Lake Mungo lunette, Willandra Lakes" to theAustralasian Archaeometry Conference, 5-9th Feb., at the University of Auckland, New Zealand. He gave a talk on optical dating and applications at a joint Physics/Geology meeting at the Department of Physics and Maths Physics, University of Adelaide, 24th April. Dr N. Spooner gave a seminar on dating and megafaunal extinction at Lake Mungo, in the Centre for Archaeological Research seminar series, ANU, 31st August and was an invited speaker on "Geochronological techniques applicable to the megafaunal extinction problem" at the Megafaunal Extinction Workshop, Australian National Museum, 28th September. He was also invited speaker at a workshop on the chronology and stratigraphy of the Joulni archaeological site, Lake Mungo, Willandra Lakes, NSW, ANU, 20th November.

Dr P. Tregoning attended the European Geophysical Society conference in Nice, France (25-29 March) and presented two papers.

Professor J.S. Turner attended the 14th Australasian Fluid Mechanics Conference held at the University of Adelaide in December, where he presented a paper on "Double-diffusive plumes in a homogeneous environment".

Mr N.G. Ware attended the 6th Biennial Symposium on the Australian Microprobe Analytical Society held in Sydney in February and presented a paper on "Poisson Statistics and the Electron Probe".

Dr I.S. Williams attended the Allan White Symposium on S-type Granites and Related Rocks, La Trobe University, January 11-12, and presented a paper on the interpretation of inherited zircon. May 21-25 he attended Goldschmidt 2001, Hot Springs, Virginia, and presented an invited paper on SHRIMP micro-geochronology at the Krogh Symposium. September 17-21 he presented four invited lectures on ion microprobe analysis at the NorFa SIMS Course, Stockholm. These were followed by a week working in the NORDSIM laboratory at the Naturhistoriska Riksmuseet on reconfiguration of the Cameca IMS1270 for oxygen isotope analyses. December 10-14 he attended the fall meeting of the American Geophysical Union, San Francisco. July 2-8 Dr Williams, with geoscientists from the Chinese Academy of Geological Sciences and the Hubei Institute of Regional Geology and Mineral Resources, sampled ultrahigh-pressure rocks from the western Dabie Mountains, central China, in preparation for a collaborative study of the metamorphic history of the region. Dr I.S. Williams was also a member of the organizing committee of a three-day conference, 'Exploring the Earth: a Celebration of Four Journeys' held at the RSES in February to mark milestones in the lives of four eminent members of RSES staff, Professor W. Compston, Professor D.H. Green, Professor A. Hales and Professor I. McDougall.

Dr G. Yaxley attended the Australian Diamond Conference held in Perth during December.

COOPERATION WITH GOVERNMENT AND INDUSTRY

AUSTRALIAN ACADEMY OF SCIENCE

Professor B.L.N. Kennett is a Chairman of the Subcommittee on Seismology and Physics of the Earth's Interior. He is Chair of the Academy Committees for Postdoctoral Opportunities in Japan and exchange arrangements with N.E. Asia (China, Japan, Korea, Taiwan).

Professor B.L.N. Kennett is Chair of the Committee for the Frederick White Conferences.

Professor K Lambeck is currently Foreign Secretary of the Australian Academy of Science and a member of its Council.

Dr F.E.M. Lilley is a member of the Geomagnetism and Aeronomy Subcommittee.

AUSTRALIAN NATIONAL SEISMIC IMAGING RESOURCE (ANSIR)

Professor B.L.N. Kennett is Deputy Director of the Australian National Seismic Imaging Resource (ANSIR), a Major National Research Facility operated as a joint venture by AGSO–Geoscience Australia and the Australian National University.

The portable instrument facility of ANSIR is housed at the Research School of Earth Sciences and equipment is available via a competitive proposal scheme. In 2001 instrumentation has been provided to:

- University of Western Australia for studies of the use of mine blasts for seismic refraction.
- Broad-band equipment to RSES for the Western Australian Craton experiment.
- 50 ANSIR + 35 RSES solid-state recorders to AGSO–Geoscience Australia as part of the major Leonora-Laverton reflection refraction experiment in WA. A.J. Percival and A. Arcidiaco provided support to this experiment, which also used 40 of the ANU designed solid-state recorders from the Joint University Seismic Facility housed now at the University of Adelaide.

AUSTRALIAN NAVY

Dr F.E.M. Lilley contributed some notes entitled "Searching for a sunken ship by magnetometry" to a seminar held by the Royal Australian Navy on the sinking of the cruiser HMAS Sydney (2). The seminar was held in Fremantle on 16 November 2001, the 60th anniversary of the sinking of the HMAS Sydney in an engagement with the German auxiliary cruiser HSK Kormoran.

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION (ANSTO)

Dr A.J. Berry continued his collaboration with Dr M. James on neutron diffraction studies of humite minerals.

AUSTRALIAN RESEARCH COUNCIL

Dr F.E.M. Lilley worked as a "Reader" for a number of ARC grant applications during the month of May.\

AUSTRALIAN SCIENTIFIC INSTRUMENTS PTY LTD

Professor Griffiths continued collaboration with ASI on marketing and manufacture of the Geophysical Flows Rotating Table. Three units are now in operation in North America and one further order was received this year (from the Courant Institute of Mathematical Sciences, New York). Purchases are currently being discussed with three other customers.

Dr I.S. Williams continued his longstanding collaboration with Australian Scientific Instruments Pty Ltd (a subsidiary of ANUTECH Pty Ltd) in the manufacture and marketing of SHRIMP ion microprobes. January through March he worked with ASI on the final tuning of the SHRIMP II purchased by the Chinese Ministry of Land and Resources, Beijing. This included 4 weeks in February-March training four scientists from the Chinese Academy of Geological Sciences in SHRIMP analytical procedures at RSES, and was followed by a 3-week visit to Beijing in June-July to assist in the commissioning of the instrument, to perform the acceptance tests, and to provide further training for Chinese scientists on-site. In December Dr Williams spent a week in San Francisco assisting ASI with SHRIMP marketing at the fall meeting of the American Geophysical Union.

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION (CSIRO)

Dr H. O'Neill and Mr W.O. Hibberson continued to collaborate with Dr I.E. Grey of the Division of Minerals on a study of novel crystalline phases synthesised at very high pressures in the system $CaO-Al_2O_3-SiO_2$. Dr O'Neill also continued his collaboration with Dr M.I. Pownceby of the Division of Minerals on the experimental calibration of solid-state redox sensors, and on Fe^{2+}/Mg partitioning between co-existing minerals.

Mr N.G. Ware continued to collaborate with Mr B.W. Robinson, Division of Exploration and Mining on the AutoGeoSEM project.

GEOLOGICAL SOCIETY OF AUSTRALIA

Dr F.E.M. Lilley, as a committee member of the ACT Branch of the Geological Society of Australia, hosted six meetings of the society at the Research School of Earth Sciences during 2001.

GEOSCIENCE AUSTRALIA (formerly Australian Geological Survey Organization)

The Ion Microprobe subgroup continues to maintain a close working relationship with GA geochronologists, sharing expertise, standards, time, costs and maintenance responsibilities re the SHRIMP I and II ion microprobes.

The paper describing the work by Dr A. Hitchman and Dr F.E.M. Lilley in collaboration with Dr P. Milligan of Geoscience Australia on the use of aeromagnetic crossover misfits as data of opportunity for studying electromagnetic induction in the Earth was published in 2001.

Professor M.T. McCulloch continued cooperative research with Dr Patrice de Caritat, Geoscience Australia, on Sr isotopes in Australian groundwaters.

OTHER GOVERNMENT AND INDUSTRY

Dr R. Armstrong has participated in a number of collaborative projects with a number of scientists from the **Geological Surveys of Britain, Brazil, Botswana, South Korea, South Africa and Namibia**. A number of geochronological projects for Australian and international exploration companies and consultants were completed during the year.

Mr J. Ballard and Drs I.H. Campbell and J.M. Palin concluded their work with **CODELCO** on geochemical and geochronologic studies of igneous rocks in and around the super giant Chuquicamata porphyry copper deposit in northern Chile.

Drs I.H. Campbell, J.M. Palin and C.M. Allen collaborated with **Rio Tinto Exploration**, Indonesia on zircon U-Pb geochronology of high grade metamorphic rocks in Sulawesi.

Mr C.M. Fanning continued collaborations with the **Geological Surveys of South Australia, Victoria, and Queensland**. He collaborated with Mr G. Teale, Teale and Associates and a number of mineral and petroleum exploration companies.

Mr C.J. Heath and Drs I.H. Campbell and J.M. Palin continued their investigation on the origin and composition of ore-forming fluids in the super giant Golden Mile gold deposit in collaboration with **Kalgoorlie Consolidated Gold Mines** and support from the **ARC Linkages** scheme.

Professor B.L.N. Kennett has continued to provide support to the **Comprehensive Nuclear-Test-Ban Treaty (CTBT) Organisation** in Vienna. With J. Grant in Tennant Creek he has continued to be involved with the upgrade of Warramunga Array to meet the requirements of the treaty for both seismic and infrasonic recording. Certification of the seismic array was made at the end of December 2000 and the infrasound array was also certified to treaty standard in September 2001. Data is transmitted continuously to the **International Data Centre in Vienna** via satellite link.

Professor K. Lambeck is Chair of the **Antarctic Science Advisory Committee**, a member of the **AUSLIG** Geodesy Reference Group and a member of an **AUSAID** Technical Advisory Group. He was also a member of the **Pangea Resources International Science Review Board.**

Dr M. Norman is involved in joint studies with Dr R. Skirrow, **Geoscience Australia** and with **Anglo American, AngloGold, Normandy, Delta Gold, and BHP-Billiton**.

Dr N. Spooner collaborates with Dr P. Hughes, **HEH Pty Ltd**, acting for **Coal & Allied Ltd**, utilising optical dating to study the formation of source bordering dunes in the Hunter Valley region, NSW.

Ms Amanda Stoltze and Drs I.H. Campbell and J.M. Palin are studying fluid pathways around mesothermal gold deposits in the Laverton region of Western Australia in collaboration with **Placer Granny Smith Pty Ltd** and support from the **ARC Linkages** scheme.

COLLABORATION WITH AUSTRALIAN UNIVERSITIES

Dr R. Armstrong completed an U-Pb geochronological study of selected rocks from Macquarie Island with Dr B. Goscombe of the **University of Adelaide**, as well as a collaborative project on provenance of sediments from central Australia with Dr A. Camacho and Professor B. Hensen of the **University of New South Wales**.

Dr A.J. Berry continued to work with Dr E.R. Krausz, Research School of Chemistry, **Australian National University**, on the study of fluid inclusions by optical absorption spectroscopy.

Drs I.H. Campbell, J.M. Palin, and C.M. Allen collaborated with Mr Anthony Harris of the **University of Queensland** on the U-Pb geochronology and geochemistry of zircons in volcanics associated with the giant Bajo de la Alumbrera porphyry copper-gold deposit of Argentina.

Professor S.F. Cox continued the supervision of **University of Newcastle** PhD student, Mr K. Ruming. He is also collaborating with Dr M. Knackstedt (**ANU, RSPhysSE**) in the development and application of percolation theory approaches to modelling fluid flow in hydrothermal systems. He is also collaborating with Dr M. Knackstedt in the development of a x-ray tomography facilities to characterise fracture and pore geometries in deformed rocks.

Dr S. Eggins is an Associate Investigator with Associate Professor Bill Collins (Chief Investigator), **University of Newcastle**, on ARC funded Large Grant (2000–2002) titled Magmatic expressions of orogens formed at retreating subduction boundaries: the cause of widespread silicic magmatism in some fold belts.' *collaborating university?*

Mr C.M. Fanning collaborated with Associate Professor C. Fergusson, **University of Wollongong** on the Anakie Inlier of Queensland, Dr A Crawford and a number of PhD students, **University of Tasmania** on the timing of Ordovician igneous activity in New South Wales and Professor J. Roberts, **University of NSW** on the timing of Carboniferous-Permian volcanic rocks in the Tamworth belt NSW.

Professor R.W. Griffiths continued a collaborative project with Dr J. Bye of the **University of Melbourne** on the dynamics of air-sea interaction, with funding from the University of Melbourne Small Grant Scheme.

Professors Grün and McCulloch and Dr Spooner collaborate with Dr Murray-Wallace on the Large ARC Grant "*Late Quaternary sea levels: the south Australian Gulfs region in a global context*" and Dr Magee, **Department of Geology, The Faculties**, **ANU** on "*The environmental context of megafaunal extinction in Australia*". Professor Grün collaborates with Professor A. Gleadow, Department of Geology, **University of Melbourne**, to study the thermal stability of paramagnetic centres from cores of the Otway basin, Dr P. White, Department of Anthropology, Dr J. Field, Department of Archaeology, **University of Sydney** to date the site of Cuddie Springs, and Dr R. Wells, **Flinders University**, to date a series of

South Australian sites with faunal remains including Naracoorte Cave. Professor Grün and Dr Spooner collaborate with Professor R. Twidale, **University of Adelaide**, on the onset of dune formation in the Stretzlecki Desert.

Dr T.R. Ireland has been collaborating with Dr G. Clarke, Dr J. Hollis and Dr N. Daczko of **the University of Sydney** on geochronology and petrogenesis of metamorphic rocks from Fiordland, New Zealand.

Dr F.E.M. Lilley is collaborating with Dr A. White of **Flinders University** and Dr G. Heinson of the **University of Adelaide** on a number of marine electromagnetic studies, the most recent of which is OCELOT2000.

Professor M.T. McCulloch continued collaborative work with **James Cook University**. This work included research on the last interglacial sea levels and carbonate formation along the Western Australian coastline with Dr P. Hearty; fish otoliths as environmental proxies in the Great Barrier Reef with Professor M. Kingsford and fish otoliths as indicators of the role of estuarine environments in the life cycle of tropical fish with Mr James Amend, PhD student.

Dr C.E. Martin collaborates with Dr Dhia Al Bakri of the **University of Sydney**. She is a co-supervisor of PhD student Alma Joglekar at the **University of Sydney, Orange Campus**. They are investigating the sources of nutrient-rich sediments to the reservoirs in the Orange water supply catchment.

Dr W. Müller collaborated with Dr Roland Maas, **La Trobe University**, Melbourne, on improved Sr thermal ionisation strategies.

Dr M. Norman is collaborating with Professpr R. Large and Drs G. Davidson, P. McGoldrick and A. Rae (CODES, **University of Tasmania**) in a study of Laser ablation ICP-MS of trace elements in sulphides and with Drs P. Robinson and Z. Yu (CODES, **University of Tasmania**), working on method development for laser ablation ICP-MS analysis of trace elements in silicate rocks and ores. He is also involved with Drs V. Kamenetsky and L. Danyushevsky and Mr D. Bombardieri in studies of sulphide saturation in lunar basalts from olivine-hosted melt inclusions. Dr Norman is cooperating with Dr R. Maas and Mr C. Ihlenfeld (**La Trobe University**) in work relating to the climatic significance of seasonal trace element and stable isotope variations in modern freshwater tufa.

Dr D. Rubatto started collaboration with Dr M. Hand from **Adelaide University** on the duration of metamorphism in the Mt Isa Block. Extensive dating of monazite and rutile suggested that the area was subject to metamorphism for a period of ca. 100 Ma. Further investigation will be aimed to understand if metamorphism occurred as a series of events or as a single prolongated event.

Dr N. Spooner collaborated with Dr E. Bestland, **Flinders University**, applying single-quartz grain optical dating in an investigation of the evolution of the economically-significant *terra rossa* soils of the Coonawarra wine-region, South Australia. He also collaborated with Professor J. Chappell and Dr A. Heimsath using single-grain quartz OSL to investigate soil formation and erosion processes, and in the development of novel luminescence means to identify saprolite-derived grains. Dr N. Spooner collaborates with Associate Professor R. Wells, **South Australian Museum**, R. Gresham and Professor R. Grün on megafaunal extinction at selected SA sites, at Burra, Naracoorte Caves, Flinders Ranges, Hallett Cove, Eyre Peninsula and Kangaroo Island. He continues to collaborate with Dr J.W. Magee, Department of **Geology, The Faculties**, Professors R. Grün and M. McCulloch and Professor G. Miller, **University of Colorado**, on the timing and spatial distribution of megafaunal extinction at various sites in the Lake Eyre basin and Menindee Lakes regions. The Cuddie Springs archaeological and palaeontological site is the subject of a collaborative dating study on sediment and megafaunal remains involving Dr N. Spooner and Professors R. Grün and M. McCulloch. Dr N. Spooner continued collaboration with Dr J.W. Magee, **Department Geology, Faculties**, on the palaeohydrology of the Lake Eyre basin and sites on northern Eyre Peninsula and Lake Gregory, WA. He also commenced collaboration with Professor R. Twidale, **University of Adelaide**, on the timing of dune formation in the Waikerie region, SA. Dr N. Spooner collaborated on the chronology, stratigraphy and archaeology of beach ridges at Lake George, with Dr P. Hughes, **HEH Pty Ltd**, Professor J. Chappell, Dr W. Shawcross and Dr P Cook, **CSIRO**. He continued collaboration with Professor J. Bowler, **University of Melbourne**, and colleagues on the chronology and stratigraphy of the Lake Mungo lunette, NSW.

Dr I.S. Williams continued his collaboration with Professor B.W. Chappell, **Macquarie University**, and Professor A.J.R. White, formerly **Victorian Institute of Earth and Planetary Sciences**, in the study of the evolution of the Lachlan Fold Belt as recorded in zircon preserved in igneous and sedimentary rocks; and with Dr I. Buick, **La Trobe University**, and Dr M. Hand, **Adelaide University**, in the study of metamorphism in central Australia and South Africa. Dr Williams also began a collaborative project with Professor J. Hergt, Dr J. Woodhead and Mr R. Kemp, **Melbourne University**, using Hf isotopes in zircon to study magma genesis in south-eastern Australia.

Dr G. Yaxley is collaborating with Dr V. Kamenetsky (**University of Tasmania**) in a melt inclusion study of the petrogenesis of flood basalts.

INTERNATIONAL COLLABORATION

During 2001, Dr R. Armstrong participated in a number of international research projects on a collaborative basis with scientists from Africa, Asia, Europe and South America. These include Professor U. Reimold, Dr R. Gibson, Dr M. Poujol (**University of the Witwatersrand, RSA**); Professor S. McCourt (**University of Durban-Westville, RSA),** Professor A. Wilson (**University of Natal, RSA**); Professor M. de Wit, W. Board, Professor D. Reid, R. Baillie (**University of Cape Town, RSA**); Professor S. de Waal and Dr I Graham (**University of Pretoria, RSA**); Professor A.B. Kampunzu and Dr R. Mapeo (**University of Botswana**), B.K. Paya **(Geological Survey of Botswana)**; K. Hoffmann (**Geological Survey of Namibia**); D. Jamal (**Eduardo Mondlane University, Mozambique**); H. van Niekerk and H. Dorland (**Rand Afrikaans University, RSA**), Profs. R. Scheepers and A. Rozendaal (**Stellenbosch University, RSA**), Professor C. Koeberl (**University of Vienna**), Dr J. Konzett (**University of Innsbruck, Austria**), Dr R. Key **(British Geological Survey, UK**); Dr Deung-Lyong Cho (**Korea institute of Geology, Mining and Materials**), Dr M. Pimentel, D. Fischel, M.H. de Hollanda (**University of Brasilia, Brazil**). Dr L. da Silva (**Geological Survey of Brazil**), Dr B. Thomas, Dr B. Eglington, Dr R.H. Harmer, Dr G. Grantham (**Council for Geoscience, RSA**), Dr B. Seth (**University of Bern, Switzerland**), Dr M. Worthing (**Sultan Qaboos University, Oman**), Dr J. Leven (**Mauritius Oceanographic Institute**), K. Macowiak (**Geological Institute, Poland**), Dr T. Seifert

(**Freiberg Institute of Mining and Technology, Germany**) and M. Werner (**University of Würzburg, Germany**).

Dr V. Bennett continued collaborations with Professor M. Garcia **(University of Hawaii)** on geochemical studies of Hawaii plume lavas, with Dr G. Ryder **(Lunar and Planetary Science Institute, Houston)** on the siderophile element characteristics of lunar samples, with Dr C. Friend **(Oxford-Brookes University)** on the geochemistry of early Archean terranes of Greenland and initiated a project with Professor D. DePaolo (U**niversity of California, Berkeley**) on tracing the Sr isotopic evolution of the Archean and Proterozoic mantle.

Dr A.J. Berry continued his collaboration with Drs S. Wimperis and S.E. Ashbrook, **University of Exeter**, UK, on ^{17}O nuclear magnetic resonance studies of silicate minerals.

Dr Campbell is collaborating with Professor Nakamura of the Institute for Study of the Earth's Interior, **Okayama University** to analyse oxygen isotopes in zircons of different ages.

Drs Campbell and Palin collaborated with Dr Clift of the **Woods Hole Institute of Oceanography** to date detrital zircons from the Indus River. Drs Campbell and Palin also collaborated with Dr Orestes of the **Geological Survey of Brazil** to date detrital zircons from the Amazon, Negro and Madeira rivers.

Drs Campbell, Palin and Allen collaborated with Professor Eriksson of the **Virginia Institute of Technology** to date detrital zircons from USA rivers and Palaeozoic sandstones from the eastern USA.

Professor S.F. Cox is collaborating with Drs Boullier, **Universite Joseph Fourier, Grenoble**, N. Mancktelow **ETH, Zurich** and G. Pennachioni **Univerity of Padova** in research on evolution of fluid flow patterns in the Mont Blanc and Aar Massifs in the European Alps. The collaboration forms part of an ARC Large Grant project, held in the Geology Department, The Faculties.

Professor S.F. Cox and Dr E. Tenthorey are collaborating with Dr C. Hilgers **RWTH-Aachen** in an experimental invistigation of crack sealing at elevated temperatures.

Mr C.M. Fanning collaborated with Professor F. Hervé of **University of Chile**, Santiago, Chile, Dr R.J. Pankhurst and Dr I. Millar of the **British Antarctic Survey**, UK, Dr C.W. Rapela, **Universidad de la Plata**, Argentina, Dr A. Cocherie, **BRGM**, Orleans, France, Dr R. Mundil of the **Berkeley Geochronology Center**, San Francisco, USA, Dr J.A Aleinikoff and Mr W.V. Premo of the **US Geological Survey**, Denver USA, Dr C. Smith-Siddoway, **Colorado College**, Colorado Springs, USA, Dr K. Shiraishi, Dr K. Misawa and Dr T Hokada of the **National Institute for Polar Research**, Tokyo, Japan, Dr J. Goodge, **Southern Methodist University**, USA, Dr J.J. Peucat of **Geosciences, Rennes**, France, Professor P. K. Link of **Idaho State University**, Dr J. Jacobs of **University of Bremen**, Germany, Professor D. Gebauer and Dr A. Liati, **ETH Zürich**, Switzerland and Dr A. Morton, **British Geological Survey and HM Associates**, UK.

Professor R.W. Griffiths and Dr R.C. Kerr continued a collaboration with Professor K.V. Cashman, Department of Geological Sciences, **University of Oregon**, United States of America, in laboratory modeling of the surface solidification of long basaltic lava flows.

Professor Griffiths is collaborating with Dr A.A. Bidokhti, **University of Tehran**, Iran, in modelling of the role of internal gravity waves in ocean outflows from gulfs and marginal seas.

Professor R. Grün collaborates with many international scholars on the timing of modern human evolution. Professor Grün has collected hominid samples from the anthropological sites Cave of Hearths, Hutjiespunt and Swartkrans, South Africa (Professor V.A. Tobias, Dr L. Berger, Department of Anatomy, Medical School, **University of the Witwatersrand**, Professor J. Parkington, Department of Archaeology, **Cape Town University**, Dr F. Thakeray, **Transvaal Museum**, Pretoria), Skhul, Israel (Dr J. Pilbeam, **Peabody Museum**, Harvard University and Professor O. Bar-Yosef, Department of Anthropology, **Harvard University**), Tabun (Professor C.B. Stringer, **Natural History Museum, London**) and Atapuerca, Spain (Dr J.L. Arsuaga, Department of Palaeontology, **Universidad Compultense, Madrid** and Dr J. Bermudes de Castro, **Museo de Ciencias Naturales, Madrid**). He collaborates with Dr J. Brink, **Bloemfontein**, on the dating of a range of sites in South Africa, including the newly discovered human site of Cornelia. Collaboration continues with Dr A. Pike, **Research Laboratory for Archaeology and the History of Art** on uranium uptake of bones and Professor Trinidad de Torres, **Escuela Tecnica Superior de Ingenieros de Minas de Madrid**, on the calibration of amino acid racemisation in bones and cave bear evolution. Professor Grün collaborates with Professor Helmut Wopfner and Dr Alexandra Hilgers, **Universität zu Köln**, on the onset of dune formation in the Stretzlecki Desert.

Dr J. Hermann is collaborating with Dr O. Müntener, **University of Neuchatel**, Switzerland on the exhumation of lower crust and upper mantle during rifting; with Professor R. Compagnoni, **University of Torino**, Italy, on features of UHP-metamorphism in the Dora-Maira Massif; with Professor V. Shatsky and A. Korsakov**, Geophysics and Mineralogy**, Novosibirsk, Russia, on age and exhumation rate of diamondiferous rocks from the Kokchetav Massif, Khazakhstan; with Dr M. Scambelluri, **University of Genova**, Italy, on constraints on subduction zone fluids derived from the high pressure break down of serpentinites and Dr B. Cesare, **University of Padova**, Italy, on magmatic and metamorphic evolution of mafic cumulates of the Tauern window, Alps.

In September 2001 Miss E. Hendy took part in a Canadian cruise, on the *CCGS Martha L. Black*, co-funded by **McMaster University** (Ontario), **UQAM** (Quebec) and **Dalhousie** (Nova Scotia). The scientific purpose was to collect deep-sea corals from the North Atlantic, along the Nova Scotia coast, using an unmanned submersible. The research leaders were Professor M. Risk (**McMaster**), Professor D. Scott (**Dalhousie**) and Professor C. Hillaire-Marcel (**UQAM**). While in Canada she visited the three institutes involved and the University of **British Columbia**, Vancouver, to discuss possible Post-Doctoral research.

Dr M. Honda is collaborating with Dr J. Harris of **University of Glasgow** on noble gas studies of diamonds.

Dr G.O. Hughes began a collaboration with Dr M.G. Worster, Department of Applied Mathematics and Theoretical Physics, **University of Cambridge**, United Kingdom, in modelling very stable diffusive interfaces.

Dr Ireland has longstanding collaborations in cosmochemistry with Professor E. Zinner, Physics Department, **Washington University in St Louis**, USA., Professor K. McKeegan, Department of Earth and Space Science, **University of California**, Los Angeles, USA and Professor B. Fegley, Department of Earth and Planetary Science, **Washington University in St Louis**, USA.

Dr Ireland is collaborating with Dr S. Weaver, **Canterbury University**, and Dr M. Rattenbury, **IGNS**, New Zealand, on geochronological studies of rocks from New Zealand and Western Antarctica.

Dr I. Jackson was involved this year in the planning of new collaborations with Drs Liebermann, Li and Kung at **SUNY Stony Brook** on ultrasonic measurements of the temperature dependence of elastic wave speeds with Dr Itatani at **Sophia University** in Tokyo in the fabrication and mechanical testing of polycrystalline magnesium oxide.

Professor K Lambeck has been the Tage Erlander Guest Professor of the **Swedish Research Council** from May until October carrying out research into the glacial history, sea-level change and crustal rebound in Sweden. Collaborative projects have been established with the **Universities of Lund and Stockholm**, the **Geological Survey of Denmark** and the **Norwegian Geological Survey**, **Norsk-Hydro** in Oslo and the **Finnish Nuclear Waste Management Industry**, Posiva.

Professor B.L.N. Kennett is President of the I**nternational Association for Seismology and the Physics of the Earth's Interior** (IASPEI) and in that position is a member of the Executive Committee of the **International Union of Geodesy and Geophysics** (IUGG).

Professor Kennett is collaborating with Dr E. Debayle, **Université Louis Pasteur,** Strasbourg, France on surface wave tomography, and with Dr T. Furumura at the Earthquake Research Institute, **University of Tokyo** on a variety of issues in seismic wave propagation.

Dr R.C. Kerr continued a collaboration with Dr C.M. Lesher, Mineral Exploration Research Centre, **Laurentian University**, Canada, and Dr D.A. Williams, Department of Geology, **Arizona State University**, United States of America, in developing and applying numerical models of the submarine flow of komatiite lavas. He also collaborated with Dr L. Bloomfield, Institute for Theoretical Geophysics, **University of Cambridge**, United Kingdom, on inclined turbulent fountains.

Dr F.E.M. Lilley is collaborating with Professor J.T. Weaver and Dr A.K. Agarwal of the **University of Victoria**, Canada, on methods for the analysis of magnetotelluric data. Dr Lilley is also collaborating with Associate. Professor I.J. Ferguson, of the **University of Manitoba**, Canada, on the interpretation of magnetotelluric data from western Queensland.

Professor M.T. McCulloch collaborated with Professor Halliday and Dr Stirling, **ETH Zürich**, on sea levels changes and Dr Gray, **University of San Diego**, California.

Professor I. McDougall actively collaborated with Professor F.H. Brown of the **University of Utah**, and Dr M.G. Leakey of the **National Museums of Kenya** on numerical time scale studies of stratigraphic sequences in the Turkana Basin, northern Kenya, in relation to the time framework of hominid evolution.

Dr H. McQueen and Professor K. Lambeck collaborated with Professor T. Sato of the **National Astronomical Observatory of Japan** in operating and analysing a

Superconducting Gravimeter at Mt Stromlo to monitor dynamic processes in the Earth. Dr McQueen also collaborated with Dr Martine Amalvict of the **Université Louis Pasteur** in Strasbourg on analysis of high precision absolute and relative gravity observations. Dr McQueen also collaborated with staff of **AUSLIG** on absolute gravity measurements and instrument calibrations at the Mt Stromlo Gravity Station in support of the Superconducting Gravimeter installation.

Dr C.E. Martin continued to collaborate with Drs Bernhard Peucker-Ehrenbrink and Greg Ravizza, **Woods Hole Oceanographic Institution**, on studies of Os isotopes and platinum group element and Re distributions in oceanic sediments and estuarine waters. Dr Martin collaborates with Dr Cathy Wilson, **Los Alamos National Laboratory**, on tracing the movement of sediments and phosphorus in catchments.

Dr W. Müller collaborated with H. Fricke, **Colorado College**, USA on Iceman stable isotopes and A. Halliday, **ETH Zurich**, CH, P. Tropper, **University of Innsbruck**, and E. Egarter-Vigl, **Bolzano**, Italy, on various aspects of Iceman work. He also collaborated with G. Rabeder, **University of Vienna**, Austria, on U-series dating of cave bear teeth and P. Eichhubl, **Stanford University**, USA, on U-series dating of cyclic seismogenic fault cements to establish earthquake recurrence intervals.

Dr M. Norman is currently collaborating with Professor M. Garcia (**University of Hawaii**) and Professor M. Rhodes (University of Massachusetts) in a study of the origin of Hawaiian plume basalts. He is also working with Dr L. Nyquist (**NASA Johnson Space Center**), Dr L. Borg (**University of New Mexico**) and Professor I. McCallum (**University of Washington**) on the age and origin of the lunar crust. A project titled "Targeting the Impactors: Siderophile element compositions of impact melts from the Moon and asteroids" is being undertaken by Dr Norman in conjunction with Dr G. Ryder (**Lunar and Planetary Institute, Houston**) and Drs D. Mittlefehldt and A. Brandon (**NASA Johnson Space Center**).

Drs J.M. Palin, I.H. Campbell, and C.M. Allen are collaborated with Dr S.E. Kesler and Mr D.P. Core of the **University of Michigan** on U-Pb geochronology and geochemistry of zircons in igneous rocks from the Park City mining district of Utah.

Emma-Kate Potter, Dr Tezer Esat and Professor Malcolm McCulloch collaborated with Professor Ulrich Radtke, of the **University of Cologne**, and Professor Gerhard Schellmann of the **University of Bamberg** in the mapping and dating of the uplifted coral terraces at Barbados.

In 2001, Dr D. Rubatto concluded her collaboration with Dr B. Cesare from the **University of Padova**, Italy, on the mafic rocks of the Tauern Window (Eastern Alps) with a final publication. Her work on the chemical and isotopic behaviour of metamorphic titanite in collaboration with Dr D. Castelli from **Torino University**, Italy, was also successfully completed with a publication.

Dr M. Sambridge and PhD student Mr T. Nicholson continued their collaboration with Dr O. Gudmundsson, of the **Danish Lithospheric Centre**, on a project concerning teleseismic earthquake location by pattern recognition. In October, Dr Sambridge was a member of the Committee of Visitors which reviewed the Instrumentation and Facilities Program of the **National Science Foundation** in Washington DC.

Dr N. Spooner collaborates with Professor G. Miller, **University of Colorado**, on chronological and stable isotope study of environmental change using sedimentary cores from the Wolfe Creek Meteor Crater and Lake Gregory region, northern WA. Collaborative work with Professor G. Miller and Professor M. Fogel on the extinction of the giant bird *Genyornis newtoni* continues on sediment and eggshell collected from the Menindee Lakes region, NSW and Lake Eyre basin, SA. Professor. A. Franklin, **University of Maryland**, collaborates with Dr N. Spooner on the kinetics of the stable high-temperature blue and red thermoluminescence of quartz. Dr N. Spooner also collaborates with Dr R. Tedford, **American Museum of Natural History**, and Associate Professor R. Wells, **South Australian Museum** on the timing of megafaunal extinction in the Lake Eyre basin, South Australia.

Dr P. Tregoning has continued his cooperation with Drs R. King, T. Herring and S. McClusky of the Department of Earth, Atmospheric and Planetary Sciences, **Massachusetts Institute of Technology** in the development and testing of the GAMIT GPS software. He also continued to collaborate with Mr R. Curley (Department of Surveying and Land Studies, **The Papua New Guinea University of Technology**) and Mr S. Saunders (**Rabaul Volcano Observatory**) in the ongoing measuring of tectonic motion in Papua New Guinea. He has collaborated with Dr John Beavan (Geological and Nuclear Sciences, NZ) in investigating the motion and rigidity of the Pacific Plate.

Dr I.S. Williams continued his collaboration with Dr J. Goodge, **Southern Methodist University, Dallas**, and Professor P. Myrow, **The Colorado College, Colorado Springs**, on the provenance of late Proterozoic and early Palaeozoic Gondwanan sediments of Antarctica and India. He also resumed his work with Dr S. Claesson and Dr M. Whitehouse, **Naturhistoriska Riksmuseet, Stockholm**, on oxygen isotopes in zircon. Dr Williams remains first-contact at RSES in providing advice to scientists working in laboratories that have purchased SHRIMP ion probes. He hosted Dr K. Terada, **Hiroshima University**, for a 5-week visit to RSES to learn analytical procedures for stable isotope analysis, Dr K. Misawa, **National Institute of Polar Research, Tokyo**, for a 5-day visit to discuss analytical procedures, and Dr Song Biao, Dr Wan Yusheng and Dr Jian Ping, **Chinese Ministry of Land and Resources, Beijing**, for a one-month visit to be trained in ion probe sample preparation and analysis techniques. He also travelled to the **Naturhistoriska Riksmuseet, Stockholm**, to give a lecture course and to the **Chinese Ministry of Land and Resources, Beijing**, to assist with commissioning of their new SHRIMP II. Dr Williams commenced a collaborative study of Chinese ultra-high pressure rocks with Dr J. Ping, **Chinese Ministry of Land and Resources, Beijing**, and collaborated in SHRIMP analytical work with Dr T. Nakajima, **Geological Survey of Japan, Tsukuba** and Professor W.E. Stephens, **University of St Andrews**.

Dr G. Yaxley is collaborating with Professor Dr Gerhard Brey of the **Institut für Mineralogie, Universität Frankfurt** in a study of the phase relations of carbonate in eclogite under upper mantle conditions, and with Dr Hans-Michael Seitz (**Institut für Mineralogie, Universität Frankfurt**) in a study of the distribution of the trace element Li between upper mantle phases and its potential use as a tracer of different metasomatic styles.

EDITORIAL RESPONSIBILITIES

Dr C. Allen was a special editor for the *Australian Journal of Earth Sciences* for a volume to be titled "25 Years of I & S Type Granites". Dr C. Allen has also been appointed to a 3-year term on the editorial board of the *Australian Journal of Earth Sciences*.

Dr R. Armstrong has been appointed to the editorial board of the *Journal of African Earth Sciences*.

Professor S.F. Cox continued as a member of the editorial advisory boards of *Journal of Structural Geology*, and *Geofluids*.

Mr C.M. Fanning is an Associate Editor of the *Bulletin of the Geological Society of America*.

Professor R. Grün is Editor of *Quaternary Geochronology (Quaternary Science Reviews*), associate editor of the *Journal of human Evolution*, member of the Editorial Boards of *Quaternary International* and *Radiation Measurements*, and Member of reviewers' panel of *Ancient TL*. He is also a standing member of the scientific committee and editor of the proceedings of the *International Conferences on Luminescence and Electron Spin Resonance Dating*. The next conference in this series will be held in Reno in July 2002.

Dr I Jackson continued on the Editorial Board of *Physics and Chemistry of Minerals* and joined the board of *Physics of the Earth and Planetary Interiors*. He also commenced a three-year appointment as Associate Editor for the *Journal of geophysical Research*.

Professor B.L.N. Kennett is an associate editor for *Physics of the Earth and Planetary Interiors* and *Earth and Planetary Science Letters*.

Professor K. Lambeck is an Editorial Advisory Board Member for *Quaternary Science Reviews* and for *Earth and Planetary Science Letters.*

Dr C.E. Martin is an Associate Editor of the *American Journal of Science*.

Allen Nutman is member of the Editorial Board, *Precambrian Research*.

Dr M. Sambridge continued to serve on the editorial board of *Geophysical Journal International*. He handles papers through the Pacific Region Office.

Dr H. O'Neill is on the editorial advisory board of *Earth and Planetary Science Letters* and *Chemical Geology*.

OUTREACH AND WORKSHOPS

In March Professor Cox gave invited presentations at workshops on aspects of structural controls on fluid flow in hydrothermal systems at the University of British Columbia (Canada) and at the Prospectors and Developers Association of Canada Annual Meeting in Toronto. In June, Professor S.F. Cox presented a lecture on applications of advanced structural geology techniques in minerals exploration to geoscientists at WMC Respources Ltd St Ives Gold Operations, at Kambalda, WA. He also provided informal advice in the field to WMC Resources geoscientists at the St Ives Gold Operations.

Professor S.F. Cox is a member of the committee of the ACT Board of Senior Secondary Studies which oversees Year 11/12 curricula in Earth Sciences.

In January Professor R. Grün and Dr M. Sambridge hosted the National Youth Science Forum at the Research School of Earth Sciences.

Dr W. Müller's media involvement relating to his Iceman research includes: Science, vol. 293 (28. 9. 2001), p.2373: Ben Shouse – For Iceman, the Band Plays On; Neue Zürcher Zeitung (CH), 19. 9. 2001, p.51: Genevieve Lüscher: Mord im Hochgebirge; Die Weltwoche (CH), 27. 9. 2001, p.47: Urs Fitze: Aus Ötzis Zähnen kommt die Wahrheit; Dolomiten (I), 21. 9. 2001, p.11: Heißeste Spur führt ins Eisacktal; Sächsische Zeitung (D), 29./30. 9. 2001, p M2: Stephan Schön: Mord am Gletscher; Dagens Nyheter (S), 23. 9. 2001: Per Snaprud: Ismannen Ötzi var italienare; Spiegel ONLINE (D), 21. 9. 2001: Ötzi war ein Südtiroler; TV Interview, 20. 9. 2001, German-speaking Television N-Italy (ORF Südtirol); Shooting for Discovery Channel's documentary 'Mystery of the Iceman', to be broadcast March 2002; and Radio Ö1 (A), 25. 9. 2001: Dimensionen.

Dr N. Spooner was interviewed and filmed in the Luminescence Laboratory by documentary film maker TANGRAM, Germany for a television documentary, "The Odyssey of Man". He was also interviewed for a feature article on chronology by the National Geographic magazine, carried in the September 2001 issue. Dr N. Spooner, Professor R. Grün and Dr J.W. Magee, Department Geology, ANU, were interviewed for a radio report on the extinction of the Australian megafauna by D. Röhrlich, Deutschlandfunk, Germany.

Dr I.S. Williams hosted a visit to the SHRIMP laboratory in January by 6 science teachers from Hawker College and in August by 16 science students from Canberra Girls Grammar School. In September he presented four invited lectures on ion microprobe analysis at the NorFa SIMS Course, Stockholm, and in October presented an invited lecture at Macquarie University, Sydney.

NEW GRANTS

Dr A.J. Berry received a grant from the Australian Institute of Nuclear Science and Engineering (AINSE) to undertake neutron diffraction experiments at ANSTO.

Drs A.J. Berry and J.A. Mavrogenes were supported by two grants from the Access to Major Research Facilities Fund to investigate the speciation of copper in fluid inclusions at the Advanced Photon Source, Argonne National Laboratory, USA.

Dr A.J. Berry in collaboration with Dr H.StC. O'Neill received two grants from the Australian Synchrotron Research Program to continue their work on oxidation states in silicate melts at the Australian National Beamline Facility, Tsukuba, Japan.

Dr J. Hermann was awarded a 3 year fellowship as "Advanced Scientist" funded by the "Swiss National Science Foundation" at the Research School of Earth Sciences starting on December 1st 2001.

Dr I. Jackson was awarded a 3-year ARC Discovery grant valued at $184,000 for a project entitled Seismic wavespeeds and attenuation in upper-mantle rocks: a laboratory study of the effects of partial melting.

An ARC major equipment grant was given to Professor K. Lambeck and Dr P. Tregoning for replacement GPS equipment for remote, all-year geophysical observatories in Antarctica.

Professor M.T. McCulloch obtained the grant "Sea Levels, Sea Surface Temperatures and El Nino variability during warm Interglacials (DP0209059)" jointly with Dr Hearty, John Curtin University, and Professor Halliday, ETH, Zurich. He also obtained a grant entitled "The coral record of Environmental Impacts in the Great Barrier Reef: Quantification of Anthropogenic Fluxes (DP0209021)" jointly with Dr Lough, Australian Institute of Marine Science.

Professor I. McDougall was awarded a grant from the Australian Institute of Nuclear Science and Engineering to facilitate irradiation of geological samples in the HIFAR nuclear reactor, operated by the Australian Nuclear Science and Technology Organization, in relation to dating of rocks by the ^{40}Ar-^{39}Ar method.

In January Dr M. Sambridge was awarded a one-year grant under the Comprehensive Test Ban Treaty Organization (CTBTO) Calibration program for a project on regionalized travel times. Dr K.A. Marson-Pidgeon worked on the project through the year as a research associate.

In October Dr M. Sambridge and Professor B.L.N. Kennett were awarded an ARC Discovery grant for a three-year project (2003-2005) entitled "Data adaptive geophysical inversion".

Dr N. Spooner is an Associate Investigator on an NERC (UK) grant on "The human colonisation of Australia: Breaking the 40 ka BP radiocarbon barrier", with Principal Investigator, Dr C. Turney, University of London.

OTHER MATTERS

Dr Jean Braun is a Member of the Earth System Evolution Program of the Canadian Institute for Advanced Research. Attended two CIAR workshops in Edinburgh (June 2001) and Vancouver (December 2001). Dr Jean Braun was an invited Professor at l'Universite Joseph Fourier de Grenoble (France) in December 2001 and January 2002.

Dr J.D. Fitz Gerald was a member of the Advisory Board for the ANU's Centre for Science and Engineering of Materials.

Dr T.R. Ireland is a Senior Fellow in the Department of Geological Sciences, Canterbury University, New Zealand.

Professor I. McDougall became Treasurer and a member of Council of the Australian Academy of Science in May.

Drs M. Sambridge and J. Braun have continued to distribute a computer software program (NNquick) for scattered data interpolation. In 2001 researchers from numerous national and international institutions requested and received a copy of the program.

TEACHING ACTIVITIES

As part of his joint appointment at RSES and the Department of Geology (The Faculties), Professor S.F. Cox taught the one semester GEOL 3002 Structural Geology and Tectonics course, half of GEOL 2012 Introduction to Structural and Field Geology and part of the GEOL3001 Field Geology courses in the Geology Department. He also contributed a four week lecture/lab module to the GEOL1002 unit.

Professor R.W. Griffiths was lecturer for a third year unit on the Physics of Fluid Flows within the undergraduate physics curriculum.

Dr U. Faul taught at the Geology department, ANU, the third year course Geology 3017 "Fundamentals of Geophysics".

Dr J. Hermann gave 4 lectures in third year geology at ANU Geology on Alpine metamorphism and tectonics and related 6 hours of practicum on high pressure metamorphic rocks from the Alps.

Professor R. Grün gave a lecture series on topics of Quaternary geochronology to students of the Department of Archaeology and Anthropology, The Faculties.

Dr I. Jackson contributed a four-week module of lectures, tutorials and laboratory visits on condensed matter continuum mechanics to the undergraduate physics subject PHYS2016.

Dr C.E. Martin presented a guest lecture to honours students in the Environmental Geochemistry and Mineralogy class at the University of Otago, New Zealand, in May 2001 and participated in a class field trip to look at the environmental impact of the Macraes Flat gold mine.

Dr J. M. Palin presented a series of lectures on the theory and use of stable isotope geochemistry to students of the Ore Genesis Group.

Dr D. Rubatto taught, together with Dr J. Hermann, a three hours course on petrography of high-pressure metamorphic rocks from the Alps for third year students at the Geology Department, ANU.

Mr N.G. Ware taught the Microanalysis component of the 2001 workshop series in the Australian National University Electron Microscope Unit.

Dr Williams assisted several students with SHRIMP analyses, including Ms H. Degeling and Ms S. O'Callaghan, PhD and Honours students respectively from the ANU Geology Department, and Ms P. Lavery and Ms A. Storkey, PhD students from La Trobe University, Melbourne.

HONOURS SUPERVISION

Dr Campbell and Professor Arculus co-supervised Mr Kurt Worden of the Geology Department, ANU.

Professor Cox supervised the Honours project of Mr R. O'Leary ("Structural controls on fluid flow and gold mineralisation, Argo deposit, St Ives Goldfield, WA") in the Geology Department, The Faculties.

Dr J. Hermann supervised Ms S. Williams, the Australian National University Geology Department, on the Tien Shan eclogites from SW-China.

Dr M. Honda co-supervised Mr D. Gillen, an Honours student from the School of Geosciences, University of Wollongong, on a project entitled "Exposure dating in young lava flows using cosmogenic neon-21".

Dr J. Mavrogenes supervised the Honours project o Ms Aleks Kalinowski ("An experimental investigation into the causes and effects of sulfide partial melting at Broken Hill NSW, Australia") in the Geology Department, The Faculties.

RESEARCH SUPPORT

ELECTRONICS GROUP

Demand for Electronics support remained strong during the year, despite the unexpectedly low requirement for SHRIMP MultiCollector development. Maintenance activities accounted for 22.3% of human resources, administration and group support 14.5%, ASI support 0.96%, with the remaining 62.2% devoted to development activity.

Notable developments undertaken included:

- Design of a precision, evacuated "Input Node Switch Box" to facilitate evaluation and development of low level 'Electrometers' for the NG61 instrument and the Finnigan company. (D. Corrigan).
- Four user configurable Data Acquisition interface systems for geophysical Fluid Dynamics (A. Welsh and others).
- Three integrated high performance Ion Pulse Counting System (IPCS) for use on SHRIMP instruments and the NG61 mass spectrometer (A. Latimore, J. Lanc and N. Schram).
- Ongoing refinement, safety interlocking and Data Acquisition development for various high pressure apparati within the Petrophysics group. (A. Forster and J. Lanc).
- Fabrication, testing and calibration of four 'tesla tamer' © magnetic field probes for sale to ASI, and progress towards completion of a further 4 probes. (J. Arnold).
- Development and manufacture of a 4 channel Salimeter for GFD. (J. Arnold).

- Considerable progress towards completion of three 'FC3' Field Controller Units, for application to SHRIMP II, SHRIMP RG, and the NG61 Mass Spectrometer. (J. Lanc).
- Design, manufacture and testing of five Sublimator Pump Controllers for the NG61 instrument (N. Schram).
- Design, manufacture and testing of two Filament Supplies for the EG&G Filament Degasser project. (N. Schram).
- The completion of a range of smaller development projects, including evaluation of Keithley 6430 electrometers (N. Schram), modifications and upgrading of AntPAC hardware (A. Welsh), Noble gas extraction line automation (N. Schram), and the fabrication of two Getter Pump supplies for GIG (J. Arnold) .

Staffing

The group comprises 7 permanent Technical Officers, including D. Corrigan who remained seconded to the group for the year, whilst engaged in electro-mechanical design for the NG61 Mass Spectrometer project. The group anticipates appointment of two Trainee Technical Officers during 2002, as part of the school's succession planning strategy.

Outlook

2002 promises to be an interesting year, as we return our attention to the SHRIMP MultiCollector, and further development for the NG61 Mass Spectrometer project. The profound changes to costing and accounting envisaged from 2002 will present a challenge to the group. We anticipate an initial period of adjustment, followed by a long term, unpredictable effect on the scope and nature of operations.

RSES ENGINEERING WORKSHOP

We have had no large exciting projects this year but have never the less been very busy. The year started with a complete rebuild of Shrimp 1's source chamber due to a massive oil dump in the works. Valther Baek-Hansen assisted John Foster in this rebuild resulting in a much-improved machine.

We have lost Chris Morgan to Geophysical Fluid Dynamics and he will not be replaced as we were one staff member over strength due to the appointment of Andrew Wilson when he completed his fitting and machining apprenticeship. We hope to appoint another apprentice when circumstances permit.

The requests for workshop time from campus users is still being met although with the joint RSES, RSPhysSE computer controlled Electrical Discharge Machine situated in RSPhysSE workshop the work is being shared and because of the expertise developed, drawing complex work from interstate.

We have had some success quoting for external work and fitting it in with our school commitments and priorities. This work is generally of an unusual or demanding nature. This is in line with the school's new approach to funding.

Geoff Woodward built Jim Dunlap's new helium line with Xiadong Zhang supervising and assembling. Geoff also built the solar cell supports for Paul Tregoning's Antarctic project.

David Thompson built a new chiller for Malcolm McCulloch with Les Kinsley designing and testing.

Andrew Wilson is building an optically-stimulated luminescence lens and camera system for Nigel Spooner and is working with Iain McCulloch on this project.

Roger Willison built the supplementary coring equipment for the trip to Indonesia sampling corals. This was for Nerilie Abram and Mike Gagan. The trip went well with few problems.

Chris Morgan completed the heat exchanger parts for Geophysical Fluid Dynamics before moving onto his new position in the GFD laboratory.

We are building a new larger and improved filament degasser for Environmental Geochemistry and Geochronology to a concept by Malcolm McCulloch designed by the workshop.

All of this is happening around the usual emergencies, consumables, minor jobs and Shrimp multiple collector development.

Research School of Earth Sciences Annual Report 2001

Overview

The Research School of Earth Sciences (RSES) conducts research at the highest international level and takes a leadership role in defining new directions of research in geophysics and geochemistry – particularly those which have relevance to the needs and geologic setting of Australia. During 2001, Professor David Green stepped down after seven distinguished years as Director of RSES. David's tenure as Director was notable for the move towards the study of the Earth's environment, particularly with regard to establishing a geologic baseline for climate change. This initiative is now fully integrated into the School's scientific culture and has substantially reshaped our view of what constitutes the study of the solid Earth. The first priority of my Directorship has been to position the School as strongly as possible to benefit from the changed operating environment resulting from the Institute 'buy-in' to the ARC grants scheme. The School has chosen to devolve budgetary control of most non-infrastructure support with the view that managing those funds as closely as practicable to the level of the individual investigator minimizes potential mismatches between research expenditures and grant income. The School's first foray into contesting ARC funds was highly successful, with 40% of our applications receiving support. Our goal is to eventually derive approximately 20% of our total support from both ARC competitions and from Department of Education, Science and Technology (DEST) funds, distributed on the basis of our performance against key research and research training indicators. It is to our clear advantage that we take these steps to take maximum advantage of the opportunities that exist in the new funding environment. While the need to devolve budget authority within the School has been dictated to us by outside events, I anticipated these actions having the effect of further empowering individual investigators to not let the limitations of internal resources suppress their scientific ambitions. My role remains to provide overall academic leadership to the School and undertake strategic planning to maintain the School's position among the world leaders in geophysics and geochemistry research. Federal grants schemes are intrinsically cautious: they are unlikely to support long term and high risk endeavours, including the development of experimental and analytical devices, in which RSES has a distinguished history. Neither will they support collection of data sets which are of fundamental importance to understanding the earth as a complex system. We have therefore chosen, in concert with budget devolution, to sequester a portion of block grant funding for planning purposes. The planning fund, which will eventually grow to $750,000 per year, will be used to seed new scientific initiatives; as matching funds for external grants; and to support original, on-going research efforts that are outside the funding priorities of federal grant schemes. It will be derived from savings largely realized by external support of technical and fixed term academic posts. Our first initiative is an effort with the Research School of Astronomy and Astrophysics to create a joint centre to study the fundamental nature of planetary systems. Consistent with my first priority as Director, I have chosen to focus this Annual Report to Council on the structural changes agreed within the School in 2001, for implementation in 2002 and succeeding years, to position it for success in the coming years. Those changes have been discussed in detail with all staff through Faculty, Faculty Board and local meetings of staff. I have been gratified by the increasing acceptance over time and, mostly, enthusiasm of staff towards a model focussed on growth and success. However, this focus of the report is not intended to diminish in any way the outstanding research achievements of the School in 2001. These and other aspects of School activity are highlighted below.

Key Statements

Enhancing our national and international roles

- national (and international) provider of state-of-the-art instrumentation to universities, government agencies and industry (through direct collaboration and through PRISE)
- continuation of key role in Australia's activities in support of the Comprehensive Nuclear Test Ban Treaty (CTBT) through expert advice and successful commissioning of new equipment at one of the world's most sensitive seismic and infrasound monitoring facility at Tennant Creek, NT

Improving the educational experience of our students

- enhanced opportunity for RSES students to gain valuable research or laboratory experience overseas through the generous endowment by former professor of the School, Mervyn Paterson, and his wife, Katalin, of a fellowship, to be awarded annually to an RSES student for this purpose

Enhancing our research performance

- structural and budgetary change within the School, including the establishment of a substantial internal planning fund – see Overview

Enhancing our role in research training

- recognising the inadequacy of Government-funded IPRS, establishment by the School of a fund, from external earnings, for tuition fee waiver scholarships for excellent international students

Continuing to develop our staff

- continuing commitment to upgrade the skills of support staff through attendance at IT and other relevant courses and through formal technical and professional study
- investment in developing the advanced technical skills required by the School through employment and support of trainee technical officers

Seeking appropriate partnerships and alliances, both academic and business

- continued strong linkages with AGSO (now Geoscience Australia), involving a growing corps of GA staff working within the School
- partner in two CRCs – Greenhouse Accounting, and Landscape Evolution and Mineral Exploration (LEME)
- continuing close cooperation with ASI Ltd in the development of SHRIMP ion microprobes

Diversifying funding base

- maintenance of a substantial external funding base resulting from the School's CTBTO contracts, a range of instrumental and consulting services (to industry and Australian and international government agencies) and returns from instrument sales – with further diversification to come in 2002 as a result of ARC first cohort success

Budget Performance

The School's operating grant in 2001 of $8,644,000 was supplemented by transfers from other areas in the University, student fee income and other external income of $724,585. The resulting recurrent budget, coupled with savings from 2000, produced a cash surplus which is committed to ongoing fixed-term academic appointments, major equipment purchases and building modifications to house the OSL laboratories to be transferred from RSPAS in 2002. Approximately 73% of the School's recurrent expenditure budget was taken up by salaries. It is clear that the reduction in our operating grant beginning in 2002 when the IAS enters into the ARC competitive funding arena, has the potential to absorb most of the School's discretionary budget. Total income to the School in 2001 from sources external to the University was just over $3,300,000 – a small increase from the previous year. Some 32% of the School's expenditure from all areas (R, Q, S and E) was funded from external sources – concentrated on scholars, fieldwork/travel and equipment. Funding for students is being given priority. The School was pleased to receive matching funds of $200,000 from the Endowment for Excellence for the Jaeger Scholarship fund. The School has also topped-up the Hales Honours and the Ringwood Scholarship funds. In order to provide some flexibility in recruitment of overseas scholars, funds have been set aside to provide up to two Tuition Fee waiver scholarships a year.

Gender Equity Performance

The School's gender profile did not change significantly in 2001. At the end of the year, 21 (30%) of general staff were women. Of the 10 School staff at ANUO9 or above, two were women. The small number of women academics continues to be of concern. Five (11%) of 47 academic staff were women, of which only one held a standard appointment. Women are not applying for academic positions in the School and it is apparent that School staff will need to be more pro-active in 2002 in encouraging applications from women.

Significant Achievements in Research and Teaching

In March 2001, the quality and impact of the School's research was highlighted by two of the School's staff, Professor David Green and Professor Malcolm McCulloch, being designated ISI Citation Laureates. The Laureates were awarded to the 33 Australian scientists having the largest number of high impact papers over the period 1981-1998. Media interest in the School's chronology work, in particular, was again high. Dr Nigel Spooner and his dating work featured in a National Geographic article on chronology, and on German radio and television documentaries. Some highlights from each of the thematic areas were: Earth Physics

- better understanding of the effect of the Indo-Asian collision on the Cainozoic evolution of Australia by successfully modelling the puzzling nature of intracratonic deformation of the Australian continent
- better understanding climate variation by development of ways to study the effect of wind variability on instabilities in ocean currents
- development of a new approach to surface wave tomography which permits data from a wide variety of sources to be incorporated resulting in more refined estimates of the Earth's internal structure

Earth Chemistry

- showing for the first time that the sulfide ores of Broken Hill — the largest known lead-zinc deposit on the planet — must have been partially molten during peak formation. Implications of this discovery could transform our understanding of how giant ore deposits form and lead to refinements in the tools we use to discover them

Earth Materials

- better understanding the properties of sulfur in silicate melts by examining very oxidizing conditions, under which the sulfur dissolves as sulfate not sulfide. Implications of this work include understanding sulfur degassing from magmas during major volcanic eruptions, a known cause of global climate modification
- discovering that the partial melting expected beneath mid-ocean ridges results not only in very low seismic velocities, but produces an unusual frequency dependence that could fingerprint molten parts of the overturning upper mantle and thus help us better understand the nature of the Earth's deep interior

Earth Environment

- shedding new light on Australian megafaunal extinction – the remains of a giant kangaroo at Lake Mungo were dated at no more than 35,000 years old, whereas nearby aboriginal hearths are at least 41,000 years old. An apparent implication of this result is that, contrary to current thought, at least one species of giant marsupial survived long after the arrival of humans on this continent
- discovery that brief climatic excursions occurred periodically throughout the last 8000 years, suggesting greater global climate instability following the end of the last ice age than previously appreciated

Student Numbers

At the end of 2001 the School had 21 postgraduate students enrolled (20 PhD and one MPhil). 18 were in the Earth Sciences Graduate Program and three in the Quaternary and Regolith Studies Program. The most popular broad areas of study were Earth Physics (seven students) and Earth Environment (six students). The popularity of environmentally-focused studies is steadily increasing, particularly amongst Australian students. During 2001, six students commenced postgraduate study (compared with four in 2000) and nine students submitted their theses.

Major Prizes, Honours and Awards

Staff

- Professor Ross Griffiths – Fellow of the Australian Academy of Science and Fellow of the American Geophysical Union.
- Professor Kurt Lambeck – Prix International Georges Lemaître 2001, awarded by Louvain University, Belgium, for research in astrophysics and geophysics; and 2001 Tage Erlander prize, awarded by the Swedish Research Council to carry out research into the glacial history, sea-level change and crustal rebound in Sweden. The second stage of this Erlander Professorship is to be taken up in 2002

- Professor Malcolm McCulloch and Professor David Green – ISI Citation Laureate Awards for authoring multiple high-impact papers from the period 1981-1998
- Dr Ian Campbell – Centre of Excellence Fellowship from the Japanese Government to work in Japan for up to twelve months
- Professor Rainer Grün – visiting fellow, St Catherine's College, Oxford, during his overseas study leave.
- Dr Ross Kerr – Fellow of the Australian Institute of Physics

Students

- Mr Wilfred Lus and Mr Kazonori Yoshizawa – Outstanding Student Paper awards at the American Geophysical Union Fall Meeting, San Franscisco, December 2001

New Grants

This section reports grants other than ARC grants awarded in 2001. I will report those in 2002, their year of commencement.

- Dr A.J. Berry – grant from the Australian Institute of Nuclear Science and Engineering (AINSE) to undertake neutron diffraction experiments at ANSTO
- Dr Andrew Berry and Dr John Mavrogenes – two grants from the Access to Major Research Facilities Fund to investigate the speciation of copper in fluid inclusions at the Advanced Photon Source, Argonne National Laboratory, USA
- Dr Andrew Berry in collaboration with Dr Hugh O'Neill – two grants from the Australian Synchrotron Research Program to continue their work on oxidation states in silicate melts at the Australian National Beamline Facility, Tsukuba, Japan
- Dr Joerg Hermann – 3 year fellowship as "Advanced Scientist" funded by the "Swiss National Science Foundation" at the Research School of Earth Sciences starting on December 1st 2001.
- Professor Ian McDougall – grant from the Australian Institute of Nuclear Science and Engineering to facilitate irradiation of geological samples in the HIFAR nuclear reactor, operated by the Australian Nuclear Science and Technology Organization, in relation to dating of rocks by the 40Ar-39Ar method.
- Dr Malcolm Sambridge – one-year grant under the Comprehensive Test Ban Treaty Organization (CTBTO) Calibration program for a project on regionalized travel times
- Dr Nigel Spooner – Associate Investigator on an NERC (UK) grant on "The human colonisation of Australia: Breaking the 40 ka BP radiocarbon barrier", with Principal Investigator, Dr C Turney, University of London.
- Dr Paul Tregoning – Australian Antarctic Science Grant on "Crustal rebound in the Lambert Glacier area".

Future Directions

Research

Over the next five years, the School will evolve consistent with the structural adjustment which has commenced in 2002. Areas of research which do not succeed in obtaining external funding and which do not meet the criteria for support through the Planning Fund will be phased out progressively. We look to both the Planning Fund and success in ARC competitive grants serving to align our research with national priorities. The former will be used to maintain support for those high risk, long term activities of national significance for which the block grant is properly used. Our goals for success in winning national competitive grants will ensure that our efforts are focused in areas of national importance.

As I have noted, our first planning initiative will be an effort with the Research School of Astronomy and Astrophysics to create a joint institute to understand the formation, evolution, diversity and fate of planetary systems in the Universe and their relationship to our own Solar System. Since the first planet outside our Solar System was discovered seven years ago, over 80 extrasolar planetary systems have been found, none of which resemble ours. As a result, the long-standing paradigm of solar system formation and evolution is under serious challenge and further discoveries may fundamentally alter our views on the habitability of the universe. Theoretical modelling of this new state of knowledge is in its infancy and represents a fertile area of future research that connects directly with the goals of RSES. Our initiative is very timely as our unique analytical resources (e.g., SHRIMP-RG) place us in a highly competitive position to investigate the first returned samples from the Sun (GENESIS mission) in 2005, primitive asteroids and comets (STARDUST mission) in 2006, and a differentiated planet (Mars sample return mission in about 2010).

At present, this nation does not have a major presence in this vital, cross disciplinary area of science. Our initiative will spotlight Australia's scientific capabilities on a global stage and provide an attractive platform from which our brightest young minds can be recruited into the areas of science and technology. Investigations in this field will surely lead to spin-off benefits in the areas of instrument development and photonics and provide a natural mechanism for fledgling links into space science industry.

Students and Teaching

The School will give priority to increasing student numbers, particularly Australian students, who count as student load in DEST funding formulae. My target is a progressive increase to a student load of around 40. This represents a strong challenge, particularly given decreasing enrolments in physical sciences and the propensity of Australian universities to work against the ultimate best interests of both students and the universities themselves by encouraging their own students to pursue postgraduate study within their undergraduate department. I have noted the establishment by the School of a fund for tuition fee scholarships. Beginning 2003, I will provide an internal incentive for student enrolments by including a student load factor in the formula for internal allocation of funds. This is consistent with my belief that individual staff, using personal contacts and networks, are an important component of recruitment success.

The School will seek to introduce both Honours and coursework Masters programs in 2003 which will allow physical science graduates to gain specialist knowledge in geophysics for which it has unique national strengths. The School and Australia's industries depending on geoscience need advanced graduates firmly grounded in the disciplines of physics, chemistry and mathematics. The program will give such graduates the opportunity to gain Honours and postgraduate geoscientific qualifications for employment or further postgraduate study.

Mark Harrison

Director

March 2002

GEOPHYSICAL FLUID DYNAMICS

Geophysical Fluid Dynamics is the study of fluid flows and their roles in transporting heat, mass and momentum in the Earth's hydrosphere, crust and deep interior. In the Research School of Earth Sciences, the research in this field is focussed on the exploration of physical processes of importance in three different areas: convection, mixing and circulation in the oceans; magmatic and volcanic processes; and the convection of the solid silicate mantle, with its implications for plate tectonics. The Geophysical Fluid Dynamics Group continues to emphasise the importance of dynamical modelling and a rigorous understanding of the underlying dynamical principles. Much of the research program is anchored strongly in experimental fluid dynamics and relies on laboratory facilities. A new purpose-built laboratory was occupied in 2000 and this year became fully operational (Figure 1). The research relies also on advanced computing facilities within the Research School and the Australian Partnership for Advanced Computing National Facility located at the University.

Figure 1: Work in the recently opened Geophysical Fluid Dynamics laboratory, showing apparatus being used to study cooling and solidifying channel flows and the dynamics of basaltic lava channels.

The research topics in Geophysical Fluid Dynamics this year include aspects of both the wind-driven upper ocean circulation and the buoyancy-driven thermohaline circulation of the oceans. Numerical modelling of circulation in a simple laboratory model driven by a surface wind stress continued, with the appointment of an Australian Postdoctoral Fellow, Dr A.E. Kiss, and an emphasis on the generalisation of an approximate mathematical formulation of the equations of motion suitable for numerical solution. A new PhD student, Ms J. Mullarney, joined the study of convective circulation driven by a horizontal gradient of surface heat flux and a freshwater (or salinity) input. The work has shown oscillatory behaviour for steady forcing, specifically for some values of the ratio of heat and freshwater buoyancy fluxes. Dr A.A. Bidokhti continued his nine month sabbatical leave from Tehran University and examined the structure of outflows from the Persian Gulf and Red Sea. He completed laboratory experiments with turbulent and double-diffusive (warm, salty) outflows, the results of which suggest that low-frequency internal gravity waves propagating downward in the water column may influence the observed vertical splitting of the outflows. Another visitor, Dr J.R. Taylor, spent five months in the Group on sabbatical leave from the University of New South Wales at the Australian Defence Force Academy, and carried out laboratory experiments modelling the formation and propagation of fronts in the atmospheric boundary layer resulting from differential surface heating over plateaux or escarpments. The results have been used to interpret data for inland propagating fronts over the highlands of south-eastern Australia.

In the area of mantle dynamics, Dr G. Davies has continued his modelling of the stirring of chemical heterogeneities in the convecting mantle driven by internal heating and the subduction of lithospheric plates. The modelling has predicted mean isotopic ages of mid-ocean ridge basalts of two billion years, which is much older than previous modelling had suggested and consistent with measured ages. If subducted oceanic crust is given a small mass anomaly in the new models, there is consequently a small degree of buoyant settling of this material and the models predict the depletion of mid-ocean ridge basalts, relative to ocean island basalts, in incompatible trace elements. Novel experiments, in this case in the laboratory, have also been carried out, by Professor R.W. Griffiths and Dr R.C. Kerr, to understand rapid basaltic lava flows in channels. These experiments form part of collaborative work with volcanologist Professor K.V. Cashman from the University of Oregon, and involve measurement of flows of fluid down a long sloping channel while it is solidifying at its surface (Figure 1). This work is at an early stage, but has already indicated a criterion for formation of lava tubes rather than open lava channels. It also demonstrates the usefulness of fluid dynamics experiments as a tool with which to learn more about the processes that govern cooling, solidification and flow front advance in lava flows.

The staff of the Group was complemented this year by Mr C.J. Morgan, who joined us as a Senior Technical Officer. Mr M. Wells submitted his PhD thesis, received his doctorate, and took up a research position in fluid mechanics at Eindhoven University of Technology, The Netherlands. Two long term visitors Dr J.R. Taylor and Dr A.A. Bidokhti have been mentioned above and the Group continued to enjoy the presence of Emeritus Professor J.S. Turner. The staff, students and visitors all acknowledge the vital contributions of our technical and administrative support staff, R. Wylde-Browne, A.R. Beasley, C.J. Morgan and F.A. Chivas, to our research program. Collaboration continued with Australian Scientific Instruments, who received a further order for the 'Geophysical Fluids Rotating Table'.

Inclined turbulent fountains

R.C. Kerr and L.J. Bloomfield[1]

Turbulent fountains are formed when a continuous jet of dense fluid is injected rapidly upwards into a less dense environment, or when a continuous jet of buoyant fluid is injected rapidly downwards into a denser environment. They arise in a number of important situations both in engineering and in nature, including: the forced heating or cooling of aircraft hangers, buildings or rooms; the disposal of brines, sewerage and industrial waste into the ocean; the improvement of water quality by forced mixing in reservoirs, small lakes and harbours; vehicle exhausts and accidental leaks of hazardous gases; the evolution of volcanic eruption columns; the replenishment of magma chambers in the Earth's crust; and the exit snow from snowploughs.

Motivated by these diverse applications, we have explored the dynamics of turbulent fountains in a number of experimental and theoretical studies over the past six years. In particular, extensive investigations have been made of both axisymmetric and two-dimensional fountains in homogeneous environments, in stratified environments, and in environments with confining boundaries. In this latest study, we have examined experimentally the effect of the angle of inclination of the source on the behaviour of turbulent fountains in both homogeneous and stratified environments (Figure 2).

In a homogeneous environment, the initial fountain height was found to decrease monotonically as the inclination was increased, due primarily to the decreased vertical momentum of the source fluid. In contrast, the final fountain height was also affected by the

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turbulent interaction between the upflow and downflow, which decreased rapidly as the inclination was increased. As a result, the final height was found to increase, and then to decrease, as the inclination was increased. The maximum height of the fountain was found to occur at an angle of about 10 degrees, at which point the fountain was about 20% higher than the height of a vertical fountain.

In exploring the behaviour of inclined turbulent fountains in a stratified environment, we first examined the limiting case of zero buoyancy flux at the source. We found that the effect of inclination angle on both the fountain and the spreading heights is small, although there is some suggestion of a maximum in both heights at about 10 degrees. The small variation in this case was explained as being due to both the weak (1/4 power) dependence of the fountain height on the source momentum flux and the weak turbulent interaction between upflow and downflow. We then quantified the initial, final and spreading heights for a fountain inclined at 10 degrees, as a function of the strength of the stratification in the environment. In particular, we determined the stratification required for a maximum spreading height or a zero spreading height.

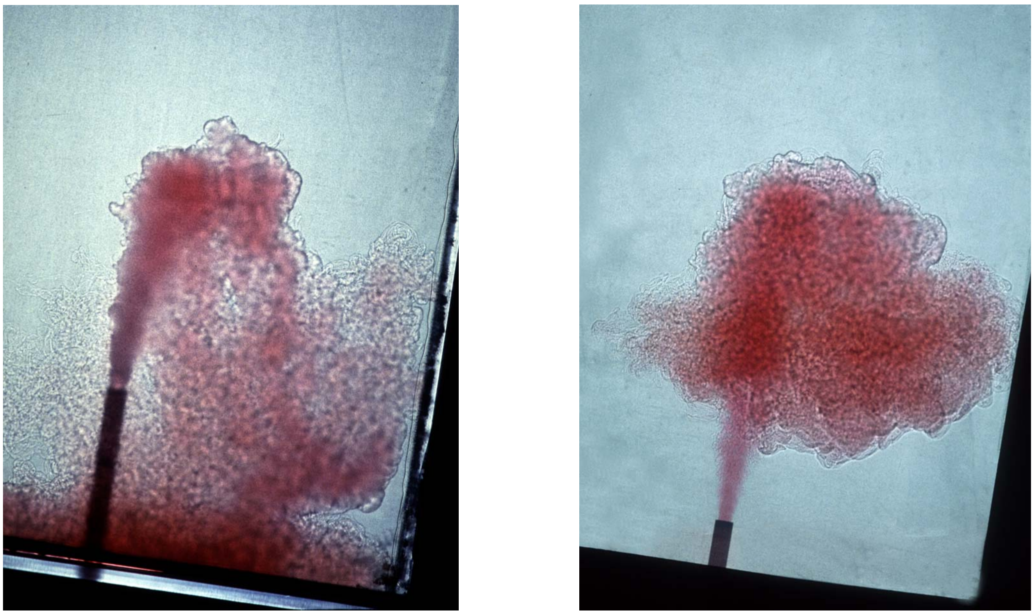

Figure 2: Photographs of turbulent axisymmetric fountains formed from a source inclined at 10 degrees to the vertical, in a homogeneous fluid (left), and in a stratified fluid, for the limiting case of zero buoyancy flux at the source (right).

Surface solidification in long channelized lava flows

R.W. Griffiths, R.C. Kerr and K.V. Cashman[2]

In a new project begun this year we are exploring the behaviour of basaltic lava flowing through large channels, with a view to predicting the distance that lava travels. Molten basaltic lava from large eruptions on volcanoes such as Hawaii is often channelled into rapidly-flowing rivers of melt. Channels are commonly 10—100 m wide and of the order of 10 km in length, with the flow being 2—10 m deep during its active period. Much longer channels, up to 750 km, were important in transporting lavas from large prehistoric flood basalt eruptions and spreading them over broad areas of the Earth. Lava tubes, channels that become fully encased in solidified lava, are also common. Tubes arise when the lava surface solidifies and forms a connected roof over the flow. The roof greatly reduces the rate of heat loss and hence enables

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the lava to flow much greater distances than would be possible if the roof were continuously disrupted. The dynamics of solidifying channel flows thus influence the surfacing of much of the Earth's crust. These dynamics may be central to the interpretation of the geological evidence and estimates of the rates and volumes of prehistoric eruptions. We therefore search for an understanding of the relationships between eruption conditions, the form of lava flows and the distances they spread. Similar questions arise in attempting to infer the geological histories of Venus, Mars and the Moon from remote images of their surfaces.

The physical processes that govern the formation of channels and the continued flow through them are complex, and involve the interaction of fluid and solid mechanics. Even small amounts of solidification on the surface will influence the rate of cooling of the flow. Rapid crust formation tends to insulate the flow and strongly affect the morphology of the flow front, as in the case of Hawaiian pahoehoe flows (Figure 3). In the first stage of a new study of channel flows, and in collaboration with volcanologist Professor K.V. Cashman of the University of Oregon, we are using laboratory fluid dynamics experiments with a material that serves as analog to lava. In the experiments polyethylene glycol wax flows under cold water down a 3m-long, sloping channel. Our flows are laminar, having Reynolds numbers of 0.2—70 based on flow depth and centre-line speed. For a constant source volume flux we have found two steady state regimes, depending on the flow velocity and the temperatures of the wax and the water relative to the freezing temperature of the wax.

Figure 3: Professor Griffiths examining the rheology of freshly exposed melt in a Hawaiian pahoehoe flow.

For sufficiently high flow speeds and temperatures a solidified surface crust develops in the centre of the laboratory channel at some distance from the source (Figure 4) and is carried downstream. This crust remains separated from the walls by shear regions in which solid phase is continually forming but fragmented into small pieces by the shear, before being carried down into the interior of the flow by convection currents. At lower flow speeds and temperatures solidification creates a stationary roof and flow continues through an insulated tube beneath (Figure 4). Our initial results indicate that the condition for tubes is $U_0 t_s / W < 0.75 \pm 0.2$, where U_0 is the surface speed without cooling at the centre-line, t_s is the predicted time for onset of solidification in an idealised initial-value problem and W is the channel width. Time-dependent behaviour occurred under conditions near the transition from open channel to tube flow. We also found that small non-uniformities in the channel that increase flow speed can promote open channel flow, while large irregularities in the channel width tend to cause the formation of tubed flow.

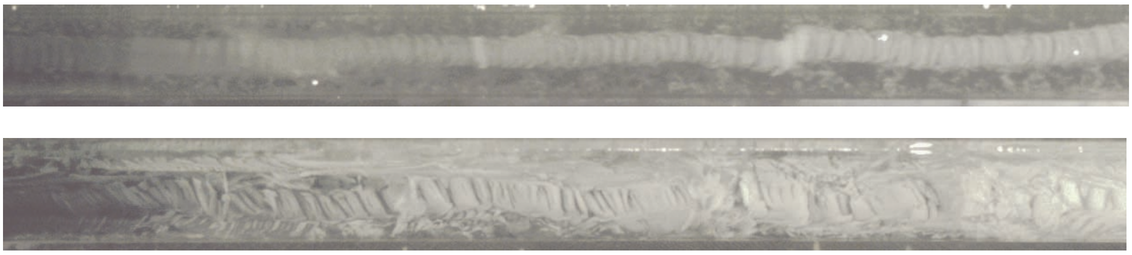

Figure 4: Overhead photographs showing the two apparently steady state regimes of surface solidification in a channel flow cooled from above. The upper photograph shows a mobile central crust with lateral shear zones when $U_0 t_s / W = 2.2$. The lower photograph shows tube flow when $U_0 t_s / W = 0.43$. Solid wax is white, liquid PEG is transparent and the base of the tank is painted black. Flow is from left to right. The photographs correspond to distances from the entrance sluice gate of 0.5m to 1.1 m and 0.2m to 0.8m, respectively.

Oscillations in models of the ocean thermohaline circulation

R.W. Griffiths and J.C. Mullarney

A new laboratory model designed to help us understand the processes that control the strength and patterns of large-scale overturning circulation in the oceans has begun to yield results. The experiment follows up a much earlier recognition that thermohaline circulation of the oceans is forced by the meridional gradient of surface heat flux, and modified by surface water fluxes. Our experiments involve a long channel that is heated and cooled non-uniformly along its base, thus turning the ocean upside down. The heat flux gradient forces a large-scale convective circulation which includes a stable thermal boundary layer, similar to the upper ocean thermocline, and deep convection strongly confined to a small region at one end of the tank. We introduce a small flux of more dense salt solution at one bottom corner in order to model the input of buoyancy by relatively fresh water at the surface of the ocean at high latitudes.

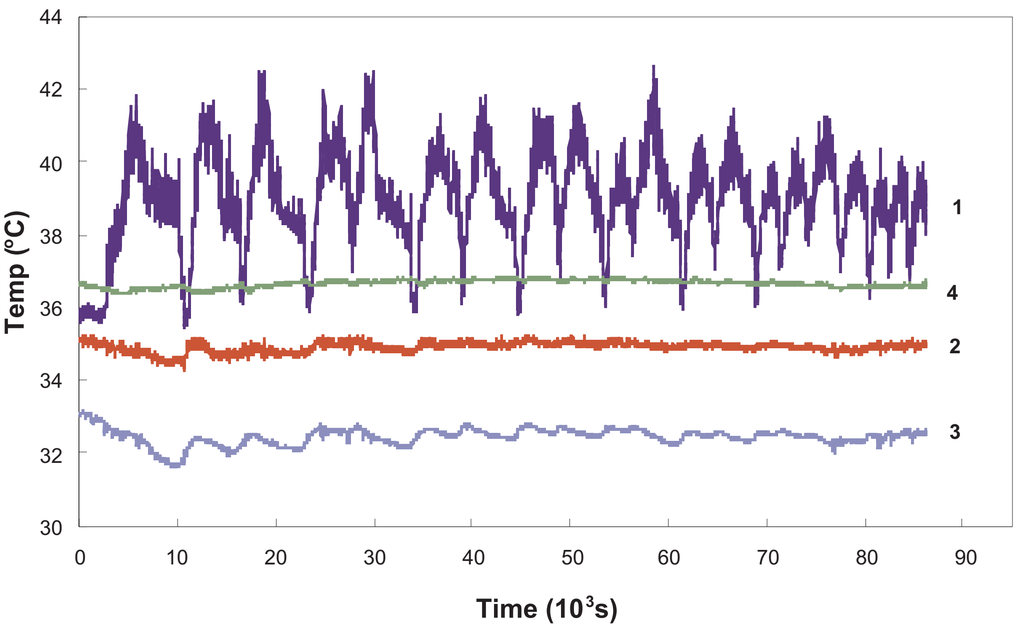

Figure 5: An example of temperature records from the laboratory experiment with thermal and salinity buoyancy fluxes in a ratio that leads to oscillatory behaviour. Three records shown are from thermistors fixed 1cm above the base in the bottom boundary layer of the flow and (1) within the warm, salty bottom layer near the salt input, (2) at the centre of the heated base, (3) at the centre of the cool base. Record (4) is from the flow near the top of the tank.

Using prototype apparatus we have begun to map out in parameter space a number of different flow regimes. We have also shown that an unstable convectively mixed layer, not unlike the surface mixed layer of the ocean at high latitudes, forms above the heated portion of the boundary. The salinity flux leads to another mixed layer and a stable interface (or halocline) within the thermal boundary layer. There are conditions under which the circulation is essentially steady, conditions under which the halocline periodically breaks away (Figure 5) and conditions under which oscillations give way to a stable salty layer that floods the entire base. The latter case leaves a strongly layered 'ocean' with little transport between the forcing surface and the bulk of the water depth. The temperature evolution has been monitored (Figure 5), and we have developed a means of observing and measuring, using 'synthetic schlieren', the (two-dimensional) distribution of refractive index gradient, hence density, throughout the entire tank.

Modelling thermally driven circulations in the atmosphere

J.R. Taylor[3]

Similar differential heating and cooling phenomena to those that drive the ocean thermohaline circulation are also important at much smaller scales in the atmosphere. They result in local winds such as sea breezes and plateau winds. The Canberra summertime easterly is a local example of this type of flow. However, in contrast to the ocean, the daily cycle of heating and cooling at the Earth's surface and the resulting change from stable to unstable conditions in the boundary layer result in complex unsteady circulation systems. Buoyancy, inertial forces and turbulent friction all play important roles at different stages. Particularly interesting is the formation and acceleration of an inland-propagating afternoon wind surge.

An unsteady differential heating experiment has been set up in the GFD laboratory to model frontal development in a diurnally forced plateau circulation system. The main dynamical regimes of the flow can be adequately delineated by simple scaling arguments. However, measurements of the velocity field from particle imaging velocimetry and the temperature field from rapid thermistor traverses give a more detailed picture of the frontal development process. The laboratory results will help in the interpretation of atmospheric observations and the design of future field experiments.

Damping of internal gravity waves

G.O. Hughes

In stratified environments such as the atmosphere and oceans, internal gravity waves are commonly generated when the density field is disturbed from equilibrium. These waves transport both energy and momentum vertically, and are an important means of coupling the motion at different levels in a stratified flow.

In most geophysical flows the internal gravity wave field is subject to damping by the stresses arising from background turbulence. To help understand the evolution of such wave fields I have used laboratory experiments in which the damping is due to viscosity. Sufficiently strong damping is observed to both attenuate the wave amplitude with distance from the wave source and to modify the intrinsic frequency/wavelength of wave motion. Measurements of the wave field (Figure 6) have been compared with existing inviscid theory and with a theory developed last year that incorporates damping due to viscosity. The experimentally observed wave field is much better predicted by the theory that incorporates viscous damping. Damping has been found to be particularly important for internal waves with low excitation frequencies — up to at least $O(10^{-2})$ of the maximum frequency — over a wide range of experimental conditions.

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[3] University of New South Wales at the Australian Defence Force Academy

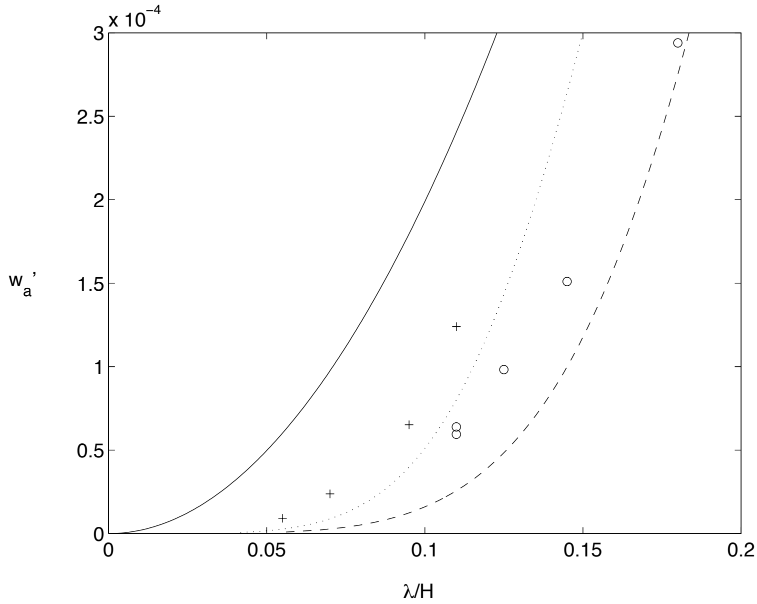

Figure 6: Comparison of theoretical predictions and experimental measurements for strongly damped internal gravity wave fields. The dimensionless vertical phase velocity w_a' of a wave mode is plotted as a function of dimensionless vertical wavelength λ/H: ———— inviscid theory; + and O, experimental measurements for two different levels of damping; ··········· and – – – – –, damped theory corresponding, respectively, to the two levels of damping.

Internal waves as a source of finestructure at ocean fronts

A.A. Bidokhti[4] and R.W. Griffiths

Laboratory experiments carried out during the year have shown that vertically travelling internal gravity wave modes excited by outflows from marginal seas can produce counter-flowing shear layers that may split up the outflows into a series of counter-flowing interleaving layers. Turbulent plumes of relatively dense waters commonly flow out of marginal seas such as the Mediterranean Sea, Persian Gulf and Red Sea, and tumble down the sloping bottom until they reach a depth at which they become neutrally buoyant. There the water intrudes into the surrounding ocean, forming a large mass having anomalous temperature and salinity. These intrusions are found to be rich in finestructure, with temperature and salinity gradients broken into many uniform layers and sharp interfaces. Similar finestructure is common at temperature-salinity fronts (regions of large horizontal temperature and salinity gradient but with little or no density gradient) in the open ocean where two water masses meet.

The fine-scale layering has commonly been attributed to the action of thermohaline convection, which draws on the vertical gradients of both temperature and salinity and produces density 'staircases'. Our new experiments with plume outflows into a density-stratified tank of salty water show that a series of counter-flowing horizontal layers can be formed even in the absence of thermohaline convection. These layers are forced by excitation of a preferred internal wave mode. This mode propagates downward while being advected upward from the depth of the outflow and its phase is therefore nearly stationary in the water column. In other experiments using two turbulent dense plumes at opposite ends of a large channel, we have formed a density front near the centre of the channel and again observed the generation of strong counter-flowing horizontal shear layers. These layers cause interleaving of the water from each side of the front, and are qualitatively similar to the interleaving layers found in the oceans. When the two plumes have differing temperatures and salinities, the front separates two distinct

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water types and the interleaving layers are modified slightly by thermohaline convection. However, their vertical scale is not altered by the convection. We propose that low-frequency internal wave modes in the oceans excited by a variety of sources may be responsible for establishing the scale of interleaving layers in ocean fronts and plume outflows.

Dynamics of ocean circulation driven by surface wind stress

A.E. Kiss

At mid-latitudes the large-scale mean horizontal circulation of the upper ocean is dominated by recirculations ("gyres") which are driven by the surface wind stress and span the width of ocean basins. The gyre circulation consists of a broad, slow flow in most of the basin (towards the equator in subtropical gyres). This flow is returned by a narrow, rapid boundary current at the western side of the basin and which separates from the coast as an unstable meandering jet. The Gulf Stream in the northern Atlantic is the best-known western boundary current, but similar currents are found in all ocean basins, and the local example in the south west Pacific is the East Australia Current. The western boundary currents (WBCs) of subtropical gyres form an important part of the global climate system by carrying a large amount of heat from subtropical to subpolar latitudes. The flow in WBC separation regions is highly energetic, and strongly variable on timescales of a few years to a few decades; this variability is thought to be an important factor in climate fluctuations.

In June I commenced an ARC Postdoctoral Fellowship to investigate the dynamics of WBC variability through the application of simplified laboratory and numerical models which capture the essential physical processes controlling the wind-driven circulation. This research builds on my PhD work to explore the modes of instability and their dependence on parameters such as the strength of the wind forcing. Steady wind forcing has been employed in the initial stage to map out the stability boundaries in parameter space, prior to an investigation of the influence of time-dependent forcing. This study also explores the effects of steeply sloping topography such as continental slopes, which form the lateral boundaries of ocean basins. Such large relative depth variations preclude the use of standard quasigeostrophic equations to describe the flow. I developed a modified formulation during my PhD, which permits large depth variations but retains the simplicity and most of the conservation properties of the usual quasigeostrophic equations. The scope of applicability of this formulation has been investigated in greater detail this year in preparation for its use in further modelling.

Plume zonation

C. Mériaux

Basalts from hotspot ocean islands, such as the Hawaiian and Galàpagos Islands, are widely attributed to melting of mantle plumes, which likely ascend from the core-mantle boundary layer. While it has long been recognized that lavas in these islands have different compositions, different geochemical domains across the hotspot tracks have now been identified and found to be persistent along the hotspot track. Complex processes related to partial melting and melt migration can produce some geochemical variability, but they do not explain all of the observations. Thus, many geochemists believe that the variability within oceanic islands basalts also reflects a source characteristic.

A series of laboratory experiments has been undertaken to assess whether a distribution of "heterogeneities'' entrained in a plume conduit sheared by plate motion will maintain its identity. For transport in a vertical conduit, we expect simple stretching and thinning of heterogeneities. When horizontal shearing motion is superimposed on the buoyancy-driven vertical motion, the conduit is carried horizontally, becoming bent over. This leads to a complex recirculation in the conduit and entrainment of surrounding fluid. Thus "heterogeneities" at the source can be stirred, possibly to the extent that heterogeneities observed at the surface might no more reflect their distribution at the source. The amount of stirring depends on the buoyancy flux of the plume and the imposed shear, which together determine the angle of tilt of the conduit. In the experiments, a slowly rotating lid drives horizontal motion in a cylindrical tank of glycerol 60 cm in diameter and 24 cm deep. A hot plume is generated by an electrically heated pad 10 cm in diameter on the tank base. Two small tubes filled with dyed glycerol were set at diametrically opposite positions on the heated pad relative to the plume origin and perpendicular to the shear direction. The flow can be characterised by a Rayleigh number and a ratio of the lid velocity divided by the ascent velocity.

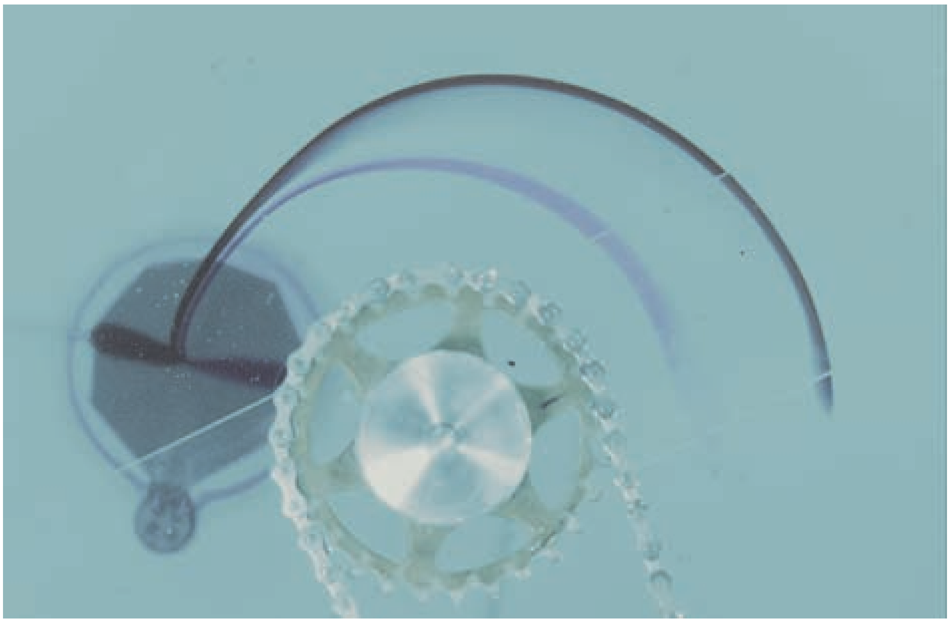

Figure 7: View from the top of a steady tilted plume conduit in a shear flow. Two streams of dyed glycerol are entrained into the plume within the heated bottom boundary layer (Rayleigh number $1.4x10^{10}$ and velocity ratio 0.4).

We find that tracers from opposite sides of the source region are gently stirred within the tilted conduit, but remain separated on opposite sides of the vertical plane through the axis of the conduit. Near the surface lateral spreading of the conduit further separates the two streams (Figure 7). For Rayleigh numbers larger than 10^{10} and velocity ratios less than 0.6 the extent of wrapping of dye tracers within the conduit by the time the tracers reach the surface is insignificant. Three-dimensional numerical modelling of the problem is currently being tested using the software package 'FLUENT'.

Stirring of chemical tracers by mantle convection

G.F. Davies

Work on this project has progressed well since a preliminary report last year. Stirring of tracers simulating a basaltic component has been studied in models (Figure 8) that feature stiff surface plates and subducting lithosphere, migrating subduction zones and a higher-viscosity lower mantle. An important innovation has been to take account of the likelihood that the mantle was turning over faster in the past, because radioactive heat sources were stronger. This was done by running the models for the equivalent of 18 Ga at present rates, and re-scaling the tracer ages. Chemical differentiation associated with melting was simulated by partitioning tracers into an oceanic crust as they entered a melting zone defined by a prescribed depth of first melting. The melting depth decreased with time, to take account of mantle cooling.

The most striking result of these computations is that the mean age of simulated mid-ocean ridge basalts (MORBs) is routinely greater than 2 Ga. This contrasts with previously published models, which have yielded ages much less than the apparent ages of lead isotope heterogeneties, which are approximately 1.8 Ga. Since there are several reasons why the new exploratory models might have over-estimated the ages, the models open the way to matching the observations and remove the need for *ad hoc* layering to explain the isotopic ages.

Assigning a positive mass anomaly to the tracers, to represent excess density of subducted oceanic crust, causes depletion of the tracer concentration in the upper-most mantle and a modest accumulation of tracers at the base of the mantle. These effects can explain the depletion of MORB, relative to ocean island basalts (OIBs), in incompatible trace elements.

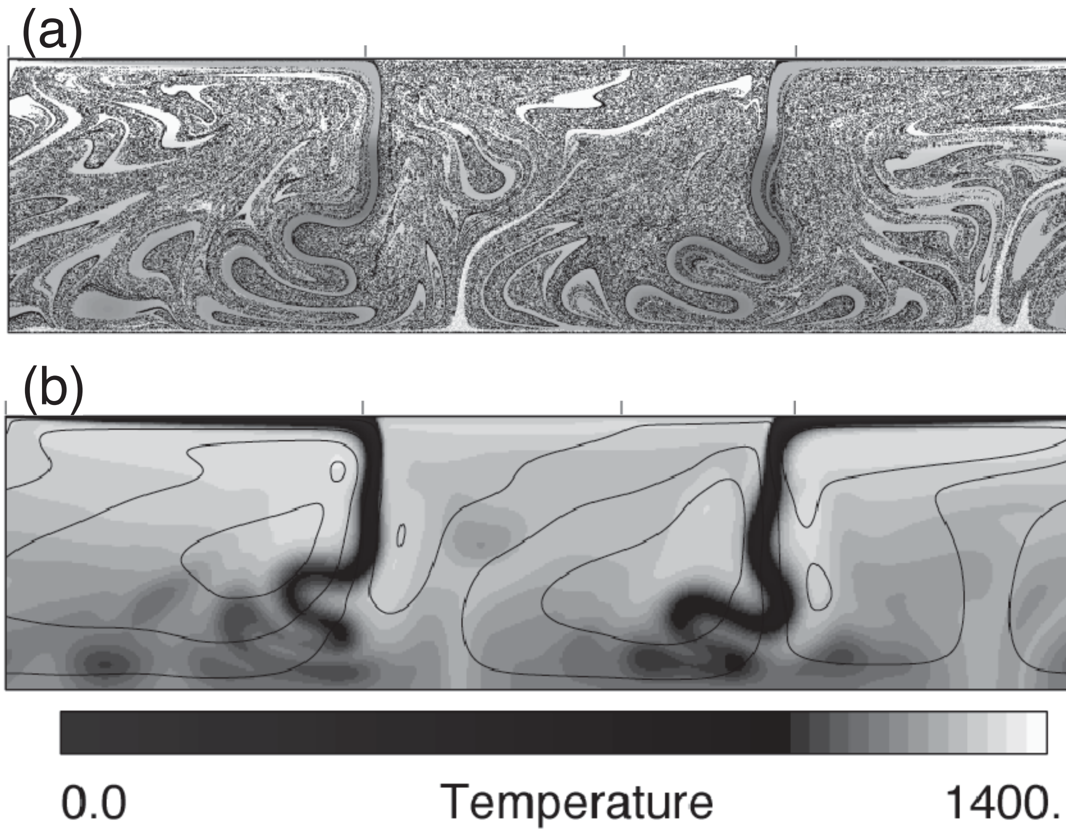

Figure 8: The pattern of tracers after stirring in a model of the mantle for the age of the earth. (a) The tracers, plotted as black dots, with tracer-depleted zones representing melt residue. The tracers are plotted over a background shaded according to viscosity, darker representing higher viscosity. Tracers that have passed though the lowermost 20km of the mantle are plotted as white dots, and are evident as columns rising from the base. (b) Temperature (grey scale) and streamlines at the same time as (a). There are two plates, left and right, approaching and subducting under a notional continental plate in the centre. Subducted lithosphere has high viscosity because it is colder, and it buckles as it enters the lower mantle, whose viscosity is ten times greater than the upper mantle.

In these models, OIB is assumed to be produced by plumes that rise from the base of the mantle, so that each plume samples the lowermost mantle. The mean age of the OIB sample increases as the mass anomaly of tracers increases. With zero mass anomaly, the mean OIB age is less than the MORB age, and a modest but plausible mass anomaly yields a mean age comparable to the MORB mean age. The reconciliation of geophysical and geochemical observations of the mantle has been puzzling and controversial, and these results show that models that include reasonably realistic plates, a moderately-high-viscosity lower-mantle and the faster overturn of the mantle in the past show great promise.

Double-diffusive plumes in a homogeneous environment

J.S. Turner

In experiments described in last year's report Turner and Veronis used horizontally separated point sources of salt and sugar to study the structures and motions generated by compensating horizontal and vertical gradients of T and S in the ocean. This system, with the more rapidly diffusing salt used as the analogue for heat (T) and sugar as the analogue for salt (S) has proved to be a very effective method of studying double-diffusive processes. It was shown that, starting with equal densities of the homogeneous tank fluid and both the input solutions, the asymptotic state (after about 100 hours) was the same when the experimental tank contained either homogeneous salt or sugar solution initially. In both cases large vertical density and property differences developed, with a weakly unstable salt and a very stable sugar distribution (corresponding to cold fresher water over hot salty water in the ocean, the 'diffusive' state). The early behaviour in the two cases was different, however, and the current work seeks to explain this and its effect on the overall evolution.

The new experiments demonstrate that this difference arises because the individual input plumes are not completely equivalent (or even antisymmetric). Salt diffuses rapidly out of a saline plume in a tank of sugar solution into a surrounding sheath, producing stronger convection in the environment than a sugar plume in a salt tank. The resulting upward and downward transports of the two properties have been measured in both cases over a range of density differences between source and tank fluid. With equal densities these two transports of salt in a sugar environment are nearly equal, while for a sugar source in a salt tank there is a larger flux of sugar downwards; the fluxes only become equal when the input is much lighter. This bias towards the production of diffusive vertical property distributions near one source, combined with continuing horizontal interleaving motions that allow communication between the two sources, is consistent with the asymptotic state observed in the previous two-dimensional experiments.