Annual Report 1999

Research School of Earth Sciences

Institute of Advanced Studies

The Australian National University

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Institute of Advanced Studies
The Australian National University
Canberra ACT 0200
Australia

School Enquiries:

Telephone (02) 6249 3406
Facsimile: (02) 6249 0738

Director's Office:

Telephone: (02) 6249 2487
Facsimile: (02) 6249 0756

RSES Home Page: http://wwwrses.anu.edu.au/

Front Cover Image
Fibrous wollastonite (cream coloured needles) produced by decarbonation reaction between quartz (golden) and calcite (fawn) under hydrothermal conditions. The quartz grain is about 15 μm wide (see page 65).
(Photograph by Shuqing Zhang and Harri Kokkonen)

Back Cover Image
Map view at 200 km depth of the lateral variation in shear wave speed and azimuthal anisotropy across the Australian Continent. Velocity variations (in per cent) relative to a reference velocity are represented by colours, where blue is faster and red is slower than the reference velocity of 4.5 km/s. Fast directions of horizontally propagating SV waves are represented by bars; the largest bar in the centre of Australia represents about 1.5% peak to peak anisotropy. The smooth pattern of anisotropy with dominant North-South component is attributed to an effect of the northward movement of the Australian plate (see page 16).
(Figure by Eric Debayle)

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Ulrich Faul

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Ulrich Faul, Brian Kennett, Anne Gillard and Group Administrators of the Research School of Earth Sciences

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STAFF AND STUDENTS

ACADEMIC STAFF

Director and Professor:
D.H. Green, BSc MSc DSc, DLitt (Hon) *Tas*, PhD *Camb*, FAA, FRS

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[†]
R. Grün, DiplGeol, Dr rer nat habil *Köln*, DSc *ANU*
M.T. McCulloch, MAppSc *WAIT*, PhD *CalTech*
I. McDougall, BSc *Tas*, PhD *ANU*, FAA

Senior Fellows:
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*
F.E.M. Lilley, BSc *Syd*, MSc PhD *WOnt*
H.St.C. O'Neill, BA *Oxf*, PhD *Manc*
B.J. Pillans, BSc PhD *ANU*

Fellows:
M.I. Bird, BSc *Syd*, PhD *ANU*[♥]
J. Braun, LicSc *Liège*, PhD *Dalhousie*
M.K. Gagan, BA *CalifSantaBarbara*, PhD *JamesCook*
R.C. Kerr, BSc *Qld*, PhD *Camb*[♥]
A.P. Nutman, BSc PhD *Exeter*
M.S. Sambridge, BSc *Loughborough*, PhD *ANU*
S.L. Webb, BSc *Qld*, PhD *ANU*, *Habil Göttingen*[†]
I.S. Williams, BSc PhD *ANU*

International Fellow (ARC)
S. Vergniolle de Chantal, BSc MSc *Ecole Normale Superieure deLyon* PhD *Paris VII*[†]

Research Fellows:
C.A. Alibert, MS *Paris VII*, PhD *CRPG*[†]
V.C. Bennett, BSc PhD *CalifLosAngeles*
E. Debayle, MSc PhD *Institut de Physique du Globe de Strasbourg*[*†]
W.J. Dunlap, BA *CarletonColl*, MS PhD *Minn*
H.U. Faul, Vordiplom Ulm, PhD *UOregon*
O. Gudmundsson, BSc *Iceland*, MSc *Wash*, PhD *CalTech*[†]
J. Hermann, Diplom PhD *ETH Zürich*[♥]
J. Johnston, BSc PhD *ANU*
C.E. Martin, BSc *NCarolina at Chapel Hill*, PhD MPhil *Yale*

[†] Left during the year
[*] Changed appointment during the year
[♥] Funded by the Australian Research Council

J.A. Mavrogenes, BS *Beloit*, MS *Missouri-Rolla*, PhD *VirginiaPolyTech*
J.M. Palin, BA CalifState, MS *NewMexicoInstMin&Tech*, PhD *Yale*
N. Spooner, BSc MSc *Adel*, PhD *Oxon*
P. Tregoning, BSurv, PhD *NSW*
G.M. Yaxley, BSc PhD *Tas*[w]
S. Zhang, BSc Msc *Changchun*, DIC *Imperial College*, PhD *ANU*[*]

Postdoctoral Fellows:

A.J. Berry, BSc *Syd*, DPhil *Oxf*[w]
G. Hughes, BE ME *Auck*, PhD *Camb*
W.R. Taylor, BSc *Auck*, PhD *Tas*
C.S. Turney, BSc *East Anglia*, PhD *Lond*[w]

VISITING FELLOWS ON FACULTY DURING 1999:

Dr C. Alibert (RSES)
Dr L.P. Black (AGSO)
Dr J. Claoué-Long (AGSO)
Dr S. Clement (Consultant)
Professor W. Compston (Emeritus)
Dr S. Condie (CSIRO)
Dr T. Esat (Geology, Faculty of Science, ANU)
Dr A. Glikson (GeoSpectral Research, ACT)
Professor A. L. Hales (Emeritus)
Dr R.W. Henley (Consultant)
Dr A.M. Heimsath (Univ of California, Berkeley)
Dr J. Hermann (ETH, Zurich)
Dr G. Kaufmann (German Research Society Fellow)
Dr T. Lee (AGSO)
Dr J. Lindsay (AGSO)
Dr R.R. Loucks (RSES)
Dr P.L. McFadden (AGSO)
Professor A.C. McLaren (Emeritus)
Professor G. Miller (University of Colorado)
Dr L.N. Moresi (CSIRO)
Dr R. Page (AGSO)
Professor M.S. Paterson (Emeritus)
Ms D.G. Questiaux (RSES)
Dr D. Rubatto (ETH, Zurich)
Professor R.W.R. Rutland
Dr S.-S.Sun (AGSO)
Dr T. Sato (Earthquake Research Institute, University of Tokyo)
Professor J.S. Turner (Emeritus)
Dr S. Vergniolle de Chantal (Institute de Physique du Globe, Paris)
Professor G. Veronis (Woods Hole Oceanographic Inst)
Dr S. Webb (Geology, The Faculties ANU)

ANUTECH ASSOCIATES:

R. Armstrong, BSc MSc PhD *Witwatersrand*
C.M. Fanning, BSc *Adel* (Principal Research Scientist)
D. Phillips, BSc MSc *Rhodes*, PhD *Princeton*
A. Rastawicki, MScEng PhD *W-waUniv* (Principal Project Manager)

RESEARCH OFFICERS:

D.R. Christie, MA Tor, PhD *ANU*

J.D. Fitz Gerald, BSc *James Cook*, PhD *Monash*
S.E. Kesson, BSc *Syd*, PhD *ANU*
H.W.S. McQueen, BSc *Qld*, MSc *York*, PhD *ANU*
N.G. Ware, MSc *Durh*

RESEARCH ASSISTANTS:

A. Arcidiaco, BApp Sc, Grad Dip *SA Inst*
S. Billings, BSc *ANU*, PhD *Syd*
A. Purcell, BSc PhD *ANU*
D. Schneider, BSc Qld, PhD *ANU*[†]
C. Soames, BSc *ANU*, DipGeol *BIET*

POST-GRADUATE STUDENTS

PhD Candidates:

J.R. Ballard, BSc, *Imperial College of Science, Tech & Med*
T.T. Barrows, BSc *ANU*
L.J. Bloomfield, BSc *ANU*
D. Bright, BSc *Syd*
D.R. Burbidge, BSc *ANU*
H. Cheng, BSc *Zhangjiakou Normal College*, MSc *Beijing*[†]
G. Clitheroe, BSc *Vict Well*[†]
C. Davids, Propaedeutic, Doctoraal *Utrecht*[†]
E. Dixon, BA California, MSc *Michigan*
P.M. English, GradDipEd *Darwin Inst Tech*, BA *Alaska*, BSc *ANU*
J.M. Evans, BSc *ANU* (jointly with RSPhysSE)[†]
S.J. Fallon, BA MS *San Diego*
K.M. Fleming, BSc *UNE*, MAppSc *Curtin*, MPhil *Cant*
A.C. Hack, AssocDi AppSc CIT, BSc *ANU*
L.M. Hanley, BSc *WA*
C.J. Heath, BSc *Monash*
J.C. Hellstrom BSc *Vict Well*[†]
E.J. Hendy, DipSc *Otago*, BSc *Waikato*
A.P. Hitchman, GradDipEd *UC*, BSc *UNE*[†]
Y. Hiyoshi, BSc *Ryukyus*, MSc *Hawaii*[†]
P.W.O. Hoskin, BSc *Auck*[†]
A.M. Jellinek, AB *Hamilton*, MS *Idaho*[†]
J. Kemp, BA BSC *ANU*
A. Kiss, BSc *ANU*
S. Klemme, Vordiplom *Münster*, Diplom *Göttingen*[†]
X. Liu, MS, *ChineseAcSci*, BSc *ChinaUnivGeosci*
W.Y. Lus, BSc *PNG*
H.V. McGregor, BSc *JamesCook*
C.W. Magee Jnr, BSc *Brown*
P.C.N. Marianelli, BSc *NTU*, BSc *Flind*
K. Marson-Pidgeon, BCA BSc *Vict Well*
T.A. Nicholson, BSc *Vict Well*
D.I. Osmond, BSc *ANU*
E.-K.M. Potter, BSc *Woll*, Sc *ANU*
J. Quinn, BSc *Vict Well*
B.D. Rohrlach, BSc *Adelaide*
P. Rustomji, BSc *ANU*
B. Setiabudi, Grad *Bandung Inst Tech*, BSc *Wollongong*
D.J. Sinclair, BSc *Cant*
W. Sun, BSc BSc MSc *USTC*
B. Tan, BSci and Tech *PRC*

J.H. Tomkin, BSc *Melb*
P. Treble, BSc *Woll*, BSc *ANU*
Q. Wang, BSc MSc *Peking*[1]
M.G. Wells, BSc *ANU*
Y. Xu, BSc *Nanjing*, MS *ChineseAcadSc*[1]

Hales Honours Year Scholars:

S. Belfield, BSc *James Cook*
N. Douglas, BSc *ANU*
C. Farmer, BSc *ANU*

GENERAL STAFF

Executive Officer:
B.A. Payne, BA *ANU*

Assistant Executive Officer:
D.M. Ritherdon, BA *ANU* (seconded to ESP Program Jul–Dec 99)
T. Gallagher, BA *Vancouver* (from Jul–Dec 99)

Building and Facilities Officer:
R.L. Stone, Dip Admdin RAAF, Grad Dip Mgmt *USQ*

Technical Officers:
A. Alimanovic, BSc, MSc *Zagreb*[1]
C. Allen, AB Princeton MS *Oregon*, PhD *VirginiaTech*
J.T.A. Arnold, BSc (Agr) Syd, GradDipElect *CCAE*
A.R. Beasley, AssocDipMechEng *CIT*
V. Baek-Hansen
Biggs, Mr P.J.
J. Cali, BAppSc *QIT*
D.L. Corrigan
J.A. Cowley, BSc *ANU*
B.D. Ferguson
A.W. Forster
J.J. Foster, BSc Syd, MSc PhD *ANU*
N. Gabbitas, BSc *ANU*
J.H. Grant
Z.R. Guziak[1]
N.G. Hansen, Adv Cert (Electronic Servicing), AssocDip Eng (Elect), *RIT*[1]
W.O. Hibberson, BAppSc *CCAE*
N. Hill, BA *ANU*
G.R. Horwood[1]
I. Iatsevitch, BEng Tashkent Polytec Inst, PhD *Russian Academy of Sciences*
B. Jenkins, BASc *UTS*
D. Kelleher, Assoc Dip Cartog *CIT*
L.P.J. Kinsley, BSc GradDipSc *ANU*
H. Kokkonen, BAppSc *CCAE*
C. Krayshek
J. Lane
A. Latimore
H. Lynch, BSc Sydney
K. McAllister, AssocDipAppSc *CIT*[1]
R.E. Maier
C.J. Morgan
G.E. Mortimer, BSc PhD *Adelaide*

J. Mya, BSc *Mandalay*
S. Paxton
A.J. Percival
S. Robinson, DipAppPhys Gordon Inst Tech, MSc BSc *ANU*
N. Schram, Dip EIE *SAIT*
D. Scott
J.M.G. Shelley, MSc *Cant*
S.P. Sirotjuk, AssocDipEng (Electronics) *Gordon TAFE*
L. Taylor, BA *ANU*
D.B. Thomson
R.M. Waterford
G. Watson
A.R.W. Welsh, BAppSc *CCAE*
L. Weston, BSc *Macquarie*
P.E. Willis
R.E. Willison
A. Wilson
G.F. Woodward
R. Wylde-Browne
X. Zhang, PhD *LaTrobe*

Stores Supervisor:
W.A. Hampton

Information Technology Officer
D. Bolt, BSc *Syd*

School Librarian - Librarian's Staff:
S. Jackson, BA ANU, Grad Dip Lib Inf Man *UC*

Administration:
J.H. Blake
F. Chivas
T. Coombes
J.A. Delhaize
P.A. Gillard
V.M. Gleeson
D.H. Kelly
M. Lukatela
R. MacPherson
D. Mason[1]
K. Provins

Cleaning Staff:
R. Blake
L. Burge
S. Dejanovic
J. Harkins
Y. Liu
A.J. Norden
P.D. Norden

RESEARCH SCHOOL OF EARTH SCIENCES ADVISORY COMMITTEE

In 1999, meetings were held on 24–25 May and on 17–18 November (to coincide with the School Retreat).

1999 Membership

Dr Max Richards Chair	Chairman, Board of ANSTO and formerly Managing director Aberfoyle Ltd
Professor Frank Jackson (ex officio)	Director Institute of Advanced Studies and Chair, BIAS
Professor A.J.W. Gleadow*	University of Melbourne
Professor David H. Green (ex officio)	Director RSES
Professor S. Greenhalgh	University of Adelaide
Dr Neil Williams	Chief Executive Officer, AGSO
Professor R.J. Wasson	Director CRES
Professor M. McCulloch*	RSES
Dr I. Jackson*	RSES

*Replaced for 2000 Membership by

Professor Chris Powell	Director, Tectonics Special Research Centre Department of Geology and Geophysics The University of Western Australia
Professor B.L.N. Kennett	RSES
Dr H. St.C. O'Neill	RSES

INTRODUCTION — 1999 IN REVIEW

Professor David H. Green
Director, RSES

The Research School of Earth Sciences (RSES) has a national role to achieve excellence in basic and strategic research in earth sciences, emphasising the subdisciplines of geophysics and geochemistry and their interfaces with geology. The School has a significant research training role in relation to graduate students and particularly for postdoctoral research training emphasising facilities and equipment for research which are unique, within Australia, to ANU. The RSES undertakes research on issues which have long-term relevance to Australian needs or which exploit the unique geographic location of Australia. In recent years, RSES has increased its research activities in geological, geophysical and geochemical processes and on issues of global change and environmental processes.

Through 1999, there was major Government examination of the basis for funding research in the higher education sector. This led to publication (December 1999) of a Government White Paper entitled "Knowledge and Innovation" on research and training in the higher education sector. The paper sets out the Government's policy for higher education research and research training and is a significant re-organisation of the nature and roles of the Australian Research Council and of the DETYA programs for funding for research and training was identified.

The White Paper's impact on the Institute of Advanced Studies at ANU, and thus on RSES is considerable. The negotiations and discussions which followed the earlier discussion paper released in mid-1999 resulted in the IAS entering the ARC and DETYA-funded research system along with all other universities. The price of this entry is 20% of the IAS research budget and it is expected that the IAS will access:

a) ARC-funded research schemes — large grants, small grants, REIF and fellowships
b) DETYA program including:
   Institutional Grant Scheme (IGS)
   Research Training Scheme (RTS)
   Research Infrastructure Block Grant.

The DETYA program will return funds to IAS on a formula-driven basis with funds from IGS earnt by "external research income (60%)", "Higher Degree Research Load (30%)", and Publications (10%). The RTS component is calculated on External Income (40%), Higher Degree Research Completions (50%), and Publications (10%).

It is expected that approximately 10% of the RSES recurrent budget will be 'lost' and a greater or smaller sum will be returned to RSES by the DETYA program funding. RSES will compete for large grants, SPIRT grants, Fellowships, etc. (we already compete for REIF) in the 2001 round of submissions — for funds to be distributed in 2002. The first loss of approximately 3.3% of our recurrent budget to fund this entry is expected to occur in 2002 — i.e. the approximately 10% contribution to ARC will be phased in over three years beginning in 2002.

The changes to the role of the Australian Research Council and to the place of the Institute of Advanced Studies (IAS) within the research funding mechanisms for Australian universities will have a very significant effect on the way RSES plans its future. Firstly, the manifest benefits of the continuation of 80% of the block grant in terms of long-term planning of research programs and facilities must remain evident in terms of 'high risk' research, reward of excellent staff performance, and maintenance of the unique (in Australia) ability to design and construct prototype research equipment. However, there must be an increasing effort to attract to RSES high quality applicants for ARC-funded research projects. Applications for ARC-funded large grants, Special Research Centres, etc. will be required from RSES staff and collaborative research grant applications from RSES staff and those at other universities should now be encouraged by ARC.

The model used in the White Paper suggests that RSES should enroll additional PhD students. This must be achieved without loss of quality and in a recruiting environment of diminishing undergraduate enrolments in science. The current recruitment context is also one in which employment prospects for earth scientists in major Australian government organisations or in major minerals and energy exploration companies have decreased, coupled to increased expectations of specialised consultants. It is expected that RSES will need to seek to attract high quality overseas students and will necessarily seek funding for this. These significant changes to the way RSES is funded, and competes for growth funding, will be clarified through 2000.

RSES enters this period of change with the benefit of additional purpose-built laboratories within a new building (Jaeger 7) completed during 1999. The building is a direct outcome of a recommendation of the 1995 ARC/ANU Review of RSES, which recommended that there should be a purpose-built laboratory for Geophysical Fluid Dynamics (GFD) research. This has been achieved, including a large, high ceiling laboratory and a constant temperature, cool room for multiple fluid mechanics experiments together with attached workshop and technical support. The GFD Group staff and the Environmental Geochemistry & Geochronology staff now occupy the new building, including new purpose-built laboratories to house two new mass spectrometers for radiogenic isotope and trace element analyses and associated 'clean' chemical laboratories. A small seminar room in the new building has been named the A.L. Hales seminar room in honour of the School's first Director, Professor Anton Hales.

In 1994, RSES prepared a 10-year Strategic Plan (1995–2004) (published in the 1994 Annual Report) and in that process committed to a review and revision of the Plan in mid-1999. The need for revision if the 1995–2004 Plan was emphasised by necessary staff reductions, and limitations on change, through 1997/98 due to the absence of salary supplementation to match agreed salary increases for all University staff.

In terms of achievements against its Strategic Plan, the 1999–2000 analysis of the impact and visibility of published research through analysis of ISI citations, continue to demonstrate the international recognition of RSES research. RSES has also increased its external funding in diverse ways, including successful competition for RIEF funding for major equipment and contract or collaborative research for external agencies. The operation of Precise Radiogenic Isotope Services (PRISE) as a means of external access to RSES specialised research facilities particularly for isotope geochemistry, has proved very effective with, in 2000, four research positions being funded by this means. The collaboration with Department of Geology in the area of Economic Geology and Ore Genesis in particular has been mutually beneficial and has been the means of achieving the Strategic Plan objective of growth in research related to the understanding of the formation of metalliferous ore deposits. Similarly, the plan for growth in research activities focussed on global change has been met by the research efforts in the Environmental Geochemistry, Geodynamics and Geophysical Fluid Dynamics Groups and by the transfer to RSES from Research School of Pacific and Asian Studies (RSPAS) of the activities in quaternary research, including ^{14}C and spectroscopic dating techniques. This resulted in reorganisation of RSES group structure to form an Environmental Processes Group led by Professor John Chappell and an Environmental Geochemistry and Geochronology Group led by Professors M. McCulloch and R. Grün.

Of the activities which were 'new' at the beginning of the 1995-2004 planning period, the School has enhanced its capacities in the area of dating of recent geological materials to become the most prominent and diverse national centre for dating of Quaternary to Recent materials. These techniques are absolutely necessary for quantification of global change processes including climate change, sea-level change and human impacts on the environment.

The new (in 1994) initiative on 'Crustal Fluids' has developed techniques for chemical analysis of fluid inclusions by laser-ablation ICPMS and for *in situ* spectroscopic studies of glasses and fluids using synchrotron beams in Tsukuba, Japan and Chicago, USA. The initiative has also progressed with studies of porosity and permeability of fluids and melts under static high pressure conditions and with additional non-hydrostatic stress.

The acquisition of modern Global Positioning System (GPS) equipment of research quality has led to field observation programs in Papua New Guinea and in Antarctica. Observations in Papua New Guinea have defined the kinematics of movements of small continental blocks and of subduction of oceanic crust. This information is necessary for risk assessment and regional planning in this region of high earthquake and volcanic activity.

The acquisition of broad band seismic equipment by RSES was followed by a successful bid by Australian Geological Survey Organisation (AGSO) and RSES jointly for a Major National Facility (Australian National Seismic Imaging Resource (ANSIR)) in 1997/98. The continental scale mapping of the sub-crustal lithosphere and asthenosphere by seismic tomographic techniques has been completed and more detailed studies, past funded by the mineral exploration industry, have also been completed or are in progress.

Within the planning period, an initial increase in research support by minerals industry was followed by a downturn, directly applicable to the closing down of in-house exploration divisions and scientific expertise by most of the major mineral exploration and development companies operating in Australia. However, commercialization of RSES-developed intellectual property has continued through Australian Scientific Instruments Pty Ltd (ASI), particularly noting the sales of Sensitive High Resolution Microprobes (SHRIMPs) to Canada, Japan (2), USA and China.

In revising the 1995-2004 Strategic Plan, a subcommittee of Faculty met in late 1998 to review the current RSES facilities and research activities and plan for the future, emphasising both continuity of research strengths and identification of new research opportunities or priorities. Through 1999, the document was refined through consultation culminating in a Planning Retreat, together with members of the RSES Advisory Committee, in November 1999. The Strategic Plan, 2000-2005, which resulted from this consultation is presented immediately following this introduction.

With respect to staffing matters, Dr R.W. Griffiths was promoted to Professor during 1999 and Dr V. Bennett was appointed to a continuing level C (Fellow) position. This advertisement and appointment was in response to the 1995 Review recommendation on the need for RSES to address the absence of tenured, senior female staff. Gender equity issues were also addressed through adoption of a mentoring scheme for junior academic staff. Dr Daniela Rubatto was awarded one of five IAS Postdoctoral Fellowships following an initiative by the Institute Planning Committee (IPC) in 1999.

The PROGRESS IN RESEARCH in RSES in 1999 is summarised within the group and thematic (Centre for Advanced Studies of Ore Deposits) structure of the School, following the presentation of the 2000–2005 Strategic Plan.

RESEARCH SCHOOL OF EARTH SCIENCES - STRATEGIC PLAN

OVERVIEW

The School's goal is to carry out fundamental research in earth sciences, at the leading edge and at the highest international levels of achievement, with particular focus on issues that have long-term relevance to Australian needs and which exploit the unique geographic location of the continent and adjacent parts of the southern hemisphere.

The School's research into the structure, origin and evolution of the Earth (solid Earth, hydrosphere and atmosphere) draws upon strength, established and nurtured through block funding, in each of the following broad disciplinary fields:

Earth Physics: physical measurements and mathematical analysis of the structure of the Earth and of the physical processes operating within the Earth system.

Earth Chemistry: investigation of the chemical structure and evolution of the Earth and the nature and timing of terrestrial processes.

Earth Materials: 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: 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.

The School's expertise in each of these broad fields is described in Appendix II, which forms an integral part of this Strategic Plan.

When most recently reviewed by an international panel, RSES was described as one of the leading half-dozen institutions in the world for research in earth sciences (ARC Review, May 1996). The review also emphasized the complementarity of RSES research strengths to the more traditional geological research carried out in most other Australian universities. RSES intends to remain a world leader in its chosen research activities. It will also ensure that its research remains distinctive - complementing rather than duplicating the research strengths in earth sciences in other Australian universities and scientific institutions. In particular, RSES will seek to maintain and enhance its reputation for innovation in instrumentation, experimental techniques and geophysical modelling.

The 2000–2005 Research Program for RSES draws upon the expertise within the four disciplinary fields to define the following high-priority research objectives:

Origin and Evolution of the Earth: Mantle, Crust and Hydrosphere — emphasis on understanding the characteristics of the early Earth, the evolution of the Earth's Mantle through time, and the orogenic (mountain-building/erosional/depositional) cycle — Earth Chemistry focus with contributions from Earth Physics and Earth Materials.

Structure and Deformation of the Crust and Mantle — seismic imaging of deep crustal and mantle heterogeneity and complementary laboratory measurement of seismic properties, precise geodetic monitoring of crustal movements, and 3-D modelling of geophysical, geological and geochemical processes — Earth Physics focus with contributions from Earth Environment and Earth Materials.

Fluids, Melts and Mineralisation — studies of the generation and transport of fluids (including melts) particularly under experimental conditions simulating those in the deep crust and mantle with implications for the chemical evolution and extraction of magmas and the formation of metalliferous ore deposits — an Earth Materials and Earth Physics focus with contributions from Earth Chemistry.

Climates, Landforms and Ocean/Atmosphere Dynamics — investigation of dynamical processes in the ocean-atmosphere system related to climate change, determination of the historical record of global change, including both human impacts and climate variability, studies of uplift, erosion and soil production based on isotopic methods and modelling — an Earth Environment and Earth Physics focus with contributions from Earth Chemistry.

RSES draws its staff and students from diverse backgrounds notably mathematics, physics, chemistry and geology, and consequently, the activities within each of the major research objectives already have a strongly interdisciplinary character. In order to sustain this diversity and also achieve a greater degree of integration of these activities, the School is seeking support from the ANU's Institute Planning Committee for a new initiative *Earth Dynamics and Global Change* intended to draw together and build upon existing expertise with a focus on processes affecting the Australian lithospheric plate and its margins. This new theme for the School's research will link tectonic processes and environmental outcomes and provide a regional focus appropriate for Australia. Rapid tectonic uplift can result in a dramatic increase in the rate of erosion, and the profound climatic implications of major volcanic eruptions in our region were indicated most dramatically in 1816 ("the year without a summer") when Tamboura erupted in Indonesia. The new theme will also provide distinctive perspectives on current and future climate variability and landscape evolution through interpretation of the long geological record. Importantly, adequate resourcing of the development of the linking theme will integrate the environmentally oriented research program recently transferred from RSPAS within the mainstream activities of the School.

THE RESEARCH PROGRAM 2000-2005

The School's assessment of the external context for its Strategic Planning is outlined in Appendix I. Following a protracted and widely inclusive planning exercise, the School wishes to pursue the research priorities identified in the preceding Overview under the broadly integrative theme of *Earth Dynamics and Global Change* — thus seeking to take timely advantage of a combination of new capabilities to

- image and interpret the deeper structure of the crust and mantle, principally through seismic tomography and complementary laboratory data;
- obtain high-precision measurements of displacements across faults and strain fields using Global Positioning Satellite systems;
- measure uplift and erosion and sedimentation rates, using cosmogenic and radiogenic isotopes and a variety of physical techniques to obtain rates of change in surface environments on timescales of hundreds to millions of years;
- use proxy-climatic records provided by natural growth or depositional cycles with annual periodicity to interpret past climate and environmental conditions, combined with improved dating precision over the past one million years;
- link solid-earth behaviour and surface environments, over short (10–100 years) to long (10^5 to 10^7 years) time scales by development of high-resolution numerical models of crustal deformation which include landscape evolution and interaction with hydrosphere and atmosphere.

In this way, the School proposes to maintain the strong tradition of applying the quantitative methods of the physical sciences to the study of the Earth, that has underpinned its influential research into the origin, deep internal structure and long-term evolution of the Earth. This approach is distinctive within Australia, and the RSES work in geochronology and seismology in particular has provided the space-time framework within which the geology of the continent is understood. Now, building upon existing strengths, the School intends to focus a progressively greater proportion of its research effort upon the dynamics of the crust and upper mantle and their coupling with the processes of uplift, erosion, and soil production that shape the Earth's surface and its environment. In so doing RSES seeks to integrate research activities recently transferred from RSPAS into a coherent environmental geoscience program to study related aspects of ocean circulation, long-term climate variability, landscape evolution, and sustainable land use.

This evolutionary reshaping of the School's research profile will maintain and enhance its capacity for basic and strategic research in the earth sciences - a development clearly consistent with the long-term national interest in a country like Australia whose economic well-being is authoritatively considered to remain dependent for the foreseeable future, on minerals, energy and primary resources (land, soil and water-based). Furthermore, adoption by the School of the *Earth Dynamics and Global Change* theme would be an appropriate and timely response to community concerns with environmental issues, sustainable land use, and geological hazards in the Australasian region.

The Research Program 2000-2005 is focussed on four high-priority research objectives, each of which is an important area of investigation in terms of research impact and each of which is an existing research strength in RSES. Each of the four research objectives identified in the preceding Overview, draws on the expertise of several of the School's four disciplinary fields and each objective has achievable outcomes within a five-year time frame. In a later section, a brief statement describes each of the research objectives more fully. Current staffing and funding arrangements although closely targetted are barely sufficient to sustain these core activities. Additional funding is required to develop research opportunities with reasonable speed in a competitive environment and particularly to achieve the synergies which are implied in the regional and thematic integration, i.e. *Earth Dynamics and Global Change* in the Australasian region.

In developing priority objectives for 2000-2005, it is emphasized that the major changes are necessarily evolutionary in nature. The School's expertise in the core disciplines, and its state-of-the-art research facilities are major assets, built progressively over many years of relatively secure block funding. The strategic planning has identified research priorities which also meet the tests of competitive advantage in terms of capability and responsible use of prior investments. For example, the petrophysics facilities used in the past mainly for work on the high-temperature rheology of crustal minerals have been adapted for studies of the complex interaction between fluids and deforming rocks and for measurements of high-temperature seismic properties. The latter are directly relevant to interpretations of seismic tomographic images of the mantle beneath the rigid Australian plate and its volcanically active margins. Similarly, isotope geochemists and mass spectrometers which in past years focussed on the 'First billion years' of Earth history are currently also providing vital information concerning natural and anthropogenic factors influencing the Earth's climate, landscapes and biosphere during the past 100,000 years.

Strategic Planning in RSES has emphasized the need to maintain and enhance its core strengths. The declining budget has required that RSES also identify research activities in which it is currently or has recently been engaged, often with high visibility, but which must have low priority for 2000-2005. Support is being withdrawn from the following research programs:

- Diamond anvil research at extremely high pressures, directed towards the Earth's Transition Zone and lower Mantle. Staff have been redeployed to higher priority activities.

- Geomagnetism and palaeomagnetism. Responsibility for operation of the palaeomagnetic laboratory, which is the best equipped and most centrally located of three such laboratories in Australia, has been progressively transferred to AGSO. In response to changing priorities both in AGSO and RSES, it has been decided that the laboratory will simply be maintained in an operational state and monitored over a transition period to ascertain its viability as a fee-for-service facility. A small RSES usage, in part with CRC LEME (Landscape Evolution and Mineral Exploration) will continue on the new basis. The remaining activities in geomagnetism in RSES will be managed by due process and consultation with staff concerned.

- Geochronological research aimed at calibration of the palaeontological/stratigraphic time scale — this has been a major focus as RSES built up its geochronological facilities but responsibility for principal carriage of this research theme now resides with AGSO.
- Isotopic, trace-element and geochronological studies of Palaeozoic and Mesozoic granites in Eastern Gondwana — there is a very large body of work in preparation for publication. There are significant implications for mineral exploration in Eastern Australia and research in these directions may be externally funded, particularly through PRISE (Precise Radiogenic Isotope Services) for isotopic and geochronological data. Staff in this area will move their research interests into priority themes.
- Atmospheric physics with emphasis on phenomena observed by infrasonic arrays. Pioneering work at RSES led to incorporation of infrasound arrays as a major monitoring component in the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The key RSES staff member is seconded to the scientific arm of the CTBT in Vienna. RSES will discontinue research in this area leaving the scientific monitoring role to Australian government agencies.

RSES STRUCTURE AND PROGRAM IMPLEMENTATION

RSES will continue with a non-departmental organisational structure based upon research groups (currently nine in number), supported by administration, mechanical workshops, electronics workshop, lapidary and sample preparation staff, and a School IT officer. The group structure is based on sub-disciplinary coherence around particular experimental, field or analytical equipment, dedicated technical support staff and supervision of staff and students by Group Leaders. During the period 1997-99 RSES has restructured Groups in Geochronology and Isotope Geochemistry, Environmental Geochemistry and Environmental Processes, and appointed staff jointly to several groups. RSES has also created, with the Department of Geology, a Centre for Advanced Studies of Ore Deposits (CASOS) led by Professor Stephen Cox (joint appointment in Department of Geology and RSES).

The implementation of the Strategic Plan is monitored by the Director and Faculty Board with a program coordinator appointed for each of the four research objectives and a further coordinator for the integrating theme of *Earth Dynamics and Global Change*. A major role for the coordinators will be to organize at least one workshop each year on each research objective. Similarly, the RSES Annual Report will be restructured to include reports on progress towards each of the four research objectives.

The RSES structure is intended to create a rather fluid matrix in which the desirable attributes of sub-discipline coherence, peer review, and formal academic supervision are retained in the Group structure but the imperative for multidisciplinary research to address major earth science issues is met through more coordination to meet the shared research objectives.

RESEARCH OBJECTIVES

The following four research objectives together encompass much of the work planned by the School, each drawing upon several of its four areas of broad disciplinary expertise identified in the Overview.

Origin and Evolution of the Earth - Mantle, Crust and Hydrosphere

- *The Search for Origins: Characteristics of the Early Earth and Extraterrestrial Materials*

Focused field, petrological and geochemical studies of ancient (>3.6 billion-year old) rocks from Greenland, and potentially from Australia, the other southern continents and Canada, will be aimed at identifying the best preserved remnants of the early Earth, and addressing the nature and timing of processes by which the core, mantle, crust, hydrosphere and atmosphere have evolved. Additional major questions concerning the temperature of the mantle, global geochemical budgets, and the origins of life, can be examined through study of these very old rocks along with selected extraterrestrial samples.

- *Evolution of the Mantle and its Dynamical Regime*

The evolution of the mantle will be constrained through the integrated interpretation of isotopic and geological constraints using dynamical models of mantle stirring and chemical evolution. The isotopes of the noble gases and of refractory elements provide fundamental information on the existence, nature, and development of distinct reservoirs in the mantle and crust. The modes of convective heat and mass transport in the mantle are the fundamental drivers of the geological processes that shape, and continually reshape, the Earth's surface. The intimate coupling between mantle dynamics, mantle chemistry and convective styles and transitions will be exploited to determine the nature of the regime responsible for the formation of ancient mineral-hosting crust.

- *The Orogenic Cycle: Pressure/Temperature/Time Paths for Crustal Rocks*

Orogenesis, the process of mountain building and consequent erosion and sedimentation, results from collisions between lithospheric plates, and plays a major role in the development and evolution of the continental crust. The combined research capabilities in experimental petrology, geochronology and isotope geochemistry, will be utilized to accurately define pressure-temperature-time paths for crustal rocks from particular, carefully chosen, orogenic provinces. The techniques of isotope thermochronology, with measurements that can be related to rates of uplift, erosion and to the thermal histories of particular metamorphic terranes, coupled with those of thermometry and barometry based on mineral equilibria, are a particularly powerful means of studying crustal evolution, which RSES is well placed to further develop.

Structure and Deformation of the Crust and Mantle

- *Imaging and Interpretation of Crustal and Mantle Heterogeneity*

Seismic experiments conducted by RSES staff and students, along with work performed collaboratively with others using the Australian National Seismic Imaging Resource (ANSIR), will establish the variations in seismic properties of the deep crust and upper mantle of the Australian plate and its margins. RSES will provide particular strength in theoretical seismology to remove ambiguities in the translation of seismic velocity and anisotropy results to crustal and mantle models. The RSES Earth Materials expertise will provide laboratory characterization of elastic properties, phase assemblages (including partial melt and fluid) and microstructure which will help to distinguish between thermal and compositional/mineralogical causes of seismic heterogeneity.

- *Precise and Predictive Crustal Dynamics*

The GPS methodologies developed in 1995-1999 will be exploited to address problems in crustal motion and deformation in two distinctly different environments: the deformation zone between the Pacific and Australian plates, and in eastern Antarctica. The measurements of deformation will be integrated with geological and geophysical data and modelling to provide (i) a predictive model for crustal deformation in Papua New Guinea and the Solomon Islands, and (ii) constraints on the evolution of the Antarctic ice mass.

- *Dynamic Modelling and Geophysical Inference*

RSES will continue to develop mathematical and computational methods for modelling of Earth processes and for data analysis in 3-D and expand this work to address a variety of earth science problems at a range of scales. The recognition of coupling between various geophysical, geological and geochemical processes requires adaptation of mathematical tools and of computational methods, calling upon mathematical, physical and geological knowledge and insights. The development of "inverse methods" for finding models compatible with observations will continue to be a major focus of IT efforts in the Earth sciences. Similarly, fully 3-D modelling specifically adapted to the constraints and boundary conditions of the Earth represents the interface between mathematics, computational methods (IT) and earth models.

Fluids, Melts and Mineralisation

- *Petrological and Related Studies*

RSES is building upon its expertise in the experimental study of mantle melting with innovative studies of fluid (including melt) distribution and movement through a reactive crystalline matrix. The planned research includes the construction of a comprehensive thermodynamic model of mantle melting, and the development of an understanding of porosity/permeability relationships for partially molten upper mantle mineral assemblages, and of similar relationships for aqueous fluids in deforming crustal materials. This research will require the combined facilities of the petrophysics and experimental petrology groups and involve the development of a new experimental technique, whereby spectroscopy of individual synthetic fluid inclusions in quartz will be used to determine the speciation of metallic ions in aqueous fluid at high pressures and temperatures, previously inaccessible to experimental study. Further development of fluid dynamical models of magma segregation, ascent and emplacement is planned. There is also potential for collaboration with geophysical fluid dynamicists in modelling of flow through porous media and of the dynamics of melting and melt extraction.

- *Processes Leading to Metalliferous Ore Deposits*

The chemical studies of fluids described in the preceding paragraph will provide new insight into the transport and deposition of copper/gold and other metalliferous ore-forming elements especially in volcanic environments at active plate margins. In parallel, the nature of the coupling between fluid flow and active deformation in the crust will be explored. In particular, the relationships between permeability, porosity, deformation, reaction and rock strength will be quantified with new techniques developed for investigation of chemically reactive mineral (rock)-fluid systems in the petrophysics high-pressure laboratories. These objectives will complement other studies in which the School's expertise in stable isotopes, radiogenic isotopes, geochronology and trace elements are being applied to the study of world-class ore deposits. These studies of ore genesis are being pursued by staff and students in both RSES and the Department of Geology within the framework provided by the newly formed Centre for Advanced Studies of Ore Systems (CASOS).

Climates, Landforms and Ocean/Atmosphere Dynamics

RSES will build upon its existing expertise in fluid dynamics to understand dynamical processes that govern the Earth's climate system using theoretical, computational and experimental techniques. RSES research effort will also be directed towards identifying and analyzing past records of climate-related parameters (sea surface temperature, Antarctic ice cover, regional precipitation, ENSO events, relative sea level) that may quantify variability on the annual, decadal or hundred year time-scale. Aspects which are particularly within the RSES research profile include:

- the identification and understanding of dynamical processes in oceans and atmosphere that govern the Earth's climate system with emphasis on laboratory modelling of ocean processes at all scales.
- use of various complementary dating techniques to assign ages to significant events, including human impacts and biological extinctions, and to determine rates of geological processes.
- development and application of methods to determine rates of soil formation and denudation, as a component of the quantification of landscape evolution, essential for progress towards sustainability of land use patterns.
- study of the carbon cycle, including particular attention to carbon retention in soil, and carbon precipitation and solution in aqueous environments.
- establishment of regional proxy-climate records, especially for the last million years.
- quantification of the roles of tectonics, climate and human activity on landscape evolution, through the application of modelling techniques in conjunction with field observations and application of dating techniques.

APPENDIX I: THE CONTEXT FOR STRATEGIC PLANNING

The forward planning for RSES seeks to integrate two imperatives, excellence and leadership in basic research in significant disciplines within Earth Sciences, and societal expectations of earth science research in terms of global and national needs and priorities.

The major societal expectations of earth sciences research in its broadest sense over the next 20-30 years will include:

✿ Further development of basic knowledge and understanding of the origin and evolution of the Earth, including the biosphere, recognizing that the Earth is the cradle of life and of all human activities.

✿ Understanding of complex Earth systems at levels adequate for monitoring, prediction, and response to environmental change, including global effects (e.g. climate change) and local impacts.

✿ Understanding of Earth processes and behaviour at levels appropriate for improved identification, prediction and response to natural hazards and potential natural catastrophic events.

✿ Providing the scientific knowledge which underpins the maintenance of supply of natural resources, including hydrocarbons and minerals, and the development of innovative minerals-based materials for industrial, domestic and civic purposes.

Particular responsibilities for RSES lie in basic and strategic research and relate to:

❖ The Australian continent, its geophysics and geochemistry

❖ Australia in the global context of earth sciences, but particularly in relation to its regional setting, including Antarctica and Southwest Pacific.

❖ The Australian environment and the dating of its prehistory.

THE RSES ROLE

Basic research in the Earth Sciences in RSES will continue to be centred on

- Applications of physics, chemistry and mathematics to the study of Earth materials, Earth processes and Earth history, in concert with geological studies.
- Observations and measurements using sophisticated techniques, often newly developed within RSES, to establish the three-dimensional and time-varying character of the Earth.
- Experimental studies and modelling of Earth processes.

As a block-funded and program-oriented institution within the Australian Higher Education sector, and with a heritage of investments in particular facilities and subdisciplines, RSES has the obligation to achieve:

* Optimal use of facilities for basic research purposes, but also ensuring that research collaborations between Research Schools and Centres within the University continue to be fostered.
* A collaborative support role for earth science departments in other universities, where appropriate.
* Close collaboration with the Australian Geological Survey Organisation (AGSO), and other Government Institutions with interests in the earth sciences.
* Appropriate cooperation in the use of research facilities and programs with the Department of Geology and other departments in The Faculties at ANU, including shared responsibility for some specialist teaching and Honours supervision.
* Maintenance of the focus of the block-grant funding on basic research, together with enhancement of co-located and externally funded strategic and applied research.
* Maintenance of international links, including encouragement of visitors to RSES to include visits to other universities.
* Enhancement of short term exchange programs with other universities and scientific institutions.

GEOPHYSICAL FLUID DYNAMICS

Fluids and fluid flow are pervasive on and within the earth. The motion of fluids is responsible for shaping many aspects of the planet and the environment in which human activity is conducted, and it plays a central role in many industrial processes and their impact on the environment. The understanding and prediction of flow, of the forces created and of the associated heat and mass transport in the earth's hydrosphere, atmosphere, crust or deep interior, rely on extensive dynamical modelling of the phenomena and a rigorous understanding of the underlying dynamical principles. The research in the Geophysical Fluid Dynamics (GFD) Group is currently focussed on those processes of importance in governing (1) the circulation of the oceans, (2) magmatic and volcanic processes such as the flow of melts in and on the earth's crust and (3) the convection of the solid silicate mantle with its implications for plate tectonics. These phenomena come together in a coherent research program based on expertise in fluid dynamics and involving the dominant fluid dynamics themes of mixing, density-stratified flows, convection and the dynamics of flow with melting or solidification. Exchange of expertise and knowledge between research subjects has been a vital part of the work and the Group has initiated novel inter-disciplinary investigations of significant topics. The research is aimed at identifying the most important processes, at relating these to the observed behaviour of the Earth and, where possible, at developing predictive understanding of the natural phenomena.

Experimental fluid dynamics continues to be an essential component of the Group's research. The oceanic processes under investigation this year range across a very broad spectrum of length scales. The interaction of two phenomena responsible for ocean micro-structure, diffusion-driven salt finger convection and internal wave-driven intermittent turbulence, is being studied for its significance in the sub-tropical ocean thermocline, where these mechanisms cause a downward flux of heat and salt and thereby contribute to the overall balance of fluxes that governs the circulation patterns and water properties in the oceans. Experiments have also shown some surprising thermohaline effects on large-scale circulation caused by horizontal gradients of heat and salt fluxes. Basin-scale ocean circulation driven by surface wind stress continues as an important topic in which the combined laboratory and numerical modelling in RSES is making unique contributions to the understanding of the effects of the choice of side boundary conditions employed in modelling and of complications such as continental slope topography and density stratification. Work on crustal processes has included the modelling of melting at the base of large komatiite lava flows, the dynamics of two-phase foam flow in volcanic vents and the alteration of rocks by deposition from two-phase flow through fractures. A substantial review of the state of lava flow modelling was written this year.

The Group includes researchers having a specific interest in understanding past and present tectonic regimes through the study of mantle dynamics and melting. This work has a somewhat different emphasis, being concerned with modeling of the mantle/lithosphere system, the evolution of the mantle and convective processes that drive plate tectonics. There are strong interactions with geochemists and geologists studying the evolution of the mantle and crust, and with geophysicists and geochemists studying earth structure and composition. A key achievement this year was the completion and appearance in the bookstores of an authoritative text on the dynamics and evolution of the mantle by Dr G.F. Davies.

A major development this year has been the construction of a new building including a purpose-built fluid dynamics laboratory and the removal of the GFD laboratory to the new premises. The old laboratory and photographic darkroom have been closed down since June for relocation of fittings and construction of a link between buildings, thus strongly limiting progress in our experimental program. However, the new laboratory, which provides a larger space and specialised facilities for experimental fluid dynamics (Figure 1) and a support area for the construction of equipment, was completed in November in time for occupation before the end of the year. A period of setup of the new premises will continue into the new year, when a new range of projects will begin. A significant amount of time has again been devoted

(a)

(b)

Figure 1: The newly constructed extension (a) to RSES housing the GFD laboratory and a view of the laboratory (b) during installation of equipment.

to collaboration with Australian Scientific Instruments who are manufacturing rotating tables to the RSES design to fill orders from three North American geophysical fluid dynamics laboratories.

The Group this year hosted three long-stay visitors: Dr S. Vergniolle de Chantal continued for six months as a Visiting Fellow from CNRS, France, after completion of an International Research Fellowship (ARC, France), studying the dynamics of foam flow in magmatic systems; Dr U. Wüllner continued as a School visitor working on modelling of mantle convection; and Professor G. Veronis of Yale University, USA, spent five months as a Visiting Fellow working on laboratory models of ocean circulation processes. The Group continued to host Emeritus Professor J.S. Turner who this year was awarded a University Fellowship. It was a particular pleasure that a PhD student, D.I. Osmond, won a Pre-doctoral Fellowship from the Woods Hole Oceanographic Institution, USA, to attend the Summer Program in Geophysical Fluid Dynamics, and that another PhD student M.G. Wells was awarded a scholarship from the University of Washington to attend the Friday Harbor summer school in Oceanography. A.M. Jellinek completed his PhD in the Group and was awarded Miller and NSF Postdoctoral Fellowships at the University of California, Berkeley. The staff, students and visitors all acknowledge the vital contributions of our technical support staff, R. Wylde-Browne, A.R. Beasley and D.L. Corrigan, to our research program.

OCEAN PROCESSES

Shear layers driven by turbulent plumes

G.O. Hughes, R.W. Griffiths and A.B.D. Wong

Laboratory experiments reported last year have shown that a continuous turbulent plume falling into an enclosed volume gives rise to a more complex flow in the fluid interior than previously thought. A series of strong horizontal counterflowing 'shear layers' are observed supported by the stable density stratification set up by the plume. These layers are superposed on both the slow vertical flow and the horizontal entrainment flow into the plume known as the 'filling-box' circulation.

Shear layers are likely to have very significant consequences for the horizontal transport and subsequent vertical mixing of tracers in confined volumes such as ocean basins. We have developed a theory that explains the observed shear layer structure in terms of internal wave modes in a viscous stratified fluid. The internal wave modes are excited in our experiments by the horizontal outflow of dense plume fluid upon reaching the tank bottom. In a long channel and in the absence of viscosity, the horizontal flow velocities in the shear layers were predicted to increase with height, contrary to observations. However, when the motion is attenuated with height by including viscosity in our model, good agreement with experimental observations is obtained. A recent improvement in the understanding of the shear layer phenomenon incorporates the role of vertical advection throughout the interior. The system selects for intensification an internal wave mode whose downward phase speed is close to the upward advection speed required to match the plume volume flux. This explains the vertical wave number observed.

Properties of highly nonlinear waves

D.L. Bright, R.W. Griffiths and B.L.N. Kennett

Large amplitude waves occur regularly in the lower atmosphere. These waves are usually clear air disturbances and may be formed as the result of a variety of atmospheric events where suitable waveguide conditions exist. Waveguide layers are generally a stable layer of thermally stratified air such as the nocturnal inversion layer. A numerical (mesoscale) model has been constructed for the study of highly nonlinear waves and their radiative decay owing to vertically-propagating gravity waves in an overlying stratification. The model has also been designed to study the generation of waves in the case of a strong downdraft impacting on a ground-based stable layer.

In our numerical experiments with downdrafts there are three types of event. These are classified as non-penetrating, where the downdraft does not penetrate to the ground; non-diverging, in cases where the downdraft penetrates to the ground but does not produce a

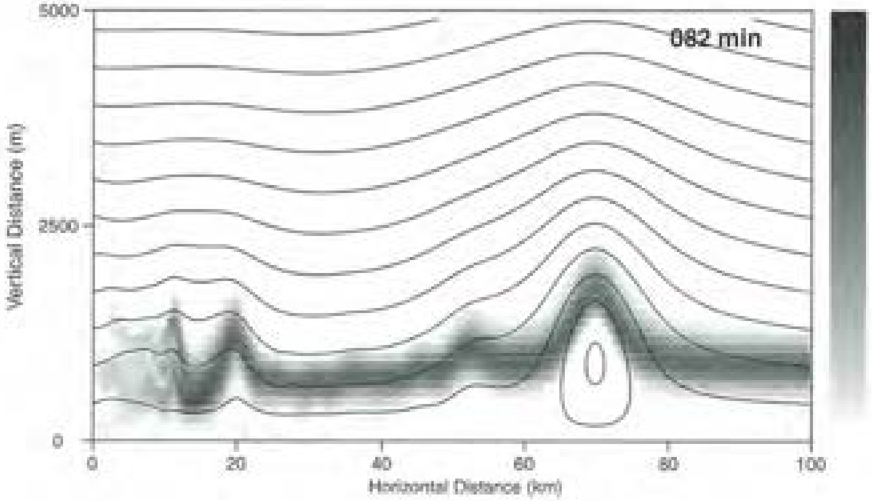

Figure 2: Results of a computer model for highly nonlinear waves on a ground-based atmospheric inversion layer.

strong horizontal outflow; and diverging, if a strong outflow is produced. This last case can lead to the formation of very large amplitude solitary waves with closed circulation. From the model results we have related the speed and amplitude of waves that are generated to the parameters of the initial forcing downdraft. We have also examined the evolution of the properties of the waves as they propagate well away from their formation site, focussing particularly on the radiative decay of such waves when there is suitable overlying stratification and whether the core of closed recirculation (hence a bulk mass transport) persists.

A complementary set of numerical experiments on the evolution of highly nonlinear waves has been carried out using quite different starting conditions. In place of the computed downdraft flow, we used initial conditions taken from solitary wave solutions to the Dubreil-Jacotin-Long (or DJL) equation. Solutions for the DJL equation, with ambient density profile similar to that used for the downdraft experiments, are first calculated as eigenvalue/eigenfunction pairs using a program designed by Brown (1990). These eigenfunctions are then transferred to the mesoscale flow model using a mapping algorithm developed for this purpose and the subsequent wave properties are analysed after a short adjustment period (Figure 2). A detailed examination of the radiative decay of the mapped DJL solutions is currently being completed for a range of ratios of the buoyancy frequency in the waveguide layer to that in the overlying atmosphere.

Dynamics of upper ocean circulation driven by surface wind stress

A.E. Kiss, R.W. Griffiths and G. Veronis[1]

Progress has been made in a continuing program to investigate the dynamics of wind-driven circulation on the scale of ocean basins by making use of both laboratory experiments and associated computational modelling. In recent years the wind-driven circulation in mid-latitudes (actually forced in the laboratory by a horizontal stress imposed by a differentially-rotating lid) has been modelled in 'sliced-cylinder' and 'sliced-cone' geometries of small aspect ratio. The latter involves a sloping topography along the boundaries of the basin, somewhat like

[1] Department of Geology and Geophysics, Yale University, USA

a continental slope, making the side boundary conditions quite different from those on the vertical wall of the 'sliced-cylinder'. Topographic steering is also important in the 'sliced-cone'. Thus we have been able to study the roles of different side boundary conditions and topographic steering on the large-scale flow forced by a uniform wind-stress curl on a beta-plane.

Figure 3: Computed model streamlines superimposed on laboratory dye streaks in the sliced cone under cyclonic forcing.

Mr A. Kiss has continued his numerical simulations of flow in the 'sliced cone' laboratory model. A vorticity equation governing flow in the laboratory apparatus was derived; this equation is more general than the standard quasigeostrophic vorticity equation and is valid in the case of vanishing fluid depth, as in the 'sliced cone' laboratory model. A computational fluid dynamics code supplied by Dr M. Page (Monash University) was modified to solve this equation, and detailed comparisons of the numerical results with those from the laboratory work of Griffiths and Veronis (1997) have shown remarkably close agreement (see Figure 3). The numerical model has revealed aspects of the flow (such as the potential vorticity structure) which are crucial to an understanding of the flow dynamics but impossible to measure in the laboratory. Analysis of the numerical results has therefore provided many valuable insights into the dynamics which operate in the laboratory model. Among the most important of these is an explanation of the remarkable stability of the flow under strong cyclonic forcing, which was shown to be due to resonance with a free inertial mode. In contrast, the vorticity structure present under anticyclonic forcing prohibits excitation of this mode, and in this case the flow becomes unstable under strong forcing. It is expected that these results are quite general, and not dependent on the details of the topography used. Analysis of the numerical results has confirmed most aspects of the vorticity balance assumed in the linear theory of Griffiths and Veronis (1998), but also revealed some minor shortcomings of this theory.

Another development this year was a move to studying the effects of density stratification in the 'sliced-cone' model, thus including the new side boundary conditions, continental slope topography and stratification. Professor G. Veronis returned to RSES for another 5 month visit. During this time Veronis and Griffiths carried out an intensive experimental program with two-layer density stratification, including new comparative runs with the vertical walls of the 'sliced-cone'. The results await analysis in 2000.

Laboratory models of intermittent turbulence and salt fingers

M.G. Wells and R.W. Griffiths

Intermittent turbulence and salt finger convection have both been proposed as important mechanisms producing diapycnal buoyancy flux in oceanic central waters. Because active turbulence disrupts salt finger convection, ocean models have often assumed that the total buoyancy flux can be described by a simple addition of the buoyancy fluxes due to the two processes weighted by the percentage of time active turbulence is present or absent. The two processes produce diapycnal buoyancy fluxes of opposite sign and therefore the net buoyancy flux is sensitive to the intermittency of the turbulence. Despite many oceanographic measurements of the heat, salt and total buoyancy fluxes, relatively few laboratory experiments have been designed to examine the interaction of these two processes.

In a series of experiments using sugar/salt and heat/salt systems, a grid of vertical bars was towed through a stable density gradient in such a way as to generate intermittent turbulence, with salt finger convection also present. Measurements of the vertical buoyancy flux for a range of 'intermittencies' of the stirring show that the resulting buoyancy flux is a strong function of the intermittency. Salt fingers provided significant buoyancy flux when the time between stirring events was longer than the time scale for exponential growth of salt fingers.

Stratification produced by a destabilizing surface buoyancy flux in lakes of variable bathymetry

M.G. Wells and B. Sherman[2]

In collaboration with CSIRO Land and Water, we have applied theoretical and laboratory results to understand a 3 -year data set collected in the Chaffey reservoir, located near Tamworth. This research continues previous work in RSES on the competition between distributed and localised surface buoyancy fluxes in confined volumes of water.

Winter cooling of lakes is usually assumed to result in complete overturning of the water column. However, it has become apparent that, when there is a large fraction of the lake that is relatively shallow, cold gravity currents flow from the shallow parts into the deeper parts of the lake and can result in the partial stratification of the lake. This stratification is constantly eroded, in the deep regions, by surface convection. However, if the area of the shallow region is sufficiently large, a steady mixed depth can result with the convecting layer and the underlying stable region changing temperature at the same rate. A simple laboratory model (Figure 4) illustrates the basic dynamics of the flow. From theoretical arguments and experimental results, we have shown that the depth of the mixed surface layer in steady state is a simple function of the aerial ratio of shallow and deep regions. When the shallow area is large in comparison to the deep region, the surface mixed layer is shallow and deep stratification can form.

Using bathymetry data from Chaffey Reservoir aerial ratios of shallow and deep regions were evaluated for the winters of 1995 and 1996. The observed stratification was as predicted for 1995 but for 1996 we found that there were significant differences due to the diurnal variability of the de-stabilizing thermal forcing. The theoretical model assumes constant forcing, whereas under the conditions of 1996 the time the system would take to reach this equilibrium is predicted to be longer than the diurnal variation. Hence, the circulation never reached the steady state. We predict that for lakes of order 1-2 km length stratification can result from a period of one week cooling at 50 W/m^2, a common situation in winter. The stratification and convection has important implications for nutrient transport and de-oxygenation in reservoirs and the theory should serve as a guide as to when one can expect stratification to develop. It also emphasises that circulation is present in winter, even when the water column is strongly stratified.

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[2] CSIRO Division of Land and Water, Canberra

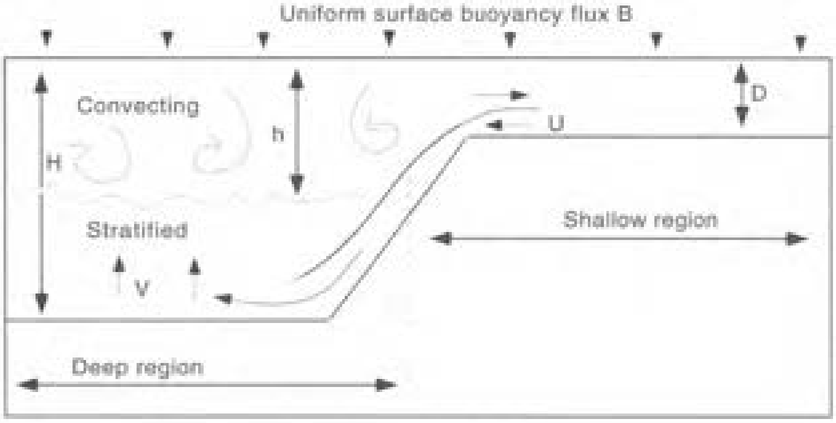

Figure 4: The pattern of winter convection in a lake having a large shallow region.

Double-diffusive layers and intrusions produced by horizontal property gradients

O.M. Phillip[3], B.R. Ruddick[4], J.S. Turner and G. Veronis[3]

Two sets of laboratory experiments exploring the effects of horizontal variations of salt and sugar concentrations have been completed and accepted for publication during the year. Using different geometries, they have both provided simple analogues of the double-diffusive processes that can affect the stratification and circulation in ocean basins. For example, observations over the past ten years have shown that the Arctic ocean has been warming because of an influx of warm water in the form of persistent intrusions from the Atlantic. There are also many measurements of layers developing across oceanic fronts, and physical oceanographers have speculated that these are produced and self-propelled by double-diffusive fluxes.

In the first study, a sharp front was set up by placing a vertical barrier at the centre of the tank and stratifying the two ends with identical density gradients, but using sugar solution on the left and salt solution on the right. The removal of the barrier led to the formation of an organized set of laterally intruding sloping layers, each containing salt fingers separated by diffusive interfaces. The depth of the layers and the velocity of extension were proportional to the local horizontal property differences, and the structure spread in a self-similar manner as the layers extended. The property fluxes across the front were measured, and found to be proportional to the square of the lateral sugar contrast, and independent of the frontal width. A theory has been developed to explain the main structural features of the laboratory results. This is based on the assumption that the flow is in a state of continuous hydrostatic adjustment, always close to equilibrium with the ambient stratification.

The second set of experiments started with homogeneous fluid in a long tank, with sources of salt solution at one end and sugar at the other, and withdrawal at the centre to keep the volume constant. We monitored the development of the vertical stratification as well as the motions. Starting with the densities of the tank fluid and the two sources all the same, the vertical density gradients increased markedly over time; this is not possible with a single stratifying property, such as salt alone. The asymptotic overall vertical sugar and salt differences, obtained after about 100 hr, corresponded to a run-down 'diffusive' stratification

[3] Department of Earth and Planetary Sciences, Johns Hopkins University, USA
[4] Department of Oceanography, Dalhousie University, Canada

(with a weakly unstable salt, and a very stable sugar distribution), even when the gradients in the early stages of an experiment were in the 'finger' sense. This final state was only quasi-steady, since fluctuations corresponding to the passage of intrusions along the tank persisted indefinitely, driven by the small residual potential energy in the salt field.

An analysis of a two dimensional double-diffusive experiment

D.I. Osmond and G. Veronis[†]

An experiment reported above by Phillips, Ruddick, Turner and Veronis provided the motivation for this work, which was undertaken as part of Osmond's fellowship at the GFD Summer program at the Woods Hole Oceanographic Institution. The experiment involved an initially homogenous fluid in a long tank which subsequently became stratified through double-diffusive processes. A source of salt solution was introduced at one end of the tank, and a source of sugar solution was introduced at the other end, with an outflow in the centre of the tank so as to maintain a constant volume of water in the tank. (The use of salt and sugar models heat and salt in the oceans.) After a couple of days, a steady state salt and sugar stratification was approached, while convection continued indefinitely. Salt fingering was active above the salt source and below the sugar source throughout the experiment, as were diffusive layers below the salt source and above the sugar source. It was thus apparent that some of the introduced salt was travelling up through the fingers, and then crossing to the other side of the tank, where it descended down through the diffusive layers. Some salt was travelling down from the source through the diffusive layers, where it crossed to the other side of the tank and ascended up through the fingers present there. Flux measurements were analysed to determine the salt (and sugar) fluxes upwards through the fingers, downwards through the layers, and horizontally across the tank to the outflow

Simple one-dimensional theories predicted fluxes through the fingers and diffusive layers that were much larger than the input sources, and were thus dismissed as being invalid. Horizontal fluxes cannot be neglected and it is impossible for the coupled system of adjacent salt fingers and diffusive layers to be sustained without another driving mechanism to transport either salt or sugar to the top of the tank. We evaluated an hypothesis that this additional mechanism is the action of tilted quasi-horizontal intrusions and showed that the resultant vertical fluxes through the fingers and layers could be up to twice as large as those through a simple one-dimensional system. We also approximated the experiment with a simple box model, the results of which indicated that the most of the salt and sugar introduced into the tank is not involved in the double diffusive process but is simply carried horizontally across the box to the outflow.

The formation of 'optimal' vortex rings, and the efficiency of propulsion devices

P.F. Linden[†] *and J.S. Turner*

The formation of a vortex ring using the common technique of forcing fluid impulsively through a pipe has been examined theoretically. The method consists of matching the circulation, impulse and kinetic energy in the injected plug of fluid to the corresponding properties of a family of rings with finite cores, as calculated by Norbury. When the length to diameter aspect ratio L/D of the plug is increased, the size of the core increases relative to the volume of fluid carried along with the ring, and a unique member of the family is identified for each L/D. This is found to be the limiting factor; for aspect ratios larger than a certain value it is not possible to produce a single vortex ring while conserving circulation, impulse, volume and energy, and further rings form behind the leading vortex. This result implies that the limiting vortex ring is 'optimal' in the sense that it has maximum impulse, circulation and volume for a

[†] Department of Mechanical and Aerospace Engineering, University of California, San Diego, USA

given energy input. Our limiting aspect ratio L/D = 4 is close to the value obtained in recent experiments by Gharib and colleagues at Caltech.

These ideas have been applied in two contexts where a series of vortices is formed, both of which have previously been discussed in terms of a Strouhal number (the frequency of vortex formation). In the breakup of a circular jet, the observed frequency of vortex production implies that the individual vortices are close to the 'optimal' form. The same is true of vortices produced by the tails of a wide variety of swimming fish, which are very efficient in the sense they give maximum thrust for a given energy input. The implication of our results for the design of propulsion devices to drive ocean vehicles is clear: individual vortices could be effective even when they are produced with arbitrary intervals between them, rather than continuously. Devices modelled on the 'jet propulsion' mechanism of swimming used by squid and salps, and designed to produce 'optimal' vortices, could be particularly effective.

The influence of laboratory experiments on the development of geophysical fluid dynamics

J.S. Turner

An invitation to write a 'Retrospective' article for the journal *Applied Mechanics Reviews* provided the incentive to trace the development of this field over the forty years since it was first recognised as a distinct discipline, and in particular to assess the part that members of the GFD group in RSES have played. The early laboratory experiments were motivated by atmospheric phenomena, particularly convection in the form of plumes, and the need to understand the mechanism of turbulent entrainment. This led on to studies of plumes in a stratified environment and in confined regions, and turbulent gravity currents; these can be treated as line plumes on a slope, with the extra feature that mixing is inhibited by the component of gravity normal to the slope. Group members have made significant contributions to all of these, and the concepts are still central to much of their current research.

Many oceanic processes too have been studied using laboratory experiments. The largest scale phenomena such as ocean currents are strongly influenced by the Earth's rotation, and so experiments need to be carried out on a rotating table. A sophisticated design for a table with a 1m diameter top was developed and built in house, and it has now been reproduced and sold to overseas laboratories. Using this, models of the wind-driven circulation in ocean basins, currents driven by horizontal density gradients, the instability of coastal currents (such as the Leeuwin Current off Western Australia) and the interactions between ocean eddies have all been successfully studied in the GFD laboratory. For smaller scales of motion, our experiments have led to a better understanding of surface mixed layers, and the interaction between distributed and localised sources of buoyancy. The group has been at the forefront of research into double-diffusive phenomena, which are now recognised to play a significant role in mixing in the interior of the ocean, whenever temperature and salinity have opposing effects on the density of water parcels.

It was first suggested by experiments carried out in RSES that double-diffusive processes will also be important in liquid rocks, in which there are many components with different diffusivities as well as temperature variations. This has led to a whole new range of experiments, extending beyond double diffusion, and to the development and recognition of the new sub-discipline now called geological fluid mechanics. We have studied analogues of the crystallization process in magma chambers using aqueous solutions in various geometries, the effects of slow or rapid replenishment, and the formation of 'black smoker' chimneys and related phenomena. Lava flows have also been modelled, the laboratory analogues being liquid waxes that solidify to produce a surface crust. Convection in the Earth's mantle has also been addressed, in experiments modelling subducting plates and mantle plumes, using fluids having a large variation of viscosity with temperature.

These most recent extensions into a new field highlight the effectiveness of doing research in a broad-based GFD group such as that in RSES. The aim has always been to identify fundamental physical processes, and to achieve a deep understanding of them, rather than focussing on the immediate applications. Looking back, we find many examples of experiments that have later been found to be very widely applicable, in fields which at first sight seem totally unrelated to the earlier work.

GEOLOGICAL FLOWS

'Excess heat' effects in the formation of precious metal veins

G.O. Hughes and R.W. Henley

The evolution of flow in a fractured hydrothermal system following the sudden dilation of fractures in the host rock has been analysed. If fluid in the system is close to vapour saturation, the sudden dilation is adiabatic and produces a rapid drop of both the fluid pressure and temperature. The depressurisation is accompanied by separation of the liquid and vapour phases, and a two-phase compressible flow will evolve through the fracture system. The temperature difference between the host rock and the two-phase fluid drives heat from the rock into the fluid. This 'excess heat' evaporates additional liquid in the two-phase flow to develop substantially larger vapour fractions than those due only to the initial adiabatic depressurisation of the fluid. The additional vapour separation is potentially important for vein formation since high solute concentrations can be produced in the residual liquid phase, resulting in faster mineral

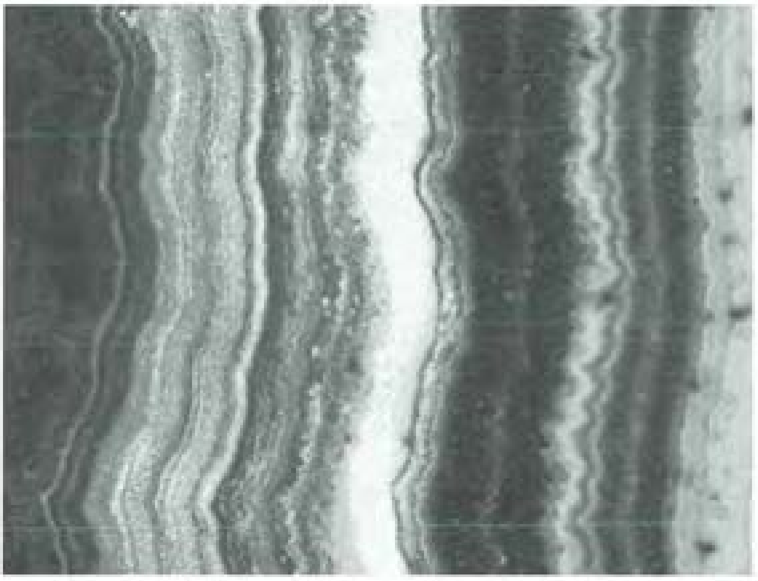

Figure 5: Oscillatory banding and lamination fabrics in a silica vein from the McLaughlin gold-silver epithermal deposit, California. The photograph shows a section about 60 mm in length: the darkest grey bands are crystalline quartz, other grey scale laminations are indicative of other silica polymorphs, and the lightest laminations which show the least internal structure may be interpreted as amorphous silica now inverted to quartz.

deposition in the fracture system and in potentially economic veins containing gold, silver and base metals. A simple model of this complex flow has been developed to show that 'excess heat' effects are likely to result in deposition within tens to hundreds of metres of actively forming veins, and are a principal cause of oscillatory banding and lamination fabrics (see Figure 5).

A Theoretical Model of a Turbulent Fountain

L. J. Bloomfield and R.C. Kerr

Turbulent fountains are produced whenever a heavy fluid is rapidly injected upward into a lighter environment. In the last few years, our laboratory experiments have shown that the dynamical structure of the fountain, as well as macroscopic properties such as its total height, depends critically on the ambient density profile. In this study, we have used a theoretical approach to provide a new model of axisymmetric and two-dimensional fountains in an arbitrary ambient density gradient.

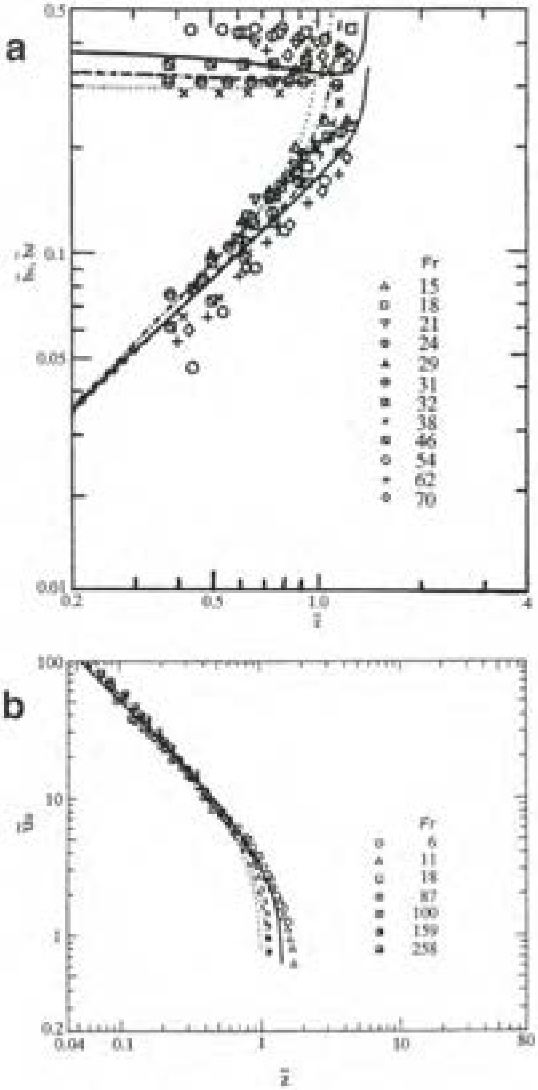

Figure 6: A comparison of the numerical results for four different formulations with experimental data for (a) the upflow and downflow radius and (b) the upflow velocity of a turbulent axisymmetric fountain. Our preferred formulation is shown with a solid line.

A set of entrainment equations were developed to quantify the fluxes of volume, momentum and buoyancy in the upflow and downflow of the fountain. Four different formulations were considered, comprising two formulations of the rate of entrainment between two turbulent flows, and two formulations of the body forces acting on the central upflow. These equations were integrated numerically to obtain predictions for the fountain height, the width of the upflow and downflow, the upflow and downflow velocity and the upflow and downflow buoyancy. The numerical calculations were then compared with previous experimental measurements in a homogeneous fluid, showing excellent agreement (Figure 6).

This theoretical model of a turbulent fountain is particularly important in a confined environment, where the density profile evolves with time as a result of the continued addition of dense source fluid. The model can be used to analyse the dynamics of fountains that arise in diverse applications such as: the replenishment of magma chambers, the heating or cooling of buildings, the collapse of volcanic eruption columns, the forced mixing of reservoirs, harbors and small lakes to improve water quality, and the disposal of brines, sewerage and industrial waste into the ocean.

Numerical models of komatiite lava flows in the Cape Smith Belt, Canada

R.C. Kerr, D.A. Williams[6] and C.M. Lesher[7]

Komatiite-associated magmatic Fe-Ni-Cu-(PGE) sulfide deposits are hosted by thick units of komatiitic peridotite or dunite, which have been interpreted to represent crystallised lava channels. The ores are localised in footwall embayments, which have been interpreted to have formed, at least in part, by thermal or thermo-mechanical erosion. As erosion of S-rich substrates by hot, metal-rich komatiite lavas is considered to be a fundamental process in the genesis of many magmatic Fe-Ni-Cu-(PGE) sulfide deposits, evaluating the role of thermo-mechanical erosion in the emplacement of komatiitic lavas is an important aspect of understanding the genesis of magmatic sulfide deposits.

To help understand the erosional potential and mineralisation of komatiite lavas, we developed last year a mathematical model that quantifies the thermal, rheological, fluid dynamical, and geochemical evolution of channelised komatiite lava flows. This year, we have applied the model to the thick ultramafic complexes in the Raglan Formation of the Proterozoic Chukotat Group in the Cape Smith Belt, Canada, typified by the Katinniq Ultramafic Complex. These complexes transgress underlying gabbros and metasediments, forming large, broad first-order embayments that localised komatiitic peridotites, with small, reentrant second-order embayments that host Ni-Cu-(PGE) sulfide deposits. The host units are interpreted to represent a series of lava channels and channelised sheet flows, and geophysical, geological, and mathematical models suggest that the they are the eroded remnants of one or more sinuous lava channels, extending for at least 20 km, possibly up to 50 km or more. If this interpretation is correct, then this system represents the first evidence of long, sinuous komatiitic lava channels on Earth. If the broad, concave embayment at Katinniq formed by thermal erosion, then our models suggest that it formed from a thick (~100m) flow erupted at high flow rates (~10^6 m^3/s) over a long duration (of months), producing volumes about an order of magnitude lower than the Columbia River flood basalts (~10^4 km^3). Our modeling shows that it is easier to erode a warm gabbro than a cold gabbro, and that it is easier to erode a gabbro than a basalt of the same composition, if the gabbro melts at a eutectic temperature lower than the solidus temperature of the basalt. The amount of contamination resulting from thermal erosion of gabbro by komatiitic basalt liquid is negligible (~1-2%), indicating that the observed contamination in the Katinniq Ultramafic Complex (~10%) must be attributable to thermo-mechanical erosion of sediment upstream during the late stages of erosion. The modeled flow distance, surface crust thickness, and degree of contamination are consistent with geophysical and geological data. Thermo-mechanical erosion of unconsolidated, sulfidic semi-pelitic sediments and decoupling of the

[6] Department of Geology, Arizona State University, USA

[7] Mineral Exploration Research Centre, Laurentian University, Sudbury, Canada

miscible silicate and immiscible sulfide components is the preferred model for the generation of the Ni-Cu-(PGE) sulfide ores in the Katinniq Ultramafic Complex and in other complexes in the Raglan Formation.

The dynamics of lava flows

R.W. Griffiths

Previous laboratory and theoretical modelling in RSES of lava flow morphologies and the dynamics of flow emplacement has this year led to the preparation of an extensive review paper invited for the Annual Review of Fluid Mechanics. Lava flows are gravity currents of partially molten rock which cool as they flow, in some cases melting the surface over which they flow but in all cases gradually solidifying until they come to rest. They present a wide range of flow regimes from turbulent channel flows at moderate Reynolds numbers to extremely viscous or plastic creeping flows, and even brittle rheology may play a role once solid has formed. The cooling is governed by the coupling of heat transport in the flowing lava with transfer from the lava surface into the surrounding atmosphere or water, or into the underlying solid, and it leads to large changes of rheology. Instabilities, mostly resulting from cooling, lead to flow branching, surface folding, rifting and fracturing, and contribute to the distinctive styles and surface appearance of different classes of flows. Theoretical and laboratory models, including those carried out in RSES, have complemented field studies in developing the current understanding of lava flows, motivated by the extensive roles lavas play in the development of planetary crusts, landscapes, sea-floor topography and nickel-copper sulphide ore deposits, and by the immediate hazards posed to people and property by active flows. However, the review concludes that much remains to be learned about the mechanics governing creeping, turbulent and transitional flows in the presence of large rheology change on cooling, and particularly about the advance of flow fronts, flow instabilities and the development of flow morphology.

MANTLE DYNAMICS AND TECTONIC EVOLUTION

Geophysically constrained mantle mass flows and the ^{40}Ar budget: a degassed lower mantle?

G.F. Davies

It has been inferred previously that the lower mantle is much less degassed than the upper mantle, by about two orders of magnitude, based on estimates of the amount of ^{40}Ar expected to have been generated during earth history. Such a gas-rich lower mantle would severely limit the permissible mass flow rate into the upper mantle. However a gas-rich lower mantle conflicts with evidence from refractory trace elements and their isotopes that most of the mantle has been processed, and with increasingly strong geophysical evidence for a large mass flow between the upper and lower mantle. Neither is a gas-rich lower mantle implied any longer by isotopic compositions of He, Ne and Ar from oceanic island basalts, which are nearly as radiogenic (within factors of 2-4) as those from mid-ocean ridge basalts. The budgets for mantle He, Ne and Ar have been reassessed from geophysical and other geochemical constraints, but without assuming the total ^{40}Ar content of the silicate earth to be known. These budgets permit the lower mantle to be only slightly less degassed than the upper mantle, though they show that the degree of lower mantle degassing inferred in this way depends strongly on poorly-constrained entrainment and degassing efficiencies of mantle plumes. A degassed lower mantle requires either (1) that the Earth has 50% less ^{40}K than is usually estimated, (2) that ^{40}Ar is sequestered in the core, or (3) that ^{40}Ar has been lost from the earth entirely. ^{40}Ar in the core is hard to reconcile with chemical systematics. A small amount of argon loss from the earth during the late heavy meteorite bombardment is plausible, but 50% loss is difficult to justify at this stage. A 50% lower K/U ratio in the earth would remove the discrepancy and may not be outside the range of uncertainties. All three hypotheses need to be considered, and some combination of them may apply.

Effects of plate and slab viscosities on the Geoid

S. Zhong[1], *G.F. Davies*

The effects of realistic plate rheology (strong plate interiors and weak plate margins) and stiff subducted lithosphere (slabs) on the geoid and plate motions, considered jointly, have been examined with three dimensional spherical models of mantle flow. Buoyancy forces are based on the internal distribution of subducted lithosphere estimated from the last 160 Ma of subduction history. While the ratio of the lower mantle/upper mantle viscosity has a strong effect on the long-wavelength geoid, as has been shown before, we find that plate rheology is also significant and that its inclusion yields a better geoid model while simultaneously reproducing basic features of observed plate motion, without the need for artificial velocity or stress boundary conditions. Slab viscosity can strongly affect the geoid, and the sign of the effect depends whether a slab is coupled to the surface. In particular, deep, high-viscosity slabs that are disconnected from the surface as a result of subduction history can produce significant long-wavelength geoid highs. Because of these effects, high-viscosity slabs derived from the observed subduction history lead to significantly different geoid than that observed. This suggests that slabs in the lower mantle are not as stiff as predicted from a simple thermally activated rheology.

[1] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, USA

SEISMOLOGY AND GEOMAGNETISM

The Seismology and Geomagnetism Group is engaged in a variety of studies in seismology, and electromagnetic induction. The current research activities have a common thread of using wave propagation processes to study the nature of the Earth. The work combines field observations, theoretical work, computer modelling and extensive data analysis to exploit the favourable geographic location of Australia for seismic and electromagnetic studies.

SEISMOLOGY

The major area of research in Seismology is the investigation of the internal structure of the Earth using the seismic waves generated by both natural and man-made sources as probes. Much of the work is directed towards improving our understanding of the three-dimensional variation in the seismic properties of the Earth's interior, and involves a number of activities including observation, interpretation and theoretical developments.

The group maintains an active observational program based on the use of arrays of portable recorders, with deployments this year in southeastern Australia and the Transantarctic mountains. The data from the portable instrument studies, complemented with data from permanent stations, is used in many ways. A major effort continues on the delineation and characterisation of the mantle structure and heterogeneity beneath the Australasian region using a variety of techniques for the analysis of both body and surface waves. This year attention has been focused towards the influence of anisotropy in seismic properties on surface waves, and the nature of the distribution of seismic attenuation. The observational studies are complemented by the development of techniques for studying seismic wave propagation in complex structures, with a focus on the propagation of surface waves across three-dimensionally varying structures. Research is also conducted into geophysical inverse techniques with the object of improving both the algorithms used to infer seismic structure and the reliability of the estimates of seismic parameters. The neighbourhood algorithm developed in the group has proved to be very effective in a variety of applications, particularly in source characterisation, both through event location using the arrival times of seismic phases and determination of source mechanism and depth by matching the onsets of the P and S phases of distant events.

The RELACS experiment designed to study the structure beneath the Rabaul volcano in New Britain has been able to provide impressive images of the structure in the neighbourhood of the caldera with indications of a significant magma chamber beneath the zone of recent seismicity. The successful conduct of the observational and interpretational program for RELACS owes much to the efforts and dedication of Dr O. Gudmundsson and we wish him well in his new position with the Danish Lithosphere Centre in Copenhagen.

From March to October this year the group was involved in a major observational program in southeastern Australia using broad band recorders. This experiment, designated QUOLL, combined the use of the full set of RSES broadband equipment with 11 Orion recorders from the ANSIR national facility. This enabled an experiment in which a broad array of instruments was deployed across New South Wales and Victoria for the full duration of the experiment with two lines of denser spaced instruments deployed for a shorter period. The maintenance of this instrumental deployment has involved many members of the group. The object of the experiment is to examine the gradation of structure in the crust and mantle through the Lachlan fold belt towards the ancient core of the continent. The images of mantle structure from analysis of the results of the SKIPPY experiment indicate the presence of slow seismic wavespeeds in the mantle beneath the Eastern seaboard and higher wavespeeds in the west extending to depths in excess of 150 km but not connected to the cratons. It is hoped that the higher density of data in the QUOLL experiment will help to provide a geophysical framework for the relation of the eastern highlands to mantle structure.

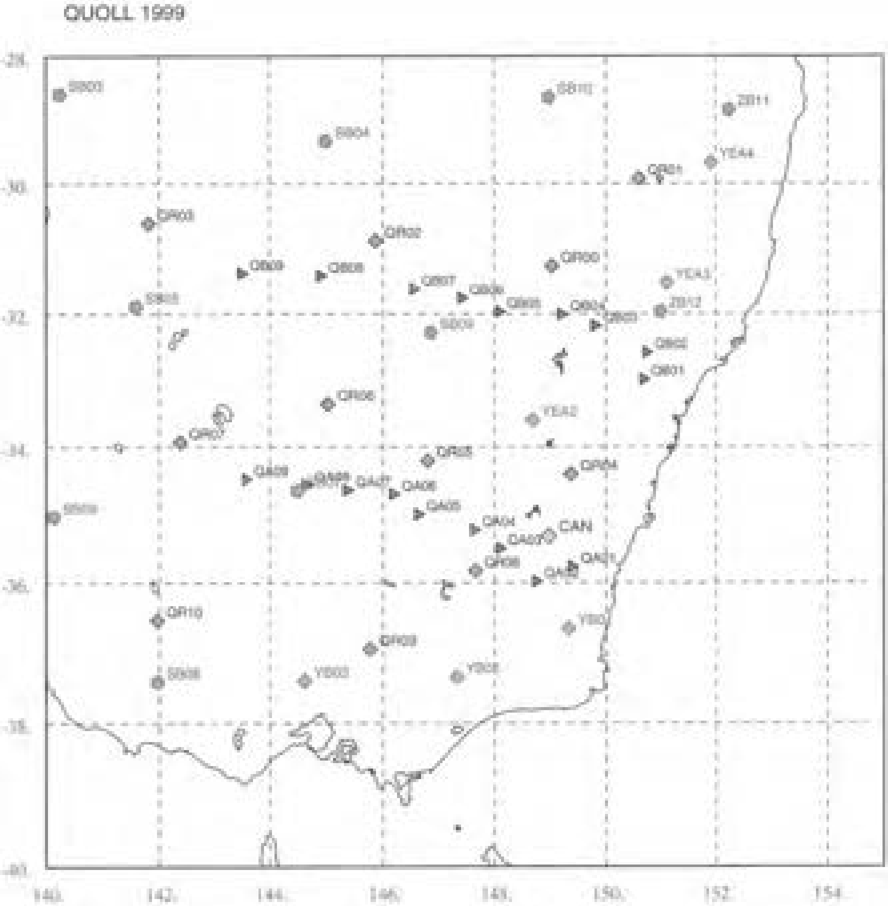

Figure 1: The configuration of broad-band seismic recorder deployments in the QUOLL experiment in southeastern Australia including SKIPPY stations (SA, SB)

In November a joint experiment with the Institute of Geological and Nuclear Sciences of New Zealand was commenced in the Transantarctic Mountains working from Scott Base using a combination of ANSIR and RSES equipment with logistic support from Antarctic New Zealand. Ten stations will be maintained over the Antarctic summer and will be retrieved in March next year. S. Sirotjuk and T. Percival have been involved with the field work in Antarctica.

Structure and deformation of the Australian upper mantle as inferred from surface wave data

E. Debayle, Y. Hiyoshi and B.L.N. Kennett

The analysis of surface waves analysis has proven to be very effective means of determining the 3D structure of the upper mantle beneath Australia. Using this class of data, a 3D tomographic model can be built from a two-step tomographic procedure: the first step is a waveform inversion for a 1D path-average depth dependent structure. This waveform matching process uses both the fundamental mode, that usually represents the dominant part of a surface wave seismogram, and also include long period body waves arising from constructive interference between the first few higher modes of the surface waves. This non-linear inversion step produces a model varying only with depth which should represent the average of the structures encountered along the path. By this means, good vertical resolution is obtained for the uppermost 500 km of the mantle. The second step, consists of combining the path average models in a tomographic inversion to retrieve the local structure. At this stage, lateral resolution of few hundred kilometres can be achieved when a dense path coverage is available in the area under study. This is the case for Australia, thanks to the various field deployments of portable seismometers across the continent by the RSES seismology group.

In the early inversions exploiting the data from the SKIPPY experiment, waveforms for Rayleigh waves from vertical component records were analysed individually and then combined in a tomographic model for isotropic structure. Last year we introduced an efficient automated procedure for waveform inversion of surface waves using secondary observables derived from the waveforms prior to inversion. With the automation, a larger volume of data could be processed which allowed resolution of both wavespeed heterogeneity and azimuthal anisotropy for horizontally propagating SV waves, at a scale of few hundred kilometres. This inversion revealed a two layered anisotropic structure which has been confirmed with later studies. In the upper 150 km of the mantle, anisotropy is likely to be related to past deformation frozen in the lithosphere. At greater depth, a smoother pattern of anisotropy is found which appears to correspond to present day deformation due to the northward motion of the Australian plate. In addition, compared to previous inversion, we observed a somewhat thinner high velocity lid beneath Proterozoic Australia. These results have strong implication for the deep structure of continents. They suggest that at least for Australia, most of the Proterozoic mantle experiences present day deformation at relatively shallow depth, making the development of large scale deep continental root difficult.

The investigation of upper mantle anisotropy beneath Australia has now been extended by including the horizontal components of the seismograms in the inversion. From the component of the seismogram transverse to the path we can extract information on the wavespeeds horizontally polarized shear waves (SH) while the vertical components constrain the SV waves with vertical polarization. In an isotropic medium, SV and SH waves are expected to propagate at the same velocity, but if anisotropy is present the two seismic phases will generally propagate with different wavespeeds. This discrepancy is often referred as "polarization" or "radial" anisotropy and can be included in the waveform inversion through an additional parameter to represent the anisotropy of the model, and thereby provide independent information to constrain both the depth extent and the strength of anisotropy. The automated procedure has allowed us to perform a wide variety of tests to assess the presence of polarisation anisotropy in the upper mantle. These include the waveform analysis of the horizontal component alone, the simultaneous waveform inversion of both horizontal and vertical components and the waveform inversion of all the data using different starting models and parameterization. In addition, a detailed analysis of the waveforms for selected epicenter-station paths has been carried out as a cross-check of the tomographic results.

For most of the paths sampling the Australian continent, we found that it is not possible to explain both horizontal and vertical component within a simple isotropic structure (Figures 2,3). For most of Australia, the patterns of wavespeed variation for SV and SH are clearly different (Figure 2). Polarisation anisotropy is required in the uppermost 200-250 km of the mantle (Figure 3). The zone of faster SV wavespeeds seem to outline the shape of the Proterozoic craton, but high SH wavespeeds extend further East under Palaeozoic Australia in the part of the model where the strongest azimuthal anisotropy is observed. The observed SH perturbations are large, resulting in amplitudes of polarisation anisotropy that are difficult to reconcile with current mineralogical models. It is possible that crustal corrections and the assumptions for the individual path models may influence this result, but the size of the discrepancy between SV and SH poses many questions on the origin of continental anisotropy.

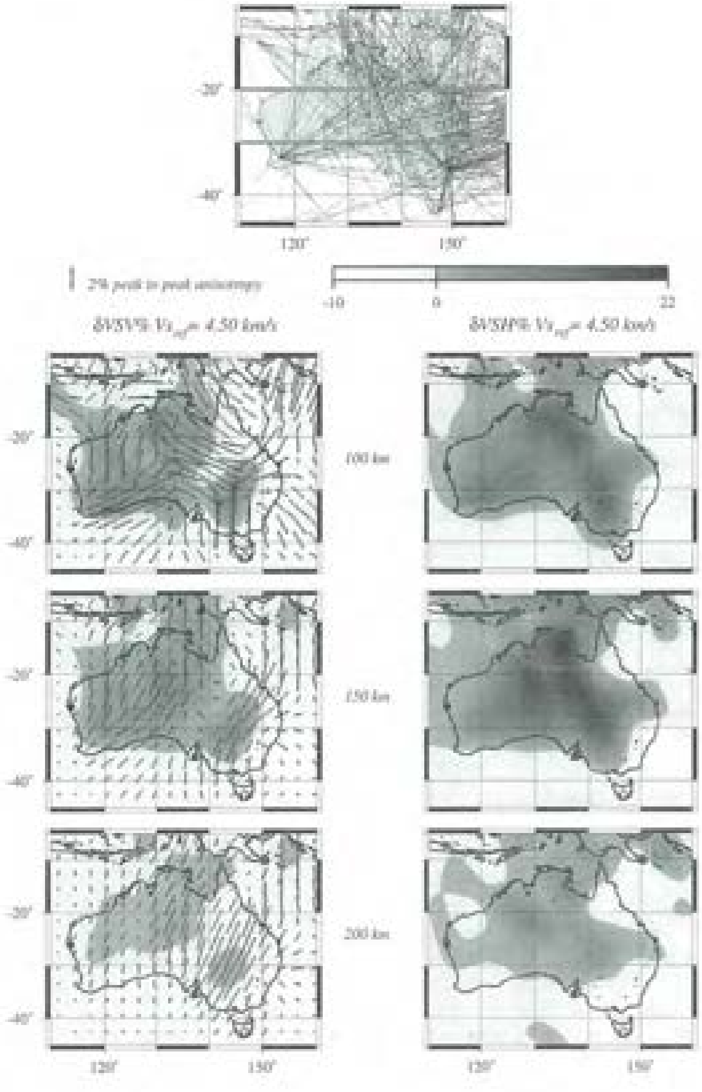

Figure 2: Top - Path coverage achieved for simultaneous Rayleigh and Love waveform inversion using PREM as a starting model. More than 1300 seismograms are involved in this inversion; bottom, left column - SV wave heterogeneities and azimuthal anisotropy; right column - SH wave heterogeneities (tones represent velocity contrasts and bars display azimuthal anisotropy, the length of the bars indicating the strength of anisotropy).

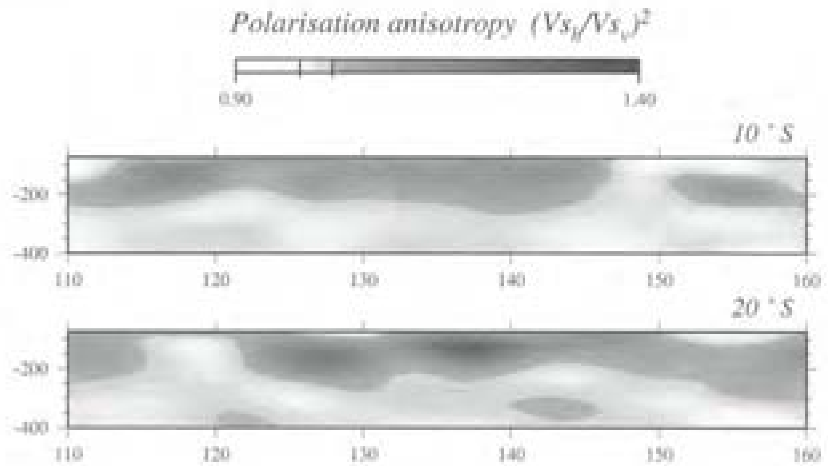

Figure 3: Cross section at -20S and -30S (see path coverage on Figure 2) in the polarisation anisotropy model. SH waves propagate significantly faster than SV waves in the uppermost 200-250 km of the model.

Surface wave tomography with irregular cells

E. Debayle and M. Sambridge

The appearance of a tomographic image is strongly affected by the limitations of sampling of the region of interest. The character of the results, particularly with regard to lateral resolution in the model, is imposed by the physics of the problem (e.g. the wavelength of the seismic waves) and the density of seismic rays sampling the structure. At the surface of the Earth, the distribution of ray path is controlled by the positions of available events and stations and is almost always uneven. Improved tomographic images should be available if the parametrization of the model can be adapted to the density of ray paths.

Computational tools that allow arbitrary parametrization of a geophysical model have been developed in the School over the last few years. These tools have now been applied to the problem of surface wave tomography. Starting from a given set of observed ray paths, a set of Voronoi cells on the Earth's surface can be defined about the points where two or more raypaths cross. Such Voronoi cells are 'nearest neighbour' regions around the crossing points. An example is shown in Figure 4. Note that the size and shape of the cells is adapted to the path density, with large cells in regions poorly sampled by the data and smaller cells where the data allow better resolution. The cellular structure has been refined by developing a quality criterion which ensures resolution of anisotropic structure in each of the final cells. The resulting Voronoi diagram may then be used as either a measure of resolution available in different parts of the Earth, or as the basis of a new parametrization in Surface wave tomography.

Our preferred approach is to use the Voronoi diagram to provide improved controls on the horizontal smoothing imposed on the tomographic inversion. This will allow the inversion to be tuned to the available data and so achieve a better extraction of structural information. The aim is to be able to combine very heterogeneous data sets, as for example when studying a region that covers both oceanic and continental areas. In the oceanic zones few seismic stations are available so paths are sparse, but in continental areas the number of measurements and the path density continuously increases with the deployment of portable seismometers (see Figure 4).

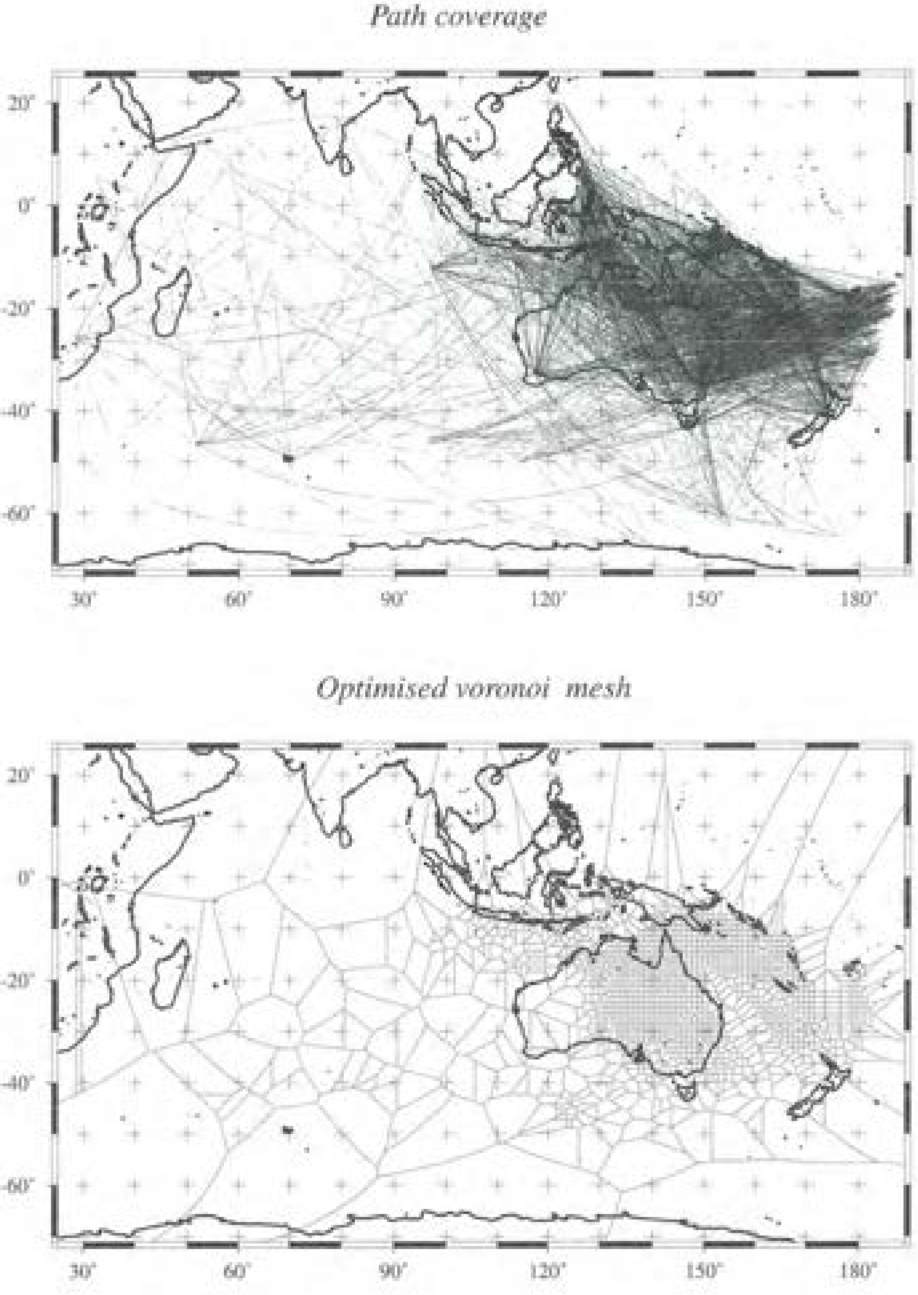

Figure 4: Example of a heterogeneous path coverage collected for the Indian Ocean and Australia. In this example, the path coverage has been used to define an optimised Voronoi mesh. The quality criterion was chosen so that in each cell, there is enough coverage to resolve SV wave azimuthal anisotropy.

The adaptive model representation will accept different levels of horizontal resolution in the two regions. At a regional scale the approach may also be used to increase the resolution in one particular region of a model, following further deployment of stations in the area.

Propagation of surface waves in a 3-D global model

K. Yoshizawa and B.L.N. Kennett

Surface waves are the most prominent phase in an observed seismogram. Although surface waves propagate two-dimensionally along the Earth's free surface, their energy reaches into deeper part of the upper mantle, resulting in the dispersive character of surface waves. Crust and upper mantle structures have been extensively investigated by many researchers exploiting dispersion directly or through the character of seismic waveforms. However, global-scale numerical modelling specifically for surface waves, has been much less common than for body waves.

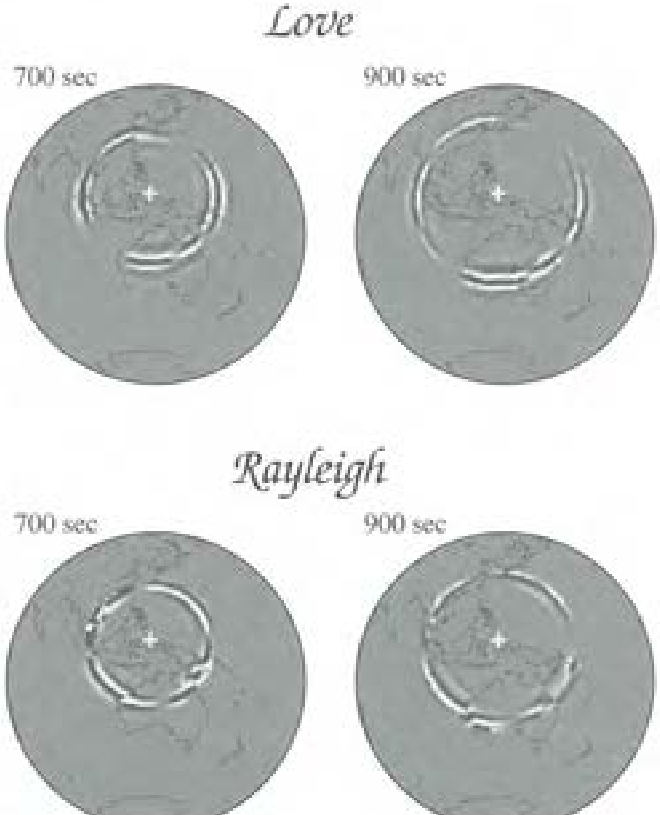

Figure 5: Snapshots of fundamental-mode Love (top) and Rayleigh (bottom) waves passing through the Australian continent. The source location is marked with a cross.

In order to visualise and understand the nature of surface wave propagation in 3-D structure, long-period surface wavefields for the whole the surface of the Earth have been computed by using WKBJ theory in which surface waves are represented by summation of normal-modes at every point on the ray path. The 3-D structure employed for the surface-wave modelling is the 3SMAC model of Nataf and Ricard 1996 which was developed by assembling a variety of geophysical and geological information.

The development of the wavefield away from a source in Indonesia is illustrated in Figure 5 with snapshots of fundamental-mode Rayleigh and Love waves at 700 and 900 seconds after the origin time. The amplitude is indicated by the intensity of shading. The black and white stripes, which suggest phases of surface wave, are clearly distorted in and around the Australian continent compared to surrounding oceanic regions. Unfortunately the Love and Rayleigh waves do not sample regions with the same sensitivity because of the differences in radiation patterns from the source. Both waves, however, are strongly affected by lateral heterogeneities around the Australian continent. For example, phase advances in western part of Australia compared to eastern part are apparent for Love wave, and strong effects from the continent-ocean boundary are clearly seen on the western margin of the Australian continent for Rayleigh waves.

Such numerical simulation of the surface wavefield provides a variety of insights into the nature of surface wavefield in a 3-D laterally heterogeneous medium which cannot readily be obtained in other ways.

Seismic body wave attenuation and its frequency dependence in the upper mantle beneath the Australian continent

H.-X. Cheng and B.L.N. Kennett

Because the Earth is not perfectly elastic, propagating seismic waves attenuate with time due to various energy-loss mechanisms, such as movements along mineral dislocations or shear heating at grain boundaries. The attenuation can be characterised by a Q which generally has weak frequency dependence below 1 Hz.

The dense set of observations of body waves turning in the upper mantle which have previously been exploited in studying the velocity distribution provide a good coverage for studying attenuation, particularly under northern Australia. A significant challenge in attenuation studies is the separation of anelastic effects from both propagation and source effects. The spectral ratio between the P and S wave arrival provides a means of cancelling the frequency dependent factors common to the two wave types.

Over a narrow band in frequency the Q can be treated as nearly frequency independent and then the slope of the logarithm of the spectral ratio is then directly related to the difference in attenuation between P and S in the passage from source to receiver. The systematic application of this spectral ratio approach to the estimation of the differential attenuation between P and S (t*_PS) to the broadband data recorded at portable stations in Australia stations provide measurements along nearly 2000 refracted raypaths mostly sampling the northern part of the continent for frequencies centred around 0.5 Hz. The measurements clearly delineate major variations in attenuation between the cratonic structures in the centre and west and the eastern part of Australia, with much stronger attenuation in the east.

The differential attenuation correlates well with the velocity structure. In the areas of high S wavespeeds, the attenuation is weak. Whereas, the strong attenuation corresponds to zones of low wavespeed. Weak attenuation of S waves was found in central and western Australia where the S velocity is high. But strong attenuation of S waves was found in eastern Australia and Coral Sea with low S wave velocity.

The broad-band seismic observations also allow the examination of a wider frequency range (up to 4.5 Hz) to look for frequency dependence of attenuation. With the assumption of a simple power law dependence of frequency (f)

$$Q = Q_0 f^{\alpha}$$

the spectral ratio information can again be used and α can be extracted from the rate of change of the logarithmic slope of the spectral ratio with frequency. There turns out to be a strong correlation between alpha and the differential attenuation (t^*_{PS}).

When the differential attenuation is low so the spectral content of P and S waves are similar, the exponent α is close to zero. The slope of the logarithmic spectral ratio departs further from linear as the differential attenuation increases and α departs from zero. For the strongest differential attenuation where the frequency content of S is much lower than that for P, α deviates noticeably from zero and the logarithmic spectral ratio shows distinct curvature over the frequency range from 0.25 to 2-3 Hz, although there is often little high frequency content. Normally alpha is not too large and so a linear approximation to the logarithmic ratio is a good representation over the interval less than 1 Hz.

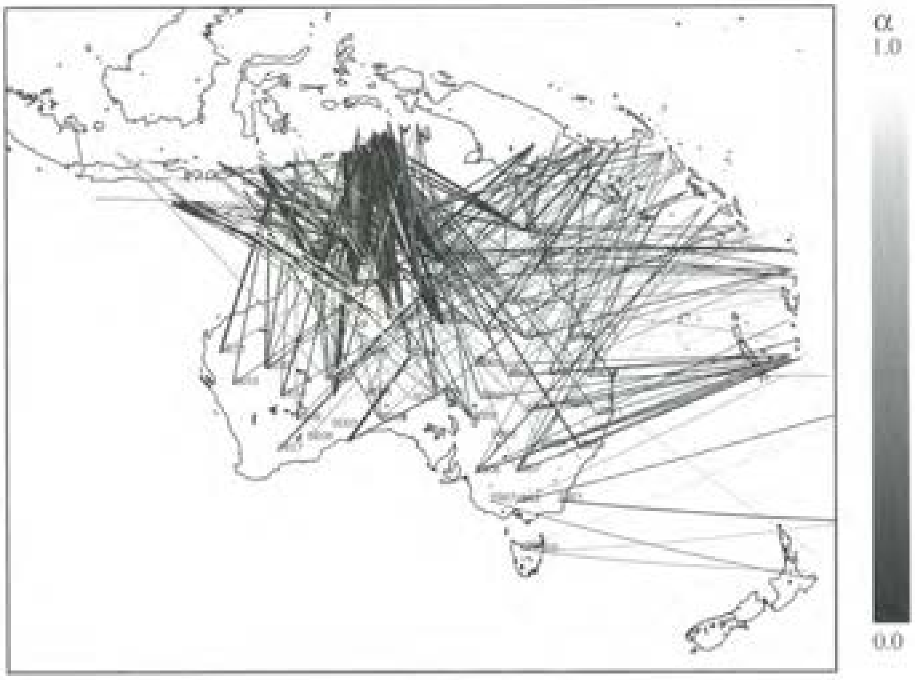

Figure 6: Paths to portable stations coded by the coefficient of frequency dependence α.

Figure 6 summarises the geographic behaviour of the exponent α over the full set of path coverage. The lines are displayed with a thickness inversely proportional to the error in the estimation of α. Thus thick lines represent paths for which α has on small error and thin paths have large errors. Smaller values of α are also normally associated with smaller errors. There is significant variation in α. The raypaths covering the north-west part of Australian continent show α close to zero with a small error in alpha; so that the frequency dependence of Q in this area is relatively weak. In eastern part of Australia and Coral Sea area, there is a mixture of paths with small and larger α so that the frequency dependence in those area are more complex and depends on the depth of penetration of the waves.

The wide range of differential attenuation measurements SKIPPY data set can be exploited to invert for attenuation structure, by making use of the velocity information extracted from stacked body wave arrivals. A set of fifteen 1-D velocity models have been constructed for different azimuthal corridors across the continent by combining data from different events and stations (see last years report). These models provide a suitable framework for attenuation inversion. The differential attenuation data has been organised into the same azimuthal corridors as used for the velocity study and have been inverted to produce a set of 1-D Q profiles.

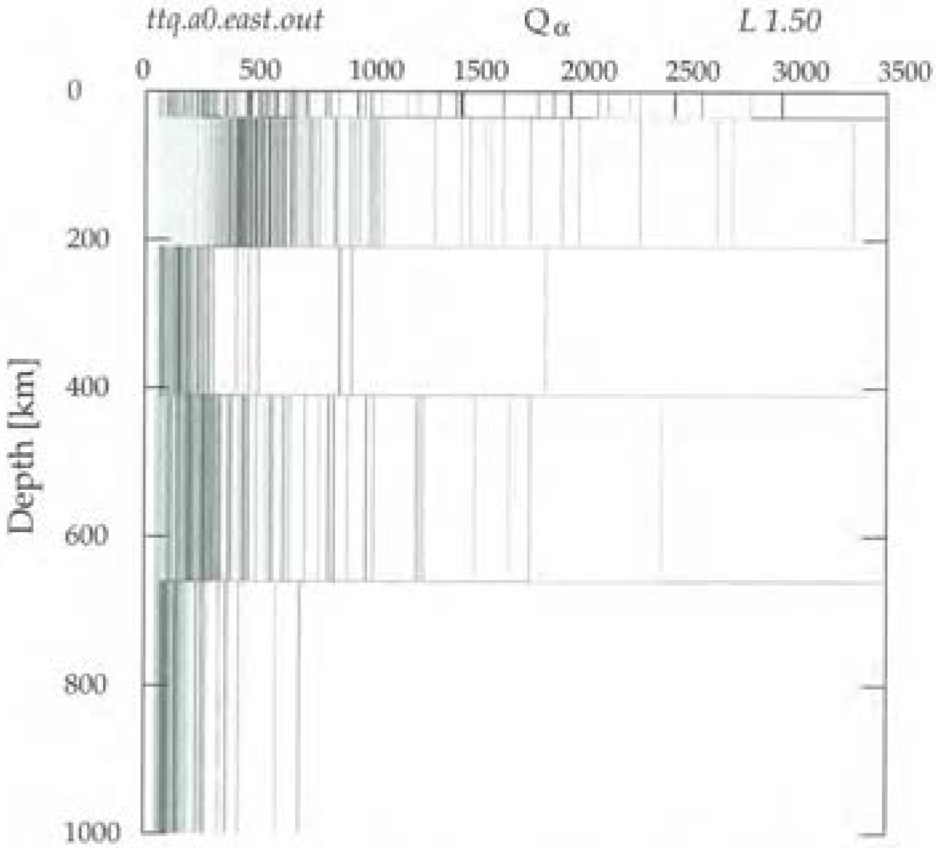

Figure 7: The set of Q models sampled in the NA inversion process coded by misfit. The darker tones indicate the best fit.

The inversion has been accomplished using the neighbourhood algorithm approach for parameter space exploration, which allows an assessment of the properties of a group models with good fit to data as well as just the best fitting model. Figure 7 shows an example of the inversion for a 1-D Q profile.

The next step will be to synthesise a 3-D representation of the attenuation structure beneath the Australian region. The initial stage will be to combine the various 1-D models.

Seismicity patterns

T. Nicholson, M. Sambridge and O. Gudmundsson

Earthquake distributions are used to infer information about earth processes and structure. The degree of clustering or ordering within any earthquake distribution can vary significantly between tectonic regimes, e.g., a mid ocean ridge and a subduction zone. Mislocation of events can occur for a number of reasons including picking errors, misidentification of phases and lateral heterogeneity within the earth. These errors tend to increase the scatter of hypocentre distributions and blur underlying structure in the seismicity.

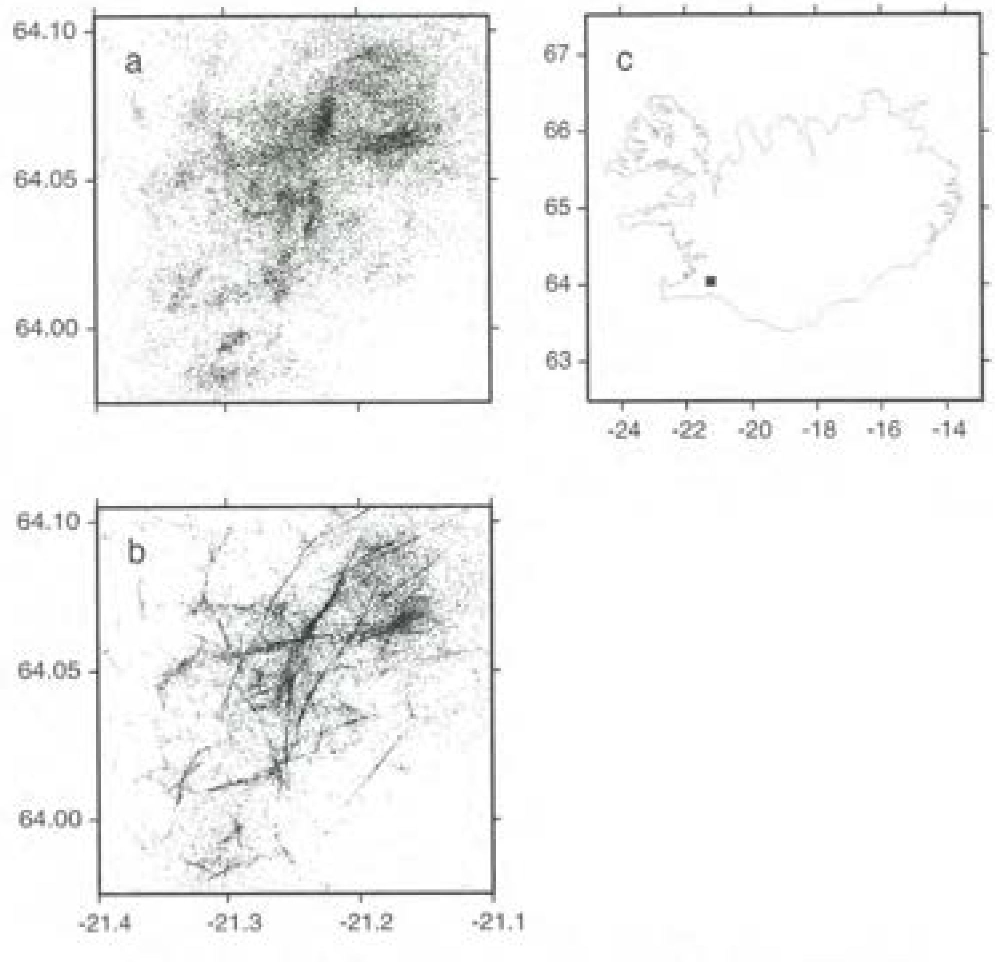

Figure 8: Earthquakes in the Hengill region of Southern Iceland a) The original locations. b) The locations after the entropy reduction method has been applied.

Work over the past year has led to a new concept which we call 'earthquake entropy'. This is a new measure which makes it possible to quantitatively compare scatter within earthquake distributions occurring over different lengths of time and in contrasting regions of the earth.

We have developed a new method which reduces entropy while conserving the fit to the data of the original events. Classically, entropy is used as a measure of disorder or scatter. This suggests that by changing a distribution of hypocentres in such a way that entropy is reduced, then unnecessary scatter might be removed from the seismicity. By reducing entropy we are enhancing the 'image' of underlying structure that earthquake distributions provide us The time sequence of earthquakes can also be used to further enhance the method and allow the identification of earthquake clusters.

Figure 8 shows an example of earthquake locations in the region around Hengill, Iceland (panel c). Panel a shows the original locations while panel b shows the results of the new method. Lineations are particularly clear in panel b. N70E trends become apparent and individual swarms line up along similar directions as estimated by Rognvaldsson (1998). The centre of the domain has some nearly north striking features but also lineations striking N30E. This direction correlates well with the dominant surface faulting in the area. An interesting lineation in the western half of the domain with a direction close to N20W stretches from the centre south to the north east corner of the domain.

Seismic Location using a Neighbourhood Algorithm

M. Sambridge and B.L.N. Kennett

The neighbourhood algorithm (NA) approach to parameter space exploration has been adapted to the problem of estimating the location of seismic events. The algorithm uses stochastic sampling of a 4-dimensional hypocentral parameter space, to search for solutions with acceptable data fit. No derivatives of travel times need to be calculated which allows considerable flexibility in the choice of misfit measure.

At each stage of the inversion procedure, the hypocentral parameter space is partitioned into a series of convex polygons called Voronoi cells. Each cell surrounds a previously generated hypocentre for which the fit to the data has been determined. As the algorithm proceeds new hypocentres are randomly generated in the neighbourhood of those hypocentres with smaller data misfit. In this way all previous hypocentres guide the search, and the more promising regions of parameter space are preferentially sampled.

The NA procedure makes use of just two tuning parameters. It is possible to choose their values so that the behaviour of the algorithm is similar to that of a contracting irregular grid in 4-D. This is the feature of the algorithm that we exploit for hypocentre location.

In experiments with different events and data sources, the NA approach has been shown to achieve comparable or better levels of data fit than a range of alternative methods; linearised least-squares, genetic algorithms, simulated annealing and a contracting grid scheme. Moreover, convergence was achieved with a substantially reduced number of travel-time/slowness calculations compared with other nonlinear inversion techniques. Even when initial parameter bounds are very loose, the NA procedure produced robust convergence with acceptable levels of data fit.

The NA location scheme is illustrated for an event in Sulawesi in June 1999 as recorded by stations reporting to the Prototype International Data Centre of the Comprehensive Nuclear-Test-Ban treaty. The intermediate depth event is reasonably well controlled with a sparse network of stations (see Figure 9). The NA location procedure is applied for a region 2 degrees across in both latitude and longitude, with a depth interval of 60 km and a time interval of 40 s centred on the PIDC location. Figure 9 illustrates the progress of the NA procedure with points coded by the misfit to the data using an L1 norm i.e. the sum of the absolute values of the time residuals scaled by the estimates of picking error.

Figure 9: The distribution of stations used in the hypocentral estimates for the Sulawesi event. Polar projection centred on the hypocentre.

The neighbourhood algorithm initially explores much of the allowed domain but quite quickly shifts attention to a zone with improved misfit. The convergence towards a cluster of well-fitting location estimates is rapid. Each of the symbols in Figure 9 represents one of the location estimates which has been assessed in the progress of the NA inversion. The symbols are coded in greytone by the level of misfit with darker tones indicating better fit. The display in Figure 10 shows only a portion of the original search region and so shows the nature of the misfit function in the neighbourhood of the best fitting model. The lightest symbols have a misfit approximately twice that of the best. The immediate neighbourhood of the best locations shows relatively slow variation but away from this region the misfit in arrival times grows quite rapidly. The distribution of misfit in hypocentral space can be used directly as an indication of the reliability of the postulated hypocentre e.g. in Figure 10 the cluster of the darkest symbols (indicating least misfit) occupy a zone about 7 km E/W by 8 km N/S.

The sampling of the misfit function in the course of the NA inversion can also be put to use in a retrospective assessment of the probability distribution for the hypocentre parameters.

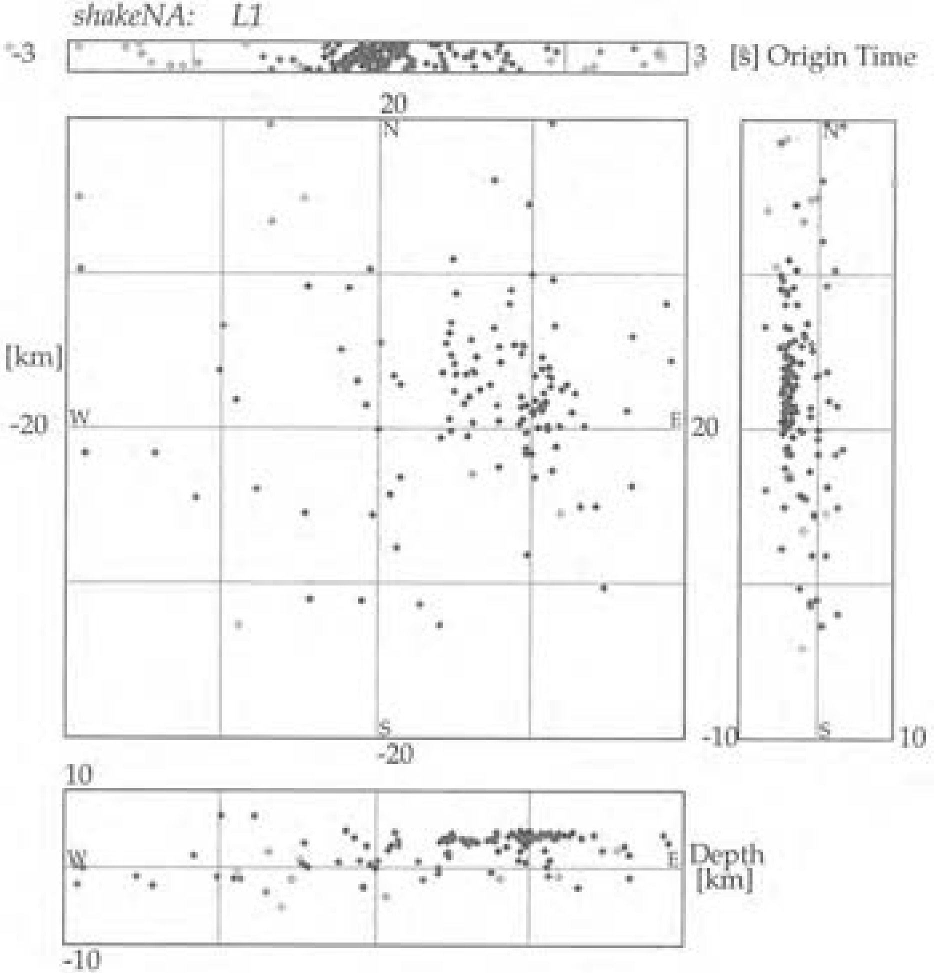

Figure 10: The central portion of the parameter space showing the sampling of model misfit in the NA procedure. The darker symbols indicate better fit and their distribution indicates the reliability of the estimated hypocentre. The environs of the best fitting model are well explored and this information is available for assessment of the probability distribution of the hypocentral parameters.

Source inversion at teleseismic distances using a Neighbourhood Algorithm

K. Marson-Pidgeon, B.L.N. Kennett and M. Sambridge

The neighbourhood algorithm (NA) is a new direct search method for inversion (see previous annual reports), and has recently been applied to the problem of source inversion at teleseismic distances. The algorithm preferentially samples those regions of a multidimensional parameter space which have low data misfit. Any suitable definition of misfit can be employed, and the algorithm is based on the rank of the misfit function.

The first application of the NA approach is to event location using arrival time, slowness, and azimuth information. The resulting hypocentre information is then linked to a waveform inversion of short period or broadband records, which uses the NA approach to invert for source depth and mechanism. The depth estimate obtained from the location inversion is used to initiate depth bounds for the waveform inversion. The source time function is specified by a trapezoid, and we invert for the rise time parameter. The source mechanism is represented via the superposition of a double couple and an isotropic component (giving a six dimensional parameter space), or alternatively, in terms of a general moment tensor (giving an eight dimensional parameter space).

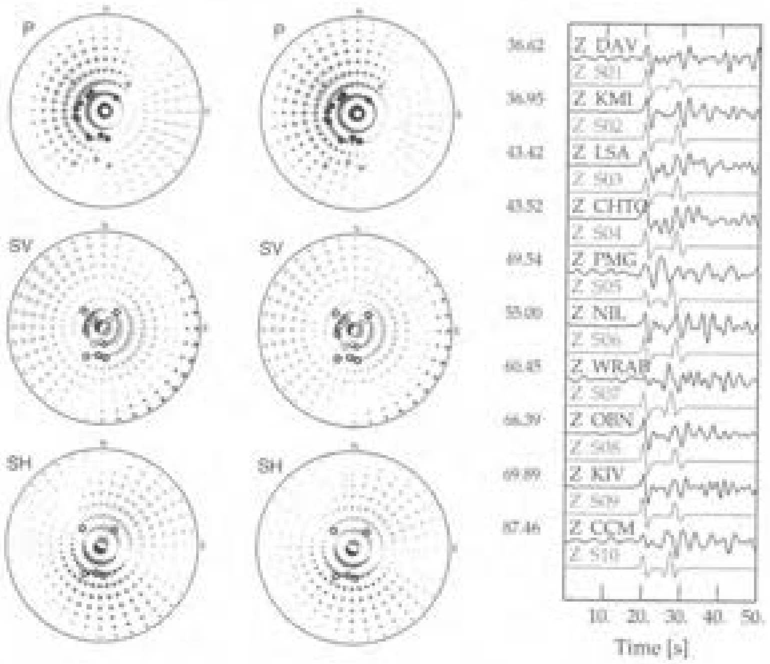

Figure 11: Source radiation pattern and seismogram comparison for Honshu event. (left) CMT solution. (middle) Resulting source radiation pattern from inversion. (right) Comparison between the 'observed' (black traces) and 'predicted' (grey traces) seismograms, for the vertical component of P.

Synthetic tests with sources at crustal depths, using few stations, have recovered good estimates of the source parameters, in particular the source depth. With good azimuthal coverage ambiguities in source mechanism can be resolved. For smaller events, which will not be recorded at many stations, it is important to exploit all the available information, and make use of both SV and SH wave data in addition to P wave data.

The waveform inversion has been applied to an event which occurred off the east coast of Honshu, Japan. This event has an estimated source depth of 19 kilometres, obtained from the centroid moment tensor (CMT) solution. Initial inversions resulted in poor fits to the observed data, though the depth estimate of 22 kilometres is close to the CMT depth. By allowing for a water layer above the source, the seismogram fit is much improved (Figure 11), and a depth estimate of 18 kilometres is obtained. Thus it seems that the source depth is fairly insensitive to other factors, such as the velocity model, which allows us to achieve good depth resolution.

RELACS – Imaging the Rabaul volcano

O. Gudmundsson

The RELACS project was completed during the year. Among the project's results are detailed two-dimensional velocity models along two profiles crossing the northwest Gazelle Peninsula, one crossing the Rabaul caldera complex, the other crossing the Tavui caldera to the northwest of Rabaul. The project also resulted in a detailed three-dimensional velocity model for the top 15 km and an area within 25 km from Rabaul. The distribution of seismicity within the Rabaul volcano was also re-examined using the three-dimensional velocity model.

A clear low-velocity anomaly was found to lie at 3–5 km depth directly beneath the Blanche Bay caldera, the youngest and seismically active collapse structure of the volcanic complex. This low-velocity zone is about 5 km across and its margins underlie a ring of volcanic vents which have been active after the formation of the collapse structure. The data cannot resolve the velocity within this low-velocity zone clearly, but do constrain it to lie in the range from 3.0 to 4.5 km/s. This represents a major anomaly compared to adjacent velocities of 5.5–6 km/s at the same depths. This anomaly lies beneath the seismicity of the Rabaul volcano and is interpreted to be a shallow magma reservoir.

The surface velocities above the magma reservoir, within the caldera structure are found to be very low, between 1.5 and 2 km/s. These low velocities may be explained by the fracturing of shallow rocks caused by the collapse event and by soft sedimentary infill.

Tavui caldera is not underlain by a shallow crustal magma reservoir. At depths comparable to the magma reservoir beneath Blanche Bay the Tavui caldera is underlain by fast velocities. These may be the cumulates of a crystallised magma reservoir which then would have to be interpreted as being very old (more than one hundred thousand years). The implications for risk associated with this volcanic structure are clear, however, a deeper (> 10 km) crustal magma reservoir beneath Tavui cannot be ruled out.

The seismicity of the 25 years leading up to Rabaul's last eruption in 1994 is arranged in a roughly oval pattern underlying the Blanche Bay collapse structure. This seismicity had been determined to lie in the top four km, but considerable uncertainty had to be assigned to that estimate due to the uncertain velocity structure around the volcano. The RELACS project has significantly constrained this velocity structure and thus tightened the constraint on the depth extent of seismicity. The result is that the seismicity extends to 3–4 km depth and that while the oval pattern stays largely intact it has slightly shrunk and shifted. These changes of pattern of seismicity are verified by corrected mislocation of explosions conducted by the RELACS project.

Figure 12 highlights the main results from the RELACS project on the velocity structure around the Rabaul volcano. The top panel shows a depth slice at 4 km depth dominated by the central low velocity anomaly beneath Blanche Bay. The lower panel shows a cross section to 10 km depth along the profile indicated in the map view above. Again the model is dominated by the confined low-velocity anomaly beneath Blanche Bay and other structures associated with the volcano. The shallow fast velocities to the northwest of the caldera (beneath point A) are probably due to shallow lying carbonates (limestone outcrops in the area). The shallow fast velocities around the western rim of the caldera may be due to a high volume fraction of intrusives.

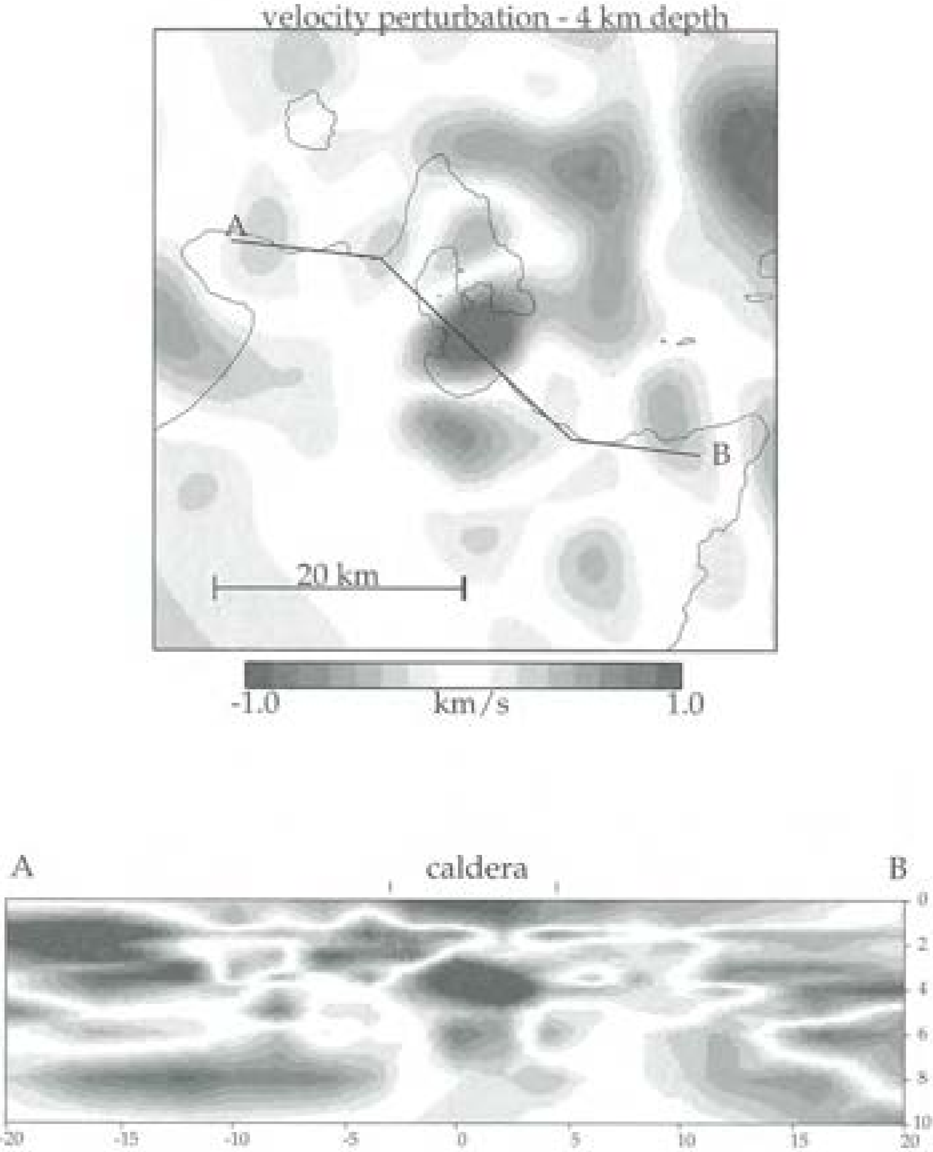

Figure 12: Images from the 3-D model of the velocity structure in the Rabaul region. The top panel shows a depth slice at 4 km depth dominated by the central low velocity anomaly beneath Blanche Bay. The lower panel shows a cross section to 10 km depth along the profile indicated in the map view of the panel above.

Characterising and enhancing seismic phases

C.-Y. Bai and B.L.N. Kennett

The detection and identification of seismic phases continues to be a significant issue in seismogram analysis. Any individual method of phase detection is based on separation of signal and noise in a particular domain and cannot ensure consistent onset time picking under all source, receiver, path and noise conditions. However a combination of three methods based on differing aspects of seismograms can be used to provide automated and consistent phase detection and interpretation using a single three-component record. An energy analysis approach based on the relative energy on the vertical and horizontal components with respect to the total energy is used as means of exploiting changes in amplitude. Changes in the nature of arrivals are detected using a number of different definitions of instantaneous frequency and also via changes in the correlation properties of the seismogram as expressed through the character of the coefficients in an autoregressive representation of the seismic trace.

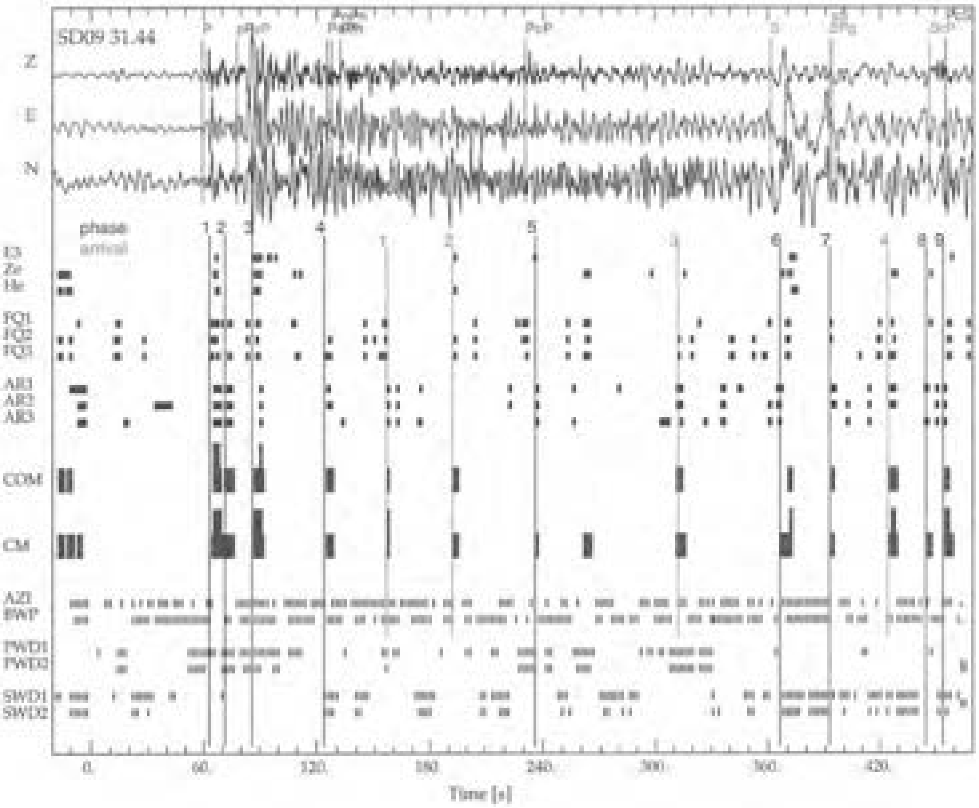

Figure 13: The use of multiple techniques to detect and characterise seismic phases (see text for explanation of traces).

The combination of energy analysis, differences in instantaneous frequency and an auto-regressive representation of the seismic record is used to develop an algorithm for robust phase detection. A detector based on the ratios of short term averages to long term averages is applied to each of the measures derived from the seismograms. When several methods indicate a trigger within a short time gate a phase detection is flagged. The character of the phases is extracted using polarization analysis using complex traces to separate S and P wave phases.

An illustration of the approach is shown in Figure 13 for an event at 79 km depth in Fiji recorded at one of the SKIPPY stations in South Australia (SD09) at a distance of 31.4 degrees.

The short-term window used for the three different methods is 2 s; the long-term window for energy analysis is 62 s, and for frequency and autoregressive coefficient analysis is 31 s.

The upper three traces represent the 3-component seismic records without rotation, with the superimposition of the predicted times of arrivals using the iasp91 travel time tables for the event parameters. E3, Ze, He are the total, vertical and horizontal energy ratio of current value to long-term trend. FQ1, FQ2 and FQ3 represent frequency ratios of the local value to the long-term trend. AR1, AR2 and AR3 are the low-order, medium-order and high-order correlation coefficient ratio of temporal behaviour to long-term trend. We note that we would miss the first arrival of the P wave and the depth phase sS if we just relied on the amplitude behaviour.

Two different approaches to combining the different detection measures are employed, CM where each of the measures has equal weight and COM when we require at least of the different styles of measures to be triggered. The long vertical bar reaching to the bottom of the frame represents the case where both the iasp91 travel times and the combination algorithm both indicate a phase, denoted as phases 1,2,...n. A shorter vertical bar in grey indicates where only the combination algorithm indicates a detection, denoted as arrivals 1, 2,...n.

The polarisation analysis results divide into three classes: AZI and BWP combined form a separation of body wave from background noise via the linearity of the polarisation; PWD1 and PWD2 are detectors for P phases, and SWD1 and SWD2 are the detectors for S phases. Phases 1,2,3 and 5 can be distinguished as P phases and phases 6,7 and 9 as S phases.

This event provides a good example of the way in which the individual methods reinforce each other when used in combination. The energy analysis pick only the P, sP and S phase, frequency analysis and AR coefficient analysis pick P, pP, sP, PnPn, S, S, sS, ScP and PcS but the significance of the picks are reinforced by the coincidence of the two methods.

Warramunga Seismic Array

J. Grant and B.L.N. Kennett

The seismic and infrasound arrays at the Warramunga Array Station (WRA) near Tennant Creek have been designated as major components of the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The seismic array is a primary station which will provide data directly in real-time to the International Data Centre in Vienna. A major hardware upgrade was completed in May to bring the seismic array up to treaty standards: the new configuration retains the original twenty seismic sites in along two 25 long arms (B1-B10, R1-R10) and adds 4 new sites (C1-C4) to improve analysis capability for events at regional distances (figure 14). Satellite connectivity to Vienna was completed in early December.

Currently work is underway on site preparation for the installation of a new infrasound array which will have four long-period sensors in a triangular configuration with an additional set of three high-frequency sensors surrounding the central site. In order to reduce the influence of wind noise, each sensor will have a radiating pipe array from the sensor vault with distributed inlets.

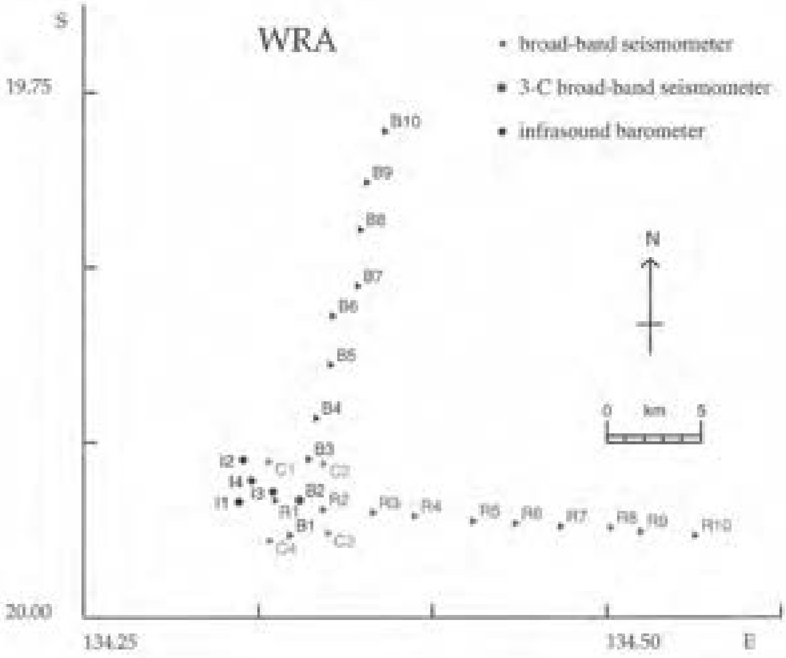

Figure 14: Configuration of the seismic array (PS2) and infrasound array (IS7) at the Warramunga Array station near Tennant Creek.

GEOMAGNETISM

F.E.M. Lilley and A. Hitchman

The magnetic field of the Earth changes on a very wide range of time-scales. Almost all reflect processes of electromagnetic induction taking place. These processes may be due either to electromagnetic induction in a stationary Earth due to external source fields which vary with time; or to motional electromagnetic induction, as in the oceans, and (on a much stronger scale) in Earth's core. The work at RSES during 1999 has concentrated on various projects based on observations of the time-varying magnetic field observed at Earth's surface, and on the information which may thus be obtained about processes in the Earth and oceans.

Such projects involve an observational component which may take some years to develop and follow through. During 1999 attention concentrated on a number of projects which were brought to a stage of conclusion by the completion of the PhD thesis of Adrian Hitchman. Dr Hitchman presented his research results at the IUGG meeting in Birmingham, England, and this meeting was well-timed for his participation at the end of his research scholarship. Dr Lilley took two months of outside studies leave towards the end of the year, which enabled him to continue collaborations in North America, and to present recent Australian results there. He participated in a workshop on electromagnetic induction held in Salt Lake City.

Marine Investigation of the Eyre Peninsula Conductivity Anomaly

F.E.M. Lilley, A. White[1], G.S. Heinson[1], I. Popkov[1], S.C. Constable[2] and P.R. Milligan[3]

During 1999, reduction and analysis of the large data-set obtained during the SWAGGIE experiment of the previous year was advanced at both Flinders University and ANU. The purpose of the marine electromagnetic investigation is to investigate the conjectured extension offshore of the Eyre Peninsula Conductivity Anomaly (EPA), which is a major linear electrical conductivity structure found in the Eyre Peninsula, South Australia. The marine investigation was supported by two cruises of the research vessel *Franklin*, and was notable for involving, through both national and international collaboration, the largest array of seafloor EM instrumentation yet assembled for an experiment in Australian waters. On land, recording magnetometers were deployed in an array across the southernmost part of Eyre Peninsula.

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

Electrical conductivity structure at the eastern edge of the Mt Isa Block

F.E.M. Lilley, L.J. Wang[1], F.H. Chamalaun[1] and I.J. Ferguson[4]

A period of outside studies leave spent by F.E.M. Lilley at the University of Manitoba enabled substantial progress to be made on completing the interpretation of data from the line of magnetotelluric stations occupied in 1997 between Julia Creek and Cloncurry in western Queensland. The major electrical conductivity structure (termed the Carpentaria conductivity anomaly) crossed by the line of stations is well-imaged in pseudo-sections based on the observed data, in 'stitched-1D' conductivity sections, and in conductivity sections resulting from 2-D inversions.

The conductor lies in the Mt Isa Block where it is covered by sediments of the Eromanga Basin. A pleasing test of the application of the magnetotelluric method to the present problem is that the known depth of the Basin (order 200 m, determined from drilling) is well resolved in the data inversions.

Detection and use of a daily-variation signal in aeromagnetic data

A.P. Hitchman, F.E.M. Lilley and P.R. Milligan[3]

An aeromagnetic survey is generally comprised of a series of parallel lines, and a set of ties flown at right angles to the lines. This practice gives rise to crossover points where ties intersect lines, and where two independent measurements of the magnetic field have been made. Commonly these two measurements are different and a 'misfit' exists.

Methods have been developed to analyse such misfits for evidence of electromagnetic induction in the Earth. The methods developed recover a representative quiet daily-variation from crossover misfits in the aircraft data, and a similar variation derived from base-station data

[1] Flinders University
[2] Scripps Institute of Oceanography
[3] Australian Geological Survey Organisation
[4] University of Manitoba, Canada

(usual aeromagnetic procedure includes running a base-station observatory, perhaps at the airfield from which the aircraft is operating). Comparison reveals enhancement or reduction of the aircraft variation relative to the base-station variation. Such enhancement or reduction is interpreted in terms of contrasting electrical conductivity structure between aircraft and base-station locations.

The method has been tested for a range of Australian aeromagnetic data-sets. Figure 15 shows sample results for an aeromagnetic data-set from South Australia, which covered a major known inland electrical conductivity structure (the Flinders anomaly, named after the Flinders Ranges). As can be seen, the aircraft results give a clear indication of the presence of the structure, demonstrating the potential of the method for reconnaissance purposes.

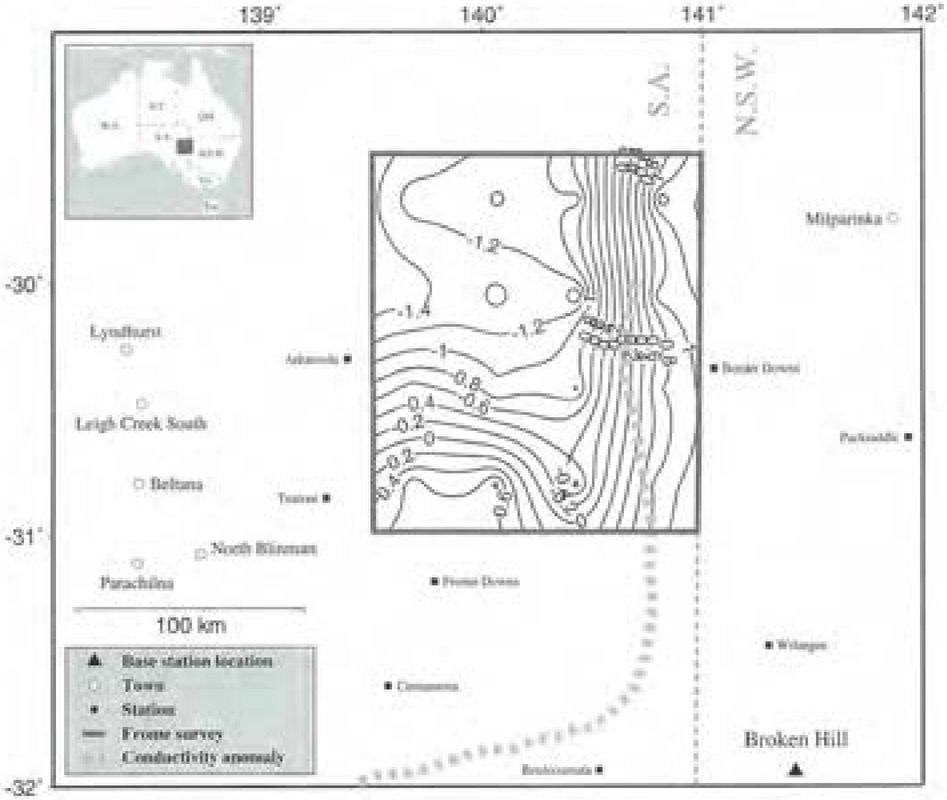

Figure 15: Contoured map showing use of aeromagnetic data for electrical conductivity purposes, Frome area, South Australia. Note that the contour pattern highlights the position of the Flinders conductivity structure, known from ground observations.

Applications of the concept of a magnetic amphidrome

A.P. Hitchman and F.E.M. Lilley

Figure 16 shows, by example, the concept of a magnetic amphidrome. The data originate from the Australia Wide Array of Geomagnetic Stations (AWAGS) of ten years ago, and they have been accessed from the PhD thesis (Flinders University) of J.M. Whellams. The figure shows, as a snapshot in time, the amplitude of the sudden commencement of a geomagnetic storm, as it would be measured by total-field magnetometers spaced over the continent of Australia.

It can be seen that the signal is generally subdued across the southern border of the continent. This effect is due to magnetic amphidrome conditions being created there by the ocean-continent electrical conductivity contrast.

The implications of this phenomenon are both subtle and widespread for magnetic mapping activities. Those which seek high-resolution results, and the removal of the time-varying part of the field from the spatial variations, need to be aware of amphidrome patterns where they are making measurements.

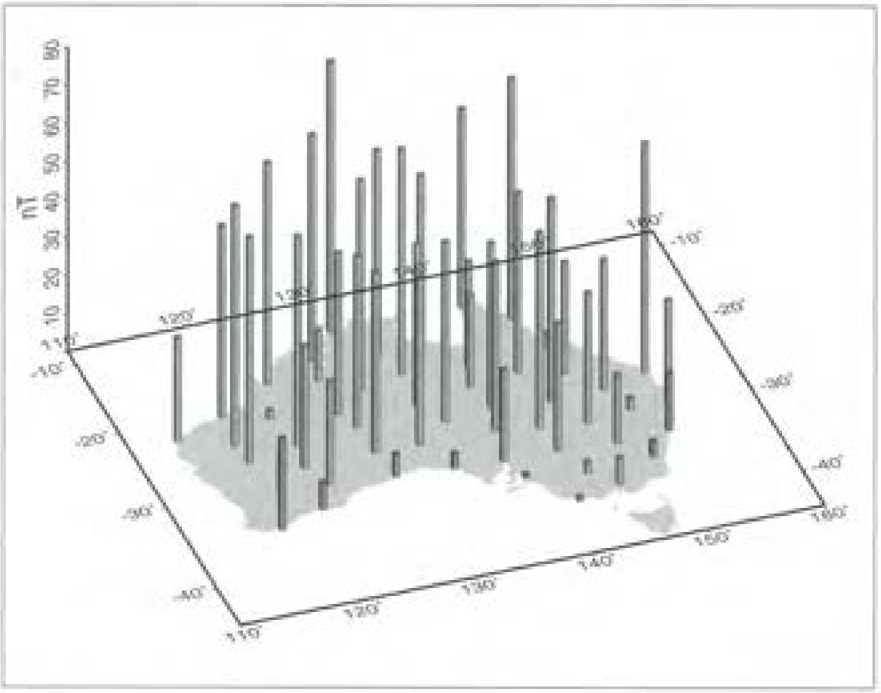

Figure 16: Each column marks an AWAGS magnetometer station and shows the amplitude of the onset of a geomagnetic storm. The generally suppressed response across the southern band of the continent demonstrates the magnetic amphidrome conditions prevailing there.

Results from floating magnetometers

A.P. Hitchman and F.E.M. Lilley

Novel data were obtained during 1998 by releasing a total-field magnetometer to float on the surface of the deep ocean for several days, tracking its position by satellite technology. In an associated experiment, in the more shallow water of the continental shelf, a magnetometer was moored for several days at each of a number of sites.

Analysis of these data has proceeded during 1999 with several objectives in view. Firstly, it has proved possible to combine the sea-surface total-field data with nearby land data to give induction arrows for the sea-surface sites, thus introducing a new technique to marine electromagnetic methods. The sea-surface data were obtained during the SWAGGIE98 experiment off the coast of South Australia, and the induction arrows thus obtained augment the information available for the conductivity structure of the continental shelf.

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

Thirdly, ocean swells generate magnetic signals by motional electromagnetic induction, and the Great Australian Bight, with its exposure to the Southern Ocean, was seen as a good place to seek the magnetic signals of ocean swells, for comparison with theory. Good data were obtained, and Figure 17 shows an example of the power spectrum of the sea-surface signal, superimposed upon that of a nearby land station for the same period. (The land station recorded data at 60 s intervals, and so its spectral window is not the same as the sea-surface instrument.) The peak in the sea-surface spectrum at 14 s period, due to the ocean swell, is clearly evident.

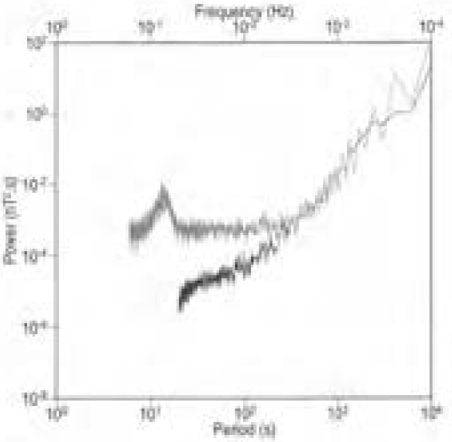

Figure 17: Power spectrum for data recorded by a total-field magnetometer, floating on the sea-surface of the Great Australian Bight (light trace). Note the peak in energy at 14 s, due to the magnetic signals generated by the motional induction of ocean swell. The heavier trace is for an instrument on nearby land.

Specification of the invariants of the magnetotelluric impedance tensor

F.E.M. Lilley, J.T. Weaver[5] and A.K. Agarwal[5]

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

The seven invariants then summarise the electromagnetic response of the Earth, and, as a set, may be specified in various different ways. With the first two invariants containing the 1-dimensional scale of the tensor, and the next two invariants its 2-dimensional characteristics, three invariants are left to express the 3-dimensional characteristics of the tensor (and thus of the Earth).

[5] University of Victoria, Canada

In 1999 collaborative work continued on the best specification of the invariants, especially with a view to clarifying the frequently-encountered case in actual data of "galvanic distortion"[7]. Forward calculations of hypothetical situations have helped this process greatly. At present, all magnetotelluric inversions depend on 1-dimensional and 2-dimensional invariants determined from observed data, and, as 3-dimensional modelling and inversion advance, 3-dimensional invariants will assume an increasing importance.

Magnetometer records from the floor of the Southern Ocean

F.E.M. Lilley and A. White[1]

The reduction of magnetometer data observed on the floor of the Southern Ocean, near the Australia-Antarctica Spreading Ridge, commenced in 1999. An interesting feature of the total-field time series for station *Girardin*, (51 deg 45.06 min S, 143 deg 16.82 min E, depth 3500 m) is its steady increase over six months, shown in Figure 18. The phenomenon is not thought to be due to either base-line drift or calibration drift in the magnetometer, and may be a measure of the geomagnetic secular variation at that point, which (on a global scale) is relatively near the south magnetic dip pole.

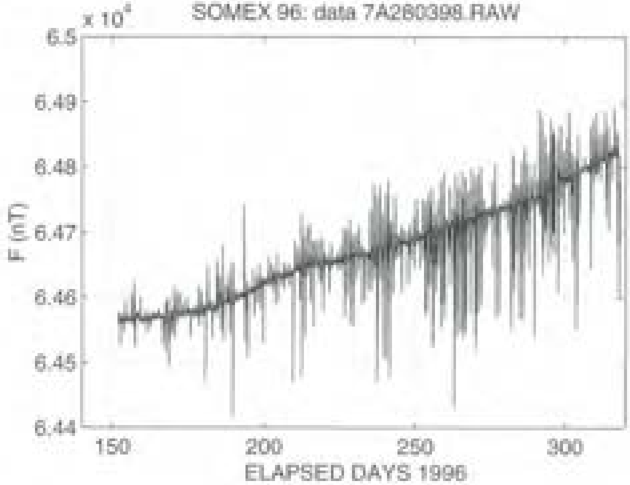

Figure 18: Example of magnetometer data recorded at the station Girardin on the floor of the Southern Ocean. The amplitude of the magnetic field vector is shown as a compressed plot, for the full duration of recording. The instrument is near Earth's auroral zone and magnetic storms show as spikes on the graph. The events are a powerful energy source for the magnetotelluric probing of the electrical conductivity structure of the Australia-Antarctica spreading ridge.

While the variations in the data on short time-scales (minutes to 1 day) are suitable for studying the electrical conductivity of the seafloor, those on time scales of 1 day - 1 month will be examined for evidence of ocean currents. The major international oceanographic experiment in the Southern Ocean in 1995–1996, with which the ANU-Flinders magnetometer observations were intended to be simultaneous, is now yielding results. An account by Professor D. Luther and colleagues may be viewed at:

http://www/soest.hawaii.edu/~dluther/SAFDE/WOCE_SAFDE_poster.html

GEODYNAMICS

Research within the Geodynamics Group of RSES covers three areas: (i) precise geodetic monitoring, modelling and analysis of crustal motion and deformation, (ii) glacial rebound and sea-level change and (iii) modelling of tectonic processes, including surface processes.

In the area of crustal motion and deformation research using geodetic methods the principal outcomes have been in two areas: the construction of a stand-alone Antarctic-conditioned GPS capability, powered by a combination of solar cell and hydrogen fuel cell technologies and with data transmission back to Canberra. At years end two packages are *en-route* to Antarctica for installation at Davis and Beaver Lake. This development follows on from very successful experiments in the previous two years with solar powered systems for day-light conditions. Two additional solar powered packages are also *en-route*, one for installation in the Southern Prince Charles Mountains and the other on the Prydz Bay coast. The purpose of the experiment is to measure differential vertical displacements between coastal and inland sites that may result from ice withdrawal from the Lambert Glacier drainage basin. The other major crustal displacement research has been the on-going Global Positioning System (GPS) surveys in Papua New Guinea with the survey of a detailed network in New Britain and New Ireland and a very recent survey in the northwestern region. With the principal first-order features of the plate tectonics of the region now defined with the GPS surveys, attention is now focussing on the details of the deformation across the boundaries. An important aspect of this work is the very close successful cooperation established with the National Mapping Bureau of Papua New Guinea, the Papua New Guinea National University of Technology at Lae, and the Rabaul Volcano Observatory.

In the area of glacial rebound, the work continues to focus on (i) new observational evidence from critical areas and times, such as north western Australia during the Last Glacial Maximum and the Ross Coast of Antarctica, (ii) the inference of ice sheet dimensions during the deglaciation phase from the sea-level data of Europe, and (iii) the inference of mantle rheology from the same data. Particular attention is placed on whether an effective separation of ice-and earth-model parameters can be achieved and the new inverse methods developed suggest that this is the case.

The third area of research is in lithospheric and crustal tectonic modelling which includes studies of the deformation of the Australian continent in early Palaeozoic time and more localized deformation in accretionary wedges and thrust belts. The numerical methods developed initially for these lithosphere-scale problems have also proved to be most applicable and efficient for studying surface processes and is leading to new insights into matters as diverse as glacio-fluvial erosion and karst aquifer evolution.

Dr Y. Yokoyama successfully defended his thesis this year and will join the Lawrence Livermore Laboratory, Berkeley, early in 2000. Ms E.-K. Potter joined the group as a PhD student. Two exchange students Ms S. Frederiksen and Mr Y. van Brabant, respectively from the Universities of Åarhus and Liège, joined the group for part of this year. Dr G. Kaufmann leaves the group to move to the University of Göttingen.

GEODETIC MONITORING OF MOVEMENTS AND DEFORMATION OF THE CRUST

Papua New Guinea

P. Tregoning, H. McQueen , K. Lambeck, R. Jackson[1] *and R. Little*[1]

In 1999 the RSES equipment which is on long-term loan to the University of Technology, Lae, was used by staff and students at that University, and on our behalf, to make repeat observations at key sites on the Huon Peninsula in and around the Ramu-Markham Fault zone and observations were made at Wewak by a student from RSES. We also supported staff at the Rabaul Volcano Observatory in their monitoring of active volcanoes in the New Britain/New Ireland region by supplying GPS equipment for fieldwork and by analysing the data and providing up-to-date coordinates of the sites monitored.

In addition, several sites in the northwestern region of Papua New Guinea were observed in late November at sites first observed with GPS in 1993. These data have allowed crustal velocities to be estimated at sites surrounding the location of the July 1998 earthquake and tsunami, which devastated the northern coastline near Aitape. The new information is leading to a better definition of the kinematics of this region and, ultimately, to the tectonic forces responsible.

On 1 April, 1999, a M_w=6.2 earthquake occurred on the Weitin Fault, New Ireland. The earthquake location is within the GPS network observed by RSES and Unitech in September 1998. At our request, staff and students at Unitech organised and executed a repeat survey at the four sites closest to the epicentre of the earthquake. Analysis of the data is underway; preliminary estimates indicate that the earthquake caused less than 20 mm displacement at the GPS monitoring sites. This highlights the need for long-term station occupation in order to separate inter- and co-seismic deformation on and adjacent to the faults.

The data collected in the New Ireland and New Britain regions in 1998 have been combined with other GPS and terrestrial geodetic data observed since 1975 to estimate a preliminary velocity field for the Gazelle Peninsula and southern New Ireland. The pattern of individual site velocities with respect to the South Bismarck Plate reveals a relatively uniform velocity gradient across a 150 km region between the rigid South Bismarck and Pacific Plates, indicative of a locked strike-slip boundary (Figure 1). Anomalous velocities at two sites on the west coast of New Ireland indicate that a M_w=7.1 earthquake in 1985 may have caused co-seismic deformation between the 1975 terrestrial survey and 1994–1998 GPS surveys.

We have developed a DOS-based computer program that synthesizes the current understanding of present-day tectonic motion to allow users to estimate the velocity of a site anywhere in Papua New Guinea. From input coordinates of the site(s), the program calculates on which plate the site resides, the site velocity and the site coordinates at any other epoch. It also allows users to calculate the distance (and rate of change of distance) between any two points, and to calculate the coordinates of new sites while accounting for the effects of tectonic motion. The program has been provided to the Papua New Guinea National Mapping Bureau and interested university groups within Papua New Guinea to provide them with a tool for accounting for the active tectonic environment in their geodetic measurements.

[1] Department of Surveying and Land Studies, The Papua New Guinea University of Technology, Lae

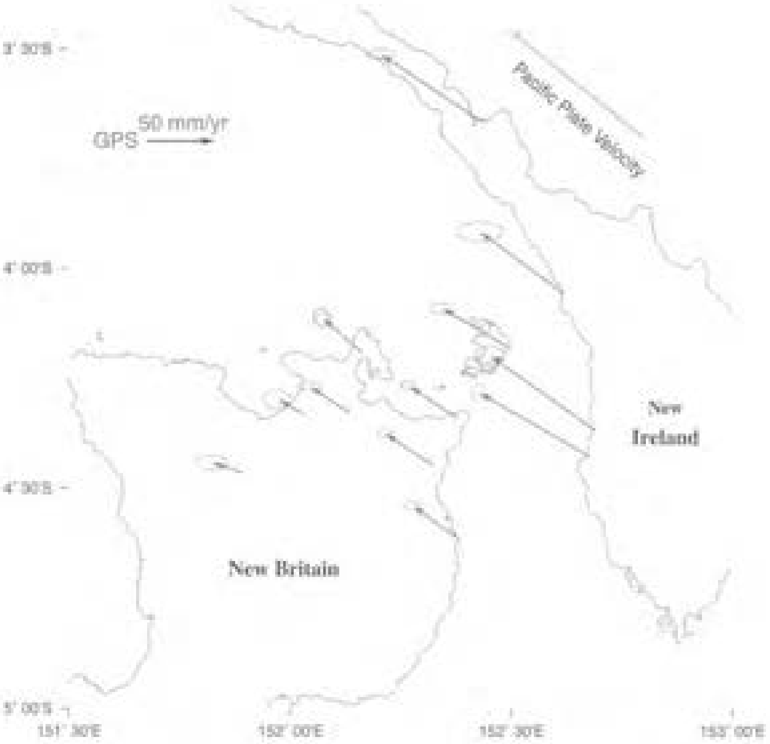

Figure 1: GPS site velocites relative to the South Bismarck Plate. The relative motion of the rigid Pacific Plate is indicated with a white arrow.

Antarctica - Isostatic Rebound

P. Tregoning, H. McQueen, A. Welsh, N. Schram and K. Lambeck

In January 1999, the equipment installed at Beaver Lake, Antarctica in January 1998 was revisited and found to have survived the winter intact. Ten weeks of GPS data were recovered, along with diagnostic data which showed that the solar-powered system operated until 26 March by which time solar energy was insufficient to power the system. This was a major achievement since other international groups attempting to operate remote GPS installations are suffering from major equipment failures whereas our simple, solar-powered system operated as expected. A new set of six solar panels have been installed, along with a new GPS receiver. Ten days of data were recovered before the system was left unattended for the rest of the year. It will be revisited in January 2000, at which time we expect to recover additional data observed in February/March 1999.

There is currently no proven means of providing significant power to remote equipment throughout an Antarctic winter, and during 1999, a major new initiative was undertaken to enhance the equipment for the remote GPS installations in Antarctica. A 1998 ANU Major Equipment proposal to purchase hydrogen fuel cells (manufactured by Hydrogenics Corporation) and a Satcom-B satellite phone was successful and these items were purchased this year. The fuel cells combine hydrogen gas with oxygen from the surrounding air to generate electricity, heat and water. The electricity supplies the power to operate the equipment during the winter periods of darkness when there is insufficient solar power available. This will be the first time that fuel cells have been used to provide power to remote equipment in Antarctica and will represent a significant scientific breakthrough if successful.

The RSES Electronics Group designed and built power controllers, computers and power switching devices to integrate the solar and fuel power and to provide power to peripheral equipment when required. The power controller runs continuously (consuming ~ 0.8 W) and constantly monitors the battery voltages and the internal temperature of the equipment housing. Diagnostic data is logged, including information about the performance of the fuel cell, and is transferred to the computer each day. Once per day, the computer is powered up (2.5 W) to download the data from the GPS receiver, to convert it to a more compact format, collect the diagnostic data from the power controller, and transmit all the data back to RSES via satellite phone.

Equipment housings and mounting structures are shown in Figures 2 and 3. All equipment is raised above the ground to prevent snow drifts forming on the leeward side of the structures. The insulation of the equipment was designed to be a passive system without the need for venting or any active, moving components. Knowledge of the expected temperature ranges and changing power usage inside the equipment housing has been used to create an enclosure that will maintain an internal temperature of between 5° and 50°C. In the event that the outside temperature falls below -40°C, heaters will automatically switch on inside the enclosure to ensure that the inside temperature remains above 5°C; otherwise, the heat of the operating equipment will be sufficient to keep itself warm.

The equipment will be installed at Beaver Lake in January 2000 and it is expected to operate throughout the whole of the year. A similar system will be operated at Davis, where the performance of the fuel cell can be monitored directly to provide feedback on how the Antarctic environment affects the operation (eg icing up of the exhaust outlet, rate of hydrogen consumption). In addition, two new solar-powered sites will be installed in January in the Lambert Glacier region as part of a long-term expansion of the GPS network.

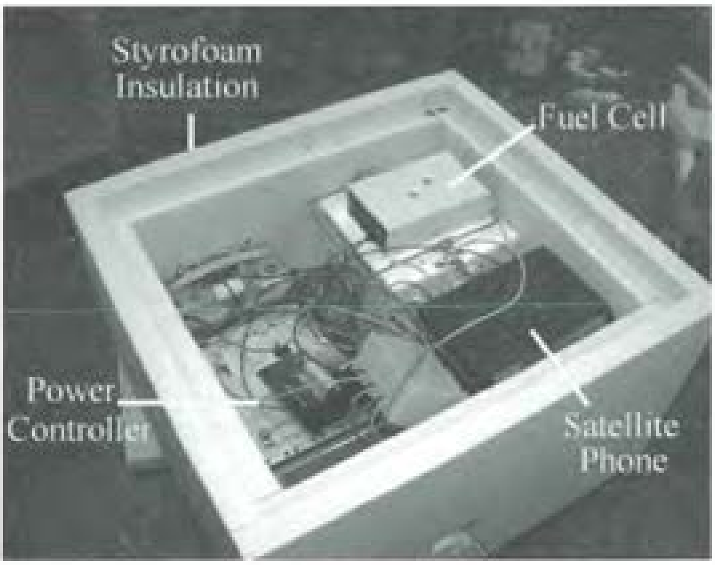

Figure 2: Power controller, fuel cell, satellite phone and associated electronics developed at RSES for the remote Antarctic GPS installations.

Figure 3: Part of the equipment setup to be deployed at Beaver Lake and Davis in January 2000. The satellite phone radome can be seen on the left. An additional set of three solar panels will be installed further to the left of the radome, resulting in six panels to generate solar power at each site.

Super-Gravimetry

H. McQueen , K. Lambeck and T. Sato[2]

Mt Stromlo Gravity Station continues to operate successfully and is proving to be one of the most sensitive of the worldwide Superconducting Gravimeter (SG) sites. A major calibration with an FG5 Absolute Gravimeter was performed at the station in February during a visit by Dr Amalvict from EOST at the Université Louis Pasteur in Strasbourg with support from AUSLIG. These determinations provide the necessary calibration of the superconducting instrument and permit the measurement of its drift characteristics and the secular change of gravity at the site, which is essential for analysis of long period processes.

The SG is currently the most sensitive type of gravity meter, built around a superconducting niobium sphere levitated by a magnetic field in an evacuated chamber and cooled by a liquid Helium bath. Gravity fluctuations down to one part in 10^{12} of earth's surface gravity can be determined by accurate monitoring of the sphere's position. Operation of the Canberra site is a collaboration between the Geodynamics group in RSES and the Japanese National Astronomical Observatory, Mizusawa, and data is regularly archived at the data centre of the Global Geodynamics Project. It is part of a world-wide array making precise observations of faint gravity signals in an attempt to detect motions in the deep interior, infer details of Earth's internal structure, and provide information on a range of problems in global geodynamics.

The Canberra site is one of the few at which background free oscillations of the Earth, apparently unrelated to major earthquake excitation, have recently been observed. These faint oscillations constitute a steady hum of subtle vibrations of the whole earth whose source has not yet been definitely identified. The main suspect at this stage is excitation by atmospheric pressure fluctuations but longer and more sensitive records at several sites are needed to test this hypothesis. Because of its sensitivity, the Canberra site will provide one of the most important records in this study.

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[2] National Atronomical Observatory of Japan, Mizusawa

ICE SHEETS, SEA LEVEL AND MANTLE VISCOSITY

Sea-level constraints on the termination of Last Glacial Maximum and global ice volume variations

Y. Yokoyama, K. Lambeck, P. De Deckker[3], P. Johnston, L.K. Fifield[4], A. Purcell

New sea-level observations from the Bonaparte Gulf in north western Australia constrain the magnitude and rates of change of ice volumes during the Last Glacial Maximum (LGM) and early period of the Late Glacial stage. The region is tectonically stable and far from the former ice-covered regions. The glacio-hydro-isostatic adjustment of the coast is relatively small and the corrections for this effect are not sensitive to details of the rebound model. Microfossil analysis and AMS radiocarbon dating of a number of cores taken across the shelf and Bonaparte Gulf demonstrate that (i) the LGM sea-levels were locally at -125 ± 4 m, (ii) the LGM terminated abruptly at 19,000 cal yr BP with a rapid rise in sea-level of about 15 m over the next 500 years, (iii) the onset of the minimum sea-levels occurred before 22,000 cal yr BP. When corrected for the glacio-hydro-isostatic effects, the increase of LGM ice volumes over present day ice volume is 52.5×10^6 km^3. The termination of the LGM is marked by a rapid ice discharge of 5.2×10^6 km^3.

Sea-level change along the French Mediterranean coast for the past 30 000 years

K. Lambeck, E. Bard[5] and A. Purcell

Observational evidence for sea-level change along the French-Mediterranean coast has been examined and compared with glacio-hydro-isostatic models to predict the spatial and temporal patterns of change for about the past 30,000 ^{14}C years. These predictions are pertinent to discussions of changing ocean volumes during this interval, the tectonic stability or otherwise of the coastal areas, mantle rheology, and the timing of possible human occupation of the now-submerged coastal plain and caves, such as Cosquer Cave near Marseille. The principal results from the analysis are: (i) Sea levels along this section of the coast have risen continually since the time of the Last Glacial Maximum (LGM) and at no time during the Holocene has mean-sea-level been higher than that of today. (ii) The coast has been tectonically stable between Marseille and Nice as well as further to the west in Roussillon. Western Corsica may have experienced a slow tectonic uplift of between 0.15 to 0.3 mm/year for the past 3000 years but northernmost Corsica appears to have been stable during this same interval. (iii) During the LGM sea levels along the coast and immediate off-shore areas stood at between 105–115 m below present level, the range reflecting the importance of the isostatic contributions. During oxygen isotope stage 3 sea levels do not appear to have risen locally above about -60 m. (iv) The rebound parameters (describing the mantle rheology and ice sheets) required to match the limited observational evidence are consistent with the results of similar analyses carried out for other parts of Europe. Because of its distance from the former northern ice sheets the isostatic factors are particularly sensitive to the value of the lower mantle viscosity. (v) The model predictions for sea-level change at the Cosquer Cave site and for its immediate environments indicate that the cave was last readily accessible before about 10,700 ± 500 ^{14}C years (about 12,500 ± 500 cal. years) BP and that the cave entrance was completely flooded by 9000 ± 200 radiocarbon years BP (between about 9800 and 10,300 calibrated years BP). The cave was above sea level throughout the oxygen isotope stage 3.

[3] Department of Geology, ANU

[4] Department of Nuclear Physics, RSPhysSE, ANU

[5] CEREGE, Universite d'Aix-Marseille III, CNRS, France

Constraining late glacial ice in the Ross Embayment

J.M. Quinn, K. Lambeck and J.O. Stone[a]

A number of different dating methods have been applied to the isostatically-raised shorelines of McMurdo Sound, in the Ross Sea, Antarctica. AMS ^{14}C dating of molluscs and penguin eggshell from within raised deltas and beaches have been combined with a recently published dataset to form a relative sea-level curve for the Scott Coast of McMurdo Sound. OSL dating in progress, is indicating a Holocene age for the same beaches and is in agreement with the radiocarbon dating.

Surface exposure dating of the beach boulders, bedrock platforms and boulder pavements using the isotope chlorine-36 has also been carried out. The results from this dating show an age progression with height from sea level but with a component of earlier exposure. These field results have been combined with forward modelling of the isostatic rebound of the coast in response to changes in ice loading, to determine possible end members of ice volumes for Antarctica in Late Glacial times, specifically in the Ross drainage basin. The starting point for these models has been to use a recognised maximum model (Denton and Hughes 1981) in which ice extends out to edge of the continental shelf, and a minimum model with less ice from Huybrechts. Modification of these two models for the Ross Embayment area predict relative sea-level curves for McMurdo Sound which are compared to the field results to develop a suite of possible ice models for the Ross drainage basin. Ice melting from the area of Antarctica outside of the Ross drainage basin has a minimal isostatic rebound effect in McMurdo Sound. The results show the importance of knowing the timing of melting as well as the regional ice volume. Sites at a distance from Antarctica can help constrain melting times. Using a melting scenario similar to the Northern Hemisphere ice sheets, only about 50% of the maximum model ice volume for the Ross drainage basin area is required.

Inference of ice sheet history

P. Johnston and K. Lambeck

Sea-level observations from sites close to the ice sheets of the last ice age contain information on the glacial history of these regions and the Earth's response to glacial loading. If the Earth's rheology is well known, the observations can be used to estimate the ice thickness through time. However, many different glaciation histories are capable of producing a given set of observations, so an extra criterion is required to select the best model from all possible models. Previously, the best fitting model has been selected from the population of adequately fitting models. But the best fitting model is usually unrealistically rough and introduces spurious details into the inferred model not warranted by the observations. Instead, we have developed a method of selecting the smoothest model which adequately fits the sea-level observations. Also, near the edge of large ice sheets, and for smaller ice sheets, some mountains protruded through the ice at the Last Glacial Maximum as nunataks. Trimlines marking the boundary between glaciated and unglaciated terrain can be observed in the field and their elevations are used as constraints on the maximum elevation of ice during the last ice age.

The above method has been applied to 441 sea-level observations from the British Isles dating back to 15,000 years ago. The extent and timing of the retreat of the British ice sheet was compiled from field data and digitised onto a 50 km grid at 1000 year intervals from 27 to 13 thousand years ago for a total of 2077 model parameters. The model with the smoothest elevation which fits the sea level data with a root mean square error of 1.3 and fits all of the trimline observations is shown in Figure 4. The ice heights are shown for every second time step and the maximum elevation of ice in Scotland is about 1500 m. The fact that a root mean square error of 1 is not possible with this earth model suggests that it may be possible to infer mantle viscosity with this method as well as the ice sheet history. Such an estimate would be

[a] Department of Geological Sciences and Quaternary Research Center, University of Washington

more robust because it would not depend necessarily on the assumed ice distribution as is the case for previous inferences of earth rheology.

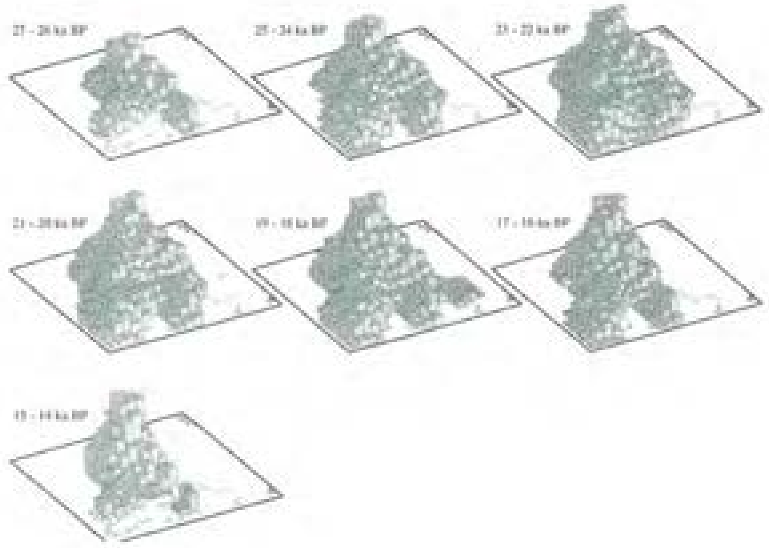

Figure 4: Minimum roughness ice elevation model inferred from sea level and ice elevation observations in the British Isles.

Mantle dynamics, postglacial rebound and the radial viscosity profile

G. Kaufmann and K. Lambeck

We infer the radial viscosity structure of the Earth's mantle from observations of the long-wavelength geoid and glacially-induced sea-level changes, changes in the Earth's rotation and gravitational field. We employ a combination of forward and formal inverse modelling of long-term mantle circulation driven by large-scale density differences deduced from seismic tomography. Based on the resulting unscaled mantle viscosity profiles, we model the time-dependent glacial isostatic adjustment of the Earth related to past and present changes in the ice-ocean mass balance and we deduce scaled mantle viscosity profiles, which simultaneously fit the long-wavelength geoid constraint and glacially-induced changes of the Earth's shape.

Two mantle viscosity profiles fit the observational data equally well (Figure 5). Both profiles are characterised by a two order of magnitude variation of viscosity within the Earth's mantle. Variations of viscosity in the upper mantle are less than one order of magnitude. In the lower mantle, the viscosity differs significantly with depth for both models. The first model is characterised by a rather smooth variation in viscosity across the 660 km seismic discontinuity, and viscosities increase towards the central parts of the lower mantle, then they decrease again towards the core-mantle boundary. Average viscosities in the upper and lower mantle are around 1×10^{21} and 3×10^{22} Pa s, respectively. In the second model viscosity jumps by two orders of magnitude across the 660 km seismic discontinuity, and peak values in the lower mantle occur around 1000 km depth. Below, viscosity decreases towards the central parts of the lower mantle, and increases again closer to the core-mantle boundary. Average viscosities in the upper and lower mantle are around 5×10^{20} and 8×10^{22} Pa s, respectively.

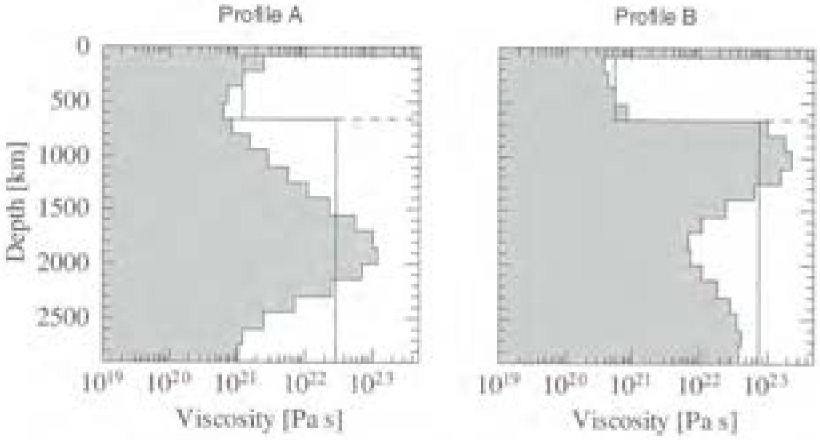

Figure 5: Preferred viscosity profiles derived from this study. The thick dashed lines indicate the volume-averaged upper- and lower-mantle viscosity values, the thin dashed lines represent the 660 km seismic discontinuity.

Glacial isostatic adjustment in Fennoscandia on a laterally heterogeneous Earth

G. Kaufmann, P. Wu[1] *and G. Li*[1]

Glaciation and deglaciation in Fennoscandia during the last glacial cycles has significantly perturbed the Earth's equilibrium figure. Changes in the Earth's solid and geoidal surfaces due to external and internal mass redistributions are recorded in sequences of ancient coastlines, now either submerged or uplifted, and are still visible in observations of present-day motions of the surface and glacially-induced anomalies in the Earth's gravitational field. These observations become increasingly sophisticated with the availability of GPS measurements and new satellite-gravity missions.

Observational evidence of the mass changes are widely used to constrain the radial viscosity structure of the Earth's mantle. However, lateral changes in earth model properties are usually not taken into account, as most global models of glacial isostatic adjustment assume radial symmetry for the earth model. This simplifying assumption contrasts with seismological evidence of significant lateral variations in the Earth's crust and upper mantle throughout the Fennoscandian region. On the assumption that the short-term seismologically-inferred variations in Earth properties are at least in part related to long-term viscosity variations, we deduce a three-dimension viscosity structure for our model calculations.

We compare predictions of glacial isostatic adjustment based on a realistic ice model over the Fennoscandian region for the last glacial cycle for both radially symmetric and fully three-dimensional earth models. Our results clearly reveal the importance of lateral variations in lithospheric thickness and asthenospheric viscosity for glacially-induced model predictions. Relative sea-level predictions can differ up to 10–20 m, uplift rate predictions by 1–3 mm yr, and free-air gravity anomaly predictions by 2–4 mGal, when a realistic three-dimensional earth structure as proposed by seismic modelling is taken into account.

[1] Department of Geology and Geophysics, University of Calgary, Canada

Last ice age millennial scale climate changes recorded in Huon Peninsula corals

Y. Yokoyama, T.M. Esat, K. Lambeck and L.K. Fifield[1]

Uranium series and radiocarbon ages have been measured in corals from the uplifted coral terraces of Huon Peninsula, Papua New Guinea, to provide a calibration for the radiocarbon time-scale for times older than 30,000 years BP (before present). Diagenetically altered samples were eliminated through improved analytical procedures and quantitative criteria for sample selection. The base-line of the calibration curve follows the trend of increasing divergence of the radiocarbon timescale from calendar ages established by previous studies. Superimposed to this trend are four well defined peaks of excess atmospheric radiocarbon level (>200% relative to current levels). These peaks correlate with the timing of specific periods of reef growth at Huon Peninsula and appear to be synchronous with Heinrich events and concentrations of ice-rafted debris found in North Atlantic deep sea cores. Timing of these phenomena suggests the following sequence of events: An initial sea-level high (interstadial period) is followed by a large increase in atmospheric radiocarbon as the sea-level falls during the next phase of ice growth. Over ≈1800 years the atmospheric radiocarbon drops to below present ambient levels. This cycle bears a close resemblance to ice-calving episodes of Dansgaard-Oeschger and Bond cycles and the slow-down or complete interruption of the North Atlantic thermohaline circulation. The increases in the atmospheric radiocarbon levels are attributed to the cessation of the North Atlantic circulation.

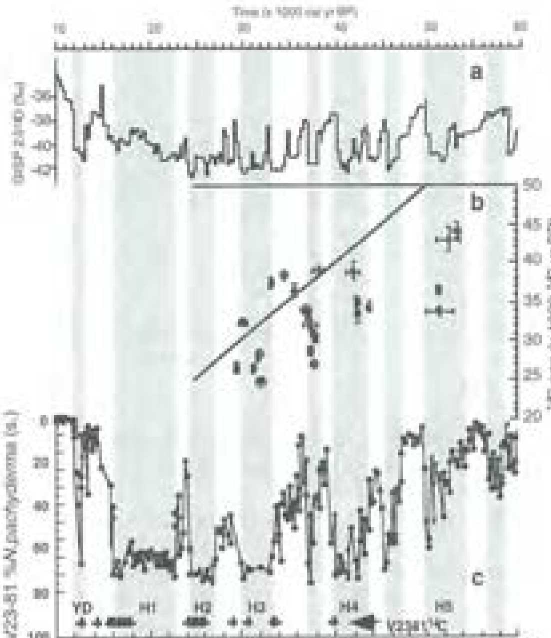

Figure 6: Four discrete $\Delta^{14}C$ peaks found in the present study (b) are coincident with Heinrich events (H) found in the North Atlantic Sea Surface temperature record (c: after Lund and Mix 1998) and temperature fluctuations appeared in the Greenland ice core record (a). U/Th dated $\Delta^{14}C$ peaks can defined exact timing of H3, H3.5, H4, and H5.

MODELLING OF TECTONIC PROCESSES AND LANDSCAPE EVOLUTION

The OZBLOCK project: a thin-plate model of Palaeozoic deformation of the Australian lithosphere.

J. Braun and R.D. Shaw[a]

We have developed a thin-plate model of the continental lithosphere in which deformation is driven by in-plane forces originating along plate boundaries. The geometry of the model, the strength of each lithospheric block, and the boundary forces have been chosen to reproduce the major tectonic episodes experienced by the Australian continent during a 200 Myr time period starting in the Ordovician (ie 470 Ma). The model's focus is on the reactivation and/or reworking of zones of weakness within the continent that have either been set a priori or have developed in response to previous tectonic regimes.

The tectonic history of the Australian continent has been used as a natural laboratory to test hypotheses on the nature and style of intracratonic defomation. We demonstrated that intracratonic deformation (ie deformation that takes place away from active plate boundaries) results from the concentration of horizontal stress originating at plate boundaries into regions of decreased lithospheric strength; these weak zones are often caused by previous intracratonic deformation and/or develop at the interface between regions of contrasting strength. We also showed that repeated episodes of deformation may lead to strain localization. Concentration of strain in narrow corridors may also result from the constructive interaction between two sets of tectonic forces acting on separate margins. Our study also demonstrated that there are mechanisms that operate within the lithosphere (such as post-extensional mantle healing) by which deformation leads to local strengthening.

Numerical modelling of strain localisation in the mantle lithosphere

S. Frederiksen[b]*, J. Braun and S.B. Nielsen*[b]

Deep seismic data from the Central Graben in the North Sea (see Figure 7) shows dipping reflectors in the upper mantle. It has been debated whether these features are traces from a subduction zone or shear zones developed during extension. Joint inversion of seismic (MONA LISA) and gravimetric data gives a good constrain on the outline of the basin and the crust beneath.

Using numerical models developed at RSES, we have shown that large-scale shear zones can develop in the mantle lithosphere when strain softening takes place during lithospheric extension and rifting. The development and geometry of the shear zones depends on the value of model parameters such as the assumed geothermal gradient, the rate of extension and the assumed pre-extension crustal thickness. Furthermore results show that the deformation pattern in the lithosphere can be strongly affected by the strength of the syn-extensional sediments.

[a] Australian Geological Survey Organisation
[b] Department of Geophysics, University of Aarhus, Denmark

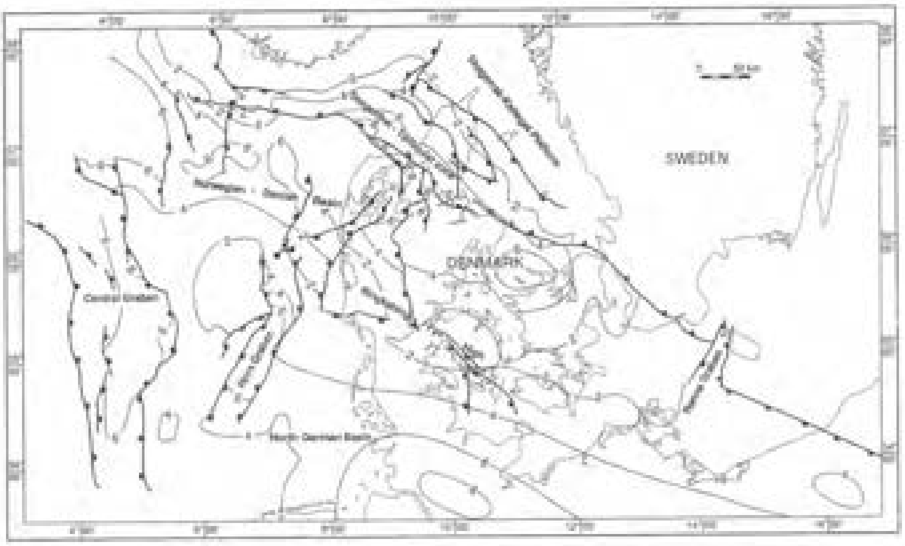

Figure 7: The main tectonic and structural features in the Danish and surrounding area. Isolines shows the depth in kilometers to the pre-zechstein surface.

Numerical models of faulting during crustal compression

D.R. Burbidge and J. Braun

The long-term evolution of the mechanical behaviour of the crust under compression (eg in accretionary wedges and fold-and-thrust belts) has always been difficult to model with traditional physical and numerical methods. This is primarily due to the large amounts of strain localization that characterizes the upper brittle crust (ie faulting). A new type of numerical method (the Distinct Element Crustal Model, or DECM) has been developed over the last few years which allows us to study problems involving substantial amounts of strain localization, even after large accummulated strain.

A large range of numerical experiments have been conducted to better understand the behaviour of brittle-frictional crustal material accreting against a rigid backstop. This could (for example) correspond to a sedimentary layer being accreted against stronger material (the continental basement) at a subduction zone. Two types of behaviour were observed, which depend mainly on the value of the basal friction coefficient. For low basal friction (eg a weak or wet base), the deformation occurs mainly by frontal accretion and the formation of so-called "pop-up structures" (Figure 8a). For high basal friction (strong base), the deformation is primarily accommodated by accretion near the back of the sedimentary pile following basal underthrusting under a flat-ramp fault (Figure 8b). At intermediate values of the basal friction, the behaviour of the accreting sedimentary wedge oscillates between these two modes (Figure 8c). Both end-member behaviours can be observed at subduction zones, and the oscillation between the two could explain observed changes in slope along the strike of some accretionary wedges (eg the Alaskan accretionary prism).

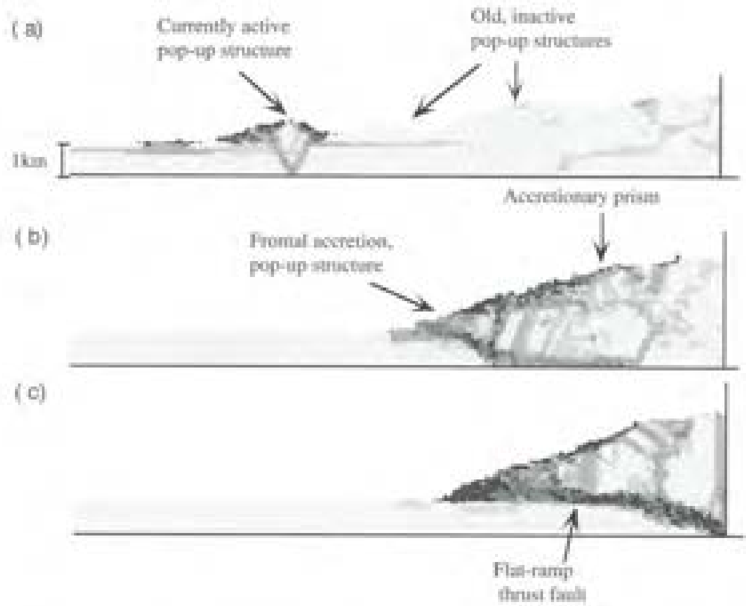

Figure 8: Three models illustrating the different faulting behaviour for three accretionary prisms with three different basal frictions: (a) low friction (basal co-efficient of friction (μ_b) of 0.2, (b) high basal friction ($\mu_b = 0.8$) and (c) intermediate basal friction ($\mu_b = 0.5$). All models have the same element-element friction of 0.5. (a) is dominated by frontal accretion and the formation of pop-up structures, while (c) is dominated by underthrusting and uplift near the rear of the prism. (b) oscillates between the two modes (it is pictured during a period of frontal accretion). During periods of frontal accretion (b) undergoes normal faulting near the top of the prism. Synorogenic extension like this has been observed at the top of some accretionary prisms (eg Taiwan).

Landforming processes in a tectonically active region: a glacio-fluvial erosion model of the Southern Alps, New Zealand

J.H. Tomkin and J. Braun

The Southern Alps of New Zealand is a zone of tectonic activity, caused by the collision between the Pacific and Australian plates. For the last few million years, convergence across the plate boundary has not led to substantial growth of the mountain belt, suggesting that, in the South Island of New Zealand, rock uplift is in equilibrium with surface erosion. Although present-day surface erosion is dominated by landsliding of over-steepened valley walls and transport of debris by fluvial transport, it is well documented that, during the last two million years, the Southern Alps were affected by glaciations during which glacial abrasion must have played an important role in setting the equilibrium between uplift and erosion.

Previous geochronological studies based on fission track, K-Ar and Ar-Ar dating of surface rocks from the region have led to the formulation of a range of scenarios to describe this equilibrium. The distribution, amount and rate of uplift along and across the strike of the orogen are still matters of debate. By using a surface processes model that incorporates fluvial, hillslope and glacial erosion, we are able to test the validity of proposed uplift regimes. We have simulated a variety of uplift scenarios and produced quantitative estimates of the resulting denudation for a range of parameters of our surface processes model. In particular, we tested the relative importance of each land-sculpting process, as well as the effect of the observed asymmetry in precipitation. As an example, we show in Figure 9 the predicted topography from a model run at the peak of an assumed glacial maximum, with the overlying ice thickness denoted by the shading.

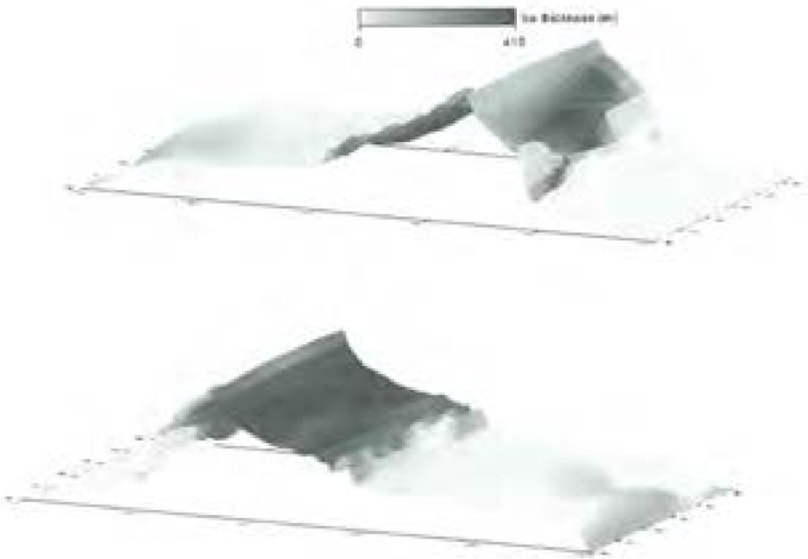

Figure 9: Two opposing views of the same simulated landscape. The shading represents ice thickness (the ice itself is not shown in the figure). Note the difference in topography between the ice covered and ice free regions.

Karst aquifer evolution in fractured, porous rocks

G. Kaufmann and J. Braun

The evolution of flow in a fractured, porous karst aquifer is studied by means of the finite element method on a two-dimensional mesh of irregularly spaced nodal points. Flow within the karst aquifer is driven by surface recharge from the entire region, simulating a precipitation pattern, and is directed towards an entrenched river as a base level. During the early phase of karstification, both the permeable rock matrix modeled as triangular elements and fractures within the rock matrix modeled as linear elements carry the flow. As the fractures are enlarged with time by chemical dissolution within the system calcite–carbon–dioxide–water, flow becomes more confined to the fractures. This selective enlargement of fractures increases the fracture conductivity by several orders of magnitude during the early phase of karstification. Thus, flow characteristics change from more homogeneous, pore-controlled flow to strongly heterogeneous, fracture-controlled flow.

Several scenarios for pure limestone aquifers, mixed sandstone-limestone aquifers are studied, and various surface recharge conditions as well as the effect of faulting on the aquifer evolution. Our results are sensitive to initial fracture width, faulting of the region, and recharge rate.

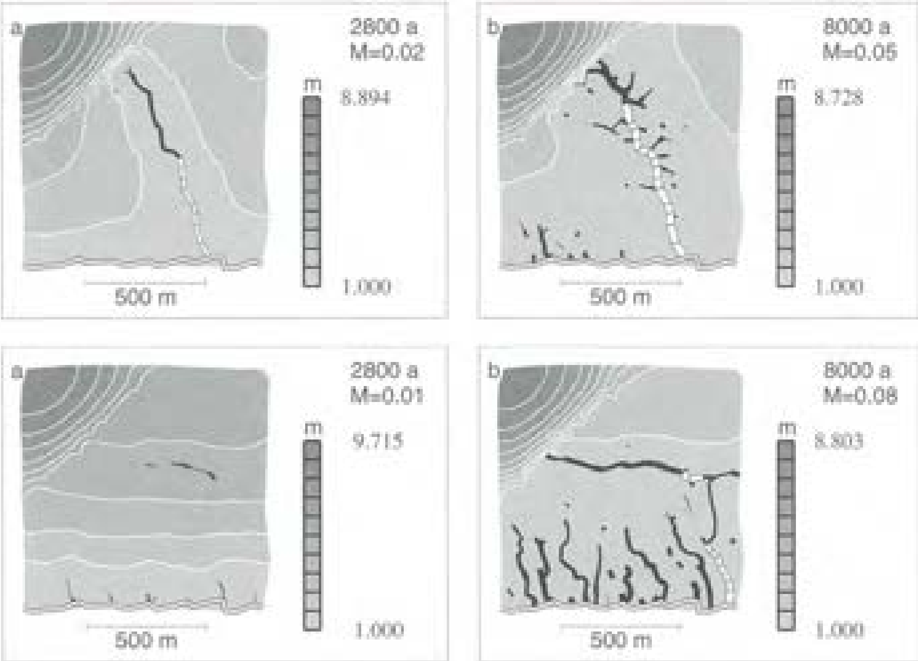

Figure 10: Enlargement of protoconduits in a sandstone-limestone aquifer by chemical dissolution. The hydrostatic head distribution in the aquifer is shown as greyscale image, with heads increasing from one meter along the base level (the double line representing a river) to around nine meter in the sandstone subdomain (top left corner). Enlarged fissures are shown as black boxes (laminar flow) or white boxes (turbulent flow). The initial protoconduits within the model domain have a diameter of 2 mm along a fault and 0.2 mm elsewhere. Shown are two time slices for an aquifer with a fault running from the sandstone subdomain to the river (top), and with a fault running approx. west-east and not connected to the base level (bottom).

PETROPHYSICS

The Group's approach is essentially that of materials science. We observe and seek to understand the physical behaviour of geological materials under controlled laboratory conditions, and then apply such insights to the structure and processes of the Earth. Measurements of macroscopic physical properties (e.g., strength, 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 geological materials is shared by members of the 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 magnitude 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, 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.

Major achievements for 1999 include

- exploratory experimental studies of the interplay between metamorphic devolatilisation reactions, pore-fluid pressure and permeability
- extension to 1300°C of capability for accurate measurement of elastic wave speeds by ultrasonic interferometry
- major advances in the study of seismic wave dispersion and 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 new 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 Petrophysics group has been providing leadership in the development of a higher profile for this university in materials science and engineering. Through their respective roles as Director of the Centre for the Science and Engineering of Materials (until December 1999), and Materials Science Coordinator on the Advisory Committee of the ANU Electron Microscope Unit, Drs I. Jackson and J. Fitz Gerald have been seeking to improve opportunities for research and training in this multi-disciplinary field. A new analytical TEM to serve the needs of the ANU materials science community was successfully commissioned this year. This instrument, housed within the School, is being operated by Dr J. Fitz Gerald and Mr D. Llewellyn on behalf of the ANU Electron Microscope Unit. In this capacity, Dr J. Fitz Gerald collaborates intensively in microstructural aspects of various materials science programs of the Research School of Physical Sciences and Engineering. In 1999 the Group maintained its strong commitment to the enrichment of undergraduate/graduate teaching.

A fourth-year course in *Materials Characterization* was once again presented primarily by Dr J. Fitz Gerald and Dr Z.H. Stachurski of the Engineering Department of the Faculty of Engineering and Information Technology.

The Group has this year substantially reshaped its staffing profile to better meet its current and future needs for research support. Following the departure of Senior Technical Officers Mr G.R. Horwood and Mr Z.R. Guziak, the Group recruited a Trainee Technical Officer (Mr J. Carr) and a Research Assistant (Ms L.J. Weston) with complementary responsibilities in support of the Group's research activity. The successful operation of novel equipment, and the development and exploitation of associated experimental techniques, depend heavily upon the skill and commitment of the these staff, along with Mr H. Kokkonen and the staff of the School's Mechanical and Electronics Workshops. Mrs K. Provins provides invaluable administrative support for the activities of the group and of the Centre for the Science and Engineering of Materials, now including responsibility for website development. The Group takes this opportunity to thank Mr G. Horwood for his many contributions during more than 20 years of committed service to the School.

HIGH-TEMPERATURE SEISMIC PROPERTIES OF EARTH MATERIALS

Inadequate knowledge of the temperature dependence of elastic wavespeeds for key high-pressure minerals continues to be a major barrier to the robust interpretation of seismological models for the Earth's interior in terms of chemical composition, mineralogy and temperature. Coherent polycrystalline specimens of the major transition-zone and lower-mantle phases have been successfully prepared during the past decade, and accurate measurements of the pressure dependence of their elastic wave speeds have been performed. Despite considerable progress in recent years with diamond-anvil based opto-acoustic techniques and with ultrasonic interferometry in multi-anvil apparatus, much less is known about the temperature dependence of elastic wavespeeds.

In addition, there are substantial uncertainties associated with extrapolation of experimental data generally obtained at *high frequencies* (MHz–GHz) into the realm of low frequency seismic wave propagation (mHz–Hz). Uncertainties in extrapolation are likely to be particularly important at high temperatures owing to the thermally activated mobility of point defects and dislocations and their interactions with grain boundaries.

In order to address these issues, we are extending to very high temperature (1300°C) our capability for elastic wavespeed measurement through high-frequency (10–100 MHz) ultrasonic interferometry. In parallel with such studies, direct access to the realm of seismic frequencies is accomplished by an apparatus, designed and built in house, that measures shear modulus G and the associated strain-energy dissipation Q^{-1} through torsional forced oscillation and microcreep tests.

High-temperature ultrasonic interferometry

S.L. Webb, I. Jackson, D.A. Boness[1] and L.J. Weston

We have developed a new experimental assembly for ultrasonic measurement of P- and S-wave speeds in polycrystalline samples at temperatures to 1300°C at 300 MPa within an argon gas-charged pressure vessel. A compound cylindrical buffer rod made of hardened steel, alumina and molybdenum components is used to isolate the piezo-electric transducer from the high-temperature high-pressure environment. Intimate contact between successive sections of the buffer rod and the sample, which are all enclosed within a thin-walled iron jacket, is ensured by the application across each optically flat interface of a normal stress equal to the confining pressure. This pressure also counteracts any tendency towards thermal cracking of the sample at high temperature. The mechanical coupling across each interface in the buffer rod assembly is

[1] Seattle University

improved by use of a one-micron vapour-deposited layer of gold at the 'cold' steel/alumina interface, and by three-micron thick iron foils at the 'hot' alumina/molybdenum/sample interfaces. The choice of the individual buffer rod materials was based both on the requirement for adequate contrast in acoustic impedance to ensure high amplitude reflections, and on thermal considerations. The sample mounted on the high-temperature end of the buffer rod is surrounded by a cylindrical 'cup' made of weak, pressure transmitting material (CaF_2) located within the sealed iron jacket.

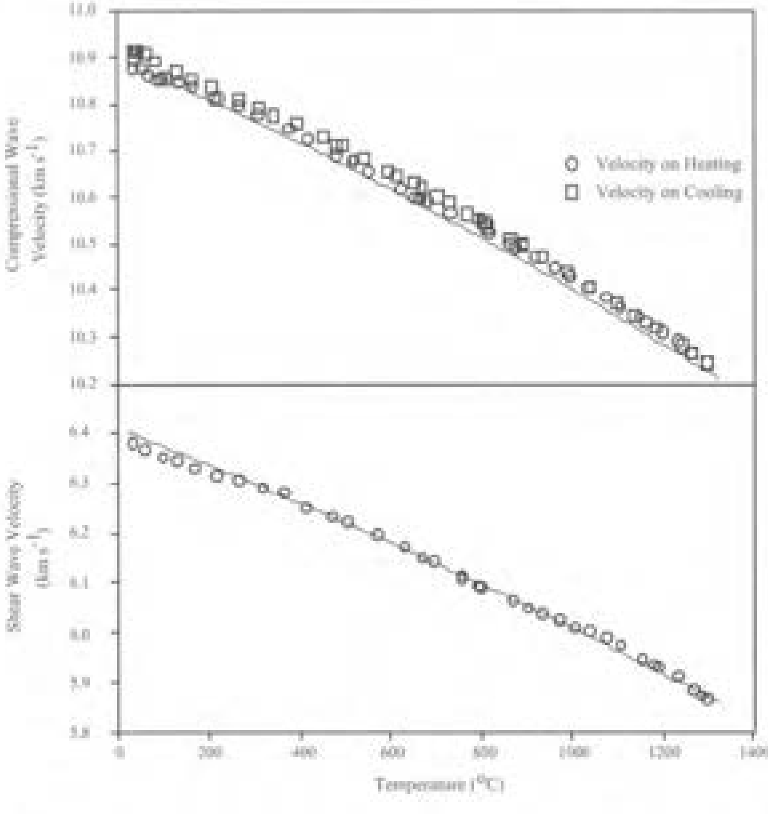

Figure 1: Compressional (a) and shear (b) wavespeeds for polycrystalline (Lucalox®) alumina determined by ultrasonic interferometry compared with the corresponding wavespeeds (solid lines) calculated from published single-crystal elasticity data (Goto *et al*., 1989).

The P- and S-wave speeds in polycrystalline Lucalox® alumina have been measured to 1300°C. Notwithstanding the excellent consistency between these results and expectations based on single-crystal data across the entire temperature range (Figure 1), the alumina specimen and the alumina component of the buffer rod were both found to be severely cracked on recovery at ambient pressure and temperature. The damage is attributed to high deviatoric stresses caused by the contrast in thermal expansion between Mo and Al_2O_3. A possible solution now being explored involves elimination of the Mo section at the high-temperature end of the buffer rod. The presence of the Fe foil along with departures from 'welded interface' boundary conditions has the potential to provide sufficient reflectivity at the buffer rod/sample interface.

High-temperature viscoelasticity in synthetic polycrystalline olivine: towards a mechanistic understanding of seismic wavespeeds and attenuation in the upper mantle

I. Jackson, J.D. Fitz Gerald, U. Faul, H. Kokkonen, J. Carr and B. Tan

Much of the variation of seismic wavespeeds and attenuation in the Earth's upper mantle is plausibly attributed to high-temperature viscoelastic relaxation in rocks composed mainly of the mineral olivine. Quantitative interpretation requires rheological data obtained under controlled laboratory conditions on well-characterised materials. In order to build a mechanistic understanding of high-temperature viscoelastic relaxation in such ultramafic materials, we have continued a program involving fabrication and characterisation of a suite of synthetic polycrystalline olivine aggregates and measurement of their mechanical properties at high temperature through a combination of torsional forced oscillation and microcreep tests. Specimens of composition Fo_{90} ($[Mg_{0.9}Fe_{0.1}]_2SiO_4$) have been fabricated from pellets of precursor powders by hot-isostatic pressing in an internally heated gas-medium apparatus typically for 25 hr at temperatures of 1200–1300° C and pressures of 200–300 MPa. Particular emphasis this year has been placed on the use of $Ni_{70}Fe_{30}$ containers conducive to the thermodynamic stability of natural Ni-bearing olivines, and the use of synthetic (solgel) as well as natural (San Carlos) precursors.

The hot-pressed specimens are typically texturally well-equilibrated dense polycrystalline aggregates with average grainsizes in the range 2–60 µm. They are generally of low dislocation density and contain low concentrations of impurity. In the materials of natural origin, trace amounts of CaO and Al_2O_3 are detected in the grain boundaries. Small amounts of glass (<< 0.1 vol %) representing melt formed at high temperature, are present mainly in grain-edge tubules. Local departures from ideal olivine stoichiometry are manifest as orthopyroxene and magnesiowüstite widely distributed in the synthetic material. Measurement in the forced oscillation tests of the amplitudes and relative phase of the applied alternating torque and the resulting angular distortion of the cylindrical specimen yield determinations of the shear modulus G and associated dissipation Q^{-1}, typically for oscillation periods of 1–100 s. Complementary information concerning the material response at longer periods and a measure of the recoverability of the non-elastic deformation are obtained from torsional microcreep tests to maximum strains of order 10^{-5}.

At relatively low temperatures T the response is essentially elastic and G(T) is closely consistent with expectations based on single-crystal elasticity data obtained at MHz frequencies with ultrasonic techniques (Figure 2). With increasing temperature beyond a threshold near 900°C, the behaviour becomes markedly viscoelastic with progressively lower and more frequency-dependent modulus, and associated strain energy dissipation. The proportion of the non-elastic strain that is recoverable (i.e. anelastic) decreases systematically with increasing temperature. The broadly similar behaviour of materials of similar grainsize fabricated from natural and synthetic origin, and tested in Fe and $Ni_{70}Fe_{30}$ containers respectively, stands in marked contrast to evidence for strong grainsize sensitivity among the specimens of natural origin fabricated and tested in Fe containers. It is tentatively concluded that trace element impurities and oxygen fugacity have much less influence upon the high-temperature viscoelasticity than does the variation of grainsize – consistent with control by diffusional processes. The (irrecoverable) viscous deformation is probably dominated by diffusion-accommodated grain-boundary sliding, whereas the recoverable anelastic behaviour is thought to originate in elastically accommodated movement (both normal migration and sliding) of grain-boundary segments with dimensions typically much smaller than the grainsize.

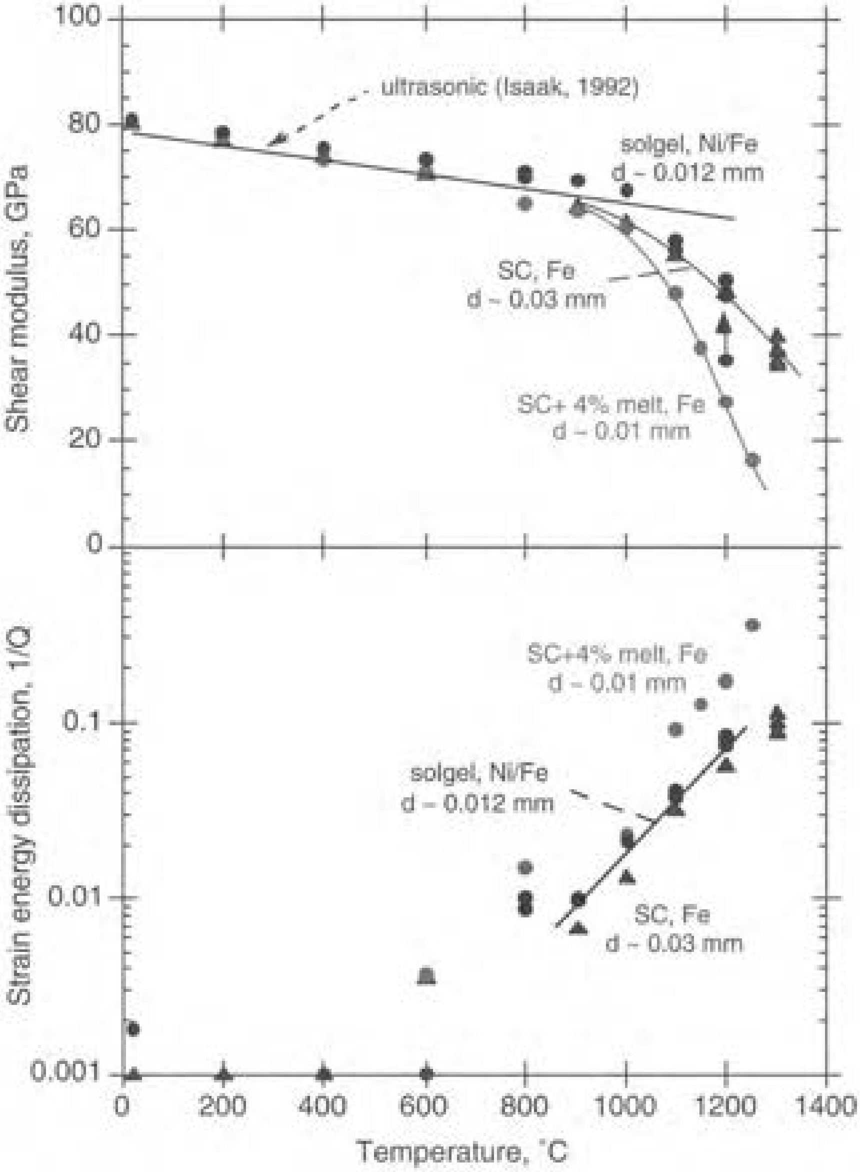

Figure 2: The variation of shear modulus and associated strain energy dissipation with temperature for various fine-grained Fo_{90} olivine polycrystals. Each dataset is labelled with the identity of the precursor ('SC' for San Carlos, or 'solgel'), the container material ('Ni/Fe' for $Ni_{70}Fe_{30}$, or 'Fe'), and the grainsize.

High-temperature viscoelasticity of polycrystalline MgO

S.L. Webb and I. Jackson

The lower mantle of the Earth is thought to be composed mainly of $(Mg,Fe)SiO_3$ perovskite plus (Mg,Fe)O magnesiowüstite, with $CaSiO_3$ perovskite next in abundance. Therefore, the study of the velocity and dissipation of seismic waves propagating through magnesiowüstite (and perovskites) is critical to our understanding of seismological models in terms of temperature and composition of the lower mantle. A comprehensive study of the calcium and strontium titanate analogues for the silicate perovskites was reported last year. This year MgO has been studied as the end-member of the magnesiowüstite series.

A relatively fine-grained polycrystal was fabricated by hot isostatic pressing MgO powder at 1300°C and 300 MPa for 4 hours. The sample had a Gaussian distribution of grainsizes ranging from 15–150 μm, with an average grainsize of 55 μm (Figure 3). The frequency dependence of the shear modulus and dissipation for a cylindrical specimen prepared from the hot-pressed boule were determined at 20–1300°C and 200 MPa confining pressure using the previously described torsional microcreep and seismic-frequency forced oscillation techniques. No change was observed in the modulus (±2 GPa) or dissipation (±10%) determined from the forced oscillation data at 1300°C over the 80 hour total exposure to temperatures above 1000°C. This is taken to indicate that there was no significant microstructural evolution during the course of the measurements.

The shear modulus G and dissipation 1/Q were determined as functions of frequency (10 mHz–1 Hz) and temperature during staged cooling from 1300°C to room temperature (Figure 4). Several distinct regimes of mechanical behaviour are readily identified. For 20 < T < 700°C (regime I), G is essentially frequency independent with a temperature derivative consistent with literature values from ultrasonic (MHz frequency) measurements, and 1/Q is relatively low.

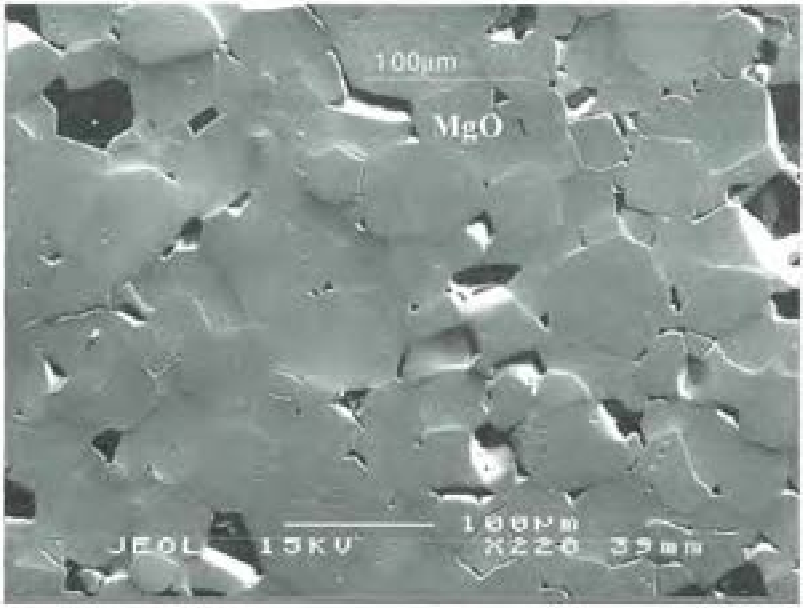

Figure 3: SEM micrograph of polycrystalline MgO sample revealing the distribution of grainsize and significant residual porosity.

Within regime II (700–900°C), the dissipation increases markedly with increasing temperature accompanied by progressively greater modulus dispersion. The largest values of 1/Q at least at short periods, and most strongly temperature dependent modulus are measured in regime III (900–1100°C). Within the upper half of this temperature range, a maximum in 1/Q is observed at short periods and G becomes less temperature sensitive. Finally in regime IV, both modulus and dissipation again become markedly more strongly temperature dependent.

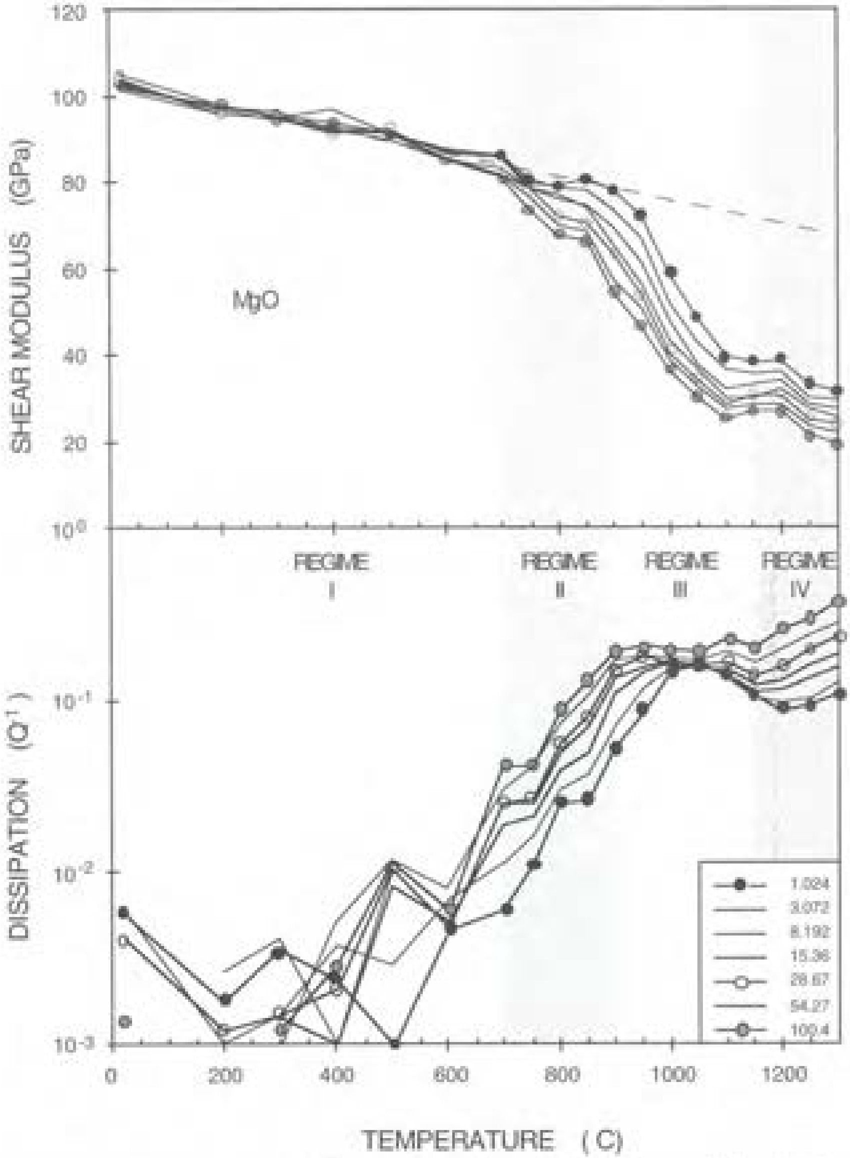

Figure 4: Frequency dependent shear modulus and associated strain energy dissipation for polycrystalline MgO as functions of temperature and oscillation period (in s). The four regimes of mechanical behaviour are indicated. The dashed line is fit to the frequency independent data in the temperature range 20–700°C.

Torsional microcreep data (Figure 5) provide key additional insight into this relatively complicated behaviour. For temperatures <1100°C, the non-elastic deformation is fully recoverable (i.e. anelastic) following removal of the applied torque. At higher temperatures, there is an irrecoverable viscous component that becomes progressively more important as the temperature increases. The plateau observed at 1100–1200°C in the G(T) data, and the peak/shoulder seen in the temperature dependence of 1/Q result from the transition between these two distinct types of mechanical behaviour, which are here more clearly separated in frequency-temperature space than is the case for other materials recently studied in our laboratory.

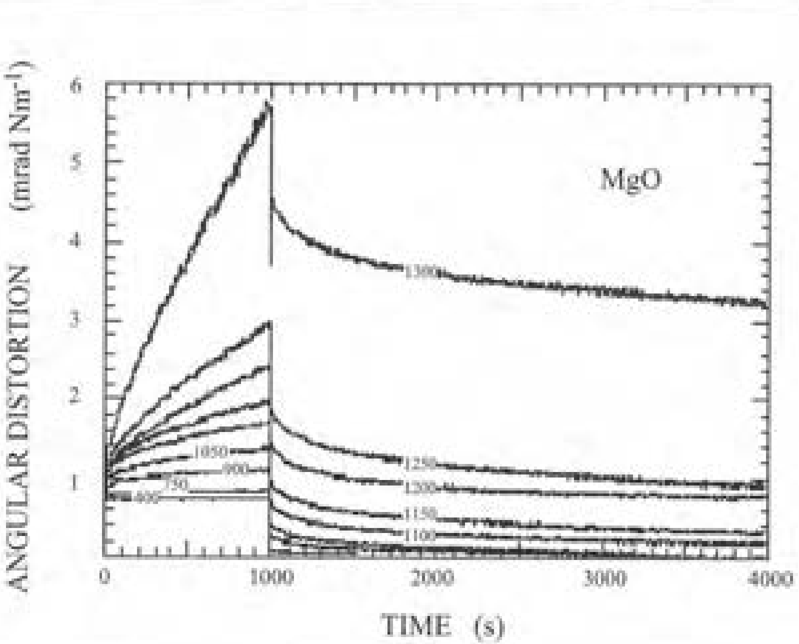

Figure 5: Torsional microcreep data for polycrystalline MgO. For temperatures ≤1050°C, the records show complete recovery following removal of the applied torque, whereas at higher temperatures, a progressively larger fraction of the strain is irrecoverable and therefore viscous in nature.

High-temperature viscoelasticity of amorphous SiO_2

S.L. Webb

The same torsional forced oscillation/microcreep methods have been employed this year in the preliminary phase of a major study aimed at characterisation of the influence of volatiles on magma rheology. The frequency dependent shear modulus and hence effective viscosity of amorphous SiO_2 (Suprasil® containing 1200 ppm water) have been measured over the frequency range 10 mHz to 1 Hz at temperatures to 1125°C under 200 MPa confining pressure.

Two distinct regimes are identified for the shear-mode properties of the specimen. At relatively low temperatures (20–700°C), the behaviour is elastic with a room temperature shear modulus of 29 GPa and a positive $\partial G/\partial T$ of 4 MPa K^{-1} in good agreement with previous studies of the temperature dependence of the shear modulus of SiO_2 glass at MHz frequencies. At the highest temperatures of this study (800–1125°C), strongly viscous deformation is observed with frequency-independent Newtonian viscosities of 10^{10}–10^{14} Pa s.

If the relaxation mechanism for silicate melts is viscous flow, the activation energy for flow can be determined from the position of the frequency dependent peak in the imaginary part of the shear modulus as a function of temperature. The activation energy calculated in this manner is 385 kJ mol^{-1}. This is slightly higher than the 309 kJ mol^{-1} calculated by Mills (1974) in his study of the frequency dependence of the viscoelastic properties of Suprasil®, but less than that determined in Hetherington *et al.*'s (1964) fibre elongation study of SiO_2 viscosity (548 kJ mol^{-1} for a SiO_2 melt containing 1400 ppm water, in the temperature range 900–1400°C).

The frequency dependent viscosity data collected at different temperatures can be plotted on a master curve as in Figure 6. The effect of temperature is removed by plotting the data as a function of the ratio of forced oscillation period to structural relaxation time. The relaxation time is taken from the data at 1050°C and calculated at higher and lower temperatures using the activation energy for viscous flow.

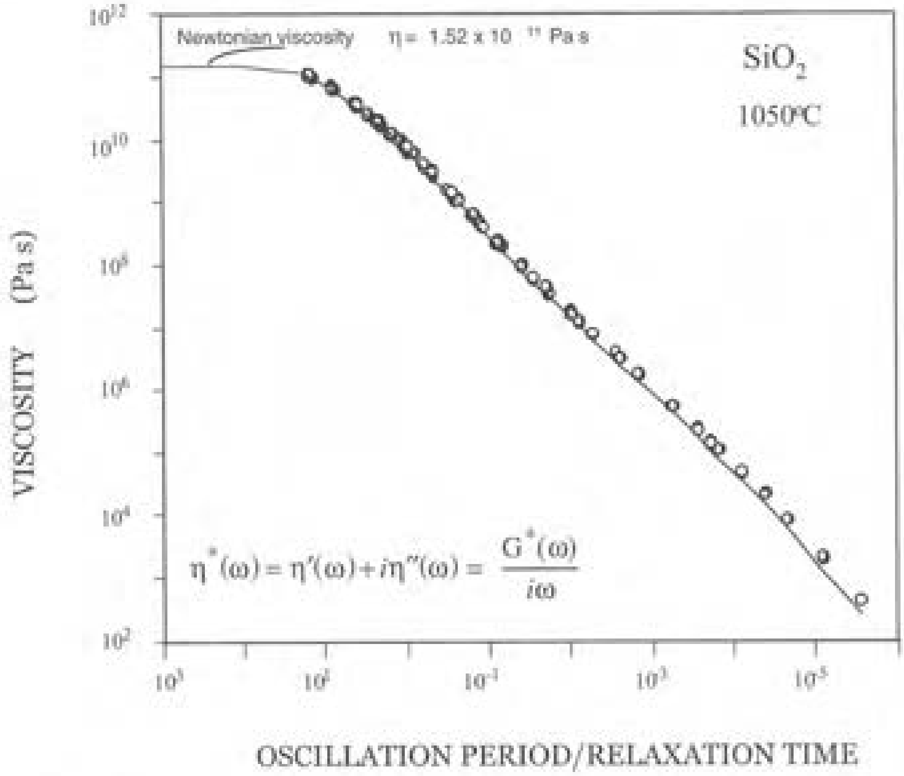

Figure 6: Real component of the frequency dependent viscosity of SiO_2 calculated at 1050°C from the activation energy and for an assumed relaxation time of 1 s at 1050°C.

FLUID-ROCK INTERACTION: LAB- AND FIELD-BASED STUDIES

Dynamic permeability during the water-infiltration-driven reaction Calcite + Quartz -> Wollastonite + Carbon Dioxide

S. Zhang, S.F. Cox and J.D. Fitz Gerald

Competition between permeability reduction due to plastic deformation and permeability increase due to decarbonation reaction was examined during hydrothermal hot-pressing of calcite – quartz aggregates. The starting materials are mixtures of 90 wt% calcite powder of 2–3 µm grainsize and 10 wt% quartz of grainsize either < 5 µm (mixture A) or 30–50 µm (mixture B). Mixtures were first cold-pressed in a copper jacket at an uniaxial stress of 100 MPa and then hot-pressed at 400°C and a confining pressure of 25 MPa for three hours. Hydrothermal experiments were conducted at confining pressures of 225 and 300 MPa, a water pore pressure of 200 MPa, and temperatures of 600°–850°C.

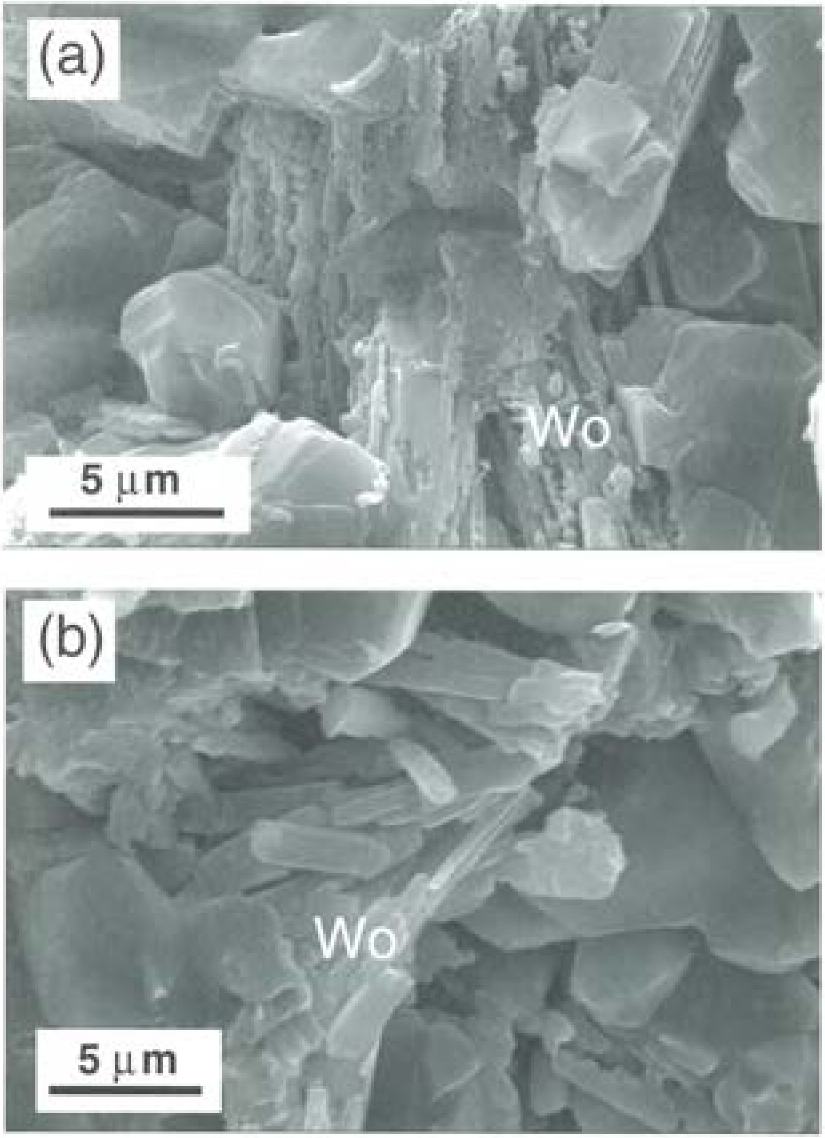

Figure 7: Formation of wallastonite aggregates at temperatures of (a) 600°C and (b) 700°C, confining pressure of 225 MPa, and pore water pressure of 200 MPa.

Under the experimental conditions, the release of carbon dioxide into the aqueous fluid phase is continuous. For mixture A, permeability remained at its initial value of about $10^{-16.5}m^2$ during 30 hours at 25 MPa effective pressure and 600°C. Radiating wollastonite aggregates fill irregular-shaped pore spaces (Figure 7a). During 8 hours subsequent exposure to 700°C, permeability decreased to about 10^{-19} m^2. Almost all quartz particles were consumed and wollastonite aggregates with tabular grain shapes are present along most calcite/calcite interfaces

(Figure 7b). At an effective pressure of 100 MPa, permeability decreased from 10^{-17} to about $10^{-19.5}$ m^2 over 30 hours at 600°C. Formation of wollastonite is limited. Further treatment at higher temperatures produces dense wollastonite aggregates on calcite surfaces and results in rapid decrease of permeability to $< 10^{-21}$ m^2. For mixture B at 25 MPa effective pressure and 600°C, permeability decreased by less than half an order of magnitude over 30 hours. Remnant quartz particles are surrounded by wollastonite fibres. Further treatment of the specimen at 700°C decreased permeability by one order of magnitude with the removal of all quartz particles and formation of porous wollastonite aggregates.

Our experiments demonstrate the importance of effective pressure in influencing reaction progress and permeability evolution during metamorphic reactions. The present experiments clearly suggest that many water-infiltration decarbonation reactions in siliceous carbonates must occur under near-lithostatic fluid pressure conditions where reaction kinetics can be very fast and the release of carbon dioxide.

Frictional sliding of granitic gouge material to large strain under hydrothermal conditions

S. Zhang, J.D. Fitz Gerald and S.F. Cox

Previous frictional sliding experiments on quartz and granitic gouge materials under hydrothermal conditions have revealed the role of dissolution-precipitation processes in reducing the apparent coefficient of friction by localising shear deformation along slider/gouge interfaces. Therefore it remains unclear how dissolution-precipitation processes affect the bulk frictional behaviour of gouge material. We have designed a double vertical shear assembly capable of shearing gouge material up to shear strains of 8 under hydrothermal conditions. Uniform shear deformation in this assembly occurs within the central third-to-half-width of the gouge layer.

We used crushed Westerly granite powder of grain size < 90 µm as starting material. Two layers of gouge each 0.5 mm thick are assembled between three alumina sliders. Axial compression of the assembly pushes the central alumina slab downward relative to the other two outer alumina sliders, thereby generating shear deformation within both gouge layers. The gouge material was first hydrothermally hot-isostatically-pressed at a temperature of 600°C, a confining pressure of 300 MPa and a water pore pressure of 200 MPa for about 8 hours. Shear deformation was at the same pressure and temperature conditions and at sliding velocities of 0.025–0.25 µm/sec. The friction coefficient reached a peak of 0.85 at a shear strain about 1 and then gradually decreased to about 0.7 with further sliding up to a shear strain of 8. During deformation, we measured permeability parallel to the gouge layer. The permeability initially decreased by about half an order of magnitude and then remained constant. Slide-hold-slide tests were conducted at large strains with hold period ranging from 32 sec to 10^{5} sec. Although there was significant permeability decrease during hold periods, there is no appreciable frictional strengthening with time for hold periods up to 10^{4} sec. However, frictional strengthening with time does occur with hold periods above 10^{4} sec. Severe grain crushing and the development of both Y and R shears as well as P foliation indicate deformation predominantly by cataclastic flow. Our results suggest that frictional strength of granitic gouge under high-temperature hydrothermal conditions is dominated by cataclastic flow.

Fluid-driven faulting processes in an intrusive-related hydrothermal system, Porgera, Papua New Guinea

S.F. Cox and S.M. Munroe[2]

Fault zones which host hydrothermal mineralisation were typically active structures which localised high fluid flux during ore genesis. Extensive three dimensional exposures provided by mining operations commonly make such structures spectacular natural laboratories in which to investigate deformation processes in faults, especially the role of fluid in controlling these processes.

The Roamane Fault Zone (RFZ) formed within an active hydrothermal system during cooling of the 6 Ma Porgera Intrusive Complex in the western highlands of PNG. Faulting occurred at temperatures around 200°C, and at a depth of approximately 3 km. The fault and its associated fracture systems localised the deposition of more than 350 t of Au. The extent of hydrothermal alteration associated with the RFZ indicates that the formation of this structure disrupted the pre-existing, intrusive-related hydrothermal flow regime and strongly localised fluid flow above, and at the southern margins of the intrusive complex.

The steeply SSE-dipping RFZ began with dextral strike-slip movement, but underwent a period of normal slip prior to reverting to a dextral strike-slip regime in the waning stages of the hydrothermal system. The fault is continuous along strike for at least one kilometre; the net slip has not been determined.

The principal displacement zone (pdz) of the RFZ comprises a core, up to 2 m wide, containing multiple generations of massive to banded cataclasite, wear breccia, and minor foliated cataclasite, injection cataclasite and veins. Localised polished slip surfaces are also present. A damage zone containing up to 15 m of coarse implosion breccia is present in the fault footwall. The intensity of brecciation decreases progressively away from the pdz. Repeated episodes of brecciation and multiple generations of cataclasite indicate episodic, probably seismic slip in the RFZ. Foliated cataclasites are interpreted to have formed during aseismic creep.

Early growth of the RFZ was associated with formation of steeply-dipping, WNW trending breccia-veins which splay predominantly from the pdz into the fault footwall. These structures are dilational normal faults, with lengths up to 200 m and net slips up to 30 cm. They are interpreted as wing cracks formed in association with dextral slip on the RFZ. Internal structures in breccia-veins indicate formation by wall-rock implosion into dilating fractures, driven either by concurrent slip on the pdz, or by rapid, aftershock-related fracture propagation from the tip of slip patches on the pdz.

Localised suprahydrostatic fluid pressures are interpreted to be a major factor initiating growth of the RFZ within an active hydrothermal system (Figure 8). Competition between episodic, slip-induced porosity-creation and interseismic hydrothermal pore sealing promoted fluctuations in fault zone permeability throughout the slip history. Associated repeated fluctuations in fluid pressure and shear stress must have influenced fault shear strength and rupture nucleation. Co-seismic dilatancy on the pdz, and possibly within the large footwall wing cracks, was potentially important in controlling rupture arrest.

[2] SRK Consulting

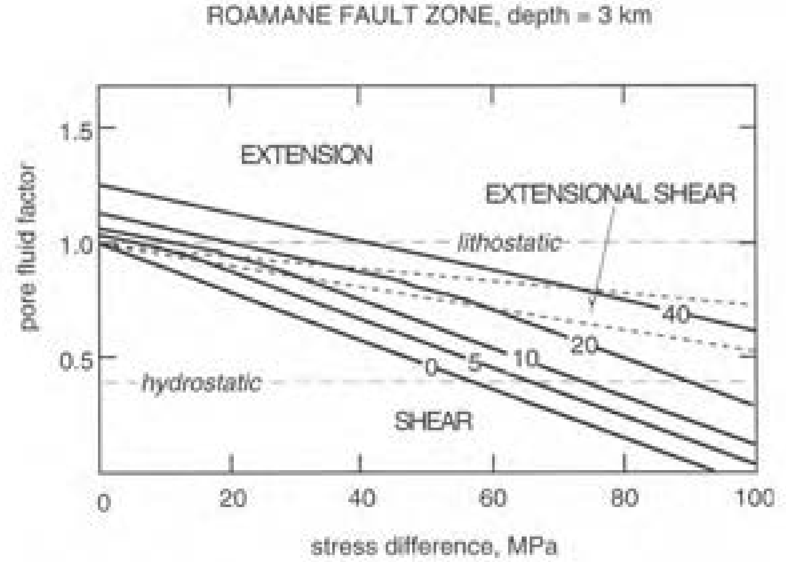

Figure 8: Failure mode plot as a function of pore fluid factor (ratio of pore fluid pressure to vertical stress) and stress difference, calculated for failure on the Roamane Fault Zone at a depth of 3 km. Failure criteria are plotted for faults with cohesive strengths ranging between 0 and 40 MPa. For likely stress differences in the range 40–50 MPa, fluid pressures in excess of hydrostatic are required to initiate shear failure on the RFZ. Extensional shear failure of the footwall wing cracks requires pore factors as high as 0.8 at stress differences of 40–50 MPa, or substantially higher stress differences at lower pore fluid factors. The latter option is consistent with the wing cracks nucleating (co-seismically, or as aftershock structures) from stress concentrations at the propagating tip of the principal displacement zone.

METEORITIC IMPACT RECORDS AND CRUSTAL EVOLUTION

Evidence is accumulating that terrestrial crustal evolution has been severely perturbed by post-3.8 Ga impact by large asteroids and comets, as predicted from the cratering flux in the solar system and increasingly borne out by the geological record. The research program summarized below includes (1) a search for distal impact fallout deposits in Archaean terrains, identified by spherulitic condensates from impact-released silicate vapor, and other mineralogical and geochemical relics these impacts in early Archaean sediments; (2) elucidation of possible impact origin of the Permian–Triassic boundary extinctions, and (3) study of Australian impact structures, notably the newly proven 120 km–diameter Woodleigh multi-ring impact structure of probable Late Devonian age, and the Late Eocene to pre-Miocene Carolyn strewn crater field, possibly reflecting cometary fragmentation or an asteroid breakup event.

Archaean extraterrestrial impact signatures

A.Y. Glikson

Three 3.26–3.24 Ga-old units of spherulitic condensates identified at the base of the Fig Tree Group, Barberton Mountain Land, eastern Transvaal, are characterized by marked PGE (platinum group elements) anomalies, quench-textured and octahedral resorbed Ni-rich chromites, iridium nano-nuggets, and negative 53Cr/52Cr ratios diagnostic of C1 chondrites. These units constitute the best-defined mega-impact cluster known in the Archaean record. Scanning electron microscopy coupled with energy dispersive spectrometry of Ni-chromites-bearing spherules (with G.R. Byerly and D.R. Lowe) indicate internal Ni zonation of the chromites; a follow-up study of the PGE is planned. Mass balance calculations of Ir and Cr, based on an assumed global distribution of fallout, can be used to estimate projectile composition and dimensions. For spherule unit S4 the model suggests projectile diameter >30 km, consistent with estimates based on vapor-liquid equilibria by Melosh and by O'Keefe and Ahrens. Crater size scaling suggests a >600 km-diameter structures, likely to have formed in a simatic crustal environment in view of the lack of shocked quartz fragments, thus constituting an Archaean terrestrial mare equivalent.

3.26–3.24 Ga events are also well recorded in the Pilbara Craton of Western Australia, including the Strelley Group which consists of komatiite, andesite, dacite and chert interbeds. This sequence is overlain by a yet-undated granitoid clast-bearing siltstone-banded ironstone sequence of the Gorge Creek Group. This break and the contemporaneous break between the Onverwacht Group (komatiite-tholeiite-felsic volcanic assemblage) and Fig Tree Group (turbidite-felsic volcanic assemblage) in the Barberton Mountain Land, represent fundamental changes from simatic to sialic volcanic-sedimentary facies. The onset of rifting and exposure of granitoids following the impacts suggest strong vertical tectonic movements, possibly related to Archaean mega-impacts. Modeling of the effects of very large impacts on thin thermally active oceanic crust overlying shallow asthenosphere predicts development of propagating lithospheric faults and regional to global magmatic and tectonic effects. The post-3.8Ga impact flux indicated by lunar cratering data and the modern asteroid and comet flux underpin the significance of these events for crustal evolution.

Woodleigh impact structure of probable Late Devonian age

A.Y. Glikson, A.J. Mory[1], R.P. Iasky[1], F. Pirajno[1], and T.P. Mernagh[2]

The impact origin of Woodleigh has been proved by drilling into both the ~25 km-diameter central granitoid uplift and the breccia-bearing >600 m-deep rim syncline. Petrological, SEM, EDS, and Laser Raman studies of samples from the shocked granitoid core demonstrate planar deformation features in quartz and feldspar, microbrecciation, pseudotachylite veining, and pervasive vitrification of feldspars. Pseudotachylite veins contain highly refractory micron-scale comminuted breccia and glass enriched in the refractory elements (Mg, Al, Ca) and depleted in relatively volatile elements (K, Si) (Figure 9). Experimental laser fusion/volatilization studies and systematic relations between chemical fractionation and boiling points suggest a role for shock-induced volatilization. High Mg levels (<4.0% MgO) and Fe levels (<2.0% FeO) in diaplectic amorphous inclusions within MgO-free feldspars constitute a distinct anomaly.

ICPMS analyses of shocked pseudotachylite-injected granitoid samples indicate that, while the lithophile and chalcophile trace metals (Pb, Sn, Wo, Mo, Bi, Ag, Sb, Zn, Cu, Au) vary by factors in the range of ×0.1 to ×10.0 relative to average granite (AG), the siderophile trace metals are strongly enriched, including V (<390 ppm; ×6–20AG), Cr (<125 ppm), Co (<48 ppm), and Ni (< 66 ppm). Ni/Cr ratios fall in the range 0.12–0.53, more similar to typical mantle pyrolite (Ni/Cr ~ 0.75) than chondritic values (Ni/Cr ~ 4.0). The evidence tentatively suggests introduction of a chondrite-contaminated component through volatile condensation and melt transport, represented by the pseudotachylites. Selective volatilization of the projectile and mixing with granitoid components may not allow direct identification of original meteoritic chemical parameters.

Stratigraphic age limits on the age of impact are defined by overlying lower Jurassic Woodleigh Formation circular basin sediments and by deformed middle Devonian sediments. Core samples from the central granitoid uplift yielded either Precambrian basement ages or signify post-impact alteration, as follows: (1) biotite yielded a Rb–Sr model age of 835 Ma determined by R.A. Armstrong, and K-Ar ages of 800–700 Ma determined by S.P. Kelley; (2) zircons yielded a range of Precambrian U–Pb ages determined by J. Smith; (3) K-feldspars

[1] Geological Survey of Western Australia

[2] Australian Geological Survey Organization

yielded ages mostly in the range of 180–130 Ma, younger than the overlying early Jurassic sediments, representing alteration; No K–Ar ages could be measured on the pseudotachylite veins, due to loss of K, among other volatiles determined by S.P. Kelly. Diamictites from the base of the inner ring syncline include clasts of shocked granitoid and siltstone fragments containing Sakmarian (Early Permian) palynomorphs. The ductile deformation of clasts and their injection by flow-textured matrix suggests thermal alteration. K–Ar isotopic analyses of illite and smectite from the diamictite yielded ages of (1) 364±8 Ma (551.9 m; 0.3–2.0 micron illite fraction); 352±8 Ma (585.2 m; <0.3 micron smectite fraction; (3) 342 Ma (586.9 m; <0.3 micron smectite fraction analysed by T. Uyssal. The apparent conflict between a Late Devonian impact age and the Early Permian diamictite clasts may be understood in terms of repeated vertical isostatic movements of the central granitoid core, with consequent erosion and re-deposition of the granitoid and overlying crater lake sediments, resulting in sedimentary mixing of different age components. The results corroborate the significance of the Late Devonian global impact cluster, which also includes Charlevoix (Quebec), Siljan (Sweden), Ternovka and Ilynets (Ukraine), Kaluga (Russia), and Elbow (Saskatchewan).

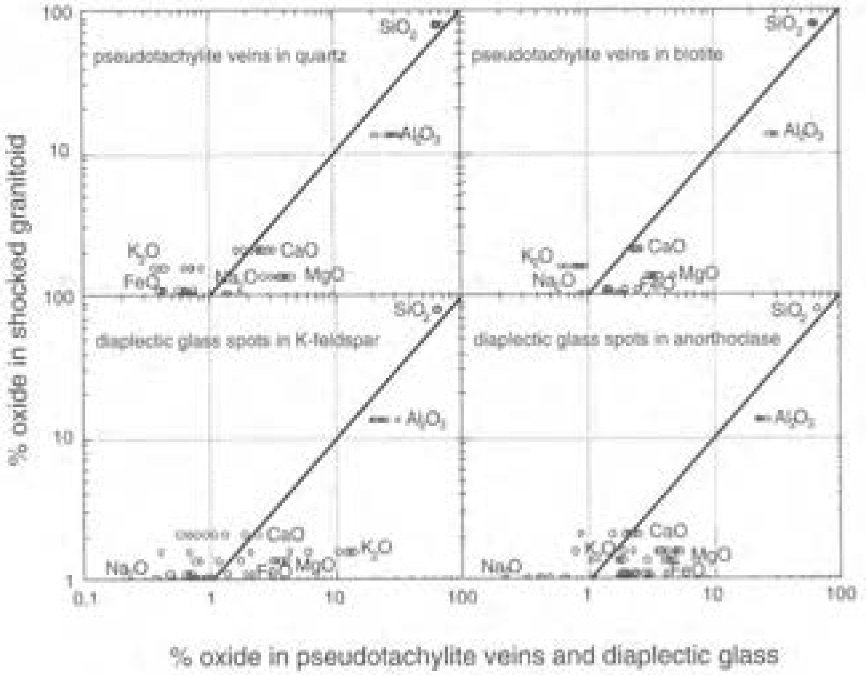

Figure 9: Plots of pseudotachylite veins (PTV) and diaplectic glass compositions (DG) versus mean scanned whole rock (WR) composition of shocked granitoid sample W149142 from a drill core of GSWA Woodleigh 1A well. MgO and Al_2O_3 show strong enrichment in PT and DG relative to WR, CaO is mostly enriched in PT and depleted in DG, SiO_2 is consistently somewhat depleted in PT and DG, K_2O is consistently depleted in PT and variable in DG, and Na_2O is variable in PT and consistently depleted in DG. The strong enrichement of the refractory MgO within feldspars and the general depletion in the volatile alkalies in peseudotachylite and in melt spots/streaks suggest a role for vapor fractionation and transfer.

The Carolyn crater field: SL9-type cometary fragmentation or asteroid breakdown?

A.Y. Glikson and J.D. Gorter[1]

The discovery of Fohn – a late Eocene to pre-Langhian (37.5_24 Ma) impact structure, northern Bonaparte Basin, Timor Sea, allows tests of the origin of an ENE-striking 120×25 km swathe of 43 analogous and smaller circular features excavated in the pre-Langhian erosional surface. Fohn forms a 4.8 km-diameter ring structure including a faulted central uplift, a circular rim syncline and a poorly defined raised outer rim. The rim syncline contains lower Miocene infill overlying a 350 meter-thick lens of melt breccia, showing high gamma counts and near-chondritic PGE anomalies and metal element ratios. The presence in the breccia of redeposited Campanian and Maastrichtian microfossils suggests rebound of strata from levels deeper than 1250 m below the pre-Langhian unconformity and places upper limits on post-impact erosion. Larger craters of the strewn field are structurally similar to Fohn. Smaller circular features (diameter < 2 km) include crater-form and bulge-form structures, and are interpreted as both original and eroded remnants of larger craters. Morphometric analysis of crater diameter-depth and diameter-central uplift relations indicate poor seismic definition of the crater floors and strong faulting of central structural uplifts. It is suggested the north Bonaparte Basin strewn crater field represents either a high impact flux of 3.8×10^{-10} impactors $km^{-2}.yr^{-1}$ (for craters ~2.0 km-large) during the period 37.5–24 Ma or, alternatively, a cometary fragmentation event or a low-angle asteroid breakdown event, possibly contemporaneous with the late Eocene global bombardment episode. The minimum pre-disintegration diameter of the projectile is estimated from Ir abundance as 800 meters. Platinum group elements and trace metal ratios in breccia samples suggest a chondritic composition of the parent body. An analogy with the Shoemaker-Levy-9 comet is suggested by the extensive fragmentation, the linear-to-back-scattered shape of the array of craters, and the chondritic composition.

[1] British-Borneo Australia Limited

PETROCHEMISTRY AND EXPERIMENTAL PETROLOGY

The Petrochemistry and Experimental Petrology (P&EP) Group uses the experimental investigation of chemical and physical processes 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 1800°C, several of which are equipped for precise control of oxygen and sulfur fugacities by gas mixing; nine solid-media piston-cylinder devices for generating pressures to 6 GPa and temperatures to 2000°C, 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, IR spectroscopy and visible-UV spectroscopy. This year a Major Equipment grant has been awarded to purchase a new ICP-MS; this analytical tool has become increasingly important to the group over recent years, and currently plays a significant part in many of the group's investigations. The group is making increasing use of X-ray absorption spectroscopy to characterise minerals and melts, using synchrotron radiation at the Australian National Beamline Facility at Tsukuba, Japan.

Most of the group's activities are concentrated into five areas: 1) Origin of the Earth and core formation; 2) Phase equilibria in mantle systems; 3) Phase equilibria related to crustal evolution and ore deposits; 4) Physics of melting and melt extraction; and 5) Spectroscopy and thermodynamic property measurements.

To constrain better models of core formation, Drs H. O'Neill and S. Eggins have investigated in detail the effects of silicate melt chemistry on siderophile element partitioning. These data should also be useful in evaluating the effects of melt composition on trace element partitioning behaviour. In the area of mantle studies, the group continues to focus on the role of chromium. Mr L. Xi has begun an experimental project investigating the effect of Cr on melting relations in the simplified mantle system CMAS-Cr_2O_3, while Dr A. Berry and several co-workers have used X-ray absorption spectroscopy to determine Cr^{2+}/Cr^{3+} oxidation states in silicate melts, and to search for Cr^{2+} in terrestrial minerals. Dr W. Taylor has used the laser-ablation ICP-MS to search for characteristic trace element patterns in diamond indicator minerals, as aids to diamond exploration; Mr C. Magee and Dr W. Taylor have used a wide variety of analytical methods to understand the origin of diamonds from unusual occurrences (ie, from other than kimberlites). Mr W. Lus and Professor D. Green continue their investigation of the mantle/crust contact exposed in the Papuan Ultramafic Belt. In the field of melt extraction, Drs U. Faul and S. Zhang report a pioneering permeability study using texturally equilibrated calcite as an analogue.

Dr J. Hermann and Professor D. Green continue their investigation of phase relations applicable to ultra-high-pressure metamorphic terrains. Drs J. Mavrogenes and A. Berry and Mr A. Hack are employing innovative experimental methods based on synthetic fluid inclusions to investigate ore-forming fluids both spectroscopically and thermodynamically in the supercritical regime. The experimental study of sulfur in silicate melts continues with a detailed investigation of the effects of melt composition on sulfide solubility. Dr S. Kesson has concentrated on developing expertise for the group in the field of powder X-ray diffraction using the Rietveld method.

The group contains five PhD students. Dr S. Klemme defended his PhD Thesis successfully earlier in the year, and Ms L. Hanley has completed her mid-term appraisal; her project is a study of the Antrim Plateau flood basalts of the Northern Territory.

This year the group hosted three Honours students from the Department of Geology. Mr M. Richardson used the laser ablation ICP-MS to study trace elements in diamond indicator minerals, and Ms S. Belfield used the same microanalytical tool to investigate chemical variability in melt inclusions in the Taupo volcanic sequence. Ms N. Douglas looked at Au-Bi phase relations in the hope of improving our understanding of gold deposits.

Of the technical staff, Mr M. Shelley has constructed a high-temperature furnace for X-ray absorption spectroscopy in silicate melts to 1450°C. Mr W. Hibberson has continued the development of the 6–7 GPa piston-cylinder apparatus, and has been extensively engaged in large-sample synthesis of high-pressure phases in the 30 mm piston-cylinder apparatus. Mr P. Willis continues in R&D for commercialization of the diamond and cubic boron nitride composites patented by the University. Mr N. Ware maintains and operates the group's CAMECA electron microprobe.

A spectroscopic determination of the oxidation state of chromium in silicate melts

A.J. Berry, H.StC. O'Neill, J.M.G. Shelley, D.R. Scott and W.O. Hibberson

In order to understand the partitioning of Cr in igneous processes it is necessary to identify the Cr^{2+}/Cr^{3+} ratio as a function of composition, temperature, pressure, and oxygen fugacity. There is evidence to suggest that the solubility of Cr in silicate rocks increases dramatically with temperature, possibly due to stabilisation of Cr^{2+}/Fe^{3+} in preference to the expected Cr^{3+}/Fe^{2+}. We have recorded K-edge X-ray absorption spectra at the Australian National Beamline Facility, Tsukuba, Japan, to quantify Cr^{2+}/Cr^{3+} in Fe-free quenched silicate glasses.

The most sensitive indicator of oxidation state was found to be the 1s→4s pre-edge transition. This transition is forbidden but may gain intensity through orbital mixing in low symmetry environments. For the coordination freedom available in a glass, the high symmetry octahedral geometry favoured by Cr^{3+} results in this transition being weak or absent. The transition becomes allowed in the Jahn-Teller distorted coordination common for Cr^{2+}. Features in the absorption edge are most easily identified in a derivative spectrum, with the Cr^{2+} 1s→4s transition appearing as a peak near 5997 eV. The intensity of this peak is directly proportional to the amount of Cr^{2+} in the sample.

It is apparent that a positive correlation exists between SiO_2 content and the capability of a melt to stabilise Cr^{2+}. The glasses exhibiting the highest degree of stabilisation are characterised by the most intense 1s→4s transitions indicating the lowest symmetry coordination environment. Cr^{2+} is also favoured by increasing temperature and decreasing pressure.

The effect of Fe relative to these results can only be determined from measurements at temperatures since on quenching Cr^{2+} oxidises in the presence of Fe^{3+} ($Cr^{2+} + Fe^{3+} \rightarrow Cr^{3+} + Fe^{2+}$). To do this we have designed and constructed a spectroscopy furnace from which spectra have been recorded at temperatures up to 1400°C.

This furnace has been tested with satisfactory results using an inert atmosphere of N_2. Future work will use CO/CO_2 gas mixtures to control fO_2 accurately.

The interpretation of hydroxyl stretching bands in the infrared spectra of mantle olivines

A.J. Berry, H.StC. O'Neill, S.E. Ashbrook[1], S. Wimperis[1] and M. James[2]

Nominally anhydrous minerals such as olivine frequently exhibit infrared absorption bands corresponding to structurally bound water. The amount of water is usually less than 200

[1] Physical Chemistry Laboratory, University of Oxford, UK

[2] Neutron Scattering Group, ANSTO

ppm but may be sufficient to accommodate the expected water content of the upper mantle. This has implications for a range of mantle physical and chemical properties. The number, energy, and relative intensity of the hydroxyl stretching bands, and the geological equilibration conditions they may represent, are all poorly understood. Natural samples generally exhibit broadly similar spectra although there is considerable variation which does not appear correlated with petrogenesis. To determine the chemical signature of these bands synthetic olivines are being prepared under conditions of varying silica activity, oxygen fugacity, temperature, and pressure.

In our experiments characteristically different infrared spectra are observed for samples synthesised in equilibrium with enstatite and magnesiowustite. Further, the spectra of most natural samples are different to those recorded from enstatite buffered experiments but similar to the spectra of samples equilibrated with magnesiowustite. It is also apparent in unbuffered experiments that the olivine water content increases with oxygen fugacity and that the resulting spectra resemble those of natural samples. Bands associated with iron have been identified by comparing spectra of synthetic olivine and forsterite.

The spectra of many natural olivines contain infrared bands that correlate with those of titanian clinohumite suggesting the possibility of water incorporation as a clinohumite type defect. Similarities also exist between the spectra of clinohumite and synthetic forsterite that indicate a possible generality of this defect structure. Samples of ^{17}O enriched clinohumite and chondrodite have been prepared and analysed by multiple-quantum magic angle spinning nmr spectroscopy. The expected number of oxygen sites can be determined including the distinctive hydroxyl resonance. It is hoped that the identification of this resonance in synthetic forsterite will help define the number and type of hydrogen coordination environments. Neutron diffraction patterns of clinohumite and deuterated clinohumite have also been recorded to allow correlation of the hydrogen positions with polarisation of the infrared spectra.

Permeability of texturally equilibrated calcite

U. Faul and S. Zhang

Processes important for the chemistry and dynamics of crust and mantle involve the movement of fluids and melts. In contrast to the upper few kilometres of the crust, deep movement of fluids take place at elevated temperatures, in a regime where significant solubility of the solid matrix in the fluid allows surface energy rather than random grain shape or compaction processes to determine pore geometry. Most permeability measurements however are made at room temperature on rocks characteristic of the shallow crust (eg sandstones) where textural adjustments driven by surface energy are minimal or absent and the pore geometry is highly irregular. Simple (isotropic) models of the pore geometry in texturally equilibrated rocks predict a completely regular pore space, and therefore much higher permeabilities than for upper crustal rocks. Recent analysis of the geometry of basaltic melt inclusions in an olivine matrix shows that the melt geometry is much more complex than predicted by the isotropic model. Permeability measurements on texturally equilibrated samples are therefore needed to resolve this discrepancy.

Since direct permeability measurements on partially molten systems are not possible at this point we equilibrated aggregates of high purity, fine grained calcite at 800°C and 1 GPa for six days in a 30 mm piston cylinder apparatus with varying amounts of water to generate a range of porosities. After quench the ends of the cylindrical samples were cut off, the remaining plug wrapped in shrink tubing and re-jacketed for the permeability measurements in a modified Paterson apparatus. The measurements were performed at different effective pressures from 25 to 75 MPa to ensure that quench-cracks are closed and do not contribute to the measured permeability.

As the permeability is directly related to pore structure, characterisation of the pore geometry is important for extrapolation of the measurements to partially molten systems. This is accomplished by processing backscattered electron images of vertical sections through the samples. Individual pores are approximated by ellipses which allows the overall porosity to be described by aspect ratio distributions (the ratio of the short over the long axis of an ellipse).

Figure 1 indicates that for calcite at low porosity the distributions are nearly Gaussian with a mean aspect ratio near 0.4, and a range from 0.1 to about 0.9. At higher porosities the distributions are skewed to low aspect ratios with slightly lower means. In comparison the olivine-melt sample has a distribution which is strongly peaked at the lowest aspect ratios (around 0.05) with an exponential drop to the maximum aspect ratio around 0.5. Overall the pore geometry in the calcite samples is much more regular than the melt geometry in olivine aggregates.

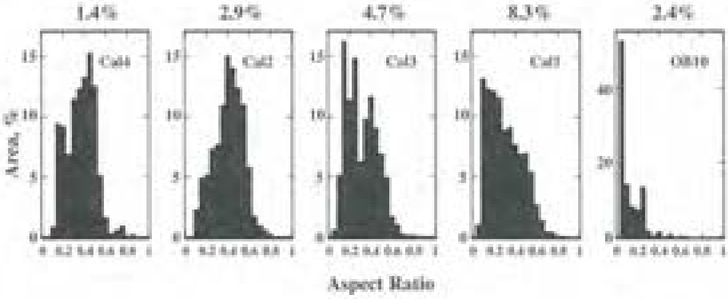

Figure 1: Aspect ratio distributions of four calcite samples with porosities ranging from 1.4% to 8.3%, and of a partially molten olivine aggregate for comparison. The bins in the histogram show pore area as percentage of the overall porosity for a given aspect ratio, indicating which type of pore shape contributes most to the porosity. The porosity is shown above each histogram.

The results of our permeability measurements as well as measurements by Wark and Watson and the permeability predicted from modelling by von Bargen and Waff are shown in Figure 2. One important difference between the calculations and the two sets of measurements is the exponent n in the permeability-porosity relationship. While the model predicts an exponent of two, resulting in relatively high permeabilities at low porosities (< 1%), the measurements yield an exponent of three or larger, which leads to a much steeper drop in permeability at low porosity. This difference in exponent indicates that the pore geometry is less regular than predicted by the isotropic model. The low porosity behaviour is important for melt segregation in the mantle, where the porosity is sometimes inferred to be as low as 0.1%.

As Figure 2 shows, our measured permeabilities are systematically lower by about two orders of magnitude than those of Wark and Watson. While our measurements were performed under high confining pressure using a steady state flow method with water as pore fluid, the measurements by Wark and Watson were conducted at ambient conditions using a transient air flow method. We tentatively attribute the higher permeabilities measured by Wark and Watson to incomplete closure of cracks produced during quench and the larger uncertainties of their method.

Our results indicate that despite the predictions of the isotropic model of disconnected pore space below porosities of 2.5% for the system calcite plus water the permeability remains finite. Similar systems, where the tendency for the development of facets is small and the pore space fairly regular, will therefore be permeable at relatively low porosities. Partially molten olivine aggregates, where faceted crystal–melt interfaces are much more predominant and the pore space therefore much less regular, will have lower permeabilities at low porosities, substantially lower than predicted by the isotropic model.

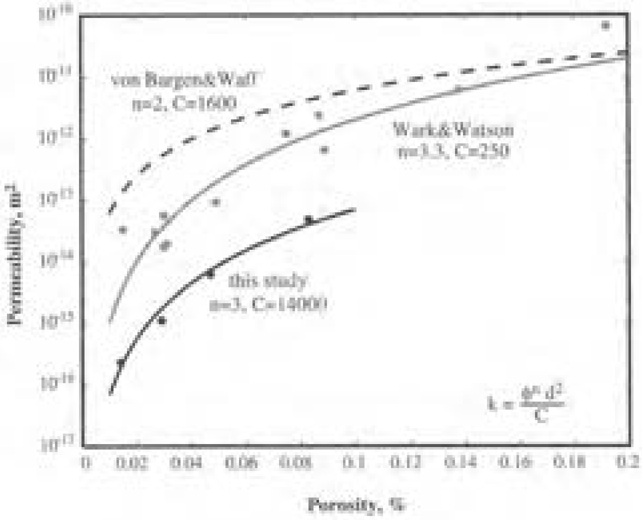

Figure 2: Comparison of two sets of permeability measurements on calcite with the permeabilities predicted from modelling by von Bargen and Waff. The permeabilities (k) are all normalised to a grain size (d) of 1 mm. The exponent n and constant C are obtained from a power law fit to the data. The equation relating permeability to porosity is shown on the bottom right.

Primary magmas and mantle potential temperatures beneath 'ridges' and 'hot-spots'

D.H. Green, S.M. Eggins[3], T.J. Falloon[4] and G.M. Yaxley

In volcanic centres, the identification of 'primitive' magmas of mantle derivation relies on the observation of the most magnesian phenocrysts of olivine and, if possible, of coexisting spinel, and the determination of the liquid composition in equilibrium with these phases. For primitive magmas derived from lherzolitic upper mantle, the phenocrystal olivine should have $Mg^\# \geq 89$ and the spinel should lie on the 'mantle array' from highly aluminous ($Cr^\# < 29$) to chrome-spinel ($Cr^\# = 70$). Recent data from Hawaiian tholeiitic volcanoes demonstrates that olivine phenocrysts of $Mg^\# = 89$-91 occur in picrites from six volcanoes and are responsive to host magma composition in Ca_2SiO_4 solid solution. The liquidus temperatures for these primitive magmas average 1354°C anhydrous or 1318°C if the effects of the water present in the magmas are included. A similar analysis of primitive MORB olivine-rich glasses or picrites with olivine phenocrysts of $Mg^\# = 91.5$-92.1, and of both N-MORB and E-MORB type, gives liquidus temperatures of 1345°C (anhydrous) or 1325°C if the effects of water present in the glasses are included. The evidence from the primitive magmas of 'hot-spots' and at mid-ocean ridges, is that there is no large temperature anomaly associated with 'hot-spots'. A mantle potential temperature of 1430-1450°C appears to be required for mid-ocean ridge, 'hot-spot', back-arc basins and convergent margin magmatism.

Although we do not find any evidence for contrasting temperatures between 'hot spot' and ridge magmatism, the differences in major element compositions (and thus in phase relationships in melting studies) are very significant. MORB picrites are inferred to be products of 15–20% melting leaving lherzolitic residues. In contrast, Hawaiian picrites clearly define harzburgite residues (Kilauea, Mauna Loa, Hualalai, Kohala and Koolau) or lherzolite to

[3] Department of Geology, ANU

[4] School of Earth Sciences, University of Tasmania

harzburgite (Loihi). Consistent with this difference, near-liquidus spinels from Hawaiian picrites have high Cr# (65–75) implying a refractory source/residue in contrast to near-liquidus spinels from MORB picrites.

The new information on Hawaiian primitive magmas confirms previous experimental investigations of Kilauean magmas which established high pressure liquidus fields for olivine+orthopyroxene, but not for coexisting garnet and clinopyroxene. These data argued for a relatively high degree of melting and a harzburgite residue, assuming a model mantle of lherzolite (pyrolite) composition. In contrast to the major element data and to experimental phase equilibria studies, the enrichment in LILE and particularly the LREE-enrichment and HREE depletion of Hawaiian olivine tholeiites relative to MORB tholeiites has been consistently interpreted as indicative of residual garnet, low degrees of melting and high pressures for melt extraction or segregation.

The Hawaiian 'plume source' is inferred to be a lherzolite to harzburgite bulk composition, more refractory in major elements (Mg#, Cr#) than the MORB source but with a pre-enrichment (re-fertilisation) history producing the LILE and LREE enrichment. The potential temperature of the plume source is 1430–1450°C, which matches the potential temperature for MORB sources. A possible model for the Hawaiian 'hot spot' volcanism has a composition and buoyancy anomaly at >100 km depth (arising from old subducted lithosphere with neutral buoyancy relative to ambient mantle). Volatile enhanced melting and extraction of melt from re-fertilised residual lherzolite to harzburgite can explain major element, trace-element and isotopic fingerprints of Hawaiian plume volcanism. The broadly constrained model calls for:

1. Refractory, subducted lithospheric slabs suspended in the upper mantle because of lower density than normal, fertile mantle (?MORB pyrolite). These should record earlier melt extraction events of >>100 million years and their temperature, initially below enclosing mantle, would slowly equilibrate with normal (MORB) mantle.

2. Within the inferred subducted slab and particularly near to old eclogite (altered oceanic crust)/peridotite boundaries, melting of subducted oceanic crust to produce rhyodacitic liquids and reaction of such liquids with enclosing harzburgite would produce refertilisation (orthopyroxene>garnet>clinopyroxene) of harzburgite, with minor and trace-element patterns reflecting rhyodacite liquid/eclogite residue partitioning. The protolith approaches homogeneity in mineral compositions but remains very inhomogeneous in mineral proportions.

3. A redox contrast is present between oxidised, old subducted slab and reduced ambient mantle (fO_2)~IW+1 log unit). In the presence of a (CH_4+H_2O) fluid from deeper mantle, incipient melting occurs in this interface region – the melt has the character of olivine nephelinite to olivine melilitite and its mobility may add further LILE and HFSE enrichment to the plume source.

4. Upwelling from this plume source region leads to increased partial melting along the adiabat – melt segregation occurs at ~60–80 km in the main cone-building stage. Melts are tholeiitic picrite, residues are harzburgite (Ol~Mg_{91}) and the degree of melting may be around 5-10% if the mean source composition is peridotite with 1-1.5% Al_2O_3, 0.8–1.1% CaO_3, Mg#~91.

A new SHRIMP zircon age for an Early Cambrian dolerite dyke from the West Kimberley - an intrusive phase of the Antrim Plateau flood basalts of Northern Australia

L.M. Hanley and M.T.D. Wingate[1]

The Antrim Plateau Volcanics are Australia's largest Phanerozoic flood basalt province and originally covered an area of at least 300,000 km^2 across northern Australia. The Antrim basalts are centred in the East Kimberley and Victoria River Region and include the stratigraphic equivalents, Nutwood Downs, Helen Springs and Peaker Piker Volcanics which are located in the central and eastern Northern Territory. Stratigraphic constraints suggest the Antrim Plateau Volcanics are of Neoproterozoic or Early Cambrian age (~580 Ma – 509 Ma), however previous attempts to date the Antrim basalts by radiometric methods have been unsuccessful. A new SHRIMP zircon age of 513±12 Ma has been obtained for the ~250km long Milliwindi dolerite in the West Kimberley. The dolerite is identical geochemically to Antrim Plateau basalts and was probably a feeder dyke for Antrim basalts that have since been eroded.

Geochemically the Antrim Plateau Volcanics and the Milliwindi dolerite exhibit depletion in the high field strength elements (Ti, Nb, Ta and P) relative to incompatible elements (Figure 3) and have elevated Rb, Th and Ba relative to primitive mantle. This signature is similar, but not identical to other low-Ti continental flood basalts and dolerites. Trace element and rare earth element (REE) abundance patterns for the Antrim Plateau Volcanics basalts and stratigraphic equivalents display remarkable homogeneity across northern Australia.

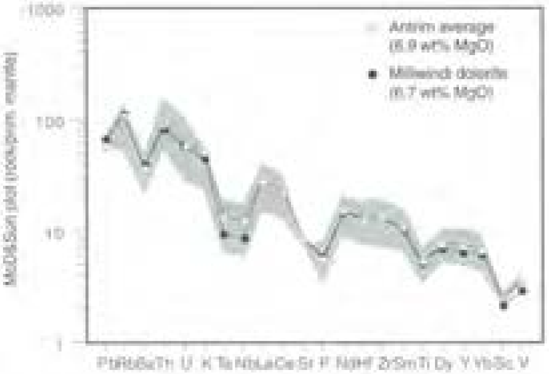

Figure 3: Primitive-mantle element abundance diagram (normalising values from McDonough and Sun, 1995). The shaded area represents the range between the most primitive and fractionated Antrim basalts.

Geochemistry of the Antrim Plateau continental flood basalts

L.M. Hanley

Representative samples of the Antrim Plateau Volcanics from across the breadth of northern Australia and also from a ~760m stratigraphic section in the East Kimberley, Western Australia, have been geochemically analysed by XRF (major elements) and laser-ablation ICPMS (trace elements).

The Antrim Plateau basalts have SiO_2 values ranging from 49 to 54 with a mean of 52 wt%. TiO_2 values are ~1 wt% with Ti/Y <300, classifying them as low-Ti tholeiites. MgO

[1] Tectonics Special Research Centre, Dept of Geology and Geophysics, University of Western Australia

values range from ~4 to 9 wt% and FeO_t values are typically 7.6 to 12 wt%. K_2O contents are higher in the more altered rocks, indicating mobility of this element. The FeO_t values are low compared with MORB and other continental tholeiites, such as the Deccan and Siberian Traps, but are similar to the Tasmanian Dolerite.

The basalts display well defined fractionation trends on plots of major and trace elements against MgO. However, the effect of crystal fractionation on the geochemical signature of the Antrim Plateau Volcanics is minimal as the abundance ratios between adjacent elements does not change significantly between the least and most fractionated samples.

In contrast to other continental flood basalts, the Antrim, the Tasmanian Dolerites and the low-Ti tholeiites of the Deccan Traps can be distinguished by their elevated Th/Nb ratio (Figure 4) reflecting involvement of a crustal component similar to Post-Archaean Terrigenous Shale or PATS. The remarkable similarity of the geochemical pattern of the Antrim Plateau Volcanics compared to PATS suggests involvement of a recycled crustal or sedimentary component in the mantle source region. Alternatively, the signature may involve high-level crustal contamination of the basalt via assimilation and fractional crystallisation (AFC) processes. Isotopic studies to distinguish these possibilities are currently in progress.

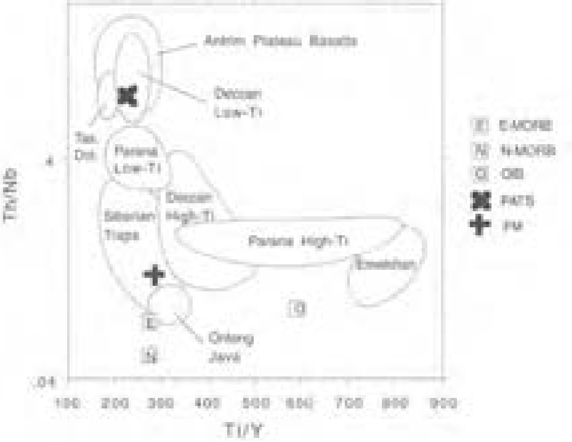

Figure 4: Trace element discrimination plots for major igneous provinces, Th/Nb v Ti/Y.

An inverse correlation between MgO and FeO_t is apparent. Evidence for alteration is represented by an increase in Na_2O, Al_2O_3 and MgO with accompanying decrease in CaO and FeO_t in sample 99PL040. Overall, it appears that the first phase of eruptive activity was more primitive (0-200m). This was followed by a period of fractionation in the magma chamber prior to eruption of an essentially homogeneous series of lavas (200-550m). There is more variability towards the top of the sequence (550-760m).

Geochemical variation within a ~760m stratigraphic section through the Antrim Plateau basalts at Purnululu National Park in the East Kimberley, has been investigated. In Figure 5, major elemental oxides are plotted against stratigraphic height.

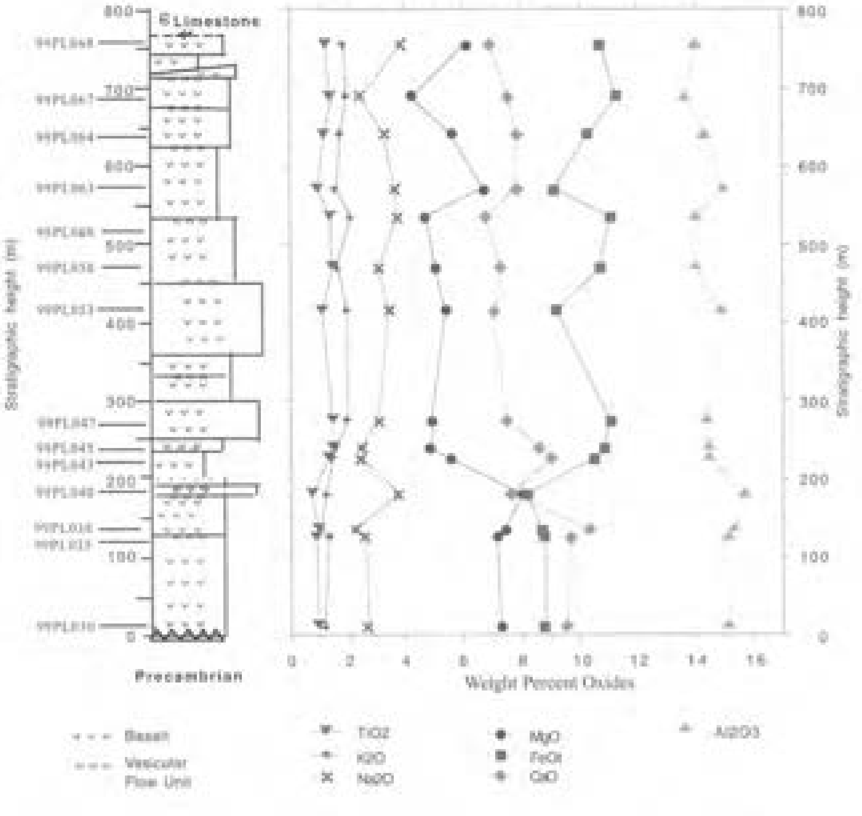

Figure 5: Purnululu Section for Antrim Plateau Volcanics – Major Oxide Variation

Experimental constraints on continental rocks in ultra-high pressure metamorphism

J. Hermann and D.H. Green

Exhumed ultra-high-pressure (UHP) metamorphosed rocks permit insights in the dynamics of subduction zones and are crucial for the understanding of convergent plate boundaries. Piston cylinder experiments in the range 700–1100°C and 2.0–4.5 GPa using gneissic to pelitic compositions were carried out in order to understand better the phase and melting relations in deeply subducted continental crust. The paragenesis coesite+kyanite+garnet+clinopyroxene+phengite is stable at UHP conditions in various rock types of the continental crust. The simplest chemical system to produce this paragenesis consist of K_2O-CaO-MgO-Al_2O_3-SiO_2-H_2O (KCMASH). The proportion of the elements was chosen in order to get saturation of kyanite and quartz/coesite.

Generally, five phases plus fluid/melt were present in the experiments in agreement with the phase rule indicating the absence of metastable phases. In the range 2.0–3.0 GPa and 700–900°C the paragenesis changed in small P-T intervals and is thus an excellent indicator for metamorphic conditions. A common feature in all parageneses is the absence of feldspars which may be used to define HP-metamorphism in gneissic to pelitic rocks. At pressure above 3.2 GPa, T<900–1000°C, the divariant parageneses coesite+kyanite+garnet+clinopyroxene+ phengite is stable over a significant P-T range.

Phengite, biotite, clinopyroxene and garnet display a systematic change in composition with P and T. The Si-content (pfu) of phengite changes from 3.3 at 740°C, 2.5 GPa to 3.55 at 720°, 3.5 GPa to 3.35 at 950°C, 3.5 GPa. The Si-content of biotite is also a pressure sensor and changes from 2.9 at 900°C, 2.0 GPa to 3.22 at 800°C, 3.5 GPa. The Al_2O_3-content of pyroxenes is mainly temperature dependent and increases from 1.5 wt% at 720° to 11 wt% at 1150°C, 3.5 GPa. The grossular content in garnet increases with pressure at T=1000°C from 17% (2.0 GPa) to 31% (4.5 GPa) and with temperature at P=3.5 GPa from 18% (900C°) to 29% (1150°C).

The stability of hydrous phases is very important because their break-down liberates fluids or melts which might be responsible for mass transfer from the slab to the mantle wedge. Amphibole was stable at T<750°C, P<3.0 GPa and clinozoisite at T<850°C, P<3.0 GPa. Below 3.0 GPa biotite has the highest thermal stability up to temperatures of about 900–950°C. At higher pressures biotite reacts to phengite which was stable at 950°C, 3.5 GPa and 1000°C, 4.5 GPa. Talc was observed at 720°C, 3.5 GPa. Melts resulting from the breakdown of the hydrous phases were granitic in composition.

White schists from the Dora Maira UHP-unit consist of quartz (ex coesite), kyanite, garnet, phengite and minor talc. The breakdown of talc to kyanite and garnet occurs at about 750°C above 3.5 GPa in the experiments. The measured Si content of 3.6 (pfu) in phengite indicates a pressure of about 3.8–4.0 GPa for the white schist formation. The Dora Maira UHP-unit represents thus a slice of continental crust which was subducted to about 120 km depth.

Stability of allanite to high pressure and temperature: implications for the LREE budget in subducted crust

J. Hermann

Dehydration and partial melting of subducted crustal material is an important process for mass transfer from the slab to the mantle wedge. This mass transfer is strongly dependent on the stable phases at the time of dehydration or melting. Synthesis piston cylinder experiments in the KCMASH system were carried out in the range 700–1150°C and 2.0–4.5 GPa. Rb, Sr, Ba, Y, Zr, La, Ce, Nd, Sm, Eu, Gd, Yb were added at a 100–300 ppm level. The addition of trace elements led to the stabilisation of allanite as an accessory mineral well above the determined stability of clinozoisite (Figure 6). Allanite is an epidote group mineral which can incorporate significant amounts of light rare earth elements (LREE). Allanite was stable at 4.5 GPa, 1000°C together with clinopyroxene, garnet, coesite, kyanite and phengite. Even above the fluid-absent melting due to phengite breakdown, allanite is present up to temperatures of 1050°C (Figure 6). However, the abundance of allanite decreases with increasing temperature parallel to an increase in melt volume. The partitioning of LREE between allanite and melt is in the order of D(allanite/melt) = 300 demonstrating that the LREE are highly compatible in allanite. Allanite has been found in several rock types of the Dora-Maira massif (Alps) which were metamorphosed at about 750°C and 3.8 GPa. Allanite coexists with garnet, omphacite, phengite, quartz (ex coesite) and rutile in eclogites and with and garnet, kyanite, phengite, quartz (ex coesite) and rutile in metasediments in agreement to parageneses produced in the experiments. This indicates that at about 120 km depth allanite is still stable in rocks of crustal composition.

The stability of allanite to unexpectedly high temperature and high pressure has important consequences for the composition of fluids/melts generated in the presence of allanite because allanite buffers the LREE contents of these melts. Already an abundance of 0.5% of allanite can increase the bulk rock/melt partition coefficient of an eclogite by about a factor of about 20. Allanite is stable at higher temperatures than the dehydration of phengite (Figure 6) which is an important water reservoir in subducted oceanic crust. The transfer of LREE from the subducted slab to the overlaying mantle wedge by melts/fluids originating from dehydration of subducted crust is thus restricted as long as allanite is stable.

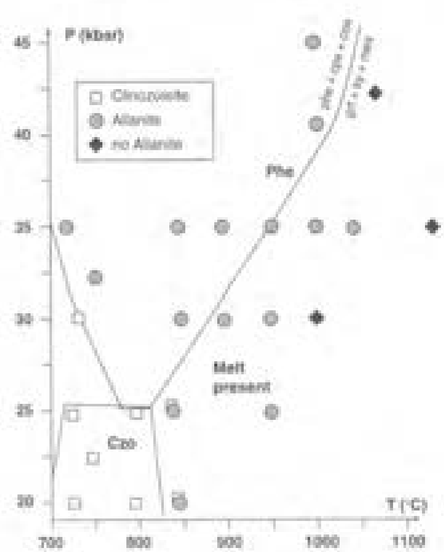

Figure 6: Runs with allanite present (dots) and clinozoisite stable (squares). White square indicates a run with only minor clinozoisite. The determined stability of phengite and clinozoisite are shown.

Metamorphic sole of the Papuan Ultramafic Belt (PUB) ophiolite: Field mapping, petrology, trace and major element geochemistry, geochronology, and experimental studies

W.Y. Lus, D.H. Green, I. McDougall, S. Eggins[1] and H.L. Davies[2]

An ophiolite is a fragment of oceanic crust and upper mantle produced at a mid-ocean ridge or a back-arc spreading centre which is exposed at a continental margin or in an island arc. The PUB ophiolite in southeastern Papua New Guinea is a large and well known section of former oceanic crust and upper mantle emplaced in the western Pacific marginal region at the collisional boundary between the Pacific and Indo-Australian plate. Detailed west-east transects along creeks in the Musa-Kumusi divide area by Lus (1994 and 1999) showed that the Emo Metamorphics grade into amphibolites which grade up into the granulites which grade up into or are in contact with the ultramafic base of the PUB ophiolite.

The ultramafics at the base of the PUB are both massive harzburgites, and banded peridotites consisting of lherzolite, pyroxenite and harzburgite layers. The harzburgites in the ultramafics have Fo[illegible] olivine but there are small and correlated differences in Cr/Al ratio of both spinel and orthopyroxene and in CaO content. The pyroxenes in the lherzolite are very Ca-rich diopside and co-exist with orthopyroxene with low CaO content, but higher than that of orthopyroxene in harzburgite. Temperature of equilibration by two pyroxene thermometry is 814–865°C, at 3 kbar. However, the Al_2O_3 content of both pyroxenes, the absence of plagioclase and the significant Al_2O_3 content of spinels in both the lherzolite and wehrlite suggest that the assemblages crystallized at pressures greater than olivine + plagioclase (anorthite) stability, ie ~6–8kb at 900°C. Hornblende is the dominant mineral phase in the granulites and amphibolites coexisting with olivine, orthopyroxene, clinopyroxene, plagioclase, ilmenite and magnetite. The hornblende grains in this group of rocks are characteristically reddish brown (Z & Y directions), but the intensity of colour is variable from pale to very deeply coloured and the typical Z-colours

[2] Department of Geology, University of Papua New Guinea

may vary from orange brown to deep green. The amphiboles in the granulites are titanium-rich and range in composition from magnesio-hornblende through pargasite to magnesio-hastingsite. In the amphibolites the amphiboles are magnesio-hornblende and actinolite at the amphibolite to greenschist boundary.

Lower SiO_2, CaO, Al_2O_3 and higher MgO, TiO_2, (Na_2O+K_2O), P_2O_5 contents of the granulites and the high MgO content and normative olivine (>10%) suggest that the sole granulites are essentially picritic in composition and are similar or transitional to the basic rocks of the Emo Metamorphics, and differ from the gabbroic rocks of the PUB ophiolite in lower TiO_2, lower Na_2O, higher Al_2O_3, lower FeO and lower P_2O_5 of the PUB, at similar MgO contents. A conventional A K-Ar, ^{40}Ar-^{39}Ar total fusion and incremental step-heating ^{40}Ar-^{39}Ar geochronological study on the metamorphic sole using amphiboles from emplacement-related granulites and amphibolites has been concluded. Currently melting experiments are being conducted to understand the mechanism for generation of boninite melts within the mantle wedge above subduction zone. Eruption of the Cape Vogel boninites and the emplacement of the PUB ophiolite and the formation of the metamorphic sole occurred in the Paleocene between 60 Ma to 58 Ma.

SHRIMP measurement of carbon isotopes in diamond

C.W. Magee, I.S. Williams and W.R. Taylor

A technique has been developed to make in situ measurements of the isotopic composition of carbon in diamond using the SHRIMP ion probe with a spatial resolution of approximately 30 microns. Although machine-induced fractionation can be severe (around 30%), careful control of operating parameters achieves reproducibility of approximately 1.5 ‰, close to the

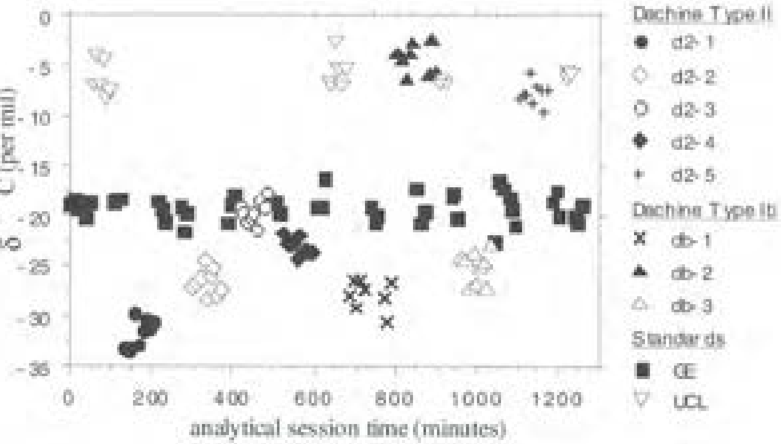

Figure 7: Isotopic compositions of two standards (GE, UCL) and eight Dachine microdiamonds. The d2 diamonds are low N (<20 ppm), type II diamonds, db diamonds are higher N (100-400ppm), type Ib diamond, where the nitrogen is partially aggregated. N contents were measured using FTIR. GE and UCL are standards- GE is synthetic, while UCL is natural. All compositions are normalised to a GE value of -19.2‰ PDB, and corrected for long term drift. The standard error of the drift-corrected measurements of GE is 0.193‰.

theoretical precision of 1 ‰ for 10^8 ^{13}C counts per analysis. Primary O_2^- ions were used to sputter the sample, and the carbon was analysed as C^+. Because a resolution of only 2679 is required to differentiate ^{13}C from $^{12}C^1H$, mass spectrometer resolution could be decreased from 5000 by opening the collector and source slits to 200 μm, thereby reducing variability in secondary ion fractionation. By carefully controlling secondary ion steering, regularly measuring standards, and paying careful attention to sample preparation, reproducible measurements to within 2‰ precision have been achieved. Use of this technique shows that the microphenocrystic diamonds in Brazilian carbonado are isotopically lighter than the matrix diamonds by 2.5‰. Diamonds from the Dachine talc schist of French Guiana have also been measured, revealing a range in isotopic composition from -30 to -5‰. The isotopic composition does not correlate with the nitrogen content of these diamonds, as measured by FTIR (Figure 7).

Diamond and chromite geochemical constraints on the nature of the Dachine complex, French Guiana

C.W. Magee and W.R. Taylor

The Dachine talc schist, located in French Guinea, is of interest because it contains numerous small diamonds, but it is geochemically unlike kimberlite or lamproite. Capdevila *et al.* (1999) suggested on the basis of the geochemical signatures of the refractory, immobile elements that it may be a komatiite, a high temperature magma which has never before been associated with diamond occurrences. However, because the original rock chemistry has been affected by metamorphism and hydrothermal alteration, resulting in mobilization of many characteristic elements, there are other plausible alternatives to a komatiitic affinity. A possible candidate for the Dachine rock is picritic shoshonite, the magnesian endmember of the shoshonitic appinite-suite rocks, which are known intrusive rocks of the Guyana Shield. Appinite-suite intrusions are generally associated with post-collisional, arc-related magmatism.

A study of the diamonds and chromite from the Dachine body suggests that the komatiite hypothesis is unlikely. The diamonds in the Dachine are characterised by highly variable $\delta^{13}C$ values (-30 to -5‰). Diamonds having a light carbon signature, which suggest an origin from recycled biogenic carbon, appear to be more abundant than those with a -5 per mil mantle signature. The diamonds are all low in nitrogen (max. 400 ppm), and are classified on the basis of their IR spectra as either type II or type Ib-IaA stones. The low nitrogen aggregation state of the type Ib-IaA diamonds indicates that these stones have been at mantle temperatures for less than 1 million years, and they cannot have been at komatiite temperatures (1700–1750 °C) for more than 24 hours.

Detrital chromites occur in streams directly draining the Dachine body and because there are no other identified metasedimentary and volcanic sources of chromite in the area these can all be assumed to have weathered from the Dachine rock. There are two populations of Dachine chromite. Ten percent of the chromites appear to be traditional diamond-indicator chromites derived from sampling of mantle peridotite. The remaining chromites are magmatic in origin but have higher Nb concentrations than typical komatiite chromites. The chemistry of these chromites is consistent with derivation from a shoshonitic magma.

If the Dachine body is of shoshonitic affinity, a subduction zone environment seems the most likely place in which to form diamonds with a biogenic signature since it is at these zones that recycling of crustal material into the mantle occurs. The low N content of the diamonds suggests they may have formed by transformation from graphite which was originally derived by metamorphism of carbonaceous matter. The low nitrogen aggregation state of the diamonds suggests that the graphite to diamond transformation was not followed by an extended diamond storage period in the mantle, this may be possible if the fluids that catalysed diamond formation were produced in the same event that led to formation of the shoshonitic magma.

Calibration of the (Co, Mn)O+Co oxygen sensor

H.StC. O'Neill and M.I. Pownceby[1]

Activities of CoO in (Co,Mn)O solid solutions in contact with metallic Co have been determined on 10 compositions ranging from 0.12 to 0.84 X_{CoO} in order to calibrate the divariant equilibrium between (Co, Mn)O oxide solutions and Co metal as an oxygen fugacity sensor for application in experimental petrology. Experiments were conducted over the temperature range 900–1300 K at 1 bar, using an electrochemical technique with oxygen-specific calcia-stabilized zirconia (CSZ) electrolytes. Co+CoO or Fe+FeO was used as the reference electrode. Compositions of the (Co,Mn)O solid solutions were measured after each run by electron microprobe, and these were checked for internal consistency by measuring the lattice parameter by X-ray diffraction. Activity-composition relations were fitted to the Redlich-Kister formalism. (Co, Mn)O solid solutions exhibit slight positive deviations from ideality which are symmetrical (corresponding to a regular solution mixing model) across the entire composition range with $A_0(G) = 3690(\pm 47)$ $Jmol^{-1}$. Excess entropies and enthalpies were also derived from the emf data and gave $S^{ex} = 0.77(\pm 0.08)$ JK^{-1} mol^{-1} and $H^{ex} = 4558(\pm 90)$ $Jmol^{-1}$ respectively. The experimental data from this study have been used to formulate the (Co,Mn)O/Co oxygen fugacity sensor to give an expression: $fO_2 = fO_2(Co\text{-}CoO) + 2RT \ln X_{CoO} + 2(1-X_{CoO})^2[4558 - 0.773T]$ $(900<T(K)<1300)$ where $fO_2(Co\text{-}CoO) = -492{,}186 + 509.322\ T - 53.284\ T \ln T + 0.02518\ T^2$, taken from O'Neill and Pownceby (1993). The (Co, Mn)O+Co oxygen sensor has been used to test the high temperature furnace built for X-ray absorption spectroscopy (see Berry *et al*, this report).

The effect of melt composition on the activity coefficients of some siderophile element components (FeO, NiO, CoO, MoO₂, MoO₃ and WO₃) in silicate melts in the CMAS system

H.StC. O'Neill and S.M. Eggins[1]

The partitioning of trace elements between silicate melt and crystalline phases is one of the main tools used by geochemists to unravel the origin and evolution of igneous rocks. There is, however, a complication: trace element partition coefficients are generally not constants, but vary with the major element composition of both the silicate melt and the crystalline phase, as well as temperature and pressure.

The reason why such an important issue should remain controversial for so long is that, in direct studies of crystal/melt partitioning, it is not possible to vary independently melt composition, crystal composition, temperature or pressure, so as to deconvolute the effects of each of these variables. Consequently, experimental trace element partitioning data, with their attendant experimental uncertainties, can generally be fitted adequately (statistically speaking) to several alternative models, and so cannot be used to select which model is correct theoretically. Only a theoretically correct model is likely to be of much use for extrapolation.

However, for certain elements whose oxide components are easily reduced to the metal (ie, siderophile elements), it is possible to measure the effect of melt composition on activity coefficients directly, while keeping all other variables constant, using oxidation-reduction reactions of the type:

$$\underset{metal}{M} + x/4\ O_2 = \underset{sil\ melt}{MO_{x/2}}$$

We have used this approach to determine the effects of changing major element melt composition on the activity coefficients ($\gamma_{MOx/2}$) of FeO, NiO, CoO, WO_3 and MoO_2 and MoO_3 in simple system $CaO\text{-}MgO\text{-}Al_2O_3\text{-}SiO_2\pm(TiO_2)$ silicate melts at 1400°C and atmospheric pressure.

[1] CSIRO, Victoria

Beads of each composition were loaded onto wire loops made from the pure metal of interest, and hung, six or seven at a time, in a vertical tube furnace equipped for gas mixing. Oxygen fugacity was imposed using CO-CO_2 gas mixtures. The fO_2 for each metal was selected from previous work to produce concentrations of ~ 4000 ppm of W, Co and Ni in most compositions. Since Mo occurs in two oxidation states at experimentally accessible fO_2s (Holzheid, A. *et al.*, GCA, 1994), this element was studied as a function of fO_2 over as wide a range of fO_2 as was experimentally feasible. For Fe, the CO/CO_2 ratio that would be needed to impose the fO_2 producing ~4000 ppm in the melt is too extreme for accurate work, and we settled on a target concentration of ~3 wt% Fe. Time series experiments showed that ~four hours was all that was needed for the samples to closely approach equilibrium, but most experiments were run for ~ 40 hours. Samples were quenched by dropping into water.

The major element compositions of all samples were checked by electron microprobe analysis in the EDS mode. Concentrations of Fe, Ni, Co and, in a few runs, Mo, were also determined by electron microprobe using WDS and the pure metals as standards. W is difficult to determine this way because of overlap of the L lines with the Si K lines and was not attempted. W was determined as well as Mo, Ni and Co by laser-ablation ICP-MS, a relatively new analytical technique which is ideally suited for this type of study. Analytical precision from either method is about 3%, one standard deviation.

In deriving activity coefficients ($\gamma_{MOx/2}$) from the measured element solubilities, the only other significant non-systematic experimental uncertainty is that in fO_2, which is estimated to be ± 0.02 log-bar units (1 s.d.). However, for the sets of six or seven samples hung in the furnace in one go, any error in fO_2 is common to all samples and may therefore be ignored in comparing the relative effects of melt composition. Hence activity coefficients are measured to a relative accuracy of ± 3%.

For MoO_2, MoO_3 and WO_3, solubilities at constant fO_2 (hence $1/\gamma_{MOx/2}$) vary with melt composition by nearly an order of magnitude, much of the variation being explained by a strong positive correlation with [CaO] in the melt, suggesting the importance of $CaMoO_3$, $CaMoO_4$ and $CaWO_4$ as melt species. For FeO, CoO and NiO the variation with melt composition is much more limited, and, as a first approximation, γ_{FeO} could be represented by a single value for all CMAS compositions to within ±30%, and γ_{CoO} to within ±20%. Ternary CAS compositions tend to have lower solubilities (higher $\gamma_{MOx/2}$) for all three elements, MAS samples high solubilities. For the quaternary CMAS samples, when the small variations are considered, there is almost no correlation between γ_{FeO} and γ_{CoO}, γ_{FeO} and γ_{NiO} or γ_{NiO} and γ_{CoO}. This implies that attempts to parameterize values of γ_{MO} for these elements using simple global melt descriptors such as NBO/T or melt basicity will not be successful.

Laser-ablation analysis of niobium and zirconium in chromian spinel and the problem of chromium argide interference

W.R. Taylor

Niobium and zirconium are present in trace quantities in solid-solution in chromian spinel (Nb ~0.05 to ~15 ppm; Zr ~0.1 to ~30 ppm). Although present in small amounts these elements typically show large differences (up to several orders of magnitude) between chromite of high-pressure, diamond-facies peridotitic origin (Nb >0.5 ppm, Zr >1 ppm) and chromite from crustal magmatic sources (typically Nb <0.5 ppm, Zr <1 ppm). Because chromian spinel is widely used as an indicator mineral in diamond exploration, the ability to distinguish diamond-indicator chromian spinel from other types, that otherwise have identical major and minor element contents, has become increasingly important in the exploration industry. With the advent of laser-ablation ICPMS technology it has become possible to analyse concentrations of elements such as Nb and Zr down to the tens of parts-per-billion level enabling their use as geochemical discriminators. However, a significant problem exists with analysis of niobium and zirconium in Cr-rich substrates by laser-ablation ICPMS in which Ar is used as the carrier gas. This arises from the formation, in the plasma, of isobaric chromium argide molecular species ($^{50}Cr^{40}Ar^+$,

$^{52}Cr^{40}Ar^{+}$, $^{53}Cr^{40}Ar^{+}$) that interfere with the isotopes ^{90}Zr, ^{92}Zr and ^{93}Nb, respectively. In some particular laser and machine configurations the argide interference may reach levels of 50% or more of the primary isotope signal at the 1 ppm level. In the case of niobium this presents significant problems for low level trace analysis because ^{93}Nb is the only isotope of niobium. Fortunately one isotope of zirconium, ^{91}Zr, is interference-free in chromian spinel (though of relatively low abundance) and can be used to evaluate the extent of the chromium argide interference problem.

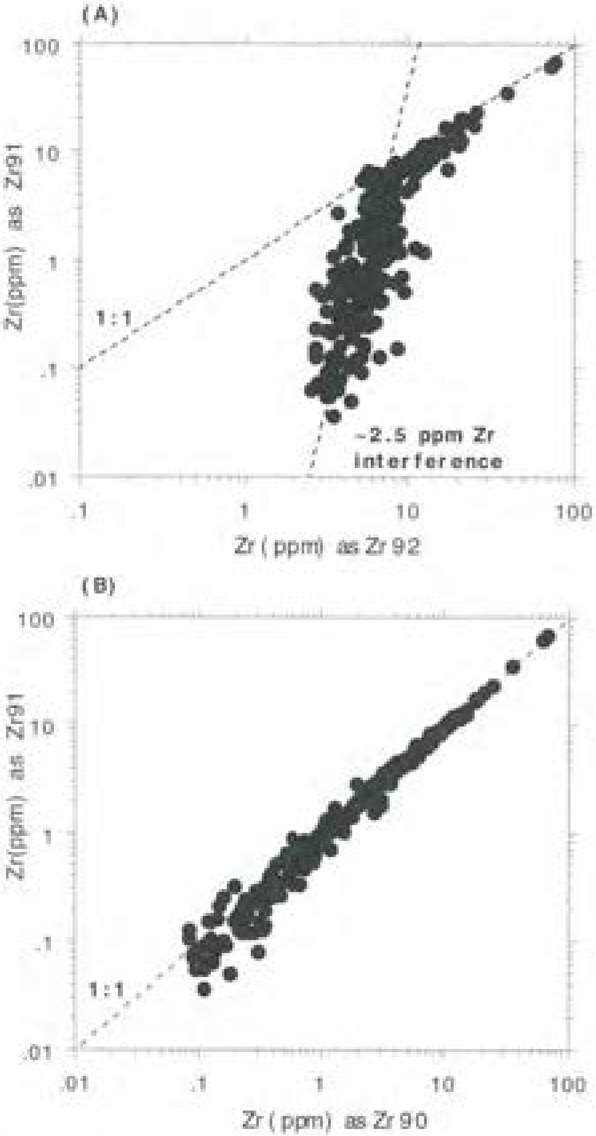

Figure 8: Analysed Zr(ppm) in chromian spinel using different Zr isotopes. (A) ^{91}Zr versus ^{92}Zr showing strong effect of $^{52}Cr^{40}Ar$ interference (equivalent to ~2 to 3 ppm Zr). (B) ^{91}Zr versus ^{90}Zr showing minimal interference from $^{50}Cr^{40}Ar$.

Several hundred chromian spinel grains containing >40 wt% Cr_2O_3 from a range of upper mantle and crustal origins have been analysed for Nb and Zr using the RSES laser-ablation facility. The facility consists of an ArF Eximer ultraviolet laser (193 nm) coupled to a modified VG PQ2+ quadrupole ICPMS. Ablation occurs in a controlled atmosphere cell containing a stratified mixture of He and Ar and ablation products are transported to the ICPMS via a signal smoothing manifold. For chromian spinel, a laser repetition rate of 10 Hz and spot sizes of 170-225 microns were used. Standardization was against the NIST 612 glass standard with vanadium used as the internal reference element.

Results are shown in Figure 8 as plots of Zr (ppm) determined using the ^{91}Zr, ^{90}Zr and ^{92}Zr isotopes (for ^{92}Zr a correction to account for ^{92}Mo in the glass standard was applied). In the plot of ^{91}Zr versus ^{92}Zr (Figure 8A) it is clear that there is a large interference from $^{52}Cr^{40}Ar^+$ (^{52}Cr makes up 83.8% of the isotopic composition of Cr) that is particularly noticeable in grains containing <7 ppm Zr. The interference corresponds to a relatively constant amount of ~2–3 ppm extra Zr and this seems to be largely independent of the Cr content of the chromian spinel (presumably because a saturation level of $CrAr^+$ molecules is reached in the plasma). In the plot of ^{91}Zr versus ^{90}Zr (Figure 8B) the effect of Cr argide interference is slight because ^{90}Zr is a major isotope of Zr (51.5%) and ^{50}Cr is a minor (4.3%) isotope of Cr. The interference corresponds to ~34–50 ppb Zr which is near the detection limit for Zr and therefore can be neglected for all but the lowest Zr (<0.4 ppm) chromian 2 spinels. For niobium, the Cr argide interference is also small and corresponds to ~39–58 ppb Nb. As with Zr, this is near the detection limit for Nb (typically 30–50 ppb for a 170 µm spot) and a small correction is warranted only for the most Nb poor (<0.5 ppm) chromian spinels. Further evidence that Cr argide interference is small is provided by the excellent correlations found between Nb and Ta, since Ta is interference-free, but shows geochemical behaviour essentially identical to that of Nb. Nb and Ta show strong linear correlations in chromian spinel with Nb/Ta=7 and only slight deviation from this value at low Nb levels. Furthermore, boninitic spinels, which contain the highest known Cr of all terrestrial spinels, regularly return Nb below detection limits.

In conclusion, Nb and Zr can be analysed in Cr-rich matrices to sub-ppm levels using the RSES laser ablation system. Compared to other laboratories, the low levels of Cr argide interference may be due to a combination of the He/Ar atmosphere and Eximer ultraviolet laser used at RSES. Analyses of Nb and Zr in chromian spinel from other laboratories should be treated with caution unless rigorous testing of Cr argide interference has been undertaken.

Tectonic classification of the felsic alkaline rocks and development of the "SYENDAT" geochemical database

P. Wallace[1] and W.R. Taylor

In most cratonic regions of the Earth strong spatial and temporal associations exist between alkaline rock complexes and deep-seated kimberlite or lamproite magmatism. However, in Australia the deeply eroded and weathered nature of Precambrian cratons has erased or obscured evidence of kimberlite intrusion. A kimberlite or lamproite exploration strategy in such areas may be to identify prospective regions within the craton by locating alkaline intrusive (eg syenitic) complexes. However, Precambrian cratons are geologically complex and have typically been built up by amalgamation of geologically distinct terranes by plate tectonic processes. Therefore not all alkaline rocks will have an appropriate tectonomagmatic association with kimberlite and methods for geochemically discriminating "kimberlite favourable" alkaline rocks (ie those from continental intraplate settings) and "kimberlite unfavourable" alkaline rocks from other settings are required. With this aim in mind, a geochemical database (SYENDAT) of the basic to felsic alkaline rock compositions (46% < SiO_2 <72%) containing over 2,600 rock samples from world-wide sources has been established.

Twelve variables based mainly on ratios of commonly analysed elements to Zr (which corrects for crystal fractionation effects) were found to discriminate with varying degrees of success between samples from *intraplate*, *arc* and *postcollisional* tectonic settings. Additional categories were assigned for alkaline rocks of *lamproitic* and *alkali metasomatic* affinity. Application of multigroup discriminant analysis methods produced three linear discriminant functions which could be used to classify samples in the database relative to their literature classification with an accuracy of 96% for *intraplate*, 95% for *lamproitic*, 74% for *arc*, and 70% for *postcollisional*. For comparative purposes, the standard Pearce plots of Nb *vs* Y and Rb vs. (Y+Nb), widely used in the literature for tectonic discrimination of "granitic" rocks, was applied to a subset of SYENDAT fitting the "granitic" classification. The Pearce plots show considerable overlap between different tectonic groups and demonstrate the effectiveness of the discriminant function approach.

The geochemical classification has been applied to Late Archaean-aged syenitic rocks of unknown tectonic setting from the Yilgarn block. The results show over 90% of these samples to have *arc* or *postcollisional* signatures consistent with the proposal of a number of authors that the Yilgarn craton represents an amalgam of microcontinental and island arc complexes younging toward the east. Only syenites from the southern margin of the Yilgarn block have an unequivocal *intraplate* signature suggesting this area may warrant consideration for kimberlite exploration.

Preliminary results of melting experiments of simplified lherzolite in the system CaO-MgO-Al_2O_3-SiO_2-Cr_2O_3(CMASCr)

L. Xi and H.StC. O'Neill

How the wide compositional variety of basaltic magmas may be generated from a peridotitic upper mantle is one of the most fundamental problems in earth sciences. The behaviour of the simplest model system, CaO-MgO-Al_2O_3-SiO_2(CMAS), which contains all the major phases making up the upper mantle, has been studied well. Future work will concentrate on additional minor components which are known to have significant effects on phase relations under upper mantle conditions. Cr_2O_3 is arguably the most important one of these, and indeed there has been significant work on the effect of Cr_2O_3 on the sub-solidus transition from garnet lherzolite to spinel lherzolite. Chromium's effect on mantle melting is, however, still poorly understood. We have therefore begun an investigation on the effect of melting relations in the system CMASCr at upper mantle pressures (1.1 GPa).

The determination of initial melt compositions in assemblages which contain all 5 phases (olivine, orthopyroxene, clinopyroxene, spinel and melt) in this 5-component system is difficult because the temperature interval between the temperature of the solidus ("melt-in") and that of the disappearance of clinopyroxene (Cpx-out) is extremely small.

To address this difficulty, we initially exploited the sandwich method. However, the experimental results demonstrate that this introduces further problems, in that the compositions of the minerals and melts are rather inhomogeneous, and therefore interpretation of the experimental results becomes difficult.

This approach has therefore been abandoned, and experiments are now being conducted using an intimate mixture of all four solid phases. Results obtained so far suggest that addition of Cr_2O_3 to CMAS raises the solidus temperature slightly (by up to approximately 20°C in the compositions studied). The compositions of orthopyroxenes and clinopyroxenes in equilibrium with spinels of different Cr/(Al+Cr) ratios have also been obtained.

Future work will focus on extending our study to higher pressure conditions and utilising the data extracted from our experiments to model thermodynamically the melting behaviour of this simplified lherzolite system.

ENVIRONMENTAL PROCESSES GROUP

Research in the Environmental Processes Group is concerned with landscape processes and climate change, and aims to establish detailed chronologies and rates of past changes at the earth's surface, including appropriate contributions to the chronology and impacts of prehistoric humans. Work of the Group in 1999 was focussed on high-resolution climatic variation in the last 7000 years, as well as on aspects of the global carbon cycle, and the chronology of landscape evolution and the regolith. Research is underpinned by laboratory facilities, particularly stable isotope mass spectrometry and various methods of dating surficial deposits, including ^{14}C, ^{10}Be and ^{36}Cl. The latter are measured by accelerator mass spectrometry (AMS), as a collaborative program with the Department of Nuclear Physics Department (RSPhysSE). There are close links with the Environmental Geochemistry Group, particularly where luminescence and trace element methods are required for dating and analysing past variations of hydrologic, climatic and geomorphic processes. Palaeomagnetic measurements of the age of ancient regolith continued in conjunction with the Cooperative Research centre for Landscape Evolution and Mineral Exploration (CRC LEME), and are made in the RSES-AGSO palaeomagnetic facility. The Radiocarbon Dating Laboratory became a adjunct member of the new cross-campus Centre for Archaeologic Research.

All research projects progressed well in 1999, with major topics being high-resolution palaeoclimatology, assessment of the role of soil as a carbon store, and measurement of rates of soil formation and erosion. The dual questions of past climatic changes and human impacts upon on earth surface systems are basic to much of the Group's research. Dr Bird extended his sample array for determining fluxes and residence times of carbon in soil, with new sites in Africa and elsewhere. The coral-based palaeoclimatology project deepened its study of the role of the western Pacific warm pool in El Niño patterns over the last 6000 years, and Dr Gagan and Ms Lynch extended the sample base with a major field trip in eastern Indonesia, in the region of the Pacific-Indian Ocean throughflow. Applying new methods of sample preparation in AMS radiocarbon, Dr Turney and Dr Bird extended the radiocarbon chronology of human occupation of Australia to beyond 47,000 years. Knowledge of late Pleistocene changes from sclerophyll to rainforest in Queensland was advanced by radiocarbon dating soil charcoal by Mr Alimanovic and Professor Chappell in collaboration with members of the CRC for Tropical Rainforest. Measurement of rates of erosion and landscape evolution across semi-arid Australia using cosmogenic nuclides, a project initiated in 1998, was strengthed in 1999 by arrival of Dr Heimsath, while measurements of processes of erosion and soil transport have been integrated into numerical models of landscape evolution by Dr Braun, in the Geodynamics Group.

The Group's support staff are vital to its research, who continue to devote effort beyond the call of duty to ensure continued operation of equipment and sample handling. Scientific advances by our PhD scholars make a major contribution; and in 1999 our two new scholars, Ms Treble and Mr Rustomji, are engaged with problems central to our major themes of climatic change and landscape evolution.

^{10}Be determination of erosion rates in semi-arid Australia

J. Chappell, A. Alimanovic, A. Heimsath, K. Fifield[1] and R. Cresswell[1]

As the first phase of a new project to determine rates of long-term erosion, soil production and landscape changes throughout Australia, rates of erosion in selected semi-arid catchments were assayed using measurements of ^{10}Be, which is produced in rock outcrops by cosmic rays. Samples came from sites in the Flinders Ranges, the gibber plains and table-top hills west of the Simpson Desert, the Macdonnell Ranges west of Alice Springs, the east Kimberly Ranges, the Mt Isa region and the great dividing ranges. Based on some sixty samples, erosion rates were found to vary from an extremely low value of 0.1 metres per million years in the silcrete gibber

[1] Nuclear Physics, RSPhysSE, ANU

plains, up to about 10 metres per million years in the Flinders and Macdonnell Ranges. Even the latter figure is low by world standards and up to 1000 times less than in the mountains of Papua New Guinea and New Zealand, where extreme values range up to 10 kilometres per million years. These very low rates in semi-arid Australia show that the production of soil and sediment by rock weathering is also very slow.

In the second phase of the project, detailed sampling has been conducted in the same regions, both of bedrock sites and of sediments from streams of different catchment sizes in order to measure the rates of erosion on different landforms and slopes, as well as residence times of the derived sediments in different landscape compartments. Pilot results from catchments east of Hall's Creek indicate that downstream passage of sediment grains can be as slow as 1 km per thousand years; early results from the Macdonnell Ranges suggest that sediments are trapped for periods exceeding 100,000 years and episodically released, in response to Quaternary climatic changes.

Determination of rates of soil production and mixing, using cosmogenic nuclides and optically stimulated luminescence

A. Heimsath, J. Chappell, N. Spooner and D. Questiaux

The downhill movement of soil is assisted by natural "stirring", caused by treefall and by burrowing animals including ants, worms, and (in southeast Australia) wombats. We are evaluating the process and rate of stirring at sites on soil-mantled hillsides in the Bega Valley, NSW, from optically stimulated luminescence (OSL) ages of individual mineral grains, sampled from difference soil depths. The OSL age indicates the time elapsed since a grain was last exposed to sunlight, which we assume happened when the grain last visited the ground surface. We refer to this as the mixing time. A estimate of the particle mixing "velocity" is given by dividing the sample depth by the mixing time. Determinations were made for samples ranging from 5 to 85 cm depth, with 48 individual OSL ages per depth sampled.

Results show that the average mixing velocity decreases with depth, from about 0.3 $m.ky^{-1}$ at 0.1 m down to 0.08 $m.ky^{-1}$ at 0.8 m depth (the average mixing time increases from about 0.3 ky to around 11 ky). Combined OSL and thermoluminescence (TL) measurements also show that some grains at all depths have never been exposed to sunlight, but remain fully within the soil during its transport downhill by soil creep and slopewash. The percentage of unexposed grains increases with depth, from 25% at 0.1 m to 60% at 0.8 m.

We found that the mixing time is substantially shorter than the residence time of soil at a point, which can be assessed as the soil thickness multiplied by the rate at which soil is produced from bedrock weathering. At our Bega Valley site, the rate of soil production under different depths of soil cover was previously measured by A.H., using ^{10}Be and ^{26}Al produced in quartz grains by cosmic rays. The rate of soil production P was found to decrease with increasing soil thickness H, fitting the equation $P = 0.053\ e^{-2H}\ m.ky^{-1}$. Thus, where the soil depth is 0.1 m, the mean residence time is about 2.3 ky, and is about 73 ky where soil depth is 0.8 m thick. Results so far indicate that the residence time is about 6–8 times greater than the mixing time, at our Bega Valley site, implying that most grains visit the surface many times before they are removed by erosion, irrespective of soil depth. Noting that mixing velocity and soil production rate both decrease with increasing soil depth, we speculate that bioturbation has a strong influence on sub-soil rock weathering.

Holocene environmental and cultural changes in northern Arnhem Land

J. Chappell and R. Jones[2]

Landscapes and habitats have changed greatly in coastal regions of northern Australia in the last 10,000 years, owing partly to the invasion of prior valleys by rising sea level – at least until 6000 years ago. Climatic changes and coastal sedimentation account for the rest. The patterns are broadly known from previous studies in the South Alligator and other estuarine plains of Northern Territory, but the environmental histories of each particular area, being governed by tides, sediments and local features of the drowned topography, differ considerably, affecting aspects of cultural prehistory and land inheritance. Furthermore, the responses to any future rise of sea level will vary from place to place.

Coastal and estuarine lowlands of the Blyth and Glyde Rivers in northern Arnhem Land, together with the Arafura Swamp, comprise some of the largest and most diverse wetlands of northern Australia, not only of continuing importance to the Aboriginal residents but also, arguably, a centrepoint of prehistoric cultural changes and dispersion.

Based on field work in 1997–1999, the environmental prehistory of the Lower Glyde, Blyth and associated freshwater wetlands over the last 8000 years has largely been established. A good radiocarbon-dated chronology shows that the coastline advanced seaward at up to 50 m per century in the last 5000 years and that large mangrove swamps changed into freshwater wetlands, as recently as 2000 years ago in some areas. Measurements of tidal and sedimentary processes are being used to predict the effects of any future rise of sea level, which is likely to reverse the recent trends. Results in progress are periodically communicated to people of the region, through public meetings and the Northern Land Council.

Paleomagnetism of early to mid Pleistocene paleosols, and evidence for diachronous arid climate shifts in northern and southern Australia

B. Pillans

In South Australia, in coastal sections near Adelaide, and on Kangaroo Island, the Brunhes/Matuyama (B/M) polarity transition (0.78 Ma) is identified in the strongly oxide-mottled Ochre Cove Formation. The Ochre Cove Formation is overlain by a calcareous grey-green aeolian clay, called Ngaltinga Clay, which in turn is overlain by calcareous sediments of the Christies Beach and Taringa Formations. The marked change from an oxide-dominated weathering regime to a carbonate weathering regime is estimated to have occurred at about 500 to 600 ka, and is interpreted as a major arid shift in regional climates. Similar arid shifts are inferred from the Murray Basin in southeastern Australia and Lake Lefroy in southern Western Australia, where changes from lacustrine clays to evaporites and dune sediments are estimated to have occurred between 400 and 700 ka, and about 500 ka, respectively. An increase in aeolian dust input to Tasman Sea sediments also occurs in the last 400 ka.

In northeast Queensland soils developed on basaltic lava flows with ages up to 5.6 Ma show a trend of increasing soil thickness of ca. 0.3 m/Ma. Reverse polarity magnetisation of pedogenic hematite in the lower B horizons of the soils on the four oldest flows indicates acquisition of the remanence prior to the B/M transition at 0.78 Ma. Preservation of reverse polarity implies that the pedogenic hematite has been unchanged by chemical weathering or physical disturbance by soil biota for at least 0.78 Ma. It is inferred that prior to 0.78 Ma soil weathering may have occurred to greater depth because summer rainfall was significantly higher than present, which is consistent with evidence from Lake Amadeus in central Australia indicating a change from lacustrine clays to evaporites and dunes at about 1 Ma.

[2] Research School of Pacific and Asian Studies, ANU

Between 600 and 900 ka, oxygen isotope fluctuations in deep sea cores show a pronounced change in frequency, from a 40 ka (obliquity dominated) to a 100 ka (eccentricity dominated) pattern. At the same time, glacial-interglacial amplitudes increased, with a marked enrichment of glacial ^{18}O values consistent with larger continental based ice-sheets. Climatic responses to these global changes were not synchronous across the Australian continent.

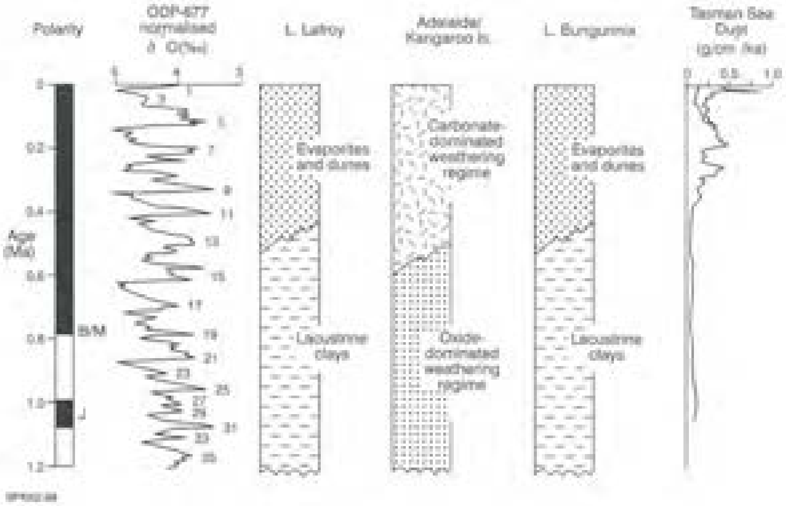

Figure 1: Comparison of paleoclimatic records in southern Australia showing a mid-Pleistocene arid shift, with oxygen isotopic record in deep sea cores.

Diagenesis limits to radiocarbon dating of the Nauwalabila archaeological site, Northern Territory

M.I. Bird, C.S.M. Turney[3], L.K. Fifield[1], R. Jones[2], L.K. Ayliffe[4] and R.G. Cresswell[1]

The Nauwalabila 1 site in Kakadu National Park, Northern Territory is a sandstone rock shelter with a sequence of ~3 m of sandy sediments. Artefacts are distributed almost to the base of the sequence, and occupation of the site has previously been dated to between ~55 and ~60 ka before present using optically stimulated luminescence (OSL) dating. The reliability of the OSL dates has been questioned in part because published radiocarbon dates from the site have suggested a coherent age-depth relationship down to about 1.3 m, but below this point there is little coherence in the dates, suggesting the possibility that the profile has been disturbed and therefore the artefacts close to the base of the profile are not in situ.

In order to attempt to understand the radiocarbon chronology at Nauwalabila, 18 new measurements were made from the lower half of the sequence, using a variety of pretreatment protocols on a charcoal of a variety of sizes from 1cm down to <150μm. Results presented in Figure 2 confirm that there is no coherent age-depth relationship below ~1.3 m in the sequence, with most ages below ~1.5 m depth being in the range 7–12 ka B.P. regardless of size or pretreatment. An analysis of the profile indicates that the coherent age-depth relationship breaks down at the level of first appearance of the authigenic iron pisolites, which normally indicate the existence of a fluctuating water table. Scanning electron microscope imaging and element mapping and elemental analysis indicate that large original charcoal fragments from below

[3] University of London, Egham, Surrey, United Kindom

[4] Laboratoire des Sciences du Climat et de l'Environnement, Unité Mixte de Recherche, Cedex, France

~1.3 m have been substantially replaced by iron, and now contain only 4–14% carbon. This is interpreted as having been introduced during the alteration of the charcoal, and not the original carbon present in the charcoal. The alteration must have occurred after 12 ka B.P., which is the oldest charcoal age obtained from above the level of the authigenic iron pisolites.

Small (<500µm) handpicked and apparently unaltered charcoal fragments from the deepest levels of the deposit also have ages of <10 ka B.P. suggesting that there has been some post-depositional redistribution of fine grains in the deposit, probably as a result of ant or termite activity. The coherence of the radiocarbon stratigraphy above 1.3 m suggests that there has been little, if any, post-depositional movement of large charcoal fragements (and hence artefacts) in the deposit. The radiocarbon chronology below 1.3 m is therefore not considered to be reliable, due to the pervasive alteration of original charcoal and the post-depositional movement of small charcoal fragments. The radiocarbon stratigraphy above 1.3 m is considered to be reliable and a decrease in apparent sedimentation rate inferred from a break in slope of the radiocarbon age-depth relationship at 1.1 m suggests that the inferred depositional age of the bottom-most sediments in the deposit is consistent with the OSL ages of 55–60 ka.

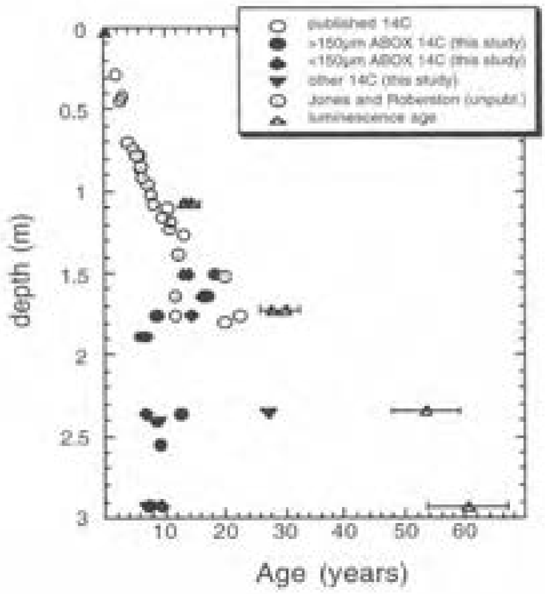

Figure 2: Radiocarbon and OSL ages obtained from the Nauwalabila site, and the distribution of pisolites in the deposit. Note: Radiocarbon ages are not calibrated (calibration to calendar years would make the ages 2–3ka older in the 15–25 ka BP time range).

Breaking the radiocarbon barrier and early human occupation at Devil's Lair, southwestern Australia

C.S.M. Turney[5], M.I. Bird, L.K. Fifield[4], R.G. Roberts[5], M.A. Smith[6], C.E. Dortch[7], R. Grün, E. Lawson[8], G.H. Miller[9], J. Dortch[10], R.G. Cresswell[4], L.K. Ayliffe[4]

Devil's Lair (30°9'S. 115°4'E.) is a single chamber cave (~75 m^2) on the Leeuwin-Naturaliste Ridge, 5 km from the modern coastline[7-9]. The stratigraphic sequence consists of 660 cm of sandy sediments, with >100 distinct layers, intercalated with flowstone and bands of indurated sediment. There is archaeological evidence for intermittent human occupation down to layer 30 (~350 cm depth), with hearths, bone and stone artefacts found throughout. Layer 30 represents a fan of topsoil that accumulated rapidly following widening of the cave mouth, and contains the earliest evidence for occupation of the cave itself. *In situ* artefacts below layer 30 are sparse and none have been found below layer 37. The three artefacts in layer 34 and one small flake in layer 37 were washed into the cave with the sediments, and indicate human activity in the surrounding area sometime before the deposition of layer 37.

Initial occupation of this site has previously been dated by conventional ^{14}C techniques to 30–35 ka BP. The redating program reported here included radiocarbon dating of charcoal and Emu eggshell, optical dating of quartz grains, and ESR dating of marsupial teeth. Accelerator mass spectrometry (AMS) was used to measure the ^{14}C activity of charcoal using both the conventional ABA-BC (acid-base-acid bulk combustion) technique and a newly developed ABOX-SC (acid-base-oxidation stepped combustion) technique. While the ABA-BC ages are indistinguishable from background beyond 42 ka BP, the ABOX-SC ages form a coherent ^{14}C stratigraphy to ~55 ka BP. The ABOX-SC chronology suggests that people were in the area by at least 47–48 ka BP and occupied the cave itself, after widening of the mouth, at ~46 ka BP. Optically stimulated luminescence (OSL), electron spin resonance (ESR) ages and Emu eggshell carbonate ^{14}C dating are in agreement with the ABOX-SC ^{14}C chronology. These results, based on four independent techniques, reinforce arguments for an earlier colonisation of the Australian continent.

Coral seismochemistry and the great Tambora eruption of 1815

M.K. Gagan, K. Sieh[11], W.S. Hantoro[12], H.S. Lynch and R.L. Edwards[13] and J. Zachariasen[11]

The April 1815 eruption of Mt Tambora in Sumbawa, Indonesia was the largest volcanic eruption in modern history. The year 1816 in the northern hemisphere was so cold and wet that it is known as the "year without a summer", yet little is known about the climatic impact of the Tambora stratospheric aerosol cloud in the tropics where systematic meteorology did not exist. Reconstructing the impact of low-latitude volcanic eruptions on tropical climate is important for predicting their global climatic effect via teleconnections from the tropics.

We present a new method for reconstructing the volcanic aerosol-induced reduction in solar irradiance in the tropics using carbon isotope ratios (δ^{13}C) in *Porites* microatolls. The living edge of a coral microatoll grows horizontally because upward growth is limited by the lowest tide level. We tested the hypothesis that δ^{13}C in *Porites* skeletons is sensitive to light intensity by sampling a slab cut horizontally into a large, dead *Porites* microatoll from southwest

[5] Department of Earth Sciences, La Trobe University, VIC
[6] National Museum of Australia, ACT
[7] Anthropology Department, Western Australian Museum, WA
[8] Australian Nuclear Science and Technology Organisation, NSW
[9] Department of Geological Sciences, University of Colorado, Boulder, CO, USA
[10] Centre for Archaeology, University of Western Australia, WA
[11] Seismological Laboratory, California Institute of Technology, USA
[12] Research and Development Center for Geotechnology, Indonesian Institute of Sciences
[13] Department of Geology and Geophysics, University of Minnesota, USA

Sumatra, Indonesia, in the equatorial eastern Indian Ocean. The sampling protocol allows us to compare coral data for one depth within the water column, which helps to ensure that there is no bias when reconstructing light intensity through time.

Three methods were employed to establish exact time-control for the reconstruction. First, the age of death of the microatoll was determined to be 1824 ± 5 AD using high-precision TIMS ^{230}Th geochronology. Second, the δ^{13}C-response to the magnitude 8 earthquake that rocked southwest Sumatra on 10 February 1797 provides an additional exact time-marker (Figure 3a).

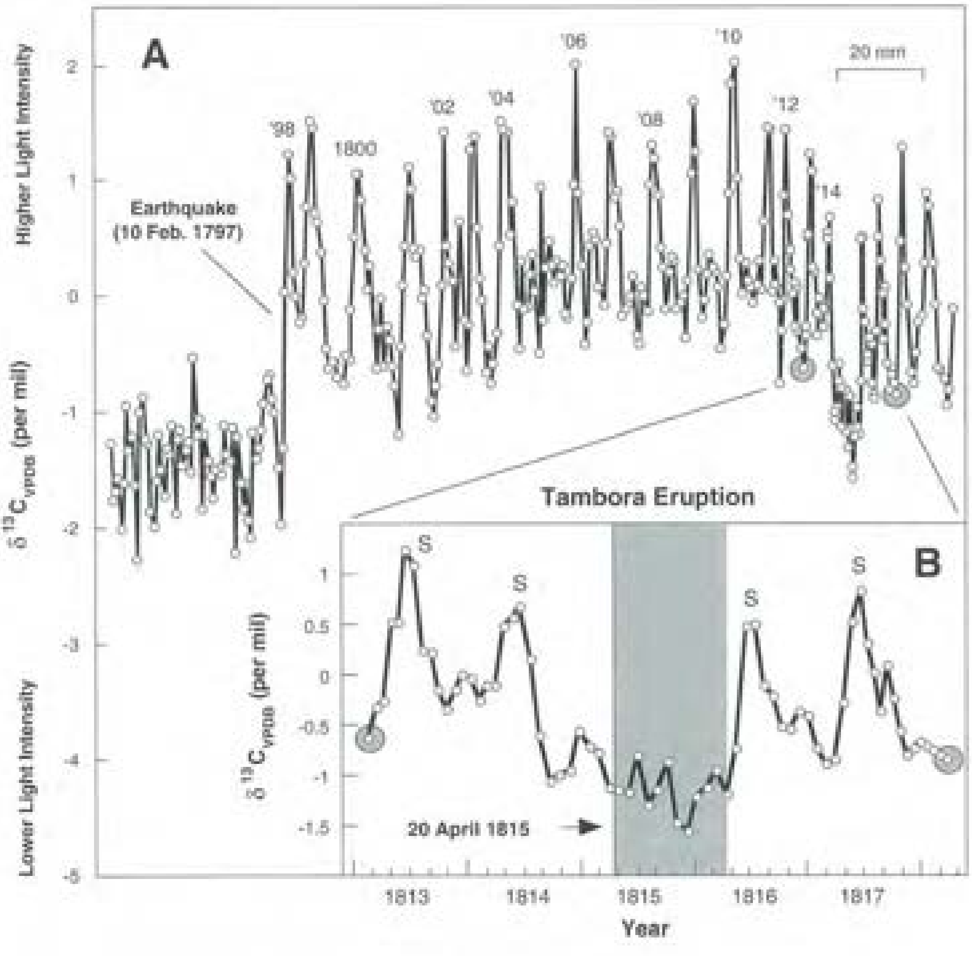

Figure 3: (*A*) Plot of coral δ^{13}C as a function of horizontal distance within a *Porites* microatoll (^{230}Th age of death = 1824 ± 5 AD) from Sipora Island, southwest Sumatra, Indonesia (2.36°S, 99.75°E). The abrupt shift in δ^{13}C marks co-seismic uplift during the major earthquake on 10 February 1797. (*B*) Time-series of coral δ^{13}C assuming the highest δ^{13}C value in each annual cycle (marked "S") coincides with maximum irradiance during the austral winter solstice (21 June). The vertical line marks the timing of the Tambora eruption. The stippling spans the period of lower than expected δ^{13}C values in response to the aerosol-induced reduction in solar irradiance following the eruption.

The enrichment in coral $\delta^{13}C$ immediately following co-seismic uplift of 0.7 m is a response to higher light intensity in the shallow water where the coral continued to grow. We then established an annual chronology using the clear annual cycle in the coral $\delta^{13}C$ record following uplift to shallow water. In equatorial settings, such as this one, the northern growth surfaces of microatolls are shaded during the austral summer and exposed to direct sunlight in the austral winter, resulting in an annual cycle in $\delta^{13}C$.

Having established an annual chronology, and that the timing of the 1797 earthquake agrees within error with that predicted by the ^{230}Th age determination, the timing of the Tambora eruption could be established. The vertical line in Figure 3b marks the position the of the 20 April 1815 eruption, which is followed by sharply lower $\delta^{13}C$ values for ~15 months. The peak in $\delta^{13}C$ associated with maximum seasonal irradiance is absent following the Tambora eruption. Moreover, the level of irradiance appears to be lower than that observed during a typical cloudy monsoon season. The result suggests that the reduction in solar irradiance produced by the stratospheric aerosol was strong and, in equatorial latitudes, may have been restricted primarily to the year following the eruption. The optical effects of the Tambora aerosols were observed for 2–3 years in the mid-high northern latitudes, which suggests that there may have been significant differences in the timing of aerosol-induced irradiance changes with latitude.

Microatolls appear to be exceptional natural instruments for extending the record of earthquakes and volcanic eruptions into the pre-instrumental past. Work is underway to establish a baseline of earthquake recurrence intervals, equatorial sea-surface temperature, and solar irradiance changes for key time-slices during the past several millennia.

Late Pleistocene glaciation in southeastern Australia

T.T. Barrows, J.O. Stone[14], L.K. Fifield[7] and R.G. Cresswell[7]

Despite being one of the hottest and driest continents on Earth, Australia experienced considerable expansion of cold-climates during the last glaciation. Most of southeastern Australia over 600 m in altitude was periglacial and many mountains above 1850 m held permanent snow or ice. The Kosciuszko Massif is the only area of irrefutable glaciation on the Australia mainland and remapping of the glacial extent on the Massif shows that glaciers covered no more than 15–20 km², even less than previously believed. Glaciation was far more widespread in Tasmania however.

Our dating program over the last 4 years has focussed on improving the stratigraphy and chronology of the last glaciation in the Snowy Mountains and Tasmania. Nearly 100 new dates based on the cosmogenic isotopes ^{10}Be and ^{36}Cl provide chronologies for 8 regions of glaciation and 4 periglacial deposits. Among the most surprising findings was evidence for 4 separate glacial advances during the last glacial-interglacial cycle at Blue Lake and Lake Cootapatamba (Kosciuszko Massif). Grouped within the Kosciuszko Glaciation, the earliest of these advances occurred during the Early Kosciuszko at ~60 ka and the latest three advances occurred during the Late Kosciuszko at ~32 ka, ~19 ka and ~17 ka. The last 3 advances occur at very similar times to lake level highs at Lake George (Canberra) and to increased discharge into the Riverine Plain, indicating considerable changes in regional climate.

The dating of Late Kosciuszko Glaciation in Tasmania has shown conclusive evidence that the timing of the Last Glacial Maximum was synchronous across southeastern Australia. Additional dates from North America and France hint that the LGM was probably synchronous in both polar hemispheres, an observation which should shed light on the mechanisms of climate change. The dating of periglacial deposits shows considerable promise and preliminary results indicate that it is possible to derive good chronologies for these landforms. In particular we have shown that low altitude blockstreams were active during the Late Kosciuszko providing convincing evidence that temperatures in the Snowy Mountains were at least 8–9°C colder than

[14] Department of Geological Sciences/Quaternary Research Centre, University of Washington, WA, USA

present during the Last Glacial Maximum. In northeastern Tasmania, our dates on dolerite blockslopes show that block production was persistent throughout the last glaciation and that the base of the slopes are of considerable antiquity, near the limit of the dating technique.

Channel geometry relationships and palaeochannels, Lachlan River, NSW

J. Kemp

Regional channel geometry relationships for inland flowing rivers of the Murray-Darling basin have been established, as a basis for estimating past discharges for a complex network of palaeochannels in the middle Lachlan Valley, central western New South Wales. The nature of channels which existed around the Last Glacial Maximum, in particular, are a conundrum in the regional environmental record, because the largest meandering palaeochannels on the Murrumbidgee and Murray rivers feature meander wavelengths 5–8 times greater than the modern stream, from a time which most other environmental records point to as the coldest, windiest and driest during the last glacial cycle. On the Lachlan River, in the northern Murray Basin, the apparent disparity is greater, similar channels having meander wavelengths 12–15 times the modern river.

A data set comprising 46 sites from 9 rivers in the Murray-Darling Basin was compiled. Regional investigation showed a great variability in bankfull frequencies, reflecting different flood regimes, degree of floodplain confinement, a diversity of channel patterns as well as widely different methods of calculating bankfull stage. This precluded the use of standard flood indicators, and all relationships were based on natural bankfull stage. Regional relationships between channel bankfull width, depth and meander wavelength were quite poor but the relationship between width and discharge was improved by including a sediment size parameter. Reconstructions indicate that the largest Pleistocene bankfull discharge was 6–12 times that of the present river, which is significantly lower than estimates based on meander wavelength alone.

A chronology of palaeochannel ages on the Lachlan is being developed using optically stimulated luminescence (OSL) techniques for the older, organically impoverished Pleistocene channels. A younger palaeochannel system with larger discharge than today is recognised in the upper reaches of the Valley, which does not appear to be represented on other Murray-Darling rivers, and radiocarbon ages indicate this phase terminated between 3–5,000 years BP.

Coral reconstructions of mid-Holocene ocean-atmosphere variability in the central Western Pacific Warm Pool

H.V. McGregor, M.K. Gagan and M.T. McCulloch

The ocean water off the north coast of Papua New Guinea is part of the Western Pacific Warm Pool (WPWP). The WPWP plays a key role in modulating tropical climate and in the initiation of El Niño - Southern Oscillation (ENSO) events, however it is not known how the Warm Pool and ENSO will respond to future greenhouse warming. This study uses records of sea surface temperature (SST) and rainfall from mid-Holocene fossil corals to examine ENSO when SSTs appear to have been warmer than present. We drilled several cores from modern and fossil *Porites sp.* and *Diploastrea heliopora* corals from Blup Blup, Koil and Muschu Islands, located within the flood plume of the Sepik River, Papua New Guinea, which is sensitive to ENSO.

Oxygen isotope and Sr/Ca ratio analyses of two fossil corals from Muschu Island, radiocarbon dated to 5090 and 5400 yBP, and a third coral from Koil Island (7470 yBP) are used to examine changes in sea surface temperature and rainfall. Oxygen isotopes ($\delta^{18}O$) for two modern corals from Koil and Muschu Islands agree to within 0.06‰ for the years 1981–1997; ENSO events are clearly marked by high $\delta^{18}O$ values driven by cool SST and reduced monsoonal rainfall. Fossil coral oxygen isotope results show decrease in $\delta^{18}O$ values from 7470 to 5090 yBP followed by a small increase to present $\delta^{18}O$ values: together with Sr/Ca, the isotopic data indicate SST was ~1°C warmer than today, about 5400 years ago. The 5090 and 5400 BP corals show a reduced interannual range in $\delta^{18}O$ values compared to the modern corals, suggesting that ENSO was weaker during the mid-Holocene (Figure 4 a, b).

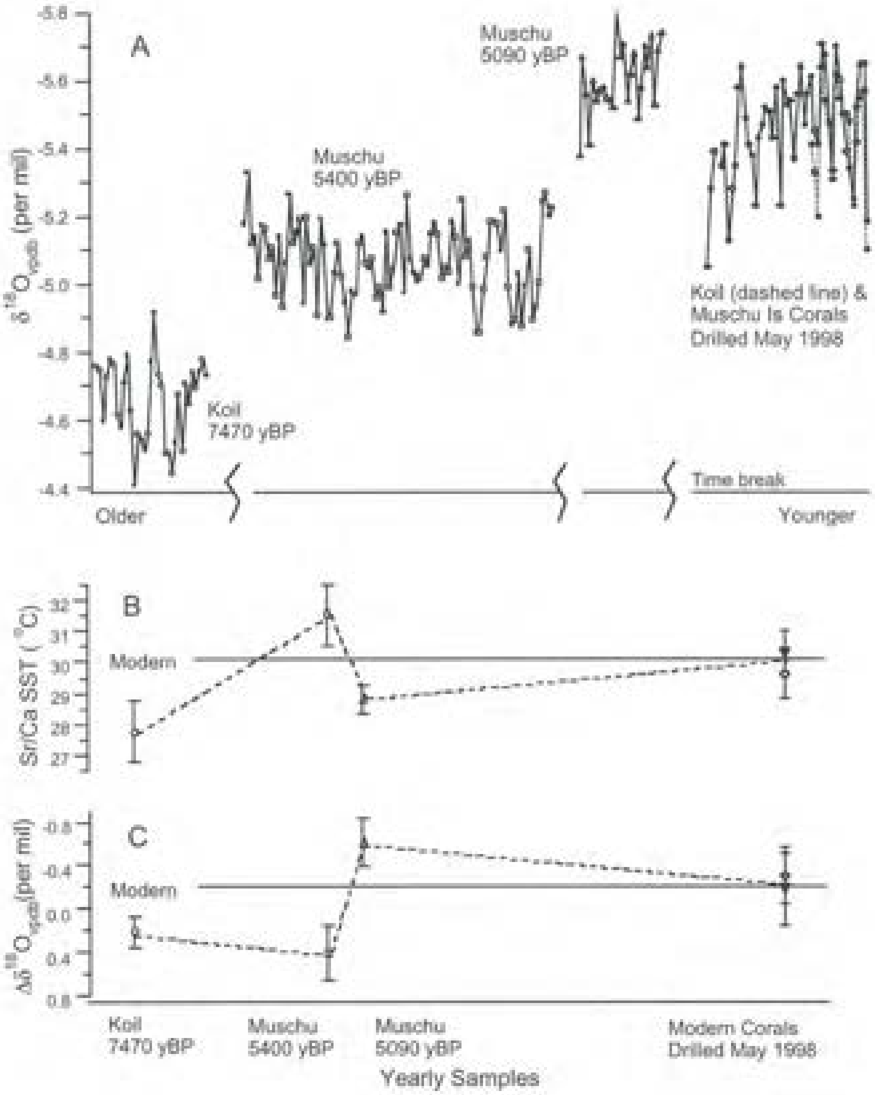

Figure 4: (A) Summary of $\delta^{18}O$ results for the modern and mid-Holocene corals from Koil and Muschu Islands. (B, C) Summary of mean Sr/Ca SST and $\Delta\delta^{18}O$ values calculated for modern and fossil corals. Bars indicate the spread about the mean (2σ) annual temperatures and oxygen isotope residuals for each coral. All $\Delta\delta^{18}O$ values are calculated relative to the $\Delta\delta^{18}O$ of the central Great Barrier Reef.

Reconstructing palaeoclimates of Tasmania using stable isotope proxy records from speleothems.

P.C. Treble

Speleothems (cave calcite formations) have the potential to provide a continuous well dated record of palaeoclimate conditions. Preserved in the calcite is the isotopic chemistry of past precipitation which may be used to reconstruct past climates. Despite the potential of speleothems to be effective palaeoclimate recorders, some of the processes influencing the palaeoclimatic signals are complex and have not always been dealt with appropriately. This research aims to address this problem by investigating the isotopic record of very young speleothems (which formed while our climate was not very different from the present) and by collecting and analysing modern precipitation and stalactite drip samples at the sites where the speleothems were collected.

Stalagmites from north, central and south Tasmania have been obtained for this study, and collectively amount to a near continuous record since the last glacial maximum (LGM) (as determined by uranium series disequilibrium dating). Stable isotope analysis (oxygen and carbon) will be performed on sections of the stalagmites thought to represent key climatic periods since our emergence from the LGM and similarly for the purpose of calibration, the analysis of modern precipitation and drip samples will involve the measurement of oxygen, carbon and deuterium stable isotopes.

Understanding the Bemboka Valley landscape

P. Rustomji

Knowledge of baseline environmental data for landscapes, such as long term rates of soil formation, catchment wide erosion rates and landscape denudation rates are of vital importance when managing natural resources. They provide a quantitative base against which current patterns and rates of human-induced landscape change can be assessed in terms of their long term sustainability, and can also be used to constrain and better understand landscape process. Despite the importance of such data, they have traditionally been difficult to determine in landscapes without dateable stratigraphic features such as lava flows. The use of cosmogenic isotopes, such as ^{10}Be, which is a naturally occurring radioactive isotope ($t_{1/2}$ = 1.5 Ma) produced in quartz crystals in soil and rock profiles, enables determination of such rates.

Current research involves measuring ^{10}Be concentrations at field sites near Bemboka in the Bega Valley, a landscape that has evolved on the Bega Batholith, to determine rates of soil formation and landscape denudation at and beneath the Great Escarpment. Detailed topographic surveying of the headwaters of Three Mile Creek, a tributary to the Bemboka River in the Bega Valley has been completed using high precision Global Positioning System equipment, to calculate topographic attributes for the catchment which will be used with the cosmogenic isotope data to examine hillslope soil transport, for modelling evolution of this landscape.

GEOCHRONOLOGY AND ISOTOPE GEOCHEMISTRY

Research in the Geochronology and Isotope Geochemistry Group is focused on the study of the origin and evolution of the Earth using geochemical tracers and geochronological techniques, the latter to provide time scales for geological processes and events. Progress in our research is heavily dependent upon a range of sophisticated instrumentation, much of which has been developed within the School, including the SHRIMP ion microprobes, which, together with our gas source mass spectrometers, enable us to undertake a wide variety of relevant analyses on geological samples. Geochemical studies range from isotope analyses on meteorites and on the earliest rocks known on Earth, as well as on samples that have been derived from the mantle in the recent past, enabling a broad perspective to be obtained on the Earth's origin and evolution. Our studies in geochronology principally utilize the U/Pb dating technique on zircon and other suitable minerals, and the $^{40}Ar/^{39}Ar$ isotopic dating method on minerals exhibiting a wide range of closure temperatures for argon. With these techniques we can obtain precise and accurate ages for individual events as well as reconstructing cooling histories, providing better understanding of the evolution of the continents, including their growth and their tectonic history, and also providing important input and constraints for geodynamic modelling.

During the year two graduate students, Corine Davids and Paul Hoskin, completed and submitted their PhD theses, and Eleanor Dixon has made progress in writing up her thesis.

The efforts of the SHRIMP subgroup have been directed three ways, towards 1) the development of new instrumentation, 2) experimentation with new analytical techniques and 3) application of established techniques to explore the behaviour of isotopic systems and to solve a wide range of geological problems.

After several years' work by Dr J. Foster and the School's engineering and electronic workshops, an experimental multiple collector for SHRIMP II this year was installed and testing begun. Many problems of multiple collection remain to be solved, but the lens system in the new collector is working well, making it possible to stage the implementation of multiple collector analysis in tandem with an active analytical program. Substantial progress also was made on the SHRIMP RG, which has yet to operate to its design expectations. During a three-month visit to the School, the instrument's engineering designer, Dr S. Clement, in consultation with Emeritus Professor W. Compston, worked closely with technical officer Mr B. Jenkins comparing the design performance with that predicted by a ray-tracing program written independently by Jenkins. The ability of the SHRIMP RG design to achieve high mass resolution with high transmission was confirmed, but it also was discovered that such performance is particularly sensitive to the dimensions and potentials of the various lenses. Now that the lens fringing fields are better understood, electrical and mechanical solutions for improving the focus of SHRIMP RG are being sought.

Several advances were made in analytical techniques. Foremost amongst these were Dr V. Bennett's successful measurements of Ni isotopic zoning in Fe-Ni metal grains from carbonaceous chondrites, showing unexpectedly a zoning pattern inconsistent with simple closed system condensation. Techniques developed by Mr C. Magee in his study of C isotopes from diamonds (see P&EP report) proved very useful in improving the reproducibility of isotopic analyses of other light elements (Li, B etc). An algorithm for matrix correcting Pb/U analyses of very high-U zircon, proposed by Dr I. Williams following work on the Tasmanian Dolerites, has much improved the accuracy of such measurements.

Amongst the many zircon studies carried out during the year, three are of particular note. Dr D. Rubatto showed by carefully targeted studies of zircon grown or recrystallised at high metamorphic grade that the Rare Earth Element (REE) composition of such zircon reflects other REE-bearing minerals that were growing at the same time, thereby recording the metamorphic grade at the time and providing a specific time point in the metamorphic P-T-t path. Professor W.R. Van Schmus, who visited the group for a 3-month sabbatical mid- year, made several important and unexpected discoveries regarding the tectonic history of NE Brazil by studying the changing provenance of Proterozoic sediments from the region. Emeritus Professor W. Compston discovered a formerly neglected source of error in zircon isotope dilution analyses, and developed new approaches to the calibration of SHRIMP analyses, both of which assist in explaining supposed discrepancies between zircon ages measured by the isotope dilution and SHRIMP techniques.

Thermochronological studies on the Victoria Range, South Island, New Zealand, utilizing the $^{40}Ar/^{39}Ar$ isotope dating technique, have confirmed that the range is an exhumed lower plate of a Late Cretaceous core complex, with its formation linked to the opening of the Tasman Basin as New Zealand separated from Australia.

By means of $^{40}Ar/^{39}Ar$ dating of single feldspar crystals, and by step-heating experiments, a detailed time framework has been established for a sequence exposed at Lothagam, northern Kenya, in which a rich vertebrate fauna has been recovered, including some hominoid fossils. The history extends from about 14 to 2 Ma ago in the Miocene to latest Pliocene, and the new results help provide constraints on the evolution of this part of the Kenya Rift.

The second edition of the book "Geochronology and Thermochronology by the $^{40}Ar/^{39}Ar$ Method" by Ian McDougall and Mark Harrison was published mid year by Oxford University Press.

Notable achievements during the year in noble gas geochemistry include further consideration of the remarkably primitive neon isotope composition found in some young Icelandic basalts, the analysis of several very old zircons for their fission xenon signature, and the measurement of cosmogenic neon ages on quartz, demonstrating the youthful nature of exhumation of an old terrane in northern Australia.

We wish to particularly acknowledge the important role played by the technical staff in our research achievements. Mr R. Waterford and the staff of the mechanical workshop and Mr N. Schram and the staff of the electronics workshop were involved in the major developments during the year as well as in the maintenance and refurbishment of laboratory facilities as required. In the noble gas area, Mrs R. Maier effectively maintained the K-Ar dating laboratory and assisted with the $^{40}Ar/^{39}Ar$ dating operations. Dr X. Zhang brought the VG1200 and its extraction line to full automated operation, as well as developing new code for our major acquisition and data handling programs, Noble and KArDate, and supporting the operation of the $^{40}Ar/^{39}Ar$ geochronology laboratory. Dr I. Iatsevitch has designed and is currently building an automated noble gas extraction system, and has maintained and assisted in the operation of the VG5400 mass spectrometer and associated facilities. Mr N. Gabbitas very ably took responsibility for the operation of SHRIMP I and its supporting facilities. Mr J. Mya and Mr S. Paxton continued to provide excellent service in rock crushing and mineral separation for the group as well as for the School as a whole.

An experimental high sensitivity multiple collector for SHRIMP II

J.J. Foster, S.W. Clement[1]*, R. Waterford, N. Schram, P. Lanc*[2]*, W. Compston and I.S. Williams*

The widespread use, in thermal ionization mass spectrometry, of multiple collection in place of a single collector with peak switching, has resulted in major improvements in the precision of isotope ratio measurements. Because of the high spatial resolution of the SHRIMP ion microprobes and their sensitivity to small scale changes in target composition during analysis, it is expected that even greater benefits would be obtained through developing a multiple collector for those instruments.

In 1985 an experimental multiple collector, with a fixed array of eight multiplier channels designed particularly for the study of Ti isotopic anomalies in meteorites, was fitted to SHRIMP I. It proved difficult to obtain reproducible isotope ratios, but there was a substantial improvement in short-term analytical precision, showing that it was worth persisting with development of the concept. Because the Ti anomalies subsequently discovered were large, and readily measured using single collection, experimentation with the fixed-array multiple collector was discontinued. When the decision was made to build a second generation ion microprobe, SHRIMP II, the secondary mass analyzer was redesigned with a multi-element, adjustable multiple collector in mind.

A prototype multiple collector for the ANU SHRIMP II has now been manufactured at RSES. Development of the multiple collector has been directed towards high precision simultaneous measurement of the relative intensities of ion beams over a wide dynamic range. The design therefore incorporates multiple electron multipliers in addition to multiple Faraday cups, the latter able to operate in either current or charge mode, providing the capability to measure the isotopic composition of both trace and major elements, and to measure very large isotopic ratios. Special design features include detector shielding, low input capacitance for the Faraday cups and the use of sapphire insulation, all of which should optimize the charge-mode performance of the three low-noise Keithley® 642 electrometer heads.

The multiple collector is designed to allow the simultaneous collection of five isotopic species in ion counting mode using continuous dynode electron multipliers (CDEMs) which will operate in particle counting mode in conjunction with an Ortec multichannel counting system controlled by an RSES-built pulse counting system interface (PCSI). Close packing of the CDEMs is achieved by off-axis mounting and the use of conversion electrodes. Provision has been made for three of the CDEMs to be mechanically interchangeable with Faraday cups under computer control. The beam defining slits for the five channels can be nested together closely enough to enable simultaneous measurement of heavy isotopes such as Hf or Pb. The collectors immediately adjacent to the central collector are adjustable over a range of 1 mm. The two outer collector assemblies can be moved over a range of 10 cm. In the extended position they can be set for the measurement of light isotopes such as ^{16}O and ^{18}O.

The entire multiple collector can be traversed parallel to the central ray trajectory to allow the beam defining slits to be placed on the focal plane for any chosen mass range. In addition, the outermost collector assemblies can be moved independently to compensate for any minor curvature in that plane. A choice of four beam defining slits of different widths has been provided for each collector.

The central multiple collector assembly can be withdrawn completely to pass the beam to an ETP electron multiplier for single collection using magnet field switching. A transfer lens refocuses the central beam to the entrance of an optional retardation lens that enhances abundance sensitivity. All slits, multiplier positioning motors and electrometers are under computer control.

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[1] Ion Optical Consulting, Crapaud, Prince Edward Island, Canada

[2] Echidna Technologies, Canberra

The multiple collector has recently been fitted to the RSES SHRIMP II, replacing its single collector, and is currently undergoing testing and evaluation. Very satisfactory focus and sensitivity have been achieved in single collector, ion counting mode, enabling analytical work and multiple collector experimentation to be interspersed as required.

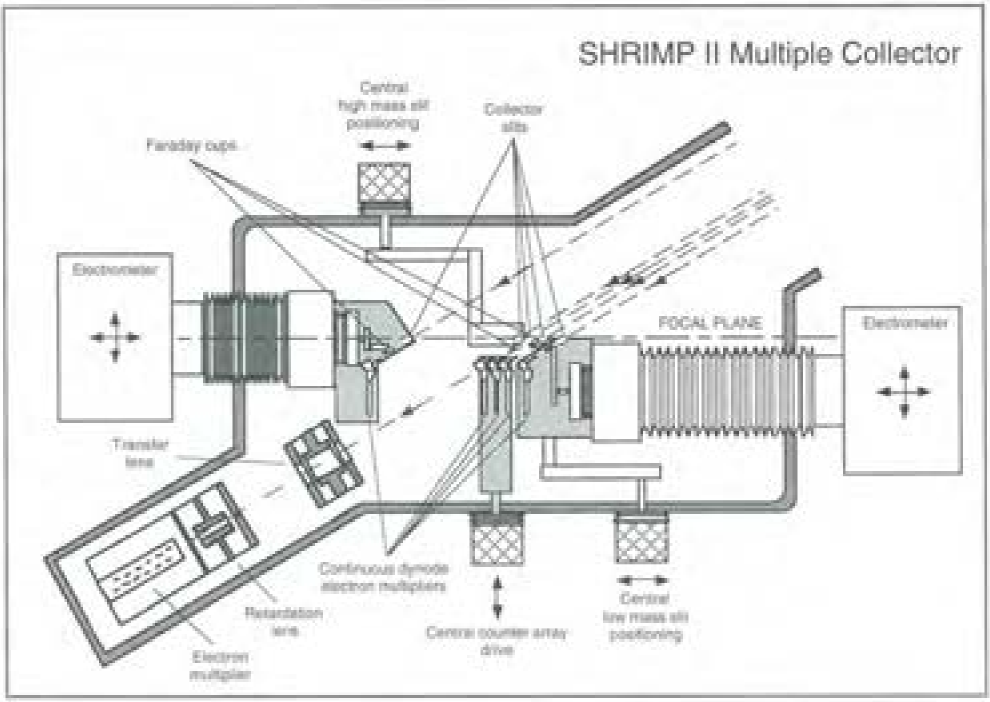

Figure 1: Sketch of the main functional elements of the SHRIMP II experimental multiple collector.

SHRIMP RG

S.W.J. Clement[1], W. Compston, J.J. Foster and B. Jenkins

The RSES SHRIMP RG so far has not operated to its design expectations. It achieves high mass-resolution only when the angular divergence of the secondary ion beam is greatly restricted, contrary to the ion optic design. The last year was spent exploring whether the effect could be lessened by (i) adjustment of the mass-analyser alignment and its various quadrupole lenses and (ii) using a low-divergence but wide cross-section beam through a wide source slit. The latter gave enough sensitivity for zircon U-Pb analyses but it does not solve the basic focusing problem. Further empirical experiments with the instrument were suspended until a better theoretical understanding of the observed effects could be obtained.

1999 was spent mainly on an in-house review of the ion optical theory for the SHRIMP RG mass analyser. Using the LabView platform, Jenkins extended his first order ray-tracing treatment to second order, producing a program (SOIO) which incorporates the second order equations included in Matsuda and Matsuo's third order program (TRIO) on which the SHRIMP RG design is based. Clement visited RSES for three months from July to implement a new version of TRIO. Using beam transport theory and hand calculation, he checked each operation and term in TRIO up to second order (time did not permit checking all third order terms). One inconsistency in the TRIO formulation was found which, although it does not appear to be serious, will need clarification by Matsuo and Matsuda. Clement also changed TRIO's input program to make it easier to use, and wrote a new program that plots the output as the image shape at the collector slit. This supplements the original numerical listing of aberration coefficients. Clement and Jenkins compared the matrix outputs from TRIO and SOIO item by item to identify and eliminate small but important arithmetical errors. The two programs are now close to agreement at second order, and the effects of third-order terms on the image can be distinguished.

Using the TRIO program, Clement confirmed that the focus of the SHRIMP RG is much more sensitive to small changes in lens strengths than that of the SHRIMP FG. In addition, considerable shifts of the image were observed for small changes in the assumed magnet fringing field, making it clear that the latter must be known accurately before the position, and possibly the quality, of the focus can be predicted. There are other fringe fields, such as at the entrance and exit of the ESA, which also may shift the focus substantially. Both programs agreed in showing that the beam should be at least two millimetres wide in the energy focal plane due to second- and third-order aberrations. This had been observed earlier by experiment, but had been interpreted as allowing the possibility that the pole-edge curvatures on the magnet might not be correct. The TRIO program also answered a long-standing question concerning the behaviour of the projection lens that follows the ESA: it keeps the energy- and directional-focus superposed at all values of lens strength.

Both the SOIO and modified TRIO programs can now be applied to examine whether the quality of the focus and its position are strongly altered by the different shapes and strengths of the various fringe fields. In particular, the mass-analyser configuration produced by Matsuda, with its very high quality image, assumes effective lengths for the quadrupole lenses that are different from those that we have built. Is it possible to adjust the lens strengths and/or other parameters to achieve an image of comparable high quality, or must the lenses be modified physically to approach the original design? Using SOIO, Jenkins has begun to answer this question by searching systematically for a minimum sum of selected second-order aberration coefficients, varying input parameters such as quadrupole lens voltages and dimensions, drift lengths and magnet pole face curvatures. Using his modified TRIO program, Clement is now preparing to produce an independent, third-order answer.

As stated last year, the SHRIMP RG would benefit from an extended period of use for analysis to shake out any remaining electronic and computing bugs in its control, to test the long-term stability of its refocussing, and to determine any mass and elemental biases peculiar to the reverse-geometry design. Armstrong and Fanning of PRISE kindly undertook several zircon U-Pb and feldspar Pb isotope analysis sessions early in the year, but were discouraged by variations in measured isotope ratios attributed to short term changes in the secondary ion focusing. The matter could not be pursued because by then Foster's priority was the SHRIMP II Multiple Collector, with which he has been occupied for most of the year. Experimental work using SHRIMP RG will not be resumed until he is again available.

Ni isotope compositions in zoned metal grains within chondritic meteorites measured using SHRIMP II – a record of early solar system processes

V.C. Bennett and A. Meibom[1]

Carbonaceous chondrites are the most primitive meteorite group known. It is certain that they have never been involved in planetary processes and as such they provide direct samples of the chemical composition of the solar nebula and record processes operative during the earliest history of our solar system. Most chondritic components, however, have undergone significant nebular and asteroidal processing, such as melting/heating during chondrule formation and parent body metamorphism/aqueous alteration, that have erased or significantly modified the original chemical and isotope signatures imparted during condensation from the solar nebula.

[1] Hawaii Institute of Geophysics and Planetology, University of Hawaii

The exceptions are a few chondrites which contain compositionally zoned Fe-Ni metal grains. These grains are up to 150 μm in diameter and are unique in having well preserved core-rim zonation patterns, for example in Ni, Co, Cr and Si, with the Ni concentrations varying from 10% in the cores to 4% in the rims. The most straightforward interpretation of these variations is that they represent a condensation sequence from the cooling nebular gas with the zoning patterns consistent with predicted alloy compositions. These rare, well preserved grains provide a means of exploring and constraining the history of solar nebula regions where the metal grains formed.

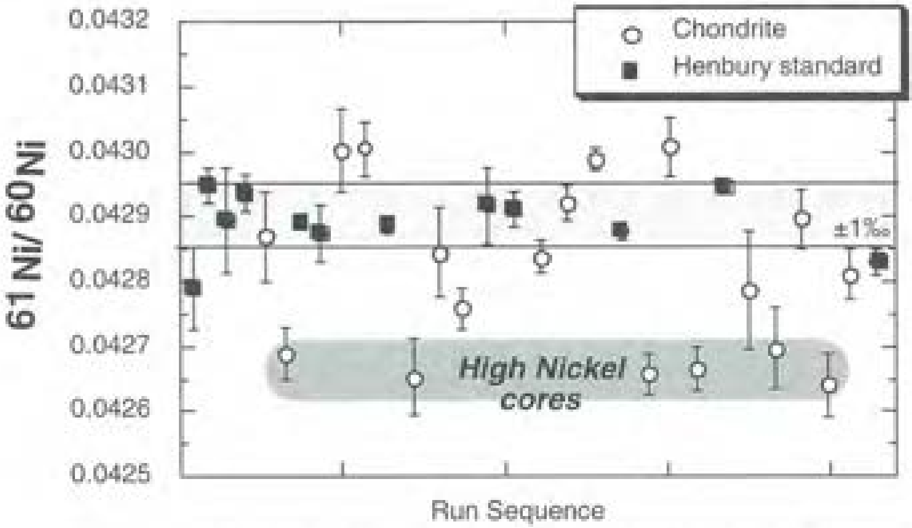

Figure 2: Ni isotopic ratios from compositionally zoned metal grains within a chondritic meteorite. The high Ni cores of the zoned grains have low isotopic ratios compared with the standard (Henbury). This may reflect complex fractionation processes within the solar nebula.

We are investigating the origin of these metal grains using the high spatial resolution and high isotopic precision measurement capabilities of the SHRIMP II. If the zoning represents a condensation sequence then it could be expected to be accompanied by isotopic fractionation as well as compositional variability. All of the isotopes of Ni are stable and any variations in composition will likely result from thermal fractionation effects. Using SHRIMP II we have determined Ni isotopic (^{60}Ni, ^{61}Ni, ^{62}Ni, ^{64}Ni) profiles in meteorite thin sections across the zoned grains. The data were referenced to a standard (Henbury iron meteorite) as well as to synthetic Fe-Ni mixtures. Ni isotopic compositions were constant between standards with external reproducibility from a 40-minute analysis being ± 1‰. The results for the zoned metal grains (Figure 2) show that significant and reproducible variations were present between the cores and rims in some cases with, for example, the cores being up to 4 ‰ isotopically light (low $^{61}Ni/^{60}Ni$), and the rim compositions within error of the standards. No isotopic effects were found in the unzoned grains.

The observed fractionation effects are opposite to those calculated for a simple closed system. Predictions from condensation models are that the first condensed material would be isotopically heavy, in this case having a high $^{61}Ni/^{60}Ni$, becoming isotopically lighter as condensation proceeds. We are currently conducting additional experiments to confirm these data as validation of these results will demonstrate that this approach can have a significant impact on the level of our understanding of nebular processes. One possible explanation is that the observed isotopic effects represent the mixing between distinct chemical reservoirs in the solar nebula during the formation of these grains, reservoirs that require separate early histories. These types of isotopic observations combined with textural and other chemical data provide a window onto the earliest events in our solar system more than 4.5 billion year ago.

Further evidence for matrix effects in SHRIMP measurements of Pb/U on high-U zircon

I.S. Williams and J.M. Hergt[a]

Recent work by several research groups on high-precision dating of African and Antarctic segments of the Jurassic Karoo-Ferrar continental flood basalt province, which once extended over 5000 km along the proto-Pacific margin of Gondwana, has made it timely to look afresh at the age of another segment of that province, the Tasmanian Dolerites. Previous K-Ar studies of the dolerites have yielded a range of apparent ages, suggesting problems with argon mobility, so the present study utilized zircon U-Pb instead.

Most of the Karoo-Ferrar dolerites are not zircon bearing, but differentiation in rare layered intrusions and some of the thicker sills has produced granophyres in which there is a sufficient concentration of Zr and SiO_2 for trace zircon to have crystallized. One such granophyre, in the upper part of a large dyke rising from a thick dolerite sheet, is exposed at Red Hill near Hobart, Tasmania. This unit, one of the most strongly fractionated compositions known in Tasmania, contains both zircon and baddeleyite.

Zircon occurs in the granophyre as highly elongate grains characterized by very simple parallel growth zoning, such as is common in the zircon from relatively rapidly cooled mafic igneous rocks. Initial SHRIMP analyses, however, revealed a very wide range of Pb/U ages. Although it could be argued that the range is a consequence of Pb or U mobility, or that some of the zircon is inherited from older rocks, a strong correlation between measured Pb/U and U content suggests instead that these samples are displaying U-dependent bias in SHRIMP Pb/U measurements similar to that reported in an earlier study of high-U zircon from Sri Lanka. The large range in zircon U content (~400–10,000 ppm) and relative youthfulness of the granophyre provide an opportunity to quantify this bias.

Figure 3 shows the Pb/U apparent ages for zircon from one of the granophyre samples plotted against U. Below about 2500 ppm U the measurements of Pb/U are internally consistent, the weighted mean radiogenic $^{206}Pb/^{238}U$ yielding an age of ~186 Ma, which is similar to U-Pb zircon and baddeleyite ages measured by others elsewhere in the Karoo-Ferrar province. Above 2500 ppm U, the measured Pb/U increases as a function of U content at a rate of between 1.5 and 2.0% per thousand ppm U. The pattern is similar in two other granophyre samples, and a brief survey of the RSES data base suggests that both the cut-off point, and the magnitude of the effect, are similar for a wide range of zircon ages. There is no evidence that high U biases the measurement of Pb isotopic composition, so that it has no effect on the measurement of $^{207}Pb/^{206}Pb$ ages.

Recognition of this analytical bias has a number of wider implications for SHRIMP zircon geochronology. First it helps to explain several published data sets in which the higher U zircons in a population were found to be consistently reverse discordant. This in turn weakens the evidence that zircon losing U in preference to Pb is other than a very rare phenomenon. Secondly, it offers a means of, albeit crudely, correcting SHRIMP analyses of high-U zircon, providing a more reliable test for concordance and increasing the range of zircon types that can be dated accurately by SHRIMP U-Pb. Thirdly, and most importantly, it emphasises that the most accurate SHRIMP Pb/U measurements are those made on zircon with relatively low U contents. This is particularly relevant to the strategy adopted in choosing the zircon to analyse for calibration of the numerical time scale, and to the interpretation of Pb/U ages measured on relatively young, high-U metamorphic zircon overgrowths.

[a] School of Earth Sciences, The University of Melbourne, Parkville

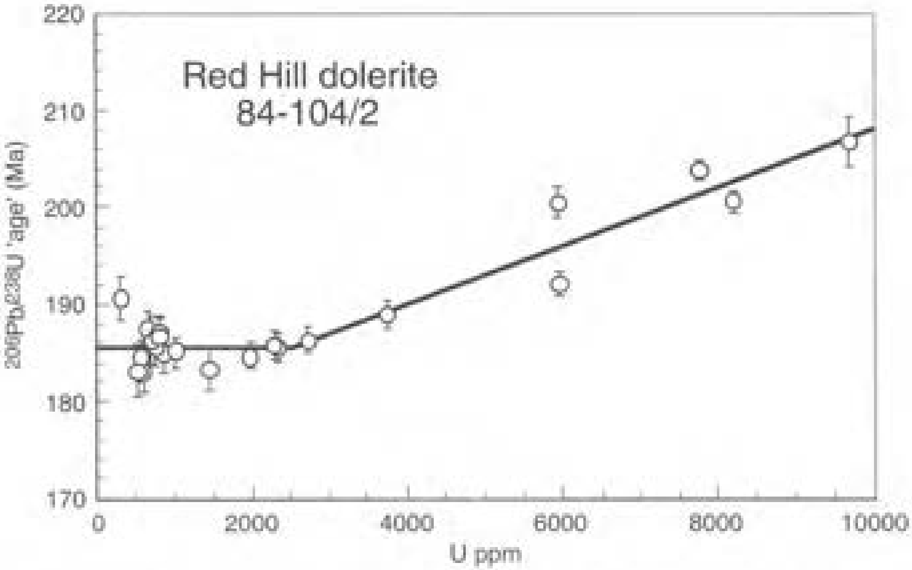

Figure 3: SHRIMP measurements of $^{206}Pb/^{238}U$ apparent ages of zircon from dolerite 84–104/2. In this and the other granophyre samples studied, the apparent ages are mostly equal within analytical uncertainty up to about 2500 ppm U, after which they increase at a rate of between 1.5 and 2.0% per thousand ppm U.

Zircon trace element geochemistry: the link between U-Pb ages and metamorphism

D. Rubatto and I.S. Williams

Zircon geochronology has long had difficulty in linking U-Pb ages to specific segments of metamorphic P-T paths. Unlike other minerals used in geochronology, such as micas or garnet, the metamorphic reactions leading to zircon (re)crystallisation are largely unknown. This makes the correct interpretation of zircon U-Pb dating of metamorphic rocks extremely difficult. We have approached the problem by marrying in-situ U-Pb dating of zircon with in-situ trace element analyses of the different zircon domains. From the trace element composition of zircon that grew or recrystallised during metamorphism it is possible to obtain information on the metamorphic conditions at the time of zircon formation.

Zircon formed in different metamorphic settings has been analysed for U-Th-Pb using the SHRIMP ion microprobes, and for trace elements (Y, Hf, U, Th and REE) using both SHRIMP (RSES) and LA-ICPMS (RSES and ETH, Zurich).

Zircon grains from granulite grade metasediments of the Reynolds Range Group, central Australia, have metamorphic rims that have overgrown detrital cores mostly of magmatic origin. The zircon overgrowths are present only in samples that crossed the melting reaction biotite + sillimanite → cordierite ± K-feldspar + melt. This indicates that new zircon growth occurred at granulite facies and was triggered by partial melting, a conclusion that is confirmed by the zircon REE composition. Metamorphic zircon overgrowths from both the leucosome and metapelitic melanosome have steep REE patterns with strong enrichments in heavy REE, moderate negative Eu anomalies and strong positive Ce anomalies (Figure 4a). The cores have more variable REE patterns, are relatively flat in the heavy REE, and have a strong negative Eu anomaly and positive Ce anomaly. The metamorphic overgrowths differ from the detrital cores also in having systematically lower Th/U ratios (≤ 0.1). Similar REE concentrations and patterns of the zircon overgrowths from the leucosomes and the melanosomes suggest that both reached equilibrium with the melt. The negative Eu anomaly reflects the presence of feldspar during zircon formation, whereas the strong enrichment in HREE reflects the absence of garnet in the assemblage. Therefore, the zircon overgrowths crystallised after the breakdown of white mica to form K-feldspar + sillimanite. Garnet-bearing granulites that had the same metamorphic history also contain zircon with metamorphic overgrowths with low Th/U ratios. In that case, the presence of garnet in the paragenesis is reflected in the zircon REE patterns by a significant depletion in HREE (Figure 4a). Therefore, the metamorphic zircon grew after the breakdown reaction of biotite to form garnet ± cordierite + melt, which occurs at granulite-facies conditions.

An eclogite facies metasediment of the Sesia-Lanzo Zone, Western Alps, contains zircon with detrital magmatic cores surrounded by metamorphic rims with low Th/U ratios (<0.1). The detrital cores have higher U, Th and REE contents than the rims and steeper REE patterns with strong negative Eu anomalies (Figure 4b). On the other hand, the metamorphic zircon rims are characterised by extremely low contents of U, Th and REE. Their REE patterns show only a moderate enrichment in HREE, and no Eu anomaly. Flat REE patterns reflect the presence of garnet, which competes for the HREE. The absence of Eu anomalies indicates recrystallization of the zircon rims after the high pressure breakdown of plagioclase. These data demonstrate that the zircon rims formed during eclogite facies metamorphism at relatively low temperatures of 550–600°C.

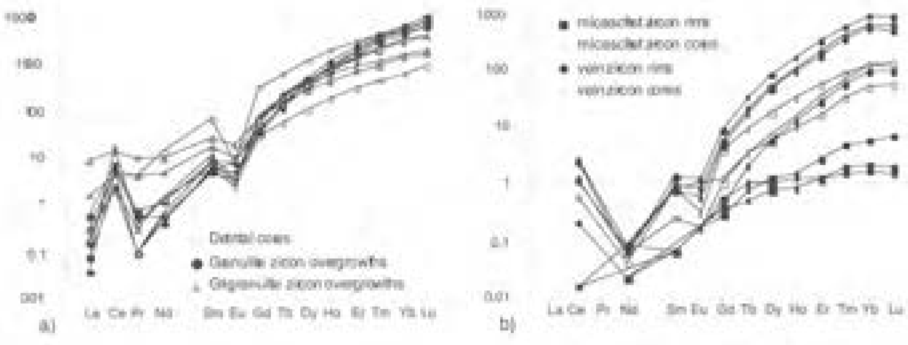

Figure 4: REE patterns, normalised to chondrites, of zircon from a) granulites from the Reynolds Range and b) eclogite-facies rocks from the Sesia-Lanzo Zone.

Hydrothermal zircon from a metamorphic vein within the eclogitic micaschist of the Sesia-Lanzo Zone is rich in U and REE and poor in Th (Th/U <0.1). Its REE patterns (Figure 4b) indicate that the zircon grew in equilibrium with feldspar and in the absence of garnet. This implies that the zircon crystallised at low temperature, prior to the formation of the present eclogite-facies mineral assemblage, probably during prograde greenschist facies. This conclusion is supported by the U-Pb age of the zircon in the vein being 10 Ma older than that of the zircon rims in the eclogitic micaschist. The eclogite-facies metamorphism has not changed the chemical and isotopic composition of the pre-existing zircon. The formation of zircon in the low-grade vein and its resistance to higher metamorphic grade support the hypothesis that zircon crystallisation and isotopic resetting are not necessarily controlled by temperature alone, and can be driven by fluids or melts.

Zircon grains from a diamond-facies gneiss of the Kokchetav massif, northern Kazakhstan, have sector-zoned cores that contain inclusions of various metamorphic minerals. The mineral inclusions are stable at a range of P-T conditions from peak to retrogression, suggesting that zircon grew throughout that part of the P-T path. The ages of the zircon cores with different mineral inclusions, and of the zircon rims, could not be mutually distinguished by SHRIMP. However, the two zircon domains have different REE compositions. The zircon cores have flat REE patterns indicating growth in equilibrium with garnet. In contrast, the steep REE patterns and the marked negative Eu anomalies of the inclusion-free rims point to formation at amphibolite facies grade. From the trace element and isotopic analyses of the

Kokchetav zircon it is concluded that the host rock was exhumed from great depth to amphibolite facies conditions in less than 10 Ma.

Distinctive REE patterns and low Th/U ratios characterise metamorphic zircon and make it possible to link zircon formation with particular metamorphic stages. This correlation is the key to the precise dating of metamorphic events and particularly important because it is now evident that zircon formation can occur over a wide range of P-T conditions in different metamorphic settings.

Detrital zircon studies of Neoproterozoic supracrustal sequences in the 600 Ma Borborema Province, NE Brazil: Implications for tectonic assembly of western Gondwana

W.R. Van Schmus[a], I.S. Williams and B.B. de Brito Neves[b]

The Borborema Province in NE Brazil comprises part of a major Pan-African / Brasiliano orogenic collage that formed as a consequence of the late Proterozoic (*ca.* 600 Ma) assembly of western Gondwana. The province consists of Paleoproterozoic to Archean basement blocks with mid to late Proterozoic metasedimentary and metavolcanic sequences which form major fold belts within the central and southern part. Ten years of U-Pb, Sm-Nd and field studies by the senior authors, their students and colleagues have raised several questions that might be answered by SHRIMP analyses of detrital zircon populations. In particular:

1. Why do most of the metasedimentary sequences have Sm-Nd model ages (T_{DM}) of 1.2 to 1.6 Ga, even though there are no known igneous units in the Borborema Province with ages in this range?

2. Why does one of the younger metasedimentary sequences, the Seridó Group, have T_{DM} ages of 1.2 to 1.6 Ga, but detrital zircons (measured by ID/TIMS) as young as 740 Ma? Was this unit really deposited about 2.0 Ga ago as some local geologists suggest?

3. Do the several metasedimentary sequences in basins flanking the Cariris Velhos magmatic belt, which also have *ca.* 1.3-1.6 Ga T_{DM} ages and younger (*ca.* 1.0 Ga, ID/TIMS) zircons predate or postdate formation of that belt?

SHRIMP analyses of detrital zircon populations from twelve metasedimentary units within the Borborema Province both answered these questions and provided unanticipated insights into other aspects of the tectonic history of the Province. For example, a single *ca.* 970 Ma zircon population from a siliciclastic unit interbedded with 970 Ma metarhyolite in a basin flanking the Cariris Velhos magmatic belt suggests that the detritus was derived primarily from proximal Cariris Velhos volcanic rocks and that the T_{DM} age of 1.51 Ga, which is similar to those found in the metavolcanic and metaplutonic units, is inherited from that source.

A low-grade member in the Seridó Group, with a T_{DM} age of 1.39 Ga, yielded detrital zircon ranging in age from <700 Ma to >2500 Ma, indicating derivation from several sources. The T_{DM} age is significantly greater than the ages of most of the zircons, consistent with most of the igneous units in the Borborema Province having had a prior crustal history. The presence of a detrital zircon population ca. 650 Ma old confirms that this rock was deposited at or after that time. As the collisional phase of this Pan African / Brasiliano orogen started about 620 Ma ago, the depositional age is now constrained to be within the interval 620-650 Ma, implying that the Seridó basin(s) developed on extended continental crust as pre-collisional flysch basins. This unexpected finding contributes significantly to regional tectonic interpretations.

Several metasediment samples collected from basins on the east and west flanks of the Cariris Velhos magmatic belt all contained detrital zircon from multiple sources. There was a

[a] Department of Geology, University of Kansas, Lawrence, Kansas

[b] Instituto de Geociências, Universidade de São Paulo, São Paulo, Brazil

contrast between the ages of those zircons, however (Figure 5). Samples from east of a major fault (Serra do Caboclo Fault) all contained detrital zircon ≥970 Ma old, consistent with those basins being syn- to post-depositional with respect to the *ca.* 970 Ma Cariris Velhos magmatism. Samples from west of the fault, on the other hand, all also contained younger zircons, down to *ca.* 630 Ma old, indicating sedimentation much younger than the magmatism. This conclusion that there are two major metasedimentary sequences separated by as much as 340 million years in depositional age was not anticipated, although it is consistent with limited ID/TIMS results for the region that had seemed anomalous prior to obtaining the SHRIMP data. Independent field and geochemical studies had indicated the duality of sequences, but not the large gap in age.

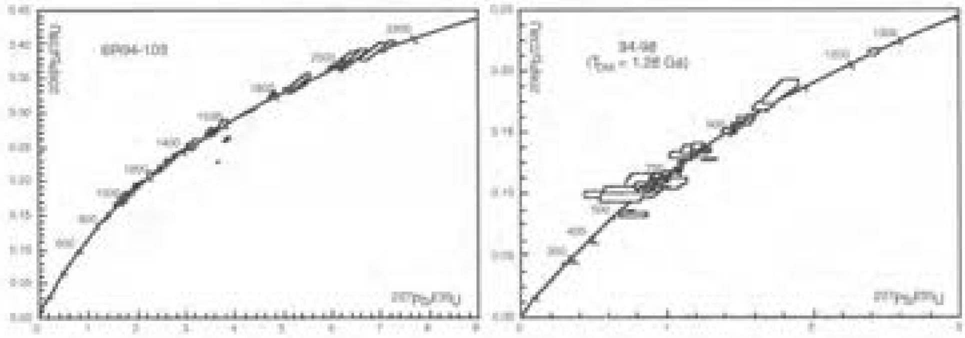

Figure 5: Examples of detrital zircon populations from east (BR94–103) and west (94–98) of the Serra do Caboclo Fault, representing the two major metasedimentary sequences now recognised in the region.

This study of detrital zircons from metasedimentary units in the Borborema Province has shown that the Sm-Nd T_{DM} model ages could be the product of a variety of scenarios, ranging from a single source having older crustal residence ages to multiple sources ranging in age from 650 to 2500 Ma. Each case has its own depositional and tectonic implications, all of which contribute to a much better understanding of the pre-collisional (pre-600 Ma) history of Precambrian crust in this province. The SHRIMP has provided data on the depositional ages and provenance of Precambrian sedimentary sequences unobtainable in any reasonable time by more conventional means. The data do not solve all questions however; several of the age populations found in the detrital suites do not have recognized sources in NE Brazil, implying that much of the detritus may have been derived from distant, and presently unknown, sources.

Problem-solving in defining the Palaeozoic Time Scale

W. Compston

For the past ten years, SHRIMP time-scale work using zircon Pb/U dating has endured criticisms by practitioners of mass spectrometric isotope dilution (MSID) also working in this field. They are that the SHRIMP ages are '1–2%' low owing to an analytical bias, and that SHRIMP errors are too large for useful time-resolution by present-day standards. These issues have been addressed now in several papers this year that review and compare SHRIMP and MSID dating from the early 1990s. Both of the above criticisms have been refuted and furthermore, several large errors in MSID dating have been discovered that arise from a neglected error-source.

The supposed bias has been attributed to our use of the SL13 zircon as an age-reference. Two known defects in SL13 as a standard, micron-sized excesses of radiogenic Pb and an internal variability in Pb/U on a larger spatial scale, are now known to be related to each other and interpretable as caused by metamorphic Pb redistribution some 10–20 Ma after original crystalliztion. However, the defects can be tolerated. Age systematics within SL13 combined with a one-off external calibration provide a parameter per analytical session that allows for the internal variability, and in practice, adjustment to the ages for samples based on this parameter is usually less than 0.5% and averages around zero. Use of this procedure replaces an otherwise unknown uncertainty in SL13-related ages by a known and quite acceptable level of uncertainty.

In the early 1990s, the errors we assigned to SHRIMP ages were too big. It was assumed that the precision per spot-age for any sample could never be better than that of the concurrent SL13 ages, and as a consequence the internal errors were deliberately augmented by the observed SL13 standard deviation. The latter dominated the errors in most cases, and this in turn lead to the masking of small age differences between zircons. The apparently single zircon age that resulted for many rocks suited the dogma of the times. The early 1990s was the era of belief in the perfectability of zircons as time-recorders, belief that cogenetic zircons in rocks could be recognized by eye (and others excluded), and belief that the zircons from an igneous rock were predominantly formed during its magmatic precipitation. Improved treatment of SHRIMP errors now shows that single-age zircon populations are the exception, and that inherited zircons just a little older than the latest magmatism are commonly present. This realization has occurred independently in MSID dating with the advent of single-grain analysis.

The original SHRIMP time-scale work on the Ordovician and Silurian British stratotypes has been revised and documented in detail using the above procedures and is now in press. Some of the original ages have gone up slightly and some down. There is agreement within error with $^{206}Pb/^{238}U$ ages by MSID for the same biostratigraphic stages, but generally the MSID $^{207}Pb/^{206}Pb$ ages are a little older. The latter reflects a newly realized potential for bias in the MSID ages caused by the common Pb correction, to which $^{207}Pb/^{206}Pb$ ages are especially sensitive. This was first understood by comparison between the SHRIMP age for the early Arenig and a surprisingly older MSID age for the adjacent late Tremadoc.

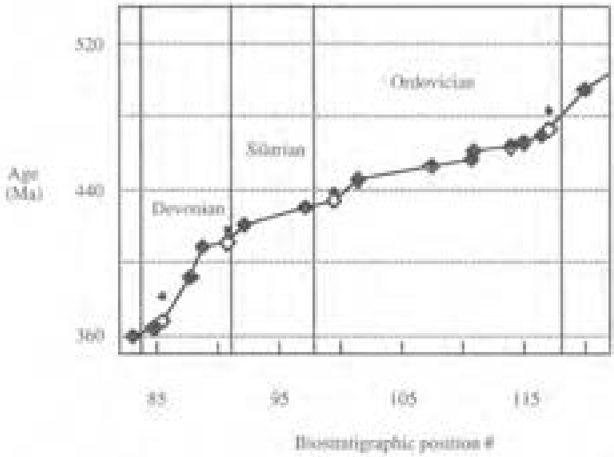

Figure 6: Comparison of SHRIMP and reinterpreted MSID (open symbols) and published MSID (filled) ages for the Ordovician to the early Devonian. The line shown is interpolated between the SHRIMP points. The MSID ages either agree with or are older than the SHRIMP ages, and if older, it is due to the use of $^{207}Pb/^{206}Pb$ ages together with the choice of common Pb composition.

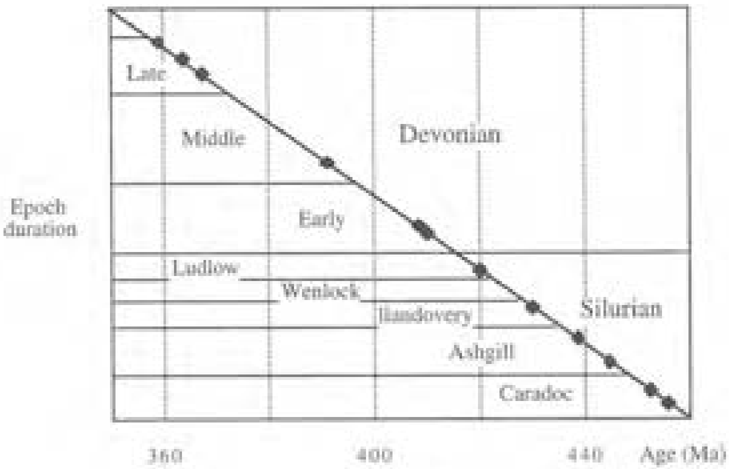

Figure 7: A 'linearized' time-scale based on SHRIMP and reinterpreted MSID ages from the mid-Silurian to the end of the Devonian that emphasizes the unequal durations of biostratigraphic units.

The dependence of the derivative $^{207}Pb/^{206}Pb$ age on the amount and composition of the common Pb in the processed MSID sample became evident by reconstructing the raw observational data then applying slightly different values for the common Pb composition. If the latter was taken as 2% more radiogenic than that given by the global model traditionally used, the apparent single age population with variable Pb loss changed into two age groups, the younger of which agreed very well with expectations from the SHRIMP age. What first read as a conclusive age determination was transformed into an ambiguous one. Scrutiny of other MSID zircon ages that conflicted either with SHRIMP or well-documented ages by other radioactive decay schemes showed that the same ambiguity was present, and the conflict could be removed by adjusting the common Pb correction and allowing more than a single age population. This was especially so for recently published MSID ages for the Devonian that conflict with Rb-Sr and K-Ar determinations for the Frasnian in NE Victoria.

A large body of published and unpublished SHRIMP ages for biostratigraphically-defined volcanics within the Cambrian and late Proterozoic are now being reassessed and compared with recently published MSID ages. The main task is to make a correct and objective identification of age-groups as being inherited, cogenetic with the volcanics, or a post-extrusive Pb loss 'group'.

NOBLE GAS GEOCHEMISTRY AND GEOCHRONOLOGY

The techniques of noble gas geochemistry and K-Ar and ^{40}Ar-^{39}Ar geochronology have close affinities. In all cases, measurements are made on very small amounts of noble gases extracted from geological samples, usually by heating in ultrahigh vacuum systems, with isotopic ratios and amounts of the noble gases determined in gas-source mass spectrometers operated in the static mode, that is isolated from the pumping systems. Particularly stringent requirements must be met in relation to cleanliness of the systems in order for the analyses to be made successfully.

Both the K-Ar and ^{40}Ar-^{39}Ar techniques for dating rocks are based upon the decay of the naturally occurring radioactive isotope of potassium, ^{40}K, which produces ^{40}Ar as one of its daughter products. Measurement of the accumulated argon and the amount of potassium in appropriate minerals and rocks, together with knowledge of the rate of decay of ^{40}K, enables the time since the system became closed to argon diffusion to be determined. Rapidly cooled igneous rocks commonly yield precise ages, accurately recording the time since eruption. Such measurements are very helpful in stratigraphic geochronology and for determining numerical time scales for a wide range of geological events and processes. The ^{40}Ar-^{39}Ar dating technique is especially useful in relation to determining thermal histories of geological terranes, providing numerical cooling rates associated with the tectonic evolution of orogenic belts.

The K-Ar and ^{40}Ar-^{39}Ar laboratories have been quite productive in the year under review with more than 2600 argon isotopic analyses having been made. Approximately 70 new K-Ar age measurements were produced, about 60 ^{40}Ar-^{39}Ar age spectra, averaging some 28 steps per spectrum, were measured, and over 130 single crystal ^{40}Ar-^{39}Ar total fusion age measurements were made. A summary of some of the work accomplished follows. Technically, the major achievement during the year was the full commissioning of the automation on the VG1200 mass spectrometer and its associated extraction system, mainly through the efforts of Dr X. Zhang. Isotope ratio measurement of argon using the electron multiplier in the VG1200 was undertaken successfully, enabling samples about one fiftieth of the size previously measured to be utilized for age measurement on a routine basis.

We welcome Dr D. Phillips, who is employed by PRISE, as a user of the facilities in the K-Ar and ^{40}Ar-^{39}Ar dating laboratories. The automation of the extraction lines and mass spectrometers is making the laboratories more efficient and productive, and is particularly important in enabling a service to be offered to the wider geological community at a reasonable cost.

The noble gases, helium, neon, argon, krypton and xenon, are 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. In recent years 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 within the Earth of solar composition. It is clearly desirable to ascertain whether the primordial heavier noble gases, argon, krypton and xenon in the Earth were also solar in composition. Important insights also may be found by studying other volatiles in the mantle, including nitrogen and carbon dioxide. To better constrain the evolution of noble gas compositions in the mantle we plan to undertake noble gas studies on old mantle-derived materials, including Archaean komatiites and diamonds. Research projects related to cosmogenically-produced noble gases are being considered for the future. Research student Eleanor Dixon has completed her noble gas measurements on suites of basalts from Iceland and West Greenland, and she is currently writing her PhD thesis.

During the year we installed a Balzers secondary electron multiplier with a pulse counting system on the VG5400 mass spectrometer. The necessary source codes for operation of the pulse counting system and the data acquisition were written. The detection limit and precision of measurement of small ion beams of krypton and xenon have been significantly improved using ion counting, compared with the existing Daly measurement system. Currently we are modifying the noble gas extraction system for the automation of gas handling procedures. When completed, we hope that there will be a considerable increase in both productivity and efficiency, allowing us to start some new projects.

In 1999 a total of 14 samples were analysed for noble gases. These included a number of very old magmatic zircons from Greenland, with the noble gases measured following step-wise heating from 400°C to 2000°C. Additional samples measured included quartz samples from central Australia and clinopyroxenes from the Alexandra Volcanic Province, New Zealand. The overall number of analyses on the VG5400 mass spectrometer was 177 during the year. About two-thirds of these analyses were related to measurement of blanks in the ultrahigh vacuum (UHV) system and calibrations of sensitivity and discrimination of the mass spectrometer. Summaries of some of the studies undertaken are given in the following sections.

Stratigraphic geochronology at Lothagam, northern Kenya

I. McDougall and C.S. Feibel[7]

Lothagam, located west of Lake Turkana in northern Kenya, is an uplifted fault block comprising a gently westward-dipping sequence of volcanic and sedimentary rocks, about 900 m thick, deposited in a half-graben basin within a zone of extension in the northern part of the Kenya Rift. A lower sequence of volcanic and volcaniclastic rocks (the Nabwal Arangan beds) is followed by a sedimentary sequence of sandstones, siltstones and mudstones of the Nawata Formation and the Nachukui Formation, deposited in fluvial, alluvial fan and lacustrine environments (Figure 8). An expedition led by Dr M.G. Leakey of the National Museums of Kenya has recovered a very rich and diverse fauna from this sequence, with a number of the vertebrates new to science. This fauna documents a turnover from Late Miocene forest communities to the early inhabitants of the Plio-Pleistocene in more open bush and woodland. Because of the remarkable faunal record, including the earlier discovery of a fragmentary hominoid mandible from the Apak Member of the Nachukui Formation, we have undertaken a detailed K-Ar and ^{40}Ar-^{39}Ar dating program on the sequence. The early volcanism recorded in the sequence extended from about 14 Ma to 9 Ma ago (Figure 8). A number of altered tuffaceous horizons in the lower member of the Nawata Formation contain small pumice clasts from which crystals of alkali feldspar were recovered, providing ideal material for single crystal ^{40}Ar-^{39}Ar age measurements. Highly precise, concordant results were found for feldspars from any one level, and excellent concordancy with the stratigraphic order also was found (Figure 8), demonstrating that the lower member was deposited over more than 1 Ma from >7.4 Ma to 6.5 Ma in the Late Miocene. In a mudstone just below the Lothagam Basalt in the Apak Member of the Nachakui Formation, small (~10 mm) altered pumice clasts were found; single crystal age measurements on feldspars from this horizon yielded a very precise age of 4.22 ± 0.03 Ma (Figure 8), presumed also to give a good estimate for the age of deposition. The overlying Lothagam Basalt proved very difficult to date because of the surprising presence of excess argon, but ^{40}Ar-^{39}Ar age spectra on whole rock samples and plagioclase separates yielded a best estimate age of 4.20 ± 0.03 Ma for the basalt, consistent with the other results. The hominoid mandible from the lower Apak Member could only be placed as older than 4.2 Ma and younger than 5.0 Ma on the basis of these results. Nevertheless, the new age control on the Lothagam sequence places the fossil faunas in a much better time framework than previously available, helpful also in relation to regional and global patterns of change in and around the Messinian Stage at the end of the Miocene. In addition, the sequence at Lothagam provides good documentation of some of the earlier history of rift valley evolution in this part of the Kenya Rift.

[7] Rutgers University, New Jersey, USA

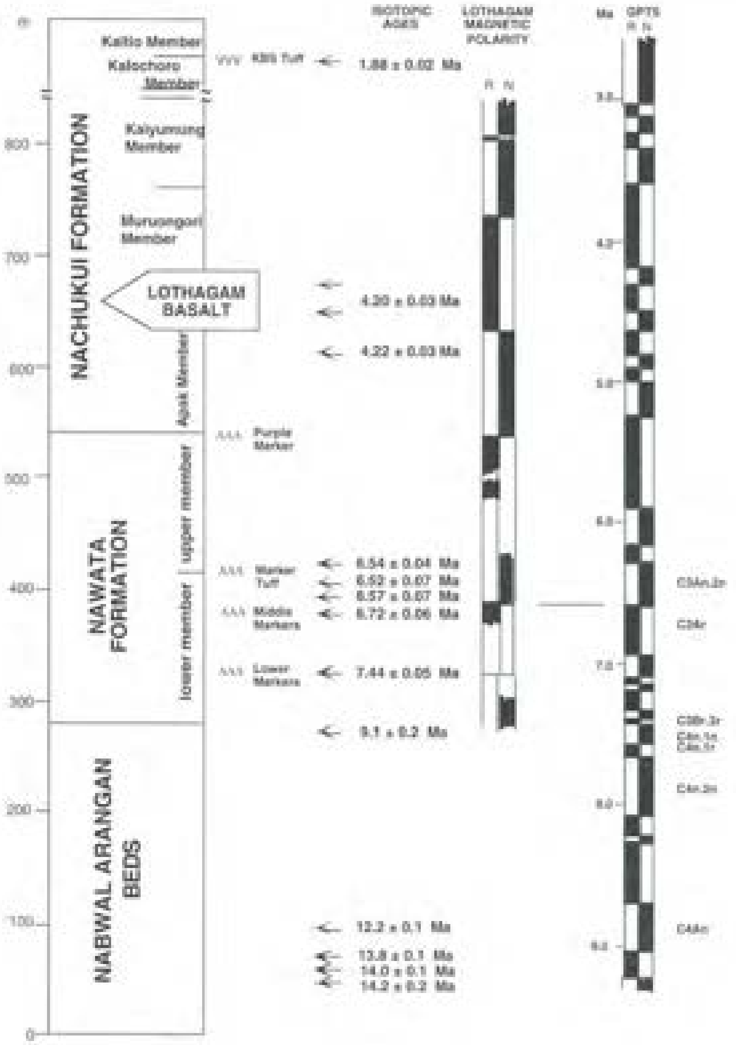

Figure 8: Schematic composite stratigraphic column for Lothagam. Isotopic ages shown at the appropriate stratigraphic level. Magnetostratigraphy, together with the geomagnetic polarity time scale, shown on the right.

Victoria Range, Cretaceous core complex confirmed

W.J. Dunlap, J. Braun and A. Tulloch[8]

Exploration of the Victoria Range, Westland, New Zealand, has confirmed suspicions that this portion of the Paleozoic-Mesozoic Karamea batholith is an exhumed lower plate of a Late Cretaceous core complex that formed at about the time of the initial opening of the Tasman Sea, and in a manner similar to that documented for the Paparoa Range to the west. The geometry,

[8] Institute of Geological and Nuclear Sciences, Dunedin, New Zealand

fault kinematics and cooling history of the Victoria Range core complex have been explored through reconnaissance field study, detailed ^{40}Ar-^{39}Ar step heating experiments on K-feldspars, and 3D numerical studies of block uplift, erosion and cooling. In studying the Late Cretaceous crustal evolution, however, we have been able to place constraints on subsequent Miocene tectonism, just prior to formation of the adjacent Alpine Fault.

In the field it is observed that the dominant Late Cretaceous extension direction was essentially strike-parallel. We believe that the complex was unroofed in a transtensional regime with a large component of strike slip. The strike slip motion was accommodated on steeply dipping faults in valleys at the margins of the complex whereas the cover rocks were removed from above the topographically high granitic core on low-angle detachments kinematically linked to the bounding strike slip faults. It is not yet clear if the dominant regional kinematics were right lateral or left lateral. Extensive sheets of granitic magma were emplaced during or shortly before the onset of extension and relatively rapid cooling of the lower plate granitic rocks ensued as the cover was removed.

Evidence for Cretaceous rapid cooling is preserved in both the fault zone microstructures and the age gradients of the K-feldspars. Fault zone microstructures in the core of the complex formed under lower amphibolite facies conditions whereas those in the bounding fault zones formed at sub-greenschist facies temperatures, as indicated by deformation mechanisms of quartz and feldspars, suggesting progressive unroofing during fault zone evolution. The age gradients preserved in the K-feldspars (Figure 9) have been used to track the lateral removal of the cover rocks through time. In addition, the vertical thermal gradients that prevailed at the end of Cretaceous tectonism are well resolved by the K-feldspar thermochronology.

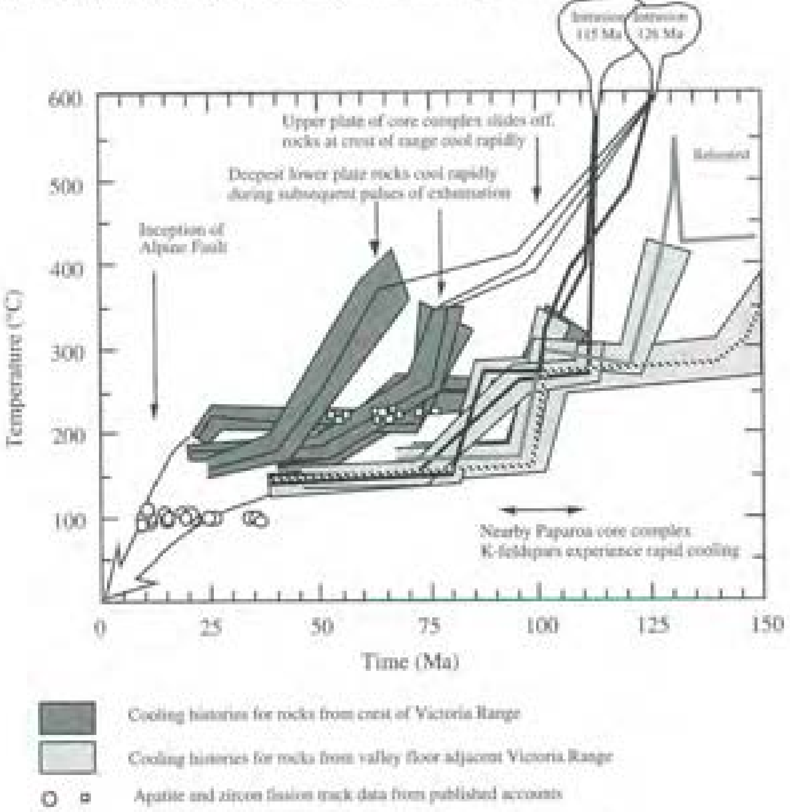

Figure 9: Temperature – time history for the Victoria Range.

Subsequent Miocene block uplift, possibly related to activation of the Alpine fault, or precursor transpression, is limited to a few kilometres. The geometry of this block uplift is relatively simple, which allowed us to use a straightforward 3D numerical code to model the uplift as a rigid block advecting vertically through a fixed topography, and track the thermal response to uplift and exhumation. Numerical results for the Cretaceous to Miocene exhumation show remarkable agreement with the thermochronological models from the K-feldspars, suggesting that the thermal gradient from mountain top to valley floor can only be preserved if the geotherm in the granitic core of the complex stabilized during tectonic quiessence from about 90 Ma to less than 20 Ma. Renewed exhumation later in the Miocene drove cooling to below the lower closure temperatures of the K-feldspars, as independently confirmed by published apatite fission track data. Moreover, we find no conflict between multi-diffusion-domain models of argon diffusion in K-feldspars, the general geologic history of the region, the numerical model of exhumation and cooling, and the independent geochronologic data.

Preservation of solar neon isotopic ratios in Icelandic basalts

E.T. Dixon, M. Honda, I. McDougall and I. Campbell

Neon isotopic ratios measured in olivine and basaltic glass from Iceland are the most primitive ever observed in terrestrial mantle-derived samples. Ratios were measured in gas released from olivine and basaltic glass from a total of ten youthful samples from the Reykjanes Peninsula, Iceland, and include solar, mid-ocean ridge basalt (MORB)-like and atmospheric compositions. Neon isotopic ratios near the air-solar mixing line were obtained from the total gas released from olivine and glass separates from four samples. MORB-like neon isotopic compositions were measured in the total gas released from olivine and glass separates from six samples (Figure 10).

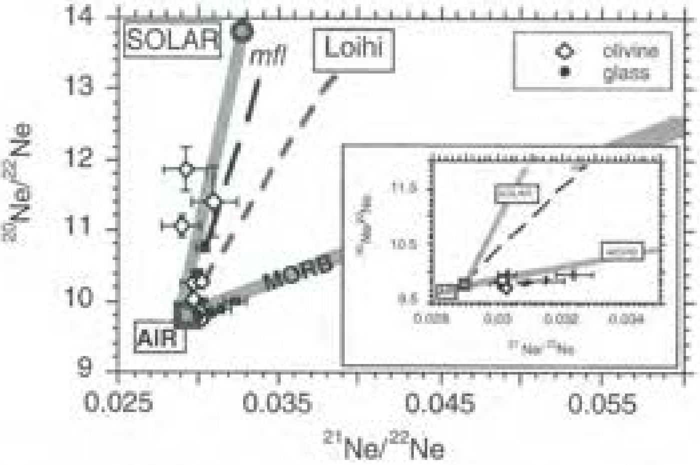

Figure 10: Neon three isotope plot, showing total gas ratios from a total of 10 samples for 8 olivine and 10 glass separates. The air-solar mixing trend, the mass fractionation line from air (mfl), the Loihi trend and the MORB trend are shown for reference. Inset plot shows detail of samples that lie near the MORB trend and are distinct from the neon composition in air within two sigma uncertainty. One sigma uncertainties shown.

Although there is clear evidence for a solar neon component in some of the Icelandic samples, there is no corresponding evidence for a solar helium ratio (320 Ra > $^3He/^4He$ > 100 Ra). Instead, $^3He/^4He$ ratios are between 12 ± 2 and 30 ± 2 Ra, similar to the range observed in other ocean island basalts, indicating that the He-Ne isotopic systematics are decoupled. Calculations show that such decoupling can be achieved by mixing between noble gases from the Icelandic plume with those from a MORB-like component, provided that the two components have different $^{3}He/^{22}Ne$ ratios (Figure 11). The mantle source of Icelandic basalts is interpreted to be highly heterogeneous on a local scale to explain the range in observed helium and neon isotopic ratios.

Identification of primitive solar neon isotopic ratios in some Icelandic samples implies that solar neon trapped within the Earth has remained virtually unchanged over the past ~4.5 Ga. Such preservation requires a source with a high $[Ne_{solar}]/[U + Th]$ ratio so that the concentration of solar neon overwhelms the nucleogenic $^{21}Ne^{*}$ produced as a result of decay of U and Th in the mantle over time. High $[Ne_{solar}]/[U + Th]$ ratios are unlikely to be preserved in the mantle if it has experienced substantial melting. A primitive, undegassed mantle component is postulated to be the host of the solar neon in the Icelandic plume source. Relatively small amounts of the primitive mantle component are likely to mix with more depleted and degassed mantle such that the primitive mantle composition is not evident in other isotopic systems (e.g., strontium and neodymium). The primitive, undegassed mantle in the Icelandic plume source can be compared with the MORB mantle source, which is known to have experienced substantial melting and degassing. The proportion of solar neon in the Iceland plume source is estimated to be at least 13 times greater than that in the MORB source. In comparison, the Hawaiian plume source, with a less primitive neon mantle endmember ratio than the solar neon end-member in Icelandic plume source, has a fraction of solar neon that is only about 6 times greater than in the MORB source. The lower mantle plume source is inferred to be relatively heterogeneous owing to being more viscous and less well stirred than the upper mantle. This discovery of near-solar Ne isotopic ratios is significant to our understanding mantle convection and degassing processes because it suggests that relatively primitive mantle may be preserved in the Icelandic plume source.

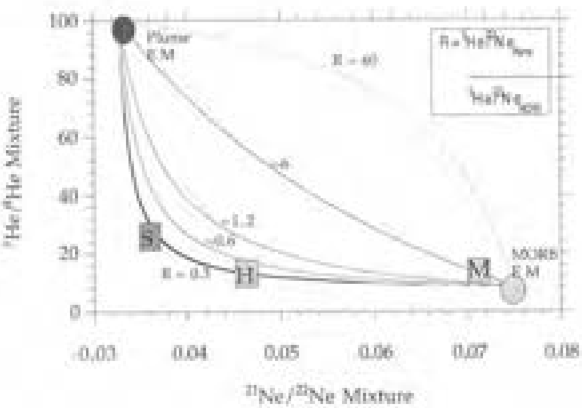

Figure 11: Calculated mixing curves between solar noble gases in the Icelandic plume with MORB-like noble gases showing predicted variation in the $^{3}He/^{4}He$ and $^{21}Ne/^{22}Ne$ ratios as a function of R. The box labelled "S" represents the results from this study with solar neon isotopic ratios and $^{3}He/^{4}He$ ratios near 20–30 Ra, and "H" represents the results of an Icelandic noble gas study by Harrison et al., (1999, EPSL 171, 199–207) with comparatively less primitive mantle helium and neon ratios. Mixtures with an R value of 0.3 can explain the results from both the present study with solar neon ratios and those of Harrison et al. (1999). Mixtures with higher values of R near 6 can explain the results from this study with MORB-like neon ratios and $^{3}He/^{4}He$ ratios near 12 Ra (box labelled "M") that are higher than the expected MORB ratio of 8.5 Ra. The required differences in the R values can be explained by variable degrees of elemental fractionation of helium from neon in the plume or MORB-type magma prior to mixing.

Xenon composition of magmatic zircons from 3.63 and 3.81 Ga granitoids from Greenland

M. Honda, A. Nutman and V. Bennett

Excesses of ^{129}Xe relative to atmospheric xenon have been observed in mantle-derived samples, including MORB glasses and ultramafic xenoliths from Samoan ocean island basalts and from ancient diamonds. The excess ^{129}Xe has been attributed to radioactive decay of the extinct nuclide ^{129}I (half-life of 17 million years), present in the Earth at its formation. The difference between atmospheric xenon and that observed in mantle-derived samples generally is thought to be related to early degassing of volatiles from the solid Earth, implying that degassing must have occurred before all the ^{129}I decayed, that is within about 100 million years after the formation of the Earth. The excess in ^{129}Xe in mantle-derived samples appears to be correlated with excesses in $^{131-136}$Xe relative to atmospheric xenon. The majority of excesses in $^{131-136}$Xe are attributed to spontaneous fission of ^{238}U (half-life of 4,468 million years), although an additional potential source is from another extinct nuclide, ^{244}Pu (half-life of 82 million years). If the Earth had a chondritic ^{244}Pu/^{238}U ratio of 0.007, as observed in meteorites, accumulation of fission ^{136}Xe derived from ^{244}Pu should be 30 times more than ^{238}U-derived fission ^{136}Xe. The apparent lack of Pu-derived fission xenon, in the presence of ^{129}I-derived radiogenic ^{129}Xe in samples from the mantle, is a paradox in relation to the early degassing of the Earth. This is because the half life of ^{244}Pu is longer than that of ^{129}I so that we would expect a significantly greater fraction of ^{244}Pu-derived fission xenon to remain in the mantle in comparison with ^{129}I-derived radiogenic ^{129}Xe.

In order to solve the fundamental problem as to whether some ^{244}Pu was included in the Earth when it formed, we have analysed magmatic zircons from three early Archaean granitoids from Greenland for xenon. Two samples, a granite and a ferrogabbro/ferrodiorite, are from the same intrusive body about 3.63 Ga old. The third sample is a well-preserved metatonalite with an age of ca 3.81 Ga. The U-Pb ages of these zircons were determined by SHRIMP. Xenon from the 3.63 Ga magmatic zircons is dominated by the products of spontaneous fission from ^{238}U. In contrast, the 3.81 Ga magmatic zircons appear to have some excess fission xenon different from the ^{238}U-derived fission xenon. This excess fission xenon is consistent with that expected from ^{244}Pu fission, so that this may indicate that these zircons incorporated ^{244}Pu when they crystallised at ca. 3.8 Ga; this would be expected if the primitive Earth had the chondritic ^{244}Pu/^{238}U ratio at 4.55 Ga. Reaching this provisional conclusion required that all zircons in the 3.8 Ga sample were consumed. We plan to collect more of the sample in 2000 in order to authenticate these exciting xenon results.

Cosmogenic ^{21}Ne in a central Australian quartzite

D. Patterson, M. Honda, D. Belton*, R. Brown* and B. Kohn**

In situ spallation reactions between silicon and cosmic rays produce cosmogenic ^{21}Ne in near-surface quartz samples. Under favourable conditions (high altitude, high geomagnetic latitude, and surface exposure) production rates are sufficiently high to produce detectable amounts of cosmogenic ^{21}Ne in less than 10 ka of exposure. Cosmogenic ^{21}Ne in natural samples can be used to estimate exposure ages that constrain rates of uplift and erosion.

On the basis of stratigraphic and geomorphic evidence, Stewart *et al.* (Science, **233**, 758, 1986) suggested that the present day land surface of parts of the Davenport Province of the Tennant Creek area in central Australia may be remnants of a Cambrian or Precambrian surface. If correct, this area is one of the oldest landscapes on Earth, and would be expected to have extraordinarily high cosmogenic exposure ages. This view, however, is being challenged by ongoing apatite fission track and cosmogenic ^{10}Be studies by investigators at the School of Earth Sciences, University of Melbourne, who argue that this landscape is instead a relatively recently exhumed paleosurface. The Davenport Province therefore provides an excellent

* School of Earth Sciences, University of Melbourne

opportunity to apply cosmogenic ^{21}Ne exposure dating to investigate whether the landscape might be an ancient one.

We analysed two quartz samples from quartzite at the surface from the Davenport Province (provided by University of Melbourne) for all five noble gases: DR98–6C (565 m altitude, 20°46.952′ S, 134° 35.969′ E) and DR98–16 (565 m altitude, 21° 21.934′ S, 135° 18.564′ E). Both samples were collected from within 5 cm of the present day surface. The samples are characterized by radiogenic $^{3}He/^{4}He$ ratios of $< 10^{-8}$ and non-atmospheric $^{21}Ne/^{22}Ne$, $^{40}Ar/^{36}Ar$ and $^{136}Xe/^{130}Xe$ ratios (~ 0.037, ~ 10,000, and ~ 2.3, respectively). The high $^{40}Ar/^{36}Ar$ and $^{136}Xe/^{130}Xe$ ratios indicate unambiguous crustal-derived radiogenic and fissiogenic components, possibly trapped in fluid inclusions in the quartz. A significant fraction of the non-atmospheric ^{21}Ne is therefore nucleogenic ^{21}Ne ($^{21}Ne_{Nuc}$), produced by the $^{18}O(\alpha,n)^{21}Ne$ reaction, where α is generated from uranium and thorium decay in the crust. It is necessary to estimate the amount of $^{21}Ne_{Nuc}$ in the samples before attempting to calculate cosmogenic ^{21}Ne ($^{21}Ne_{Cosmo}$) exposure ages. For the following calculations, we assume that all ^{4}He and non-atmospheric ^{40}Ar ($^{40}Ar^{*}$) is radiogenic in origin. Combining observed ^{4}He and $^{40}Ar^{*}$ with known crustal $^{21}Ne_{Nuc}$/radiogenic ^{4}He and $^{21}Ne_{Nuc}/^{40}Ar^{*}$ production ratios provides an estimate of the $^{21}Ne_{Nuc}$ present. Subtracting $^{21}Ne_{Nuc}$ from the non-atmospheric ^{21}Ne yields the abundance of $^{21}Ne_{Cosmo}$. Based on this approach we estimate that only about 30% of the non-atmospheric ^{21}Ne in DR98–6C is cosmogenic. Similarly, for DR98–16, about 38% is cosmogenic. The amounts of estimated $^{21}Ne_{Cosmo}$ in DR98–6C and DR98–16 are approximately 4.6×10^{-13} and 6.1×10^{-13} $cm^3STP\ g^{-1}$, respectively.

To calculate cosmogenic ^{21}Ne exposure ages we have taken the production rate of cosmogenic ^{21}Ne in quartz of 21 atoms $g^{-1}\ a^{-1}$ at high geomagnetic latitudes (> 60°) and sealevel given by Niedermann et al. (EPSL, **125**, 341, 1994). When scaled for latitude and altitude using the equations of Lal (EPSL, **104**, 424, 1991), we estimate the local production rate in the Davenport Province to be 22 atoms $g^{-1}a^{-1}$ or 8.2×10^{-19} $cm^3STP\ g^{-1}\ a^{-1}$. Using this production rate, we estimate quite young exposure ages of 560 ka and 750 ka for DR98–6C and DR98–16, respectively. These exposure ages are inconsistent with long-term subaerial survival of the Davenport landscape from Cambrian or Precambrian times, and support the suggestion of relatively recent exhumation.

ENVIRONMENTAL GEOCHEMISTRY AND GEOCHRONOLOGY

Research of the Environmental Geochemistry and Geochronology Group focuses on the long-term interaction between mankind and its environment. Investigations are directed towards two main aspects: firstly, determination of the timing and rate of change of major environmental and earth surface processes, and secondly utilising isotopic systems that provide basic constraints on past and present environments. The Group emphasises the study of records spanning a few tens to several hundred thousand years of the Earth's recent history, which serve as a guide to the understanding of the past, present and future environments.

Our studies of the modern environment are aimed at tracing the provenance and fluxes of sediments and associated nutrients that are entering waterways and near-shore environments and quantifying how these have changed since European settlement. These environmental changes are compared with those that occurred with the arrival of Australia's first human occupants, some 60,000 years earlier. Complementary research topics include the timing of extinction of Australia's megafauna, hominid evolution in Africa and Australasia, and climate and sea level changes over the past several glacial/interglacial cycles. All these activities are underpinned by a unique combination of laboratory facilities consisting of thermal ionisation mass spectrometry (TIMS), laser ablation ICP-MS, optically stimulated luminescence (OSL), electron spin resonance (ESR), and gamma-ray counting equipment.

A highlight of the past year was the achievement of fully quantitative elemental abundance measurements on corals by laser ablation ICP-MS, which are in excellent agreement with precise but more labour intensive TIMS measurements. In addition to higher spatial resolution, laser ICP-MS has the advantage of rapid, simultaneous measurement of elements such as B, Mg, Sr, U, as well as Mn, Ba and P, the latter group being important indicators of flood plumes and nutrient fluxes that are entering the Great Barrier Reef. This work formed a major part of both Dr Sinclair's and Mr Fallon's PhD theses, and was undertaken in collaboration with Dr Alibert, Mr Kinsley and Professor McCulloch. Following the initial developmental work of Dr Sinclair, which was based on a synthetic wollastanite coral standard, a significant improvement has resulted from the development by Mr Fallon of a well characterised coral powder standard together with the reduction of other uncertainties. Complementary studies of oxygen, carbon Sr/Ca and Ba/Ca have been undertaken by Ms Hendy for her PhD thesis in collaboration with Dr Gagan and Dr Lough. This work has examined 5-year increments of complete 300–400 year long sections of coral cores collected from the Great Barrier Reef and is aimed at determining the long-term robustness of climate proxies in corals. For his PhD thesis, Mr Marshall is examining the teleconnections between the Indian and Pacific Oceans during El Nino events, using oxygen and Sr/Ca records in coral cores from the Cocos-Keeling and Christmas Islands.

Dr Martin, Dr Canals, a School visitor in 1999, Ms Watson and Professor McCulloch have been using Nd-Sr isotopic 'fingerprints' for tracing the source of suspended sediments and associated particle reactive nutrients that are entering the Great Barrier Reef as well as inland waterways. This approach is based on the geochemical similarity of Nd and P and the relatively well understood Nd-Sr isotopic characteristics of different geologic provenances. Investigations of the Chaffey Dam reservoir near Tamworth NSW (Martin and McCulloch, 1999), and the Johnstone River catchment of northern Queensland, have shown that the major contributor of P into rivers is from increased erosion of the basalt derived soils which are the subject of intensive agriculture.

Another highlight of 1999 was the publication of ages of between 56,000 and 68,000 years for the Lake Mungo III skeleton now shown to be Australia's oldest human remains (Thorne *et al.*, 1999). In a related study Miller *et al.*, (1999) showed that the extinction of the large flightless bird *Genyornis* occurred at about the same time; providing strong circumstantial evidence for human involvement in the demise of the megafauna. A distinctive feature of both of these studies was the comprehensive, integrated chronological approach, using ESR and U-series (mass spectrometric and gamma counting) dating of teeth, bones and eggshells

(Professors Grün, McCulloch, Dr Mortimer and Ms Taylor), together with OSL dating of the surrounding sediments (Dr Spooner).

During his PhD studies, Mr Marianelli has completed a re-assessment of models of oxygen isotope systematics in speleothems as well as work on TIMS U-series dating of the spectacular cave deposits of South-Western Australia. The work has resulted in an unexpected finding that the present-day, interglacial climate is much wetter than previous interglacials; probably indicating shifts in the westerly wind systems. Work on sea-level changes focuses on the Last Interglacial with collaboration between Dr Esat (ARC Senior Fellow) and Professor McCulloch. A new project has been initiated on Barbados with Professor Radtke (University of Cologne).

Laboratory facilities are developed on several fronts. The solid state photon counting imaging system now being tested by Dr Spooner is showing extremely promising results and will allow for the first time simultaneous OSL analyses of relatively large numbers (up to 52) of individual grains. This is in many ways analogous to the improvement made by SHRIMP single grain compared to conventional multi-grain U-Pb zircon geochronology. The new solid state detector for OSL, together with the refurbishment of associated laboratories has now made this a world class facility with unique capabilities. Additional laboratory and office space has also been obtained in the new RSES extension. This will enable the TRITON thermal ionisation mass spectrometer and NEPTUNE ICP-MC to be housed in the same laboratory complex, both pieces of equipment being supplied by Finnigan MAT as part of a next generation instrument development program.

During 1999 there have been a number of personnel changes. Drs Daniel Sinclair and John Hellstrom have both graduated with PhD degrees. Dr Hellstrom has now taken up a Post-Doctoral position at Royal Holloway University of London and Dr Sinclair at ANSTO. Dr Sinclair is also to be congratulated for his award of the Robert Hill memorial prize. Unfortunately, due to financial stringencies it has not been possible to replace the Research Fellowship post formerly occupied by Dr Alibert and the OSL technical post occupied by Mr Hill has now been reduced to a part-time, short-term position. It is hoped that these positions can be restored by a combination of external sources and new strategic development funds.

Variations of trace metal concentrations (Mn and P) in seawater as derived from Porites coral records from the Great Barrier Reef, Australia and the western equatorial Warm Pool, PNG

C. Alibert, L. Kinsley, S.J. Fallon and M.T. McCulloch

Within the carbonate skeletons of corals an essentially continuous chemical record is preserved of the ambient marine environment. In order to better understand how these geochemical records are incorporated into coral skeletons we report here trace element abundances measured by laser ablation ICP-MS for corals living in two contrasting environmental regimes; the oligotrophic waters of North Papua New Guinea (Kavieng: 150E, 2.5S) in the western pacific Warm Pool versus the turbid waters of the inner shelf of the central Great Barrier Reef (GBR).

In the central GBR, the U/Ca and Mg/Ca ratios in a coral from Pandora Reef (Figure 1) track the sea surface temperature (SST) seasonal variations of about 7°C. For the PNG coral, both the amplitude and average value for U/Ca variations (and also Sr/Ca) are higher than those expected based on the calibration derived from GBR corals. This indicates that processes other than SST (e.g. trade winds) are the main forcing mechanism for U and Sr variations in the PNG coral. The second figure compares Mn and P at the two sites. Both Mn and P are much higher in the in-shore coral skeleton from the GBR (Mn > 0.2 ppm, P > 100 ppm), an expected consequence of the large plumes from the Burdekin River. Both Mn and P also exhibit seasonal variations similar to those displayed by U and Mg. Seasonal fluctuations have also been reported for inorganic soluble P in GBR rivers (Furnas *et al.*, 1997) which has been interpreted as being due to slow desorption of P from fine suspended sediments. In the GBR coral, Mn shows narrow positive spikes that are probably related to the re-suspension of sediments during the passage of tropical cyclones (e.g. 1994 Tropical Cyclone "Sadie" that occurs at a distance of ~73 mm from top of the coral PAN 98-2).

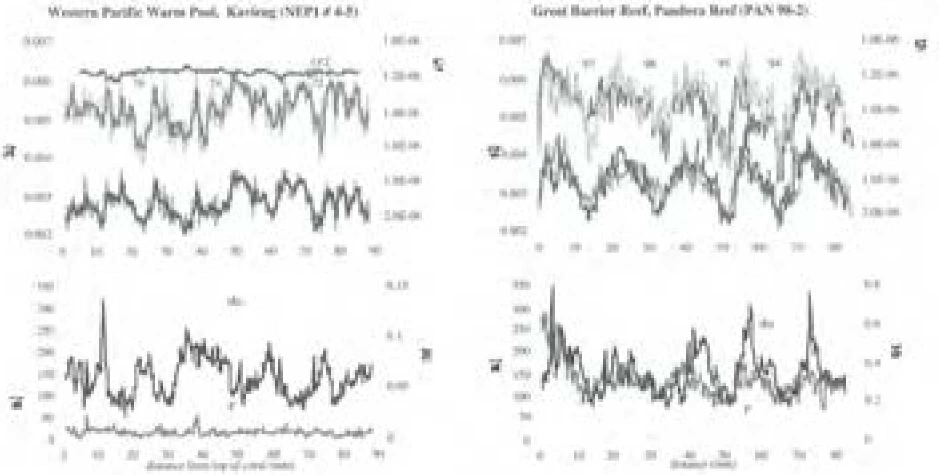

Figure 1: Mg/Ca, U/Ca ratios and Mn and P concentrations in two *Porites* corals from Kavieng (left) and Pandora Reef (right, 2 runs for U/Ca and Mg/Ca). Note the different scale for Mn between the two sites.

For the Kavieng coral, P concentrations are low (10–30 ppm) and do not show seasonal variations. In spite of its very low content, Mn, displays seasonal maxima in phase with those indicated by U/Ca, suggesting a link to trade winds. In the absence of any significant riverine source, an alternative source is proposed such as hydrothermal fluids and particulates associated with the under-sea smokers of the Manus back-arc basin. This hypothesis will be tested on other corals from the same region.

Fine-scale chronology of major flood plumes from the Burdekin River as deduced from coupled Sr/Ca (TIMS) and Ba (LA-ICP-MS) measurements in a coral from the inner shelf of GBR.

C. Alibert, S.J. Fallon, M.T. McCulloch, L. Kinsley and R. Berkelman[1]

A high-precision record of Sr/Ca (TIMS), has been obtained at nearly weekly resolution, for a large *Porites* coral head collected at Pandora Reef in Oct 1998. The top 5 years has been calibrated against in-situ sea surface temperatures measured at the nearby Orpheus Island, as part of a GBRMPA long-term monitoring program. The time-series shown in figure 2 (top) was obtained by fitting ~10 points per year of the Sr/Ca record to fine structure in the SST curve. This allows corrections to be made at approximately monthly scale to variations in the coral extension rate which ranges between 30–65 microns/day, with a minimum in July–August and a maximum in October. A least-square regression provides the following relationship: Sr/Ca = A – B*T, with A = 10.3 (±0.01), B = 0.0542(±0.0005), Sr/Ca in mmol/mol and T in °C. Realistic errors are equivalent to a temperature uncertainty of ±0.25°C and encompasses all the data. This calibration is within errors of an earlier calibration (Alibert and McCulloch, 1997) found for mid-shelf corals of the GBR, suggesting that the Sr/Ca partitioning between coraline

[1] Great Barrier Reef Marine Park Authority

aragonite and seawater is not significantly influenced by environmental parameters such as light intensity or availability of nutrients. It is noted that the high-temperature peak in mid-Feb 1998, responsible for a major bleaching event in the GBR, is well recorded by Sr/Ca variations.

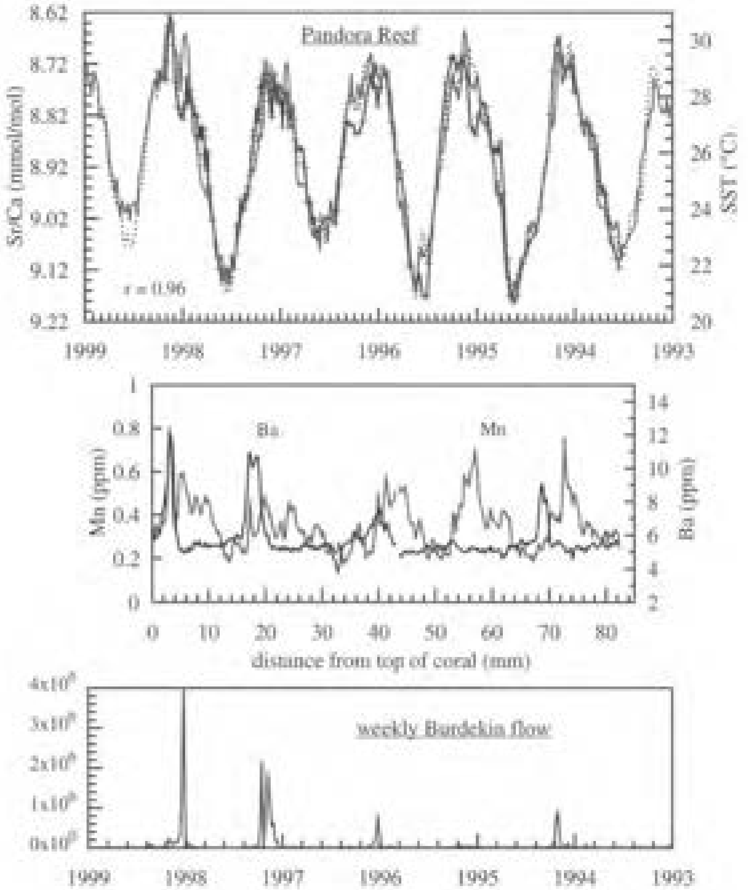

Figure 2: (top) Time fit for a *Porites* coral from Pandora Reef, central GBR and least-square fit between TIMS Sr/Ca and in-situ measured temperatures at Orpheus Island (dark grey) from GBRMPA; also reported are satellite-derived SSTs (pale grey) from IGOSS corrected to in-situ data for winter. (middle) Laser ablation ICPMS Ba (black) and Mn (grey) concentrations versus distance along a 500 µ wide track, using the NIST #614 as external standard. (bottom) Burdekin River weekly flow data (ML) from Queensland Natural Resources.

Ba was measured by laser ablation ICP-MS (Figure 2, middle) along a track close to that used for TIMS measurements and shows an average concentration close to 5 ppm. Well defined peaks are associated with the fresh water plumes of the Burdekin River, 130 km to the south-east. Depending on the path of the plume and the river flow, salinity of surface waters in the vicinity of Pandora Reef can drop from 33 (average) down to 28 (for the 1991 event), according to data and modelling developed at AIMS. As an example, during the 1994 event, the Burdekin River discharge (Figure 2, bottom) peaked around the 15th March and the plume reached the region of Pandora Reef in late March-early April. The fine time-fit derived from the Sr/Ca TIMS record was used to determine the date and duration of the coral Ba peak: the maximum of the Ba peak occurred in early to mid April for a duration of ~30 days, in excellent agreement with observations, especially when errors on the distance along the laser coral track are considered. The Ba levels in the corals provide a semi-quantitative estimate for suspended sediment loads reflecting the role of Ba desorption from suspended sediments as the flood plume enters the marine environment. This is in contrast with Mn which generally shows a seasonal pattern with only tropical cyclone "Sid" in early January 1998 being in phase with the Ba peaks. From this short record, it is concluded that coral Ba at Pandora Reef gives a precise timing for past major flood events and provides a semi-quantitative proxy for the Burdekin River discharge and suspended sediment flux.

Testing the reproducibility of coral environmental proxy records

E.-J. Hendy, M.K. Gagan, M.T. McCulloch, C. Alibert and J. Lough[2]

The combination of a number of records over a wide area is a basic technique in dendrochronology to enhance spatially significant environmental signals, while suppressing those that are localised or caused by non-optimal characteristics of individual trees. Such composites are rare in other climate proxy research, and yet the need to demonstrate replication in coral proxy data is just as important. Physiological effects and the three-dimensional architecture of coral skeletons mean proxy records are vulnerable to distortion through growth effects. In addition, proxies often reflect more than one variable, complicating their interpretation.

The most reliable environmental reconstructions should therefore be gained by combining information from several independent records. This approach has been applied to the stable isotope records from eight long *Porites* coral cores spanning the last 120 to 420 years and analysed in 5 year increments. The cores, selected from the Australian Institute of Marine Science's collection, come from seven reefs in the central Great Barrier Reef (between 17.78–18.51°S, 146.13–147.06°E). The combined records presented in Figure 3(A) and (B) were calculated from the normalised $\delta^{18}O$ and $\delta^{13}C$ core data. The number of cores contributing to the curves are plotted at the base of the graphs.

Both sea surface temperature (SST) and seawater isotopic composition are influencing the coral $\delta^{18}O$ record. The Kaplan SST data set for the 5° grid containing the central Great Barrier Reef correlates well with the coral record (r=0.52), however the instrumental warming trend measured for the 20th century is half that suggested by the $\delta^{18}O$ record. Sharp decadal variations in $\delta^{18}O$ of up to 0.3‰ are clearly replicated between cores, and if interpreted in terms of temperature, are equivalent to improbable 1.5°C shifts in SST. The isotopic composition of seawater is fractionated through evaporation, precipitation and freshwater input from river discharge. These processes are obviously influencing the $\delta^{18}O$ record. Further evidence is that the offset between the $\delta^{18}O$ record and the Kaplan SST data set occurs during the wet decades of the 1890s, 1950s and 1970s.

The complicated and poorly understood behaviour of $\delta^{13}C$ in corals has limited its use as a reliable environmental indicator. Combining the eight $\delta^{13}C$ records (Figure 3) strengthens the common feature: a depletion in values (-0.72‰ for 1840–1990), steepening towards present. The coral $\delta^{13}C$ curve strongly mirrors the change in atmospheric $\delta^{13}C$ CO_2 as recorded in ice cores (-1.03‰ from 1840 to 1990), which is attributed to the release of CO_2 depleted in ^{13}C by the combustion of fossil fuels and reduction of forest and soil carbon reservoirs. This research has shown that corals can resolve the atmospheric $\delta^{13}C$ CO_2 signal, a result that has been difficult to identify in previous coral records.

[2] Australian Institute of Marine Science, Townsville Qld

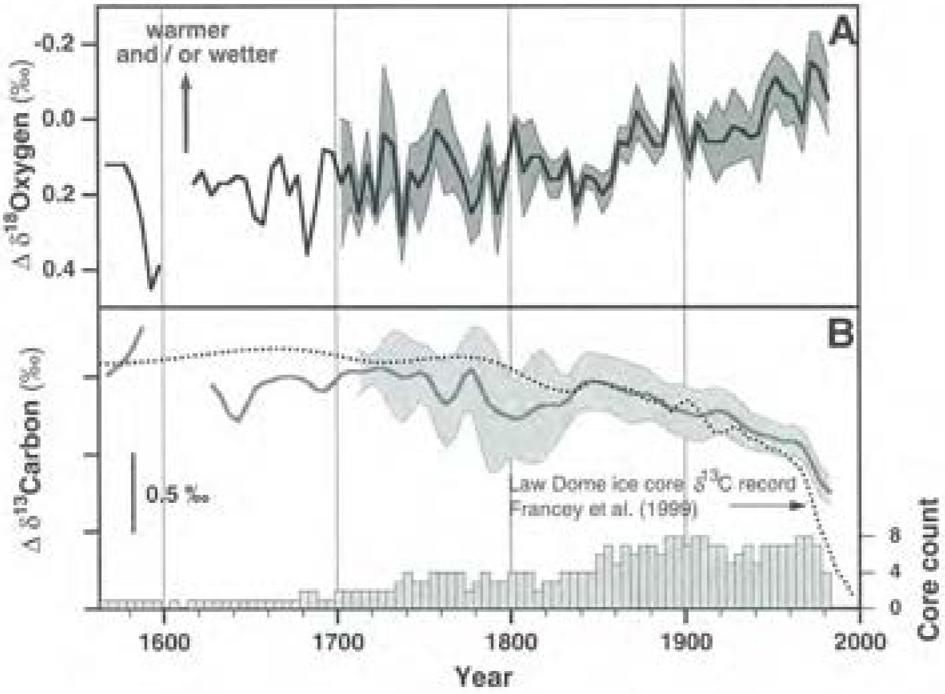

Figure 3: (A) $\delta^{18}O$ record calculated from eight Great Barrier Reef Porites corals (resolution of 5 year intervals), normalised to the period 1860–1985. The grey bounding area represents the 95% confidence interval for the curve. The number of cores contributing to each interval is plotted at the bottom of panel B. (B) $\delta^{13}C$ record calculated as for (A), and smoothed to 20 year resolution (solid curve). The 50 year smoothed $\delta^{13}C$ CO2 curve measured in the Law Dome ice core (Francey et al. 1999, dashed curve) is shown for comparison.

Porites corals as environmental recorders of mining activities on Misima Island, PNG

S.J. Fallon, M.T. McCulloch D.J. Barnes[1] and J.M. Lough[1]

In 1989 open pit gold mining commenced on the island of Misima in Papua New Guinea. Open pit mining by its nature causes a significant increase in sediment transported into the nearby coral reefs. In Misima this was exacerbated by direct dumping of soft mine waste into the ocean. This increased sedimentation and affected the nearby fringing reef to varying degrees and in some areas caused coral mortality. Sediment dumped into the reef consists of soft mine waste which is made up of quartz feldspar, greenstone and schist. These rocks have distinct chemical constituents (rare earth elements [REE], zinc and lead etc.), that are entering the near-shore environment in considerably higher than normal concentrations. In this study we evaluate whether *Porites* corals can be utilized as a tool for recording environmental input of trace elements into near-shore environments.

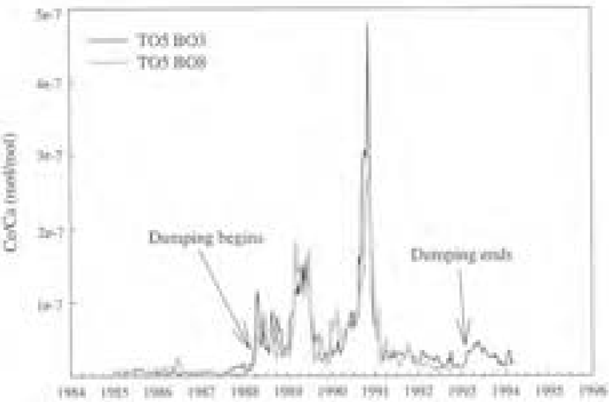

Figure 4: Ce/Ca ratios from the two high sedimentation corals. Both show dramatic increase of cerium levels after mining began in 1989.

Coral density, extension and calcification has been examined by Drs Barnes and Lough (AIMS) for the same *Porites* coral colonies as used in this study. These workers concluded, that high sedimentation did not significantly perturb coral growth characteristics. However, they did note a positive correlation between decreasing coral tissue layer thickness and proximity to the highest sedimentation, which is consistent with corals under stress. Using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) we analyzed four colonies (2 from high sedimentation, 2 from control sites) for uranium, cerium (REE), zinc, manganese, lead and barium. The two "severely" affected corals show low steady "background" levels prior to the commencement of mining. After 1988 they show dramatic increases of the cerium, zinc, manganese and to some degree lead. The Ce/Ca ratios from the two high sedimentation area corals are shown in Figure 4. The control sites, which are distal from the mining operations, do not show similar increases in these elements after mining commenced. In mid 1993 dumping ceased, and this study shows that the cerium and other elemental concentrations may be returning to pre-mining concentrations. This study indicates that trace element studies of Misima Island corals clearly record the dramatic changes in the environmental conditions at this site and provide a basis to evaluate whether subtle anthropogenic influences are occurring on corals in the GBR.

Analyzing a new technique: Measurements of Sr/Ca in corals using LA-ICP-MS and TIMS

S.J. Fallon, C. Alibert, M.T. McCulloch and J. Marshall

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) is gaining wide acceptance as an analytical tool for the analysis of trace elements in diverse range of sample materials. Semi-quantitative and quantitative elemental concentrations using LA-ICP-MS are being reported using chemically and matrix matched standards. Recent investigations using NIST glasses have shown their value as calibration standards, but there are limitations from matrix dependent biases. In order for this technique to become fully quantitative, more testing and comparison with other techniques (thermal ionization mass spectrometry (TIMS), solution ICP-MS, ion/electron microprobe etc) are needed. Here we compare TIMS versus LA-ICP-MS measurements of Sr/Ca in corals and LA versus isotope dilution ICP-MS measurements of U/Ca and Ba/Ca in corals and coralline sponges.

Using an in-house standard prepared from a finely crushed and cleaned coral we are able to provide accurate measurements of the ratios Sr/Ca, U/Ca and Ba/Ca in corals. To test our accuracy for Sr/Ca we compared the TIMS to LA-ICP-MS measurement of four corals from the Great Barrier Reef (Figure 5). The corals were from different locations and they have different growth rates, in order to test the spatial resolution characteristics of the LA-ICP-MS. The annual average and intra-annual variation are reproduced by the LA-ICP-MS with the fine scale variations having slightly higher amplitude when measured by LA-ICP-MS (Figure 5). This higher amplitude probably reflects the ~×1000 smaller sampling size of the LA-ICP-MS compared to TIMS. Whether these fine scale fluctuations represent changes in SST or growth related phenomenon remains to be ascertained.

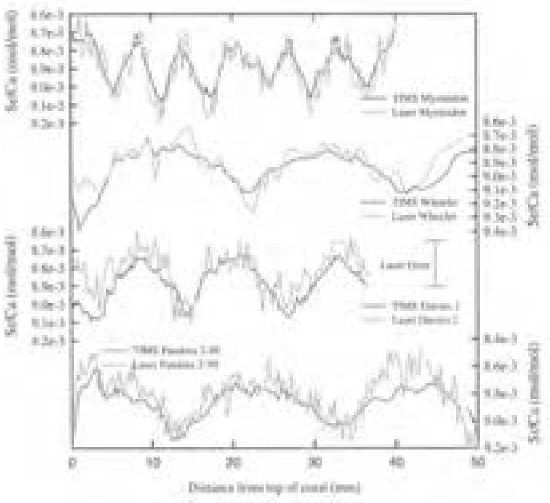

Figure 5: TIMS and LA-ICP-MS measurements of Sr/Ca at a resolution of 0.25 mm from four corals collected in the Great Barrier Reef.

Figure 6 shows the comparison between ID-ICP-MS and LA-ICP-MS estimates for U/Ca and Ba/Ca from a coral at Huon, PNG, an aragonite coralline sponge (Ribbon Reef, GBR) and a calcite coralline sponge (North Direction Island, GBR). All of these ratios are within error for the two methods. This demonstrates the accuracy of the method over a wide range (>×10) of concentrations.

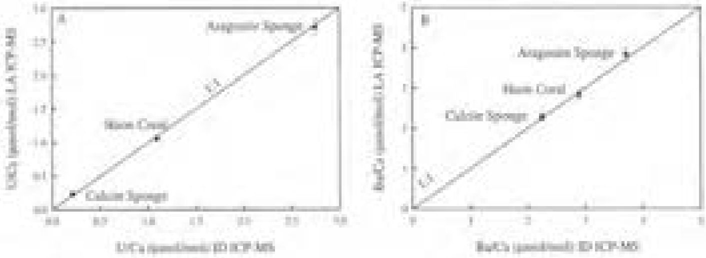

Figure 6: U/Ca (a) and Ba/Ca (b) measured by LA-ICP-MS and ID-ICP-MS in two coralline sponges and one coral from Huon, PNG.

Decadal-scale, high resolution record of sea surface temperature in the eastern Indian Ocean from proxy records of the strontium/calcium ratio of massive Porites corals

J.F. Marshall and M.T. McCulloch

Global climate has become a matter for international concern, mainly as a result of projected warming brought about by the Greenhouse effect. While this has focused world attention on the potential problems of climate change, it is also apparent that natural interannual climatic variations can have a profound impact on mankind. The most prominent of these variations is known as the El Niño/Southern Oscillation (ENSO). While centred on the equatorial Pacific Ocean, ENSO tends to perturb climates worldwide. Comparison of sea surface temperature (SST) anomalies between the Indian and Pacific Ocean suggests that ENSO does affect both, and it has been argued that the ENSO cycle cannot be fully understood without considering the effect of the Indian Ocean on SST, and whether or not the Indian monsoon modulates the ENSO signal. Records of past SST from the eastern Indian Ocean could provide clues to teleconnections between the Indian and western Pacific Oceans.

The top 25 cm of a 1.48m core of modern *Porites* coral, collected from Cocos (Keeling) atoll (12° 12'S, 96° 54"E), was measured for Sr/Ca using isotope dilution thermal mass spectrometry (TIMS), and stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) using gas source mass spectrometry. The Sr/Ca ratio is considered to be a proxy for SST, whereas $\delta^{18}O$ acts as a proxy for both SST and salinity. A twenty two year record of SST is shown by the Sr/Ca record in Figure 7.

Both the Sr/Ca ratio and $\delta^{18}O$ records show a more variable SST record compared with satellite derived SSTs for the region (1x1) degree grid) and air temerature records at Cocos (Keeling) Atoll. This suggests that much of this variation is controlled by local heating and cooling within the lagoon.

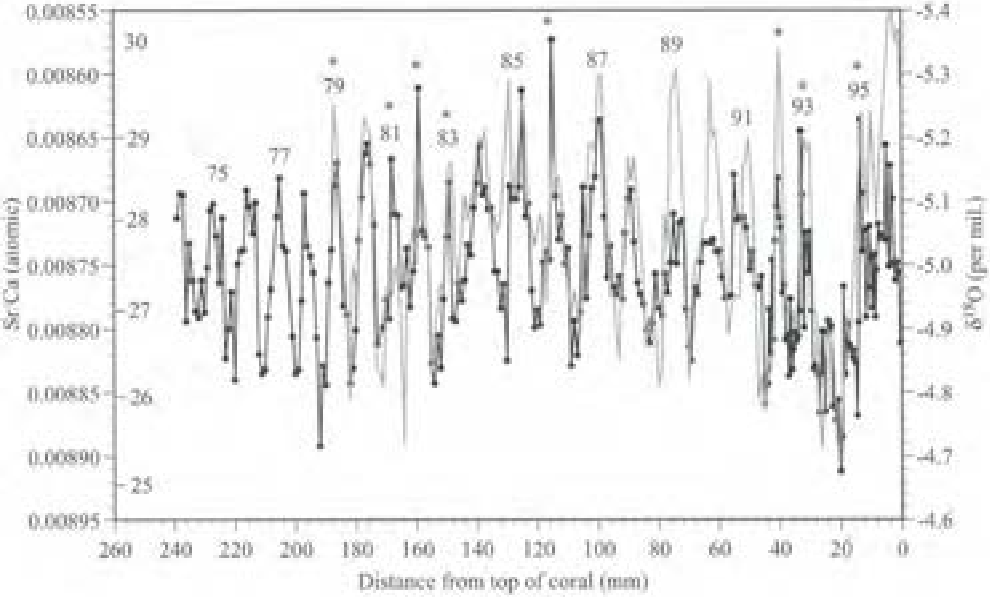

Figure 7: Plot of Sr/Ca (black) and $\delta^{18}O$ (*grey*) vs distance from the top 25 cm of a coral core from Cocos (Keeling) Atoll. Odd years are marked, and asterisks denote periods when the coral is considered to have undergone bleaching. Numbers on the inner left hand axis are indicative SSTs (°C)

The Sr/Ca record shows summer/winter variations of 1°C to 4°C, whereas the $\delta^{18}O$ record shows evidence of increased summer rainfall during 1989–92 (Figure 7). Apart from these anomalies, both Sr/Ca and $\delta^{18}O$ show a reasonably good correspondence, particularly in 1994 where summer SSTs did not exceed 27°C. Measurement of the Sr/Ca ratio in another coral shows a similar cooling at this time. In general, the extension or growth rate of the coral is about 10 mm yr^{-1}, but during some years only about half this growth is recorded. This appears to be a result of bleaching of the coral during the onset of increasing SSTs within the atoll. The onset of the bleaching has brought about a cessation or slowdown in coral calcification. Bleaching has occurred during 1981–83 and 1992–96. These periods coincide with large-scale El Niño events, but there is insufficient evidence at this stage to associate the two phenomena.

Rummaging around in the black box: fine scale trace element variations in coral skeletons challenge calcification models

D.J. Sinclair and M.T. McCulloch

A coral skeleton has been analysed at high spatial resolution (70 µm spot) using laser-ablation ICP-MS. The analysis reveals large amplitude fluctuations in uranium and magnesium over distances corresponding to days to months of coral growth. These fluctuations are strongly negatively correlated, with a slope approaching -1 (see Figure 8).

The magnitude of the Mg and U variations are too large to be caused by rapid variation in sea surface temperature or seawater chemistry. Contaminants within the coral (such as centres of calcification, microborings, and detrital phases) may explain some of the variation, but contaminant phases make up only a small volume percent of the coral skeleton, and cannot therefore account for a strong negative correlation with a 1:1 slope. This suggests that the Mg and U variations are a feature of the bulk skeletal aragonite.

Daily to monthly variation in the rate at which the coral calcifies might explain the large Mg and U fluctuations. There is still much debate over the biochemical mechanism of coral calcification. One of the leading models proposes that aragonite precipitates freely from a membrane bound pocket of supersaturated calcifying fluid. This fluid is essentially seawater, and the coral enhances calcification by raising the $CaCO_3$ supersaturation. This is achieved through an enzyme mediated exchange of two H^+ ions in the calcifying fluid for one Ca^{2+} ion. This increases the Ca^{2+} concentration in the fluid, while the raised pH results in an increased CO_3^{2-} concentration.

A trace element substituting for a major structural ion in $CaCO_3$ will be incorporated in proportion to it's ratio to that structural ion in the precipitating fluid. There remains some uncertainty about the mechanism for Mg and U coprecipitation with aragonite; however, the literature tentatively concludes that Mg^{2+} substitutes for Ca^{2+}, while $UO_2(CO_3)_2^{2-}$ substitutes for CO_3^{2-}. The effect of increasing calcification rate would be to increase the amount of Ca^{2+} and CO_3^{2-} pumped into the calcifying fluid by the coral. The higher concentration of these two ions would mutually dilute both Mg and U, leading to a *positive* (and nonlinear) correlation, rather than the negative relationship that is observed.

The simple discussion presented above ignores many of the complexities of coral calcification chemistry. Inorganic partitioning of trace elements within a crystal is expected to be reaction rate dependent. The poor understanding of the mechanisms controlling U and Mg coprecipitation prevents us modelling this rate dependence. The model presented above assumes that trace elements are passively transported to the calcifying surface in seawater taken from outside the coral. In reality, trace ions can be transported via a number of independent biochemical pathways each of which may be under a different physiological control. We hope that further analyses concentrating on a broader range of trace elements will allow us to deduce more of the physiological chemistry underlying coral calcification.

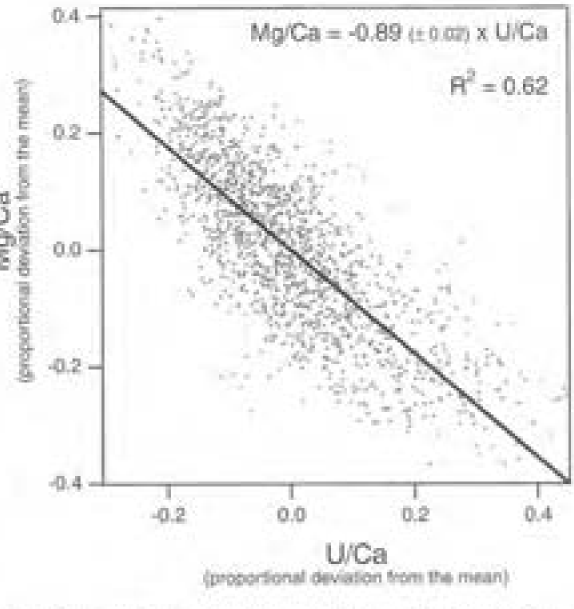

Figure 8: Mg/Ca vs. U/Ca in the Davies 8 coral. A number of short sections of the 'Davies 8' coral were analysed for Mg and U by laser-ablation ICP-MS using a 70 μm diameter spot. The data has been filtered to remove broad trends, leaving just the fine-scale variations (< 1.25 mm: equivalent to less than 1 month of coral growth). These variations are graphed as proportional deviations from the mean. The fine-scale variations are large: when converted into temperature equivalents, they span more than 20°C compared with observed daily to monthly water temperature variations of at most 4°C.

Tracing the source of sediments and nutrients (P) into the great barrier reef lagoon

M.T. McCulloch, C. Pailles[1], Philip Moody[1], C. Martin and G. Watson

An enhanced level of nutrients, especially phosphorus, is one of the main factors contributing to the degradation of near-shore coral reefs. In order to determine the sources and flux of P entering the central Great Barrier Reef (GBR) lagoon, P dynamics and Nd-Sr isotopic systematics have been investigated in sediments from the Johnstone River catchment and in several offshore transects into the central GBR lagoon. The P flux into the GBR is dominated by the transport and dispersal of fine-grained basaltic solids which have high P(3000-4000 ppm). In the Johnstone River catchment the soils are derived from alkali basalts with Nd-Sr isotopic signatures typical of plume basalts (ε_{Nd} ~ +3 to +5 and $^{87}Sr/^{86}Sr$ ~ 0.705). In contrast the more common Paleozoic granitic/metamorphic soils have lower P (300–600 ppm), negative ε_{Nd} ~ -8 and radiogenic $^{87}Sr/^{86}Sr$ >0.72 to 0.82. Using these distinctive isotopic characteristic it is shown that the coarse grained fluvial sediments of the estuary and near-shore marine environments (<5 km from the coast) are derived mainly from granitic derived detritus. Further offshore (~20 km to 30 km), adjacent to the coral reefs, fine clay-sized basalt derived soils (ε_{Nd} ~ -4 to -5) become increasing important, contributing >90% of the P, although making up only ~40% of the total terrigenous component. Phosphorus abundances and equilibrium measurements in the marine sediments, indicates that P enters the GBR lagoon by a two-stage process. Firstly, during episodic flood events, P is transported into the GBR lagoon via P retentive fine-grained suspended sediments of predominantly basaltic origin. Secondly, after deposition of the flood-plume sediments, desorption of P occurs mainly in regions of sediment

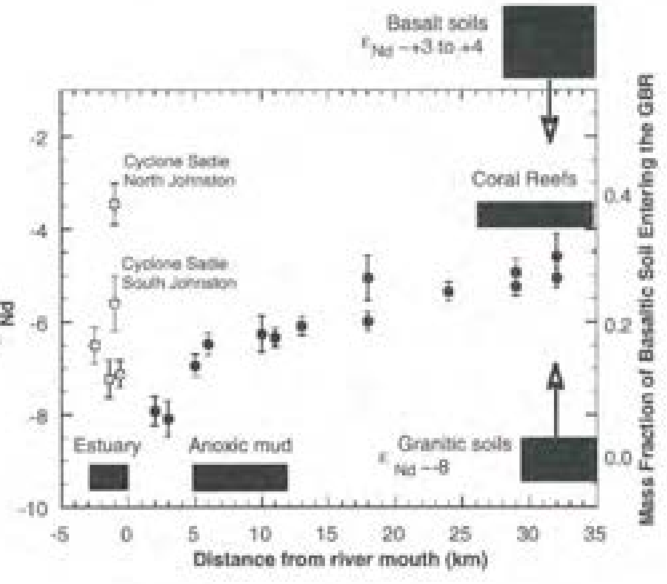

Figure 9: Plot of the Nd isotopic composition of marine bottom sediments (solid) estuarine sediments (open) and suspended sediments, the latter collected during the 1994 cyclone Sadie from the North (NJ) and South (SJ) Johnstone Rivers. In the coral reefs basalt derived soils contribute ~40% of the total terrigenous sediment, but >80% of the phosphorus.

[1] Department of Natural Resources, Indooroopilly Qld

anoxia, resulting in release of PO_4^{3-} via reduction of particulate ferric phosphates. Phosphate release into the seawater maybe enhanced during sediment re-suspension events associated with cyclones. This study demonstrates that conservation strategies that minimise loss of P-rich basaltic soils into river systems is a key element in the preservation of coral reefs in the GBR.

Strontium isotopes trace the supply of fertilizer to waterbodies

C.E. Martin and M.T. McCulloch

The inland waterways of Australia are extremely sensitive to excess nutrients especially from phosphate based fertilisers. In order to better constrain the influence of P fertilisers on catchments, Sr isotopes have been measured in storm water samples from Bundella Creek in the Liverpool Range. The catchment is dominated by Tertiary basalt (<65 million years age) and includes a number of different land-uses including native vegetation (forest), pasture, and cultivation. In addition, samples were collected at the channel near the house of the farmer undertaking the sample collection, preparation and storage. The creek, upstream of the cultivated site, drains predominantly the forested regions of the catchment but also some pasture regions as well. Some samples were also taken at the lower end of Bundella Creek.

The range in $^{87}Sr/^{86}Sr$ in these samples is quite small, from about 0.70360 to 0.70395, but clearly distinguishable relative to the analytical precision (±0.00002 or better). These values are all quite similar to the isotopic composition of basalts and pristine basalt soils from Chaffey Reservoir catchment to the east (Martin and McCulloch, 1999). However, there is a significant difference in isotopic composition of waters draining areas of different land use. The Sr isotopic composition increases from the forested site (0.7036–0.7037) to the pasture (0.7037–0.7038) to the cultivated site (0.7039). There is greater scatter in the P concentrations of the waters from each site than in their Sr isotopic compositions. The variation in P concentrations may be a seasonal effect, or it may reflect a variable dilution effect. However, in general, higher P concentrations are related to higher Sr isotopic compositions. The reason for this is almost certainly the application of fertilisers to the agricultural (cultivated and pasture) lands. Phosphate fertilisers have $^{87}Sr/^{86}Sr$ ratios of 0.708–0.709 (Martin and McCulloch, 1999), much higher than the natural basaltic sources in the catchment.

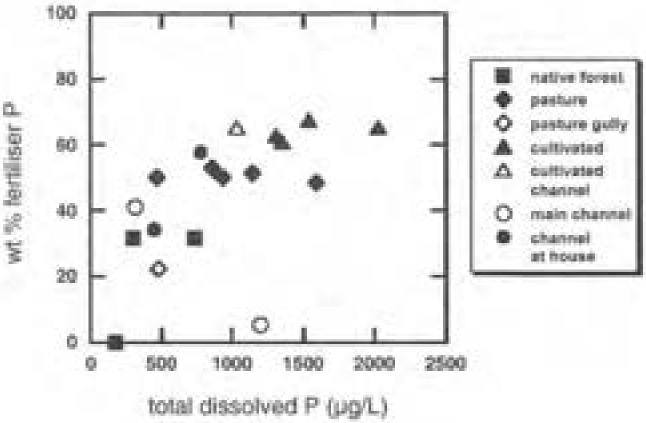

Figure 10: Plot of wt% fertiliser P calculated using Sr isotopic compositions of the dissolved load.

The Sr isotopic composition of these waters may be used to estimate the proportion of their dissolved load that is derived from fertiliser. For the fertiliser, we used the average elemental and isotopic composition of phosphate fertilisers from the Chaffey Reservoir study, $^{87}Sr/^{86}Sr$=0.70871 and for the natural catchment a value of 0.7036, which is close to the lowest measured valued. In order to relate the wt % fertiliser to the P contribution, it is necessary to make the same assumptions about proportional contributions as for Sr. This calculation shows that about 50% of the P in the stormwaters draining the pasture is derived from fertilizer, and for the cultivated land it increases to about 60%. Waters derived from different landuse areas have a fairly constant proportion of their P derived from fertilizer, despite large differences in absolute concentration. There are some uncertainties in the calculations, particularly in the 'natural' catchment endmember, but nevertheless these results illustrate the utility of this tracing approach.

Tracing the source of contaminants in the Llobregat River, Barcelona, Spain

A. Canals[1], C. Martin and M.T. McCulloch

Surface and river waters are a valuable resource that needs to be protected. The processes that affect their contamination are complex, demanding the use of new field and laboratory methods. The study of the strontium and neodymium isotopic composition of the dissolved and suspended load of the Llobregat River, Spain, is part of a project that links standard chemical parameters used in hydrological studies with isotope analyses. of light elements such as sulfur, oxygen, nitrogen. The study aims to trace not only the source of chemical components of the river but also to better understand the geochemical processes (mixing, reduction-oxidation, uptake or release by precipitation or dissolution) occurring within the river. The Llobregat River is the main recharge source of an aquifer system, by means of infiltration through the river bed in the lower valley and delta, and is an important part of the water resource for the city of Barcelona and its metropolitan area.

Strontium and neodymium isotope measurements have been performed on suspended sediment and water from the Llobregat river. The Llobregat, located in the NE of Spain, is a typical Mediterranean river with a drainage area of 4948.4 km^2 and a mean discharge of 100 m^3/s. The river crosses a number of distinct geological units, with its source situated in the Eastern Pyrenees, about 150 km north of Barcelona on Devonian limestones. In its central part the river flows through a Paleogene Basin where evaporites outcrop and where potash-mining activity has taken place since Neolithic times. The chemistry of the river clearly shows the influence from the evaporites, with high concentrations of chloride (up to 783 ppm) and potassium (up to 411ppm). Close to the Mediterranean sea, the river crosscuts the Catalonian Coastal Ranges, made up of Hercynian basement and Mesozoic to Cenozoic cover. The Hercynian basement consists of Paleozoic sedimentary rocks and late Hercynian granites and was completely peneplaned by a pre-Triassic erosion surface, upon which the Mesozoic sedimentary sequences were deposited. The Quaternary delta is comprised of conglomerates, sandstone and marine marls.

All samples analyzed in this study were collected in June 1997 and 1998. The month of June was chosen because it has the lowest rainfall and therefore results in the least dilution of any anthropogenic input. The strontium isotopic ratios of the suspended load range from 0.70784 to 0.71375. The observed variation can be explained by variation in the proportion of minerals as well as differences in the ages of the mineral provenance. Most of the data fall in a restricted band on a plot of $^{87}Sr/^{86}Sr$ ratio versus illite content of the suspended load, with the $^{87}Sr/^{86}Sr$ ratio increasing with increasing illite content. Only three samples, located in areas where the waters drain Paleozoic age materials, plot out of the band. The homogeneity of the ε_{Nd} values (-11.5, n=5) is consistent with a simple two component mixing for the suspended sediments, as there is little influence on the Nd isotopic composition of the unradiogenic strontium end-member (carbonates and sulfates).

[1] University of Barcelona, Spain

The waters have a high concentration of strontium, in accordance with a natural source dominated by high solubility chemical sediments, evaporites and carbonates. Strontium concentrations range from 0.2ppm in the headwaters to 7.7ppm in one main tributary and $^{87}Sr/^{86}Sr$ ratio varies from 0.70784 to 0.70916. Although nearly all the data plot between the $^{87}Sr/^{86}Sr$ ratios for Devonian and Paleogene sea water values, which could be interpreted as a result of a natural source for the strontium, most of them plot outside of any mixing line that can be generated from these two sources. A number of samples have a very limited range of $^{87}Sr/^{86}Sr$ along with highly variable strontium concentrations. The similarity of the isotopic composition of these samples to that of fertilizers used in the area and the positive correlation between the nitrogen content of the waters and their strontium concentration provide strong evidence of a fertilizer input. On the other hand, the most radiogenic samples, with values higher to the Devonian sea water value, correspond to the ones with highest phosphorus content. In most cases phosphorus and nitrogen positively correlate, but for these particularly high concentration samples no clear correlation exists. This, together with the location of the samples near population centers, points to an additional source for phosphorus, most likely from detergents.

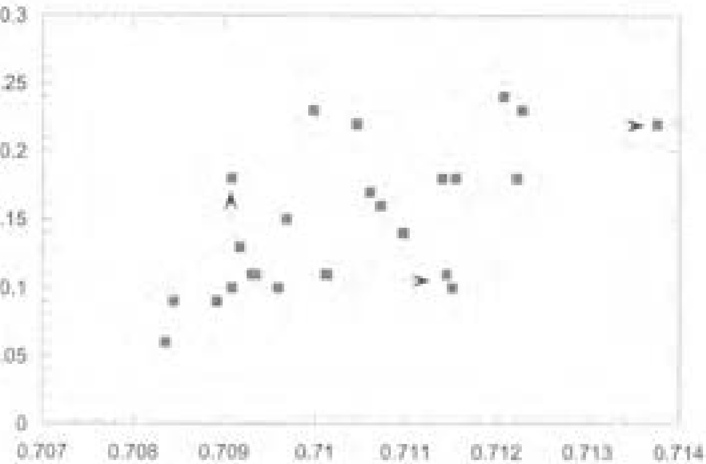

Figure 11: 87Sr/86Sr ratio of suspended sediment versus the illite proportion of this sediment. The box is a mixing band between an unradiogenic member with low illite content and a high radiogenic member with high illite content. Horizontal arrows point towards samples related to an older source. Vertical arrow indicates that sample 46 has mineral phases not considered on the illite ratio.

Correlated Uranium and Sea Level Fluctuations in Late Quaternary Oceans

T. Esat and Y. Yokoyama

Residence time of Uranium in the oceans with respect to riverine inflow is estimated to be about 300-600 thousand years, a time span accessible to U-series disequilibrium dating of corals which concentrate U from seawater in their skeletons. The principal supply of dissolved U to the oceans is derived from chemical weathering of continents and is transported by rivers. Radioactive decay and alpha recoil of ^{238}U and subsequent preferential leaching from damaged sites results in excess of ^{234}U relative to equilibrium levels and $^{234}U/^{238}$ activity ratios greater than unity are found in river waters. Current oceanic $^{234}U/^{238}U$ activity ratio measured in modern corals is 1.149±0.002.

Uranium is unique among other dissolved chemical elements in the oceans in several respects. It carries an in-built clock in ^{234}U, enabling high precision dating of corals that grew during the late Quaternary. The $^{234}U/^{238}U$ ratio in seawater, at the time of coral growth, can be derived from coral age measurements and provides a precise chronology of U abundance in seawater as isotope ratios are less affected by variations in local conditions compared to concentration measurements. Uranium is highly soluble under oxidizing conditions, in reducing environments it can be particle reactive and insoluble. Therefore, global climatic changes influencing the extent of oxic, anoxic zones in ocean sediments can influence U concentrations. Variations in the $^{234}U/^{238}U$ ratio of corals, ranging in age from 80 to 200 ka, have been identified but are mainly attributed to diagenetic effects. Last Interglacial coral reefs in Western Australia show a tight clustering of ages between 128 ka and 122 ka at elevations of +3m relative to present sea-level. When strict selection criteria are applied to select samples within a range of ±4‰ in $\delta^{234}U$ they form a band that is displaced higher from the modern 149‰ value by about 4‰. As several different WA reefs have consistent distribution of similar LI ages, the data is best explained by assuming a 4‰ difference in the ^{234}U abundance of the oceans between 125,000 years ago and at present. In contrast to positive excursions in $\delta^{234}U$, systematic negative variations have not been clearly established.

We have measured $^{234}U/^{238}U$ ratios of 30,000 to 50,000 year old corals from the Huon Peninsula terraces II and III, including sub-terraces, that have systematically low $\delta^{234}U$. Additional coral data from the last two major terminations, from the last glacial to Holocene and from the penultimate glacial to Last Interglacial show significant and rapid fluctuations in $\delta^{234}U$ correlated with sea level change and require mechanisms to allow global variations in $\delta^{234}U$ on short, millennial timescales.

Results from Huon Peninsula for the period from 90 ka to 140 ka, that includes the transition from the penultimate glacial to last interglacial and the 105 ka interstadial, are shown in Figure 12. The lower panel in Figure 12 represents the sea level curve, derived mainly from consideration of ages and location of corals in Aladdin's Cave at Huon Peninsula. The upper panel in Figure 12 shows the variation in $\delta^{234}U$ over the same time interval. There is a striking resemblance between the variations in $\delta^{234}U$ and changes in sea-level that is unlikely to be coincidental. All of the major features of the sea-level curve are reproduced in $\delta^{234}U$ and there is a 25‰ difference between the highest and lowest values or a 17% variation relative to the present concentration. Corals from Aladdin's cave and vicinity at reef tract VI record several snap-shots of sea-level change as the sea level passed through the Cave location and surrounding area at least four times from 145 to 90 ka. Because of the uplift rate of 1.6 m/ky at this location the Cave kept up with sea-level rise for longer periods than would be the case for a stable site. Conversely, during periods of sea-level fall the time window for coral growth at a particular elevation would be shorter. Assuming that $\delta^{234}U$ was rapidly changing, corals that grew at the Cave site during any one transit maybe be expected to record variable $\delta^{234}U$ concentrations as shown in Figure 12. Within the analytical precision of the data, there are no variations in $\delta^{234}U$ during interglacial periods, when sea levels are relatively stable and $\delta^{234}U$ is constant over periods of 10,000 years. This last observation imposes severe constraints on any proposed mechanism to explain the connection between sea-level change and $\delta^{234}U$. Just prior to the start of the Last Interglacial at 130 ka, there appears to be a significant overshoot in $\delta^{234}U$ well above the 153‰ steady state value. There is a hint for a similar overshoot at the start of the Holocene. Clearly, a linear relationship between sea-level change and $\delta^{234}U$ is not appropriate. However, the correspondence between $\delta^{234}U$ and sea-level change as depicted in Figure 12 may give new insights into both the residence time and recycling of U within the oceans.

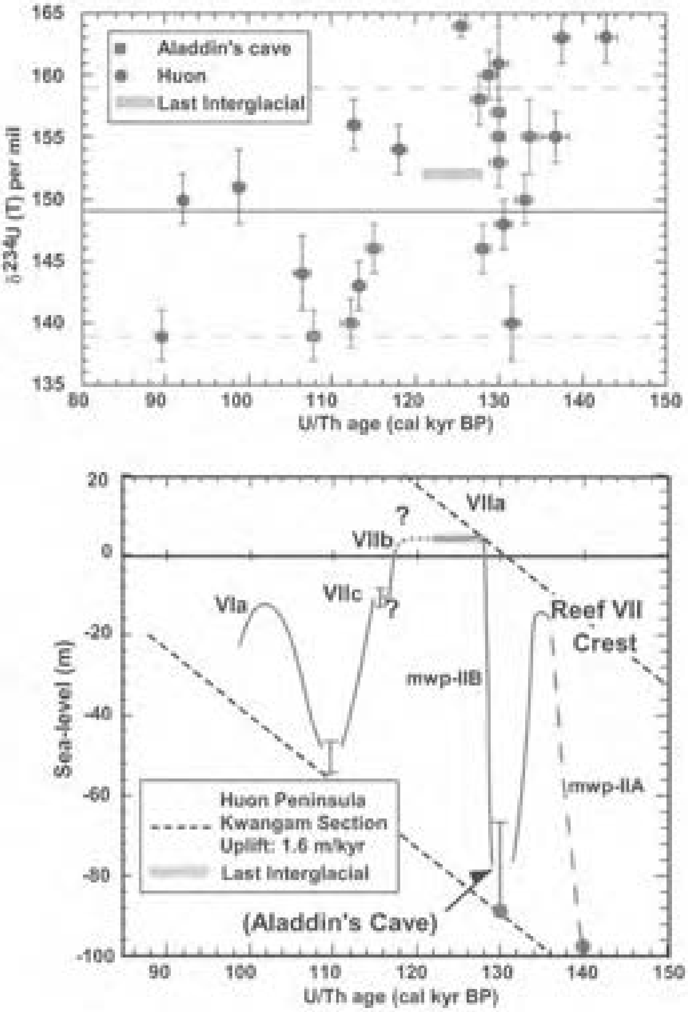

Figure 12: Plot showing rapid fluctuation in $^{234/238}U$ ratios correlated with changes in sea level.

A 500 ka high resolution effective precipitation record for South-West Western Australia from speleothem formation event

P.C. Marianelli, L.K. Ayliffe and M.T. McCulloch

High-resolution long-term records of climate are essential for our understanding of the evolution of Australian terrestrial environments, as well as for the validation of climatic models. Most of the evidence for past changes in rainfall, in particular, the balance between precipitation and evaporation, comes from the south-east of the continent, with comparatively little information available from the western margin. Some of the most significant changes in Australia's climate has occurred beyond the limit of radiocarbon dating (30,000–40,000 years) with most of the evidence being restricted to the last glacial cycle. Because the processes controlling speleothem formation are closely linked to water availability, and because they can be accurately dated by the

TIMS ^{230}Th/^{234}U method back to ~500 ka, the timing of speleothem deposition can be used to document long term fluctuations in regional water balance. High resolution records can be obtained by constructing cumulative frequency distributions of speleothem deposition events over time. The method was successfully applied to the Naracoorte region, in south-east SA., and has now been applied to the Margaret River region, south-west WA. Results from a data set of 50 ^{230}Th/^{234}U TIMS dated speleothem samples (37 being shown in Figure 13 with the SPECMAP normalised δ^{18}O record) indicate that deposition occurred mostly during stadials and interstadials of the last 4 glacial-interglacial cycles. Four principal depositional events are identifiable: 0–16 ka; 22–35 ka; 170–200 ka and 280–360 ka. Deposition is initiated sometime after the interglacial, and in 3 of the last 4 cycles occurs right up to the glacial maxima. Glacial maxima appear as comparatively arid, as do the previous 4 interglacials. Significantly, the Holocene is the only interglacial that appears comparatively wet. The record suggest that the Holocene, at least for south-west Western Australia, is a poor analogue for past interglacials.

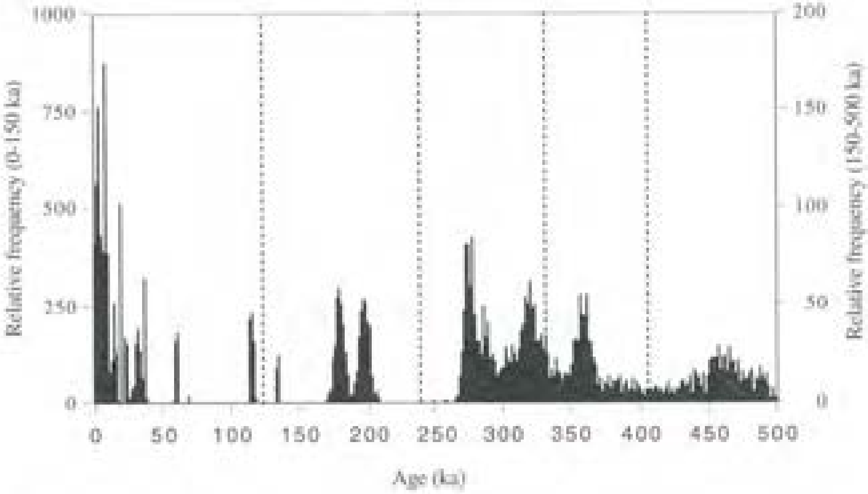

Figure13: Cumulative frequency distribution of speleothem deposition in southwestern WA over the last 500 ka, with the SPECMAP normalised δ^{18}O record (solid line). The dashed lines represent the timing of previous 4 interglacials.

Border Cave revisited: revised ESR chronology and an update on hominids BC1 to BC8

R. Grün and P. Beaumont[3]

The Border Cave in South Africa is an important archaeological site because it contains some of the earliest modern human remains. In 1990 we published an elaborate ESR chronology on tooth enamel samples recovered from the sedimentary sequence at Border Cave. Although spanning between 28 to 140 ka, the results were disputed because the ESR data were somewhat younger than expected. The major points of contention were:

1) the ESR results were significantly lower than the radiocarbon data on the same layers;
2) the ESR results were significantly younger than the amino acid chronology;
3) the age for the Howieson's Poort industry was too young and its duration too long.

[3] McGregor Museum, Kimberley, South Africa

There are a number of reasons for re-assessing the 1990 data. First of all, the data set represents the most detailed ESR sequence published so far. Furthermore, the site is ideally suited for ESR dating, because no samples contain significant amounts of uranium, thus, differences caused by modelling U-uptake are virtually negligible. Border Cave is therefore an ideal test case for ESR dating.

Since 1990, the following has changed in ESR data evaluation:

1. The fitting of the dose response curve is now carried out with a more appropriate algorithm and errors are calculated with an analytical method;
2. In 1994, we carried out a detailed gamma survey of the cave, showing that the earlier measurements were correct but some layers have a more complex gamma ray distribution than originally supposed.
3. In 1997, experiments and Monte Carlo simulations were carried out at McMaster University for the assessment of beta attenuation factors. These new attenuation factors are significantly smaller than those previously used.
4. In 1998 new dose rate values were published by a research group at the University of Oxford which are slightly different from previous values.

Figure 14 shows the revised chronology for Border Cave. It also includes samples 753 and 754 from 5WA which were analysed after the original study.

Samples from Border Cave were also analysed by a variety of other dating techniques, particularly radiocarbon and amino acid racemisation:

Table 1: Comparison of ESR data with independent age estimates

Unit	^{14}C (Beaumont)	^{14}C (Miller)	AAR (Miller)	Revised ESR
1 BS LRC	31-40	38±1		33±1 ka
1 WA	31-48	38-40		35-42 ka
2 BS up	43->49	> 49	47±5	41±2 ka
2 BS LRC			56±6	48±1 ka
2 WA			69±7	63±2 ka
4 BS/4 WA1			>100	80-122 ka

AAR = amino acid racemisation

The comparison of the revised ESR data set with independent chronologies shows now good agreement. A recent compilation of amino acid racemisation data from other sites concluded that the age of the Howieson's Poort industry was centred on 66±5 ka. The revised data set confirms this estimate with a time span of between 60 and 79 ka.

The study demonstrates that ESR can provide precise and accurate dates for at least the last 200,000 years. The two modern hominid remains that were found in sedimentological contexts, BC5 and BC3, have ages of about 66 ka and 34 to 79 ka, respectively. BC1 and BC2, which were tentatively correlated with layers 4 BS or 5BS may be as old as 200,000 years. However, the exact age of BC1 and BC2 can only be established by precise, direct dating analysis, possibly combined Th/U - Pa/U dating.

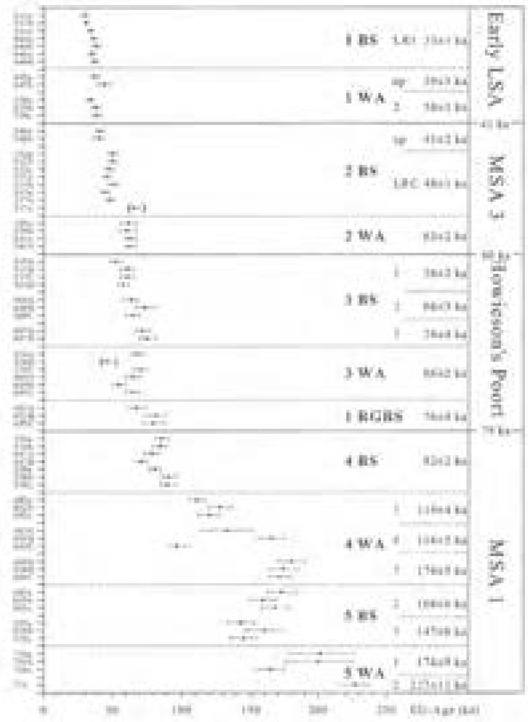

Figure 14: Revised ESR chronology for Border Cave. Lowercase letters following the sample number denote sub-samples of a single tooth, capital letters separate enamel fragments. The two bracketed results were not used for the calculation of the average ages of the units.

The Photon-counting imaging system (PCIS)

N.A. Spooner

Optical dating of sediments has conventionally relied on the detection of composite signals from multiple-grain aliquots, and more recently on new single-aliquot (single-grain) protocols relying on sequential measurements performed on the same aliquot. However these approaches suffer disadvantages: uncertainty of complete resetting when multiple-grain aliquots are used; considerable laboratory time required to measure each individual grain for single-grain dating. The latter means that statistically sound single-grain data sets are in practice awkward to collect, and furthermore, properties of the quartz dose response curves make some quartz not amenable to dating by the regenerative methods which form the basis of these techniques.

These handicaps, among others, presently inhibit single-grain dating from realizing its full potential, but progress may be made through the continued development of single-grain dating protocols with the PCIS, using simultaneous measurement of arrays of individual grains (see Figure 15). Observations of quartz single-grains have also revealed a range of previously unknown but apparently ubiquitous luminescence emission bands at wavelengths > 650nm; these are now under investigation to determine their potential for dating and dosimetric applications.

The PCIS is currently a unique facility, and while its main purpose is simultaneous dating of arrays of individual mineral grains, the dual advantages of the PCIS over conventional photomultiplier-based luminescence readers, namely spectral response extending from the UV into the near-IR, and spatial resolution enabling identification of the position of origin of detected photons, open up numerous novel applications for this system in Quaternary science, particularly to fluvial and marine environments, and the use of single quartz grains as small as 1 µg as tracers in studies of soil processes. Also now possible are the dating of slices of suitable stone artifacts, and ground-breaking investigation of the use of man-made phosphors, particularly Al_2O_3:C, for environmental dosimetry. The latter has great value for *in-situ* gamma ray and cosmic ray dose-rate measurement for luminescence dating and, along with porcelain, for retrospective nuclear accident dosimetry.

Investigation of luminescence mechanisms can also be uniquely performed. For example the phenomenon of short-timescale charge loss in feldspar from apparently deep trapping sites is well known and has been widely studied previously but the mechanisms governing this effect remain little-known, with debate as to whether they are thermally-assisted or athermal quantum mechanical tunneling processes. The PCIS permits direct observation of this fading by detection of the red recombination phosphorescence, and so is enabling laboratory testing of the competing theoretical models. The intended benefits for optical dating of feldspathic materials are dating protocols designed to account for this serious effect.

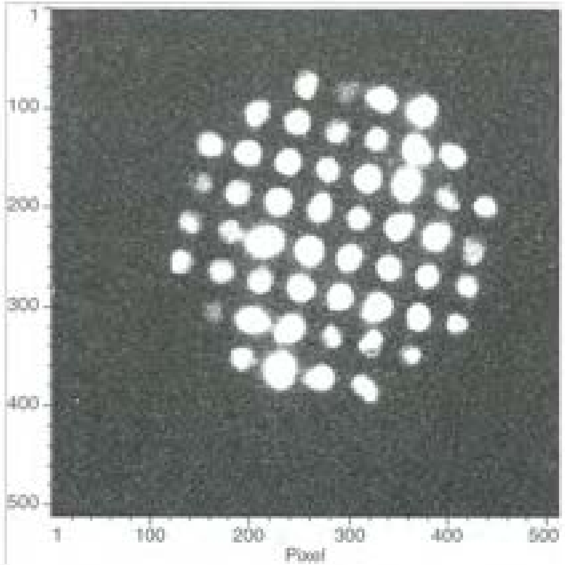

Figure 15: An array of 52 quartz grains of 350–425 µm diameter, from Lake Woods, Northern Territory, are imaged in their own thermoluminescence following a 3 Gy test dose. The emissions detected range from 390– 610 nm. The brightest grain here has a light sum of approximately 330,000 photons.

ORE SYSTEM STUDIES

The Centre for Advanced Studies of Ore Systems (CASOS) is a joint initiative between RSES and the ANU Department of Geology (The Faculties). CASOS links together researchers with a common research and training focus on themes dealing with various aspects of the formation of ore systems.

The CASOS mission is:

- To advance fundamental understanding of processes involved in the genesis of large and economically significant mineral resource systems on a lithosphere and province scale.
- In collaboration with the international minerals industry, to develop and apply new techniques and new models to drive the development of new minerals exploration concepts, as well as strategies to direct resource definition and mine development more effectively.
- To provide high level training of graduate students and postdoctoral fellows so that Australian scientists are at the international forefront of ore systems research and minerals exploration technology.

Expertise at ANU in the development and application of new microanalytical techniques, high-pressure/high-temperature experimental facilities, and modelling capabilities, provide unique opportunities to explore some of the fundamental physical and chemical processes involved in ore genesis from metal source, through the transport path, to resource accumulation sites. Ore Systems research at ANU is conducted within six programs:

- Ore Fluids
- Deformation and Fluid Pathways
- Magmatic Processes
- Stable Isotope Studies
- Radiogenic Isotope Systems
- Diamond Systems

During 1999 at RSES, Ore Systems research was conducted across a number of the School's Groups, but principally in Ore Genesis, Petrochemistry and Experimental Petrology, Petrophysics and Geophysical Fluid Dynamics.

A major focus of our activities continues to be the relationship between gold mineralisation and the evolution of Archaean, granite-greenstone terrains in the Yilgarn craton of Western Australia. Dr M. Palin and Ms Y. Xu have been using stable isotopes to study the genesis of the gold deposits in the Kalgoorlie-Kambalda area of Western Australia. It has been known for some time that mesothermal gold deposits are commonly hosted by Fe-rich host rocks, and this has lead to the suggestion that the gold precipitated as a consequence of desulphidation, when sulphur in the ore fluid reacted with Fe in the wall rocks. However many important gold deposits are not hosted by Fe-rich wall rocks. Palin and Xu have found that the sulphides associated with the highest gold grades at Kambalda have the lightest sulphur isotopes. They have shown that this relationship results from oxidation of the ore-forming fluid which converts sulphur in the auriferous fluid from sulphide to sulphate, destabilising the gold-carrying sulphide complexes in the fluid and causing gold to precipitate. Destabilisation of the gold-carrying complex and precipitation of gold can therefore occur both as the consequence of reduction or oxidation of sulphur in the ore fluid. It appears that it is the second of these mechanisms that is the more important, because many of the world's giant gold deposits, including the Golden Mile, Hemlo, Kirkland Lake and Hollinger-McIntyre, have sulphides with light sulphur isotopes, indicative of oxidised ore fluids. Oxygen isotopes have been used to show that formation of the gold deposits also involves mixing between a high-temperature deep-crustal fluid and a low-temperature, presumably oxidised, fluid that is probably seawater or meteoric water. The conclusions of Palin and Xu are being further tested at the Golden Mile by Mr C. Heath as part of a new PhD project that is being funded through the SPIRT program with Kalgoorlie Consolidated Gold Mines. Finally, Dr Loucks has found a relationship between Archaean mesothermal gold deposits and anticlines which has lead to the suggestion that anticlines act as a focussing mechanism for metamorphic fluid flow.

Professor S. Cox, in collaboration with WMC Resources Ltd and University of Newcastle PhD student, Mr K. Ruming, is investigating structural and deformational controls on fluid flow associated with gold mineralisation in faults, shear zones and associated fracture systems at the St Ives Goldfield, near Kambalda in Western Australia. Fluid-pressure-driven growth of faults and reaction-weakening in the gold-hosting structures has been found to influence their localisation. Accordingly, current work is focussing on understanding how the distribution of vein-rich and vein-poor mineralisation across the 20 km long, 5 km wide goldfield relates to the distribution of fluid pressure regimes in the fault/shear controlled hydrothermal system that generated gold mineralisation. A contractional jog on a major shear system is recognised as playing a key role in nucleating low displacement structures which host some of the major mineralisation at St Ives. The ore-hosting structures are being interpreted as aftershock structures associated with major slip events on adjacent, crustal-scale shear systems.

A principal focus of research in the Ore Genesis Group is the development of copper and gold deposits at convergent plate margins. This research program involves three PhDs and Dr R. Loucks. Mr B. Rohrlach has been analysing oxygen isotopes in hydrothermally altered volcanic samples from the Tampakan stratovolcano, which hosts a major porphyry copper-gold deposit in the Philippines. The isotopic study examines the interaction between magmatic hydrothermal fluids and meteoric water, as influenced by volcanic topography on the hydrology of the ore-forming system, and the relationship of the fluid mixing to ore deposition. Mr B. Setiabudi has analysed samples from Kelian gold mine in Indonesia for major elements and for a wide range of trace elements. The major elements and some of the trace elements have been affected by the extreme hydrothermal alteration of the mine area, so samples from the unaltered and petrological similar Magerang area to the northwest were also analysed for comparative purposes. Trace element ratios, for elements that are normally regarded as immobile in hydrothermal fluids, are the same for the two areas, suggesting that the Magerang data provide a good analog for the Kelian volcanics and can be used to study the chemical evolution of the ore forming system without the complication of alteration. Mr J. Ballard has been studying the giant Chuquicamata copper deposit in Chile. This year he used the excimer laser (ELA) ICP-MS to date igneous zircons in the three porphyries in the mine and showed that they span a resolvable age range, consistent with the hypothesis that Chuquicamata owes its enormous size to three superimposed porphyry systems. He also used variations in the Ce anomaly in zircons to show that the productive porphyries in the Chuquicamata area crystallised from a more oxidised magma than the barren intrusions.

A feature of the Tampakan, Chuquicamata and Kelian studies is that Y and the heavy rare earth elements decrease with increased magmatic differentiation in the felsic suites associated with the ore deposits. This is unexpected because these elements are usually "incompatible" in major igneous minerals, and so accumulate in the residual melt as magmatic differentiation proceeds. The unusual depletion trend is attributed to extensive amphibole fractionation and implies that the ore-producing systems are unusually water-rich. The addition of water to a magma expands the stability field of amphibole at the expense of plagioclase. As a consequence, it should be possible to use variations in Sr, which partitions strongly into plagioclase, and Y, which partitions into amphibole, to distinguish ore-bearing and barren felsic systems. Dr Loucks has shown that the Sr/Y ratio in fertile segments of convergent margins increases with fractionation but decreases in barren segments. Furthermore, within ore-bearing segments, the productive stocks and porphyries have higher Sr/Y ratios than barren intrusions. This study suggests that Sr/Y ratios will be a valuable aid to mining companies in the exploration for copper and gold deposits at convergent plate margins.

Professor Cox, in collaboration with Dr S. Munroe (SRK Consulting), has been examining the coupling between stress states and fluid pressure regimes in generating the fault/fracture system which hosts the giant intrusive-related gold deposit at Porgera in PNG. The development of suprahydrostatic fluid pressures, and a change in the stress regime during the evolution of this intrusive-related hydrothermal system, is a key factor controlling a change from distributed fluid flow to highly localised, fracture-controlled flow. Early distributed fluid flow produced high-tonnage, low grade mineralisation, whereas the later fault-hosted flow regime produced extremely rich mineralisation.

Activities in the Petrochemistry Group complement the field-based and analytical approaches on convergent margin Cu-Au deposits. PhD student, Mr A. Hack, and Dr J. Mavrogenes are conducting an experimental campaign to explore Cu solubility in supercritical and two-phase aqueous solutions, Cu solubility in silicate melts, and the critical issue of Cu partitioning between silicate melts and co-existing vapour. Significant advances are being made using high pressure/high temperature laboratory facilities at RSES and the ANU Geology Department, in conjunction with ELA-ICP-MS techniques. The study is providing fundamental information on the processes leading to the formation of porphyry-type mineral deposits at convergent plate margins.

Using the high temperature laboratory facilities in the Petrochemistry Group, Drs Mavrogenes and H. O'Neill are studying sulphur solubilities in silicate melts under controlled fO_2 and fS_2 conditions. The results indicate that FeO has a stronger influence on sulphide capacities in haplobasaltic and basaltic melts than indicated by previous work. The results have implications for understanding the genesis of magmatic Ni and platinoid deposits.

High tenor mesothermal gold ores with low $\delta^{34}S$

J.M. Palin and Y. Xu

Experimental studies conducted previously at the RSES show that gold is present in sulphide-saturated hydrothermal solutions at temperatures above 300°C and at near neutral pH principally as $AuHS(H_2S)_3^{\circ}$ or $AuHS^{\circ}$. Gold solubility under such conditions is described by the general reaction:

$$Au + n\,H_2S \;=\; AuHS(H_2S)_{n-1}^{\circ} + 1/2\,H_2$$

where n is 1 or 4. Variable and low $\delta^{34}S$ of pyrite in high tenor ores of the Victory mesothermal gold deposit of Western Australia indicate progressive oxidation of initially reduced ore-forming solutions. Lowering of the activity of dissolved hydrogen gas, $a(H_2)$, increases gold solubility according to the above reaction leading to an apparent contradiction between observation and theory.

Changes in fluid chemistry and sulphur isotope values that accompany carbonation and sulphidation of wall rock can be estimated for incremental reaction of magnetite with CO_2 and H_2S in a pyrite-saturated fluid according to:

$$Fe_3O_4 + 3\,CO_2 + H_2 \;=\; 3\,FeCO_3 + H_2O$$

$$Fe_3O_4 + 6\,H_2S \;=\; 3\,FeS_2 + 4\,H_2O + 2H_2$$

Calculated reaction paths are shown in Figure 1 for two different fluid starting compositions. Solution pH is assumed to remain neutral (near the quartz–K-feldspar–muscovite buffer) in this simplified model, which is consistent with observed mineral assemblages. The stoichiometry of the carbonation and sulphidation reactions produces changes in H_2 that are the same order of those in CO_2 or H_2S, although these two species are several orders of magnitude more abundant than H_2 in the fluids. Thus, shifts in $a(H_2)$ are proportionally much larger than those in $a(H_2S)$ or $a(CO_2)$ for each increment of reaction progress. The resulting vertical reaction paths cross contours of gold solubility at steep angles (Figure 1). In the case of carbonation, gold solubility increases as the solution becomes increasingly oxidized until the HSO_4^- predominance field for dissolved sulphur is encountered. From there to the point where the solution reaches hematite or magnetite saturation, conversion of H_2S to HSO_4^- causes a rapid decrease in $a(H_2S)$ relative to $a(H_2)$, which results in flattening of the reaction paths and a precipitous drop in gold solubility. This is because the sulphide complex that carries the gold is destabilised when sulphur in the ore fluid is oxidised to sulphate. The largest decreases in $a(H_2S)$ and $a(\sum Au)$ occur around the H_2S/HSO_4^- equal-activity boundary and thus coincide with the point where sulphide sulphur isotope compositions are most strongly shifted to negative values (Figure 1). Wall-rock carbonation thus provides a straightforward explanation for the negative correlation observed between gold content and pyrite $\delta^{34}S$ in the Victory deposit. In contrast, sulphidation of wall rock results in a decrease in gold solubility as the fluid undergoes progressive reduction until pyrrhotite stability is reached, whereupon further changes in $a(H_2S)$ and $a(H_2)$ are buffered by pyrite-pyrrhotite equilibrium up to magnetite saturation. No sulphur isotope shifts occur during sulphidation because the fluids remain entirely within the H_2S predominance field for dissolved sulphur.

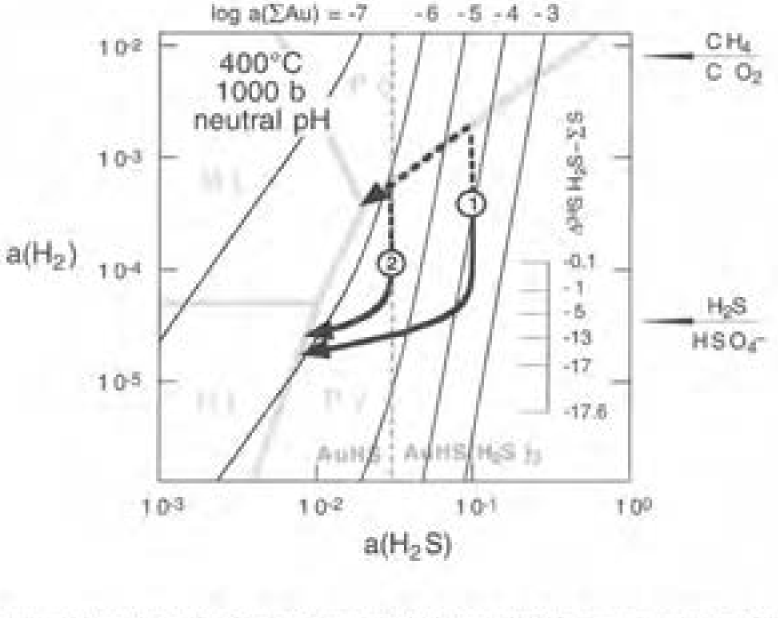

Figure 1: Reaction paths showing changes of $a(H_2S)$ and $a(H_2)$ in aqueous solution during wall rock carbonation (solid lines) and sulphidation (dashed lines) at 400°C, 1000 bars and neutral pH from two initial fluid compositions with $X(CO_2 \pm CH_4) = 0.1$. Also shown are contours of total gold solubility ($a(\sum Au)$); shifts of $\delta^{34}S$ H_2S relative to bulk sulphur in solution; equal activity boundaries for H_2S/HSO_4^-, CO_2/CH_4, and $AuHS/AuHS(H_2S)_2$; and stability fields for magnetite (Mt), hematite (Ht), pyrite (Py), and pyrrhotite (Po). Unit activity coefficients assumed for all dissolved species.

It is interesting to note that a high proportion of giant and supergiant mesothermal gold deposits worldwide exhibit variably negative sulphur isotope values and extensive carbonate alteration. In the Golden Mile, Hemlo (Canada), Kirkland Lake (Canada), Hollinger (Canada), and McIntyre (Canada) deposits, the sulphur isotope compositions have been interpreted as recording involvement of oxidized ore-forming fluids. As shown here, fluid oxidation accompanying carbonation of wall rock magnetite can be an efficient means of gold precipitation. We speculate that it may play a key role in generating very large mesothermal gold deposits.

Gold deposition by mixing of deep and surficial fluids: Inferences from stable isotope and experimental studies

J.M. Palin, Y. Xu, I.H. Campbell and R.R. Loucks

The mesothermal gold deposits of Western Australia include some of the richest gold ores in the world and account for a significant portion of total historic gold production of Australia. The deposits were generated by focused flow of hydrothermal fluids within fault and shear zones in the middle to upper crust. Determining the source and large-scale flow paths of these hydrothermal fluids is vital to understanding the processes responsible for gold mineralisation and has important consequences for developing successful exploration strategies.

Oxygen-isotope geochemistry of hydrothermal vein minerals from the Mt Charlotte deposit at Kalgoorlie and the Hunt, Junction, Revenge and Victory deposits at Kambalda suggest that quartz veins, and by inference their associated gold mineralisation, formed during influx and mixing of cooler surficial water with greenstone-buffered hydrothermal fluid. Experimental studies at the RSES indicate that such a process would lead to very efficient precipitation of gold and quartz, as both minerals exhibit strongly temperature-dependent solubility in aqueous solutions.

Equilibrium fractionation of oxygen-isotopes among minerals depends solely upon temperature, and thus the temperature of vein formation can be calculated from oxygen-isotope differences among coprecipitated minerals. The resulting temperature can be combined with the measured $\delta^{18}O$ values for the vein minerals to calculate the oxygen isotopic composition of the hydrothermal fluid from which the minerals precipitated. Using this method, we determined temperatures and $\delta^{18}O$ H_2O values of vein-forming fluids for albite-, scheelite- and magnetite-bearing quartz veins from the Mt Charlotte deposit at Kalgoorlie and the Hunt, Junction, Revenge and Victory deposits at Kambalda. The range of oxygen-isotope temperatures from each deposit is very similar to those estimated from fluid inclusions, indicating that the oxygen-isotope temperatures for the quartz veins are accurate. The relatively uniform quartz $\delta^{18}O$ values require that the oxygen-isotope compositions of vein-forming fluids varied systematically with temperature. When the data for the veins examined in this study are plotted, a positive correlation between precipitation temperatures and $\delta^{18}O$ H_2O values is clearly evident (Figure 2). Previous investigators noted the small spread of quartz $\delta^{18}O$ values for veins in many mesothermal gold deposits, including those from Western Australia, and assumed that the parental hydrothermal fluids must have had constant oxygen isotopic compositions. However, such an interpretation is valid only if the veins were precipitated over a narrow temperature interval. More recent work has established that hydrothermal activity occurred over a substantial range of temperatures (250–600°C). A temperature spread of this magnitude requires a significant variation in $\delta^{18}O$ values for the auriferous fluid.

Further examination of Figure 2 reveals that above about 450°C, the data lie along a greenstone-buffer curve; that is, the trend expected for equilibrium between a hydrothermal fluid and greenstone at variable temperature and low water to rock ratio (W/R). Such a fluid could have been generated by metamorphic dehydration reactions within the greenstone sequence or it could have originated from an external source and exchanged oxygen-isotopes during flow through the greenstones. In either case, this deep hydrothermal fluid maintained thermal and oxygen isotopic equilibrium with the enclosing greenstones due to a combination of low W/R, long residence times, and rapid oxygen-isotope exchange at high temperatures.

Below 450°C, the vein data delineate a different trend, extending away from the greenstone-buffer curve toward lower temperatures and oxygen isotopic compositions (Figure 2). These fluids lie to the left of the greenstone-buffer curve and suggest mixing with an additional fluid with a low $\delta^{18}O$ value. Previous workers have demonstrated that hydrothermal fluids in the Wiluna and Racetrack deposits contained a major component of seawater or low-latitude meteoric water. The estimated fluid temperatures and oxygen-isotope compositions for both Wiluna and Racetrack lie on the low temperature extension of our Kalgoorlie-Kambalda data array, allowing us to conclude that low $\delta^{18}O$ fluid was derived from the surface. This fluid probably descended along normal or trans-tensional faults, flowed up the ambient temperature gradient into structures hosting the deposit, and mixed with deep, greenstone-buffered hydrothermal fluid.

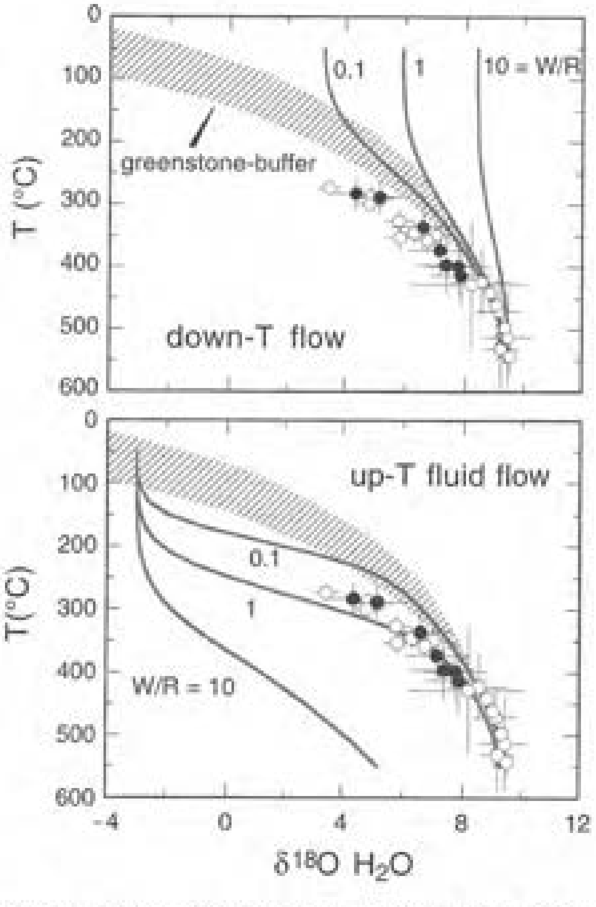

Figure 2: (Top): Temperatures and $\delta^{18}O$ H_2O values of fluids in the Mt Charlotte gold deposit (solid dots) and several deposits at Kambalda (open dots) based on oxygen-isotope partitioning in quartz-albite and quartz-scheelite veins. Also shown are expected trends for buffering of a fluid by greenstone and rate-controlled oxygen-isotope exchange between water and rock assuming an average flow velocity of 1 m/y and a geothermal gradient of 50°/km for down-T flow of a deep hydrothermal fluid initially in equilibrium with greenstone. (Bottom): Same as (top) with expected trend for up-T flow of ^{18}O-depleted surficial water.

Gold solubility in aqueous solutions buffered by magnetite-pyrrhotite-pyrite-K-feldspar-muscovite-quartz and containing 0–1 m Cl has recently been determined at elevated temperature and pressure at the RSES. The experiments involve trapping fluid at peak T and P in synthetic inclusions in quartz and subsequently measuring their compositions by ELA-ICP-MS. The results show that the solubility of gold in a likely greenstone-buffered hydrothermal fluid increases exponentially with temperature in a manner similar to that for quartz (Figure 3). As a consequence, if a deep, greenstone-buffered hydrothermal fluid encounters and mixes with much cooler water, the resulting hybrid will be supersaturated with both gold and quartz, even if the initial gold concentrations of the fluid end-members lie below saturation. Mixing between fluids of contrasting temperature therefore provides a simple explanation for the ubiquitous spatial association between gold mineralization and quartz veins in mesothermal gold deposits and can explain the occurrence of mesothermal gold ores in a wide variety of rock types.

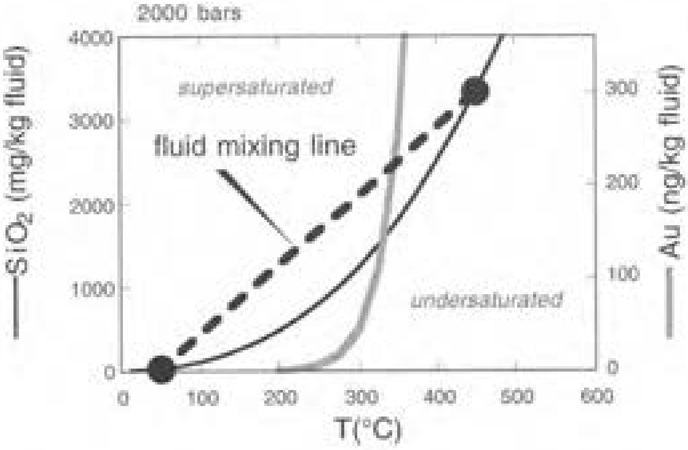

Figure 3: Hydrothermal solubility of quartz (black) and gold (grey) as function of temperature at 2000 bars. Hydrothermal fluid in equilibrium with altered, quartz-bearing greenstone at 450°C will lie on the quartz saturation curve. As a consequence of the steep temperature dependence of gold solubility in sulphur-bearing aqueous solutions, the concentration of gold in such a fluid is likely to be determined by the W/R and labile gold content of the source region. The value shown is for 1 wt% H_2O interacting with a greenstone containing 3 ppb (ng/kg) extractable gold. Mixing of this deep hydrothermal fluid with 50°C surficial water will result in hybrids that are quartz supersaturated throughout and strongly gold supersaturated below 350°C.

Greenstone-belt gold lodes localised by anticline focussing of metamorphic fluid flow

R.R. Loucks

Discussions of structural controls on localisation of hydrothermal gold ore deposition in Archean greenstone belts, such as Western Australia's Eastern Goldfields region, almost invariably focus on large-scale faults as the main conduits for delivery of metalliferous fluid to sites of gold accumulation. In the context of the RSES *Fluids in the Crust* strategic research initiative (1994–1999), an effort has been made to better characterise the evidence for, and the mechanisms of, aqueous fluid migration through deep crustal regimes hotter than 350°C which generally deform in a plastic fashion in response to moderate tectonic stresses applied on geologic time scales. The prevailing view has been that, during heat-induced metamorphic recrystallisation of hydrous minerals to form volatile-poor mineral assemblages, the liberated buoyant fluids escape via sub-vertical hydraulic fractures generated by intermittent build-up of fluid overpressures.

Metamorphic rocks hot enough to undergo plastic deformation have generally been considered incapable of sustaining the long-range continuity of permeability needed to conduct kilometre-scale fluid flow with a substantial lateral component. That traditional view that flow of buoyant fluids through metamorphic rocks is essentially vertical warrants reassessment in light of improved understanding of how percolation networks develop in deforming successions of layered rocks that contain contrasts in plasticity or brittleness. Thick successions of layered volcanic and sedimentary rock were deposited in subsiding Archean greenstone trough-basins, and were deformed as corrugation-folds with kilometre-scale amplitudes and tens of kilometres fold length. Of special interest are layered rock successions that contain extensive layers of komatiite, which is converted by fluids into serpentinite (soapstone), a rock type too plastic to retain a percolation network of open pores and cracks essential to fluid flow. Therefore, extensive, thick layers of extremely plastic serpentinite should be barriers to fluid flow and divert fluids through more brittle, cracked layers of basalt and shale.

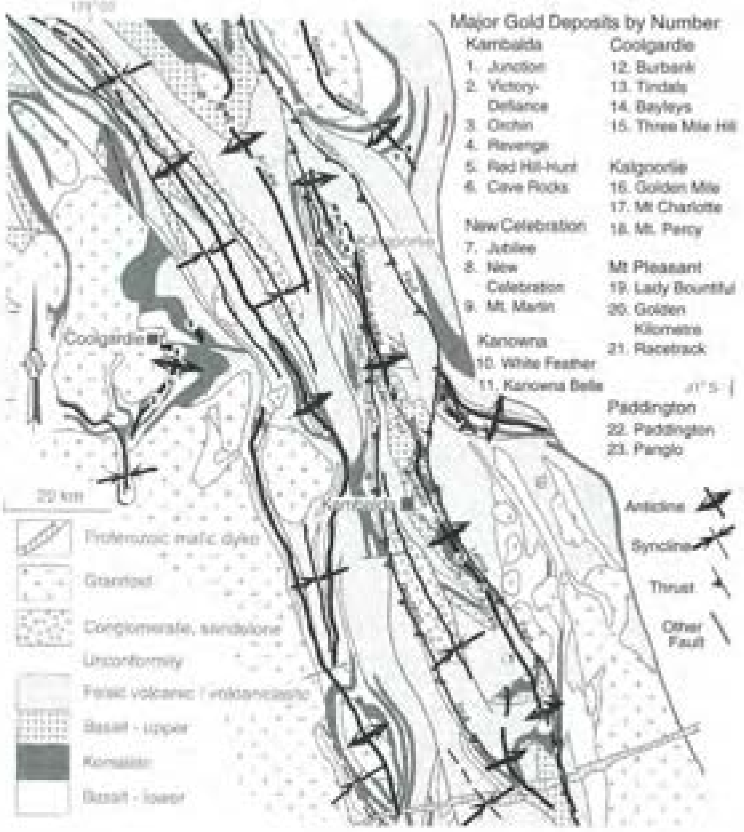

Figure 4: Geologic map of part of the Norseman-Wiluna greenstone belt in Western Australia's Yilgarn Craton, showing major early "D1" folds and coeval thrusts in relation to locations of all known gold deposits containing >10 tonnes of gold. Production + reserves in the map area exceed 2100 tonnes gold. Fold and fault distributions in the goldfields and this lithologic base-map are compiled from many published sources. Nearly all published studies discussing structural controls on ore location in this region have postulated that formation of major gold deposits requires major faults as hydrothermal "plumbing". The Boulder and Lefroy Faults are generally supposed to be the main fluid conduits along the Kalgoorlie-Kambalda trend. Simplified maps showing all major gold deposits from Victory to Paddington lined up on the "Boulder-Lefroy Fault" may seriously mislead exploration based on assumed structural controls. Of 23 gold deposits on the map, 20 lie on or near the crests of anticlines, including all four giant deposits having ≥100 tonnes contained gold (Victory-Defiance, Kanowna Belle, Golden Mile, and Mt Charlotte), and including the largest 6 of the 7 goldfields. No deposit is on the Lefroy Fault; the Boulder Fault encounters only New Celebration and Jubilee – where it intercepts the crest of the D1 anticline. Except for three shear-zone deposits not on anticlines (Cave Rocks, Paddington, Panglo), the deposits formed in minor faults on or near crests of early, major anticlines generated penecontemporaneously with diapiric emplacement of major granitoid batholiths. Coeval synclines are conspicuously unproductive.

Chert is another common rock type that behaves more plastically than interlayered basalt and shale. Chert and komatiite units typically were deposited with lateral extents of hundreds or thousands of square kilometres in subsiding Archean volcano-sedimentary trough-basins. Their broad extent and relatively plastic mechanical properties permit those rock types to play important roles in focussing regional-scale fluid flow by diverting fluids into permeable rock layers. The flow up both sides of a kilometre-scale fold converges in the crest of the fold, so fold crests should be sites of fluid accumulation, and sites of gold accumulation if the fluids carry dissolved gold.

A global survey seeking field evidence in support of this conjecture has identified many persuasive examples of fold-focussed fluid migration in gold-producing granite-greenstone terrains of Archean cratons, wherein the geochronologic, geochemical and structural data are consistent with a predominantly metamorphic origin of the gold-mineralising hydrothermal fluids. An example from the main producing region of Australia is shown here as Figure 4.

Other major producers from fold crests (anticlines) in Western Australia include the Norseman and Mount Magnet goldfields. With >1800 tonnes of recoverable gold, the Porcupine goldfield in Ontario is Canada's most important; its major producers – Hollinger-McIntyre and Dome-Preston, as well as lesser mines – are located along the crest of the Central and South Tisdale anticlines. In Ontario's other two largest goldfields, Hemlo (~630 tonnes gold) and Red Lake (>600 tonnes), the main lodes are on kilometre-scale anticlines. Most gold production from the Zimbabwe craton has come from the Midlands greenstone belt, wherein the major producers – the Cam and Motor, Golden Valley, Globe and Phoenix, Gaika, and others – lie along the ~100-km-long Kadoma anticline. Most of South Africa's greenstone gold production is from the Barberton goldfields (>250 tonnes gold), mainly from the Sheba and Fairview mines, which lie along a shear system following the axial trace of the Sheba-Barbrook anticline. In the Archean São Francisco craton, Brazil's most important gold deposits – Morro Velho, Raposas, and Cuibá (~630 tonnes of gold) lie atop the 80-km-long Rio das Velhas-Mariana anticline, and the São Bento and Santa Quiteria mines (~100 tonnes gold) lie atop the next anticline eastward in the fold series.

Structural and deformation controls on fluid flow and ore genesis, St Ives Goldfield, Western Australia

S.F. Cox and K. Ruming[1]

Ongoing structural, microstructural and hydrothermal alteration studies of a major group of Archaean gold deposits in the St Ives Goldfield (south of Kambalda, WA) aim to advance our fundamental understanding of the coupling between crustal deformation processes, crustal-scale fluid flow and ore genesis. The project is also providing new understandings of the influence of high fluid fluxes on mechanics of faults and shear zones at depths at which major earthquakes nucleate in continental crust.

Major developments in the past year include:

- Recognition of kilometre-scale variations in intensity of veining associated with mineralised shear systems. These variations are interpreted to reflect variations in the pore fluid factor (the ratio of pore fluid pressure to overburden pressure) in the gold-producing hydrothermal system in response to lateral and vertical variation in fluid flow rates.

- Increasing recognition of the role of competence contrast between rock units as a key factor localising fracture growth, permeability enhancement and ore deposition.

[1] Department of Geology, The University of Newcastle, NSW

- The recognition of multiple styles and episodes of hydrothermal alteration in some of the major ore-hosting structures, together with documentation of overprinting relationships between alteration assemblages, are providing insights about the dynamics of fluid flow and interactions between various fluid reservoirs during gold mineralisation.
- A 3D visualisation of all the geological (outcrop and drill core) data and gold assay data for the Victory Complex has been completed and will form the basis for numerical modelling and analysis of fluid flow in this major gold system.

An important result has been the recognition that contractional jogs, and not just dilational jogs, can be a key factor localising fluid flow to restricted parts of fault systems. In the St Ives goldfield, low displacement imbricate thrust systems have developed around a contractional jog on the much larger displacement, strike-slip Playa Fault. Intense shearing and associated fracturing has generated a high permeability damage zone around the contractional jog and localised some of the major gold deposits in the St Ives goldfield. The damage zone of low displacement reverse faults and shear zones extends up to several kilometres away from the jog on the Playa Fault.

By analogy with the modern distribution of seismic activity around major fault systems, low displacement structures which host gold mineralisation in the St Ives area are interpreted to be aftershock structures generated in association with major slip events on the Playa Fault and the nearby Boulder-Lefroy Fault. Modelling of stress transfer associated with seismogenic slip on modern active faults has recently been used successfully to predict the distribution of aftershocks around larger seismogenic faults (Stein, 1999). We are exploring the application of stress transfer modelling in analysing the distribution of low displacement, gold-hosting fault systems around crustal-scale shear zones.

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

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

Archaean greenstone-hosted mesothermal gold deposits are an important source of gold throughout the world. The Yilgarn craton in Western Australia is host to many significant deposits of this style, with the giant Golden Mile deposit by far the largest. Although the Golden Mile is often referred to as the type example for this style of mineralisation in Australia, it is fundamentally different in size, metal budget, mineralogy and structural control on lodes from other Archaean mesothermal gold deposits.

The aim of this study is to acquire fundamental scientific data from the giant Golden Mile deposit and establish the origin and composition of the auriferous ore forming fluids. Proposed analytical techniques include: fluid inclusion studies, mineral trace element geochemistry by laser ablation ICP-MS, hydrogen, oxygen, sulphur stable isotopes and lead radiogenic isotopes. A geochronological study to determine absolute age of gold mineralisation is also proposed.

Multiple mining leases have previously limited research at the Golden Mile to areas controlled by separate companies. This project will be the first to examine the Golden Mile in its entirety. The project is supported through the SPIRT program in collaboration with Kalgoorlie Consolidated Gold Mines.

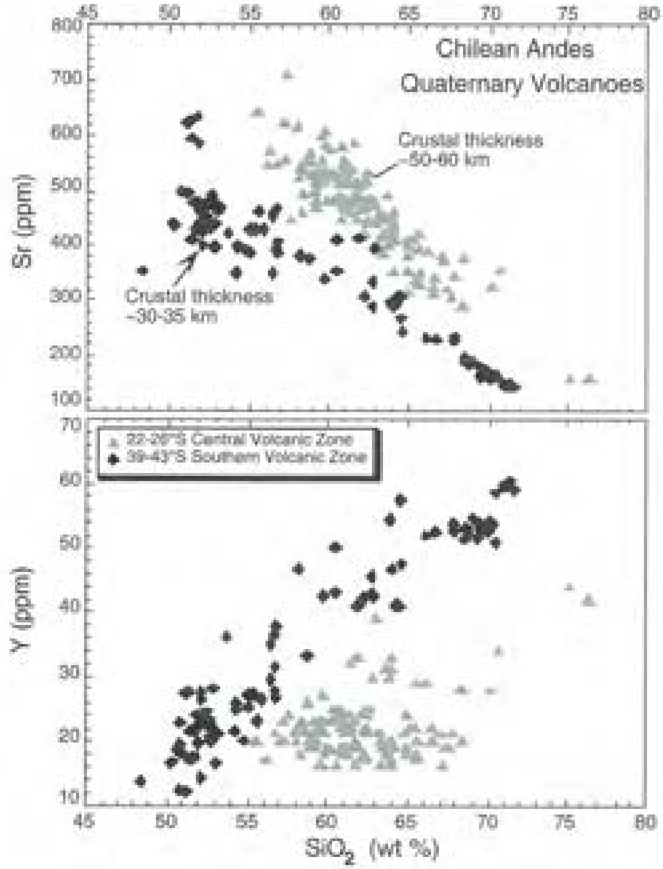

Figure 5: (Top) A compilation of data from many published studies shows that the strontium content (parts per million) in volcanic rocks decreases as weight percent silica increases during crystallisation-differentiation of magmas in two segments of the Chilean Andes. (Bottom) Yttrium measurements in the same samples show that Y accumulated as the magma evolved to higher SiO_2 in sub-volcanic magma chambers that were sampled by volcanic eruptions at varied stages of the magmas' chemical evolution. Each black or grey array represents 8–10 major volcanic centres, each of which spans a substantial range of SiO_2 content. Mantle-derived basaltic magmas are thought to pause and partially crystallise at the crust-mantle boundary. In the Southern Volcanic Zone (black symbols), the boundary is at relatively shallow depth, and the modest pressure there permits early saturation with plagioclase feldspar, which depletes Sr from the residual magma as crystallisation proceeds. In contrast, magma pausing at 50-60 km depth in the central Andes (grey symbols) crystallises less plagioclase and later, due to the higher pressure. That retardation shifts the Sr-depletion trend to higher SiO_2 values. The black array in the bottom diagram illustrates efficient residual accumulation of Y during magma crystallisation at modest depth in and beneath thin continental crust. The grey array in the bottom diagram illustrates diminished efficiency of Y accumulation. The diminished efficiency is attributable to extraction of some Y into crystallising aluminium-rich clinopyroxene, hornblende, and possibly garnet. Those minerals are stabilised by the higher pressures at the base of thicker crust in the Central Volcanic Zone of the Andes. Nevertheless, the erupted magmas (mainly pyroxene-andesites and -dacites, with minor or no hornblende) show similar trends of Sr depletion and Y enrichment in both segments, regardless of the different crustal thickness.

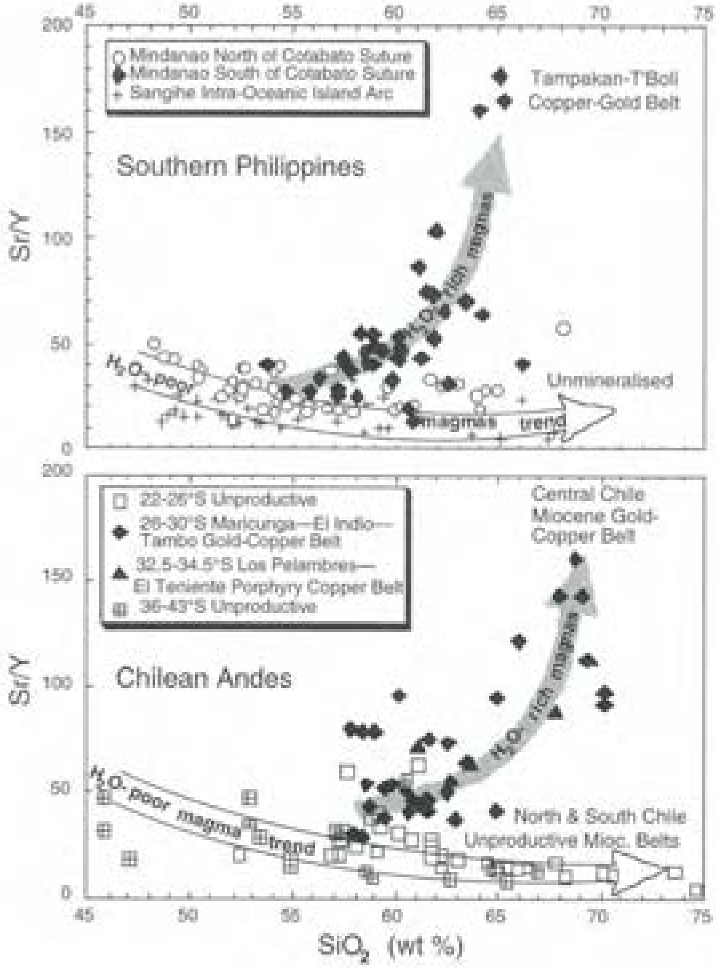

Figure 6: The upper diagram shows two contrasting trends of the Sr/Y ratio in three segments of the 770-km-long Central Mindanao/Sangihe island-arc volcanic chain. The north Mindanao and southerly Sangihe island-arc segments contain no known significant hydrothermal gold-copper ore deposits, but they bracket an intervening segment comprising several volcanic complexes in southern Mindanao that contains major copper and gold ore deposits produced by hydrothermal fluids exsolved from crystallising magmas. The contrasting behaviour of the Sr/Y ratio in the productive (black diamonds) and unproductive (circles and crosses) arc segments indicates that the productive magmas were exceptionally rich in dissolved water throughout the course of magma crystallisation. (Most black symbols represent Tampakan volcano samples analysed by laser-ablation ICPMS by B.D. Rohrlach; other data points are analyses compiled from many literature sources.) The bottom diagram illustrates a similar case in the Chilean Andes, where a rich mineral belt – with many gold mines in the 26–30°S latitude interval and 3 giant porphyry-copper mines at 32.5–34.5°S – is bracketed to the north and south by long chains of igneous complexes of similar age that formed no known minable ore deposits during the Miocene epoch (24 to 5 million years ago). All available published analyses of fresh volcanic and sub-volcanic rocks along the Miocene arc front within each latitude interval are included in the plot.

Application of the Sr/Y ratio to exploration for intrusion-related copper-gold ore deposits: discrimination of productive from unproductive stocks in sub-volcanic intrusive complexes

R.R. Loucks, J. Ballard and I.H. Campbell

At scales on the order of 100 km or so encompassing several nearly volcano-plutonic complexes, eruptive rocks often show similar trends in the behavior of the Sr/Y ratio during magmatic crystallisation-differentiation preceding eruption. But contemporaneous intrusive rocks in the same regions display much less coherence in their Sr/Y trends, so attention to the differences among individual intrusions is required for discrimination of the prospective ones. The greater regional coherence of volcanic rocks, which simplifies regional target selection, probably reflects a tendency of volcanic eruptions to provide a sampling bias toward eruption of water-rich magmas. Exsolution of hydrothermal fluid from a crystallising magma is accompanied by a substantial expansion of the magma's volume as melt→ melt+bubbles, which often triggers volcanic eruptions, spewing the sulphur and metals into the atmosphere and across the landscape, instead of making an ore deposit. Infrequently, exsolution of magmatic hydrothermal fluid occurs in a shallow magma body that is sufficiently small, or in a larger magma body that is buried sufficiently deep that the magma's volume expansion is accommodated by deformation of enclosing rocks, without triggering a volcanic eruption. Such bodies of un-erupted magma can generate ore deposits that are usually associated regionally and temporally with areally extensive volcanic rocks sharing the elevated Sr/Y chemical signature of ore-productive magma in the same volcanic-intrusive composite igneous complexes. Magma bodies can also fail to erupt if they contain too little dissolved water to exsolve a significant volume of hydrothermal fluid at any stage of crystallisation. These become barren intrusives. In other cases, relatively H_2O-poor magmatic differentiation series may eventually exsolve a magmatic hydrothermal fluid after the magma has already precipitated most of its copper and precious metals as igneous sulphide crystals, in which case the hydrothermal fluid exsolving late from metal-stripped silicate melt may be too impoverished in ore metals to make an ore deposit. We show here that the Sr/Y ratio in intrusive granitoid rocks is useful in discriminating those bodies incapable of making ore from those that contained sufficient H_2O over the course of igneous crystallisation to have a high probability of releasing an ore-producing magmatic hydrothermal fluid.

Figure 7 shows our ICPMS measurements of the whole-rock Sr/Y ratio in 19 samples from ore-productive and barren intrusives spatially and temporally associated with the giant Chuquicamata porphyry copper deposit in northern Chile. The three productive stocks (black squares) are distinguished from unproductive intrusives at Chuquicamata (open squares) by low contents of whole-rock yttrium and generally higher Sr/Y ratios. The Chuquicamata data are compared with our compilation of data from many published literature sources describing productive and barren intrusives associated with other porphyry copper-gold deposits in the Andes and in Arizona and the South Pacific. Figure 7 shows that plots of Sr/Y against Y are remarkably successful in sorting ore-productive intrusives from spatially associated intrusives of similar age that failed to generate ore. Most productive intrusives (black symbols) have low contents of whole-rock Y and Sr/Y > 40, whereas unproductive intrusives (blank symbols) plot in the lower right-hand side of the array. Comparison of this plot with Figures 5 and 6 of the previous article indicates that the arrays in Figure 7 are composites of two opposing magmatic differentiation trends. Parental basaltic magmas with initial Sr/Y ≈ 30 and relatively low initial H_2O evolved toward lower Sr/Y and higher Y as crystallisation-differentiation proceeded toward derivative magmas of granitoid compositions. Parental basaltic magmas with initial Sr/Y also around 30 but with relatively high initial H_2O contents evolved toward granitoid derivatives with low Y and high Sr/Y, due to the effects of dissolved magmatic H_2O on hornblende and plagioclase stability, as described in the preceding article.

Having selected a prospective region according to Sr/Y criteria described in the previous article, the explorationist could conduct follow-up sampling of those regions at higher spatial resolution for chemical analysis of intrusive rocks, and then select specific drilling targets using the Sr/Y indicator in the manner shown in Figure 7.

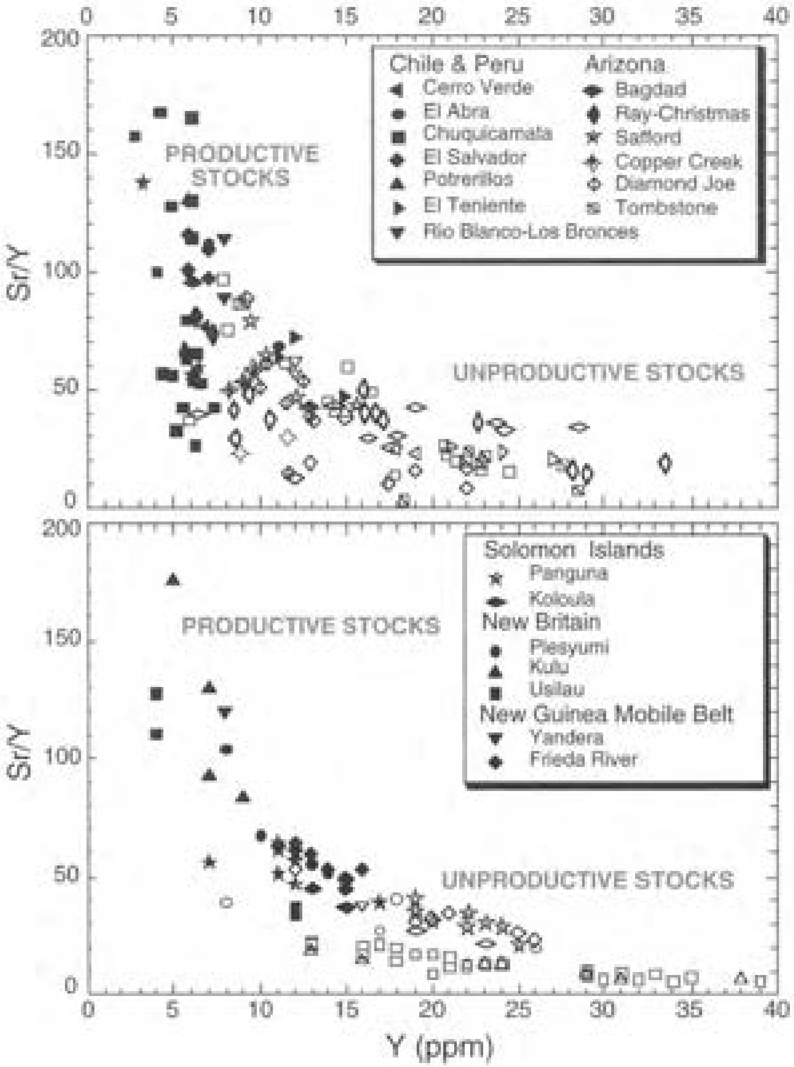

Figure 7: The ratio of parts per million strontium to yttrium is plotted against parts per million yttrium in whole-rock analyses of representative, relatively alteration-free samples of intrusive igneous rocks spatially and temporally associated with porphyry copper-gold ore deposits in three of the world's most productive regions. Black symbols identify samples of intrusives that released an ore-forming magmatic-hydrothermal fluid during crystallisation. Blank symbols of the same shape identify samples in the same district of spatially and temporally associated intrusives that failed to make ore. Data for Chuquicamata were generated for this study (J. Ballard, analyst), whereas other data are compiled from many published sources. Although there is some overlap of the data arrays for barren and ore-productive intrusives, the Sr/Y ratio is shown to be remarkably effective in sorting prospective intrusives from ones likely to be a waste of exploration expenditures.

Fluid flow within a volcanic-centred, magmatic hydrothermal system – A district-scale whole-rock oxygen-isotope study

B.D. Rohrlach, J.M. Palin and R.R. Loucks

The Tampakan porphyry-epithermal copper-gold deposit in southern Mindanao (Philippines) is hosted by a Pliocene age, erosionally truncated stratovolcano. This andesitic volcanic centre was the focus for a large magmatic hydrothermal system which formed both porphyry and epithermal copper-gold mineralisation. Current models for formation of high-sulphidation epithermal copper-gold ores involve condensation of metalliferous volcanic vapours and mixing of those magmatic fluids with overlying, shallow, meteoric ground-water flow systems high in the superstructure of volcanic edifices. Widespread intensive alteration of volcanic rocks by sulphuric-acid-rich fluids accompanies silicification and metal deposition by these shallow-level fluid mixing processes.

This study is utilising oxygen-isotope data from 137 whole-rock samples collected over an area in excess of 200 square kilometres, to investigate the interaction between magmatic fluids and meteoric ground-water in a volcanic-centred magmatic hydrothermal system. Oxygen-isotope ($\delta^{18}O$) data are being acquired on a conventional oxygen line using bromine pentafluoride as the reaction agent to extract O_2 gas. The oxygen-isotope data is being integrated with major-element compositional data acquired by electron microprobe analyses of synthetic glasses made from fused aliquots of the whole-rock powders, and with district-scale alteration mineralogy defined by whole-rock infra-red spectroscopic analyses. The study seeks to understand the hydrological structure of a volcano-centred magmatic hydrothermal system though determination of the relative influence of isotopically contrasting magmatic versus meteoric water induced alteration in different portions of the volcanic centre, by mapping of regions where fluids are migrating up or down a thermal temperature gradient, determination of the total fluid flux required to shift $\delta^{18}O$ values to those observed, and by understanding the spatial variation in time-integrated cumulative fluid-rock ratios.

Whole-rock major-element compositional data for each sample are being used to estimate an oxygen isotope fractionation factor for each whole-rock sample, thus allowing mineralogical/oxide compositional variability to be taken into account during interpretation of oxygen-isotope ($\delta^{18}O$) variation within the district. Preliminary data acquisition indicates there is sufficient variability in the whole-rock data-set to enable a district-scale oxygen stable isotope study of the Tampakan hydrothermal system and the effects of palaeo-topography on magmatic-meteoric ground-water interaction.

Magmatic oxidation state inferred from REE systematics in zircon

J. Ballard, J.M. Palin and I.H. Campbell

The western margin of the South American Plate has been associated with continental subduction since the early Jurassic. This tectonic setting has produced magmatic belts of calc-alkaline character in north Chile. In the Chuquicamata area, crustal scale structures may have acted as suitable conduits for these magmas to reach shallow levels in the crust where they produced large magmatic-hydrothermal systems.

This study sets out to understand the conditions that are favourable to the formation of world class copper deposits and in particular, the role of the oxidation state of the magma in ore formation. To achieve this, zircons were analysed by ELA-ICP-MS using NIST 612 as the standard. Ten grains from each sample were analysed from the three mineralised Chuquicamata mine porphyries and six barren regional intrusive units. The concentration of divalent, trivalent and tetravalent cations were measured in each of the zircons. The estimated Ce^{4+} to Ce^{3+} ratios in zircons from the various units' were calculated from the observed Ce concentration (from ELA-ICP-MS) and the predicted concentration for Ce^{3+} from the trivalent REE trend and Ce^{4+} from the tetravalent hafnium-thorium-uranium trend. Similarly, the Eu^{3+}:Eu^{2+} ratio was calculated from the measured Eu concentration and the predicted concentrations of pure Eu^{3+} and Eu^{2+} based on the trivalent and divalent trends respectively.

Initial findings support a positive correlation between the mineralised ore-bearing units in the Chuquicamata mine and the oxidised magmas, as illustrated by Figure 8. Based on these observations, the oxidation state of the magma appears to exert a control on the fertility of calc-alkaline magma systems. If this control proves to be critical, it may be possible to use zircon geochemistry to distinguish between ore-bearing and barren systems. This is potentially of great economic significance because zircon is a resistate mineral which survives weathering and is resistant to abrasion.

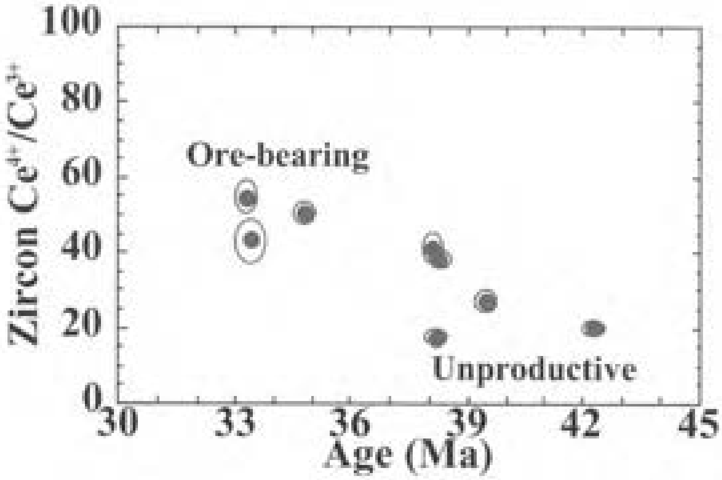

Figure 8: Zircon Ce^{4+}:Ce^{3+} ratios in three ore-bearing intrusives and five unmineralised intrusives from the Chuquicamata district of northern Chile. Each point represents the average of 10 replicate ELA-ICP-MS analyses of zircon from the 8 units studied.

High precision U-Pb zircon geochronology of multiple igneous events in the super-giant Chuquicamata porphyry copper deposit, Chile, byELA-ICP-MS and SHRIMP methods

J. Ballard, J.M. Palin, I.H. Campbell and I. Williams

The Chuquicamata mine is historically the world's largest copper producer and has been in operation for the last 85 years. The deposit is located in the Precordillera of north Chile at the southern end of the 12 by 1–1.5 km northerly trending Chuquicamata Intrusive Complex. The mineralised eastern section of the mine consists of three intrusives – the East, West and Bench porphyries. Barren Fortuna Complex is juxtaposed against the productive section of the deposit by the West Fissure, a 37 km net sinistral displacement strike-slip fault.

Previous ^{39}Ar-^{40}Ar studies suggest that more than one hydrothermal event may have affected Chuquicamata. However, there are no precise igneous ages on the three mineralised porphyries and therefore the time evolution of the igneous system remains unclear. The purpose of this study was to test an hypothesis that Chuquicamata is a super-giant deposit because two or more discrete igneous and hydrothermal events have contributed to its formation. That is, Chuquicamata is two, and possibly three, superimposed porphyry copper deposits.

The technique used to date the porphyries in this study was U-Pb dating of zircons by ELA-ICP-MS. This method has three important advantages over alternative techniques. Firstly, U-Pb systematics in young zircon are highly resistant to hydrothermal resetting. Secondly, the ELA-ICP-MS is a micro-beam technique that allows grains with inherited cores, which have been found in the Chuquicamata porphyries, to be identified and rejected. Finally, the ELA-ICP-MS is a fast and low cost method for dating young igneous rocks at high precision.

The reliability of the data produced by this technique are confirmed by comparison with SHRIMP dating of the same samples, as illustrated in Figure 9. The results for the two methods are comparable but ELA-ICP-MS consumes more material and more analyses are required to achieve equivalent precision.

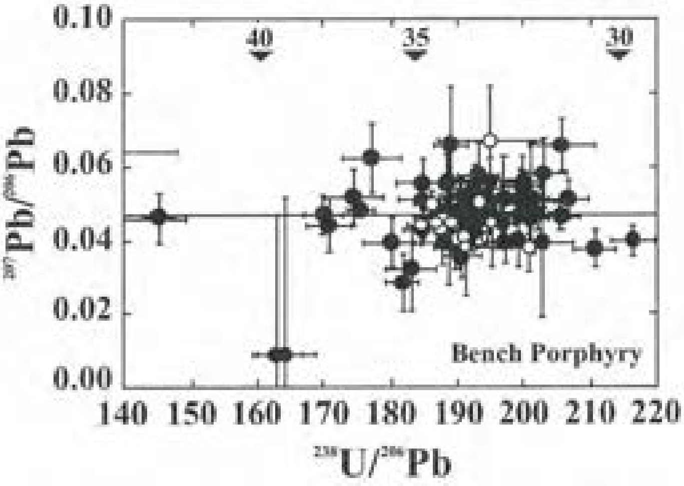

Figure 9: A Tera-Wasserburg plot of Chuquicamata's Bench Porphyry. SHRIMP ^{204}Pb corrected and EELA-ICP-MS ^{208}Pb corrected data compared.

The identification of ancient mantle plumes

I.H. Campbell

Ancient mantle plumes can be recognized from uplift prior to volcanism, the orientation of dikes that feed the volcanism, the nature of the physical volcanism, age progressions along volcanic chains and the chemistry of the magmas they produce. The thermal anomaly introduced by arrival of a plume head beneath continental crust leads to widespread uplift. A plume head, with an average temperature excess of 100°C, will produce 500 to 1000 m of uplift prior to volcanism over an area slightly smaller than the flattened plume head. During volcanism, the surface onto which the lavas erupt subsides due to deflation of the underlying mantle as melt is removed to produce the basalts. However, this is balanced by the eruption of basalt onto the surface so that the net additional change in the surface level due to volcanism is small, and may be positive or negative depending on geometric considerations. Uplift is followed by gradual subsidence as the mantle thermal anomaly decays over a period of ~1 Ga.

The domal uplift associated with emplacement of a plume head leads to extension around the circumference of the dome and to the formation of radial dyke swarms, provided there is no external force acting on the region. If there is a pre-existing external force, the dikes will tend to partially reorientate perpendicular to that force to produce radiating dikes.

The physical volcanology of plume basalts is characterized by massive flows that can be correlated over large distance. They contrast with island arc basalts, which consist dominantly of pyroclastics that are difficult to correlate over large distances, and with MORBs, which are found only in ophiolite sequences. Chains of volcanoes, which are produced by melting plume tails, show systematic age progressions that are diagnostic of mantle plumes.

The chemistry of plume magmas reflects their origin in anomalously hot zones in the mantle. High temperature magmas, such as picrites and komatiites, and high-pressure magmas such as alkali basalts, nephelinites and type-1 kimberlites, are characteristic of plumes. The high liquidus temperatures also leads to high Cr in olivines and to high Ni at a given MgO content in plume basalts. Chondrite normalized trace element patterns that are strongly LREE enrichment, with no Nb, Ta or Ti anomaly, are found only in plume basalts, but not all plume basalts share these features.

Geochemistry of the igneous suite associated with the Kelian gold deposit, Indonesia

B. Setiabudi and I.H. Campbell

The Kelian gold deposit is an intrusive-related low sulphidation system, situated within the Central Kalimantan Continental Arc which consists of andesitic-trachyandesitic volcanics and intrusives of Late Oligocene — Middle Miocene age. The hydrothermal mineralisation is hosted by a series of intercalated felsic tuff and volcaniclastic sediments intruded by andesite stocks. One of the aims of the study was to test a hypothesis that the auriferous fluid at Kelian is the product of fractional crystallisation of an igneous body at depth which is the parent to the felsic rocks that host the ore. Unfortunately it is not possible to make such a study of rocks from the mine area because they are highly altered so that many major elements, including Si, Na and K, have been extensively mobilised. However, similar rock sequences occur in the southwestern area (Nakan) and the northwestern areas (Magerang and Imang) which show little evidence of alteration and are suitable for a detailed geochemical study.

The Magerang-Imang intrusives are of low K to medium K andesite and have well-defined, linear trends when major and trace elements are plotted against SiO_2 over an SiO_2 range of 56 to 64 wt%, suggesting that chemical variations within the suite are controlled by crystal fractionation. MgO, Fe_2O_3, TiO_2 and CaO decrease and Na_2O, K_2O and P_2O_5 increase with increasing SiO_2. Highly incompatible elements such as La, Th, Zr and Hf also increase with increasing SiO_2, but weakly incompatible elements show no increase and some, such as Sm, Ho and Y actually decrease.

Within the mine area, silica has been mobilised by hydrothermal alteration so it can not be used to monitor fractional crystallisation. However, in the unaltered samples from Magerang, highly incompatible elements, such as Th correlate with SiO_2. Because Th is much less mobile than SiO_2 during hydrothermal alteration it has been used as monitor of fractionation for the altered mine samples. In the least altered samples from Magerang immobile elements, such as U, Zr, Hf, Y, Nb, Ta and REE, increase with increasing Th concentration. The plots for Kelian samples show similar trends for immobile trace elements, suggesting that the two suites are closely related. However, the data are much more scattered in the altered andesite from the mine area indicating that alteration has produced some mobility for elements that are normally regarded as immobile. The range of Th values is much greater in the mine sequences and is probably a factor of 10 greater than that in the unaltered samples. This suggests that the Kelian rocks have undergone a much greater range of fractional crystallisation than the Mayerang samples. Quantitative modelling of the effects of fractional crystallisation on the trace elements is in progress.

Future laboratory works will include geochemical analysis on the other least altered samples from Magerang and Kelian mine areas to extent the fractionation range in both areas and to test the correlation between the regions. The correlation will be further tested by U-Pb dating of zircons from both areas. PGE and gold analysis will be carried out to study the effect of fractional crystallisation in concentrating PGE and gold.

The sulphide capacities (C_S) of haplobasaltic and basaltic silicate melts at 1400°C and 1 bar

J.A. Mavrogenes and H.StC. O'Neill

Fincham and Richardson (1954) showed that sulphur dissolves in silicate melts at low oxygen fugacities (fO_2 < QFM) as S^{2-}, and does so by replacing O^{2-} on the anion sublattice, as described by the reaction: $O^{2-} + 1/2\ S_2 = S^{2-} + 1/2\ S_2$. This suggests the relationship: $[S] = C_S\ (fS_2/fO_2)^{0.5}$ where [S] is the sulphur content of the melt (conveniently in ppm) and C_S is the "sulphide capacity" of the melt, which may be thought of as an equilibrium constant, and is a function of melt composition as well as temperature and pressure. Fincham and Richardson (1954) experimentally verified the $(fS_2/fO_2)^{0.5}$ relationship for simplified metallurgical slag compositions in the system $CaO\text{-}Al_2O_3\text{-}SiO_2$ (CAS) by varying fS_2 and fO_2 independently at 1 atm. Subsequent work has repeatedly confirmed the validity of the Fincham and Richardson model for other simple metallurgical slag compositions, but there is only limited information on the solubility of sulphur in silicate melts relevant to geology.

Obviously C_S only has meaning if the $(fS_2/fO_2)^{0.5}$ dependence shown by Fincham and Richardson (1954) is obeyed. While this relationship has been confirmed for an Hawaiian tholeiite composition by Katsura and Nagashima (1974), other studies (Haughton, D. *et al.*, Economic Geology, 1974; Buchanan, D.L. and Nolan, J., Can. Mineral., 1979) have shown disturbing deviations from the relationship, which, if real, would demand a fundamental rethinking of the sulphide solubility theory as developed by the metallurgists. Moreover, there are apparent inconsistencies in the geological studies that presently preclude the development of a quantitative model relating sulphide solubility to melt composition.

Accordingly we have embarked on a program to study experimentally sulphur solubilities in silicate melts under controlled fO_2 and fS_2, firstly to test the $(fS_2/fO_2)^{0.5}$ relationship over a wide range of silicate melt compositions, and hence, if the relationship is confirmed, to determine the compositional dependence of Cs. Initially experiments have been undertaken at the relatively high temperature of 1400°C to access as wide a range of compositions as possible.

Experiments were conducted in a conventional vertical tube furnace equipped for gas mixing, using $CO_2\text{-}CO\text{-}SO_2$ mixtures to impose fO_2 and fS_2, delivered by commercial mass flow controllers. The performance of the controllers was tested repeatedly during the experimental campaign by calibrating their flow rates using the moving bubble method, and the CO_2 and CO flows were further tested in situ using zirconia oxygen sensors. The oxygen sensors deteriorate rapidly in the S atmosphere at 1400°C and could not be used to monitor gas mixtures continuously. In fact, the major experimental problem in studies of this type is condensation of solid sulphur on the cool parts at the top of the furnace, which may then fall off into the hot part of the furnace, greatly increasing fS_2 over that calculated from the gas mixture. To minimise this, we established for a range of compositions the time needed to reach steady state S solubilities, and took care not to exceed this time too much. The furnace was cooled down and the inside of the muffle tube cleaned between each run.

Four strategies were used for investigating the effect of melt composition on sulphur solubility. For the first strategy, we selected for study seven near-eutectic compositions in the CMAS system, plus compositions along the join $CaAl_2Si_2O_8\text{-}CaMgSi_2O_6$ (anorthite-diopside). Secondly, starting with anorthite-diopside eutectic as the base composition, we added the following components: SiO_2, $MgSiO_3$, $CaSiO_3$, Mg_2SiO_4, FeO, Fe_2SiO_4, TiO_2, $NaAlSi_3O_8$. The compositional range of these pseudo-binary joins extended either to the pure component where this melts below 1400°C, or to the level at which the melt becomes saturated in the component at 1400°C (eg ~15% for Mg_2SiO_4, ~60% for $CaSiO_3$). Thirdly, we studied an assortment of natural melt compositions spanning a range of FeO contents. Lastly, we have attempted to replicate some measurements on melt compositions studied by previous investigators.

Samples were hung on Pt loops (or Re or Fe-Ir loops for Fe-bearing compositions), and run generally six at a time. Quenching was by dropping into water. Samples were analysed by electron microprobe using WDS and a troilite standard for S. EDS was used to confirm major element compositions. As expected, alkali loss and Fe loss into Pt loops were pervasive problems.

The results were fitted by a global non-linear least squares regression to an expression of the form: $[S] = (fS_2/fO_2)^{0.5} \sum A_M[MO_x]$ where MO_x are the oxide components of the melt (in wt%), and the coefficients A_M are used to describe the compositional dependence of C_S. The fit to the data shows that the $(fS_2/fO_2)^{0.5}$ relationship is followed by all compositions. We find $A_{Fe} > A_{Ca} >> A_{Mg} > A_{Ti}$ with the coefficients for other oxide components (SiO_2, Al_2O_3, Na_2O) being effectively zero. The magnitude of AM correlates roughly with the magnitude of the free energies for the reactions: $MO_x + 1/2x\ S_2 = MS_x + 1/2x\ S_2$ for M = Fe, Ca, Mg, Ti, Al and Si, but this relationship breaks down completely for the alkalis, for which it would predict A_{Na} or A_K to be large, rather than negligible as observed.

Our results are not in good agreement with the previous work of Buchanan and Nolan or Haughton *et al*. (1974), although allowance needs to be made for the different temperature of the latter study. Nevertheless, we find a much higher value of A_{Fe}, indicating that FeO has a stronger influence on CS than hitherto thought. Our very high value of A_{Fe} helps explain the empirical observation that the Sulphur Content at Sulphide Saturation (SCSS) of natural melts increases with increasing [FeO] in the melt, despite the simple prediction from the law of mass action for the reaction: $FeO_{(melt)} + S^{2-}_{(melt)} = FeS_{(sulphide)} + O^{2-}_{(melt)}$ that increasing FeO in the melt should correlate with lower SCSS.

Experimental investigations of Cu in magmatic-hydrothermal systems

A.C. Hack and J.A. Mavrogenes

Cu solubility in supercritical and two-phase aqueous solutions

It has long been recognised that supercritical hydrothermal fluids must play a major role in fractionating and transporting metals in geological systems. Unfortunately, the nature of the high-temperature fluid is poorly understood. This is primarily because of the difficulties in constructing high-temperature experimental reaction cells for in situ analysis that can withstand high vapour pressures. New techniques, such as ELA-ICP-MS of fluid inclusions, now allow this region of pressure-temperature space to be investigated (eg Loucks and Mavrogenes 1999).

The limited data for Cu solubility in supercritical fluids come from analysis of quenched experimental solutions. The possibility of modification of these solutions during the quenching process means that it is not known if they truly are representative of the experimental conditions. Fluid inclusion synthesis gets around this problem by isolating the solution at the run conditions (Figure 10). An experimental project to investigate the solubility and partitioning of Cu under a range of conditions by trapping supercritical, and coexisting vapor- and liquid inclusions, combined with analysis by LA-ICPMS, is currently being undertaken.

Figure 10: Synthetic fluid inclusions trapped in quartz at 700°C and 2.9 kb under supercritical conditions.

Cu partitioning between silicate melt and co-existing vapor

Our understanding of hydrothermal systems originating from magmatic volatile exsolution, such as porphyry-type ore deposits, is limited by data for the initial melt-vapor fractionation of metals. A series of experiments to quantify melt-vapor partitioning is currently in progress. The method involves the synthesis of coexisting melt- and vapor inclusions at various experimental conditions and subsequent analysis by ELA-ICP-MS and electron microprobe. Examples of synthetic fluid- and melt inclusions are shown in Figures 11 and 12.

Controls on Cu solubility in silicate melts

A large proportion of worldwide Cu production comes from a class of magmatic-hydrothermal ore deposits known as porphyries. In these systems, the entire hydrothermal metal budget is sourced from and thus ultimately controlled by the quantity of Cu dissolved in the melt. However, Cu dissolution mechanisms in silicate melts are not well understood and synthetic melt inclusions are being used to investigate the relative effects of fO_2, fS_2, fH_2O, and ΣCl (Figure 11).

Figure 11: Synthetic melt inclusions trapped in quartz at 715°C and 3.0 kb under vapor-saturated conditions.

Speciation of ore-forming solutions at high temperature and pressure

A.J. Berry, J.A. Mavrogenes, E.R. Krausz[1] *and R.R. Loucks*

Hydrothermal ore deposits are the world's principal source of most metals. The deposits form as a result of ore-metal transport by aqueous solutions at high temperatures and pressures. To understand the formation of these deposits, it is necessary to determine both the solubility and speciation of each metal complex in solution. Progress in this area has been limited by the inability of existing experimental methodologies to sample solutions at supercritical temperatures. This problem is being addressed by studying ore-bearing fluid trapped experimentally as fluid inclusions in quartz.

The importance of metal speciation can be illustrated by our limited understanding of the relationship between porphyry and epithermal type deposits. The ores may derive from a single source by partitioning of metals between a brine and vapour associated with changes in speciation determined by ligand availability. For example, the porphyry ore may form from copper transported as a chloride complex in a high-density brine and the epithermal from a vapour phase volatile sulphide species. The mechanism of deposition may also be linked to the type of metal complex dissolved in solution; boiling (loss of H_2S) or the formation of pyrite (loss of dissolved S) may be important precipitation mechanisms for sulphide complexes, while cooling or dilution may result in the breakdown of chloride complexes.

Optical absorption spectroscopy is a well-established method for determining the speciation of metal ions. The absorption bands are characteristic of each complex, or in the case of mixed species may be deconvoluted by fitting procedures. Variations in the absorbance data as a function of ligand concentration and temperature can be used to derive thermodynamic properties such as the equilibrium formation constants. We are constructing a micro-optical imaging spectrometer to obtain absorption spectra from single fluid inclusions at elevated temperatures. This system acquires images of an inclusion at a series of illumination wavelengths. An absorption value can be determined at each wavelength from the referenced light intensity passing through a region inside the inclusion. Spectra have been acquired for cobalt(II) and nickel(II) solutions in glass capillaries with an internal diameter of < 50 μm.

A research program has also been established at the Advanced Photon Source, Argonne National Laboratory, USA, to investigate speciation in fluid inclusions by extended X-ray absorption fine structure (EXAFS) spectroscopy. Spectra have been recorded at room temperature from individual fluid inclusions and modelled to obtain bond lengths and coordination numbers. A heating stage has recently been commissioned and preliminary spectra recorded at temperatures up to 500°C.

[1] Research School of Chemistry, ANU

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Research staff from the Australian Geological Survey Organisation (AGSO) work within RSES to utilise U-Pb SHRIMP, and Pb-Pb and Sm-Nd TIMS techniques. This research is based on the longstanding relationship between AGSO and the Research School, in particular within the Geochronology and Isotope Geochemistry Group. The scientific outcomes address AGSO's role in Minerals Promotions under the National Geoscience Mapping Accord (NGMA), Petroleum Promotions, and Australian Geodynamics CRC (AGCRC). A selected range of research activities from these projects is described below.

Geochronology and provenance of sediments in the Olary Domain, South Australia

R.W. Page[1], C.H.H. Conor[2], C. Foudoulis[1] and S.-s. Sun[1]

It has long been an important objective to correlate Palaeoproterozoic Willyama Supergroup successions in the Olary Domain (eastern South Australia) with those near Broken Hill (western NSW). The Olary Domain includes a succession(s) of metamorphosed, dominantly quartzofeldspathic arenaceous and pelitic sediments, calcsilicate-bearing rocks, and minor volcanic or sub-volcanic rocks. Our SHRIMP U-Pb zircon studies aim to improve (a) lithostratigraphic correlations within the Olary Domain, and (b) stratigraphic connection between Willyama Supergroup rocks in the Olary Domain and Willyama Supergroup rocks near Broken Hill. Measurements of depositional and zircon provenance ages on a number of lithologies in the Olary succession (using SHRIMP), are being integrated with stratigraphic information and with Sm-Nd isotopic studies.

Our initial U-Pb zircon ages for metagranitoid and volcaniclastic rocks in the 'lower albite' unit of the 'quartzofeldspathic suite' show that the oldest rocks exposed in one traverse have a concordant U-Pb zircon age of 1711±2 Ma, indistinguishable from an age of 1712±2 Ma from a felsic volcaniclastic unit at the top of the 'quartzofeldspathic suite'. Because these rocks may be sub-volcanic intrusives, the ages are rigorously only minimum stratigraphic ages. Felsic volcaniclastic units in the eastern Weekeroo Inlier have virtually identical crystallisation ages (1713±2 Ma, 1710±3 Ma). Our SHRIMP results on a succession in the Redan Zone (southeastern Broken Hill) suggest a magmatic event(s) of similar age (1700–1720 Ma), although this same succession was recently advocated by others to be possibly late Archaean in age (Nutman and Ehlers, 1998. AJES 45, 687–694).

Detrital U-Pb zircon ages from Olary Domain meta-sedimentary rocks provide information on the provenance domain(s) and maximum depositional age(s). We are endeavouring to combine such provenance information with the above ~1710 Ma volcanic crystallisation ages across several stratigraphic sections in the Olary area. For this purpose, it is clearly necessary to avoid new zircon growth at ca. 1600 Ma – a product of regional metamorphism.

The clastic rocks in the Mulga Bore-Cathedral Rock and Mount Howden traverses include strongly albitised medium-grained psammites, psammopelites, and pelites. Detrital zircon age patterns are complex, indicating source terrain(s) composed of late Archaean and earlier Palaeoproterozoic rocks. Some early Archaean zircons (3700–3600 Ma) are found. The dominant Palaeoproterozoic zircon ages suggest strongly domainal provenance, from terrains around 1920 Ma, 1860 Ma, 1780 Ma, and 1730 Ma old. This provenance signature is common to most of the sedimentary rocks in the successions so far analysed. It suggests a maximum depositional age of around 1730 Ma. However, minor detrital zircon components in two 'quartzofeldspathic suite' sediments show younger maximum depositional ages of *ca.*

[1] Minerals Division, Australian Geological Survey Organisation, Canberra
[2] Primary Industries and Resources, South Australia

1710–1715 Ma. If the presence of this so far very minor 1710–1715 Ma detrital suite is verified elsewhere in the 'quartzofeldspathic suite', the age of this succession will become tightly controlled, as its maximum (1710–1715 Ma) and minimum (~1710 Ma) ages would be effectively coincident.

An economic focus in the Olary Domain is the 'Bimba suite' – a thin, base-metal prospective pyritic succession of carbonaceous schists, calcsilicates, marbles, and ironstones that is transitional into the underlying 'calcsilicate suite'. Because the 'Bimba suite' is widespread and of such economic interest (correlated in general terms with the Ettlewood Calcsilicate Member, base of Broken Hill Group) the age of deposition of this unit is an objective we will continue to pursue.

Rocks of the 'pelite suite' overlie the 'Bimba suite' sediments. Our detrital zircon ages for 'pelite suite' metasediments in the Mulga Bore traverse are ~1770 Ma and older – effectively a mimic of the 'quartzofeldspathic suite' detrital ages. In the Mount Howden area, however, 'pelite suite' rocks up succession from the Bimba mine include much younger detrital zircons. They reveal not only the same complex provenance seen in the older 'quartzofeldspathic suite', but also an additional younger component defined by a coherent array of detrital zircon at 1648±6 Ma. This zircon component is possibly from a reworked tuff. This part of the 'pelite suite' was thus deposited no earlier than 1648±6 Ma ago, indicating that there is either a structural discontinuity, a significant unconformity, or at least a ~50 million year depositional break, between the 'pelite suite' and older rocks.

The fact that part of the 'pelite suite' in the Olary Domain is no older than 1648±6 Ma invites possible correlation with the Sundown or Paragon Groups near Broken Hill. The Olary succession between this 1648 Ma position in the 'pelite suite' and 'quartzofeldspathic suite' would have been deposited in the interval 1710 to 1650 Ma, and hence may contain direct correlatives of the ~1690 Ma Broken Hill Group. This possibility, and the wider geochronological connections that now emerge between these 1650-1700 Ma successions and contemporary successions such as the Mount Isa Group and McArthur Group in northern Australia, provide an age framework against which more advanced basin analysis and metallogenic models can be considered.

What is the nature of the Tasmanian crust?

L.P. Black[1], R.J. Korsch[1], B.J. Drummond[1], M.P. McClenaghan[3], R. Varne[4] and A.M. Fioretti[5]

This project, known as TASMAP (**TAS**manian **M**apping **A**ccord **P**roject), has evolved from TASGO, a project that was completed several years ago. TASGO was primarily based on the acquisition of large geophysical (aeromagnetic and seismic) datasets, but also had a strong geochronological component. Data from both disciplines identified a major geological issue, which TASMAP is addressing.

Pre-Late Carboniferous Tasmania had been divided by Mineral Resource Tasmania (MRT) into seven different strato-tectonic elements, on the basis of geological mapping and the Aeromagnetic Map of Australia. Each element has a geological history and internal structure that is at least partly unique. The defined elements are King Island, Rocky Cape, Dundas, Sheffield, Tyennan, Adamsfield-Jubilee, and Northeast Tasmania. This sub-division poses a series of questions. First, is it justifiable to represent this region by distinct elements? If so, have they always been in their present juxtaposition, do they represent the reassembled parts of what once was a single terrane, or are they the aggregation of what were originally unrelated terranes? The resolution of these questions is fundamental to a correct interpretation of the geological evolution of Tasmania.

[3] Mineral Resources Tasmania, Hobart
[4] University of Tasmania, Hobart
[5] Centro Studi Geodinamica Alpina, Padova, Italy

Results produced during TASGO did not support the concept of seven fundamentally different geological elements. For example, the deep seismic reflection data failed to identify any significant differences between the six western elements, the lower crust for all of which is of normal thickness. Although it demonstrated that the lower crust of the Northeast Tasmania element is extended and thinned, this could have occurred, at least in part, in post-Palaeozoic times. SHRIMP dating undertaken during TASGO was similarly unsuccessful in distinguishing between the six western elements, which yielded relatively similar detrital zircon age patterns (dominated by ~1700 to ~1800 Ma grains) for widely-separated Proterozoic sedimentary rocks. Recent TASMAP results have shown (not surprisingly) that the Palaeozoic sedimentary sequence of the Northeast Tasmania element has a dramatically different age pattern that is dominated by younger (Late Neoproterozoic to Early Palaeozoic) zircon.

TASMAP is examining the reality of the different elements in more detail, by the production of a new aeromagnetic dataset, and through the acquisition of further geochronological and geochemical data. Granites are being specifically targeted, because they offer an indirect opportunity to study the deep crustal regions from which they were derived. Late Devonian to Early Carboniferous granites have been selected, in order to simplify data interpretation, and because granites of that age are known to crop out in all but one of the elements. The chemistry of these rocks will help constrain the composition of the granite source regions. Their inherited zircon, mostly occurring as discrete cores enclosed by zircon that crystallised from the Devonian-Carboniferous granitic magmas, is giving an indication of the age of the rocks from which the granites were melted. Quite clearly, SHRIMP is the only suitable means of accomplishing this task. So far, the inherited component in the western Tasmania granites is yielding broadly similar age patterns to those of the detrital sedimentary rocks from the same elements.

On completion, this study will have produced physical, chemical, and temporal documentation of the deep crust below Tasmania, which will allow the nature of, and the relationship between, the different geological elements to be more rigorously assessed.

The project is being extended to two other regions. First, it will examine the proposed juxtaposition of northern Victoria Land (NVL), Antarctica, with Tasmania in the Gondwana super continent. Two of the first NVL granites to be dated have yielded ages that are significantly younger (by up to 100 million years) than those derived from Rb-Sr whole-rock analyses. This is probably a consequence of incomplete homogenisation of the granite magmas, resulting in an initial positive correlation between Rb/Sr and $^{87}Sr/^{86}Sr$.

It has also been deduced that the rocks of the South Tasman Rise (STR) might be related to both NVL and Tasmania. Careful selection of previously collected dredge samples from the STR should allow this comparison to be tested.

Time calibration of Gondwana stratigraphy and environments

J.C. Claoué-Long[1]

An unrivalled opportunity to study a continuous record of deposition in the Cranky Corner Basin of northern NSW has been provided by the NSW Department of Mineral Resources, which drilled a stratigraphic hole and retrieved a continuous core penetrating the Permian coal measures and the underlying late Carboniferous sediments. The opportunity is important because, during the late Carboniferous and early Permian, Australia lay close to the South Pole on the margin of Gondwana. The low diversity, cold-climate fossil faunas are endemic to polar Gondwana and difficult to correlate, even between marine sediments and their local continental glacigene equivalents. More distant correlations to the equatorial stratigraphies preserved in Europe and Russia are controversial, so comparisons between the major continental masses of Gondwana and Laurasia lack precision in the timing of geological events and processes.

The 500m core records a complex clastic sequence in continental, deltaic and shallow marine environments, in which abundant volcaniclastic detritus indicates reworking of material on the margin of an active volcanic terrain. There are also 15 horizons which may be primary pyroclastic deposits (as distinct from reworked materials), varying from a partly-welded ignimbrite to several units less than 1cm thick. These offer potential for numerical age control, because the crystallisation age of their components will approximate the age of deposition. Many of them are very thin or loosely consolidated, and so unlikely ever to be found in surface outcrops, emphasising the unique value of the continuous record in the drillcore. In addition to geochronology, a multi-discipline team has cooperated in sampling the core for palaeontology, palynology, palaeomagnetic signatures, organic and inorganic geochemistry, reflectance and fluorescence, heat conductivity, stratigraphy, and studies of depositional environments.

All of the volcanics have suffered alteration processes, and zircon is the only mineral preserved that is suited to isotopic dating. The SHRIMP microbeam method of zircon analysis has been essential to dating the zircons because, with samples restricted to half-core of units as thin as 1cm, the quantity of zircon crystals available was small. Also, many of the zircon populations included grains inherited from previous magmatism, in addition to the eruption-age crystals, and it was vital to distinguish these with replicate within-grain probing. In preparation for isotopic analysis, up to four samples were co-mounted on an individual SHRIMP mount, so that they could be probed together under the same operating conditions. By this means, relative ages at key levels within the drillcore have been established independently from the SHRIMP zircon standard (which is needed to link ages obtained in different probing sessions).

The net result of this effort is 9 ages measured in the range between 306Ma and 286Ma linked in continuous sequence with detailed geological and palaeontological information, and straddling the cold climate deposition from the late Carboniferous into the early Permian. Relative ages within the core are independent from the laboratory standard, and absolute age precisions approach the 1% level. The stratigraphically lowest age is for the Mt Durham Tuff, a distinctive and geographically widespread unit, and provides a direct age reference for a marker used in mapping the glacigene Seaham Formation. Above that, the timing of deposition is shown to be sharply episodic, with a 13Ma hiatus intervening above Carboniferous shallow-marine and fluvial deposits, and before the onset of Permian delta sedimentation with coal swamps. These Gondwana environments and their associated palaeontology now have a direct calibration in numerical time. The resolution of these stratigraphic timing issues points up the unique capabilities of SHRIMP in dating problems not approachable by other dating techniques, and the value of integrating SHRIMP geochronology with wider multi-discipline projects.

Lead isotope model ages and base-metal mineralisation events in the Whim Creek and Mallina Basins of Western Pilbara

S-s. Sun[1], D.L. Huston[1] and R.H. Smithies[6]

The *ca.* 3000 Ma Whim Creek Belt lies in the central to western part of the granite-greenstone terrane of the Archaean Pilbara Craton, northwestern Western Australia. This belt hosts significant Cu-Zn±Pb deposits at Whim Creek, Mons Cupri and Salt Creek. Lithostratigraphic studies and SHRIMP zircon U-Pb geochronological data suggest that the volcano-sedimentary rocks of this belt either correlate directly with, or immediately underlie, the sedimentary rocks of the adjacent and regionally extensive Mallina Basin.

There are no absolute geological ages for the mineralising events that formed base metal deposits in the Whim Creek and Mallina Basins, due to of a lack of suitable material for accurate isotopic dating. We must necessarily rely on Pb isotope model ages of galena samples and Pb-rich gossan from the base metal deposits.

[6] Geological Survey of Western Australia, Perth

Pb-isotope model ages are particularly effective for the early Archaean because mantle convective mixing processes were more effective, and there had been less time for the continental crust to perturb U-Pb systematics of the source regions. To "fine-tune" Pb model ages we have adopted the approach of using a "local control-point" for fine-tuning. In this case we have used the Panorama VHMS deposits of the Strelley Volcanics of the central Pilbara Craton, which yield a precise zircon U-Pb age of 3238 ±4 Ma for the host rock. The single-stage Pb evolution model of Thorpe (1990) developed for the Archaean Western Superior Province of Canada also works quite well for the Pilbara. For example, this model gives 3469 Ma for the Big Stubby ore of the eastern Pilbara Craton, which has a precise zircon U-Pb age of 3465±3 Ma for the host rock, and the model gives 3245 Ma for the Panorama VHMS deposit. Furthermore, using the Panorama lead as a control-point we have obtained very similar model ages using Cumming and Richards (1975) model of progressive increase of μ value in the source region.

The double-spike method has been used to obtain very precise Pb isotope compositions. New lead-isotope model ages of base-metal mineralisation in the Whim Creek and Mallina Basins fall into two groups: (1) a nominally younger group (2920–2933 Ma) that includes a series of quartz-galena vein deposits, the Mons Cupri deposit, and the ACL prospect (near Salt Creek); and (2) a nominally older group (2942–2948 Ma) that includes the Salt Creek, Whim Creek and Egina deposits. We tentatively suggest that mineralisation in the Whim Creek Belt relates to two separate events that can be correlated with felsic magmatism throughout the Mallina-Whim Creek Basin. The younger event clearly post-dates sedimentation and nominally corresponds to the intrusion of the Bookingarra Granite (2925±4 Ma), the youngest phase of the Caines Well Granitoid Complex. The older event nominally corresponds to the intrusion of the Portree Granitoid Complex (2946±6 Ma) and the Peawah Granodiorite (2948±5 Ma), and to D_1 deformation.

Although the Thorpe model appears to work well in the east and central Pilbara Craton, it may not be fully appropriate for the west Pilbara Craton, due to a different crustal evolution history. In principle, a control point based on an independent dating technique in the west Pilbara Craton is required to test the validity of Thorpe's model. This uncertainty in model ages has greatest significance for the Mons Cupri deposit which, if a VHMS model is accepted, would be the same age or slightly older than the nearby Whim Creek deposit, even though the model age for Mons Cupri (2921 Ma) is ca. 27 million years younger.

The Egina (2942 Ma) deposit in the Mallina Basin appears to occur in a stratigraphically equivalent position to the Whim Creek and Salt Creek deposits of the Whim Creek Basin. If such a correlation is valid the Mallina Basin should also be considered highly prospective for Cu-Zn±Pb deposits. Numerous minor base metal deposits in the Mallina Basin are similar to deposits of the Whim Creek Belt, which strongly supports this view.

Some regional implications of new geochronological constraints from the Tennant Creek and Arunta Inliers, central Australia.

K.J. Hussey[7], J.B. Smith[1] and N. Donnellan[7]

NTGS and AGSO recently commenced a geochronology project to further investigate structural and stratigraphic relationships and correlations within and between the Arunta and Tennant Creek Inliers. The first samples to be dated document a newly recognised 1805 Ma period of igneous activity in the northern-most Arunta Inlier. This suggests that folding in the Davenport province is older than previously thought, broadly confirms correlations between units in the Davenport province, and precludes previously suggested correlations between the southern and northern Tennant Creek Inlier.

The Strzeleckie Volcanics were selected to test the stratigraphic link with the Wauchope Subgroup in the main part of the Davenport province. SHRIMP U-Pb dating of zircons from an

[7] Northern Territory Geological Survey, Alice Springs

ignimbrite near the base of the Strzeleckie Volcanics indicates it erupted at 1819 ± 9 Ma. This confirms the ignimbrite is broadly contemporaneous with other dated extrusive igneous rocks within the Wauchope Subgroup, and high-level felsic sills in the Davenport province, although the Treasure Volcanics, upper Ooradidgee Subgroup, is also similar in age. In the extreme north of the Davenport province only volcaniclastic sedimentary rocks are present in this stratigraphic interval. It therefore appears that subaerial felsic igneous activity at around 1820 Ma was concentrated in the southern parts of the Davenport province. Another implication is that the lithostratigraphic correlations between the Davenport province and the northern-most Tennant Creek Inlier are not correct. A maximum age of ~1784 Ma for a basal unit of the Tomkinson Creek Subgroup in the northern Tennant Creek Inlier shows that this subgroup is much younger than the 1820 Ma Wauchope Subgroup.

Two granite samples appear to constrain the age of regional deformation in the Barrow Creek Sheet area. The medium- to very coarse-grained porphyritic and enclave-bearing Ooralingie Granite shows a well developed subvertical foliation and is clearly intruded by the relatively undeformed Bean Tree Granite. These granites are part of the Barrow Creek Granitic Complex which intrudes greenschist to lower amphibolite facies Bullion Schist. SHRIMP U-Pb dating of zircons from the Bean Tree and Ooralingie Granites indicates magmatic ages of 1803 ± 6 Ma and 1809 ± 5 Ma, respectively. The closeness of these ages suggests that the Ooralingie Granite was probably syn-tectonic, and the Bean Tree Granite immediately post-tectonic, with respect to the same tectono-magmatic event. The northwest-trending foliation in the Ooralingie Granite is pervasive, and of similar metamorphic grade to the country rocks. Further, the foliation appears to parallel the trend of large-scale folds in the central-northern Barrow Creek Sheet area. It therefore seems plausible that the Ooralingie Granite, Bullion Schist and the Ooradidgee and Wauchope Subgroups were deformed immediately prior to emplacement of the Bean Tree Granite. Thus, large-scale upright folding in the Davenport province appears to have occurred around 1805 Ma.

Geochemical characteristics of ca 3.0-Ga Cleaverville greenstones and later mafic dykes, west Pilbara: implication for Archaean crustal accretion

Shen-su Sun[1] and A.H. Hickman[4]

In the Cleaverville area (west Pilbara) greenstones with mid-ocean-ridge basalt (MORB) affinities (Regal Formation), and ~3020-Ma felsic volcanic rocks (Cleaverville Formation) with relatively young Nd T_{DM} model ages (3110–3210 Ma), apparently represent juvenile crust. These rocks have depositional ages of ≥3020 Ma (Cleaverville Formation) and ≥3050 Ma (Regal Formation). Within 20 km of the west Pilbara coast, the Regal Formation stratigraphically underlies the Cleaverville Formation (mostly chert-banded iron formation (BIF) and clastic rocks). Except where faulted, as at Cleaverville, the contact is conformable or disconformable. At its base the Regal Formation is in tectonic contact with the 3260-Ma Nickol River Formation, Ruth Well Formation, and Karratha Granodiorite. The age of the Regal Formation is loosely constrained between 3020 and 3260 Ma.

New geochemical data confirm the MORB-like features of the Cleaverville greenstones. They show good consistency in Nb/Th (7–8), Nb/La (0.7–0.9) and slightly light REE depleted patterns. All samples have slight Nb depletion relative to La, and Th enrichment relative to Nb. This relative Th enrichment is an atypical MORB character. It might be an alteration effect, like Ba, or the product of crustal contamination during extrusion through thin felsic crust. Alternatively, it might be due to quicker recycling of crustal material through a subducted zone back into the hotter convecting Archaean upper mantle, which is the source region of MORB. These MORB-like Cleaverville samples have initial εNd values of +1.0 to +2.5 at 3150 Ma, similar to other early Archaean greenstones.

A northeast-trending mafic dyke intruding the MORB-like basalts is characterised by pronounced light REE and Th enrichment and Nb depletion. These features are identical with ~2.95-Ga high-magnesian basalts of the Louden Volcanics and Mount Negri Volcanics, which crop out in the Whim Creek belt on the other side of the Sholl Shear Zone. One sample from the mafic dyke has an initial εNd value of -1.5 at 2.95 Ga. This is similar to samples of the Louden and Mount Negri Volcanics, which have initial εNd values of about -2.0 at 2.95 Ga. These values are considerably lower than that (~+3) of the depleted mantle at that time and the Cleaverville greenstones. A reasonable explanation for this low initial εNd, and for Nb depletion and Th and Ba enrichment of the Cleaverville dolerite dyke and Louden and Mount Negri Volcanics, is that their mantle source was contaminated by sediments derived mainly from ~3250-Ma source rocks in the region. However, an island-arc or cordilleran environment is not essential for the generation of these basalts; rather, many basalts originating in an intraplate environment could have had their mantle source regions modified by prior subduction processes. A closer examination of all pertinent geological information and an integrated interpretation of the data of the Whim Creek Belt and Mallina Basin might reveal the evidence for such processes.

Our new geochemical data support the view that the Regal Formation represents MORB-like oceanic crust. Away from the Cleaverville-Karratha area, the Regal Formation is not as structurally complex, and evinces no stratigraphic repetition with the overlying BIF–chert succession of the Cleaverville Formation. Only at Cleaverville is there sufficient structural complexity to make a case for some type of accretionary complex produced by subduction of the oceanic crust at a continental margin, as suggested by Ohta *et al.* (Lithos 37, 199–221, 1996). One of us (Hickman, in preparation) believes that there are regional problems with this interpretation. Further to the southeast: the Regal Formation (with MORB-like basalts) has been thrust across the 3260-Ma units, indicating obduction rather than subduction. Moreover, the Cleaverville Formation does not appear to be an oceanic deposit. Sugitani et al (1996) presented chemical and sedimentological evidence that the BIF of the Cleaverville Formation was deposited in a shallow-water to evaporitic environment, possibly a marginal sea, with nearby felsic volcanic centres supplying ash. Also, recognition that the Cleaverville Formation occurs at localities 30 km and 100 km southeast of Cleaverville (Hickman, 1997), precludes this unit being regionally allochthonous.

PRISE

Established in 1989, ***PRISE*** is the Research School of Earth Sciences preferred vehicle for commercial and "commercial collaborative" work in the areas of geochronology, isotope geochemistry and trace-element geochemistry. ***PRISE*** is a joint venture between the Research School and ANUTECH Pty Ltd. It provides access to the Research School's wide range of equipment and expertise in isotope geochemistry and geochronology. As Visiting Fellows, ***PRISE*** scientific staff also carry out their own personal research projects.

During 1999, Dr David Phillips joined ***PRISE*** from the De Beers Geoscience Centre (formerly Anglo American Research Laboratories) Crown Mines, Johannesburg. David is principally involved with Ar-Ar and K-Ar studies, but has also undertaken LA-ICP-MS projects.

The inaugural ***PRISE*** Visiting Fellow, Dr K. Ludwig from Berkeley Geochronology Center, spent three weeks at the Research School during 1999. We thank Dr Ludwig for his time with us, for the seminars he presented and for his continued interest and involvement in the School's activities.

PRISE congratulates Dr R. Armstrong on being the recipient of the Honours Award for 1999 from the Geological Society of South Africa for particularly meritorious contributions to the Society or the geological fraternity of South Africa.

PRISE hosted the following visitors to the School during 1999:

- Dr J. Aleinikoff, Branch of Isotope Geology, US Geological Survey, Denver, USA
- Dr R. Pankhurst and Dr I. Millar, British Antarctic Survey, Keyworth, United Kingdom
- Dr C.W. Rapela, Centro de Investigaciones Geologicas, Universidad de la Plata, Argentina
- Professor F. Hervé, Department of Geology, University of Chile, Santiago, Chile
- Professor T. Watanabe, Geology Department, Hokkaido University, Japan
- Professor D. Gebauer and Ms A. Liati, Department of Earth Sciences, ETH Zürich, Switzerland
- Dr A. Cocherie and Dr P. Rossi, Bureau de Recherche Géologique et Miniere, Orleans, France
- Dr C. Delor, Bureau de Recherche Géologique et Miniere, Orleans, France
- Professor W.R. van Schmus, Department of Geology, University of Tennessee, USA
- Mr K. Kenyon, Anglogold Ltd, Johannesburg, South Africa
- Ms S. Perritt, Department of Geology, University of Natal (Durban), South Africa
- Dr M. Pimentel, Instituto de Geosciências, University of Brasilia, Brazil
- Dr G. Teale, Werrie Gold Ltd, Prospect, South Australia
- Dr T. Hirajima, Department of Geology and Mineralogy, Kyoto University, Japan
- Mr S. Boger, School of Earth Sciences, University of Melbourne, Victoria

A selection of projects undertaken by ***PRISE*** staff during 1999 is included below.

New insights into the stratigraphy and tectonic evolution of the Cape Fold Belt, South Africa - A SHRIMP U-Pb zircon perspective

R.A. Armstrong and M.J. de Wit[1]

The Cape Fold Belt (CFB) of southern Africa preserves the products of two orogenies, *viz.* the Neoproterozoic Saldanian Orogeny (*c.* 650–550 Ma ago) and the Late-Palaeozoic Early Mesozoic Cape Orogeny (*c.* 250Ma ago). The tectonic history is recorded in variably deformed and metamorphosed rocks from the two branches of the CFB. The north-northwest

[1] Department of Geological Sciences, University of Cape Town, Rondebosch 7700, South Africa

– south-southeast striking western branch experienced predominantly brittle deformation and here unconformable relationships between the Table Mountain Group (TMG, Cape Supergroup) and the underlying Basement rocks are clear. Deformation in the east-west striking southern branch, on the other hand, was ductile and penetrative, resulting in a regional finite strain fabric. A number of east-west elongated Basement inliers occur within this southern branch of the CFB, but deformation is intense along the contacts of the Basement and overlying Table Mountain Group rocks, obscuring or complicating important stratigraphical relationships.

Clearly, the tectonic history and the stratigraphic relationships between supposed "basement" and overlying sequences needs geochronological control. Unfortunately the general lack of suitable dating material precludes the establishment of absolute time markers in the CFB, and we have used the geochronological record preserved detrital zircons in order to place maximum age constraints on the sediments from selected areas from the Port Elizabeth "basement" inlier to Table Mountain. An earlier integrated field and SHRIMP study of sediments in one of the basement inliers (the Kango Inlier) by Barnett *et al.* (1997) identified sediments which previously had been considered as part of the basement, but contained detrital zircons with ages remarkably similar to those of the Table Mountain Group (Armstrong *et al.*, 1998). We have now examined the detrital zircon record from sediments, including deformed and undeformed clast components of the pre-TMG basement, from across the CFB. This approach, together with SHRIMP U-Pb zircon dating of granites from throughout the region and small gabbroic bodies in the Kango Inlier, has enabled us to refine and redefine the geological history of the Cape Fold Belt. Clearly, many of the sediments which were previously considered to be part of the pre-TMG basement (and deformed by the Saldanian Origeny) contain zircons similar in age to those found in the TMG, indicating a much younger age (<520 Ma) than previously thought. As these sequences are deformed, it is clear that it is the younger Cape Orogeny which has dominated in the region. This has important implications for the ages of major structures in these sediments and also of correlations not only within the Cape Fold Belt, but also for correlations with similar sequences in other parts of Gondwana.

Our combined cathodoluminescence and SHRIMP U-Pb studies of the inherited zircon in the Cape Granites have shown that the Basement in the whole region is an extension of the Mesoproterozoic Namaqua-Natal belt, rather than a Pan-African feature.

New evidence of polymetamorphic events of the Sør Rondane Mountains, East Antarctica

K. Shiraishi[1], C.M. Fanning, R. Armstrong and Y. Motoyoshi[1]

The Sør Rondane Mountains (71.5–72.5 S; 22–28 E) are underlain by a medium- to high-grade metamorphic rocks together with various plutonic rocks and minor mafic dykes. An inferred suture line (Sør Rondane Suture; SRS) divides basement rocks into two terranes; Northeast (NE) terrane which consists mainly of granulite facies rocks of intermediate and pelitic compositions and Southwest (SW) terrane which consists of amphibolite facies rocks mainly of intermediate to basic compositions. A SHRIMP U-Pb geochronological study of zircon from eleven rocks (four orthogneisses, five paragneisses, one migmatite and one granite) and sphene from three rocks (two orthogneisses and one granite) covering a wide ranging area of the Sør Rondane Mountains reveals three stages of metamorphic and magmatic events: 900–1000 Ma (M1 metamorphism, and tonalite and enderbite magmatism), 650–600 Ma (M2 metamorphism) and 570–530 Ma (M3 metamorphism, migmatisation, and granite magmatism). It is significant that inherited ages older than ca.1100 Ma are very rare, even among the paragneisses. Only one grain in 20 zircons from a pelitic gneiss from the NE terrane records an inherited component, at ca.3000 Ma. The central parts of other grains of this gneiss yield uniformly *ca.*1100 Ma.

[1] National Institute of Polar Research, 1-9-10, Kaga, Itabashi-ku, Tokyo 8515 Japan

Taking into account previous Sm-Nd and Rb-Sr data, the basement of the Sør Rondane area is seen to comprise Grenvillian age juvenile crust (*ca.*1100–1300 Ma) with minor amounts of Archaean material from the hinterland of the Sør Rondane regions. Granulite facies regional metamorphism (M1) occurred between 900–1000 Ma forming the NE terrane. Subsequently the NE terrane is metamorphosed at 630–650 Ma under granulite to amphibolite facies conditions (M2). In the eastern part of the Sør Rondane Mountains, that is, the eastern part of the NE terrane, M2 occurred at *ca.* 600 Ma, younger than the age for M2 in the central part of the mountains. Zircons from a paleosome in a pelitic gneiss from this region formed at ca.600 Ma whereas those from a leucosome segment of the same rock sampling yield an age of 534 ± 7 Ma, coeval with the formation of granitoid bodies between 570–530 Ma. The U-Pb data imply that Pan-African activity in this region started at *ca.* 650 Ma. Previous interpretations of the timing of the deformation history for the Sør Rondane Mountains should now be revised on the basis of these new U-Pb zircon and sphene results.

Mesozoic volcanism, plutonism and sedimentation in Eastern Ellsworth Land, West Antarctica.

C.M. Fanning and T.S. Laudon[3]

Eastern Ellsworth Land (EEL), West Antarctica is located at the southern end of the Antarctic Peninsula. Despite its geographical significance as the southern most outcrop of the Mesozoic magmatic chain that forms the Cordillera of North and South America, the outcrops have rarely been visited and field constraints between the various rock units is poorly understood. Nevertheless, we are in the process of carrying out SHRIMP U-Pb zircon and Sm-Nd isotopic analyses of volcanic and plutonic rocks across this southernmost section of the Cordilleran magmatic arc to provide constraints on the evolving Pacific margin of Gondwana.

The Mesozoic of EEL is dominated by subduction-related calc-alkaline volcanic and plutonic rocks, and in part coeval sedimentary rocks considered to have been deposited in a back-arc setting. The volcanic rocks are equivalent to the Antarctic Peninsula Volcanic Group (APVG) of Graham and Palmer Lands, arbitrarily named the Mount Poster Formation (MPF) south of 74 deg. 30 mins latitude. The sedimentary Latady Formation (LF) is a sequence of thick, structurally complex, shale, siltstone, sandstone and conglomerate, locally interbedded with volcanic rocks of the MPF. The MPF and LF are therefore considered coeval, deformed prior to intrusion of the Cretaceous Lassiter Coast Intrusive Suite (LCIS). Petrological and chemical studies of the LF, supported by SHRIMP U-Pb detrital zircon suggest that the trend of arc migration during the Mesozoic was the "inverse" to commonly accepted models.

Zircons from the MPF volcanic samples are dominated by simple prismatic grains with gas vapour trails interpreted to represent volcanic parageneses, and lozenge shaped grains with inherited central areas also representing components from magmatic sources. Cathodoluminescence (CL) images reveal complex internal structure in many grains with inherited centres observed within simple magmatic zircon. Our transect commences in the east, where a porphyritic rhyolite from the Sweeney Mountains records a magmatic age of 189 ± 3 Ma, with inheritance at ~600 Ma, ~1000–1100 Ma, and ~1600 Ma. Tracking west, a porphyritic rhyolite from Mount Rex records an interpreted magmatic age of 167 ± 3 Ma, with an inherited magmatic component at ~185 Ma, and older inheritance at ~600 Ma and ~1050–1070 Ma. At Mount Peterson, the magmatic age for a MPF porphyry is 188 ± 3 Ma. The westernmost sample analysed is from Fitzgerald Bluffs where a porphyritic dacite assigned to the MPF has a magmatic age of 97 ± 1.5 Ma. Clearly this latter sample is related to the Cretaceous LCIS, and highlights the necessity for more detailed mapping in this remote area.

[3] University of Wisconsin Oshkosh, WI 54901, USA

We had previously suggested that on the basis of the Mount Rex and Sweeney Mountains U-Pb zircon ages that the migration of MPF magmatism follows the generally accepted westward trend. Additional data from Mount Peterson indicates that this is not a simple migration and we are composing a more complete section of magmatic age information in this study of the Mesozoic evolution of EEL, west Antarctica.

Laser Probe 40Ar/39Ar Step-Heating Analyses of Single Clinopyroxene Inclusions Extracted from Jwaneng, Orapa and Mbuji-Mayi Diamonds.

D. Phillips, J.W.Harris[4], and G.B. Kiviets[5]

The development of micro-analytical $^{40}Ar/^{39}Ar$ laser probe systems has generated a host of new applications, including the analyses of single clinopyroxene inclusions in diamonds. These inclusions may be less than 300 microns in size and contain potassium levels below 0.3 wt.%. Initial attempts to determine diamond genesis ages from analyses of syn-genetic clinopyroxene inclusions proved unsuccessful and yielded variable apparent ages, intermediate between the times of host kimberlite emplacement and diamond crystallisation. This effect was attributed to partial diffusion of pre-eruption ^{40}Ar to the diamond/inclusion interface during mantle residence. Laser drilling to buried inclusions was considered as a possible solution to the problem of measuring genesis ages. It was also suggested that analyses of inclusions that have been totally extracted from their host diamonds should yield the age of host kimberlite eruption. The latter possibility has important implications for constraining the sources of detrital diamond populations worldwide. To test the latter contention, clinopyroxene diamond inclusions, from the Jwaneng (Botswana), Orapa (Botswana) and Mbuji Mayi (Democratic Republic of Congo) kimberlites, were analysed in the current study.

Although some inclusions yielded ages within error of the time of host kimberlite intrusion, the majority yielded apparent ages significantly older than the time of host intrusion, indicating that not all pre-eruption argon resides at the diamond/inclusion interface as originally thought. In addition, older apparent ages were obtained from lower temperature steps. Furthermore, age differences between fragments from the same inclusion indicate that the argon is heterogeneously distributed. The step-heating results suggest that the pre-eruption argon is located in low retention sites and/or at grain/domain boundaries. One possible explanation for the anomalous argon distributions involves initial diffusion of pre-eruption argon to the diamond interface region in response to mantle cooling after diamond crystallisation. This is followed by diffusion of some interface gas back into the inclusion in response to increased argon partial pressures caused by differential expansion during the eruption process. In cases where cracks develop around the inclusion, all pre-eruption argon may be lost from the inclusion.

The current study demonstrates that the interpretation of $^{40}Ar/^{39}Ar$ laser probe results from extracted or partially encapsulated inclusions is complex. While some inclusions may well yield reliable host kimberlite/lamproite emplacement ages, the partial retention of pre-eruption argon will often lead to an over-estimation of the true result. The current data also suggest minimum genesis ages of 2.2 Ga and 2.8 Ga for two Jwaneng inclusions, which are significantly older than inferred Sm-Nd diamond genesis ages obtained for the same locality. This suggests that some portion of the pre-eruption argon is extraneous, or that the Jwaneng diamonds grew over a prolonged time period.

[4] Department of Geology and Applied Geology, University of Glasgow, Glasgow, G12 8QQ, UK
[5] De Beers GeoScience Centre, PO Box 82232, Southdale, 2135, South Africa.

RESEARCH SUPPORT

ELECTRONICS GROUP

The group enjoyed another demanding and stimulating year, which saw the SHRIMP Multiple Collector bench tested, modified and fitted to SHRIMP II for beam tests, the design and commissioning of two AntPAC2000 instrument packages for temporal data logging by GPS in Antarctica, the fabrication of a third such 'Electronics Package' for sale to the University of Utrecht, the completion of an instrumentation package for the 4 kiloTonne press, together with the completion of a range of smaller development projects.

Maintenance (at system through to component level) accounted for 21.5% of human resources, the remainder distributed between Instrument Design and Development (66%), personal and group resource development (0.9%) ,Group Administration (10.1%) and School Administration (1.5%). Maintenance continued to receive the highest priority, and we believe we achieved an adequate response rate and customer focus.

Staffing

There were no staffing changes during the year, and the group continues to comprise five Technical Officers and one Trainee Technical Officer. Following university requirements, group staff reduced accumulated recreation leave credits during the year.

Major Tasks Undertaken

Antarctic GPS Instrument Package: (21.4% of total manhours).

A complex remote instrument package (AntPAC2000) was developed for deployment in Antarctica by the Geodynamics Group. Two packages were fabricated for Geodynamics, and a third for commercial sale. (A. Welsh, N. Schram, A. Forster, A. Latimore, J. Arnold and J. Lane)

Hard Materials Project: (4.9% of total manhours). Modifications to data acquisition on the 4 kiloTonne press were designed, constructed and installed. (A. Forster and A. Latimore)

SHRIMP II Multiple Collector: (6.8% of total manhours). Integration of control electronics, hardware and software continued. Bench testing was completed, and the Multiple Collector mounted on SHRIMP II for beam testing. (N. Schram).

NG61 Mass Spectrometer: (6.4% of total manhours). Design of a high performance Pulse Counting System, suitable for single or multiple collector applications was well advanced. (A. Latimore and J. Lane).

Soil Sample Drier: (2.3% of total manhours). A solar/battery/mains /fire powered oven was developed for use by the Environmental Processes Group for the field preservation of soil samples. (J. Arnold, A. Welsh, A. Forster and N. Schram).

tesla tamer© Magnetic Field Probes: (2.0% of total manhours). Nine probes were manufactured and sold to ASI in support of SHRIMP sales. (J. Arnold).

Projected Outlook

2000 promises to be another demanding year, as we turn our attention to the NG61 Mass Spectrometer, and 'Charge Mode' data acquisition developments for the new Finnigan Triton instruments. The ageing SHRIMP II design (electronics) is becoming increasingly difficult for the school's commercial partners (Australian Scientific Instruments) to replicate due to component obsolescence, and we anticipate involvement in the re-design of significant elements of that instrument.

The maintenance workload of the group remains high (currently 21.5% from 11% during 1997) due to expansion and ageing of the schools instrumentation base, and the assimilation of former RSPAS staff and operations, and this will be exacerbated as the commissioned instrument base broadens during 2000.

The bulk of maintenance continues to be undertaken by senior group members, who also lead the development effort, thus increased maintenance demand has a disproportionate effect on developmental activities. This trend will continue to limit the timely delivery of development projects during 2000.

WORKSHOP

1999 has given us time to reflect on and improve our solutions/techniques to many of the challenges and demands of recent times. Workshop training on new equipment and software is now a permanent part of our lives. Again we have no major projects being worked on at the moment but many smaller ones with deadlines just to keep us focused. We are becoming more proficient with our modern equipment and software and our reputation for having a go at the more difficult jobs has spread beyond the school. In fact we are doing an involute curve for University of Wollongong at the moment after they could find no one prepared to do it for them commercially.

We finally saw the installation of the multicollector on Shrimp II. This was a major undertaking moving the Shrimp offline for a month while some minor and major problems were sorted out.

This year we purchased a new Electrical Discharge Computer Control Wire Cut Machine in partnership with RSPhysSE. This is a significant addition to the ANU engineering capability as it gives us twice the capacity with state of the art performance in speed and accuracy. It was also the most expensive purchase of engineering equipment for the ANU made possible by a RIEF grant of a $170,000. The balance of the $320,000 cost was made up from $60,000 RSES, $80,000 RSPhysSE and $10,000 ASI. It compliments our existing machine at RSES.

There is only one major project in planning at this time, the 61CM TIMS that we expect to take a large amount of our effort in 2000.

All of our usual customers kept us busy with equipment repairs and sample preparation. Lab upgrades and system automation seems to be a continuing activity requiring our services. We have appreciated the considerable support the school has given us in building up the workshop to a relatively high engineering capability in both terms of equipment and staff.

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[**] Former member of RSES
[†] Visitor to RSES during 1998
[*] Not a member of ANU
[#] Member of IAS (but not RSES)
[+] Member of The Faculties, ANU

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ACADEMIC STAFF MATTERS

The following joined the academic staff of the School in 1999 or took up new appointments in 1999:

Dr E. Debayle	Research Fellow (Previously Postdoctoral Fellow, Seismology.)
Professor R. Griffiths	Professor (previously Senior Fellow, Geophysical Fluid Dynamics.)
Dr J. Hermann	ARC Postdoctoral Fellow (Petrochemistry and Experimental Petrology.)
Dr S. Zhang	Research Fellow (Previously ARC Postdoctoral Fellow, Petrophysics.)

The following left the academic staff of the School in 1999:

Dr C. Alibert	Left her position as Research Fellow to take up a Visiting Fellowship in the School.
Dr E. Debayle	Left his appointment as Research Fellow to take up an appointment in the Seismology Group, Institut de Physique du Globe, French National Research Agency, Strasbourg, France.
Dr O. Gudmundsson	Left his appointment as Research Fellow to take up an appointment in the Danish Lithosphere Center, Copenhagen, Denmark.
Dr C.S. Turney	Left his position as Postdoctoral Fellow (Environmental Processes Group) to take up an appointment in the Geology Department, Royal Holloway, University of London.
Dr S. Vergniolle de Chantal	Left her position as ARC International Fellow (France) to return to Institut de Physique du Globe, Paris France. Dr Vergniolle also took up a Visiting Fellowship in the School.
Dr S. Webb	Left her position as Fellow (Petrophysics) to take a position as ARC Senior Research Fellow in the Geology Department, ANU. Dr Webb also took up a five-year Visiting Fellowship within RSES.

PHD STUDENTS – THESES SUBMITTED

Ms L.J. Bloomfield	The dynamics of turbulent fountains in homogeneous and stratified fluids.
Supervisors:	Dr R.C. Kerr, Professor R.W. Griffiths
Advisor:	Professor J.S. Turner
Ms C. Davids	A thermochronological study of southern Fiordland, New Zealand
Supervisors:	Professor I. McDougall, Dr G.M. Gibson (AGSO)
Advisors:	Dr T.R. Ireland, (RSES/Stanford), Dr D. Ellis (Geology, The Faculties)

Mr P.W.O. Hoskin	Aspects of the chemistry of zircon
Supervisors:	Dr I.S. Williams, Dr H.St.C. O'Neill
Advisers:	Professor B.W. Chappell (Geology, The Faculties), Dr T.R. Ireland (RSES/Stanford)
Mr G. Clitheroe	Receiver based studies of the Australian continent
Supervisor:	Professor B.L.N. Kennett, Dr O. Gudmundsson
Adviser:	Dr M. Sambridge
Mr A.P. Hitchman	Interactions between aeromagnetic data and electromagnetic induction in the Earth
Supervisor	Dr F.E.M. Lilley
Advisers:	Professor B.L.N. Kennett, Dr M. Sambridge (RSES) and Dr P. Milligan (AGSO)
Mr D. Sinclair	High spatial resolution analysis of trace elements in corals using laser ablation ICP-MS
Supervisor:	Professor M. McCulloch
Advisors:	Professor R. Wasson (CRES) and Drs S.G. Blake (NRIC, Bureau of Rural Sciences) and L.K. Ayliffe
Mr Y. Yokoyama	Sea-level change in Australasia and the radiocarbon time scale calibration during the last 50,000 years
Supervisor:	Professor K. Lambeck
Advisors:	Drs T.M. Esat and P. De Deckker (Department of Geology)
Wang, L.J. (Grad 98)	Electrical Conductivity Structure of the Australian Continent
Supervisor:	Dr F.E.M. Lilley
Advisers:	Dr J. Braun, Professor B.L.N. Kennett, Dr C.E. Barton, (AGSO), Dr F.H. Chamalaun (Flinders University)
Ms Y. Xu	The stable isotope and trace element geochemistry of the Victory Gold Deposit, Western Australia
Supervisor:	Dr I.H. Campbell
Adviser:	Dr J.M Palin

POSTGRADUATE AWARDS AND SCHOLARSHIPS

A.L. Hales Honours Year Scholarship:

The following took up scholarships in 1999:

Full Time (Completed in 1999)

Ms S. Belfield	Australian National University
Thesis Title:	Geochemistry of melt inclusions and matrix class for 186 AD Taupo eruption, New Zealand.
Supervisor:	Professor R. Arculus (Geology, ANU) and Dr J. Mavrogenes
Ms N. Douglas	Australian National University
Thesis Title:	An experimental study of bismuth (and gold) in the hydrothermal environment
Supervisor:	Dr J. Mavrovenes

Part Time (To Complete in 2000)

Ms C. Farmer	Australian National University
Project:	Investigations of earthquake location techniques
Supervisors:	Professor B.L.N. Kennett, Dr M. Sambridge and Dr P. Chopra (Geology, ANU)

John Conrad Jaeger Scholarship
Ms E.K. Potter

A.E. Ringwood Memorial Scholarship:
Mr X. Liu
Mr K. Yoshizawa

Australian Postgraduate Award:
Ms E.K. Potter
Ms P. Rustomji
Ms P. Treble

Australian Postgraduate Award (Industry):
Mr C. Heath

IPRS Scholarship:
Mr W. Sun
Mr X. Liu
Mr K. Yoshizawa

Vice Chancelor's Endowment for Excellence Supplementary Scholarship:
Ms E.-K.M. Potter
Mr A.C. Hack

HONOURS AND AWARDS

(Academic Staff)

Professor K. Lambeck received the degree Doctor of Science *honoris causa* from The University of New South Wales and was elected Foreign Member of the Academia Europaea. He received the Sir Kirby Laing Visiting Fellowship from the University of Wales (Bangor) and was appointed Visiting Professor at Lund University, Sweden.

Professor I. McDougall was awarded a Gold Medal by the Australian Institute of Nuclear Science and Engineering for excellence in research.

Dr D. Rubatto was awarded the 1998 medal for an outstanding PhD thesis at the Federal Institute of Technology, ETH-Zürich.

Professor J.S. Turner (Emeritus) was appointed a University Fellow for two years from January 1999.

(Students)

Mr D.I. Osmond, a PhD student in the Geophysical Fluid Dynamics Group, was awarded a highly competitive Pre-doctoral Fellowship by Woods Hole Oceanographic Institution, USA, to attend the annual 10-week summer program in Geophysical Fluid Dynamics (June–August).

Mr D. Sinclair was awarded the **RSES Robert Hill Memorial Prize** and was runner up for the best student talk at the Australian Coral Reef Society Meeting held on South Mole Island.

Mr M. Wells, a PhD student in the Geophysical Fluid Dynamics Group, was awarded a scholarship by the University of Washington, Seattle, USA, to attend the 6-week (July–August) Friday Harbor Summer School in Oceanography. He also won the award for the best student presentation at the annual Australian Meteorology and Oceanography Society Meeting held in Canberra in February.

VISITORS

Ms N. Abram of the University of Sydney worked with Dr M. Gagan, Environmental Processes Group in October, to measure stable isotope ratios in mid-Holocene corals collected from raised reefs in the Ryukyus Islands, Japan. The work forms part of her Honours research in the Department of Geosciences.

Dr M. Amalvict of the Universite Louis Pasteur in Strasbourg visited for two weeks in February to conduct observations using their FG5 Absolute gravimeter at the superconducting gravimeter site at Mt Stromlo.

Mr C.-Y. Bai visited from the Xinjiang Seismological Bureau, China for a year, leaving in July, and worked on techniques for characterising and recognising seismic phases on broad-band records with Professor B.L.N. Kennett.

Mr B. Boerher, UFZ Gewässerforschung, Germany, visited the Geophysical Fluid Dynamics Group in December, to present a seminar on convective coastal currents.

Ms H. Brätz, a graduate student from the University of Würzburg, Germany, visited the Ion Probe group for three weeks in May to work with Dr I.S. Williams on a collaborative study to compare the results of SHRIMP and Köber geochronology applied to igneous and metamorphic rocks of the Ruhla Crystalline Complex, Germany.

Dr I. Buick, La Trobe University, and Ms J. Miller, Monash University, visited the Ion Probe group for three weeks in January-February to work with Dr I.S. Williams on a collaborative study of high grade metamorphism and fluid flow in the Limpopo Metamorphic Belt, South Africa.

Ms G. Burch, ANU Geology Department, visited the Ion Probe group for a week in June to work with Dr I.S. Williams as part of her Honours project, dating intrusive and volcanic rocks that provided a tight constraint on the age of gold mineralization at Mt Mackenzie, central Queensland.

Mr C. Butera, University of Melbourne, spent the three months November 1998 to February 1999 visiting the Ion Probe group as a Summer Research Scholar, where he worked with Dr I.S. Williams on an ion microprobe study of the zircon age of magmatism in the vicinity of the Goonumbla gold deposits near Parkes, NSW.

Professor A. Canals of the University of Barcelona, visited the Ore Genesis Group (jointly with Environmental Geochemistry) for six months. She worked with Dr M. Palin on laser-ICPMS analyses of Pb isotopes in galena and visited the Golden Mile with Drs I. Campbell and M. Palin and Mr C. Heath.

Dr S.W.J. Clement from Ion Optical Consulting, Crapaud, Prince Edward Island Canada, visited the Ion Probe group for three months July through October to work with members of the group, and Emeritus Professor W. Compston, on the ion optics of the SHRIMP RG.

Dr T. Correge of ORSTOM, New Caledonia visited Dr M. Gagan, Environmental Processes Group, in January to measure stable isotope ratios in late Pleistocene corals collected from submerged reefs in Vanuatu.

Ms K. DeCorte from the Royal Museum of Central Africa, Belgium visited Dr W.R. Taylor of the Petrochemistry and Experimental Petrology Group during March and April 1999 to undertake laser-ablation ICPMS trace element analyses of metamorphic microdiamonds from the Kokchetav Massif, Kazakhstan.

Professor M. Dodson, University of Leeds, visited the Ion Probe group for three days in August to work with Dr I.S. Williams completing work on dating the early Archean Mushandike granite from Zimbabwe.

Dr D. Frank of the Hydrogenics Corporation visited the Geodynamics Group to deliver and provide instruction on the use of two fuel cells to be installed in Antarctica in January 2000.

Ms S. Frederiksen, a PhD student at the University of Åarhus in Denmark, visited the Geodynamics Group for 6 months. She collaborated with Dr J. Braun on modelling strain localization in the lithospheric mantle during extension.

Professor E. Galimov, Director of the Vernadsky Institute, Moscow, visited the P&EP Group during April and presented a seminar on the latest research activities of the Institute.

Dr J. Goodge, Southern Methodist University, visited the Ion Probe group for one week in early July to work with Dr I.S. Williams in a collaborative study of the provenance of Neoproterozoic and early Palaeozoic sediments from the Beardmore Group in the Transantarctic Mountains.

Mr C. Gunton, ANU Geology Department, visited the Ion Probe group for 3 days in August to work with Dr I.S. Williams as part of his Honours project, dating hydrothermal rutile from the Ernest Henry Cu-Au deposit, Queensland.

Dr P.J. Hearty, of Nassau, Bahamas, visited the Environmental Geochemistry and Geochronology Group in June.

Dr K. Helfrich, Woods Hole Oceanographic Institution, visited the Geophysical Fluid Dynamics Group in July to discuss common interests in wind-driven ocean circulation and presented a seminar on this subject.

Dr G. Holk of Queens University, visited the Ore Genesis Group for two days to discuss the application of stable isotopes to problems in ore genesis. He gave a talk on "Crustal-scale hydrogeology of a collapsed orogenic belt: a stable isotope study of the southern Omineca Belt, British Columbia, Canada".

Dr B. Horton, University of Durham, visited the Geodynamics Group to undertake collaborative studies with Dr P. Johnston on the palaeoenvironment reconstruction techniques for the Holocene.

Mr M. Huang, a graduate student from La Trobe University, visited the Ion Probe group for a week in April to work with Dr I.S. Williams on a collaborative study of high grade metamorphism in the eastern Tibetan Plateau.

Ms J. Johnston of the ANU Botany and Zoology Department worked with the Environmental Processes Group to measure oxygen isotope ratios in seawater collected from the Southern Ocean. The work forms part of a collaborative major ARC grant with Dr J. Kalish, aimed at reconstructing Australian palaeoclimates.

Dr T. Lee of the Cooperative Research Centre for Australian Mineral Exploration Technologies (CRCAMET) has been a visitor at RSES during the year, and has contributed to discussions in the geomagnetism area.

Mr D. Lescinsky, a PhD student in the Geology Department, Arizona State University, visited the Geophysical Fluid Dynamics Group in June, to discuss the dynamics and morphology of lava flows.

J.R. Lister, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, was a Visiting Fellow the Geophysical Fluid Dynamics Group for four weeks, commencing 10 December 1999 until 13 January 2000.

Professor R. Little of the Papua New Guinea University of Technology, Lae, visited Drs H. McQueen and P. Tregoning and Professor Lambeck to discuss future cooperation in the GPS tectonics program in Papua New Guinea.

Professor D. Liu, Chinese Academy of Geological Sciences, visited the Ion Probe group for two weeks in June to work with Dr I.S. Williams on collaborative studies of the Su-Lu and Dabie ultra-high pressure metamorphic terranes, newly discovered early Archean rocks from central China, and early Archean rocks from Enderby Land, Antarctica.

Dr J. Lough of the Australian Institute of Marine Science visited the Environmental Processes Group from 20–22 October to act as adviser for a PhD mid-term appraisal and to discuss collaborative coral research for the AUSCORE program.

Dr B. Luck, Institut de Physique du Globe, Strasbourg, visited the Geodynamics Group to calibrate the SG instrument at Mount Stromlo using their FGS Absolute Gravity Meter.

Professor Ma Keyang from the Lanzhou Institute of Geology, Chinese Academy of Sciences, is visiting the Environmental Geochemistry and Geochronology Group for one year to undertake research and laboratory work.

Mr S. Matsumura, Head of the First Geodetic Division of the Geographical Survey Institute of Japan, visited the Geodynamics group in February to discuss collaboration on absolute gravity measurements in Australia.

Ms S. McLaren, a graduate student from the Department of Geology and Geophysics, University of Adelaide, visited RSES for about a month late in the year to undertake K-Ar age measurements on samples from the northern Flinders Ranges, South Australia, in relation to a project being undertaken with Dr M. Sandiford of the University of Adelaide.

Dr K. Misawa and Dr A. Yamaguchi, National Institute of Polar Research, Tokyo, visited the Ion Probe group for four weeks in May-June to upgrade their skills in SHRIMP analysis and maintenance procedures.

Dr M. Nakada visited RSES as part of the Australian Academy of Science exchange program with the Japan Society for the Promotion of Science. During his visit he collaborated with Professor K. Lambeck and Dr P. Johnston of the Geodynamics Group.

A delegation from the People's Republic of China visited the Ion Probe group in June to view the RSES SHRIMP instruments as part of negotiations for the possible purchase of a SHRIMP by the Ministry of Land and Resources, Beijing. The delegation consisted of Professor D. Liu, Mr G. Du and Ms L. Song from the Ministry of Land and Resources, Mr D. Liu from the Ministry of Science and Technology, and Mr H. Li from the China National Zhen Hua I/E Corporation.

Ms D.G. Questiaux (formerly Division ANH, RSPAS) visited the Environmental Geochemistry and Geochronology Group to investigate the validity of single-grain quartz optical dating protocols, along with means of dating which reduce reliance on U and Th disequilibria in environmental dosimetry.

Professor W. Ranson, a visitor to the ANU Geology Department from Furman University, Greenville, spent one week in March with the Ion Probe group to work with Dr I.S. Williams on a collaborative study of the age and provenance of granite gneisses from the southern Appalachians.

Professor J. Richards visited the Ore Genesis Group for two days to discuss problems associated with the genesis of porphyry copper deposits and to give a talk entitled "A single late-Eocene porphyry Cu event, La Escondida district, Chile".

Dr T. Sato from the Earthquake Research Institute, University of Tokyo, departed in April after a year's visit working in the Seismology Group, on the development of interpretation and inversion techniques for marine seismic refraction data in collaboration with Professor B.L.N. Kennett.

Professor T. Sato from the National Astronomical Observatory of Japan, Mizusawa, visited the Geodynamics Group in November to work with the Superconducting Gravimeter at Mt Stromlo and discuss analysis of observations.

Dr R.D. Shaw (formerly Australian Geological Survey Organisation) was a visitor in the Geodynamics Group. He collaborated with Dr J. Braun on the OZBLOCK project, a palaeogeography project for the Australian continent in the late Palaeozoic based on a thin-sheet numerical model developed at RSES.

Professor K. Shibuya of the Japanese National Institute of Polar Research visited the Geodynamics group to discuss geodetic work in Antarctica and visit the Mt Stromlo Gravity Station.

Mr D. Short (formerly CSIRO Division of Land and Water) visited the Environmental Geochemistry and Geochronology Group to develop a numerical model of luminescence processes.

A contract with Australian Scientific Instruments Pty Ltd to supply a SHRIMP II to the Ministry was signed in October by a visiting delegation consisting of H.E. Madam J. Shou, Vice Minister of Land and Resources, Mr D. Ye, Director-General, Department of Finance, Ministry of Land and Resources, Mr Z. Li, Deputy Director-General, Department of International Cooperation, Science and Technology, Ministry of Land and Resources, Mr F. Guan, Deputy Director-General, China Economic Research Institute of Land and Resources, Mr X. Kang, Deputy Department Director-General, Ministry of Finance, Mr G. Liu, Deputy Division Chief, General Office, Ministry of Land and Resources, Ms W. Yuan, Department of International Cooperation, Science and Technology, Ministry of Land and Resources, and Mr J. Sang, Quantum Resources.

Dr J. Strega, of Finnigan MAT, visited the Environmental Geochemistry and Geochronology Group in May to discuss various instrumentation collaboration.

Mr J. True of James Cook University worked with Dr M. Gagan, Environmental Processes Group, in November-December to measure stable isotope ratios in Great Barrier Reef corals grown in controlled environments. The work forms part of his PhD research in the Department of Biological Sciences.

Professor K. Trumble, Purdue University, visited the Petrochemistry and Experimental Petrology group to study the pallasites in our meteorite collection and discuss their textures with Dr U. Faul.

Mr Y. van Brabant, a PhD student at the University of Liège in Belgium, visited the Geodynamics Group for 3 months. He collaborated with Dr J. Braun on modelling of the tectonic development of the Variscan fold-and-thrust belt in south-central Belgium.

Professor W.R. Van Schmus, University of Kansas, Lawrence, visited the Ion Probe group for a three-month sabbatical from February through May to work with Dr I.S. Williams on a collaborative study of shifts in the provenance of late Proterozoic sediments from northeastern Brazil as a tracer for the breakup of the supercontinent Rodinia.

Mr R. Veloso, Geophysics Institute, University of Bergen, Norway, was a School Visitor in the Geophysical Fluid Dynamics Group from May 1999, and continued research into wind-driven circulation of stratified waters over continental shelves, supervised by Professor Griffiths. This work will form his PhD Thesis to be submitted to the University of Bergen.

Dr S. Vergniolle of the CNRS, Paris, France, was a Visiting Fellow in the Geophysical Fluid Dynamics Group from January to July 1999 and continued experimental studies of foaming flows begun during her International Fellowship (ARC) in the Group.

Professor G. Veronis, Yale University, spent five months from 10 January to 30 May 1999 as a Visiting Fellow in the Geophysical Fluid Dynamics Group, and collaborated with Professor Griffiths on an experimental investigation of the fundamental mechanics of wind-driven ocean circulation.

Dr B. Witt (University of Queensland, Gatton Campus) visited Dr Bird in October in order to undertake carbon-isotope analyses of wool samples.

Associate Professor C. Woodroffe of the Department of Geosciences, University of Wollongong, visited the Environmental Processes Group to discuss the results of coral stable isotope analysis. The work forms part of a collaborative project with Dr M. Gagan to reconstruct the late-Holocene climate of the equatorial central Pacific.

Professor H. Zeck, Copenhagen University, visited the Ion Probe group for a week in February to learn heavy mineral separation procedures and discuss with Dr I.S. Williams the results of their collaborative study of zircon inheritance in Miocene igneous rocks from southern Spain.

Mr C. Zimmer, science journalist from National Geographic Magazine, visited RSES for 2 days in April to interview members of the Geochronology and Isotope Geochemistry Group about their work.

Dr D. Zwartz, Utrecht University, visited the Geodynamics Group to work on several research issues including the Lambert GPS project and Queensland, Bunger Hills research.

CONFERENCES AND OUTSIDE STUDIES

Dr C. Alibert attended the EUG 10 conference in Strasbourg (28 March to 1 April 1) and the annual Australian Coral Reef Society conference in the Whitsundays (3 to 6 September).

Dr C. Allen attended the Fourth Hutton Conference on granites and related rocks in September, at Clermont-Ferrand, France and presented a poster entitled "How batholiths post-date subdu0ction: application of Ward's (1995) subduction cycle model to the northern New England orogen, Queensland".

Dr R.A. Armstrong attended the European Union of Geosciences (EUG) meeting in Strasbourg, France in March, co-authoring three papers. Dr Armstrong also attended a special meeting on the Kaapvaal Craton held in Vredefort, South Africa, and convened by researchers in the Kaapvaal Craton Project from MIT, Carnegie and southern African institutions.

Mr T.T. Barrows attended the Quaternary Long Records Workshop held at the ANU Geology Department (2–3 February). Mr Barrows also attended the EPILOG workshop: 'Global Ocean and Land Surface Temperatures during the Last Ice Age' held at the Hanse Institute for Advanced Study in Delmenhorst, Germany (3–6 May). From May to October, Mr Barrows was a Visiting Scholar at the Quaternary Research Center, University of Washington, Seattle. During this time, fieldwork was conducted in the Cascade Mountains and the Sierra Nevada. Mr Barrows also visited INSTAAR at the University of Colorado (USA).

Dr V. Bennett attended the Goldschmidt Conference at Harvard University, Boston, Massachusetts, where she co-chaired two sessions and presented papers describing results from geochemical and isotopic studies of early Archean terranes of southwest Greenland. In October she attended the SIMS workshop at Woods Hole Oceanographic Institution and presented a talk entitled: New geochemical applications of the SHRIMP II. Dr Bennett was a visiting scientist at the Department of Terrestrial Magnetism, Carnegie Institution, Washington DC from 9 October to 7 December. Her investigations included study of the Re-Os isotope systematics of the Australian lithospheric mantle.

Dr A.J. Berry visited the California Institute of Technology to undertake spectroscopic experiments on fluid inclusions. He also visited the experimental petrology laboratories at the University of Arizona and Ehime University, Japan.

Dr Bird attended the XVth International Union for Quaternary Research (INQUA) Congress in Durban, South Africa from 3–11 August and presented a paper entitled 'Million Year records of fire in sub-Saharan Africa'.

Dr J. Braun was invited to participate in two workshops of the Earth System Evolution Program of the Canadian Institute for Advanced Research (CIAR), in Calgary (May) and Toronto (December). During his stay in Toronto, Dr Braun was invited to give a seminar at the Physics Department of the University of Toronto. He also took part in the all-program CIAR conference held in Banff in May. He was invited to give a presentation at the 1999 Deformation Mechanisms, Rheology and Microstructures Workshop held in Neustadt (Germany) in March. Dr Braun was also invited to the Department of Earth and Planetary Sciences of the Massachusetts Institute of Technology (MIT) to collaborate with Dr K. Whipple on landforming processes in a glaciated environment. During his week-long visit in late November, he gave seminars at the MIT and in the Earth Sciences Department of Harvard University.

Dr I.H. Campbell gave a talk on "REE in scheelite: implications for size-charge balance substitution of trace elements in minerals" in a symposium to honour Professor Peter Roeder at the Geological Association of Canada-Mineralogical Association of Canada Meeting in Sudbury.

Mr H. Cheng attended the General Assembly of the International Union of Geodesy and Geophysics in July, where he gave a presentation entitled "Seismic Body Wave Attenuation In the Upper Mantle Beneath the Australian Continent".

Professor S.F. Cox presented an oral paper at the meeting of the Specialist Group in Tectonics and Structural Geology, held in February at Hall's Gap, Victoria. He co-authored another oral presentation with Dr J E Streit, and co-authored three poster papers. Professor Cox also presented a paper on fault mechanics in the Roamane Fault Zone (Porgera, PNG) at the December meeting of the American Geophysical Union.

Dr G.F. Davies was an invited guest speaker at the "Superplume" conference in Tokyo in January.

Mr C.M. Fanning presented a paper on the Mawson Continent at the Eighth International Symposium on Antarctic Earth Sciences, Wellington, in July. He also attended the Annual Meeting of the Geological Society of America, Denver in October and presented an invited seminar on applications of the SHRIMP ion microprobe at Idaho State University, Pocatell in

October. Mr Fanning spent two weeks in May-June at the Berkeley Geochronology Center carrying out isotope dilution analyses of potential SHRIMP reference zircons with Dr K.R. Ludwig and Dr R. Mundil. In June, he visited the new SHRIMP II facility at the National Institute for Polar Research, Tokyo working with Professor K. Shiraishi on samples from the Sør Rondane Mountains, Antarctica.

Dr J. Fitz Gerald presented a paper on olivine aggregates to the conference Deformation Mechanisms, Rheology and Microstructures held at Neustadt an der Weinstrasse in March then attended EUG10 in Strasbourg to present posters on titanates and fluid permeability. In August he was an invited speaker on the subject of grain boundaries for the Gordon Research Conference on Rock Deformation held in New London. Dr J. Fitz Gerald is co-convenor of the international conference micrOZcopy 2000 to be held in Canberra next year.

Dr U. Faul presented a paper on deformation induced changes in textures of partially molten rocks at the conference on "Deformation Mechanisms, Rheology and Microstructures" in Neustadt, Germany with co-authors M. Cmíral and J.D. Fitz Gerald and a paper at EUG 10 in Strasbourg on grain growth in olivine aggregates. He was invited to present a keynote paper at the DFG Schwerpunktprogramms "Bildung, Transport und Differentiation von Silikatschmelzen" in Hannover, Germany and was a co-organizer of a workshop on melt distributions and textures in rocks at the "International conference on textures and physical properties of rocks" in Göttingen, Germany.

Dr M. Gagan presented an invited paper summarising coral-based reconstructions of Great Barrier Reef palaeoclimates at the International Geosphere-Biosphere Program PAGES-CLIVAR Workshop on "Climate Variations of the Last 300–1000 Years" held in Venice, Italy.

Professor R. Grün was invited to chair the session "ESR Dating" at 9th International Conference on Luminescence and Electron Spin Resonance Dating, 6–10 September 1999 in Rome. He gave the presentations: "Reconstruction of cooling and denudation rates of the Eldzhurtinskiy Granite, Caucasus, using paramagnetic centres in quartz", "Methods of dose determination using ESR spectra of tooth enamel" and "Dose determination on tooth fragments". He was also co-author on the papers presented by D. Koshchug, entitled "ESR dating of lava flows of the Elbrus (Caucasus)" and "Thermal stability of paramagnetic centres in quartz in natural environments". Professor Grün is a member of the scientific committee of the Conferences on Luminescence and Electron Spin Resonance Dating and the editor for the papers on dating applications which will be refereed and published in Quaternary Geochronology. Professor Grün was invited to give a talk on *Direct Dating of Hominids Using ESR and U-Series Dating* at the 2nd Quaternary Dating Workshop, 8–9 April 1999, Lucas Heights, Sydney. He was also invited by the University of Aberdeen and presented a paper on the "Dating of the Lake Mungo III Skeleton". Professor Grün gave seminars at the Sächsische Akademie der Wissenschaften, Freiberg and the Institut für Geophysik and Geologie, Universität Leipzig.

Professor D.H. Green travelled to the UK from 8–14 June and visited Department of Earth Sciences at University of Cambridge, Department of Earth Sciences at Oxford, School of Ocean and Earth Science, University of Southampton, Department of Geology, Royal Holloway, London, met with colleagues and gave a seminar at each institution. Professor Green attended AMIRA's 40th birthday forum "Milestones to the future" in Melbourne on 18/19 August. Professor Green participated in the International School on Earth and Planetary Sciences at Siena, Italy from 24–29 September 1999 and lectured on Crust-Mantle Interactions: Magmatism Originating in the Upper Mantle. This was followed by an excursion to the Alps from 30 September to 3 October 1999. From 9 October until 7 November 1999 Professor Green was in Japan on a JSPS Fellowship and visited NIPR, Tokyo; Institute of Mineralogy, Petrology and Economic Geology, Tohoku University; Institute of Applied Earth Sciences, Akita University; Earth and Planetary Sciences, Tokyo Institute of Technology; Institute for Solid State Physics, University of Tokyo; Department of Earth Sciences, Kanazawa University; Department of Earth Sciences, Ehime University; Okayama University; as well as continuing collaboration and fieldwork with Dr Niida at Department of Earth and Planetary Sciences, Hokkaido University. A seminar was given at each institution.

Professor R.W. Griffiths attended the Australian Meteorology and Oceanography Society Meeting held in Canberra in February.

Dr J. Hermann attended the Ninth Annual V.M. Goldschmidt Conference, Harvard University, Cambridge, MA, from 22–27 August. Dr Hermann was an invited speaker at the International School of Earth and Planetary Sciences on Crust-Mantle Interactions, Siena, Italy, from 24–29 September and the Leader of the field trip of the International School of Earth and Planetary Sciences on Crust-Mantle Interactions, Val Malenco, Italy, from 30 September to 3 October. He was also invited to a seminar at Monash University, Melbourne on 19 November and to a seminar at Adelaide University on 22 November.

Mr A. Hitchman attended the International Union of Geodesy and Geophysics, held in Birmingham, England in July where he presented two papers on aspects of magnetic mapping and electromagnetic induction in the Earth. He also represented the Australian Society of Exploration Geophysicists at the Fifth International Convention of Geophysical-science Societies, held at Birmingham during the IUGG.

Dr G.O. Hughes attended the 6th Australian Meteorological and Oceanographic Society National Conference held in Canberra in February, and presented a talk entitled "Interaction of stratified flow with topography".

Dr I. Jackson co-convened two symposia and presented papers at the IUGG General Assembly in Birmingham, UK, in July. During the same trip he visited and lectured at the Universities of Bristol and Cambridge.

Dr G. Kaufmann attended the IUGG 1999 conference in Birmingham, UK from 19–24 July.

Ms J. Kemp presented a talk titled "Late Pleistocene river metamorphosis in the Lachlan River Valley, southeastern Australia" at the joint British Geomorphology Research Group/ Commission on Geomorphology and Environmental Change meeting in Hull, UK, 16–19 September.

Professor B.L.N. Kennett gave a seminar at the University of Queensland on recent progress in determining the seismic structure of the Australian region. He attended the General Assembly of the International Union of Geodesy and Geophysics in July, where he gave one of four Union Lectures on "The state of the mantle – reconciling structure and processes" and also presented a paper on a synthesis of results on upper mantle structure beneath the Australian region. In September he attended the US Research Symposium on CTBT verification in Las Vegas, Nevada, where he presented a poster on work on improving event location, depth and source mechanism using Neighbourhood Algorithm inversion. At the beginning of November he visited the University of California, Santa Barbara and presented two seminars.

Dr R.C. Kerr attended the Australasian Meteorology and Oceanographic Society Conference in Canberra in February.

Mr A. Kiss presented a paper entitled "Chaos in the 'sliced cone' model of wind-driven ocean circulation" at the Sixth National Australian Meteorological and Oceanographic Society Conference, ANU, Canberra, 8 to 11 February 1999.

Professor K. Lambeck attended meetings, visited institutions and gave lectures and seminars in a number of institutions including the Universities of Copenhagen, Lund, Uppsala, Oxford, Cambridge, Wales (Bangor and Aberystwyth), Paris, Papua New Guinea, as well as Imperial College London, Ecole Normale Superieur Paris, the Vrije Universiteit Amsterdam, the Technical University of Papua New Guinea and the Svensk Kärnbränslehantering. He attended the IUGG conference in Birmingham, the EPILOG conference in Delmenhorst, the Nordic PAGES meeting in Höör, and the CIAR meeting in Banff.

Dr F.E.M. Lilley visited the University of Victoria, BC, Canada for three weeks in September, where he collaborated with Professor J.T. Weaver on the analysis of magnetotelluric data. He then spent three weeks at the University of Manitoba, Winnipeg, where, with his host Associate Professor I.J. Ferguson, he worked on the interpretation of magnetotelluric data observed in western Queensland. He then attended the Second International Symposium on Three-Dimensional Electromagnetics at the University of Utah, Salt Lake City, from 26–29 October, where he presented a paper on applications to magnetic mapping. During this period of Outside Studies Leave he also visited colleagues at the Universities of Hawaii, Alberta, Washington (Seattle), Colorado (Boulder), UCLA, and Victoria University of Wellington, NZ, at several places giving seminars on research results from Australia.

Mr W. Lus attended the XIX Pacific Science Congress, in Sydney, at the University of New South Wales, from 4–9 July 1999 on the 1998 Sissano tsunami seabed investigations off the northern coast of Papua New Guinea. He also attended the Papua New Guinea and Region Tsunami Conference (PARTIC) in September 1999 and the Australian Disaster Conference in November 1999 in Canberra about the tsunami disaster at Sissano, Papua New Guinea entitled: "In search of the cause and assessing the risk by multibeam sonar and remotely operated vehicle".

Professor M.T. McCulloch presented a paper on U-Series using thermal ionisation mass spectrometry at a Quaternary sciences workshop held at ANSTO.

Professor I. McDougall attended the XV International Congress of the International Union for Quaternary Research held in Durban, South Africa in early August, where he presented a paper on the numerical time framework for the hominid-bearing sequence in the Turkana Basin, northern Kenya.

Ms H. McGregor presented a paper on coral-based palaeoclimate reconstructions for the Sepik River region of Papua New Guinea at the Coral Reef Society Annual Scientific Conference, South Molle Island, Great Barrier Reef. She also attended the 2nd Quaternary Dating Workshop at ANSTO, Lucas Heights and the Quaternary Long Records Workshop in the Geology Department, Australian National University.

Mr J. Marshall attended the annual scientific conference of the Australian Coral Reef Society on South Molle Island, 3–6 September and presented a poster on "Sr/Ca-derived SSTs of massive *Porites* corals from Christmas and Cocos (Keeling) Islands, eastern Indian Ocean". He also attended an international symposium on the Paleoceanolgy of Reefs and Carbonate Platforms: Miocene to Modern at Aix-en-Provence, France, 27–30 September, where he co-chaired a session on Paleoclimatic and Paleoceanographic Signals in Reef Organisms, and presented a poster 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 attended the American Geophysical Union 1999 Fall Meeting in San Francisco, where she presented a talk on the Os isotope geochemistry of riverine and estuarine sediments from Papua New Guinea and the Gulf of Papua.

Dr H. O'Neill attended the 9th Goldschmidt Conference, Harvard University, Cambridge, MA, USA, where he gave two papers. He also attended the 3rd Orogenic Lherzolite workshop in Pavia, Italy.

Mr D.I. Osmond spent ten weeks (June–August) as a Predoctoral Fellow at the Woods Hole Oceanographic Institution, USA, attending the Summer Program in Geophysical Fluid Dynamics. At the conclusion of this program he presented a lecture on his research project on thermohaline circulation models.

Dr J.M. Palin was an invited participant at the First International Conference on Golden Mile Alteration sponsored by Kalgoorlie Consolidated Gold Mines in Kalgoorlie in early June where he presented a talk entitled "Gold transport and deposition at Kalgoorlie: Inferences from stable isotope, trace element, and experimental studies". In December, Dr Palin attended the Fall Meeting of the American Geophysical Union in San Francisco and presented a poster co-authored with Drs I.H. Campbell and C. Allen, and Ms K. Smith on "A Comparison of Pb-U dating of zircon by excimer laser ablation ICPMS and SHRIMP".

Dr D. Phillips attended the "Orogenesis in the Outback" conference, held in Alice Springs during July, 1999. Dr Phillips presented a paper entitled "$^{40}Ar/^{39}Ar$ approaches to dating shear zones".

Dr B. Pillans attended the XVth International Union for Quaternary Research (INQUA) Congress in Durban, South Africa, from 3–11 August, and also participated in a post-congress field excursion to the western Kalahari and central Namib deserts in Namibia. At the conference he presented an oral paper entitled "Early to Middle Pleistocene tephrochronology, Wanganui Basin", and a poster paper entitled "Paleomagnetism of early to mid Pleistocene paleosols, and evidence for diachronous arid climate shifts in northern and southern Australia". He was also a co-author of an oral paper presented by Dr T. Naish, entitled "A Southern Hemisphere Plio-Pleistocene reference record of orbitally controlled shallow-marine sedimentary cyclicity since 2.6 Ma, Wanganui Basin, New Zealand.

Ms J.M. Quinn attended the 8th International Symposium of Antarctic Earth Sciences in Wellington, New Zealand, from 5–9 July. Ms Quinn also attended the AGU Fall meeting, San Francisco, 11–17 December.

Mr B.D. Rohrlach attended the PacRim '99 International Congress on Earth Science, Exploration and Mining around the Pacific Rim in Bali, Indonesia from the 10–13th October 1999 and gave a talk presenting a paper entitled "Geology, Alteration and Mineralisation of the Tampakan Copper Deposit".

Dr D. Rubatto attended the conference Orogenesis in the Outback in Alice Springs, where she presented two papers, one on metamorphism in the Reynolds Range, central Australia, and the other on the migration of subduction in the European Alps. She also attended the Ninth Goldschmidt Conference in Cambridge, Massachusetts, where she presented a paper on trace element characterization of metamorphic zircon. Dr Rubatto was invited to give lectures on SHRIMP U-Pb dating of metamorphism at the University of Padova, Italy, La Trobe University and The University of Adelaide.

Professor R. Rutland attended the SGTSG Field Conference, 'The Last Conference of the Millennium' in Halls Gap, Victoria, from 14 to 19 February and the associated field excursion, 'Great Southern Transect, I. from 9-14 February. He also attended the international conference on "Svecofennian Migmatites' in Pori, Finland from 26-29 August and presented a paper on the 'Tectonic Setting of Svecofennian Migmatites'. Professor Rutland acted as co-convenor of a 'Special Symposium' on Geosciences and Development to be held as part of the program of the 31st International Geological Congress to be held in August 2000 in Rio de Janeiro, Brazil. He also attended 1999 Symposium of ATSE 'The Spirit of the Snowy Fifty Years on' in Cooma from 23-24 November where he acted as Symposium Rapporteur to provide a summary report on Issues and Outcomes.

Dr M. Sambridge attended the General Assembly of the International Union of Geodesy and Geophysics in July at the University of Birmingham, UK, where he gave a paper on Monte Carlo inversion.

Dr N.A. Spooner attended the "Long Quaternary records in Australasia: trends, super cycles or steady state?" conference held in the Department of Geology ANU on 2 and 3 February 1999. He also attended the 9th International Conference on Luminescence and Electron Spin Resonance Dating" held in Rome, Italy from 6–10 September 1999.

Dr P. Tregoning attended the International Symposium on GPS held in Tsukuba in October where he presented two papers entitled "Present-day Crustal Motion in Papua New Guinea" and "Postglacial Rebound near the Lambert Glacier, Antarctica".

Professor J.S. Turner attended the annual conference of the Australian Meteorological and Oceanographic Society, held in Canberra in February. In June he spent a week at the University of Cambridge, discussing mutual research interests with members of the Department of Applied Mathematics and Theoretical Physics. He attended the Geophysical Fluid Dynamics Summer Program on 'Stirring and Mixing', held at the Woods Hole Oceanographic Institution (WHOI), Massachusetts, USA in July, and gave an invited paper on 'The neglect of two-dimensional double-diffusive processes in studies of ocean circulation' in a symposium on Oceanic Mixing. He also had stimulating discussions with biologists and ocean engineers at WHOI on the swimming of marine organisms, vortex rings, and their application to the design of propulsion devices.

Mr N.G. Ware attended the 5th Biennial Symposium of the Australian Microprobe Analytical Society held in Sydney in February and presented a paper on "Analysis of Sulphur and Weak X-Ray Measurement".

Dr S.L. Webb attended the American Geophysical Union Fall Meeting in San Francisco and presented work on "High-Temperature Elasticity, Anelasticity and Creep in MgO" and "Viscosity of Supercooled SiO_2 Melt".

Mr M.G. Wells presented a talk on "Laboratory models of intermittent turbulence and salt fingers" at the Australian Meteorological and Oceanography Society meeting held in Canberra in January. He also participated in a six-week course run by the University of Washington, USA, on "Coastal and Estuarine Geophysical Fluid Dynamics" from 19 July to 28 August.

Dr I.S. Williams attended the conference "Orogenesis in the Outback" held in Alice Springs in July, where he presented a paper on the behaviour of zircon, monazite and their U-Pb isotopic systems during high grade metamorphism of sedimentary rocks. He also was a co-author with colleagues from the University of New South Wales and La Trobe University who presented papers on dating high grade shear zones in central Australia and high grade metamorphism in the Limpopo Belt, South Africa respectively. After the conference he attended the Arunta Discussion Forum organised by the Northern Territory Geological Survey. In September Dr Williams spent two weeks on outside studies in France, the first week examining the granites of the Massif Central and the second at the Fourth Hutton Conference, held at the Université Blaise Pascal, Clermont-Ferrand, where he presented a paper on inherited zircon as a tracer for the provenance of granitic magmas. He also joined with colleagues from Université Jean Monnet and the Royal Museum for Central Africa in a presentation about the geochronology of augen gneiss and granites from the Damaran Belt, western Namibia.

Dr G. Yaxley held an Alexander von Humboldt fellowship from March until November 1999 at the Institute für Mineralogie, Universität Frankfurt, Germany. He performed an experimental investigation at high pressures of the phase and melting relations of carbonated eclogite compositions, in collaboration with Professor Dr G. Brey. During this time he presented a seminar at the Universität Frankfurt entitled "Carbonatite metasomatism of the lithosphere". He also presented two seminars entitled "The effects of eclogitic heterogeneities on upper mantle melting" at the Universität Frankfurt and at the Max Planck Institute (Abteilung Geochemie) in Mainz, Germany. Dr Yaxley attended the MinWien conference in Vienna in August, 1999, and presented a paper entitled "Phase relations of carbonated eclogite under upper mantle PT conditions – implications for carbonatite petrogenesis". In September he attended the 3rd International Orogenic Lherzolite Conference in Pavia, Italy, and presented a talk entitled "The effects of eclogitic heterogeneities on upper mantle melting". He then attended post-conference field trips to the peridotite bodies in the Ivrea-Verbano Zone and Val Malenco in the Italian Alps.

Mr Y. Yokoyama presented seminars at the Japan Earth and Planetary Science Annual Meeting at Tokyo and the AGU Fall meeting at San Francisco He also visited the National Institution of Polar Research, Japan at Tokyo, the Geological Survey of Japan at Tsukuba, the School of Geosciences, University of Wollongong and also the Space Science Laboratory, University of California, Berkeley and the Lawrence Livermore National Institution in California.

COOPERATION WITH GOVERNMENT AND INDUSTRY

AUSTRALIAN ACADEMY OF SCIENCE

Dr J. Braun is a member of the National Committee for Solid Earth Sciences.

Professor B.L.N. Kennett is a member of the National Committee on Solid Earth Sciences, and Chairman of the Subcommittee on Seismology and Physics of the Earth's Interior. He is also Deputy Chairman of the International Committee of the Academy and provided support during the illness of the Foreign Secretary of the Academy (Dr M. Pitman). He is Chair of the Academy Committees for Postdoctoral Opportunities in Japan and exchange arrangements with NE Asia (China, Japan, Korea, Taiwan). Professor Kennett represents the Academy of Sciences on the National Committee for support of International Conferences in Australia.

Professor K. Lambeck was the Secretary-Physical Sciences (till October), and is currently Vice President and Foreign Secretary of the Australian Academy of Science and also a member of its Council.

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

AUSTRALIAN GEODYNAMICS COOPERATIVE RESEARCH CENTRE (AGCRC)

Dr J. Braun has collaborated with Dr R.D. Shaw of the AGCRC on a tectonic model for the late Palaeozoic tectonic history of the Australian continent (OZBLOCK project).

AUSTRALIAN GEOLOGICAL SURVEY ORGANIZATION (AGSO)

Professor J. Chappell continued to collaborate with Dr M. Hayne of AGSO, on reconstructions of time series of cyclones over the last 6000 years, in northern Australia.

Professor D. Green is a member of the Board of Management of the Australian National Seismic Imaging Resource (ANSIR).

Ms L.M. Hanley collaborated with AGSO who provided aerial photos of the Kimberley region for the 1999 fieldwork season.

Dr F.E.M. Lilley and Mr A. Hitchman continued collaboration with Dr Peter Milligan of the Australian Geological Survey Organization in the measurement and interpretation of the geomagnetic coast effect at micropulsation frequencies. A joint field expedition took place to the coastline of south-eastern Victoria to retrieve instruments which had observed during an aeromagnetic survey there.

Mr W. Lus is collaborating with Dr P. Hill and Dr K. McCue of the Australian Geological Survey Organisation on the study of the 1998 PNG Aitape Tsunami.

Dr H. McQueen collaborated with staff of the Australian Geological Survey Organisation on absolute gravity measurements and instrument calibrations at the Mt Stromlo Gravity Station in support of the Superconducting Gravimeter installation .

A data-base established by Dr L.J. Wang and Dr F.E.M. Lilley during the former's research scholarship at RSES is being expanded at the Australian Geological Survey Organisation by Dr Wang and Dr C.E. Barton, to form a national data-base for observed electromagnetic induction values.

The Ion Microprobe subgroup continues to maintain a close working relationship with AGSO geochronologists, sharing expertise, standards, time, costs and maintenance responsibilities re the SHRIMP I and II ion microprobes. In addition, Dr Williams was a member of a 1999 AGSO Merit Promotions Committee.

AUSTRALIAN INSTITUTE OF MARINE SCIENCE

Ms E. Hendy, Dr M. Gagan and Professor M. McCulloch continued collaborative work with Drs J. Lough, P. Isdale, and D. Barnes of the Australian Institute of Marine Science. Ms Hendy's PhD research is a core project of the AUSCORE (**AUS**tralian **CO**ral **RE**cords) initiative and aims to document decadal-to-centennial climate variability in the Great Barrier Reef region over the last 400 years.

Ms E. Hendy and Professor M.T. McCulloch are working in close collaboration with Drs J. Lough, D Barnes and P. Isdale. The collaboration involves multi-proxy analysis of long corals from the central Great Barrier Reef to demonstrate that different corals accurately record common climate signals, and to study decadal-to-centennial climate variability in the region over the last 400 years.

Ms H. McGregor and Dr M. Gagan continued collaborative research with Drs G. Brunskill, P. Isdale, J. Lough and D. Barnes of the Australian Institute of Marine Science. Ms McGregor's PhD research is part of Project TROPICS (Tropical River-Ocean Processes in Coastal Settings) and aims to use corals to reconstruct the mid-Holocene climate of the Western Pacific Warm Pool north of Papua New Guinea.

Dr C.E. Martin collaborated with Dr Gregg Brunskill (AIMS) on studies of the geochemistry of platinum-group elements and Os isotopic systematics in riverine and estuarine sediments from Papua New Guinea.

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 the Australian Geological Survey Organisation and the Australian National University. The portable instrument facility of ANSIR is housed at RSES and equipment is available via a competitive proposal scheme. In 1999 instrumentation has been provided to:

- Monash University for broadband studies in Victoria
- A consortium of CSIRO Exploration and Mining and BHP Coal for studies of seismicity in the Appin Coal Field, NSW
- RSES for the Quoll experiment in southeastern Australia
- The Institute of Geological and Nuclear Sciences, New Zealand in association with RSES for work in the Transantarctic mountains.

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION (ANSTO)

Dr A.J. Berry is collaborating with Dr M. James to determine the hydrogen positions in silicate minerals by neutron diffraction.

Dr C.E. Martin collaborated with Ron Syzmczak (ANSTO) on studies of the noble metal geochemistry of riverine and estuarine waters that were collected in Papua New Guinea on cruises of the R/V *Franklin* as part of Project TROPICS (Tropical River-Ocean Processes in Continental Settings).

AUSTRALIAN SCIENTIFIC INSTRUMENTS PTY LTD

Dr I.S. Williams continued his longstanding collaboration with Australian Scientific Instruments (now a proprietary limited subsidiary of ANUTECH Pty Ltd) in the manufacture and marketing of SHRIMP ion microprobes. Over a two-week period in February he worked with ASI on the final tuning and acceptance testing of the SHRIMP II purchased by the National Institute of Polar Research, Tokyo. In April he spent a week at NIPR helping retune the instrument after installation, and running it through its acceptance tests. Immediately afterwards, two NIPR research staff, Dr K. Misawa and Dr A. Yamaguchi visited the RSES Ion Probe group for a month of training in SHRIMP analysis and maintenance procedures. Dr Williams also undertook analyses of test samples on ASI's behalf for potential SHRIMP customers.

Emeritus Professor W. Compston continued to take a close interest in the development of the prototype SHRIMP RG in collaboration with Australian Scientific Instruments Pty Ltd.

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION (CSIRO)

Dr Bird continued to undertake work for a National Greenhouse Gas Inventory Development Project entitled 'Changes in soil carbon following land-use change in Australia'. The project was funded by the Australian Greenhouse Office, and was conducted in collaboration with Dr R. Giffod (CSIRO Plant Industry) and Professor G. Farquhar (RSBS).

Dr U. Faul collaborated with Dr B. Whittington, CSIRO Division of Minerals in Perth in an orientation contrast study of grain sizes and shapes in Gibbsite agglomerates.

Dr C.E. Martin and Professor M. McCulloch continued their collaboration with Drs Cathy Wilson, Peter Wallbrink, and Jon Olley (CSIRO Land and Water, Canberra) on tracing the sources and transport of sediment and associated phosphorus in Australian rivers.

Dr N. Spooner has collaborated with Dr J. Olley, CSIRO Division of Land and Water, Canberra, on the optical dating of a aeolian deposit on the Murrumbidgee floodplains, as a comparison between single and multiple-grain dating in an investigation of partial bleaching.

Mr N.G. Ware is collaborating with Mr B.W. Robinson, Division of Exploration and Mining, on the AutoGeoSEM project which aims to automatically identify sub-millimetre mineral grains at rates up to 10 grains per second.

Mr M.G. Wells, a PhD student in the Geophysical Fluid Dynamics Group, worked on the Research Vessel Franklin with scientists from CSIRO Oceanography from 1 to 28 September, carrying out an experiment on mixed layer dynamics in the tropical Indian Ocean. He also collaborated with Dr B. Sherman of CSIRO Land and Water in a study of convection in lakes and water reservoirs.

COOPERATIVE RESEARCH CENTRE FOR LANDSCAPE EVOLUTION & MINERAL EXPLORATION (CRCLEME)

Dr J. Braun is an Associate of the Cooperative Research Centre for Landscape Evolution and Mineral Exploration in the "Exploration in areas of basin cover" theme.

Dr B. Pillans is leader of the dating project in CRCLEME, and is primarily responsible for dating regolith materials by paleomagnetic techniques.

WMC RESOURCES LTD

Professor S.F. Cox is conducting collaborative research on structural and deformational controls on the genesis of Archaean lode gold deposits in the St Ives goldfield (Kambalda, WA), sponsored by WMC Resources Ltd (St Ives Gold) and the APA(Industry) scheme. He is also collaborating with Dr S. Munroe (SRK Consulting) in the study of fault mechanics and fluid flow at Porgera in PNG.

Mr B.D. Rohrlach, Drs I.H. Campbell, R.R. Loucks, J.M. Palin and Professor I. McDougall are collaborating with WMC Resources Ltd to understand the tectonic, hydrologic and physio-chemical controls on Cu-Au mineralisation at the Tampakan coupled porphyry-epithermal deposit in southern Mindanao (Philippines) with emphasis on establishing the genetic relationship between the two mineralisation styles.

Ms Y. Xu and Drs J.M. Palin and I.H. Campbell completed their detailed mineralogic, chemical, and stable isotopic studies of hydrothermal gold mineralization in the Victory mine complex of Western Australia with WMC Resources Ltd (St Ives Gold Mines).

OTHER GOVERNMENT AND INDUSTRY

Dr R. Armstrong continues his extensive collaboration with scientists from the **Geological Surveys of Botswana**, Namibia and has started a new collaborative programme with Dr R. Key and the **Geological Survey of Zambia**. He has also continued his work with scientists (Dr R.E. Harmer, Dr B. Eglington, Dr G. Grantham and Dr R. Thomas) from the **South African Council for Geosciences** and contributed to a feasibility study for the establishment of a new National Isotope Facility in that country. A number of geochronological projects for Australian and international exploration companies were completed during the year.

Mr J. Ballard and Drs I.H. Campbell and J.M. Palin are collaborating with **CODELCO** on a study of igneous and hydrothermal geochemistry in and around the giant Chuquicamata porphyry copper deposit in northern Chile. Drs Campbell and Palin spent ten days as guests at the mine in May during which they examined the geology of the deposit and surrounding region and discussed aspects of the investigation with mine and exploration staff.

Drs I.H. Campbell, J. Mavrogenes and Mr B. Setiabudi are working with Rio Tinto Indonesia on a study of the **Kelian Gold Mine** in Kalimantan.

Drs Campbell and Palin, in collaboration with **Placer Granny Smith Pty Ltd**, have obtained a SPIRT grant for mapping ore-fluid pathways around mesothermal gold deposits in the Laverton region, WA using alkali elements and stable isotopes.

Professor J. Chappell continued his collaboration with members of the **Northern Land Council**, Darwin NT, and with Traditional Owner groups, in research into the environmental prehistory of north Arnhem Land.

Mr C.M. Fanning continued collaborations with the **Geological Surveys of South Australia, Victoria, New South Wales, and Queensland**. He collaborates with a number of mineral and petroleum exploration companies.

Professor D. Green continued to serve as Chairman of the Greenhouse Science Advisory Committee in the **Department of the Environment**. The major task in 1999 was the preparation of "The Australian Greenhouse Science Initiative – Strategy and Business Plan 2000 to 2005". This document seeks to maintain the quality of greenhouse science research in Australia, the strength of which has served Australia well in its international standing and negotiations on Greenhouse matters.

Ms L.M. Hanley collaborated with the **Northern Territory Geological Survey**, who assisted with helicopter and vehicle field support for fieldwork during 1999.

Mr C. Heath has commenced a study of the "Origin and composition of Ore-Forming Fluids in the Giant Golden Mile Gold Deposit, Kalgoorlie" in collaboration with **Kalgoorlie Consolidated Gold Mines**. The project is being supported by a grant to Drs I. Campbell and M. Palin through the SPIRT program.

Professor B.L.N. Kennett has continued to provide support to the **Comprehensive Nuclear-Test-Ban Treaty Organisation** in Vienna. With Mr J. Grant in Tennant Creek he has been heavily involved this year in the process of the upgrade of the Warramunga Array to meet the requirements of the treaty for both seismic and infrasonic recording. The seismic upgrade was completed in June and the new array configuration is working well.

Professor K. Lambeck is Chairman of the **Antarctic Science Advisory Committee**, Department of the Environment. Member of the Technical Advisory Group South Pacific Sea Level and Climate Monitoring Project, **Australian Agency for International Development**, Department of Foreign Affairs, and also a Member of the Geodesy Reference Group, **Australian Surveying and Land Information Group**, Department of Administrative Services. Professor Lambeck was a Member of the Australia Prize Committee.

Professor M.T. McCulloch is collaborating with Ms M. Devlin and Mr D. Haynes, **Great Barrier Reef Marine Park Authority** conducting research examining salinity and trace element systematics during coral bleaching.

Dr H. McQueen collaborated with staff of **Australian Surveying and Land Information Group** on absolute gravity measurements and instrument calibrations at the Mt Stromlo Gravity Station in support of the Superconducting Gravimeter installation .

Dr J. Mavrogenes collaborated with Mr J. Watkins, **NSW Geological Survey**, on the study of fluids associated with opal formation.

Dr D. Phillips has participated in collaborative studies with the **Australian Geological Survey Organisation** as well as the **Geological Surveys of South Australia, Victoria and Western Australia**. He also collaborated with a number of Australian exploration and mining companies.

Dr B. Pillans is collaborating with Dr R. Bateman (**Kalgoorlie Consolidated Gold Mines**) in paleomagnetic dating of regolith at Mt Percy mine, Kalgoorlie.

Dr W.R. Taylor is continuing his collaborative research with **Rio Tinto Exploration Ltd** on diamond indicator minerals from the Kimberley and Pilbara regions. Further collaboration is underway with **Rio Tinto Zimbabwe** on geochemical discrimination of indicator chromites and with **Striker Resources NL** on the composition of the north Kimberley lithosphere, Western Australia.

Dr P. Tregoning collaborated with Mr B. Twilley, Mr J. Manning and Mr G. Luton of the **Australian Surveying and Land Information Group** in developing and operating solar-powered GPS systems for remote installations in Antarctica and in organising GPS surveys in the Southeast Asian region for the purposes of tectonic studies and the densification of national geodetic datums.

Dr I.S. Williams, in association with students from the ANU Geology Department and with the co-operation of the companies involved, undertook geochronology studies of the Ernest Henry deposit, **Mount Isa Mines**, and the Mt Mackenzie Prospect, **Coolgardie Gold NL** and **Terra Search Pty Ltd**. He also undertook a study of magmatism associated with the Goonumbla gold deposits, with Mr K. Butera, Melbourne University, and the co-operation of **North Ltd Exploration**.

COLLABORATION WITH AUSTRALIAN UNIVERSITIES

Dr R.A. Armstrong started a collaborative project on provenance of sediments from the Centralian Basin with Dr A. Camacho of the **University of New South Wales**. He also continued his collaboration with Professor A. Ewart, **University of Queensland** on the geochemistry and petrogenesis of the basalts of the Etendeka Province, Namibia.

Dr V. Bennett continues collaboration with Dr M. Norman, CODES, **University of Tasmania**, on siderophile trace element and isotopic characteristics of plume-related magmas.

Dr A.J. Berry continued to work with Dr E.R. Krausz of the Research School of Chemistry, ANU, on the development of an optical imaging spectrometer. He also collaborated with Dr B. Jar, Faculty of Engineering and Information Technology, **Australian National University,** on infrared spectroscopy of polymers.

Dr M. Bird collaborated with Dr B. Witt of the Gatton Campus of the **University of Queensland** on carbon-isotope records of environmental change recorded in wool He also collaborated with Dr Bruno David **(Monash University)**, Dr Bert Roberts **(La Trobe University)**, Dr J. Field **(University of Sydney)**, Mr C. Dortch **(University of Western Australia)** on the radiocarbon dating of archaeological sites in Australia.

Professor S.F. Cox is continuing the supervision of **University of Newcastle** PhD students, Mr K. Ruming (Structural and Deformational Controls on Gold Ore Genesis, Victory Complex, St Ives goldfield, WA) and Ms T. Wilson (Faulting Processes in the Northern Sydney Basin). Professor Cox is also collaborating with Dr M. Knackstedt, **CRC for Petroleum Engineering (the University of New South Wales) and RSPhysSE (ANU)**, in the development and application of percolation concepts to modelling flow in hydrothermal systems where flow is localised in fracture/fault/shear networks. Work is also commencing on application of x-ray tomographic studies to characterisation of disordered pore and fracture geometries in rocks. This work seeks to develop understanding of permeability evolution in deforming rocks.

Mr C.M. Fanning continued collaborations with Dr S. Johnson**, Macquarie University**, on the age and tectonic evolution of the Peninsula Ranges Batholith, Baja Mexico, with Professor C.J. Wilson and Mr S. Boger, **University of Melbourne**, on the age and evolution of the southern Prince Charles Mountains, Antarctica and with Dr G. Clarke and Mr N. Kelly, **University of Sydney,** on the age and evolution of eastern Enderby Land, Antarctica.

Dr U. Faul continued his collaboration with Dr T. Falloon, **University of Tasmania**, on compositions of low degree melts of lherzolites and their implications for MORB genesis.

Dr J. Fitz Gerald continued collaborations with Professor D.J.H. Cockayne and Dr J. Zou from the Key Centre for Microscopy and Microanalysis at the **University of Sydney** as part of an ongoing programme operating out of the Electronic Materials Department, **RSPhysSE**.

Dr M. Gagan continued collaboration with Dr J. Kalish, **Department of Botany and Zoology, Australian National University** to measure the stable isotope ratios of fossil fish otoliths. Collaborative research with Ms A. Mueller and Dr B. Opdyke, **Department of Geology, Australian National University**, is underway to reconstruct the palaeoceanography of the eastern Indian Ocean. Collaborations outside the ANU include coral reconstructions of the mid-Holocene climate of the equatorial central Pacific with Associate Professor C. Woodroffe, Department of Geosciences, **University of Wollongong** and the measurement of stable isotope ratios in Great Barrier Reef corals grown in controlled environments with Mr J. True and Dr B. Willis, Department of Biological Sciences, **James Cook University**.

Professor D. Green continued his collaboration with the School of Earth Sciences, **University of Tasmania** (Drs A.J. Crawford, T.J. Falloon and L. Danyushevsky). Professor Green continues to be a member of the Tectonics Special Research Centre Advisory Council at the **University of Western Australia**.

Professor R.W. Griffiths and Mr D.I. Osmond of the Geophysical Fluid Dynamics Group continued a collaboration with Professor M. Tomczak of Finders University of South Australia under an ARC Large Grant to study convective processes at ocean fronts.

Professor Grün collaborates with Professor A. Gleadow, Department of Geology, **La Trobe University**, to study the thermal stability of paramagnetic centres from cores of the Otway basin; Dr P. White, Department of Anthropology, **University of Sydney** to date the site of Cuddie Springs; Dr C. Murray-Wallace, Department of Geosciences, **University of Wollongong** to date marine sequences in the Spencer Gulf, and Dr K. Moriaty and Dr R. Wells, **Flinders University**, to date faunal remains from Naracoorte Cave.

Dr M. Honda collaborated with Dr D. Patterson of **University of Melbourne** on the study of cosmogenic noble gases in surface exposed quartzite from central Australia.

Dr F.E.M. Lilley presented a seminar at the **Australian Defence Force Academy** in March entitled "Earth's magnetic field: ocean current contributions to vertical profiles in deep oceans". Dr Lilley is also collaborating with Dr A. White and Dr G. Heinson of **Flinders University** in a number of marine electromagnetic studies. Dr Lilley visited Flinders University for three days in August to collaborate on data reduction and to make calibration measurements.

Dr F.E.M. Lilley and Dr L.J. Wang (now of AGSO) are collaborating with Dr F.H. Chamalaun of **Flinders University** on the study of a major electrical conductivity structure, known as the Carpentaria anomaly, in western Queensland. Two of three planned papers on this work are now published or in press; preparation of material for the third is at an advanced stage.

Professor McCulloch is continuing collaboration with Dr C. M. Wallace from the Queensland Museum, on U-series dating shallow water carbonator from the Spencer and St Vincent Gulfs to help constrain tertiary sea-levels. Studies are continuing with Drs R. Wells and K. Moriarty, **University of New England**, on Nd-Sr isotopic systematics of the Gympie volcanic belt in southern Queensland. Professor McCulloch continued collaboration with Dr G. Neef, The **University of New South Wales** on U-Th dating of Quaternary reefs from Vanuatu. Professor McCulloch and Mr S. Fallon continue their collaboration with Dr V. Harriott, **Southern Cross University**, on corals living on extreme environments.

Professor I. McDougall continued a collaboration with Dr G. Acton and T.J. Cobine, associated with the **University of New England**, on dating Cenozoic volcanic rocks in relation to the polar wander path for Australia. Professor I. McDougall is also collaborating with Dr R. Watkins, **Curtin University of Technology**, on a project concerned with the earlier Cenozoic history of the northern Kenya Rift, east of Lake Turkana.

Professor I. McDougall and Dr W.J. Dunlap spent a week in the field mid-year in the northern Flinders Ranges with Dr M. Sandiford and Ms S. McLaren of the Department of Geology and Geophysics, **University of Adelaide**, in relation to a joint project on the thermal history of this region. Continuation of this project involved a visit by Ms McLaren to RSES later in the year to undertake K-Ar age measurements.

Dr C.E. Martin is collaborating with Dr Dhia Al Bakri and Ms Alma Joglekar, **Orange Agricultural College, The University of Sydney**, on elemental and isotopic tracers of the sources of P in the Orange water supply catchment. Dr Martin is acting as Associate Supervisor for Ms Joglekar's PhD research.

Dr J.M. Palin provided stable isotope data for Mr C. Mitchell, Mr C. O'Neill, and Ms M. Spandler of the **Australian National University,** Department of Geology.

Dr D. Phillips collaborated with Dr I. Cartwright and Ms C. Read, **Monash University** on the geochronology of shear zones in the Arunta Block in central Australia. He also collaborated with Dr C. Fergusson, **University of Wollongong**, on the geochronology of slates from the south coast of New South Wales.

Dr B. Pillans continued his study of Plio-Pleistocene stratigraphy of Wanganui Basin, New Zealand, in collaboration with Professor R.M. Carter, **James Cook University**, and Dr B. Kohn, **University of Melbourne**. As leader of the Regolith Dating Project with the CRC for Landscape Evolution and Mineral Exploration, Dr Pillans collaborated with Professor A.R. Chivas, **University of Wollongong**, Dr P. O'Sullivan, **University of Melbourne**, and Professor R. Bourman, **University of South Australia**.

Dr D. Rubatto has continued to collaborate with Dr Ian S. Buick from **La Trobe University**, on the geochronological and geological evolution of the Reynolds Range, central Australia, with particular focus on the behaviour of U-bearing minerals during prograde metamorphism and anatexis.

Dr P. Tregoning is a member of a GPS Consortium comprising five Australian Universities. The Consortium was awarded an ARC major equipment grant to purchase 10 GPS receivers which will be used for a variety of research applications.

Dr I.S. Williams continued his collaboration with Professor B.W. Chappell, **ANU Geology Department**, and Professor A.J.R. White, **Victorian Institute of Earth and Planetary Sciences**, in a study of the evolution of the Lachlan Fold Belt as recorded in zircon preserved in igneous and sedimentary rocks; with Dr P. Blevin, **ANU Geology Department**, in the study of magmatism associated with Palaeozoic mineralization in NSW; and with Dr I. Buick, **La Trobe University**, and Ms J. Miller, **Monash University**, in the study of metamorphism in central Australia and South Africa. He also undertook collaborative work with Ms G. Burch and Mr C. Gunton, students at the **ANU Geology Department**, Mr M. Huang, a student at **La Trobe University**, and Mr K. Butera, a student at **Melbourne University**. Dr Williams renewed his collaboration with Professor J. Hergt, **Melbourne University**, in the study of the Tasmanian Dolerites, and undertook a small collaborative study of the Marulan Batholith with Dr P. Carr, **University of Wollongong**.

INTERNATIONAL COLLABORATION

Dr R. Armstrong has been involved in a number of joint international research projects with scientists from Africa, Europe, South America and the USA. These include Professor L. Robb, Professor U. Reimold, Dr R. Gibson and Ms C. Rainaud (**University of the Witwatersrand**); Professor S. McCourt and Dr. S. Johnston (**University of Durban-Westville**),; in South Africa and Zimbabwe with Professor A. Wilson and Ms. S. Perritt (**University of Natal, Durban**); Professor M. de Wit (**University of Cape Town**); Professor L. Ashwal and Mr M. Knoper (**Rand Afrikaans University**), Professor A.B. Kampunzu and Dr R. Mapeo (**University of Botswana**), Professor R. Jacob (**Rhodes University**), Dr P. Mendonidis (**Vaal Triangle Technikon**) Professor S. de Waal (**University of Pretoria**). Dr Armstrong has also collaborated with researchers from the following overseas universities and research institutions: Professor V. Lorenz and Mr B. Bangert (**University of Würzburg**), Ms H. Torrealday (**Colorado School of Mines**), Dr A. Cocherie (**BRGM, France**), Professor C. Koeberl (**University of Vienna**), Dr J. Konzett (**University of Innsbruck**) and Dr M. Pimentel (**University of Brazilia**).

Dr V. Bennett is working with Dr A. Kent, **Lawrence Livermore National Laboratories**, on determining the Pb isotopic and trace element compositions of melt inclusions in Baffin Island lavas. She is also working with Dr A. Meibom, **University of Hawaii**, on the Ni isotopic compositions of zoned metallic grains from chondritic meteorites to help understand processes in the solar nebula, and is also working with Professor M. Garcia, **University of Hawaii**, on the PGE element chemistry of Hawaiian lavas.

Dr A.J. Berry continued his collaboration with Dr S.C. Wimperis and S.E. Ashbrook of the **University of Oxford** on ^{17}O multiple quantum nuclear magnetic resonance studies of silicate minerals.

Dr M. Bird continued collaboration with Dr H. Santruckova of the **University of Southern Bohemia**, Czech Republic, on a studies of the fractionation of carbon-isotopes by micro-organisms during soil carbon degradation. He continued to collaborate with Professor J. Lloyd and staff of the Max Planck Institute for Biogeochemistry and staff of the Krasnoyarsk Forest Institute and **University of Moscow** on a study of soil carbon in the Siberian boreal forests, as part of the Eurosiberian carbon flux study. Dr Bird also collaborated with Dr E. Veenendaal **(Okavango Research Centre, Botswana)** on a study of carbon inventories in Botswanan soils and with Dr C.S.M. Turney **(Royal Holloway, University of London)** and Dr L. Ayliffe **(CNRS-CEA, Gif Sur Yvette, France)** on the radiocarbon dating of Australian Archaeological sites. Dr Bird collaborated with Dr F. Vitali and Professor F. Longstaffe (**University of Western Ontario, London, Canada**) on a study of oxygen-and hydrogen-isotope systematics in gibbsite.

Dr J. Braun is a member of the Earth System Evolution Program of the **Canadian Institute for Advanced Research (CIAR)**. Within the program, Dr Braun collaborates closely with Professor C. Beaumont of **Dalhousie University**, Canada; Dr Braun and Mr J. Tomkin are collaborating with Dr K. Whipple of the **Massachusetts Institute of Technology** on problems of glacial erosion.

Professor J. Chappell collaborated with Professor Y. Ota of **Senshu University**, on a monograph concerned with Quaternary coral terraces at Huon Peninsula, Papua New Guinea.

Professor S.F. Cox and Dr S. Zhang collaborated with Dr K. Kanagawa (**Chiba University**, Japan) in experimental studies of the effects of pore fluids on the strength and mechanical behaviour of quartz gouges in simulated fault zones.

Mr C.M. Fanning is collaborating with Dr K.R. Ludwig and 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 K. Shiraishi and Dr Y. Motoyoshi of the **National Institute for Polar Research**, Tokyo, Japan, Dr J.J. Peucat of **Geosciences Rennes**, France, Professor R.P. Menot, **Université Jean Monet, St Etienne**, France, Professor P. K. Link of **Idaho State University**, Dr T.S. Laudon of **University of Wisconsin Oshkosh**, Dr J. Jacobs of **University of Bremen**, Germany, Professor F. Hervé of **University of Chile**, Santiago, Chile, Professor D. Gebauer and Dr A. Liati, **ETH Zürich**, Switzerland, Dr R.J. Pankhurst and Dr I. Millar of the **British Antarctic Survey**, UK, Dr C.W. Rapela, **Universidad de la Plata**, Argentina and Dr A. Morton, **British Geological Survey**, UK.

Dr J. Fitz Gerald is collaborating with Dr H. Stunitz, **Geological and Palaeontological Institute, University of Basel** on the microstructures of feldspar single crystals experimentally deformed in solid media apparatus. He is also collaborating with Professor J. Urai, **University of Aachen** in providing material on analogue deformation for a teaching CD project to celebrate the work of Professor W. Means.

Dr M. Gagan continued cooperative research with Dr W. Hantoro, **Indonesian Institute of Sciences**, to extract late Quaternary climatic histories from raised coral terraces in Indonesia. A new collaboration with Professor K. Sieh, **California Institute of Technology**, aims to integrate palaeoclimatic and palaeoseismological records derived from Indonesian corals. Work continued with Drs T. Correge, G. Cabioch, and J. Recy, **ORSTOM**; Drs W. Beck and G. Burr, **University of Arizona**; and Professor R. Edwards, **University of Minnesota** to reconstruct tropical palaeoclimates of the southwestern Pacific during the Younger Dryas event. Collaborative research on coral-based palaeoclimatology continued with Dr L. Ayliffe, **CNRS-CEA**, France. Dr Gagan is also working with Professor G. Miller, **University of Colorado**, to reconstruct Australian palaeoclimates using isotopic signatures in emu eggshell.

Professor Green continued his collaboration with Dr K. Niida, **University of Hokkaido** and Professor H. Davies, **University of Papua New Guinea** on the study of ultramafic rocks. Professor Davies is continuing as co-supervisor of a PhD student in RSES, Mr W. Lus. Professor Green acted as External Examiner for the Department of Earth Science, **Sultan**

Qaboos University, Oman and examined graduating students during the first week of June. Professor Green continues to be a member of the **Cambridge Commonwealth Trust**.

Dr J. Hermann collaborated with Dr M. Wyss of the **University of Lausanne**, Switzerland, on the characteristics of mafic intrusions in the crystalline nappe, High Himalayan Range; with Dr O. Müntener, **Woods Hole Oceanographic Institution**, USA, in studies of the differentiation of mafic magma at the continental crust-mantle boundary and 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 K. De Corte, **University of Ghent**, Belgium, on diamond inclusions in metamorphic minerals of the Kokchetav Massif, Khazakhstan; with Professor V. Shatsky, A. Korsakov, **Geophysics and Mineralogy, Novosibirsk**, Russia, on age and exhumation rate of diamondiferous rocks from the Kokchetav Massif, Khazakhstan; with Professor V. Trommsdorff, A.C Risold, **ETH Zürich**, on water in olivine from ultramafic bodies in the Central Alps; with Dr M. Scambelluri, **University of Genova**, Italy, on subduction related structures in the Erro-Tobbio unit, Western Alps and with Dr B. Cesare, **University of Padova**, Italy, on metamorphism in mafic cumulates of the Tauern window, Alps.

Professor R.W. Griffiths continued a study of the fundamentals of wind-driven ocean circulation in collaboration with Professor G. Veronis, a Visiting Fellow from **Yale University**. He also continued collaboration with Professor K.V. Cashman, **Oregon State University**, on the dynamics and emplacement of long basaltic lava flows.

Professor Grün has developed a virtually non-destructive ESR dating protocol which allows the measurement of enamel fragments without the necessity of grinding them. 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, Dept 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). Professor Grün has continued his collaboration with Professor Bershov, Dr A. Gurbanov, **Institute of the Geology of Ore Deposits, Moscow** and Dr D. Koshchug, **Moscow State University**. New samples were collected from the Eldzhurtinskiy granite complex to study which surface sampling techniques can be used for ESR studies of cooling and denudation rates. Samples were also collected from the Elbrus for the reconstruction of the eruption history of Europe's highest volcano. Professor Grün has obtained samples from the German continental deep drilling project (KTB) to study the thermal equilibrium of paramagnetic centres.

Dr M. Honda completed a collaborative study with Dr A. Kent, **California Institute of Technology**, on contamination of ocean-island basalt magmas by seawater-derived components at Loihi Seamount, Hawaii.

Dr G.O. Hughes continued a collaboration with Dr S.B. Dalziel, Department of Applied Mathematics and Theoretical Physics, **University of Cambridge**, Dr P.F. Linden, Department of Mechanical and Aerospace Engineering, **University of California San Diego**, and Dr B.R. Sutherland, Department of Mathematical Sciences, **University of Alberta**. They have made use of a new laboratory visualisation technique to examine the evolution of internal gravity waves in a stratified fluid. He has also continued a collaboration with Professor I.P. Castro of the Environmental Flow Research Laboratory, **University of Surrey**, in which they have studied the interaction of stratified flows with topography using towing-tank experiments.

Dr I. Jackson is collaborating with Dr. J. Kung of the **Bayerisches Geoinstitut, Bayreuth**, Germany on the high-temperature elasticity of perovskites and implications for modelling the seismic properties of the lower mantle.

Dr P. Johnston continues to collaborate with Dr P. Wu, **University of Calgary**, on stresses due to postglacial rebound.

Dr G. Kaufmann continued his collaboration with Professor P. Wu and Dr G. Li, **University of Calgary**, Canada on the influence of lateral heterogeneities in the upper mantle on quantifying the effects of lateral variations in lithosphere and asthenosphere underneath Fennoscandia on rebound-related signatures as present-day uplift velocities and gravity changes. He is also collaborating on a project initiated last year in collaboration with Dr F. Amelung, **Stanford University**, California, on the resolving power of a series of geodetic surveys in vicinity of Lake Mead, a reservoir in the Western United States of America, for crustal and subcrustal structure in the Basin and Range Province, has been completed.

Professor B.L.N. Kennett was elected as President of the **International Association for Seismology and the Physics of the Earth's Interior (IASPEI)** at the International Union of Geodesy and Geophysics General Assembly in Birmingham, UK in July. He was previously First Vice-President of IASPEI. Professor B.L.N. Kennett was a member of the external Review Committee for the Departments of Earth and Planetary Sciences at the **University of Tokyo** in March, and combined the review with a visit and seminar at the **Japanese Marine Science and Technology Center** (JAMSTEC) and a few days at the **Earthquake Research Institute Tokyo** working with the Ocean Hemisphere Project.

Dr R.C. Kerr continued a collaboration with Dr C.M. Lesher, Mineral Exploration Research Centre, **Laurentian University**, and Dr D.A. Williams, Department of Geology, **Arizona State University**, in developing and applying numerical models of the submarine flow of komatiite lavas.

Professor K. Lambeck is a member of the **SPINOZA Commission of the Netherlands Organisation for Research** and also a member of the **Canadian Institute** for **Advanced Research**. He is a Lead Author of the **Intergovernmental Panel on Climate Change.** He has collaborative programs with groups in **Scandinavia**, **UK**, **France**, **Israel**, **The Netherlands** and **Belgium** concerned with aspects of glacial cycles and sea-level change over the last 150,000 years. Professor Lambeck was Chairman, Committee of the International Union of Geodesy and Geophysics to **Study** the **Earth's Deep Interior (SEDI).**

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

Mr W. Lus is collaborating with scientists from **Japan Marine Science and Technology Centre (JAMSTEC)** on seabed studies of the 1998 PNG Aitape Tsunami using Remotely Operated Vehicle (ROV), and manned submersible Shinkai 2000.

Professor M. McCulloch has established a collaborative project with Professor U. Radtke from the **University of Kœln** on time-scales for rapid changes in sea-level using precise U-series ages of fossil coral reefs from Barbados. Work is continuing on coral bleaching in the SW Pacific with Dr L. Ingram and Mr B. Roark (PhD student) from the **University of California at Berkeley**. A major instrument development program has commenced with Finnigam MAT on both the thermisation ion mass spectrometer (TRITON) and the multi-collector ICP (NEPTUNE). In conjunction with Dr Esat, an improved ion collection system is being developed as well as novel applications of laser ablation. Professor McCulloch continued collaboration with Dr A. Tudhope of the **University of Edinburgh** on coral terraces at Huon Peninsula, Papua New Guinea.

Professor I. McDougall continues to be involved in numerical time scale studies of stratigraphic sequences in relation to hominid evolution. This is being done in close collaboration with Dr M.G. Leakey of the **National Museums of Kenya**, Dr F.H. Brown of the **University of Utah** and Dr C.S. Feibel of **Rutgers University**.

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 M. Amalvict of the **Université Louis Pasteur** in Strasbourg on FG5 Absolute gravimeter calibrations at Mt Stromlo in support of the SG installation.

Dr C.E. Martin collaborated with Drs Bernhard Peucker-Ehrenbrink and Greg Ravizza, **Woods Hole Oceanographic Institution**, USA, in studies of the Os isotope and platinum-group element geochemistry of sediments and natural waters. She is a member of the international project **TROPICS** working group, which is studying the physical and chemical oceanography and sedimentology of the coastal margins of Papua New Guinea.

Dr H. O'Neill is collaborating with Dr S.A.T. Redfern, **Cambridge University**, United Kingdom, on the application of neutron diffraction to order-disorder problems in synthetic high pressure minerals. He continued his collaboration with Dr D. B. Dingwell, **University of Bayreuth**, Germany, Dr W. Ertel, **University of Arizona**, USA, and Dr P.J. Sylvester, **Memorial University of Newfoundland**, on the solubility of Platinum Group Elements and Rhenium in silicate melts. He also worked with Professor H. Palme and Dr A. Holzheid, **University of Cologne**, Germany, on siderophile element partitioning at very high pressures.

Dr D. Phillips participated in collaborative research projects with researchers in South African universities, including Dr R. Gibson and Ms C. Rainaud (**University of the Witwatersrand**), Dr C. Harris (**University of Cape Town**) and Dr J.S. Marsh (**Rhodes University**). During the year, he also participated in collaborative geochronological studies with Dr J. Vry and Mr N. Jackson of **Victoria University**, Wellington, New Zealand and Dr C. Delor of **BRGM**, France.

Dr B. Pillans continued his collaboration Drs B. Alloway, A. Beu and T. Naish, **Institute of Geological and Nuclear Sciences**, on Plio-Pleistocene stratigraphy of Wanganui Basin, New Zealand. He also collaborated with Dr G.W. Berger, **Desert Research Institute, Reno**, and Drs P. Tonkin and P. Almond, **Lincoln University**, on luminescence dating of New Zealand loess.

Dr D. Rubatto concluded, with a final publication on the age of high-pressure metamorphism in the Western Alps, her current collaboration with Professor D. Gebauer from the **Institute for Isotopegeology and Mineral Resources, ETH, Zürich**. She started to work with Professor V. Tromsdorff from the **Institute for Mineralogy and Petrology, ETH, Zürich**, on the geochronology of peridotite bodies from the Alps and South Spain. Dr Rubatto's interest in Alpine geology led to a joint project with Italian institutions including Dr Marco Scambelluri from **Genova University**, Dr B. Lombardo, Dr F. Colombo and Professor R. Compagnoni from **Torino University**, and Dr B. Cesare from the **University of Padova**. Together with Dr Cesare, Dr Rubatto started a SHRIMP-based project in the volcanic province of South Spain, which also involves Dr M.T. Gómez-Pugnaire from the **University of Granada, Spain**.

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 maintenance and development of the GAMIT GPS analysis software.

Dr P. Tregoning has continued cooperation with the **Papua New Guinea University of Technology, Lae** for the study of present-day tectonic motion in the region. Cooperation has also continued with Dr E. Silver of **Earth Sciences Department, University of California, Santa Cruz** in studies of convergence on the Ramu-Markham Fault in Papua New Guinea. Cooperation with the **Rabaul Volcano Observatory** has also continued, with staff at the observatory using RSES equipment to monitor local deformation at Rabaul and in the surrounding region.

Professor J.S. Turner continued his collaborations with three North American colleagues to bring to completion two papers which are now in press. The first, on the motion of double-diffusive intrusions across fronts, has been written with Professor B.R. Ruddick, **Dalhousie University**, and Professor O.M. Phillips, **Johns Hopkins University**. Experiments on the stratification and circulations produced by two horizontally separated double-diffusive sources, carried out while Professor G. Veronis, **Yale University**, was a Visiting Fellow in RSES, have also led to a joint publication. A longstanding collaboration with Professor P.F. Linden, who moved during the year from the **University of Cambridge** to the **University of California, San Diego**, has led to the submission of a manuscript on the mechanism of formation of vortex rings, with applications to the design of propulsion devices.

Dr I.S. Williams continued his collaboration with Professor H. Zeck, **Copenhagen University**, in the use of zircon inheritance in Miocene igneous rocks from southern Spain to study the processes of magma genesis and with Dr W.E. Stephens, **St Andrews University**, in a study of zircon inheritance from Scottish granites. He also began collaborative projects with Professor W.R. Van Schmus, **University of Kansas, Lawrence**, on the provenance of late Proterozoic sediments from northeastern Brazil and with Dr J. Goodge, **Southern Methodist University, Dallas**, on the provenance of late Proterozoic and early Palaeozoic sediments of the Beardmore Group in the Transantarctic Mountains. In addition he undertook small collaborative studies with Professor A. Zeh and Ms H. Brätz, **University of Würzburg** on the geochronology of igneous and metamorphic rocks of the Ruhla Crystalline Complex, Germany; with Professor P. Bowden, **Université Jean Monnet, Saint Etienne**, and Dr L. Tack, **Royal Museum for Central Africa, Tervuren**, on the age and metamorphic history of gneisses from the Central Damaran orogenic belt, western Namibia; with Professor D. Liu, **Chinese Academy of Geological Sciences, Beijing**, on the Su-Lu and Dabie ultra-high pressure metamorphic terranes, newly discovered early Archean rocks from central China, and early Archean rocks from Enderby Land, Antarctica; with Dr W. Ranson, **Furman University, Greenville**, on the age and provenance of granite gneisses from the southern Appalachians; and with Professor Y. Miura, **Yamaguchi University**, on the age of glass spherules from the Takamatsu Crater, Japan.

Dr G. Yaxley is collaborating with Professor G. Brey, **Universität Frankfurt**, Germany on a high pressure experimental study of the melting and phase relations of carbonate-bearing eclogite assemblages.

EDITORIAL RESPONSIBILITIES

Dr R.A. Armstrong is a member of the Editorial Board of the *South African Journal of Geology*.

Dr V. Bennett is a member of the Editorial Board of *Geology*.

Dr J. Braun is member of the Editorial Board of *Reviews of Geophysics*.

Prof S.F. Cox continued as a member of the Editorial Advisory Board of *Journal of Structural Geology*, and was appointed to the Editorial Advisory Board of the new journal *Geofluids*.

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

Dr J Fitz Gerald and Dr I. Jackson continued on the advisory board for *Physics and Chemistry of Minerals*.

Professor R. Grün is Editor of *Quaternary Geochronology* (Quaternary Science Reviews), a member of the Editorial Boards of *Quaternary International* and *Radiation Measurements*, Associate Editor of *Journal of Human Evolution* and Member of reviewers' panel of *Ancient TL*.

Professor B.L.N. Kennett completed a 20-year term as an Editor for *Geophysical Journal International* in September, and continues an associate editor for *Physics of the Earth and*

Planetary Interiors. He has also acted as a guest editor for *Pure and Applied Geophysics* for an issue on Source Location in relation to the Comprehensive Nuclear-Test-Ban Treaty.

Professor K. Lambeck is on the Editorial Boards of *Quaternary Science Reviews* and *Earth and Planetary Science Letters*.

Dr F.E.M. Lilley is a member of the Editorial Board of the *Brazilian Journal of Geophysics*.

Professor M.T. McCulloch is a member of the Editorial Board of *Chemical Geology*.

Professor I. McDougall completed terms as a member of the Editorial Boards of *Geology* and Isotope Geoscience Section of *Chemical Geology* during the year, but continues on the Editorial Boards of *Quaternary Geochronology* and *Terra Nova*.

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

Dr H. O'Neill is on the Editorial Board of *Chemical Geology*.

Dr B. Pillans is a member of the editorial boards of *Quaternary Science Reviews* and *Catena*. He was also a guest editor (with Professor R.M. Carter, James Cook University, Dr T. Naish, New Zealand Institute of *Geological & Nuclear Sciences*, and Dr M. Ito, Chiba University) of a special issue of *Sedimentary Geology* entitled "Sequence Stratigraphy in the Plio-Pleistocene: An Evaluation".

Dr M. Sambridge joint the editorial board of *Geophysical Journal International* in January. He handles papers through the Pacific Region Office.

TEACHING ACTIVITIES

As part of his activities in the Geology Department (The Faculties), Professor S.F. Cox taught a one semester course in Structural Geology and Tectonics and contributed to the Field Geology and Economic Geology teaching programs.

Dr U. Faul taught with Dr P. Chopra (Geology Department) the Geology 3005 "Geophysics" course to third year students in the Geology Department, ANU.

Dr J. Fitz Gerald again lectured for the ENGN4517 course in the Faculty of Engineering and Information Technology and also taught in the workshop series of the University's Electron Microscope Unit.

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

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

Dr J. Mavrogenes taught the third year Economic Geology course in the Geology Department, ANU.

Professor I. McDougall gave a lecture to students in the Department of Archaeology and Anthropology, The Faculties, on utilizing the K-Ar and ^{40}Ar-^{39}Ar methods for numerical dating of stratigraphic sequences.

Dr J.M. Palin presented two lectures and practical class on the theory and use of stable isotope geochemistry to the third year Economic Geology course in the ANU Department of Geology.

Dr D. Rubatto taught a three-hour 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 ANU Electron Microscope Unit's 1999 workshop series.

HONOURS SUPERVISION

As part of his activities in the Geology Department (The Faculties), Professor S.F. Cox supervised three honours students in 1999. All projects dealt with deformational controls on the formation or modification of ore deposits.

Dr J. Hermann supervised the honours research project of Ms S. Williams, ANU Geology Department, on the Himalayan eclogites from SW-China.

Professor B.L.N. Kennett, Dr M. Sambridge (RSES) and Dr P. Chopra (Geology Department, The Faculties, ANU) co-supervised the Honours thesis work of Ms C. Farmer on investigations of earthquake location techniques.

Dr J. Mavrogenes supervised the honours work of Ms N. Douglas on the role of Bi in gold deposits and Mr C. Gunton's work on the Ernest Henry Mine, Queensland and Ms G. Burch's study of the Mt McKenzie prospect, Queensland. He also co-supervised (with Professor R. Arculus, Geology Department, ANU) Ms S. Belfield's project on the Taupo volcanics and Mr C. Mitchell's study (with Professor S. Cox) of the Adelong gold field.

Dr W.R. Taylor supervised the honours research project of Mr M. Richardson on diamond indicator minerals and lithosphere structure of the Kimberley block, Western Australia. The project was sponsored by Rio Tinto Exploration Ltd.

SUMMER RESEARCH SCHOLARSHIPS

Kristin Butera	University of Melbourne
Project:	Zircon U-Pb dating of early Palaeozoic monzonitic intrusives from the Goonumbla area, NSW.
Supervisor:	Dr Ian Williams, Geochronology and Isotope Geochemistry (RSES)
Naomi Douglas	Australian National University
Project:	Experimental investigation of Fe-FeS melting relations at high pressure.
Supervisors:	Dr H. O'Neill and Dr J. Mavrogenes, Petrochemistry and Experimental Petrology (RSES)
Stuart Finlay	University of South Australia
Project:	ESR analysis of fluorescence bands in corals
Supervisors:	Professor M.T. McCulloch and Dr C. Martin, Environmental Geochemistry and Geochronology (RSES)
Loretta Garrett	University of Waikato
Project:	Dose response of quartz from the Eldzhurtinskiy granite.
Supervisor:	Professor R. Grün, Environmental Geochemistry and Geochronology (RSES).

Paula Hahesy	Flinders University of South Australia.
Project:	Interpretation of seafloor magnetometer data from the SWAGGIE98 Experiment
Supervisor:	Dr F.E.M. Lilley, Seismology and Geomagnetism (RSES)

OUTREACH AND WORKSHOPS

In November, Professor S.F. Cox presented three days of workshops at Leinster (WA) on structural geology and fluid flow in ore systems to geological staff from the WMC Resouces Ltd Leinster Nickel Operations and the Agnew Gold Operations. In December he gave a presentation on earthquakes to science students at Merici College, Canberra.

Mr W. Lus gave a seminar in February 1999 about the "Understanding the 1998 PNG Aitape Tsunami: results and modelling using geophysical and geological data from R/V Kairei cruise offshore from Aitape 2/1/99–12/1/99". He also hosted a PNG public lecture in September on "1998 PNG Aitape Tsunami: seabed investigations off the northern coast of PNG". Mr Lus was also part of the expert team visiting survivor villages and talking to survivors of the 1998 PNG Aitape Tsunami and about the results of the seabed survey into the possible cause of the tsunami.

Professor R. Rutland gave an invited address on "What it means to me to be a scientist" to the final session of the National Youth Science Forum held in Canberra on 29 January.

Dr I.S. Williams was guest speaker at the November meeting of the ACT branch of the Geological Society of Australia, where he presented a lecture entitled "To see the world through a grain of sand: SHRIMP geochronology 20 years on". He also hosted two visits to the ion probe laboratory by 50 high school students from the Rio Tinto National Youth Science Forum in January.

OTHER MATTERS

Dr A.J. Berry and Dr J. Mavrogenes received grants from the Access to Major Research Facilities Program to investigate the high temperature solubility and speciation of metals in aqueous fluids at the Advanced Photon Source, Argonne National Laboratory, USA in February and September.

Dr A.J. Berry, Dr H.StC. O'Neill, and Mr D. Scott investigated the oxidation state of chromium in silicate glasses and melts at the Australian National Beamline Facility, Tsukuba, Japan under a grant from the Australian Synchrotron Research Program.

Dr J. Braun is a member of the IASPEI commission on Geodynamics and Tectonophysics. He is has also distributed the computer software program CASCADE for landscape evolution modelling to researchers in seven institutions in Europe, the United States and Canada.

Dr I.H. Campbell is a member of the Commission for Igneous and Metamorphic Petrogenesis, a subcommission of the International Union of Geological Sciences and a councilor of the International Mineralogical Association.

Professor S.F. Cox continued as a member of the Australian Research Council's Research Training and Careers (Fellowships) Committee and continues as the Australian representative of the International Association of Structural and Tectonic Geologists.

Dr M. Gagan is a 3-year member of the new Ocean Drilling Program (ODP) "Scientific Drilling of Shallow-Water Systems" Planning Group. He also continues as a member of the

International Geosphere-Biosphere Program and World Climate Research Program (PAGES-CLIVAR) Joint Working Group.

Dr G.O. Hughes is co-inventor (with S.B. Dalziel and B.R. Sutherland) on a Provision Patent Application "Digital Schlieren" filed in the USA.

Professor M.T. McCulloch is collaborating with Ms M. Devlin and Mr D. Haynes, Great Barrier Reef Marine Park Authority, conducting research examining salinity and trace element systematics during bleaching. Collaborative studies have been undertaken with Dr P. Moody and Dr C. Pailles on tracing the source of suspended sediments that are entering the Great Barrier Reef from the Johnstone River.

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

Dr H. O'Neill is a member of the IASPEI/IAVCEI Inter-Association Commission on Physical and Chemical Properties of Materials of the Earth's Interior.

Drs M. Sambridge and J. Braun have continued to distribute the computer software program (NN_QUICK) for scattered data interpolation. In 1999 researchers from 15 institutions requested and received a copy of the program.

Dr S.L. Webb was appointed secretary to the IASPEI-IAVCEI Commission on Physical and Chemical Properties of Materials of the Earth's Interior.

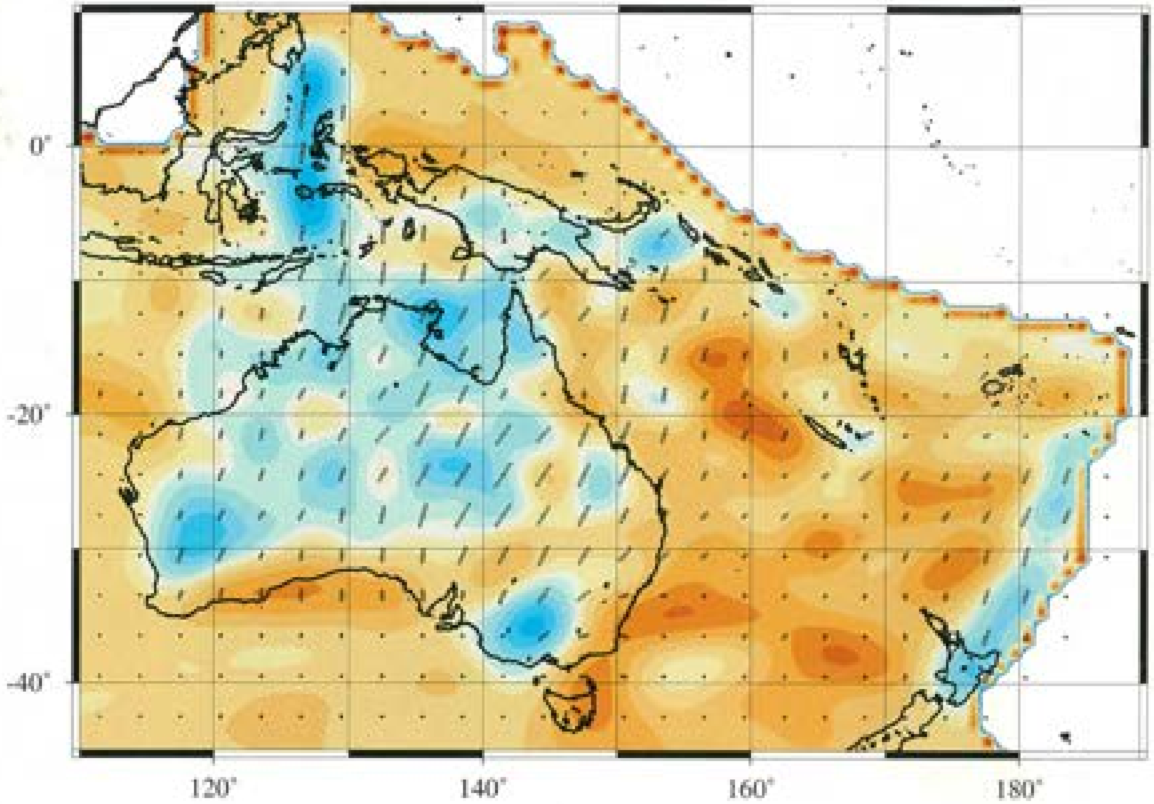
SCHOOL SEMINARS

Date	*Presented by*	*Topic*
4 February	Mr W. Lus **RSES**	Understanding the 1998 PNG Aitape Tsunami: results and modelling using geophysical and geological data from R/V Kairei cruise offshore from Aitape 02/01/99-12/01/'99
11 February	Dr P. Tregoning **RSES**	In search of tectonic hazards in Papua New Guinea
25 February	Dr M. Worthington **Imperial College, London**	Seismic attenuation in the crust; does Q stand for questionable?
4 March	Professor D. Gebauer **ETH Zürich (Swiss Federal Institute of Technology)**	Rates of subduction-exhumation as well as heating and cooling in Alpine orogens
11 March	Professor E. Galinov **Russian Academy of Science**	Diamond isotope geochemistry
11 March	Professor G.V. Gibbs **Virginia Technology, USA**	A modelling of the structure and the electron density distribution in low quartz and coesite at pressure
18 March	Dr R. Van Schmus **University of Kansas, Lawrence, USA**	Tectonic history of The Borborema Province, NE Brazil: From Atlantica to Gondwana via Rodinia?
25 March	Dr C. Barnes **Faculty of Engineering and Information Technology, ANU**	Using natural environmental tracers to manage hydrological systems
31 March	Dr A. Osborne **Sydney University**	Karst, palaeokarst, and post-carboniferous uplift of the NSW eastern highlands
8 April	Professor G. Miller **University of Colorado**	Disappearing fauna and vanishing lakes: are humans or climate responsible?
15 April	Professor R. Rutland **RSES**	The classical Palaeoproterozoic of Finland and Sweden: constraints on models of crustal growth and metallogenesis
22 April	Dr K. Ludwig **Berkeley Geochronology Center, Berkeley, CA USA**	U-series dating of soil carbonate/silica in different environments
29 April	Professor G. Veronis **Yale University**	Open discussion about global warming and global change
6 May	Dr U. Faul **RSES**	Deformation of partially molten rocks: From the laboratory to the mantle

13 May	Dr I. Jackson **RSES**	Seismic properties of geological materials at high temperature: The transition between elastic and viscous behaviour
20 May	Professor K. Trumble **Purdue University, USA**	Wetting and microstructure development in Pallasite meteorites: natural ceramic-metal composites
27 May	Dr N. Spooner **RSES**	Optical dating and thermoluminescence dating: Some fundamentals and applications
3 June	Professor M. McCulloch **RSES**	The rise and fall of Last Interglacial sea levels and sea-surface temperatures: Implications for a Greenhouse modified Earth
10 June	Dr C. Turney **RSES**	Radiocarbon dating the human colonization of Australia: The ever-changing story
17 June	Mr S. Klemme **RSES**	The influence of Cr on phase relations in the Earth's upper mantle: Experiments and thermodynamics
24 June	Professor R. Arculus **Geology Department, ANU**	From mantle to continental crust via arcs
1 July	Dr J. Braun **RSES**	From rifting to inversion: character-building episodes in the life of a passive margin
8 July	Professor R. Grün **RSES**	Dating of the Lake Mungo 3 human skeleton
15 July	Ms S. Nikolova **Flinders University of South Australia**	Atmospheric radiation modelling under broken clouds: Use of all-sky composite images
22 July	Dr J. Streit **Department of Geology, ANU**	Conditions for earthquake surface rupture along the San Andreas fault system, California
29 July	Dr J. M. Palin **RSES**	Oxygen isotope fractionation in silicate melts: A general model and petrogenetic applications
5 August	Professor B. Simonson **Oberlin College, Ohio, USA**	Evidence of late Archaean and early Proterozoic asteroids from Western Australia and South Africa
12 August	Professor D. Green **RSES**	Primary magmas and mantle temperatures
19 August	Mr A. Hitchman **RSES**	Magnetic mapping and electromagnetic induction in the Earth

26 August	Dr S. Eggins **Department of Geology, ANU**	Toward understanding subduction zones - evidence for melting a thousand times faster than beneath mid-ocean-ridges
2 September	Professor B. Kennett **RSES**	The state of the mantle: reconciling structure and processes
9 September	Professor W. Compston **RSES**	Stretching isotope dilution, SHRIMP and zircons to the limit: Trying to link biostratigraphy with numbers
16 September	Professor K. Lambeck **RSES**	Sea-level change along the French Mediterranean coast: timing of human occupation of Cosquer Cave
23 September	Dr J. Fitz Gerald **RSES**	Zooming in on grain boundaries
30 September	Dr P. Johnston **RSES**	Quaternary ice sheet history as an inverse problem
7 October	Dr S. Zhang **RSES**	Coupled metamorphic reactions and fluid flow - A laboratory study
14 October	Professor J. Chappell **RSES**	El Nino, social crises, and implications of data from earth sciences
21 October	Dr M. Bird **RSES**	Radiocarbon dating human occupation of Australia: more of it
28 October	Mr Y. Yokoyama **RSES**	Calibration of the radiocarbon time scale from 30,000 to 50,000 years ago: Direct evidence for oceanic involvement in millennial scale climate changes of The Last Ice Age
4 November	Dr D. Sinclair **RSES**	***Robert Hill Memorial Prize Lecture*** Eels, Black Boxes, and Sex on the Reef: A meander through the world of coral trace element analysis by laser-ablation ICP-MS
8 November	Professor H. Wopfner **University of Cologne**	Early Cainozoic silcretes and their morphotectonic control
11 November	Dr H. O'Neill **RSES**	Silicate melt properties and trace element partitioning
22 November	Dr O. Gudmundsson **Danish Lithosphere Center**	RELACSing the Rabaul volcano: tomography and earthquake location
25 November	Dr J. Streit **Department of Geology, ANU**	Conditions for earthquake surface rupture along the San Andreas fault system, California
2 December	Dr W. Taylor **RSES**	Kimberlites, diamonds and the nature of the mantle lithosphere of Northern Australia

9 December	Dr E. Debayle **RSES**	The Australian continental upper mantle: Structure and deformation inferred from surface waves
16 December	Dr P. De Deckker **Department of Geology, ANU**	The history of the Warm Pool north of Australia - Two modes of operation over the last 30,000 years



Research School of Earth Sciences
The Australian National University
Canberra ACT 0200
Telephone (02) 6249 3406
Facsimile: (02) 6249 0738
RSES Home Page: http://wwwrses.anu.edu.au/