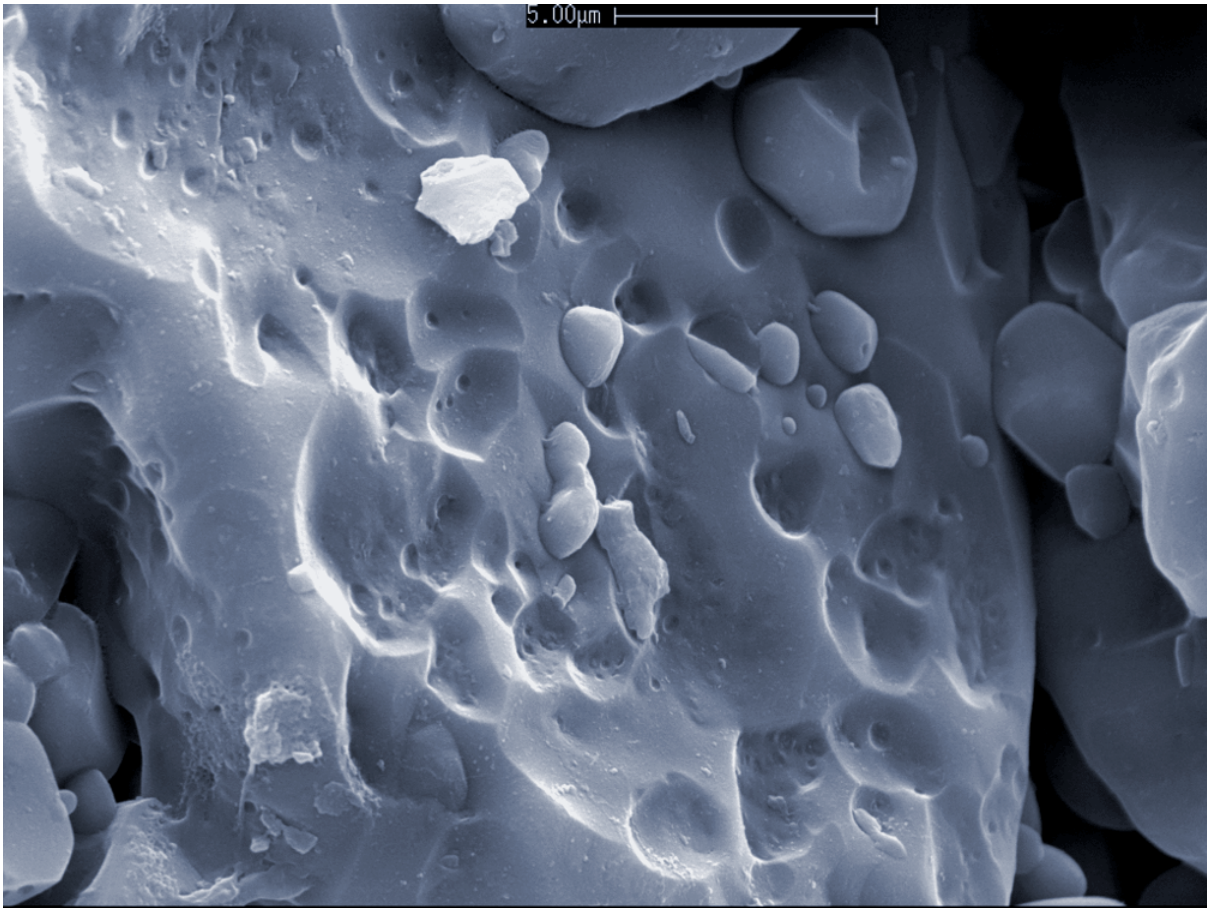
Research School of Earth Sciences

Annual Report 2004



A scanning electron microscope image (SEM) showing dissolution pits due to interpenetration of quartz grains at sub-micron scale. Quartz powders are deformed at high temperatures and pressures in the rock physics laboratory to explore permeability - and strength evolution in fault gouges. This image was taken of a sample deformed for three hours at 300MPa confining - and 200 MPa pore fluid pressure and a temperature of 1200°K.

Image courtesy Silvio Giger.

THE AUSTRALIAN NATIONAL UNIVERSITY

Report to Council

RESEARCH SCHOOL OF EARTH SCIENCES (RSES)

Major Disciplines: Earth Sciences; Chemical Sciences

STAFF AND STUDENTS								
Total Staff (FTE)	**Academic Staff (FTE)**	**General Staff (FTE)**	**Total Student EFTSU**	**Higher Degree Research (EFTSU)**	**Higher Degree Coursework (EFTSU)**	**Other Postgraduate (EFTSU)**	**Under-graduate (EFTSU)**	**Non-award (EFTSU)**
133	53	80	44	44	0.4			

GRANTS			
ARC ($)	**NHMRC ($)**	**Other ($)**	**TOTAL ($)**
3,013,920	0	992,598	4,006,518

Research

The Research School of Earth Sciences (RSES) is one of the top ten university-based geoscience programs in the world and a research leader in the physics, chemistry, material properties and environmental conditions of the Earth. Its role is to conduct research at the highest international level and take leadership in defining new directions in geophysics and geochemistry, particularly those relevant to the geologic setting and needs of Australia . RSES has the country's premier concentration of basic research facilities in experimental and observational geoscience including: the Australian National Seismic Imaging Resource (ANSIR), the Sensitive High Resolution Ion Micro-Probe (SHRIMP) facility, and the Quaternary Dating Research Centre which houses a complete set of facilities for dating the record of Earth systems over the past million years.

The work of the school is for administrative purposes grouped into four areas: Earth Chemistry, Earth Physics, Earth Materials, Earth Environment.

Earth Chemistry utilises elemental and isotopic abundances to examine the processes affecting the Earth and solar system. Tracer investigations range in scale from that of the solar system to diffusion at the atomic scale yielding information as diverse as elemental fractionation during solar system formation, to the nature of Earth's earliest crust and atmosphere, to the origin of ore deposits, to the evolution of the Himalayas .

Earth Environment specialises in revealing high-resolution environmental records preserved in fossil and modern corals, cave deposits, and layered sedimentary sequences to investigate global processes, such as climate and sea-level change, human evolution and migration, and landscape evolution. Research is underpinned by laboratory facilities that enable analysis of virtually any trace element or isotope system.

Earth Physics investigates the structure and dynamics of the Earth using a range of advanced physical and mathematical techniques. Present research focuses on the responses of the ocean and solid earth to different types of forcing and using circum-Australian earthquakes as probes for the structure in the Earth's mantle. The research effort divides into geodynamics, seismology and geomagnetism, geophysical fluid dynamics, and computational geophysics, with extensive interactions within and between the different components.

Earth Materials focuses on the interrelated chemical and physical behaviour of rocks and minerals under geological conditions using state-of-the-art facilities for characterisation and mechanical testing with the goal of understanding the structure and composition of the Earth. Key issues are first identified through field-based observations and then addressed through laboratory study. Insights thus gained are then extended through suitable models to improve our understanding of Earth.

ANU 2004 Quality Review	
Number of pieces of work submitted for assessment:	228
Number of Assessors:	8
Number of staff with work submitted: **This # includes fractional and adjunct appointments and selected academic staff in the two most junior grades.*	54*
EXTERNAL ASSESSMENT: % of assessors ranking ANU in Top 25%	69
EXTERNAL ASSESSMENT: % of assessors ranking ANU in Top 5%	24

Prizes, Honours and awards

Dr G.F. Davies was awarded the Love Medal of the European Geophysical Union.

Prof M.T. McCulloch was elected a Fellow of the Australian Academy of Science

The 2004 Walter H. Bucher Medal of the American Geophysical Union was awarded to Emeritus Professor Mervyn Paterson for 'his sustained, seminal, and innovative contributions to understanding the strength and mechanical behavior of crustal materials'.

Prof B.L.N. Kennett was announced the recipient for the Jaeger Medal of the Australian Academy of Sciences for 2005.

Prof K. Lambeck was designated an Institute for Scientific Information Highly Cited Researcher (those in the top 0.5% of cited researchers worldwide) bringing the RSES total to 9 (10% of all Australian Highly Cited Researchers).

Fellowships and senior appointments

Four Fellows of the Royal Society of London (100% of Australian earth scientists)

Ten Fellows of the Australian Academy of Sciences (45% of earth science FAA)

Ten Fellows of the American Geophysical Union (80% of all Australian Fellows)

Five Honorary Fellows, Geological Society of America (70% of all Australian GSA Honorary Fellows)

Two Associates of the Royal Astronomical Society, London

One Foreign Member of the Russian Academy of Sciences

Education

RSES graduates have been unusually successful, with >80% since 1971 remaining engaged in full-time geoscience research. Total research student enrolment 1995-2003:

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
PhD (Dom./Int.)	45 27/18	49 28/21	53 31/22	50 31/19	45 27/18	40 25/15	33 20/13	33 21/12	47 26/21
M.Phil (Dom./Int.)	1 1/0	1 1/0	1 1/0	1 1/0	- 1/0	- 0/0	1 1/0	1 1/0	- 0/0

Total PhD completion rate: 98.7%; Percent completing within four years (PhD) or two years (M.Phil): 47%; Percent of domestic students holding Australian Postgraduate awards: 56%.

Significant Outreach Activities in 2004

The White Conference was held in February 2004 to celebrate the birth of the Planetary Science Institute (PSI), a collaboration between RSES and RSAA. Held under the auspices of the Australian Academy of Sciences White Conferences , the theme of the conference was “Planetary timescales: from stardust to continents. The meeting attracted an international group of scientists to Canberra , was opened by the Science Minister Mr Peter McGauran, and included well-attended public lectures.

RSES actively participates in the National Youth Science Forum providing several day-long lectures and lab tours.

RSES continues to run successful summer scholar, research intern, and work experience programs.

The Australian National Seismic Imaging Resource Major National Research Facility based at RSES provides equipment for support of both reflection seismology and earthquake oriented work. Successful trials of reflection profiles at several mine sites in Western Australia have led to commercial adoption of this technology.

Key Achievements against 2004 goals

Our stated goals emphasized consonance with national, community and School research priorities and continued success with external funding opportunities. With respect to strategic planning, an initiative is underway to co-locate the Department of Earth and Marine Science on the RSES campus to enhance geoscience teaching and research. The Planetary Sciences

Institute, a collaboration with RSAA, made its first joint faculty appointment and extended another two offers. We developed the Marine Sciences Initiative which links RSES, SRES, DEMS, and BOZO to establish a BSc in Marine Science with a choice of majors in Biology, Geology, Chemistry, Physics, Mathematics and Meteorology. The School's new initiative in Computational Mineral Physics intended to complement its internationally recognised experimental research into the behaviour of geological materials was launched with the appointment of Dr. Andrew Walker - a recent Ph. D. graduate from the Royal Institution of Great Britain and University College , London . Our initiative in Advanced Data Inference saw the commissioning of the TerraWulf cluster for parallel and ensemble implementation of inverse methods in the Earth Sciences.

Other developments of note include:

SHRIMP II Multiple Collector development reached a milestone with demonstration of a stable isotope analysis capability. The multiple collector is now used routinely in the search for 4 billion year-old zircons and developments in stable isotope analysis will aid us in the design of SHRIMP SI (funded in the 2004 LIEF round).

We commissioned a new rotating table facility in the Geophysical Fluid Dynamics laboratory.

Successful over-wintering of portable seismic stations deep in East Antarctica and recovery of seismic data - a first for the Australian Antarctic Territory .

Synthesis of seismological information on the contrasts in the mantle associated with the transition from the Precambrian to the younger eastern portion of Australia .

The Sun’s oxygen-isotope composition is one of the outstanding parameters in cosmochemistry. Oxygen shows a wide variation in enrichments of 16O with proposed solar compositions at the extreme ends of the array (close to terrestrial or enriched in 16O by 6%). We measured metal grains from the Moon that have been implanted with solar wind. The composition measured in these grains is different from anything previously measured and is depleted in 16O relative to the terrestrial composition. It appears likely that the oxygen isotope variations in the solar system are inherited from the molecular cloud and star-forming region.

Key Directions for 2005

Proceeding with the hiring phase of the Marine Science Initiative, aimed at creating a world leading program that focuses on the southern hemisphere oceans and climate change through key research and teaching appointments.

Full implementation of the Earth Sounding Initiative with the appointment of a new continuing position in Seismology.

Development of SHRIMP SI from a concept to detailed design drawings.

Integrating research between RSES and RSAA PSI members.

Implementation of a new (LIEF and MEC-funded) ultra-short wavelength (157nm) excimer laser ablation ICPMS system for isotopic and elemental analysis of environmental, geological and archaeological materials.

Purchase and installation of the dedicated 14C accelerator (LIEF and MEC-funded) jointly supported by RSES and RSPhysE.

STAFF AND STUDENTS

ACADEMIC STAFF

Director and Professor

T.M. Harrison, BSc British Columbia , PhD ANU

Professors

J.M.A. Chappell, BSc MSc Auckland, PhD ANU, FAAS, FAA

S.F. Cox, BSc Tasmania , PhD Monash

R.W. Griffiths, BSc PhD ANU, FAIP, FAA

R. Grün, DiplGeol, Dr.rer.nat.habil Köln, DSc ANU

I.N.S. Jackson, BSc Qld, PhD ANU

B.L.N. Kennett, MA PhD ScD Cambridge, FRAS, FAA

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

G. Lister, BSc Qld, (Hons) James Cook, PhD ANU

M.T. McCulloch, MAppSc WAIT, PhD CalTech

H.St.C. O'Neill, BA Oxf, PhD Manchester

Senior Fellows

J. Braun, LicSc Liège, PhD Dalhousie (until 16 November 2004)

I.H. Campbell, BSc UWA, PhD DIC London

G.F. Davies, MSc Monash, PhD CalTech

T. Esat, MSc Queens , PhD ANU

M. Honda, MSc PhD Tokyo

T.R. Ireland, BSc Otago, PhD ANU

R.C Kerr, BSc Qld, PhD Cambridge , FAIP

C. Lineweaver, BSc Munich , PhD Berkeley (from 27 September 2004)

B.J. Pillans, BSc PhD ANU

M.S.Sambridge, BSc Loughborough, PhD ANU

I.S. Williams, BSc PhD ANU

Fellows

R.Armstrong, BSc MSc Natal, PhD Witwatersrand

V.C. Bennett, BSc PhD UCLA

W.J. Dunlap, BA CarlCol, MS PhD Minnesota

S. Eggins, BSc UNSW, PhD Tasmania

C.M. Fanning, BSc Adelaide

M.K. Gagan, BA UCSantaBarbara, PhD JamesCook

J. Hermann, Dip PhD, ETH Zürich (from 1 December 2004)

J.A. Mavrogenes, BS Beloit, MS Missouri-Rolla, PhD VirginiaPolyTech

W. Müller, DiplGeol Vienna, PhD ETH (until 1 July 2004)

M. Norman, BS Colorado , PhD Harvard

A.P. Nutman, BSc PhD Exeter

E. Rhodes , BA DPhil Oxford

P. Tregoning, BSurv, PhD UNSW

Research Fellows

A.J. Berry, BSc Sydney, DPhil Oxf

F.G. Fabel, BSc PhD Melbourne

H.U. Faul, Vordiplom Ulm, PhD Oregon

M. Forster, BSc MSc PhD Monash

G. Hughes, BE ME Auckland , PhD Cambridge

C. McFarlane, BSc Toronto, MSc Calgary, PhD Texas

A. Purcell, BSc PhD ANU

A. Reading , BSc Edinburgh, PhD Leeds

G. Yaxley, BSc PhD Tasmania

Postdoctoral Fellows:

C. Bryant, BSc UNE, PhD ANU (until 31 October 2004)

G. Dunbar, BSc MSc VicWell, PhD James Cook

A.L. Dutton, BA(Mus) Massachusetts , MSc PhD Michigan

J. Freeman, BSc Curtin, PhD Monash

A.C. Hack, AssocDip CIT, BSc PhD ANU (until 11 September 2004)

M. Heintz, BSc Nancy, MSc Strasbourg, PhD Montpellier

A.M. Hogg, BSc ANU, PhD UWA (from 3 May 2004)

A. Kiss, BSc PhD ANU (until 29 June 2004)

J.F. Marshall, BSc UNSW, MSc PhD ANU

S.N. McLaren, BSc, PhD Adelaide

S. Micklethwaite, BSc PhD Leeds

C. Pelejero, BSc MSc PhD Barcelona

A.K. Pulford, BSc ANU, PhD Wellington (until 1 August 2004)

N. Rawlinson, BSc PhD Monash

S.W. Richards, BSc Newcastle (from 9 August 2004)

W.P. Schellart, BSc Amsterdam, PhD Monash (from 1 March 2004)

E. Tenthorey, BSc McGill MSc Florida PhD Columbia

RESEARCH OFFICERS

D.R. Christie , MA Toronto , PhD ANU

P. Holden, BSc Lancaster, PhD St. Andrews

S.E. Kesson, BSc Sydney, PhD ANU

H.W.S. McQueen, BSc Qld, MSc York, PhD ANU

N.G. Ware, MSc Durham

RESEARCH ASSISTANTS

A. Arcidiaco, BAppSc, GradDip SAInst

B.J. Armstrong, BSc UNISA

E. Calvo, BSc UAB. PhD Barcelona

J.M. Desmarchelier, BSc, PhD Tasmania

M. De Kool, PhD Amsterdam

R. Decrevel BSurv SA

T. Ewing, BSc, MSc Canterbury, NZ

P. Fullsack, MAppSc Paris (until 13 November 2004)

R.W.L Martin, BSc ANU

P. Rickwood, BSc UNSW, Dip Canberra

C. Tarlowski, MSc Moscow, PhD Warsaw (until 24 April 2004)

L. Weston, BSc Macquarie

POST-GRADUATE STUDENTS

PhD Candidates

N. Abram, BSc (Hons) Sydney

A. Aikman, BSc (Hons) Edinburgh

B. Ayling, BSc Wellington

M. Beltrando, MSc Turin

R. Berdin, BSc MSc Philippines

R. Brodie, BSc QLD

S.N. Burgess, BSc (Hons) Adelaide MSc (Hons) Auckland

J. Celerier, BSc (Hons) Melbourne

R. Da Fonseca, BSc Lisbon

K. Dowell, BSc (Hons) ANU

S. Fishwick, BSc Edinburgh

T. Fujioka, BSc MSc Osaka

R. Fraser, Btech BSc Flinders

F. Herman, Civ Eng, Belgium

B. Jenkins, BSc UTS

F. Jenner, BSc (Hons) Oxf Brookes

A. Kallio, MSc Helsinki

K. Lilly, BSc (Hons) ANU

A. Lyman, BSc MSc , Arizona State

D. Maidment, BSc UNSW

I. McCulloch, BSc UNSW, GradDip ANU

M. Miller, BA Whitter, MSc Columbia NY , MEng Cornell NY

J. Mullarney, BA Cambridge, MSc Bristol

T. Prastowo, BSc ITS, MSc ITB

K. Procko, BSc Adelaide, BSc (Maths & Comp Sci) Adelaide , BSc (Hons) ANU

D. Qu, Petroleum Inst Jianghan, MSc Academy of Sciences China

E. Saygin, BSc Istanbul Technical

M. Smith, BSc UNSW

S. Sommacal, Laurea in Science Geologiche (BSc) Univ Degli Studi Di
Padova

A. Stoltze, BSc Curtin

V. Toy, BSc MSc (Hons) Auckland

J. Trotter, BSc MSc Macquarie

D. Wood, BSc Monash

T. Wyndham, BSc ANU

K. Yoshizawa, MSc Hiroshima

Y. Zhou, BSc MSc Chengdu Inst Tech

GENERAL STAFF

Executive Officer

K. Jackson

Finance Manager

M. McDonald, BAppSc CCHS, GradDip Monash

Human Resources Manager

M. Murphy

Technical Officers

C. Allen , AB Princeton MSc Oregon , PhD VirginiaTech

J.T.A. Arnold, BSc Sydney, GradDip CCAE

A.R. Beasley, AssocDip CIT

V. Baek-Hansen

P. J. Biggs (until 30 June 2004)

Z. Bruce, BSc PhD Canterbury

J. Cali, BAppSc QIT

D.L. Corrigan

J.A. Cowley, BSc ANU

J. Duan, BE DUT, MSc Murdoch

J.D. Fitz Gerald, BSc James Cook, PhD Monash

A.W. Forster

J.J. Foster, BSc Sydney, MSc PhD ANU

N. Hill, BA ANU

B. Jenkins, BSc UTS, PhD ANU

D. Kelleher, AssocDip Cartog CIT

L.P.J. Kinsley, BSc GradDipSc ANU

H. Kokkonen, BAppSc CCAE

C. Krayshek

A. Latimore

R.E. Maier (until 1 September 2004)

C.P. McFarlane (from 22 November 2004)

C.J. Morgan

G.E. Mortimer, BSc PhD Adelaide

J. Mya, BSc Mandalay

C. Norris, BSc ANU

S. Paxton

A.J. Percival

S. Savage, (from 6 September 2004)

N. Schram, Dip EIE SAIT

D. Scott

H. Scott-Gagan, BSc Sydney

J.M.G. Shelley, MSc Canterbury

S.P. Sirotjuk, AssocDip TAFE

L.J. Taylor, BA ANU

D.B. Thomson

G. Watson

C. Were

A.R.W. Welsh, BAppSc CCAE

A. Wilson

G.F. Woodward

I.O. Yatsevich, BEng Tashkent Polytec Inst, PhD Russian Academy of Sciences

X. Zhang, PhD LaTrobe

Trainee Technical Officer

B. Ferguson, BDesign(Phot) CIT

C.A. Saint

D. Clark

D. Cummins

D. Cassar

Apprentice

B. Taylor

Information Technology

D. Bolt, BSc Sydney

P. Lanc

S. Phillips (until 8 April 2004)

S. Robertson, DipAppPhys TAFE, MSc BSc ANU

School Librarian

C. Harney, Dip CIT

Administration

J. Badstuebner, BA James Cook (until 26 February 2004)

S. Blewett, BSc Swansea, PGCE Keele (until 10 March 2004)

C.J. Cullen

P.A. Gillard (until 24 July 2004)

V.M. Gleeson

W.A. Hampton (until 23 December 2004)

D.H. Kelly (until 20 November 2004)

J. Lo Presti (until 24 July 2004)

R. MacPherson

R. A. Petch

K. Provins

J. A. Talbot

E. Ward

Research School of Earth Sciences Advisory Committee

Emeritus Prof J.F. Lovering (Chair)

Prof T. M. Harrison, Director, RSES

Prof L. Cram, Deputy Vice Chancellor (Research), ANU

Prof B.L.N. Kennett, RSES

Prof H.StC. O'Neill, RSES

Prof B. Schmidt, RSAA

Prof S. O'Reilly, Director, Dept. of Earth and Planetary Science, Macquarie University

Dr C. Pigram, Chief of Division, Minerals and Geohazards Division, Geoscience Australia

Prof N. Phillips, Chief, CSIRO Exploration and Mining

Mr G. Hall, Chief Geologist, Placer Dome Asia Pacific

Dr R. Smith, Chief Geologist, Anglogold Exploration Australasia

Dr J. Hronsky, Senior Geoscientist, Exploration Division, WMC Resources Ltd

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VISITING FELLOWS ON FACULTY

Prof F. Albarede, (Ecole Normale Superieure de Lyon)

Dr C. Alibert

Dr C. Barton (Geoscience Australia)

Dr L. P. Black (Geoscience Australia)

Dr J. Blichert-Toft (Ecole Normale Superieure de Lyon)

Dr D. J. Brown (Geoscience Australia)

Prof K. Cashman (University of Oregon)

Prof W. Compston

Dr T. Correge (Institut de Recherche pour le Development New Caledonia)

Prof K. Creager (University of Washington)

Mr A. Cross (Geoscience Australia)

Dr P. R. Cummins (Geoscience Australia)

Ms G. Esterman (Technical University of Vienna)

Mr C. Foudoulis (Geoscience Australia)

Dr G.L. Fraser (Geoscience Australia)

Dr A. Glickson

Prof D. Green

Dr J. Hermann

Dr Y. Jia (University of Saskatchewan , Canada)

Prof C. Kincaid (University of Rhode Island)

Dr F.E.M. Lilley

Dr C. Magee

Dr M. Maldoni (UNSW at ADFA)

Dr N. Mancktelow

Dr C. McCammon (Universitat Bayreuth)

Prof I. McDougall

Dr C. Montross (Ringwood Superabrasives, ACT)

Ms N. Neumann (Geoscience Australia)

Dr R. Page (Geoscience Australia)

Prof M. S. Patterson

Prof G. Pennacchioni (University of Padova)

Dr B. Rohrlach

Dr D. Rubatto

Prof R. Rutland

Dr T. Sharp (Arizona State University)

Dr N. Spooner

Mr R. Stanaway

Dr C. Tarlowski (CTBTO)

Dr O. Titov (Saint-Petersburg State University)

Prof J. S. Turner

Prof P. Zeitler (Lehigh University)

SCHOOL VISITORS ON FACULTY

Earth Chemistry

Dr M. Basei, University of Sao Paulo, visited Dr A.P. Nutman from 20 February to 10 April to work on the Permian timescale in the Parana basin.

Dr J. Claoue-Long, Geoscience Australia , visited Earth Chemistry to carry out ongoing research using SHRIMP instruments.

Dr S. Clement, Ion Optical Consulting, visited Earth Chemistry from 13 February to 15 March and 6 August to 6 September for consultative development of the proposed SHRIMP SI instrument.

Prof A. Cooper, University of Otago , visited Earth Chemistry from 18 – 26 October to work with Dr I.H. Campbell and Dr C.M. Allen on detrital zircon dating.

Mr O. Holm, Geoscience Australia , visited Earth Chemistry from 5 July to carry out ongoing research using SHRIMP instruments.

Dr L. Hua-Ying, Guanghou Institute of Geochemistry, Chinese Academy of Sciences, visited Dr I.H. Campbell from 1 July to 31 October to complete two papers for publication.

Dr M-A. Kaczmarek, Institut de Geologie, Neuchatel , Switzerland , visited Dr D. Rubatto from 23 November to 10 December to further joint research on Alpine Gabbros.

Mr R. Kemp, University of Melbourne , visited Dr T.R. Ireland from 27 June to 8 July to work on granites of the Bullenbalong Suite.

Dr M. Kendrick, University of Melbourne , visited Dr M. Honda from 25 to 28 May to work on noble gas analyses of pyrite and sphalerite with a view to future collaboration.

Dr G. Kopi, Department of Mining, Papua New Guinea , visited Dr I.S. Williams from 13 to 22 February to work on deposition age, provenance and metamorphism of the Owen Stanley Metamorphics in East Papua New Guinea .

Dr T. Kuritani, Okayama University , Japan , visited Earth Chemistry from 19 to 24 July to work with Dr I.H. Campbell, Dr R.C. Kerr and Prof J.S. Turner on quantitative understandings of the thermal and chemical evolutionary processes of crustal magma chambers.

Mr M. Lombardi, Sienna University , Italy , visited Earth Chemistry from 2 September to 19 October to utilize the SHRIMP for geochronological study of the Ross Orogen in North and South Victoria Land , Antarctica .

Dr J.M. Palin, University of Otago , visited Earth Chemistry from 18 to 26 to work with Dr I.H. Campbell and Dr C.M. Allen on aspects of the zircon chronochemistry of various sedimentary and igneous rock samples.

Mr S. Phillips, University of Melbourne , visited Dr M. Honda from 25 to 28 May to work on noble gas analyses of pyrite and sphalerite with a view to future collaboration.

Ms J. Savage, Canterbury University , visited Dr T.R. Ireland from 2 November to 6 December to carry out SHRIMP analyses.

Dr P. Telouk, Ecole Normale Superieure de Lyon , France , visited Prof T.M. Harrison from 16 February to 7 March to carry out analyses using the SHRIMP and Neptune MC-ICP-MS.

Mr G. Vignaroli, Universita degli Studi di Roma Tre, Italy , visited Dr D. Rubatto from 21 October to 20 November to work on the geochronology of different Alpine terranes in Italy , France and Spain .

Dr U. Wiechert, Institute for Isotope Geology and Mineral Resources, Switzerland , visited Dr T.R. Ireland from 6 to 10 October to confer with academics at RSES and to present a seminar.

Dr K. Worden, Geoscience Australia , visited Dr T.R. Ireland on 5 July to carry out analyses on the SHRIMP instruments.

Earth Environment

Mr M. Aubert, Quebec University , visited Prof M.T. McCulloch to work on U-Th dating of aboriginal rock artworks from Australia and Indonesia .

Mr B. Burke, University of Maryland, USA, visited Prof J.M.A. Chappell from 1 to 31 December to work on the origins of the regolith of southern eastern Australia.

Dr R. Drysdale, University of Newcastle , visited Dr M. Gagan from 7 to 16 to carry out micro sampling of late quaternary speleothems.

Ms K. Durand, University of Newcastle , visited Dr M. Gagan from 21 June to 2 July and 13 to 19 December to work on speleothems from Cutta Cutta Cave and from 23 to 29 August to gain access to the micro-sampling device and the stable isotope mass spectrometer.

Mr Y. Feng, University of Queensland , visited Dr M. Gagan from 6 to 26 September to measure speleothems from northern Australia and China in order to investigate late Quaternary climatic history of tropical Australia .

Dr I Goodwin, University of Newcastle , visited Dr M. Gagan from 1 April to 30 September to measure stable isotope ratios in fossil coral microtolls from the southern tropical Pacific region.

Dr E. Hendy, Columbia University , USA , visited Dr M. Gagan from 15 January to 1 March to work on stable isotopes.

Ms M. Inoue, Tohoku University , Japan , visited Dr M. Gagan from 13 October 2003 to 15 March and from 10 May to 12 June to measure stable isotope ratios in corals from Indonesia .

Ms J. McDonald, University of Newcastle , visited Dr M. Gagan from 1 to 22 March and from 18 to 19 December to use the stable isotope mass spectrometer.

Dr H. McGregor, Universität Bremen , visited Dr M. Gagan from 29 November to 17 December to write publications based on PhD research done at RSES.

Mr B. Murphy, Charles Darwin University , visited Dr M. Gagan from 21 April to 28 May to measure stable isotope ratios in marsupial bone collagen and teeth.

Ms K. Westaway, University of Wollongong , visited Dr M. Gagan from 18 to 21 November to work in the stable isotope laboratory.

Ms T. Williamson, James Cook University , visited Dr M. Gagan from 27 January to 13 February to measure stable isotope ratios in Australian Cretaceous belemnites.

Earth Materials

Ms N. Malaspina, Universita degli Studi di Genova , Italy , visited Dr J. Hermann from 28 January to 30 April to work on ultra high pressure metamorphism of ultramafic rocks from the Dabie Shan and Sulu region, China .

Prof S. Morris, University of California Berkeley , visited Prof I.N.S. Jackson from 26 May to 19 July to work on modelling of grain boundary sliding as a mechanism for high temperature viscoelestic relaxation.

Ms S. Mussett visited Earth Materials from 1 September 2003 to 31 October to gain access to the facilities in the Rock Crushing Laboratory and the saws and coring drill in the Lapidary workshopin order to create a new body of work based on using alternative/non traditional methods and techniques for using semi precious gems and minerals in wearable objects.

Prof I. Parsons, University of Edinburgh , UK , visited Dr J. Fitz Gerald from 28 June to 3 August to carry out collaborative work on microstrctures of cryptoperthites.

Ms K. Schwendtner, South Australian Museum, visited Prof H.StC. O'Neill from 25 October to 13 November to synthesise Ni doped olivines and sulfides and then serpentinise these hydrothermally.

Earth Physics

Ms K. Broxholme, University of Adelaide , visited Dr F. Lilley from 1 to 2 July for discussion of PhD results and research.

Dr K. Gallagher, Imperial College , London , visited Dr M. Sambridge from 6 December to 14 January 2005 to apply procedures for modeling spatial processes to seismic and other inversion.

Ms A. Harris, University of Rhode Island , visited Prof R. Griffiths from 5 October to 20 December to carry out experiemental work on mantle subduction processes.

Ms S. Iwano, Kyoto University , visited Dr H. McQueen from 24 to 29 March to see the cryogeniic gravimeter laboratory.

Mr T. Kobialka, Computer Science Department, ANU, visited Dr M. Sambridge from 9 August to 3 June 2005 to work on a software construction project.

Ms S. Ling Lim, ANU, visited Dr M. Sambridge from 30 July to 31 December to provide software support for the Terrawulf Cluster.

Dr J. Lister, Institute of theoretical geophysics, Cambridge , visited Prof R. Griffiths from 14 December to 7 January 2005 to carry out research on buckling instability of sheets and streams.

Dr T. Nicholson, Victoria University of Wellington, visited Dr M. Sambridge from 6 to 17 December to apply empirical travel line software to local earthquakes in the Geoscience Australia database.

Dr A. Pulford, ANU, visited Dr J. Braun from 1 to 25 August to work on the Rheological Model for the Australian continent derived from geological and geophysical constraints.

Dr R. Stephenson, Free University of Amsterdam, visited Dr J. Braun from 14 to 20 July to work on the tectonic evolution of eastern European basins.

Dr P. van der Beek, Universite Joseph Fourier, France, visited Dr J. Braun from 2 to 26 June to work on the European Alps project.

Prof J. Weaver, University of Victoria , British Columbia , visited Dr F. Lilley from 26 August to 2 September.

Dr M. Wells, Yale University , visited Prof R. Griffiths from 1 to 31 December to present research on bottom slope currents in the ocean.

Dr Y. Yokoyama, Tokyo University , visited Prof K. Lambeck from 26 February to 5 April to make U/Th measurements on corals in collaboration with Dr T. Esat and Prof J.M.A. Chappell.

Dr K. Yoshizawa, University of Hokkaido , visited Prof B.L.N. Kennett from 1 to 12 March to conduct analysis of seismic surface waves in horizontally varying media to high frequencies.

PRISE

Dr John Aleinikoff, U.S. Geological Survey, visited Mr C.M. Fanning from 14 April to 16 May to gain access to SHRIMP II so as to continue collaborative research projects.

Mr R. Bailie, Rand Afrikaans University , South Africa , visited Dr R. A. Armstrong from 1 July to 15 September to conduct ID-TIMS and SHRIMP analyses on selected samples.

Dr D.-L. Cho, Korea Institute of Geoscience, visited Dr R. A. Armstrong from 1 to 19 October to obtain SHRIMP U-Pb data on granites and metasediments of basement and supracrustal rocks.

Dr A. Cocherie, Bureau de Recherche Geologique et Miniere , France , visited Mr C.M. Fanning from 23 August to 3 September to gain access to SHRIMP II and to continue collaborative research projects.

Prof R. Creaser, University of Alberta , visited Dr M.D. Norman to work on the geochronology and geochemistry of black shales from the ~ 1.4 Ga Roper Group NT and to present a seminar.

Prof M. Escayola, Instituto de Geosciencias, Universidade de Brasilia, visited Dr R.A. Armstrong from 15 March to 5 April for SHRIMP access to work on several scheduled projects.

Dr C. Frost, University of Wyoming , visited Mr C.M. Fanning from 13 to 22 December to carry out Archean U-Pb zircon analyses.

Prof M. Garcia, University of Hawaii , visited Dr M.D. Norman from 5 April to 28 May to work on the geochemistry and petrogenesis of Hawaiian volcanism.

Ms A. Heimann, Iowa State University , visited Mr C.M. Fanning from 18 to 23 June to analyse monazite and zircon in situ within polished thin sections.

Dr R. Hough, CSIRO, visited Dr M.D. Norman from 6 to 10 September to use LA-ICPMS to characterise the siting of gold and significant pathfinder elements in regolith samples.

Mr C. Kautz, University of Otago , visited Dr M.D. Norman from 25 to 31 August to use geochemistry to trace sources of sediments to the abyssal Bounty Fan off the eastern margin of the South Island , New Zealand .

Dr N. Kelly, University of Edinburgh , visited Mr C.M. Fanning from 10 to 17 September to gain access to the SHRIMPs.

Dr P. Macey, Council for Geoscience , South Africa , visited Dr R.A. Armstrong from 22 November to 8 December to work on a joint project on the geochronology of central Mozambique .

Dr C. Martin, University of Otago , visited Dr M.D. Norman from 25 to 31 August to use geochemistry to trace sources of sediments to the abyssal Bounty Fan off the eastern margin of the South Island , New Zealand .

Mr C. McClung, Rand Afrikaans University , South Africa , visited Dr R.A. Armstrong from 1 July to 15 September to conduct ID-TIMS and SHRIMP analyses.

Dr A. Morton, HM Research Associates, UK , visited Mr C.M. Fanning from 30 March to 7 April for analysis of SHRIMP data collection and preparation of papers for publication.

Dr P. Myrow, Colorado College , visited Mr C.M. Fanning from 16 to 23 November to gain SHRIMP access to carry out a number of detrital zircon analyses.

Dr R. Pankhurst, British Geological Survey, visited Mr C.M. Fanning from 18 September to 19 October for access to the SHRIMPs and to carry out further work on the Sierras Pampeanas Project.

Prof. M. Pimentel, Universidade de Brasilia, visited Dr R.A. Armstrong from 15 March to 5 April to gain SHRIMP access and to work on several scheduled projects.

Mr A. van der Westhuizen, University of Stellenbosch , visited Dr R.A. Armstrong from 1 to 31 May to use the SHRIMP for analysis of a suite of detrital samples from the Orange River to try to document the sources of the sediments associated with the west coast alluvial diamond deposits.

THESES SUBMITTED

PhD

Ms N. Abram Multi-Proxy Coral Reconstruction of Holocene Climate and Reef Growth in the Eastern Indian Ocean (PhD). Supervisor: Dr M. Gagan. Advisors: Prof M.T. McCulloch, Prof J.M.A. Chappell, Dr. J. Lindesay, Dr. G. Meyers.

Mr B. Jenkins Application of Ion Optical Theory to the design of Electrostatic Quadrupole Lenses (PhD) Supervisor: Dr T.R. Ireland. Advisors: Prof W. Compston, Dr S. Clement.

Ms J. Mullarney Thermal and Thermohaline convection models for the Meridional Overturning circulation of the oceans (Ph.D) Supervisor: Prof R.W. Griffiths. Advisors: Dr R.C. Kerr, Dr G. Hughes, Dr J.R. Taylor.

Mr S. Sommocal Computational Petrology: Subsolidus Equilibria in the Upper Mantle (PhD). Supervisor: Prof H.StC. O"Neill Advisors: Dr M.S. Sambridge, Prof D.H. Green, Dr J. Hermann

Ms V. Toy Revised Plate Motion Studies and Applications (PhD). Supervisor: Prof G. Lister. Advisors: Prof T.M. Harrison, Prof S.F. Cox.

Honours

Ms K. Bishop

Mr J. Clulow

Ms C. Gregory

Mr A. Reed

Mr N. Tailby

HONOURS AND AWARDS

Academic Staff

Dr G.F. DAVIES was awarded the Augustus Love Medal of the European Geosciences Union for " original contributions in the field of mantle dynamics, in particular for elucidating the role of plates and plumes and for fundamental contributions in understanding the thermal and chemical evolution of the Earth."

Prof K. Lambeck was elected Associate Member of the Royal Astronomical Society, and received a Japan Society for the Promotion of Science Award for Eminent Scientists.

Dr F.E.M LILLEY was awarded Honorary Membership of the Australian Society of Exploration Geophysicists.

Prof M. McCulloch was elected a Member of the Australian Academy of Science.

Students

A.L. Hales Honours Year Scholarship: Ms P.K. McLean

Mervyn and Katalin Paterson Fellowship: Ms N. Keller

Robert Hill Memorial Prize: Mr F. Herman

A.E. Ringwood Scholarship: Ms N. Keller

John Conrad Jaeger Scholarship: Mr S. Barker

Summer Research Scholarships

Summer Research Scholarships were awarded to:

Mr C. Mexted-Freeman (Victoria University , Wellington , New Zealand) under the supervision of Dr N. Rawlinson and Dr M. Heintz

Ms J. Bowen-Thomas (Bachelor of Science/Law, ANU), under the supervision of Dr M. Norman and Dr V. Bennett

Mr D. Hewitt (Bachelor of Science, Waikato University , New Zealand) under the supervision of Dr E. Rhodes

Mr J. Geng (University of New England) under the supervision of Dr G. Davies

Student Internships

Ms M. Ayling of Victoria University of Wellington commenced Student Internship under the supervision of Dr S. Eggins.

Ms C. Bolton of ANU commenced Student Internship under the supervision of Dr E. Rhodes.

Ms L. Brown of The University of Melbourne commenced Student Internship under the supervision of Prof R. Grün.

Ms J. Clarke of Monash University completed Student Internship under the supervision of Dr T.R. Ireland.

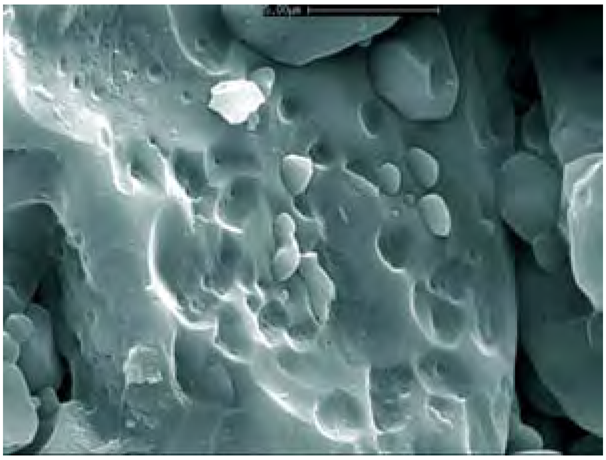
Mr J. Lapwood of University of Canterbury commenced Student Internship under the supervision of Prof B.L.N. Kennett.

Mr N. Tailby of the ANU commenced Student Internship under the supervision of Dr J.A. Mavrogenes.

Mr D. Viete of Monash University , continued Student Internship under the supervision of Prof G. Lister.

Research Activities

Earth Chemistry



Introduction

2004 yeilded the following important results

SHRIMP SI funded

In the 2004 ARC LIEF round, we were successful in obtaining support for the SHRIMP SI, an ion microprobe that will be dedicated to stable isotope analysis of geological materials. SHRIMP SI was supported by contributions from Universities of Curtin University, University of Melbourne , Queensland University, University of Wollongong , Geoscience Australia , CSIRO Exploration and Mining, and Australian Scientific Instruments.

SHRIMP II Multiple Collector developments

We continue to make good progress of the multiple collector and a stable isotope analysis capability on SHRIMP II. The multiple collector is now used routinely in the search for 4 billion year-old zircons and developments in stable isotope analysis will aid us in the design of SHRIMP SI.

Solar Wind Oxygen-Isotope Composition

One of the outstanding parameters in cosmochemistry is an oxygen isotope measurement of the Sun. Oxygen shows a wide variation in enrichments of 16O with proposed solar compositions at the extreme ends of the array (close to terrestrial or enriched in 16O by 6%). We have measured metal grains from the Moon that have been implanted with solar wind. The composition measured in these grains is different from anything previously measured and is depleted in 16O relative to the terrestrial composition. It appears likely that the oxygen isotope variations in the solar system are inherited from the molecular cloud and star-forming region.

PSI White Conference

In February, an international group of scientists came to Canberra to celebrate the birth of the Planetary Science Institute (PSI), a collaboration between RSES and RSAA. Held under the auspices of the Australian Academy of Sciences White Conferences , the theme of the conference was “Planetary timescales: from stardust to continents. The meeting was opened by the Science Minister Mr Peter McGauran and included public lectures.

Key directions for 2005

Development of SHRIMP SI from a concept to detailed design drawings.
Integrating research between RSES and RSAA PSI members.

Research Activities

Toothpaste & Tibet: deformation, anatexis and doming in the eastern Tethyan Himalaya

A.B. Aikman

Deformation, exhumation and isostasy are arguably three of the most important processes governing the geological evolution of continents. They control not only the distribution and style of topography, outcrop and continental sedimentation, but are also thought to influence the behavior of the atmospheric and oceanic domains as well (Crowley and Burke, 1998). Studying these processes by definition considers time scales that are difficult to measure directly. It is therefore judicious to examine cases where they are actively occurring, and at rates which maximize the signal to noise ratio. To this end, active orogenic zones provide the acme opportunity.

The Himalayan orogen is part of the Alpine-Himalayan chain, the world's largest active orogenic belt. Nearly a century of research (e.g. Argand, 1924) has yielded a plethora of evolutionary models, however many important aspects this disquisition still defy consensus. The eastern THS have received relatively little attention with respect to frontal parts of the orogen. Our studies in this area are already providing valuable new insights into outstanding problems.

The Tethyan Himalayan Series (THS) is a thick sequence of generally low grade metasediments outcropping along the northern margin of the Himalayan arc. East of ca. 90_E, the THS is bounded to the south by the Greater Himalayan Crystallines (GHC) and to the north by the Indus-Tsangbo Suture (ITS). The sequence comprises the most northerly segment of the Himalayan fold and thrust belt, and is thought to have originated as continental margin deposits on the northern margin of the Indian Shield prior to closure of the Tethys Ocean (e.g. Yin and Harrison , 2000).

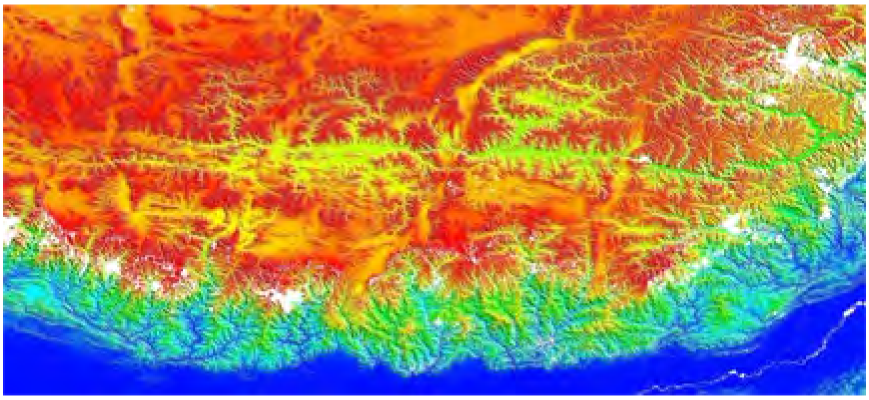


Figure 1: Digital Elevation Model of the Himalaya and southern Tibet , derived from the USGS SRTM data set.

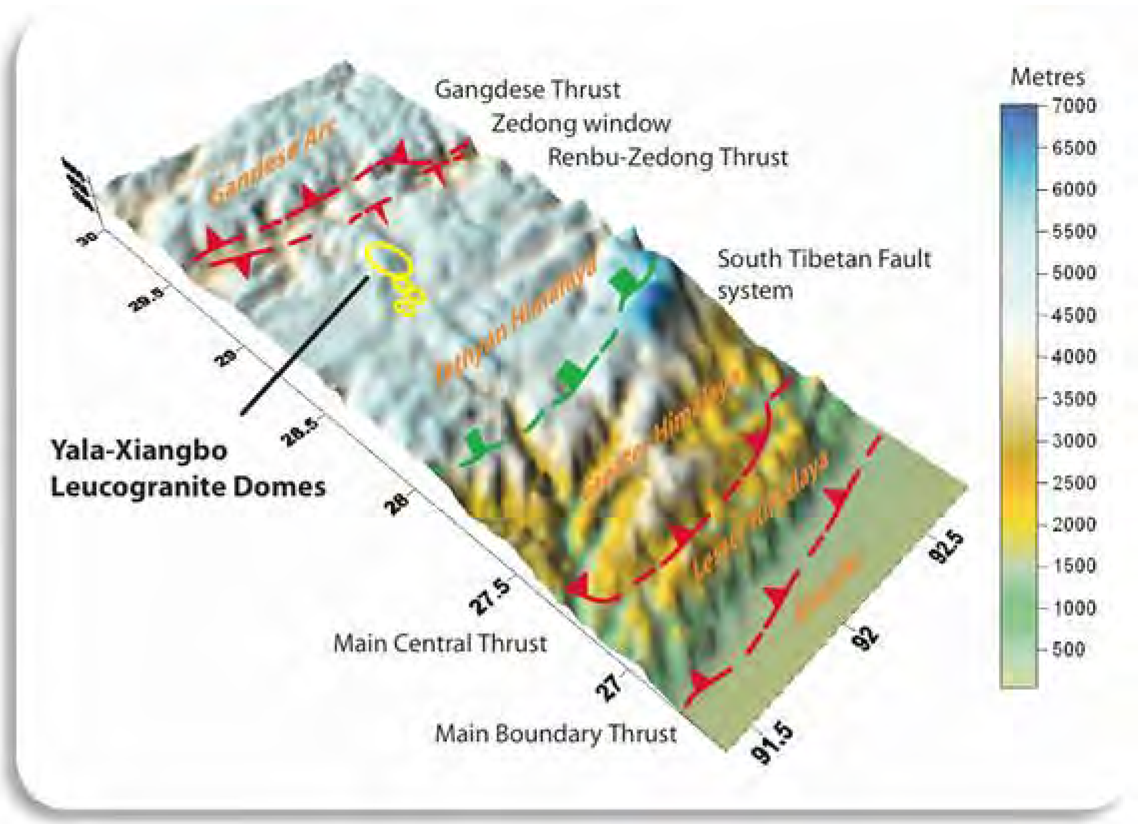


Figure 2: Digital Elevation Model the Hiamalaya at ca. 92°E, derived from the USGS ETOPO2 data set.

Tectono-structural and metamorphic histories recorded in the Tethyan metasediments and North Himalayan Domes provide a window into the evolution of the North Himalayan crust and to the early history of Indo-Asian collision. Furthermore, the THS may also be regarded as part of the roof zone of a proposed Himalayan Orogenic Channel (Lee et al., 2000; Aikman et al., 2004; Lee et al., 2004).

We document the first evidence of Eocene leucogranite plutonism (ca. 45 Ma) along the Himalayan arc. We interpret this relationship as placing a lower bound of ca. 45 Ma on the timing of south vergent deformation in the THS. Geochemical data from the Yala-Xiangbo Igneous Complex suggest that conditions under which Miocene partial melting occurred in the central eastern-Tethys were distinct from those documented for other High Himalayan Leucogranites (HHL) or North Himalayan Granites (NHG). Isotopic and geochronological data suggest that the eastern Tethyan middle crust includes material distinct from that seen elsewhere in the Himalaya . We interpret our results as consistent with underthrusting of parts of the Eurasian forearc up to 120 km beneath the eastern Tethys, by movement along the Great Counter Thrust (GCT).

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Direct geochemical evidence for a very early (>3.85 billion year old) oxidised terrestrial mantle *Vickie Bennett, Allen Nutman and Marc Norman*

Direct geochemical evidence for a very early (>3.85 billion year old) oxidised terrestrial mantle

Vickie Bennett, Allen Nutman and Marc Norman

The complex and likely significant role of the mantle in the chemical evolution of the atmosphere, hydrosphere and lithosphere, is being increasingly recognised, with for example, some studies linking the development of an oxygen rich atmosphere directly to changes in mantle redox chemistry (e.g. 1, 2; figure 1). To define conditions in the early (>3.8 Ga) mantle, we measured major and trace element concentrations, including the redox sensitive element vanadium (3,4), from rare, well-preserved, temporally and geographically distinct suites of spinel periodites from early Archean terranes of southwest Greenland (Figure 2). The sample ages are determined by U-Pb zircon dating of cross cutting and/or intrusive tonalites and by their primitive 187 Os/ 188 Os isotopic compositions (5), and include > 3.81 Ga and recently identified > 3.85 Ga peridotites. The chemical affinities of these samples such as their Si-Al-Mg proportions, olivine/orthopyroxene ratios and mineral compositions, are more similar to modern abyssal peridotites than to cratonic mid-Archean lithospheric mantle represented by xenoliths from southern Africa and Siberia ; the peridotites are interpreted as early Archean lithospheric mantle that was trapped within ancient sialic crust during its formation.

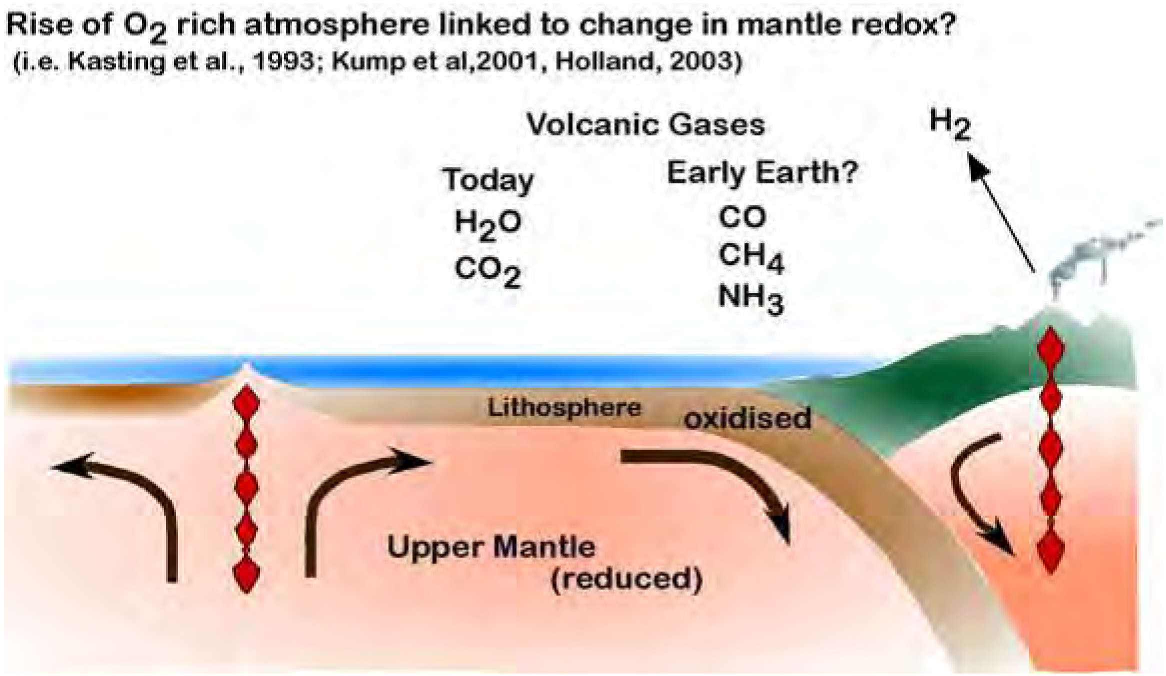

Figure 1. The mantle is a significant component of the global gas cycle. Were changes in the composition of gases released from the mantle related to the rise of an oxygen rich atmosphere?

Trace element compositions determined by solution ICP-MS are compared with suites of post-Archean peridotites of known tectonic setting, measured by identical methods, hus eliminating problems of interlaboratory bias and enabling a relative fO 2 resolution between sample suites of better than 0.5 log units. The 3.81 Ga and 3.85 Ga peridotites are indistinguishable from modern peridotites on V-MgO (figure 3) and V-Al 2 O 3 arrays, indicating melt extraction in the early Archean mantle at oxygen fugacities between FMQ-3 and FMQ, that is, identical to the present day. All early Archean peridotites fall within 0.5 log units of average post Archean mantle spinel peridotites.

Figure 2. The oldest (> 3,850 Ma) samples of the mantle are preserved in southwest Greenland and provide an important resource for testing models of early Earth evolution. Note student for scale.

Thus, the V systematics of these peridotites provide no evidence for evolving redox conditions in the mantle from > 3.85 Ga to the present day and suggest the composition of volcanic gases was similar throughout Earth history. There is no evidence for a secular change in mantle redox state from 3.85 Ga to the present day; establishment of favourable environments for the origin of life and the rise of an oxygen rich atmosphere cannot be directly linked to changes in mantle chemistry. The data also require the change from a highly reducing upper mantle, in equilibrium with metallic Fe during core formation, to an oxidised mantle must have occurred within 700 myr of core formation, that is between 4.56 Ga and 3.85 Ga.

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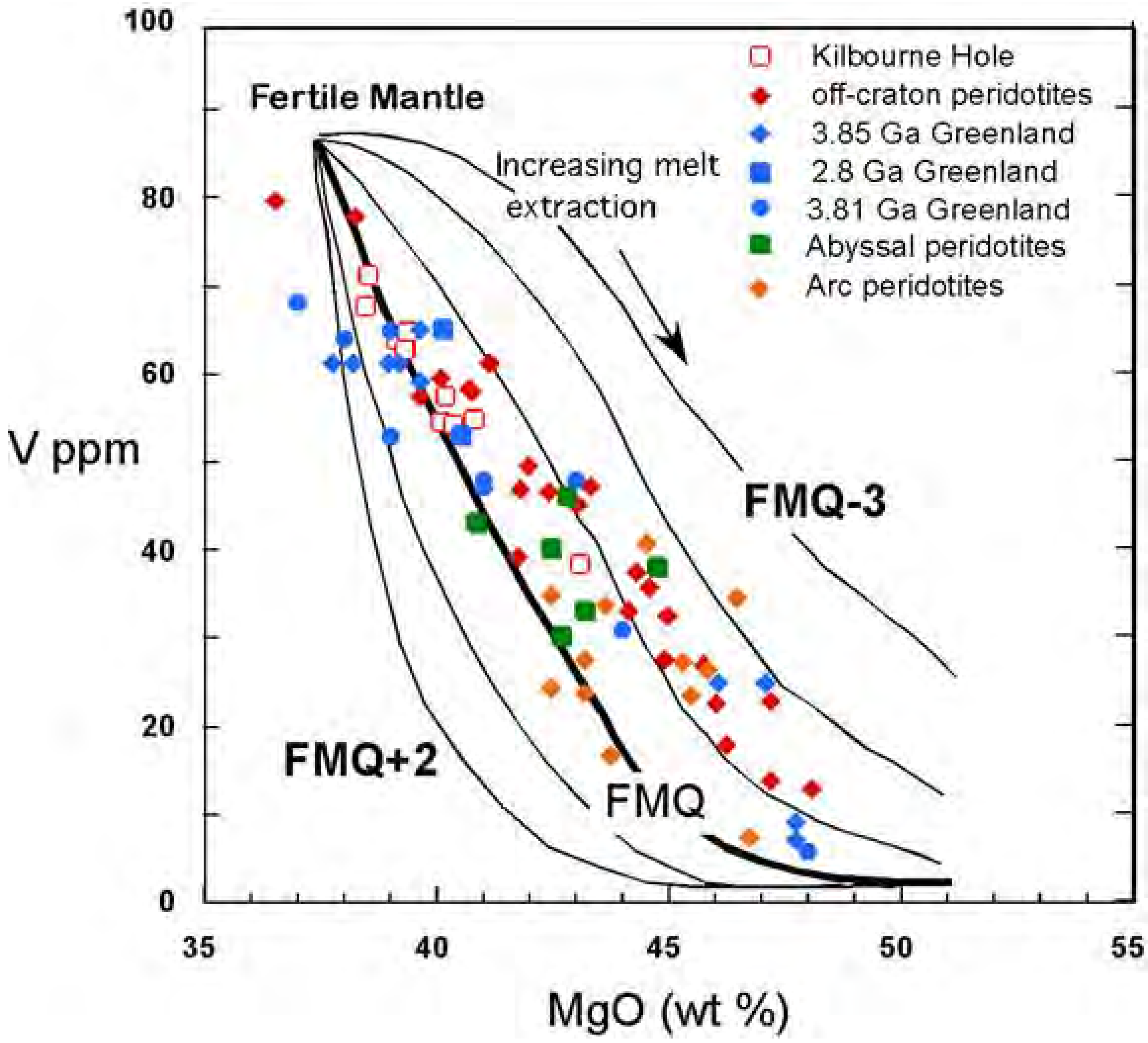

Figure 3. The compositions of the redox sensitive element V are the same in ancient and modern mantle samples demonstrating that there has not been a signficant change in mantle redox chemistry over the last 3,850 million years. Model curves are from Lee et al. (2003).

Inside the Lesser Himalaya : thermochronologic, metamorphic and structural constraints from the Kumuan Himalaya , India. *J. Célérier*

Inside the Lesser Himalaya : thermochronologic, metamorphic and structural constraints from the Kumuan Himalaya , India.

J. Célérier

The Himalaya-Tibetan orogenic system is arguably the best natural laboratory in which to understand the response of the lithosphere to continent-continent collision. Despite the key role the Himalaya play in our understanding of plate tectonics, perceived and real problems related to understanding the petrogenesis of rocks of low metamorphic grade, have resulted in fundamental quantitative geological constraints concerning ~80% of the Himalayan chain being only sparsely known. This study aims to focus more closely on the Lesser Himalayan Formations (LH), south of the well documented Greater Himalayan Crystallines (GHC) and Main Central Thrust (MCT), providing much needed quantitative data from this poorly constrained portion of the mountain range. Using a unified thermochronlogic, metamorphic and structural approach, I intend to quantitatively constrain the sequence of thrusting south of the MCT, in the Kumaun region of north-west India . With this new data, it should be possible to 1) test current paradigms of Himalayan genesis, and 2) develop more comprehensive models of Himalayan evolution.

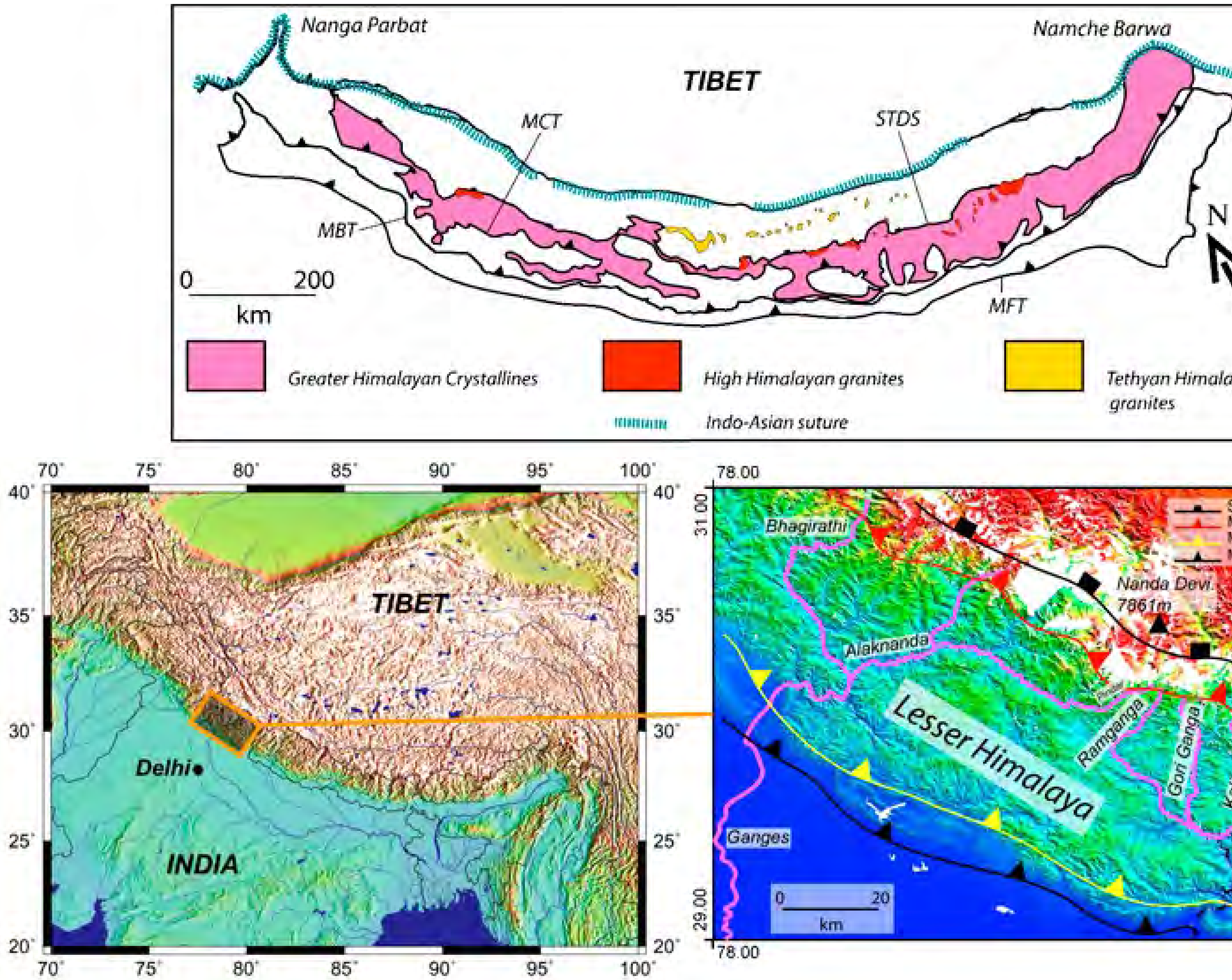

Figure 1. Top: highly simplified geological map of the Himalaya , 'the Earth's best natural laboratory for testing the effects of continent-continent collision'. The coloured units are the tectonometamorphic units for which we currently have basic quantitative constraints on metamorphic grade, timing of deformation, cooling history and exhumation. The digital elevation model on the bottom left shows the position of Kumaun within the Himalayan chain, and the image on the bottom right shows the principal drainages and structures of the region.

Two categories of structural model for the Lesser Himalaya have emerged in recent times. The first advocate large-scale nappe formation to explain the structural patterns in the Lesser Himalaya (e.g. Valdiya 1980), whilst the second, prefer duplex development (Srivastava & Mitra, 1994; Robinson *et al* ., 2003; Bollinger *et al* ., 2004). Field based structural geology, 40Ar/39Ar thermochronlogy and metamorphic petrology are being used to test these models. Sixteen 40Ar/39Ar measurements have been made on white micas separated from Lesser Himalayan quartzites to begin constraining the sequence of thrusting and exhumation within the Lesser Himalaya. Examination of Figure 2 reveals a range of ages from Early Miocene to Pliocene. There is a general trend of younger ages toward the MCT, with the youngest age of 4.3 Ma coming from a quartzite adjacent to the MCT. This general trend of younging towards the MCT is disrupted by several reversals in age. This relationship suggests that the role of out of sequence thrusting in the generally foreland propagating sequence of deformation may be greater than we currently appreciate. The range of ages from Early Miocene to Pliocene is particularly interesting as the chronological framework currently in place for the Himalaya recognises “events” or distinct, Early Miocene and Late Miocene-Pilocene, periods of activity along the MCT (Hubbard & Harrison, 1988; Harrison *et al* ., 1997; Catlos *et al* ., 2001. My initial results show less of an episodic trend of exhumation in the Lesser Himalaya, and more of a continuum.

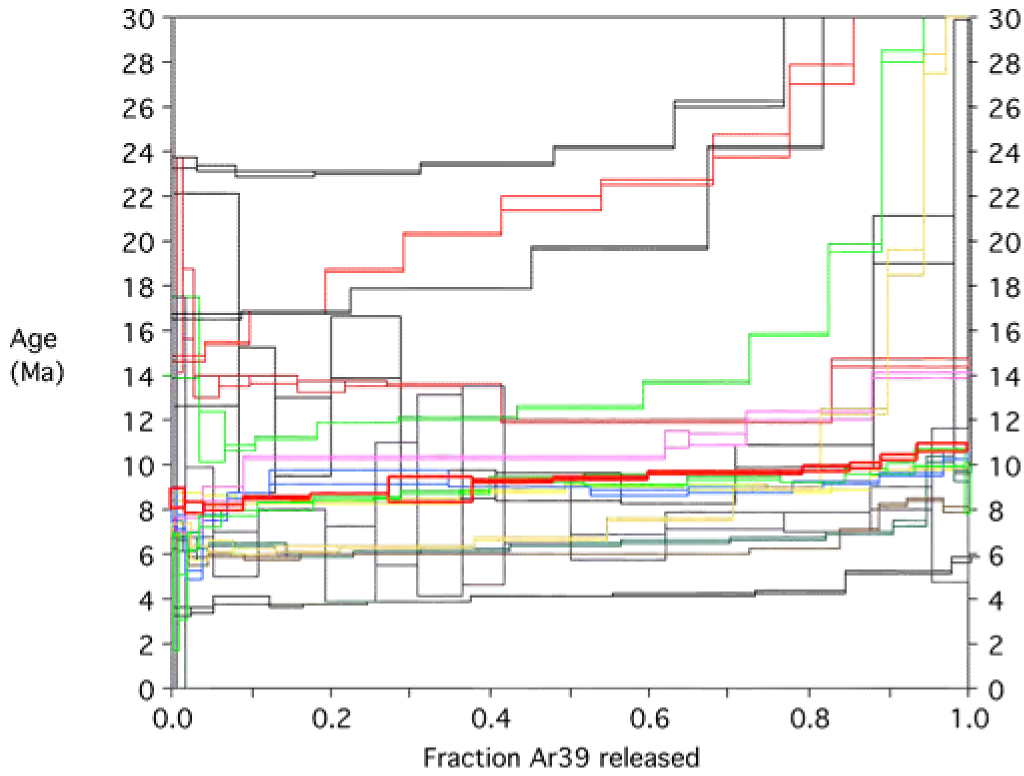

Figure 2. Projection of results from 16 step-heating heating experiments on white micas from the Kumaun Lesser Himalaya .

The conditions of metamorphism in the Lesser Himalaya are being documented using Raman Spectroscopy of Organic Material (Beyssac *et al* ., 2002). Initial results reveal that Lesser Himalayan rocks adjacent to the MCT experienced temperatures in the vicinity of 550°C and that metamorphic temperatures decrease to the south with increasing distance from the MCT. Approximately 25km south of the MCT, peak metamorphic temperatures fall below 330°C, the range of the technique. New samples collected during 2004 are soon to be analysed with the intention of quantitatively describing thermal gradients in the Lesser Himalaya.

My early results are consistent with models of Lesser Himalayan exhumation driven by duplex formation as proposed by Srivastava & Mitra (1994); Robinson *et al* ., (2003) and Bollinger *et al* ., (2004). Ongoing work will continue to elucidate the chronology of deformation and timescales of mountain building in the Himalaya outside the context of the GHC and the MCT.

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Age constraints and tectonic implications from detrital zircon U-Pb geochronology of early Palaeoproterozoic sediments of the Tanami Basin. *Andrew Cross*

Age constraints and tectonic implications from detrital zircon U-Pb geochronology of early Palaeoproterozoic sediments of the Tanami Basin

Andrew Cross

The Tanami Basin in north central Australia is a significant source of lode-Au. To date it has produced 4.1 Moz Au with a known remaining resource of 8.4 Moz (260 t) (Wygralak and Mernagh, 2001). This Au has been extracted from established gold fields at Dead Bullock Soak, The Granites, Tanami Mine Corridor and also prospects at Groundrush, Titania, Minotaur, Crusade, Coyote and Kookaburra. The Tanami regions continued standing as a major Au province has resulted in an effort by the Northern Territory Geological Survey, Geoscience Australia and the Research School of Earth Sciences (ANU) to better understand its geological history and mineral systems in order to aid further exploration in this region.

Palaeoproterozoic sediments of the Tanami basin were largely derived from the ca. 1.89 to 1.84 Ga Barramundi Orogeny. SHRIMP U-Pb dating of detrital zircon from the principal sedimentary units reveals a progression in provenance that is a record of the development of the orogen. The basal Dead Bullock Formation is a thick package of siltstone, carbonaceous siltstone, iron formation and minor sandstone, which is divided into the Ferdies Member (older) and Callie Member (younger). Detrital zircon age patterns from two Ferdies Member samples contain Archaean, basement derived zircon. One sample is dominated by zircon 2.56-2.44 Ga old, and the other contains Archaean components with ages of 3.22, 2.77, and 2.45 Ga. The youngest zircons from the Ferdies Member imply that this unit was deposited after 2.44 Ga and possibly after 2.11 Ga. However, these detrital zircon ages yield poor estimates of the depositional age. Its depositional age is inferred to be 1.88 to 1.91 Ga through correlation with the Saunders Creek Formation in the nearby Halls Creek Province . Evidence of magmatism related to the Barramundi Orogeny appears as rare intercalated tuffs within the Callie Formation, one sample giving an age of 1846 ± 7 Ma.

Overlying the Callie Member are the sediments of the Killi Killi Formation which is a part of a widespread northern Australian turbidite sequence. The detrital zircon age patterns from four samples of Killi Killi Formation are remarkably similar. Each is dominated by a ca. 1865 Ma age mode and has a subordinate late Archaean mode at ca. 2.5 Ga. The 1865 Ma age mode coincides with peak magmatism associated with the Barramundi Orogeny. The youngest zircons in the Killi Killi Formation consistently indicate a maximum depositional age of 1.84 Ga.

It is possible that the Palaeoproterozoic Tanami basin developed in response to the early ca. 1.88 Ga Barramundi Orogeny. Initial uplift and erosion of Archaean basement rocks produced sediments now represented by the Ferdies Member of the Dead Bullock Formation. However, it was at least another 40 m.y. before the plutonic products of that magmatism were exposed eroded and transported to form the Killi Killi Formation. A similar significant age contrast in detrital zircon between basal and overlying sediments shed from an orogen has also been observed by Mclennan et. al. (2001) in the lower Palaeozoic rocks in the New England region of North America . These researchers also reported that the oldest sedimentary sequences do not record contemporaneous orogenic activity, but rather reflected older recycled continental margin rocks. Detrital zircon studies thus suggest that the first sediments shed from an emerging orogen might not record contemporaneous magmatism, but rather represent the eroded products of uplifted basement rocks.

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Dating of Australian arid landforms using cosmogenic 21 Ne surface exposure dating. *T. Fujioka, J. Chappell, M. Honda, I. Yatsevich, K. Fifield and D. Fabel*

Dating of Australian arid landforms using cosmogenic 21 Ne surface exposure dating

T. Fujioka, J. Chappell, M. Honda, I. Yatsevich, K. Fifield and D. Fabel*

* Research School of Physical Sciences and Engineering, ANU

Australian climate has dramatically changed from wet to dry during the late Cainozoic period, producing various types of arid landforms such as dune field, gibber plains (stony deserts) and playas. The knowledge of the formation of these landforms would enhance our understanding of the late Cainozoic climate change in Australia . This study focuses on dating of sand dunes and silcrete/quartz gibbers in central Australia , using cosmogenic nuclides.

Cosmogenic nuclides are produced by interaction of cosmic rays with elements in Earth's surface rocks. The amounts of cosmogenic nuclides in surface rocks reflect time for which the rock has been exposed at the surface, and time-integrated erosion rates by which the rock has been eroded. Radioactive cosmogenic nuclides (e.g., 10 Be, 26 Al) are limited by their half-lives when they are used for samples with long exposure histories (> a few million years). In contrast, 21 Ne, a stable nuclide, does not have this age limitation, and is thus applicable to samples with relatively long exposure histories.

In cosmogenic 21 Ne surface exposure dating, correction of non-cosmogenic neon components including crustal and *in situ* nucleogenic components is critical to accurately determine the amounts of cosmogenic 21 Ne in a sample. The crustal neon is produced by nuclear reactions 24 Mg(n, a) 21 Ne and 18 O(a , n) 21 Ne in the crust, and trapped in fluid inclusions when quartz forms. The *in situ* nucleogenic neon is produced within the crystal lattice by reaction 18 O(a , n) 21 Ne, where a particles are provided from the decay of uranium and thorium.

Eleven silcrete/quartz gibber samples from central Australia were analysed for the full suite of noble gases (He, Ne, Ar, Kr and Xe) by fusion and crushing experiments, for U, Th by ICP-MS, and for K by Flame Photometer, to establish the neon interference correction method. Crustal nucleogenic neon was evaluated from crustal argon and xenon using crustal production ratios, while *in situ* nucleogenic neon was calculated from U and Th contents and the formation ages of the samples. After correction of crustal and *in situ* nucleogenic neon, the amounts of cosmogenic 21 Ne in silcrete range from 68 to 92% of excess 21 Ne relative to atmospheric neon (Figure). In quartz, the fractions of *in situ* nucleogenic neon in excess 21 Ne were insignificant (< 1%) owing to very low U contents (< 5 ppb), whereas those of crustal neon were relatively large (up to 72%) (Figure). In order to accurately determine the amounts of cosmogenic 21 Ne in these samples, it is essential to determine crustal neon isotopic compositions in fluid inclusions by vacuum crushing experiments and to subtract these compositions from total neon isotopic compositions obtained by fusion experiments.

Approximately 30 samples, including sand from various depths and silcrete/quartz gibbers, were collected from longitudinal dune field in the west part of the Simpson Desert in May 2004, and pure quartz samples were prepared for cosmogenic dating. It is planned that these samples will be analysed for

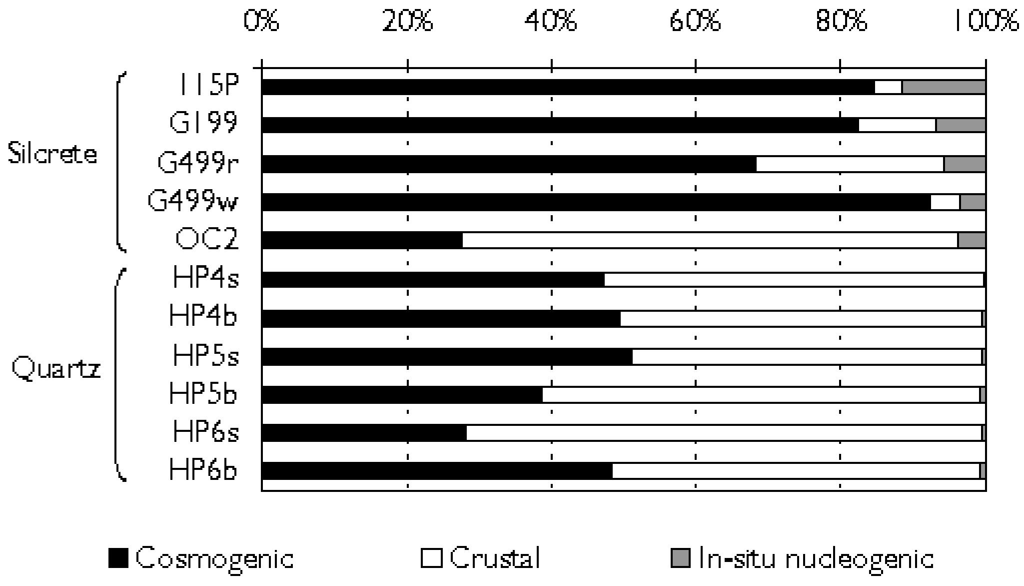


Figure 1: Contributions of cosmogenic, crustal and in situ *nucleogenic neon components of excess 21 Ne, relative to atmospheric neon, in silcrete/quartz gibber samples from central Australia .*

A primordial solar-neon enriched component in the source of EM1-type ocean island basalts from the Pitcairn Seamounts, Polynesia**.** *M. Honda and J.D. Woodhead 1*

A primordial solar-neon enriched component in the source of EM1-type ocean island basalts from the Pitcairn Seamounts, Polynesia

M. Honda and J.D. Woodhead 1

1: The University of Melbourne

Volcanic glasses dredged from the Pitcairn Seamounts of southeast Polynesia provide the least-altered basaltic material available with compositions corresponding to the EM-I mantle end-member. We found apparent correlations between mantle neon and radiogenic elements (Sr, Nd and Pb) in these samples (Figure x). Combined geochemical data from the Pitcairn Seamounts suggest apparent mixing of a MORB (mid ocean ridge basalt) component and an enriched mantle component of EM-1 type. The neon data indicate that the EM-1 component is extremely enriched in primordial solar noble gases. Since radiogenic isotope and trace element data strongly suggest the influence of a subducted crustal component in the EM-1 source, the neon results require a hypothetical reservoir in the mantle in which primordial and recycled components are mixed.

It has been argued that there may be an undegassed (and primordial noble gas enriched) source located somewhere in the deeper part of the lower mantle, and more speculatively in the layer immediately above the core-mantle boundary (CMB) and that this source may supply primordial noble gases to plumes. Combining such an hypothesis with our observations suggests that solar noble gases near the CMB may diffuse into the mantle and be mixed with other components introduced into the mantle by subduction processes. In this regard, recent seismic tomography studies have demonstrated that the roots of plumes underneath a broad region of the western Pacific extend into the lower mantle and reach the CMB. Thus, although highly speculative, these observations are consistent with the suggestion that primordial noble gases found in the Pitcairn Seamount samples may originate from the CMB. The depth of origin of mantle plumes, however, remains a subject of intense debate. It has been suggested that at least three different types of plume are likely to exist, originating at distinct mantle boundary layers. We would suggest that noble gas analysis provides a possible method for assessing the validity of these claims, and that the Pitcairn plume may itself be rooted in the deep mantle. A major task for the future will undoubtedly be the reconciliation of seismic observations with geochemical evidence. Obviously further studies of oceanic island samples are required to evaluate these hypotheses, and we would suggest that the analysis of neon isotopic compositions in suitable samples might form a fruitful avenue for such explorations.

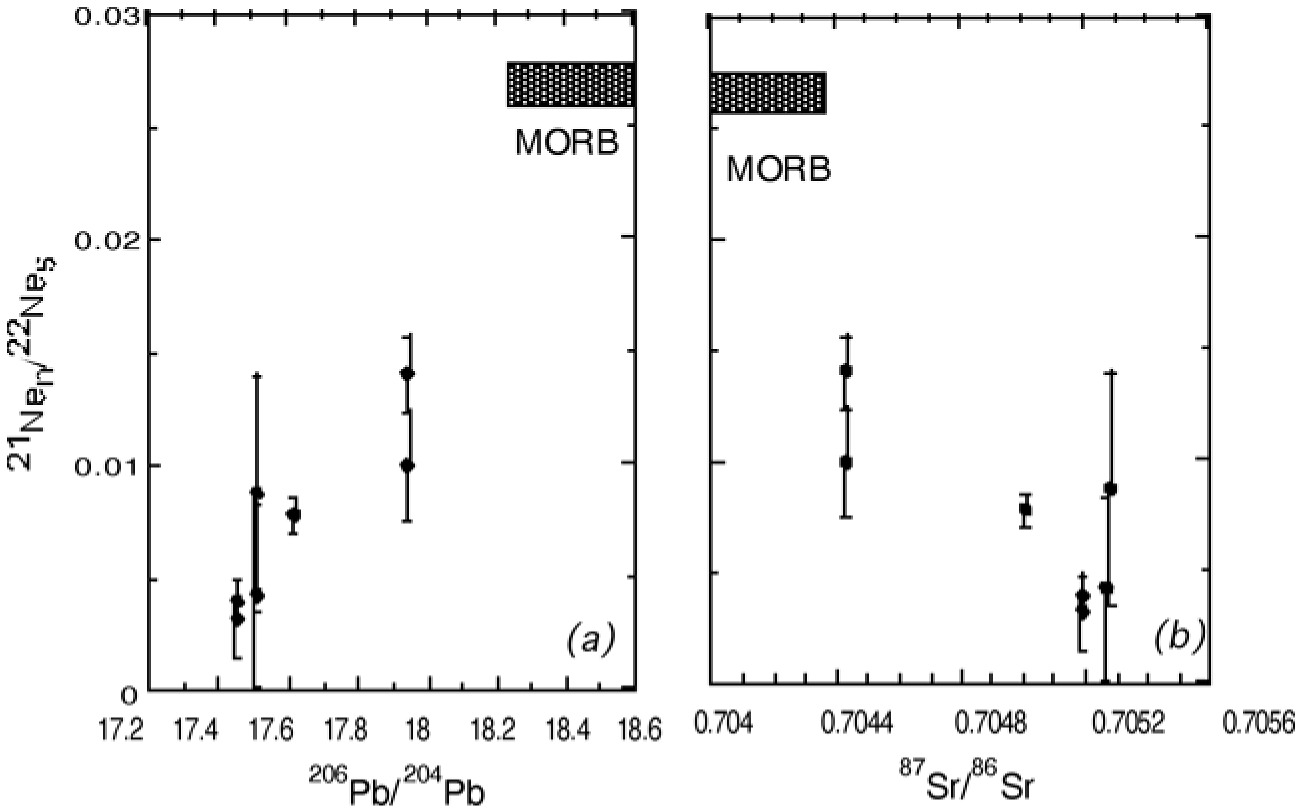


Figure x: Calculated nucleogenic 21 Ne n / solar 22 Ne s ratios against 206 Pb/ 204 Pb and 87 Sr/ 86 Sr ratios for glass samples from the Pitcairn Seamounts. There is a positive correlations between calculated 21 Ne n / 20 Ne s and 206 Pb/ 204 Pb (a) and negative with 87 Sr/ 86 Sr. At least two endmembers are required to account for the correlation, one of which appears to be a MORB component. The diagrams suggest that the other endmember, the EM-1 component is characterized by a noble gas composition highly enriched in the primordial solar noble gases.

Field Distributions of Homogeneous Magnetic Sectors. *Ben Jenkins*

Field Distributions of Homogeneous Magnetic Sectors

Ben Jenkins

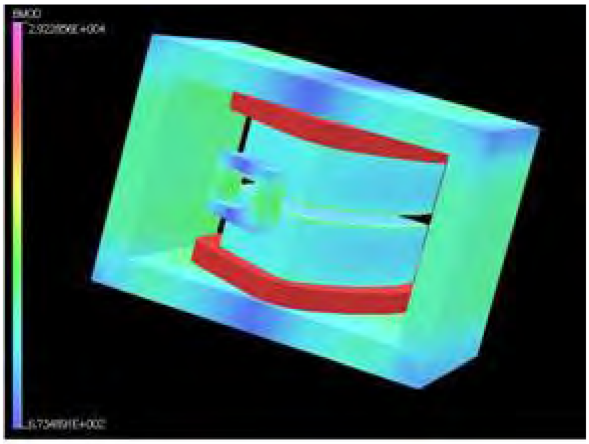
When considering the focal properties of a secondary mass analyser it is important to include the effects of any fringing fields which the ion beam experiences. Fringing fields are associated with individual components of the analyser that focus the ion beam. One source of fringing fields will be the magnetic sector.

The pole edge geometry of the magnetic sector itself determines the entry and exit fringing field distributions and these in turn determine the values of the fringing field integrals and the positions of the entry and exit ideal field boundaries.

The fringing field integrals are used in calculating the complete theoretical model of the analyser and knowledge of the positions of the ideal field boundaries is required in order to properly assemble the mass analyser.

The use of a magnetic sector possessing fringing field distributions different to those prescribed by the ion optical model tends to degrade the instruments' performance. The extent to which this occurs depends on the particular mass analyser configuration being considered as well as how different the actual distributions are from those specified by the model. In general, optimum results will be acheived when the theoretical and experimental distributions are in good agreement.

Using the Vector Fields suite of electromagnetic modelling software a variety of different magnet pole edge geometries, including those used on the SHRIMP secondary mass analyser magnets have been simulated. The results can then be used to predict the expected ideal field boundary position and fringing field integrals for an arbitrary pole edge geometry.



Simulation of flux density distribution in a sector magnet and field clamp

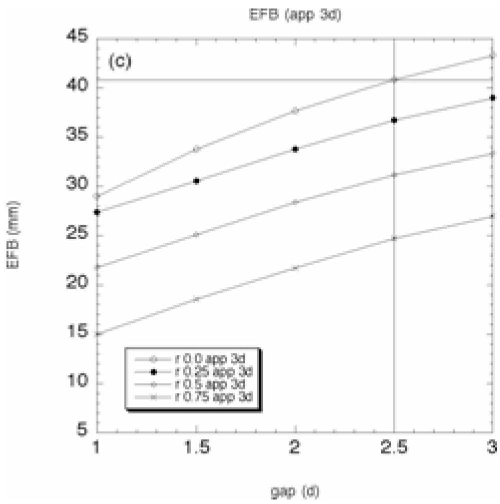


Figure 2. Variation in position of the effective field boundary (EFB) as position of the field clamp is progressively moved further away from the pole pieces. The EFB values are measured from the pole pieces and the position of the clamp is given in units of magnet gap (6 cm). The different series of plots are for 4 different radii of curvature on the pole edge.

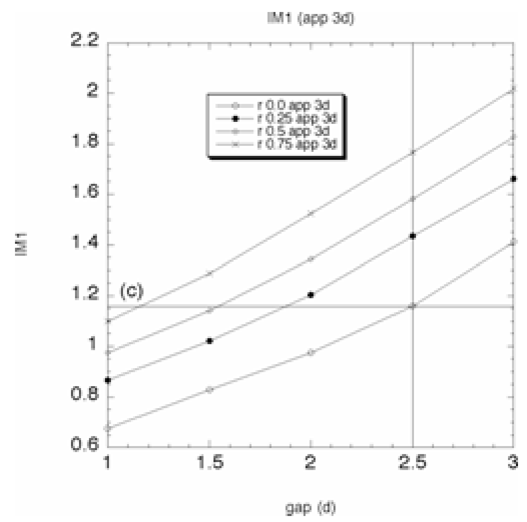
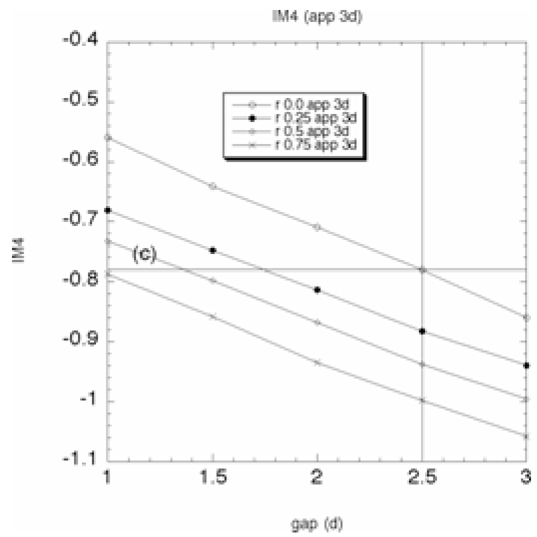


Figure 3. Variation of the first fringing field integral (IM1) as the position of the field clamp is changed



Variation of the second fringing field integral (IM4) as the position of the field clamp is changed.

The oxygen isotopic composition of the Sun. *Trevor Ireland, Peter Holden, Marc Norman, Jodi Clarke*

The oxygen isotopic composition of the Sun

Trevor Ireland, Peter Holden, Marc Norman, Jodi Clarke (research intern)

The isotopic composition of oxygen in the solar system is widely variable. On a three-isotope plot of 17 O/ 16 O vs 18 O/ 16 O there is a linear trend indicating that the predominant variable is the abundance of 16 O. Relative to terrestrial compositions, refractory inclusions are enriched in 16 O by up to 6%. The 16 O mixing array was originally ascribed to the injection of 16 O from a supernova explosion close to the solar nebula, and this supernova was also responsible for short-lived 26 Al and neutron-rich isotope anomalies in Fe-group elements in refractory inclusions. An alternative theory suggests that chemistry can play a large role in this fractionation with the low abundance isotopes 17 O and 18 O experiencing different chemical reactions than the abundant 16 O. One of the key parameters in understanding the oxygen isotope variation is the oxygen isotope composition of the Sun. For this reason, NASA flew the Genesis mission to capture a sample of solar wind and bring it back to Earth. In anticipation of this return, we have been analyzing metal grains from lunar soil, a sort of natural Genesis experiment. The metal grains have very low intrinsic oxygen and so the solar wind implant dominates the signal from below the surface of these grains. The isotope composition we measure is very unusual. It is depleted in 16 O by 5% relative to terrestrial and so it represents a reservoir that has not been seen previously in the solar system. Solar system materials show a total range of 11 % with the Sun having the lowest 16 O abundance; terrestrial oxygen is enriched by 5%, and refractory inclusions by 11 %.

It is tempting to explain this variation as a systematic increase in 16 O with increasing high-temperature processing in the solar system. Clayton (2002) suggests that self-shielding and predissociation of CO from UV radiation causes the isotopic shift seen between refractory inclusions, and terrestrial planets / planetesimals. In this model, the nebula starts with the composition of the refractory inclusions and Sun at the 16 O-enriched composition and the nebula is progressively enriched in 17 O and 18 O from dissociated CO. However, predissociation and self-shielding is only seen to occur in cold molecular clouds. Yurimoto and Kuramoto (2004) have suggested that oxygen isotope variability in the solar nebula is based on the inheritance of signatures from the molecular cloud. Altered dust (17 O, 18 O enriched) and refractory dust (original composition of the molecular cloud) mix to form the 16 O-variation array observed in the solar system. In this model, like that of Clayton (2002), the solar composition should be the same as the original composition of the molecular cloud (viz. refractory inclusions enriched in 16 O).

Our finding that the solar composition is depleted in 16 O precludes these specific models. For the model of Clayton (2002), there is no way of enriching the solid materials in 16 O, self-shielding will only cause enrichment in 17 O and 18 O in the solid phases. However, the Yurimoto and Kuramoto (2004) model can be expanded to include the solar composition but at the expense of decoupling the refractory dust from the C 16 O-enriched gas. If C 16 O is lost or diluted, the nebula composition will become heavier. This means the solar oxygen isotope composition is affected by the star-forming processes and may be decoupled from its molecular cloud origins.

Dating of Archaean amphibolite facies gold mineralisation in West Greenland – using metamorphic zircons coexisting with gold-bearing arsenopyrite. *Allen P. Nutman, Ole Christiansen and Clark R.L. Friend.*

Dating of Archaean amphibolite facies gold mineralisation in West Greenland – using metamorphic zircons coexisting with gold-bearing arsenopyrite

Allen P. Nutman (Earth Chemistry) Ole Christiansen (Nunaminerals A/S) and Clark R.L. Friend (Natural History Museum , London).

We describe a novel success in SHRIMP U/Pb zircon dating of amphibolite facies gold mineralisation – *in situ* in thin section using metamorphic zircons found with gold-bearing arsenopyrite. Dating this mineralisation and linking it with one of several possible tectonothermal events fulfils a key objective in a current ARC Discovery Grant held by Nutman and Friend. It represents a fusion between work carried out by a prospecting company and integrated use of the advanced analytical technologies available in RSES. In the Nuuk district of the West Greenland Archaean Craton, the crust consists of different-aged blocks dominated by TTG gneisses, belts of amphibolite facies volcanic and sedimentary rocks and crustally-derived granites. Late Archaean collisional tectonics in the region is manifested by stacking different blocks of gneisses on top of each other prior to regional folding.

This stack is truncated to the NW by the Ivinnguit fault that last moved at ca. 2550 Ma but may have been initiated earlier. In the southern part of the Nuuk district this stack contains a panel (mostly now <1 km thick) of 2830-2840 Ma metasediments, volcanics and gabbro-anorthosites. Close to the Ivinnguit fault, particularly on the island of Storø (Fig. 1), this panel contains gold mineralisation which in the main prospect reaches up to 32 grams per tonne. The gold is mostly concentrated in arsenopyrite (Fig. 2a), which is in textural equilibrium with hornblende + garnet + plagioclase ± titanite. Therefore, the main mineralisation in its present form is an expression of processes under amphibolite facies metamorphism – as first noted in the earlier study of Pedersen and Petersen in the 1990s (supported by Nunaminerals A/S). Gold also occurs in cross-cutting veins of loellingite (FeAs), which our LA-ICP-MS analyses demonstrate gold to be concentrated where veins change direction or meet (Fig. 2b). Detailed surveying of polished thin sections of a gold mineralised rock from Storø by electron backscatter imagery and EDS analysis, found small (<50 µm) equant zircons at the contacts of and actually within gold-bearing arsenopyrite (Fig. 2a).

CL imaging of these zircons show that they are structureless and either featureless or with sector zoning. Using SHRIMP RG, these zircons were dated *in situ* in thin section. They yielded consistent low Th/U ratios and dates are concordant within error, with a consistent late Archaean age. These zircons are interpreted to have grown during the amphibolite facies metamorphic event that gave rise to important gold mineralisation in the arsenopyrite. The date from the zircons in the mineralisation has been obtained elsewhere in the region for metamorphism and intrusion of some crustally-derived granites. This information will provide a key for understanding other amphibolite facies gold mineralisation occurrences in the region, where we have obtained the same late Archaean age from nearby granite intrusions.

Fig. 1. 1000 m high exposure of over the gold prospect on Storø, Nuuk district, West Greenland . Mineralisation is in superbly-exposed hillsides, where there is much more potential for detailed structural and geochemical studies of the mineralisation.

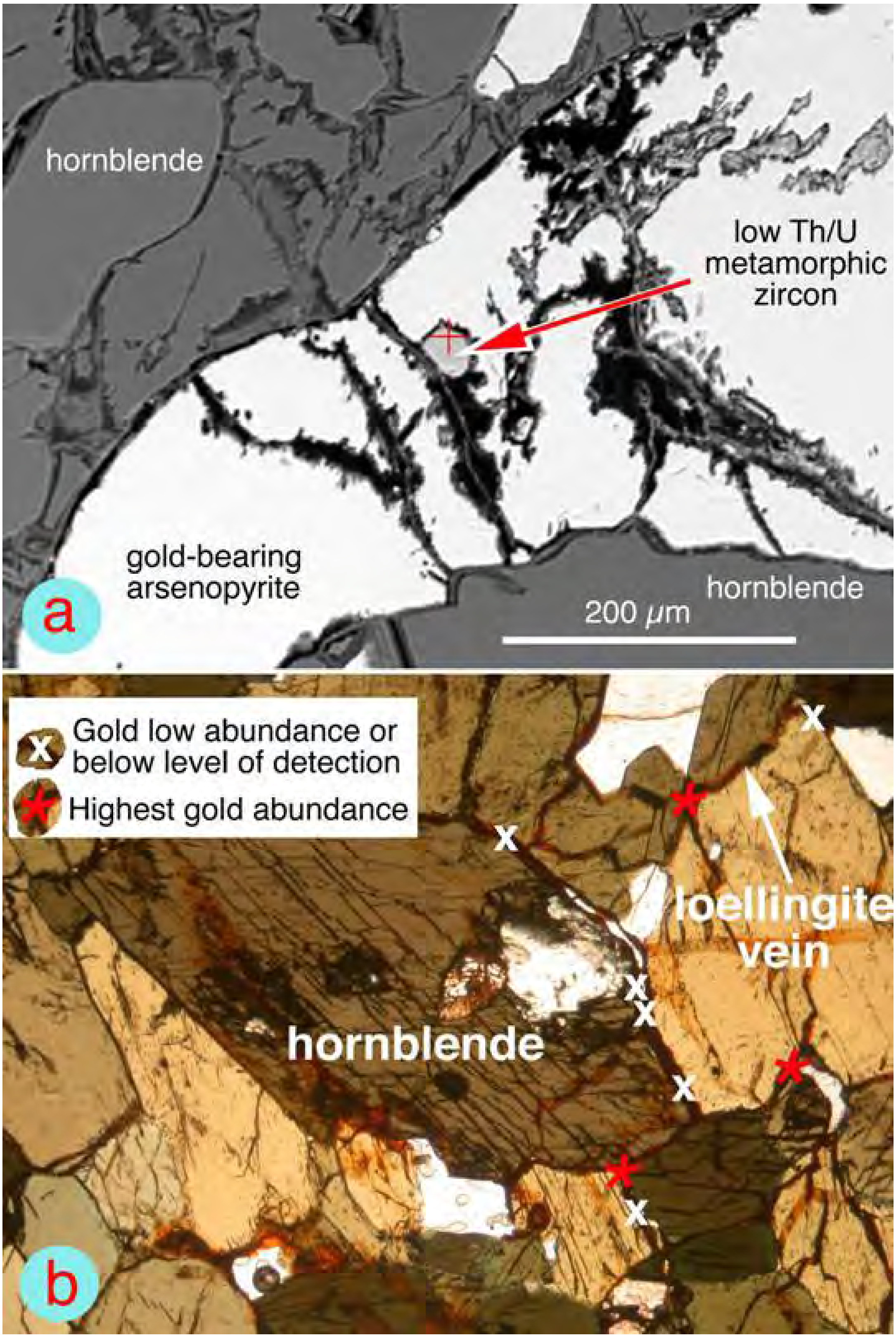


Fig. 2. Images of Storø gold mineralised rock. (a) Back-scattered electron image of gold-bearing arsenopyrite in equilibrium with hornblende. Found in association with the arsenopyrite is one of the metamorphic zircons dated in situ by SHRIMP. Our LA-ICP-MS transects across the arsenopyrites associated with the dated zircons show variable gold content. (b) Optical photomicrograph of loellingite (FeAs) veins cross-cutting the earlier

amphibolite facies assemblage with arsenopyrite. Our LA-ICP-MS exploration has found gold in these veins, confirming some gold mobilisation after peak metamorphism. Gold concentration occurs where these veins change direction or meet – a style of secondary mineralisation probably applicable at the prospect scale.

An Igneous Application For In-situ Strontium Isotopic Laser Ablation. *Amanda Stoltze, Ian Campbell, Wolfgang Muller, Malcom McCulloch*

An Igneous Application For In-situ Strontium Isotopic Laser Ablation

Amanda Stoltze, Ian Campbell, Wolfgang Muller, Malcom McCulloch

The Neptune Laser Ablation Inductively Coupled Plasma Mass Spectrometry for in-situ isotope analyses has been applied to the Wallaby gold deposit an Archaean Greenstone hosted deposit from the Yilgarn Craton. The problem was to determine whether a suite of igneous intrusions adjacent to mineralisation were the source of gold forming fluids. One method of determining a link is by radiogenic isotopic comparison between the intrusion suit and mineralisation. This is the first use of this technique on igneous and gold associated minerals, and provides a powerful tool for the study of Sr isotopes in systems that are prone to element mobilisation after mineral formation. By choosing minerals that have very high Sr concentrations and negligible Rb and rare earth elements, it is possible to exclude Rb mobility from the Sr isotope results. The data acquired with the Laser technique has been compared to that acquired using conventional isotope dilution techniques to confirm the accuracy of this technique for the current application.

Conventional isotope dilution techniques were applied to whole rock and mineral separates and the results covered a wide range of values 87Sr/86Sr = 0.69715±1 to 0.70849±1 but with the majority of samples occupying a very small range of 87Sr/86Sr near 0.70147. The large range in Sr isotopes suggests that post crystallization mobility of Rb and/or Sr has occurred as the Sr isotope range is larger than would be expected for a suite of related igneous intrusions. A change in the Rb/Sr ratio after crystallization will disrupt the correction applied to the data and result in a departure from the true initial ratio. If the Rb/Sr ratio has increased after crystallization the correction applied to the measured ratio is too large resulting in the estimated initial ratio being too low, and lowering the Rb/Sr ratio will increase the initial isotopic ratio after correction. On close inspection it was noted that all sample that fell below the common value contained mica and all samples that were above the common value contained feldspar altered to sericite (fine grained white mica). This information suggests post-crystallization Rb and/or Sr movement is facilitated by mica in a sample. It is therefore necessary to exclude any contamination of micaceous minerals from a Sr isotope sample, which is best done by in-situ analysis.

In this study only minerals with Rb/Sr ratios approaching 0 were used, these included calcite, dolomite, and scheelite. The in-situ nature of the analyses allows minerals to be chosen from thin sections and rock chips providing excellent geological control. The results obtained are displayed in figure 1 and highlight the effectiveness of this technique in systems that have experienced post-crystallization element mobility. The results also show that intrusions and ore have the same Sr isotopic ratio, suggesting the same source for Sr. This can be used as evidence for a genetic link between the igneous units and ore at the Wallaby gold deposit.

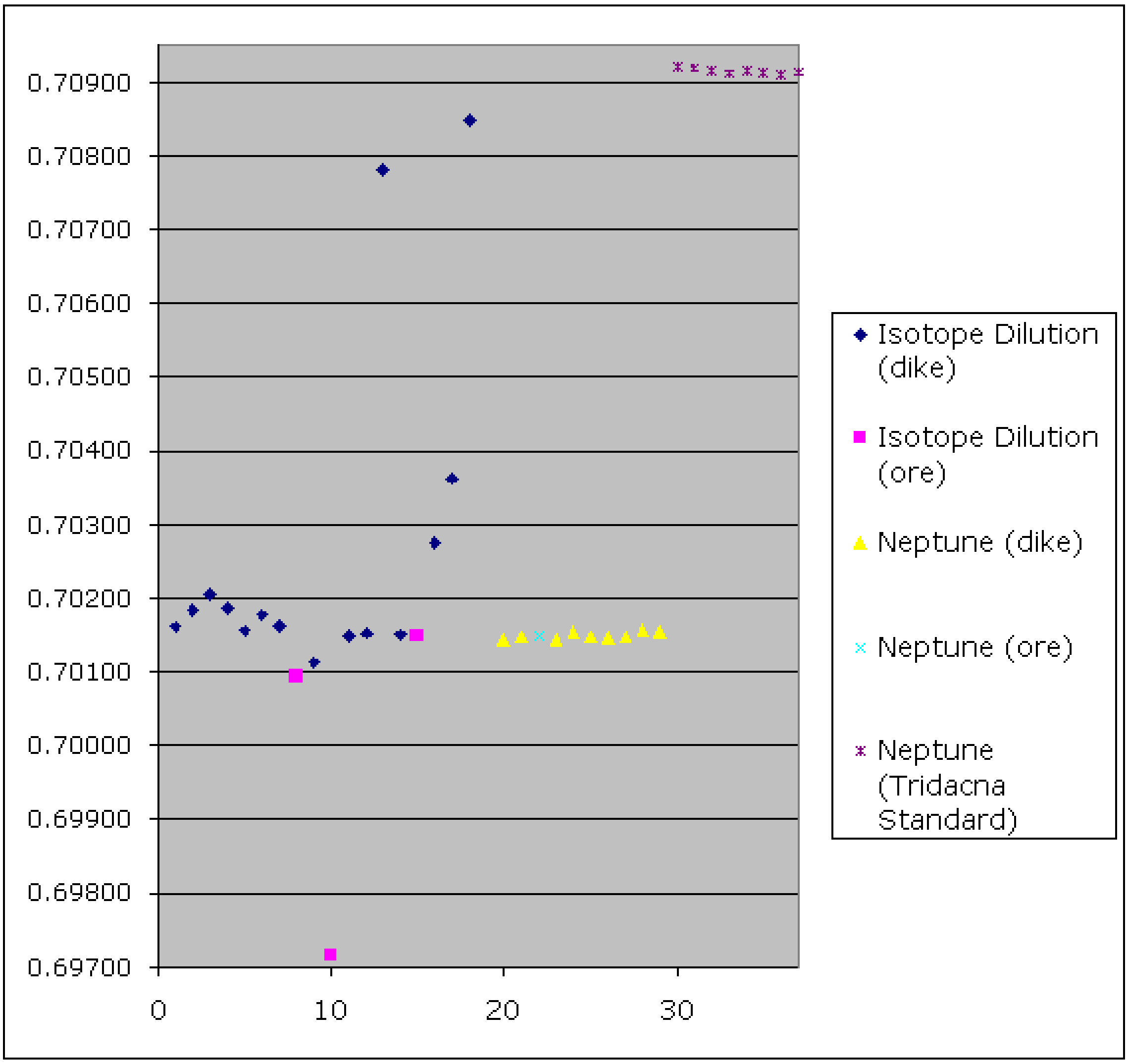


Figure 1. Results of 87Sr/86Sr using isotope dilution on whole rock and mineral separates, and in-situ minerals using LA ICP-MS. Tridacna was used as a standard during analyse, note the low variation in the standard.

Earth Environment 2004

Research Abstracts

Add in PDF's

Earth Materials Research

Research within the Earth Materials Division is perfomed by members of the Experimental Petrology, Rock Physics, Thermochronology and Structure & Tectonics Groups. The Earth Materials division is an international leader in studies of earth materials under controlled laboratory conditions simulating those occurring in nature. Through such investigations we are developing understanding of the structure and chemical composition of planetary interiors and processes by which they evolve, such as accretion, core formation, mantle convection, volcanism, metamorphism, global tectonics and the formation of ore deposits.

Areas of current research activity include:

• The making of terrestrial planets Chemical constraints on the accretion of the Earth and similar planets from the solar nebula, and the processes of core formation; mineralogical and chemical properties of the deep mantle and their influence on global tectonics.

• The nature of the Earth's upper mantle Experimental studies and thermodynamic modelling of the phase equilibria relevant to upper mantle melting and ultra-high-pressure metamorphism associated with crustal thickening and subduction; experimental and microstructural studies of phenomena associated with lattice defects and grain boundaries including incorporation of water into nominally anhydrous minerals and microscopic mechanisms of seismic wave attenuation; experimental studies and modelling of grain-scale melt distribution and its implications for melt transport, rheology and seismic properties.

• Coupling between fluid flow and fault mechanics in the continental crust Experimental studies of the role of fault healing and sealing processes in controlling the time dependence of fault strength and permeability at high temperatures and pressures; complementary field-based and modelling studies exploring fluid-driven growth of shear networks with applications to understanding the development of lode gold systems, especially in the Western Australian goldfields.

• Oxidation state and coordination of metal ions at high temperatures Studies of crystals, melts and hydrothermal solutions by X-ray absorption spectroscopy. Experiments are performed at very high temperatures under controlled redox conditions. Analysis of hydrothermal solutions trapped in synthetic fluid inclusions is providing important basic information on metal complexes at high temperatures.

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Earth Physics

Geophysical Fluid dynamics
Geodynamics
Seismology and Geomagnetism
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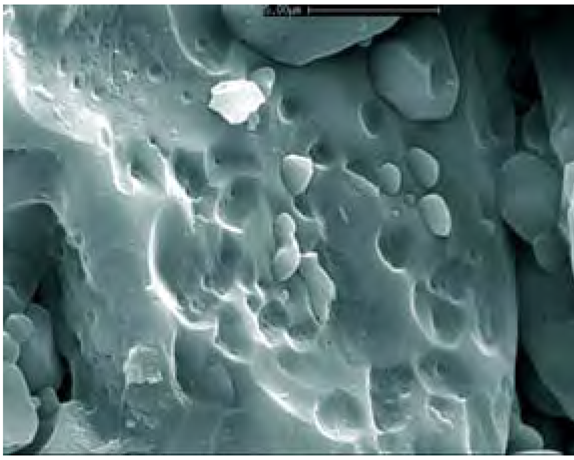

Introduction

Research into the structure and dynamics of the Earth uses a range of modern physical and mathematical techniques grouped into four themes of Geodynamics, Geophysical Fluid Dynamics and the Centre for Advanced Data Inference (CADI).
Work in Earth Physics spans observational, theoretical, computational, and data oriented studies that are all directed towards understanding the structure and processes in solid and fluid Earth, and their environmental consequences. The four themes in Earth Physics have considerable cross-interaction, particularly through a common use of computational methods. An example of cross-interaction comes from the combination of geodetic and seismic techniques to elucidate the patterns of deformation associated with large earthquake sequences near New Britain, PNG.

Dr G.F. Davies has been awarded the inaugural Love Medal in Geodynamics by the European Geosciences Union and will receive his medal at the General Assembly in Vienna in April 2005 .Dr J. Braun left RSES in November to take up a Professorship at the University of Rennes, France (but retains an Adjunct position), in consequence Dr M. Sambridge is now the Director of CADI.

Work in geophysical fluid dynamics this year has seen major effort on ocean modelling both through atmosphere-ocean coupling and the dynamics of the global thermohaline circulations. Experimental runs in the GFD laboratory have been linked to major computational simulations. Other classes of laboratory investigations include studies of lave flow dynamics and three-dimensional simulations of subduction.

The ongoing program of studies with portable seismic recorders across the continent provides a steadily improving data set for studying the structure beneath the Australian continent. These results have been critical in developing a synthesis of seismological information on the contrasts in the mantle associated with the transition from the Precambrian to the younger eastern portion of Australia. It appears that the transition involves two distinct steps in lithospheric thickness.

In the Centre for Advanced Data Inference considerable effort has been expended on a new style of modelling system for geodynamic computations based on a novel partitioning of 3-D space. A CADI inversion toolkit has also been developed to provide a simple interfaces to both software and hardware facilities I, including the TerraWulf cluster.

Research within the geodynamics group covers two principal areas: the study of the earth's response to glaciation and the associated sea level changes and the study of the earth's deformation at high frequencies. A major step forward has been the reconstruction of the Eurasian ice sheet for the past 150,000 years from an inversion of field data of palaeo sea levels and shoreline locations, the results of which lead to the conclusion that the anomalously warm high-latitude climate conditions of the Last Interglacial can be largely attributed to the extent of the preceding glaciation. Considerable improvements were also made in the accuracy of height determination using GPS through new models for the atmospheric mapping functions, atmospheric pressure loading and non-gravitational orbit perturbations and through improved global station network design.

GEOPHYSICAL FLUID DYNAMICS INTRODUCTION

INTRODUCTION RESEARCH PROJECTS

Geophysical Fluid Dynamics is the study of fluid flows and their roles in transporting heat, mass and momentum in the oceans, atmosphere and Earth’s deep interior. In RSES, the research in this field continues to focus on the exploration of physical processes of importance in three different areas:

- convection, mixing and circulation in the oceans, with implications for climate,
- magmatic and volcanic processes, and
- convection of the solid silicate mantle, with its implications for plate tectonics.

Geophysical Fluid Dynamics (GFD) emphasises the importance of dynamical modelling. At the ANU much of the research program in this area is anchored strongly in experimental fluid dynamics and relies on the excellent facilities of a recently constructed 400 sq. m laboratory and workshop area. This is the premier GFD research group and experimental facility in Australia. It is well known around the world for its contributions across fluid dynamics, oceanography and ‘solid earth’ geophysics. The research relies also on advanced computing facilities within the Research School and the Australian Partnership for Advanced Computing (APAC) located at ANU.

Figure 1: An animated solution for the potential vorticity field in an eddy-resolving ocean simulation.

This year, modelling of the wind-driven circulation of the upper ocean focused on the response of western boundary currents to variable wind forcing (Dr A.E. Kiss, an ARC Australian Postdoctoral Fellow) and on low-frequency variability in the circumpolar flow of the Southern Ocean arising out of coupling between the atmosphere and ocean (Dr A.McC. Hogg, also an Australian Postdoctoral Fellow). In both cases, computational models were used to examine the nonlinear processes and results of coupling. The western boundary current study is relevant to the East Australia Current and shows that the formation of large eddies can be tied to the forcing frequency, or can be chaotic. The simplified Southern Ocean model shows that air-sea coupling leads to inter-annual variability of the mean flow and of the eddy activity (figure 1). In other work, we commenced a study of wake flows in coastal seas, using a first set of laboratory experiments with flow around a model headland and in which the on-coming flow is either turbulent or contains a large disturbance.

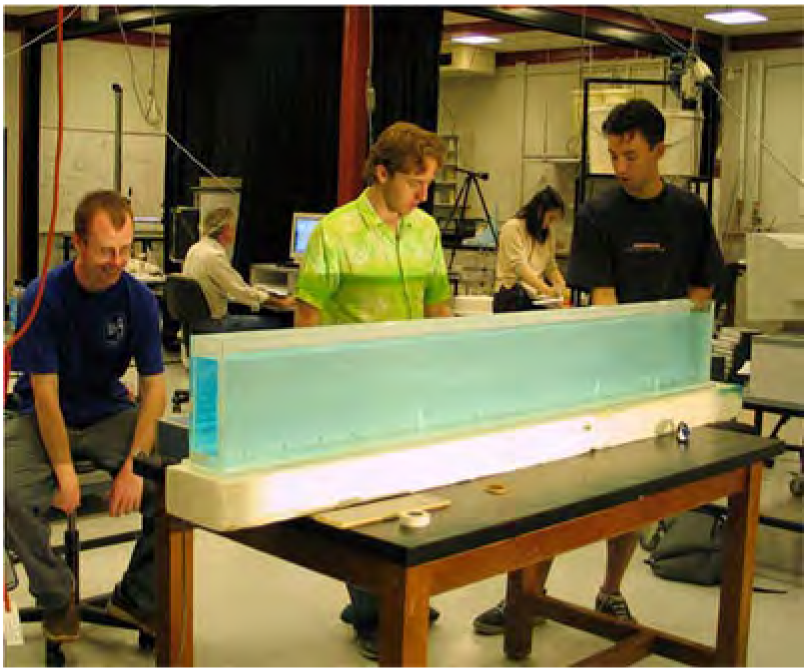

Figure 2: Undergraduate teaching in the GFD laboratory brings fluid dynamics alive for students. (John, Ben and Michael with Mayumi and Prof Griffiths in the background)

In another ocean modelling project (by Prof. R.W. Griffiths, Dr G.O. Hughes and PhD student J.C. Mullarney), the dynamics of the global thermohaline circulation of the oceans was studied using laboratory experiments with convection forced by a horizontal gradient of surface heat flux (figure 3), and with numerical solutions developed on the APAC supercomputing facility. The results were this year supplemented by a theoretical solution that incorporates turbulent entrainment into either a vertically-falling plume or a geostrophic bottom current flowing down and along a gently sloping topography. Model predictions compare well with ocean data for the density differences and overturning mass flux. The conclusion is again that heating and cooling, with zero net heat input, at a horizontal surface can drive a vigorous and at least partly turbulent overturning circulation, and indeed the application of the theory to the ocean shows that it is plausible for heating/cooling to drive the observed overturning. The predictions for the dilution of bottom currents in the ocean are also in line with observations. Work has also progressed well in a new project to describe the amounts of mixing between counter-flowing water layers of differing density in ocean straits and overflows. The mixing also reduces the rate of water exchange. This project uses a 4m long water channel with a constriction at the centre through which fresh and saline water layers exchange, and represents the first ever attempt to measure the mixing rates.

Figure 3: A movie clip of passive dye tracer in “horizontal convection” in a long box of water. The box is cooled through the right hand half of the base and heated through the left hand half of the base, and has reached thermal equilibrium in which there is zero net heat input. The box is 1.2 m long and 0.2 m high, but only the left 1/3 of the length is shown. Features include small-scale convection in a mixed layer along the heated base of the tank, a narrow turbulent plume ascending on the left hand wall, and a turbulent outflow at the top (see also Figure 7 in Research Projects).

In mantle dynamics, Dr G.F. Davies completed a major overhaul of his two-dimensional code for simulation of mantle convection, and in which he has implemented passive tracers in order to follow material parcels as they move around, disperse or congregate in the flow. He also began work with a three-dimensional code. This well-developed parallelised code represents a major expansion of our capacity to model the dynamics and chemical evolution of the mantle. In laboratory analog modelling of mantle subduction processes, Prof. C. Kincaid (Visiting Fellow from the University of Rhode Island) and Prof R.W. Griffiths carried out further experiments with a cold subducting slab in order to determine the patterns of cooling of the slab and the effects of three-dimensional flow around a slab segment. They showed marked differences in the temperature-depth trajectories for the model slab surface (implying different melting histories for mantle slabs), depending on the relative rates of slab sinking and slab rollback (or trench migration). Dr W. Schellart (a new Australian Postoctoral Fellow) commenced work on three-dimensional laboratory simulations of subduction, involving a dense high-viscosity plate, which sinks into the lower density low-viscosity mantle. In his simulations, the mantle reservoir represents the entire mantle (from the surface to 2900 km depth) and is either homogeneous throughout or layered (low-viscosity upper mantle and high-viscosity lower mantle). The experiments are designed to investigate the influence of mantle viscosity and mantle stratification on the kinematics and dynamics of subduction and subduction-induced mantle flow.

In modelling of processes relevant in volcanology, studies of lava flow dynamics continued with funding from the ARC. PhD student A.W. Lyman, with Dr Kerr and Prof. Griffiths, used rapid releases of solidifying viscous and Bingham (yield-strength) fluids to determine the stopping time and distance for flows in a horizontal channel. This work elucidates the conditions under which final flow length is controlled by yield strength or cooling and solidification. Further experiments in a sloping channel were commenced. In another experimental study, in collaboration with volcanologist Prof. K.V. Cashman from the University of Oregon, Dr Kerr and Prof. Griffiths examined the behaviour of solidifying flows on a wide sloping plane in order to understand the flow width, levee characteristics, and channel width. They also examined the solidification behaviour on the surface of flows in an established channel having irregularities, such as changes of width, bends or ridges.

Figure 3: Photograph of a solidifying gravity current of polyethylene glycol - kaolin slurry (which has an internal yield strength and freezes at 19˚C) under cold water.

Two new staff members joined the group early in 2004: Drs A. McC. Hogg and W. Schellart took up their Australian Postdoctoral Fellowships and will work on ocean-atmosphere coupling in the Southern Ocean, and the dynamics of subduction zones, respectively. Ms M.A. Coman and Ms M. O'Byrne commenced their PhD programs in GFD, working on modelling of the ocean overturning circulation, and wake structures of islands and headlands in coastal seas, respectively. Ms J.C. Mullarney submitted her PhD thesis on models of the ocean thermohaline circulation. Prof. C. Kincaid visited for 3 months from the Graduate School of Oceanography, University of Rhode Island, and carried out further experiments with models of lithospheric plate subduction into the mantle, work that followed from his previous visit in 2002. Dr S. Vergniolle, from the Institut de Physique du Globe de Paris, visited to carry out experiments with rapidly expanding foams. The group continued to benefit from the presence of Emeritus Professor J.S. Turner. Prof. Griffiths and Drs Hughes and Kerr taught the “Introduction to Geophysical Fluid Dynamics” unit in the RSES Physics of the Earth Honours program. Prof. Griffiths again taught an undergraduate course on fluid dynamics and ocean-atmosphere dynamics in the Department of Physics and Theoretical Physics, ANU. The staff, students and visitors all acknowledge the vital contributions of our technical support staff, A.R. Beasley and C.J. Morgan, to our research program. Collaboration continued with Australian Scientific Instruments in commercialisation and sales of the ‘Geophysical Flows Rotating Table’, and we installed a new rotating table in the GFD laboratory with funds from the ANU Major Equipment Committee. A new ARC Discovery grant of M$1.2 was awarded to Prof. R.W. Griffiths and Prof J.M. Middleton (University of New South Wales).

INTRODUCTION RESEARCH PROJECTS

Dynamics and Chemical Evolution of the Earth’s Early Mantle

G.F. Davies

This project aims to explore the degree of stirring and stratification, due to settling of denser components, in the Earth’s mantle. It extends previous two-dimensional numerical modelling at present Earth conditions in two ways: into the past (hotter mantle) and into three dimensions (at present Earth conditions). It will also explore, in two dimensions, the evolution of the stratification as the mantle cools over 4.5 billion years to its present condition. The project has been in a development phase, with production now imminent.

The 2D modelling will extend the previous modelling to the more extreme conditions of the early mantle, which was hotter, had lower viscosity, and convected faster with thinner thermal boundary layers. After some preliminary 2D modelling it became apparent that the 2D code needed upgrading, to make it more robust in handling the conditions of the hot early mantle. This possibility had been anticipated. The opportunity has been taken to rationalise the code to make it more transparent and easier to work with. It was also modernised to Fortran 90, which provides important advantages in this regard. These developments are now complete, verification is almost complete, and the main phase of 2D modelling is about to commence. First the behaviour in a hotter mantle will be explored: in these conditions it is expected that settling of denser components will be more pronounced. The computations will then proceed through a simulated 4.5 billion year history as radioactive heat sources declined and the mantle cooled its present state, to evaluate how much the present state depends on the cooling history.

The 3D modelling will be carried out by Research Associate Jinshui Huang, who will arrive early in 2005. This work involves adapting the 3D-spherical code “Terra” obtained from Professor P. Bunge (Munich) and Dr. J. Baumgardner (Los Alamos). Preliminary work has tested and verified the relevant capabilities of the 3D code, as well as initiating methods to simulate plates on a sphere, which will be an important part of this work. It has also been run successfully on a local Linux cluster computer.

The effect of channel irregularities on the surface crust in lava flows

R.C. Kerr, K.V. Cashman and R.W. Griffiths

In a collaborative project with volcanologist Professor K.V. Cashman of the University of Oregon, and funded by both the ARC and the National Science Foundation, we have explored the behaviour of basaltic lava flowing through long channels, with the aim of understanding the factors influencing the cooling of the flow, and the resulting flow behaviour. To model lava channels, we use laboratory experiments in which polyethylene glycol (PEG) flows under cold water down a 3m-long, inclined channel. Our flows are laminar, having Reynolds numbers of 0.2 – 70, thus covering the range estimated for basalt channels. For a constant source volume flux we have found two distinctly different steady state regimes: a 'tube' regime in which solidification of the flow surface creates a stationary roof while melt continues to flow through a relatively well insulated 'tube' beneath, and a 'mobile crust' regime in which a solid surface crust develops only in the centre of the channel. The transition between the two flow regimes occurs when ϑ = (ts Uo/Ho) (Ra/R)^1/3 reaches the critical value of 25, where ts is the surface solidification timescale, Ho and Uo are the flow depth and centreline surface velocity in the absence of solidification, Ra is a Rayleigh number and R is a constant.

This year we extended our experimental program to examine the effects of channel irregularities on crust formation and disruption. In expanding channels, and in straight channels with bottom irregularities, we found that ϑ= 25 remained a good predictor of the transition between central crust and tube regimes. Gradual channel expansion can also permit a down-flow transition from a mobile crust to tube regime if ϑ= 25 is exceeded in the widening channel. For shallow channels we predict that the central crust width (d_c) will vary with channel width (W) as $d_c \sim W^{5/3}$ for a given volume flux. Analysis of our expanding channel experiments confirmed this relationship. Channelised lava flows in Hawaii also show crustal coverage consistent with this theoretical result, along gradually widening or narrowing channel reaches (Figure 4). An important observation from our experiments was the role of crustal breakage and extension in increasing the amount of core fluid exposed at the flow surface. Breakage occurred with local acceleration of the flow surface through constrictions, around bends, or over bottom irregularities.

ϑ ϑ

Figure 4: Photograph of a 10 m wide lava channel on Kiluaea Volcano, Hawai`i, during overflow from Mauna Ulu, February 28, 1972, which illustrates the presence of solid (dark material) along the centre of the channels and incandescent melt exposed along the edges

The emplacement dynamics of rapid eruptions

A.W. Lyman, R.C. Kerr and R.W. Griffiths

Over the past two years, we have modelled the emplacement dynamics of lava flows using a combination of laboratory experiments and theoretical scaling analyses, for the case when a fixed volume of lava is rapidly released in a horizontal channel. We have focused particularly on the processes that determine the final length of the lava flow, including the effects of a constant interior yield strength (as erupted from the vent) and the growth of a crust due to surface cooling of the lava. We began by examining the isothermal flow of yield strength fluids, which were found to spread in a rapid slumping regime, that can be followed by a slower viscous flow regime, before a final viscoplastic regime where the interior yield strength eventually brings the flows to a halt. We next investigated solidifying viscous flows (Figure 5), that were also found to spread in a slumping regime, which under some conditions is followed by a viscous flow regime, before reaching a final regime where the yield strength of the growing crust stops the flows. We then analyzed the general case of solidifying flows of yield strength fluids (Figure 6), which are eventually stopped by either the interior yield strength or the growing crust. We found that the growing crust controls the runout length and emplacement time of flows if the parameter $t_s\sigma_0/\sigma$ is smaller than a critical value, where t_s is the surface solidification timescale, σ_0 is the interior yield strength and $\sigma$is the Bingham viscosity. We have also determined the yield strength of the growing crust, which is found to increase with increasing internal yield strength. The results will be helpful both in predicting the advance of flows from future volcanic eruptions, and in placing bounds on the durations of eruptions of large prehistoric flows.

Figure 5: Movie of a solidifying gravity current of viscous PEG.

Figure 6: Photograph of a solidifying gravity current of polyethylene glycol - kaolin slurry (which has an internal yield strength and freezes at 19˚C) under cold water.

The dynamics of the ocean thermohaline circulation

R.W. Griffiths, G.O. Hughes and J.C. Mullarney

Following our previous experimental work with “horizontal convection” (figure 3 and 7), we have developed a simple new mathematical model for the ocean circulation that gives preliminary predictions of the strength of the global thermohaline circulation and rates of Antarctic Bottom Water formation in close agreement with previous field estimates. From the model we also predict a thermocline thickness and density profile through the ocean depth close to the measured global averages (figure 8). The rate of supply of available potential energy from thermal buoyancy forcing alone (neglecting wind and tidal energy sources) can induce an interior rate of mixing characterised by a diffusivity of order 10^{-5} m^2s^{-1}. This value is consistent with direct measurements by others in the open oceans, but is an order of magnitude less than the diffusivity required by previous theories for the circulation that impose a uniform vertical upwelling velocity and neglect entrainment of water from the interior into the sinking currents. Our model represents an important departure from current thinking and suggests that the widespread search for sites of high rates of mixing in the oceans may not yield basin averages as high as previously expected. It also confirms that the available buoyancy flux, I concert with the measured average vertical mixing, is sufficient to drive the overturning flow.

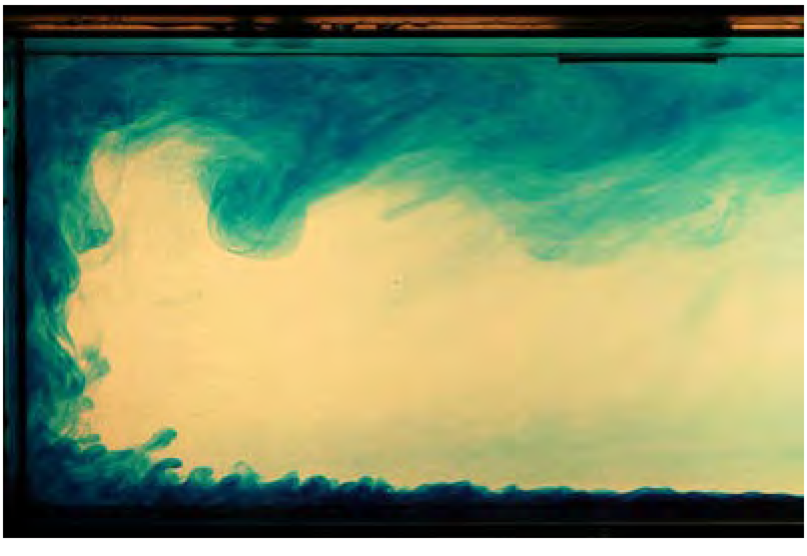

Figure 7: A photograph of dye tracer in the convective circulation in a long box of water which is cooled through the right hand half of the base and heated through the left hand half of the base. The box is 1.2 m long and 0.2 m high, but only the left 1/3 of the length is shown. Features include small-scale convection above the heated base of the tank, with a narrow plume ascending on the left hand wall. (see also movie clip in Figure 2)

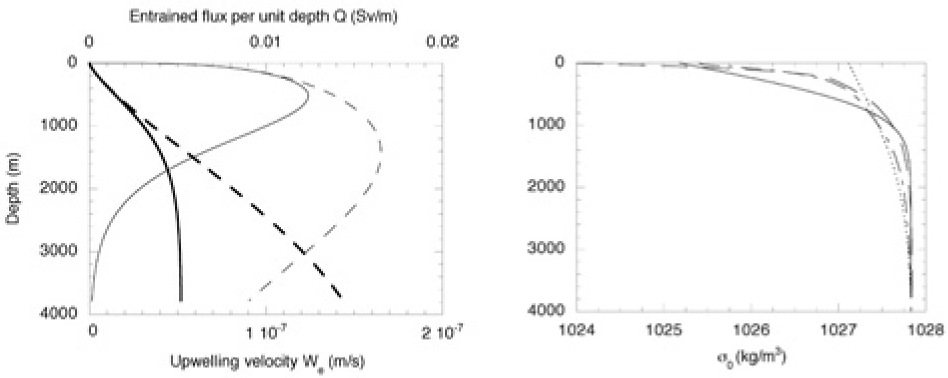

Figure 8: a) Our predictions of entrainment Q into the geostrophic bottom current from the Weddell Sea and upwelling velocity in the ocean interior (for vertical mixing rates of 10^{-5} m^2s^{-1}, solid lines, and 10^{-4} m^2s^{-1}, broken lines; curves with maxima give Q), and b) corresponding predictions for the ocean stratification (solid and dotted curves), compared with measured density averaged over the northern and southern hemispheres (broken curves). Case of sinking in the southern hemisphere only. From Hughes & Griffiths, 2005.

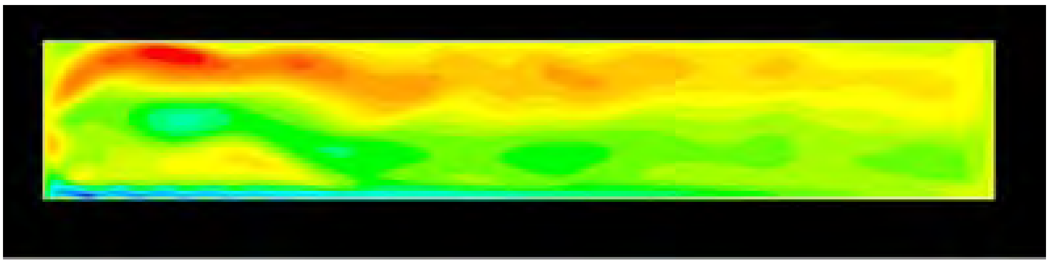

Figure 9: A two-dimensional numerical solution (showing horizontal velocity – red to the right and blue to the left) for the convective circulation in a long box of water which is cooled through the right hand half of the base and heated through the left hand half of the base. Features include small-scale convection above the heated base of the tank, with a narrow plume ascending on the left hand wall, as seen in our laboratory experiments (Figure 9).

Laboratory modelling has also examined the dynamics of a thermally-driven circulation perturbed by the addition of a stabilising salinity buoyancy flux. This flux is designed to mimic the input of freshwater to the ocean's surface at high latitudes. The fresh water spreads from the poles and tends to oppose the flow forced by the latitudinal density gradients formed by the thermal forcing. In the laboratory experiments, we use a source of more saline water at the bottom and heated end. This forms a salt layer characterised by vigorous convection and mixing (figure 10a) and can be viewed as an analogue of the 'polar halocline' found at high latitudes in the oceans. For weaker values of salinity forcing the nose of the layer can destabilize to form an intrusion above the thermocline (figure 10b). The intrusion propagates horizontally along the tank, eventually extending across the full-length of the tank (figure

10c). In the oceans, this corresponds to a tongue of relatively cold and fresh water subducting below the thermocline and spreading equatorward. The result, in the ocean context, would be a stable layering at the ocean surface and an interruption of deep water formation, known as a 'polar halocline catastrophe'. This two-cell structure is found in many forms of climate models.

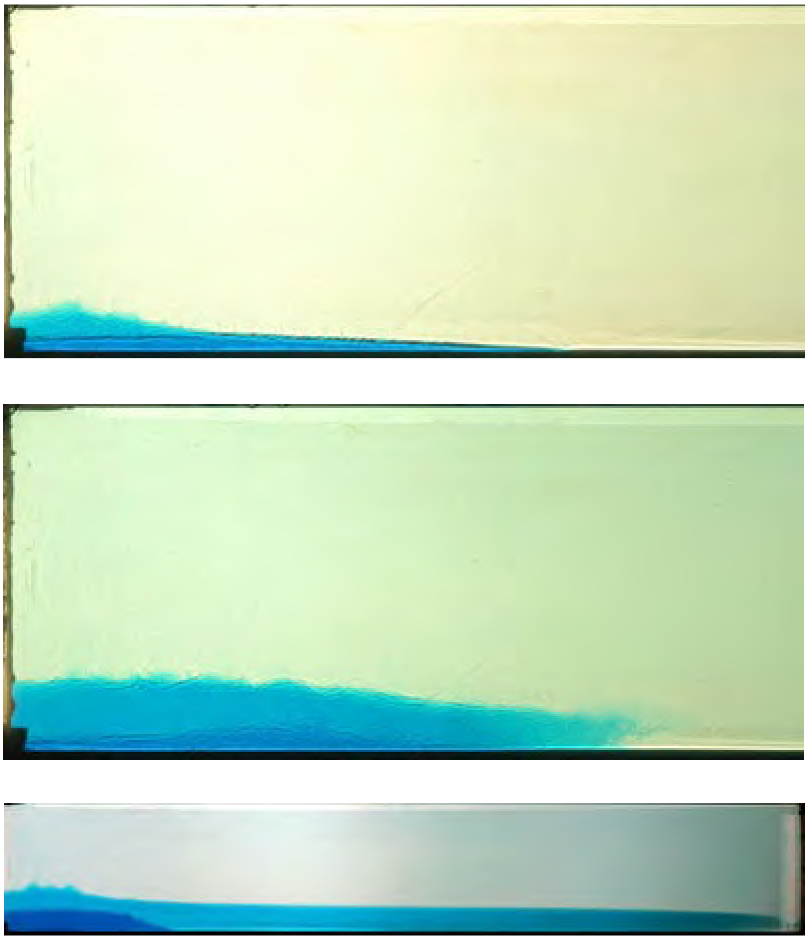

Figure 10: A sequence of shadowgraph visualizations showing the evolution of the salt layer (dyed blue). (a) shows the initial growth of the salt layer from the source. In (b) the nose of the layer has destabilised to form an intrusion a few centimetres above the base of the tank. The intrusion has propagated along the full length of the tank leaving a two cell circulation in (c). Photographs (a) and (b) show approximately 45 cm at the left hand end of the tank above the heated half of the base and (c) shows the full length of the tank. All images show the full-depth of the tank.

Convection in complex geometries

M. A. Coman, G. O. Hughes, R. C. Kerr and R. W. Griffiths

Convection drives flows throughout the atmosphere and oceans, and in many engineering and industrial applications. Such flows are driven by buoyancy forces that arise from locally destabilising variations in temperature and/or chemical composition within a fluid. These convective processes force vertical and horizontal motion, and are the primary mechanism by which heat, mass and chemicals are transferred between parts of the fluid domain. In many practical situations the confining geometry is complex and has a dramatic influence on the flow. This year we have continued to study the convection in a two-chamber cavity that is heated and cooled on opposite endwalls (Fig. 11). This flow is forced to pass through a relatively small gap connecting the chambers, a geometry that is relevant to the flow over a sill between ocean basins, or through doorways in buildings. The introduction of the barrier between the two chambers severely disrupts the flow. However, recent measurements have led to the surprising conclusion that the flow adjusts so that the mass exchange and heat transfer through the gap is nearly independent of gap size, except when the gap is very small. Ongoing work will explore how the flow structure couples with the temperature field to produce such behaviour.

Figure 11. Dye visualization of the convective exchange flow between two connected chambers driven by heating and cooling of the left and right endwalls, respectively. A coupling between the complicated flow structure and the temperature field has been discovered that acts to maintain the mass and heat exchanged between the chambers.

Dynamics of ocean circulation driven by variable surface wind stress

A.E. Kiss

Horizontal circulation of the upper 1000m of subtropical oceans takes the form of asymmetrical recirculations in which a slow, equatorward wind-driven drift is returned in a narrow, rapid current flowing along the western boundary. These western boundary currents (WBCs), such as the Gulf Stream and East Australian Current, carry warm water poleward and are a significant component of the global climate balance. WBCs separate from the coast to form unstable meandering jets. This strong variability in a region of sharp temperature contrasts results in significant variations in ocean-atmosphere heat fluxes that have been implicated in climate fluctuations.

Over recent years numerous studies of idealised WBC jets have revealed a wide variety of behaviours, including modes of variability with timescales from months to decades. These studies used steady wind forcing, and show the intrinsic timescales of WBC variability. However wind forcing of the oceans has its own timescales of variability, including a strong annual cycle, leaving open the question of whether observed WBC variability is intrinsic to the ocean, or forced by the atmosphere.

Dr Kiss has undertaken numerical and laboratory experiments which aim to clarify this issue. These employed idealised models in which the intrinsic WBC instability is periodic, and used to investigate the jet behaviour as a function of the amplitude and frequency of periodic variations in the wind forcing. This has revealed a variety of phenomena including nonlinear resonance (in which the jet period is locked on to a rational multiple of the forcing period (see Figure 12) and chaos. The chaotic response is particularly interesting, as it produces variability at frequencies far lower than those of either the forcing or intrinsic jet instability. This indicates that complex, low-frequency variability may not be due to either the ocean or atmosphere in isolation, but could arise due to their coupling. The WBC behaviour shows remarkably close parallels to a simple mathematical model of a forced nonlinear oscillator, despite the fluid system having vastly more degrees of freedom.

Dr Kiss completed his ARC Postdoctoral Fellowship at RSES at the end of June, when he took up an appointment at the University of New South Wales at the Australian Defence Force Academy.

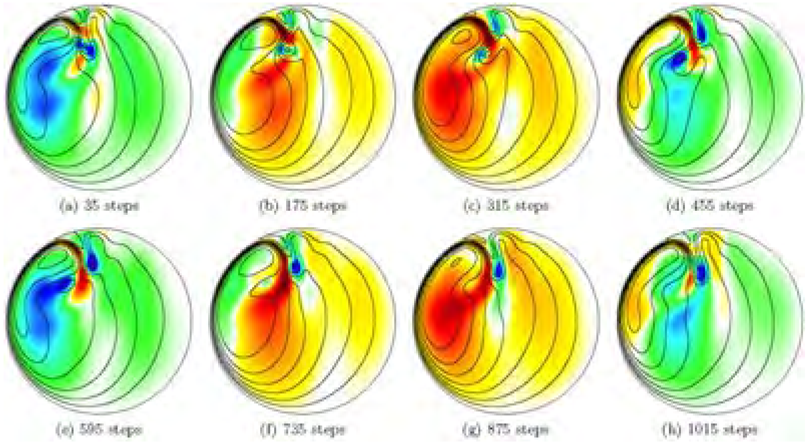

Figure 12: Eddy-shedding locked to double the forcing period, for wind forcing with a 10% fluctuation at 52% of the natural eddy-shedding period. The frames show two forcing periods, over which the flow completes one cycle. Streamlines indicate the complete flow, and colours show the perturbation relative to the unstable steady state (blue, green < 0 < yellow, red).

The role of the ocean in climate variability

A. McC. Hogg

This work focuses on how ocean variability in the midlatitudes may influence climate variability. The study depends upon the continuing development of a quasi-geostrophic general circulation model (Q-GCM), which is an idealised coupled ocean-atmosphere model (in collaboration with Mr J.R. Blundell of Southampton Oceanography Centre). The model is provides ocean-eddy resolving simulations (figure 13), which have lead to the realisation that the ocean does contribute to decadal climate variability in the midlatitudes. This project uses the APAC Supercomputing Facility and also involves collaboration with Prof. P. D. Killworth (Southampton Oceano-graphy Centre) and Prof. W. K. Dewar (Florida State University).

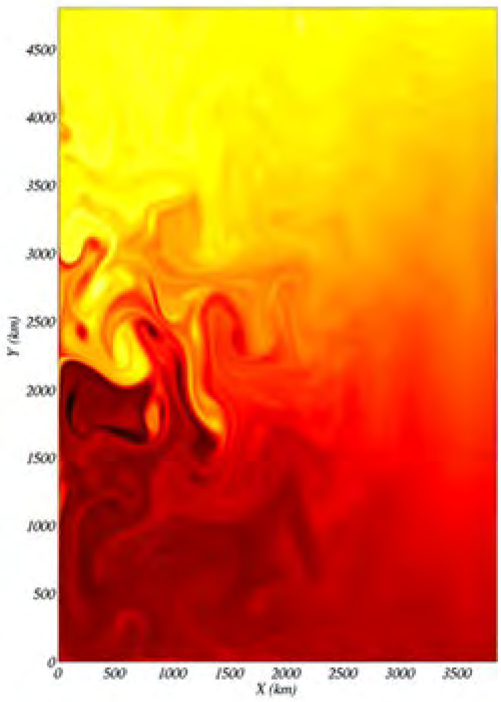

Figure 13a: Animated solution for the potential vorticity field in an eddy-resolving ocean simulation.

Figure 13b: The potential vorticity field in an eddy-resolving ocean simulation

Mixing in straits and overflows

T.J. Prastowo, R.W. Griffiths, G.O. Hughes and A.McC. Hogg

Straits and sills commonly exercise control over the rates of water transport out of estuaries and marginal seas, and between abyssal ocean basins. A new project commenced this year in which we are examining the amounts of mixing that occur in two-layer density driven exchange flows. The flow involves a strong velocity gradient between layers flowing in different directions, and this flow can become critical (ie. reach the speed of gravity waves on the density interface), so that there is a hydraulic control point in the strait or above the sill. The water mass flux through the constriction can also be influenced by mixing between the two layers. We have carried out experiments in a long channel (figure 14) and determined the amount of mixing (as a function of the density difference and constriction width), as well as the effect of the mixing on the exchange rates. The mixing can be described in terms of an efficiency - the proportion of the available potential energy (released by the flow over a given time) that goes into raising the density field by vertical mixing. We find efficiencies ranging from 8% to 17% for the early stages of exchange before the flow is influenced by the channel endwalls, and an efficiency of 12% when integrated over the complete run-down from the initial two homogeneous reservoirs to a final state with no horizontal gradients and no motion.

Figure 14: A movie of the exchange flow through a horizontal constriction in a laboratory water channel,
showing the billow instability and turbulent mixing.

Wake flows with upstream disturbances

M.J. O'Byrne and R.W. Griffiths

Coastal headlands and islands generate strong wakes within coastal currents. The wakes affect dispersion of pollutants, nutrients and sediment.
Wake flows are extensively studied for the case of a steady, uniform incident flow, whereas real flows are characterised by turbulence and large disturbances, which can alter the wake behaviour through interaction of the disturbances with the unstable shear flow.
This project has commenced with preliminary experiments in which a simple model headland is towed along the wall of a tank, generating a wake.
The on-coming flow is perturbed by suitable arrays of smaller obstacles placed upstream of the headland, and the structure of the wake is measured.
At this stage the observations are qualitative, and show how the wake instabilities can lock onto frequencies present in the on-coming flow.
PhD student Ms M.J. O'Byrne took part in a research cruise by the Southern Surveyor to measure wake flow at Nth Solitary Island in September.
This project (in collaboration with J.H. Middleton, University of New South Wales) was granted funding for 2005-2009 by the ARC.

Earth Physics - Geodynamics

Annual Report 2004

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CADI

CENTRE FOR ADVANCED DATA INFERENCE 2004

CADI activities

A result of the Research School of Earth Sciences' 2003 strategic planning exercise was to provided funding for a new Centre for Advanced Data Inference (CADI). The Centre's main goal is to develop and use state-of-the-art computational methods to analyze complex datasets and model Earth processes combining forward and inverse modelling techniques. On August 12th 2003 CADI was launched together with the TerraWulf computational facility which was built by CADI directors Jean Braun and Malcolm Sambridge.

The Centre's operations are based on collaborative projects with other groups/centres in the Earth Sciences which are supported through partial funding of doctoral and post-doctoral fellowships, and an extensive visitor program. The Centre also provides access to parallel processing on a large cluster of performance PC's (called TerraWulf) funded by an Australian Research Council LIEF grant.

The main body of the report provides a survey of the strands of work in CADI during 2004. This year projects have been conducted in surface processes, geomorphology, thermochronology, computational geophysics, seismology, airborne geophysics, and environmental inverse problems. Work on computational simulation and inversion continues in CADI with strong links to other groups in the school such as Geodynamics and Seismology, within the Earth Physics area. One highlight of the year reported on is the development of the CADI inversion toolkit whereby CADI visitors and project participants have an simple interface to both software and hardware facilities.

The TerraWulf cluster, jointly funded by the ARC, the ANU MEC, RSES and collaborators from the University of Melbourne, MacQuarie University, the University of Western Australia, Geoscience Australia and Dalhousie University in Canada, was used in most of the projects reported on here.

Late in the year CADI co-director Jean Braun departed for a professorial position at the Univ. of Rennes, France. Jean holds an adjunct faculty position at RSES and intends to continue collaborating on projects in the future.

CADI toolkit for parallel computing

P.Rickwood

To complement the purchase and installation of the terrawulf cluster, CADI has, in the last year, also developed software for large-scale parallel computing.

The principal purpose of the CADI toolkit is to make it easy for people with little or no parallel programming experience to take advantage of the terrawulf cluster. In order to achieve this purpose, the CADI toolkit aims to provide three important facilities:

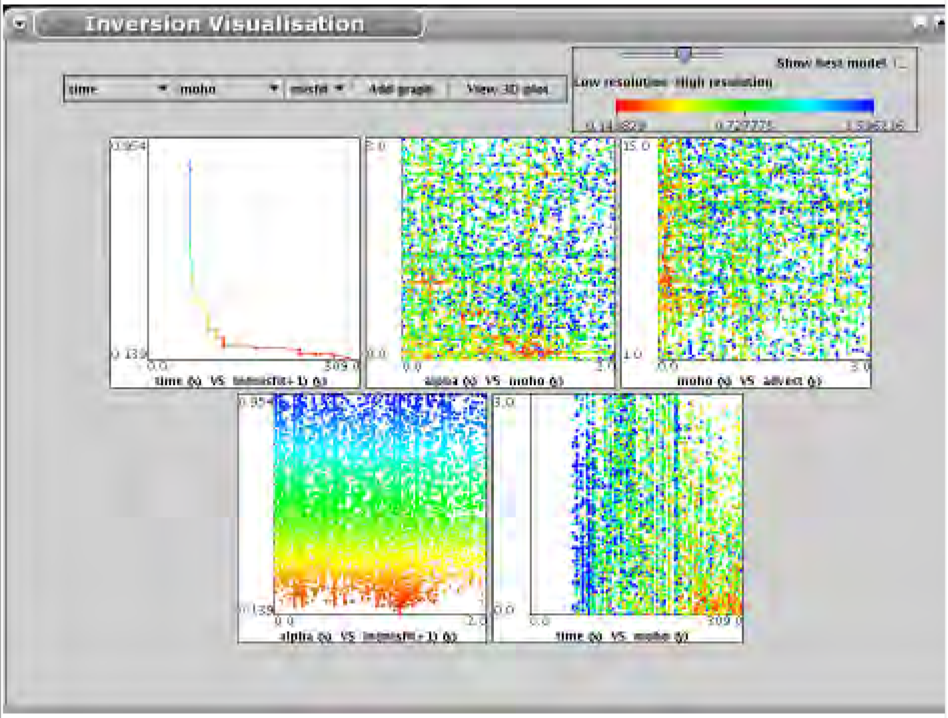
1. Reduce the amount of non-science related programming work, especially distributed programming, that scientists need to do before they can take advantage of the terrawulf's computing power. Scientists should be able to concentrate on their computation, and let the toolkit take care of distributing that computation.
2. Provide plotting and visualisation aids that update in real-time to allow scientists to better understand the nature of their computation. The immediate feedback that such real-time visual aids provide distinguishes the terrawulf from other supercomputing facilities (like APAC), where jobs are typically run in batch mode.
3. Provide efficient, robust, and easy to use distributed implementations of common algorithms for computationally intensive tasks like geophysical inversion.

Our initial focus has been on non-linear gradient-free inversion, as this has so far been the principal task performed on the terrawulf. Thus far, the toolkit provides distributed implementations of 5 different optimisation/inversion algorithms (Neighbourhood algorithm, simulated annealing, genetic algorithm, uniform monte carlo, Markov chain monte carlo). The toolkit also includes additional support for density estimation with the Markov chain monte carlo algorithm.

Features of note in the toolkit:

- **Easy to perform distributed inversion**

  Terrawulf users can use the supplied algorithms without writing a single line of extra code. In order to perform a distributed inversion, a user need only program a single subroutine that calculates the misfit/error of a model in parameter space. After this has been done, the user can use the toolkit's GUI to select any available algorithm to perform their inversion.

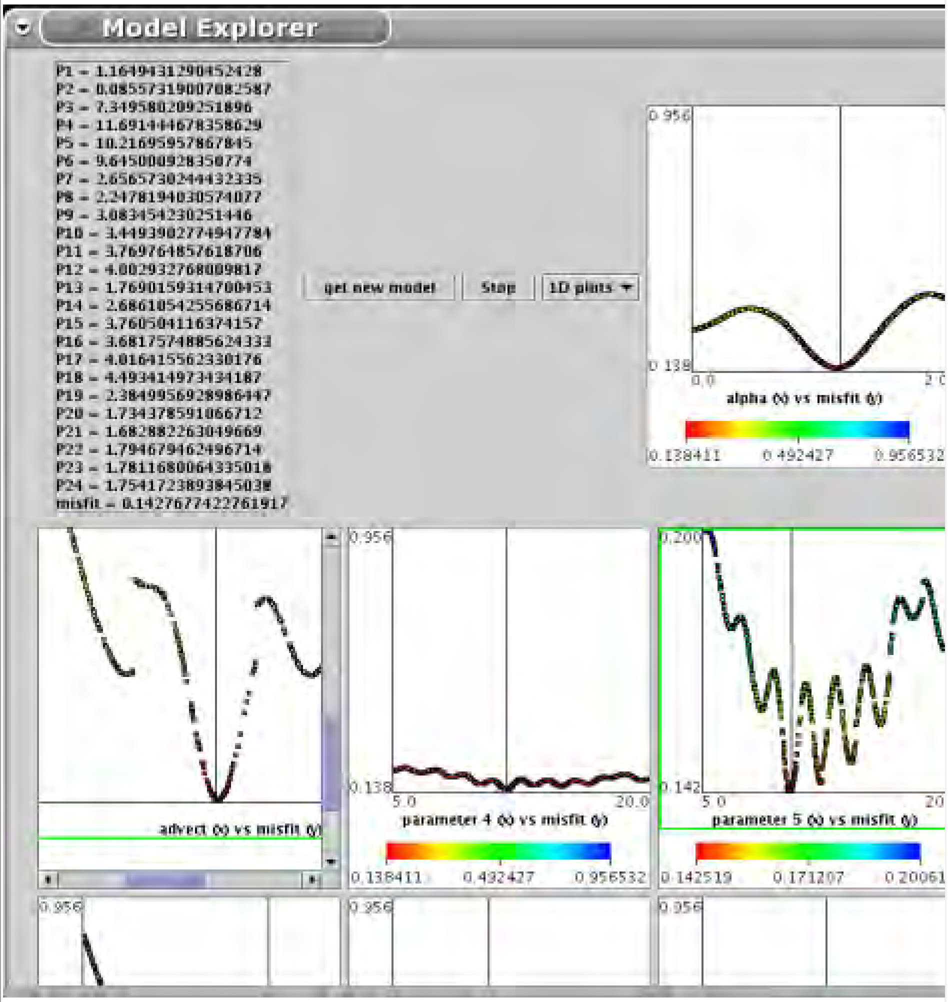


Watching an inversion in real-time

Users are provided with visual feedback as their inversion proceeds, so that they can easily tell things like whether the inversion is converging to a solution.

- **Very fast sensitivity analysis**

The CADI toolkit, using the same code the user supplies for their inversion, is able to determine how sensitive a particular parameter or pair of parameters are. That is, it performs single and pair-wise sensitivity analysis of *all* parameters in an inversion. Furthermore, it does this in parallel, and plots the results in 2D or 3D. Performing such analysis for even relatively small number of parameters is typically too time-consuming to do on a single computer. On a 128 node cluster like the terrawulf, results can be immediate.



Real-time plots of parameter sensitivity

The ability to calculate (quickly, in parallel) and then view the error/misfit surface of parameters can be a great aid in understanding the complexity of a problem, the extent of non-linearity in the problem, the existence of discontinuities, and so on. It also allows you to verify, visually, that the inversion algorithm has produced a locally optimal model.

- **Fail-safe computation**

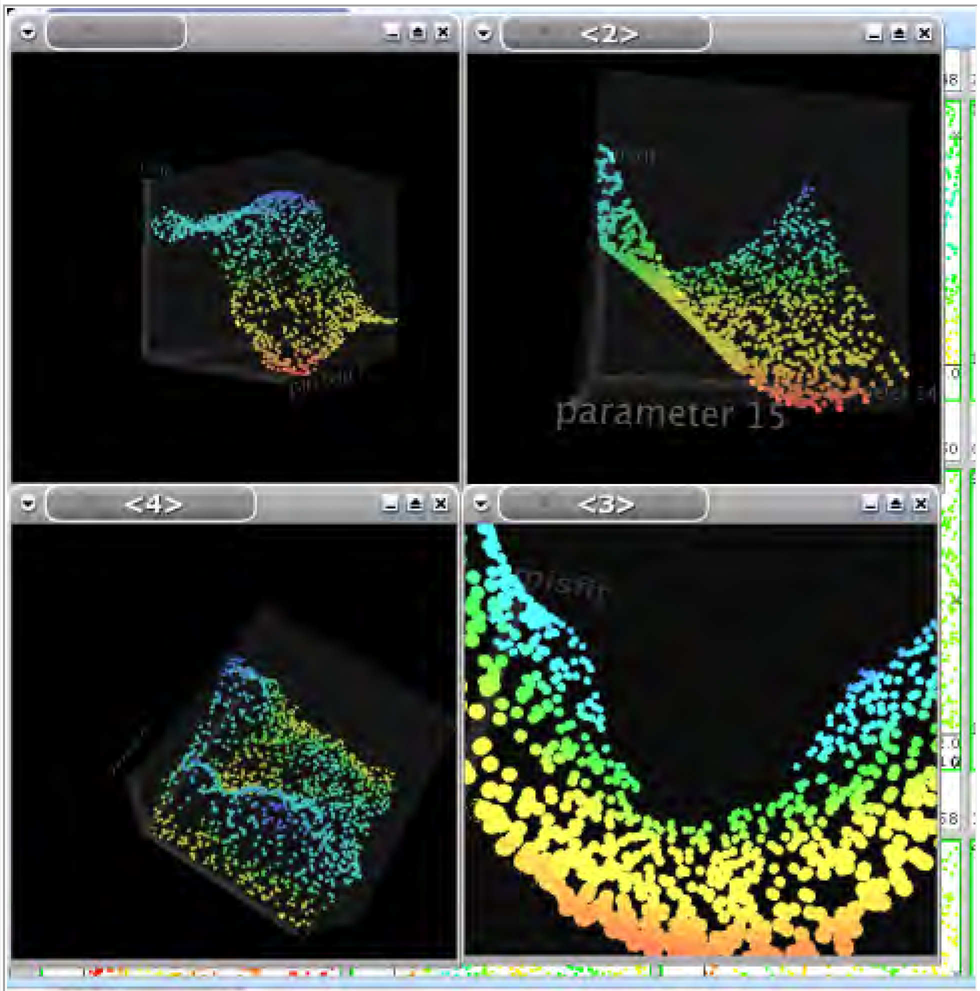
  The larger the number of machines taking part in a computation, the higher the chance that one of them will fail mid-computation. The CADI toolkit will continue working even if individual computers fail due to hardware/software faults, or because of a bug in the user's code.

- **Smart load-balancing algorithms**

  Naively implemented parallel algorithms often suffer from significant overhead. For both optimisation and sensitivity analysis, the CADI toolkit algorithms are multi-threaded, and have been designed with smart load balancing features, so that all computers are working all the time, instead of sitting around waiting for other computers to finish 'their part' of the distributed computation.

- **Visualisation aids**

  In addition to being able to watch an inversion in real-time, and view standard 2D plots and graphs that update in real time, the CADI toolkit includes OpenGL code to view (and rotate, and zoom) in 3 dimensions. This can be a valuable aid to understanding the structure of the parameter space you are searching, or whether bounds for particular parameters are set appropriately.



3D interactive visualisation

Users may manipulate (rotate, zoom, pan) 3D plots easily with a mouse.

- **Data export facilities**

  As already mentioned, the toolkit does 2D and 3D plots, and users may save these for printing, but users may also export data into simple text files for use with Matlab, Excel, xmgrace, or other plotting/visualisation programs.

- **Logging and replay facilities**

  Without requiring the user to write any code, the toolkit can log results to a plain text file (if so directed) for later analysis. Users may also ask the toolkit to 'replay' a previous inversion.

Local users of the CADI toolkit have included PhD students (Frederic Herman, Amos Aitkin) post-docs (Anna Pulford), and academic staff (Jean Braun, Malcolm Sambridge, John Chappell). Jean Braun has expressed interest in using the toolkit at the University of Rennes.

We plan to continue development of the toolkit as needed by its users. Current plans include additional visualisation support (plotting of iso-surfaces and vector fields), and ensemble evaluation.

The CADI toolkit is also capable of running on desktop machines over a local network, and we plan to assess its suitability for forming a 'virtual' cluster using idle desktop PC's.

More information on the CADI toolkit can be found on the CADI tookit homepage.

Efficient parallel search using the Neighbourhood Algorithm

P. Rickwood &amp M. Sambridge

Over the past year, we have undertaken development of the Neighbourhood Algorithm, to improve its performance as a distributed/parallel algorithm for geophysical inversion. This has involved re-formulating the Neighbourhood algorithm so that it is equivalent (in a probabilistic sense) to the existing formulation (described on the NA home page), but is capable of being more efficiently parallelised. A parallel implementation has been implemented which can be an order of magnitude faster than the currently available parallel implementation.

The existing (old) parallel implementation of the NA used simple MPI capabilities to achieve a limited form of parallelism. However, this parallelism has two important limitations:

1. **Barrier synchronisation overhead**

   In a naive parallel implementation of the NA, the objective function (i.e. the forward problem) is solved (with different parameter values) on each computer and the results are collected. If we wait for all computers to complete their computation, we can waste valuable clock cycles, as *all computers* must wait for the *slowest* computer to finish. If we take a staged running race as our analogy, the naive implementation requires that every runner wait, *at every stage* for all other runners to catch up. We can eliminate this waste entirely by removing the need to synchronise at barriers.

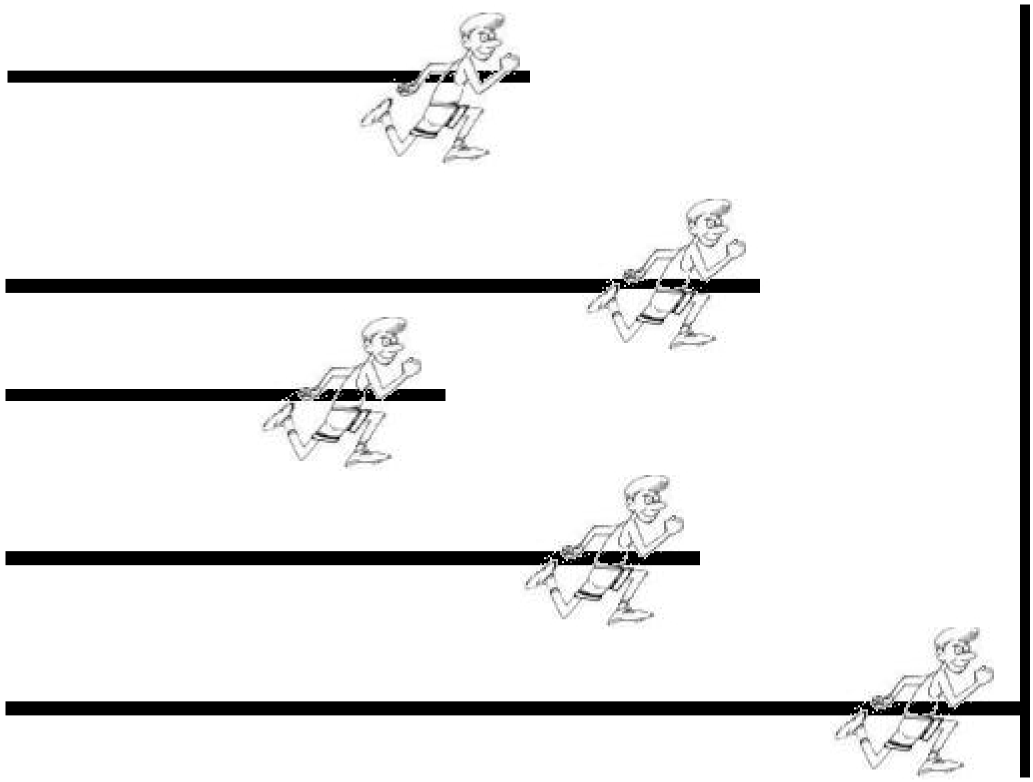


Figure 1: Barrier synchronisation overhead.
*If barrier synchronisation is used, the performance of the algorithm as a whole is determined by the **slowest** participant. Everyone else has to wait (doing nothing) until the slowest participant finishes.*

2. **Book-keeping overhead**
   The existing (old) parallel implementation of the Neighbourhood Algorithm only distributed the task of evaluating the objective function. The other elements of the algorithm (calculating the Voronoi cell structure and generating new models) were performed on every computer -- a large waste of computational resources. The new implementation distributes these other elements as well as the objective function evaluation.

The re-worked implementation of the NA takes advantage of more sophisticated MPI capabilities (asynchronous non-blocking send-receive), that, together with minor modifications to the algorithm itself (that preserve the essential nature of the algorithm), allow for a vastly more efficient implementation. Barrier synchronisation overhead is eliminated entirely, and book-keeping is distributed across all computers involved in the computation. Figure 2 demonstrates the speed-up achieved by the new implementation of the NA algorithm.

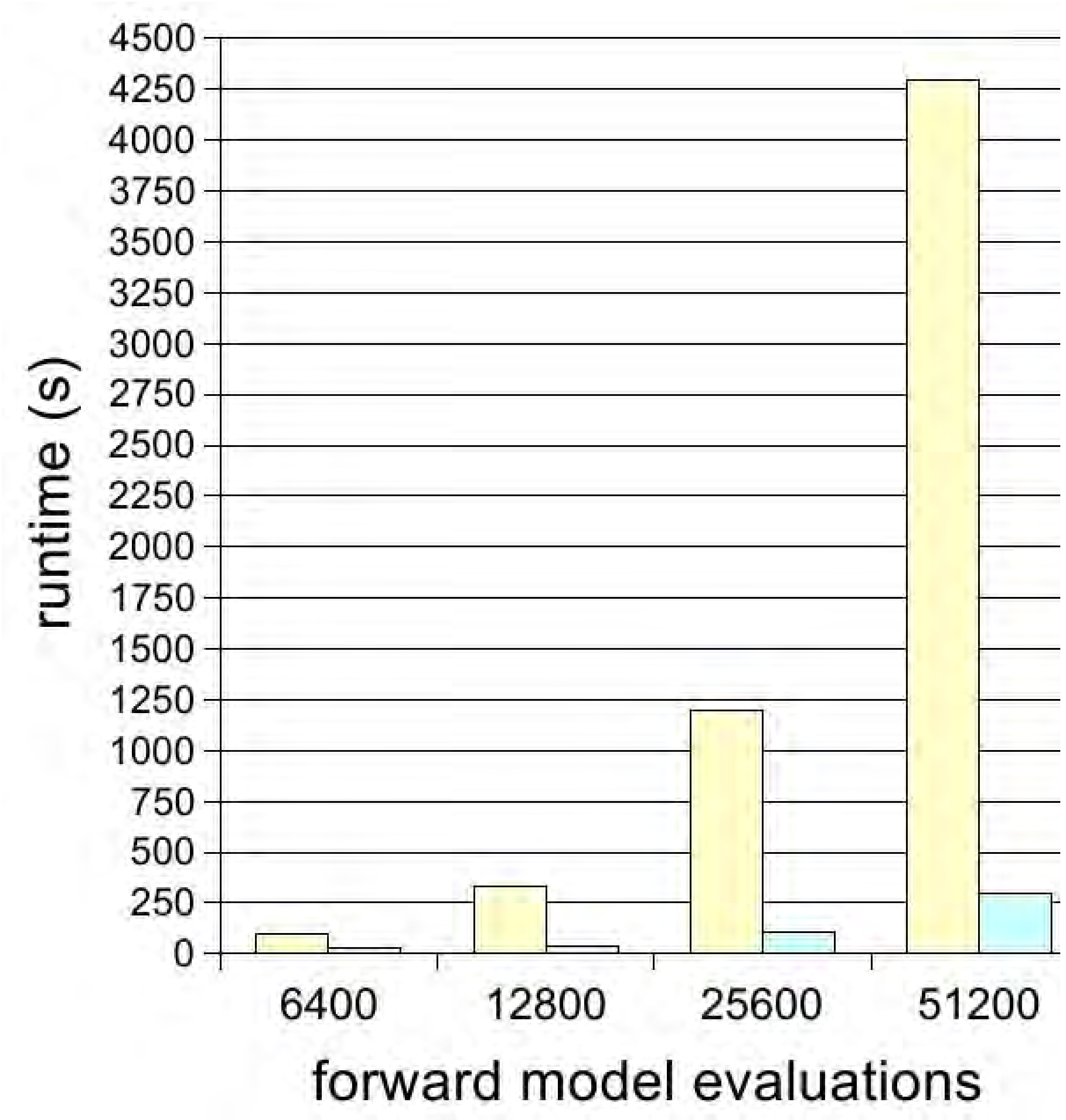


Figure 2: Performance -- old versus new
Timing results on a 128-node beowulf cluster for the receiver function inversion problem described in [Shibutani et al.](), illustrating the sort of dramatic performance increase the new algorithm can produce.

The improvement in efficiency is most appreciable for problems with objective functions that are relatively quick (&lt 1 second) to evaluate, and for problems where there is a large degree of variability in the time taken to evaluate the objective function [1].

Other work and improvements

In addition to being more efficient, the new implementation of the Neighbourhood Algorithm is also more robust, as the re-formulation of the algorithm allows an implementation that is resistant to the failure of any individual node. In other words, the parallel implementation will continue to work even in the event that nodes fail mid-computation. As clusters become larger (and cheaper), and parallel computing becomes the norm, this feature will become especially important.

The Neighbourhood algorithm has also been re-implemented in the Java programming language, to take advantage of Java's cross-platform portability. This means that the Neighbourhood Algorithm can now be distributed in pre-compiled form, and run on any platform without the need for recompilation. In addition, the Java implementation of the Neighbourhood algorithm can now be easily distributed with the CADI Toolkit, and benefit from the point-and-click interface and other plotting and visualisation capabilities of the CADI toolkit.

We plan to make both Fortran and Java implementations of the parallel Neighbourhood Algorithm available from the NA home page. Future development may involve some re-engineering of the second stage of the Neighbourhood Algorithm (the appraisal stage) for more efficient parallel execution.

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[1] This may happen in varying circumstances. In some cases, the time taken to evaluate the objective function is parameter dependent. In other cases, the computers performing the computation are not equivalent (in terms of speed), or have varying loads.

[2] Details of which can be found in:
Shibutani, T., Sambridge, M. &amp Kennett, B., 1996. Genetic algorithm inversion for receiver functions with application to crust and uppermost mantle structure beneath Eastern Australia, *Geophys. Res. Lett., 23 (14), 1829-1832.*

Inversion of coral height and age data for sea-level variations in the Huon Pennisula

P. Rickwood, M. Sambridge, J. Chappell, &amp N. Detchon

Over the past year, we have developed a new approach to inversion of coral profile and age data for past sea-level variations. Corals grow in response to the amount of light they are exposed to, which itself is a function of depth below sea-level. Against the fast moving tectonic uplift experienced in the Huon Pennisula region of Papua new Guinea, the profile of coral terraces are preserved as they emerge from the sea. The height data together with exposure age measurements provides a valuable data set to contrain past sea level variations.

Given an adequate mathematical model for coral growth rate as a function of depth it is possible to predict the position and age of each terrace if the sea-level height is known through time. This constitutes the forward problem, i.e. given an assumed sea-level one can predict corresponding observations (height and age) which can be compared to the available measurements. To address the inverse problem of constraining sea-level from the coral observations, we have used an ensemble inference approach known as Markov Chain Monte

Carlo. In this approach we generate many (millions of) sea-level histories in a randomized fashion where the sampling of parameter space is guided by fit to data.

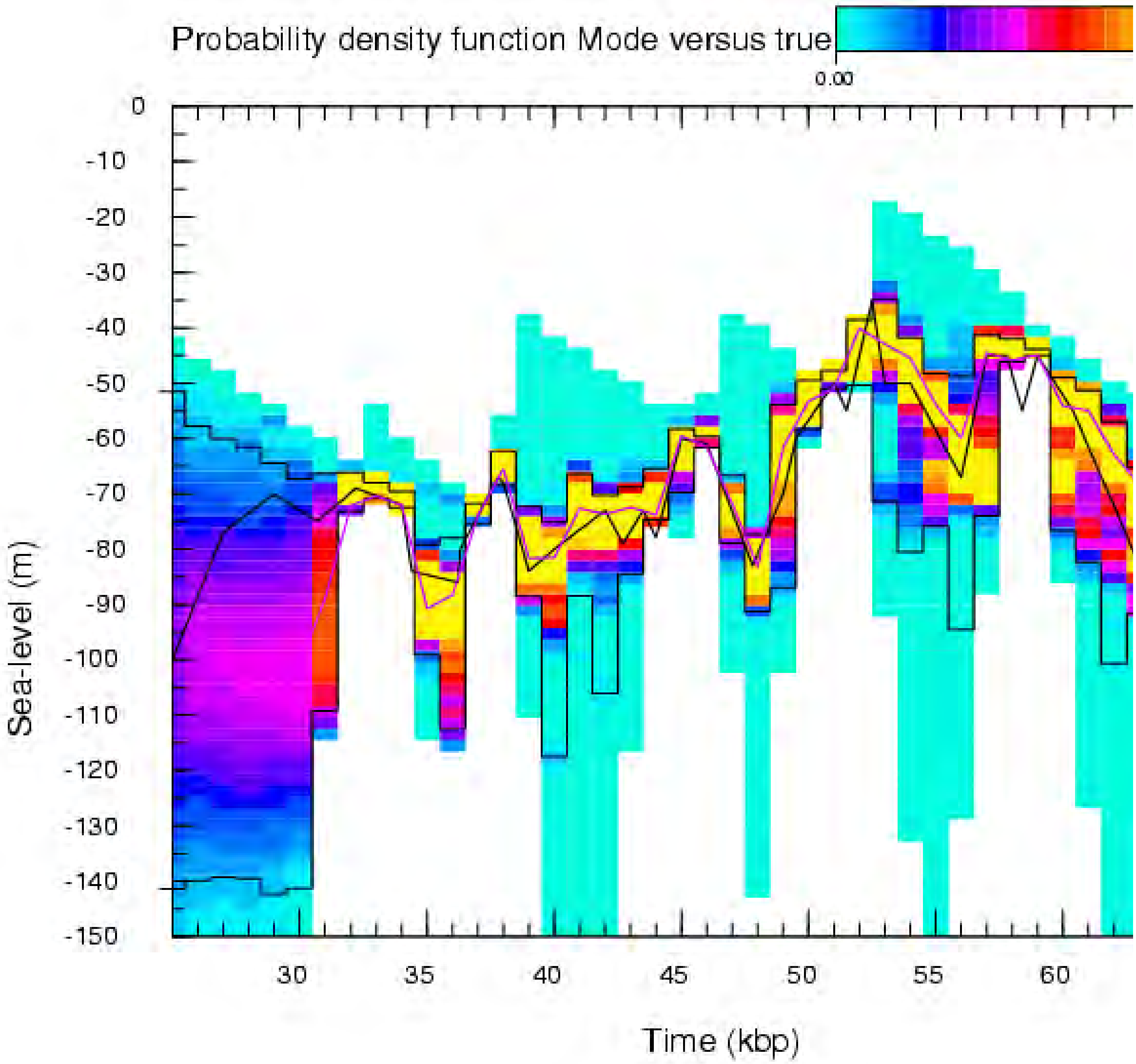

Figure 1: Results of the MCMC algorithm for a synthetic case. Here the coloured strips show the estimated Marginal Probability Density distributions for the past sea-level in each of fifty time intervals. These indicate the relative degree of constraint available with the data. The black line is the true sea-level, the purple line joins up the peaks of the marginal PDFs (known as the mode) which represents the sea-level with the highest probability within each time interval. This can often be a closer reproduction of the truth than the overall best data fit model (not shown). Black bars represent 95% confidence intervals fro sea level within each period calculated from the marginals.

We have used the Terrawulf parallel computing facility to generate many millions of potential sea-level histories in each run of our MCMC algorithm. Through a series of synthetic numerical experiments we have been investigating which properties or combinations of the measurements best constrain past sea-level. Our sampling strategy has been refined to the point where we can now produce probability density estimates for sea-level through time. Figure 1 shows an example of a synthetic case. The width of the probability density functions for each time interval indicate the degree of constraint. A typical result is that the peaks of the probability density profiles are often a better fit to the true sea-level than the best fitting model found in the ensemble. With the technique now refined we are applying the algorithm to all observations collected from coral terraces in the Huon Pennisula.

FAST AND ROBUST TOMOGRAPHIC IMAGING IN 3-D

N.Rawlinson &amp M. Sambridge

The fast marching method (FMM) is a grid based numerical scheme for computing first-arrival traveltimes to all points in a velocity field via finite difference solution of the eikonal equation. FMM distinguishes itself from other grid-based eikonal methods by combining unconditional stability and rapid computation, making it a truly practical scheme for many seismic applications including seismic tomography.

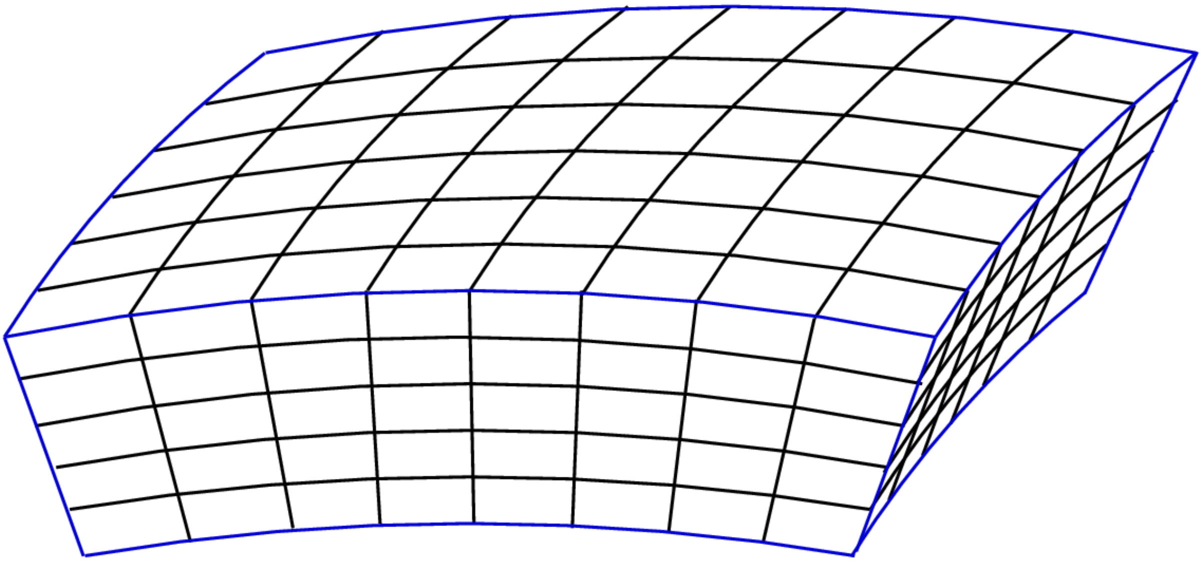

Figure 1. 3-D mesh in spherical coordinates used to control the shape of the continuous velocity field defined by cubic B-splines. FMM is used to predict traveltimes from the base of the model to the surface.

To date, FMM has been used in the migration of seismic reflection images, but not seismic tomography. We apply FMM in the context of 3-D teleseismic tomography, which uses relative arrival time residuals from distant earthquakes to image wavespeed variations in the crust and upper mantle beneath a seismic array. Lateral variations in structure are confined to a 3-D local model volume beneath the array, which is described by a mesh of velocity nodes in spherical coordinates (see Figure 1). Cubic B-splines are then used to define a smooth, continuous and locally controlled velocity field. Traveltimes to the base of the model are obtained using predictions from a global reference model (e.g. ak135). FMM is then used to compute arrival time residuals for a given 3-D velocity model. An iterative non-linear inversion procedure, which successively applies FMM and an efficient subspace inversion scheme, is used to adjust the model parameters in order to satisfy data and regularization (damping and smoothing) constraints.

3–D teleseismic tomography of the lithosphere beneath Tasmania, SE Australia: summar		
Number of velocity nodes (unknowns): 48,708	Number of phases: 110	Number o
Parameterization scheme: Cubic B–splines	Number of receivers: 72	CPU time
Coordinate system: Spherical	Number of ray paths: 6,520	RMS picki
Node spacing in depth: 10.0 km	Traveltime prediction scheme: FMM	Initial RMS
Node spacing in latitude: 0.10°	Inversion scheme: 10–D subspace	Final RMS
Node spacing in longitude: 0.14°	Regularization: Damping & smoothing	Variance r
Number of sources: 101	Reference model: modified ak135	Maximum

Figure 2. Summary of inversion parameters for an application of the new scheme to observational data. Note the rapid CPU time despite the large number of parameters and the fact that the non-linearity of the inverse problem is taken into account.

Application of the new method to a dataset collected in Tasmania as part of the TIGGER experiment (see companion article on Tasmanian lithospheric structure) shows that the new scheme is rapid and robust. For a problem involving 6,520 ray paths and 48,708 unknowns, the scheme only takes 18 minutes of CPU time (on a 1.6 GHz Opteron workstation) to complete six full iterations (see Figure 2). Synthetic tests also show that the new scheme is capable, with good data coverage, of recovering complex high amplitude structure with no sign of instability. We are currently extending the scheme to permit simultaneous inversion of multiple datasets (teleseismic, local earthquake, wide-angle, coincident reflection) for structures described by both continuous variations in wavespeed and interfaces.

Calibration and inversion of airborne geophysical data

R. Brodie &amp M. Sambridge

During 2004 a new approach for the calibration, processing and inversion of airborne frequency domain electromagnetic data was developed and then tested on synthetic and real datasets. It is dubbed the "Holistic" approach because the overarching theme is the consideration of calibration, processing and inversion simultaneously in contrast to the conventional approach of treating them as independent and sequential steps. It is formulated as a single large inverse problem. Parameters that define gain, phase, bias and height calibration errors in the data and the parameters that define a single laterally continuous 3-D conductivity model are the unknowns to be estimated. Figure 1 illustrates how the multiple B-spline meshes provide a mechanism for coupling and cross constraining all of the airborne and geoelectric data. Local 1-D conductivity structures are generated from the spline nodes at the 16 adjacent mesh intersections along with local calibration values then used as input into the forward modelling routine of the inversion.

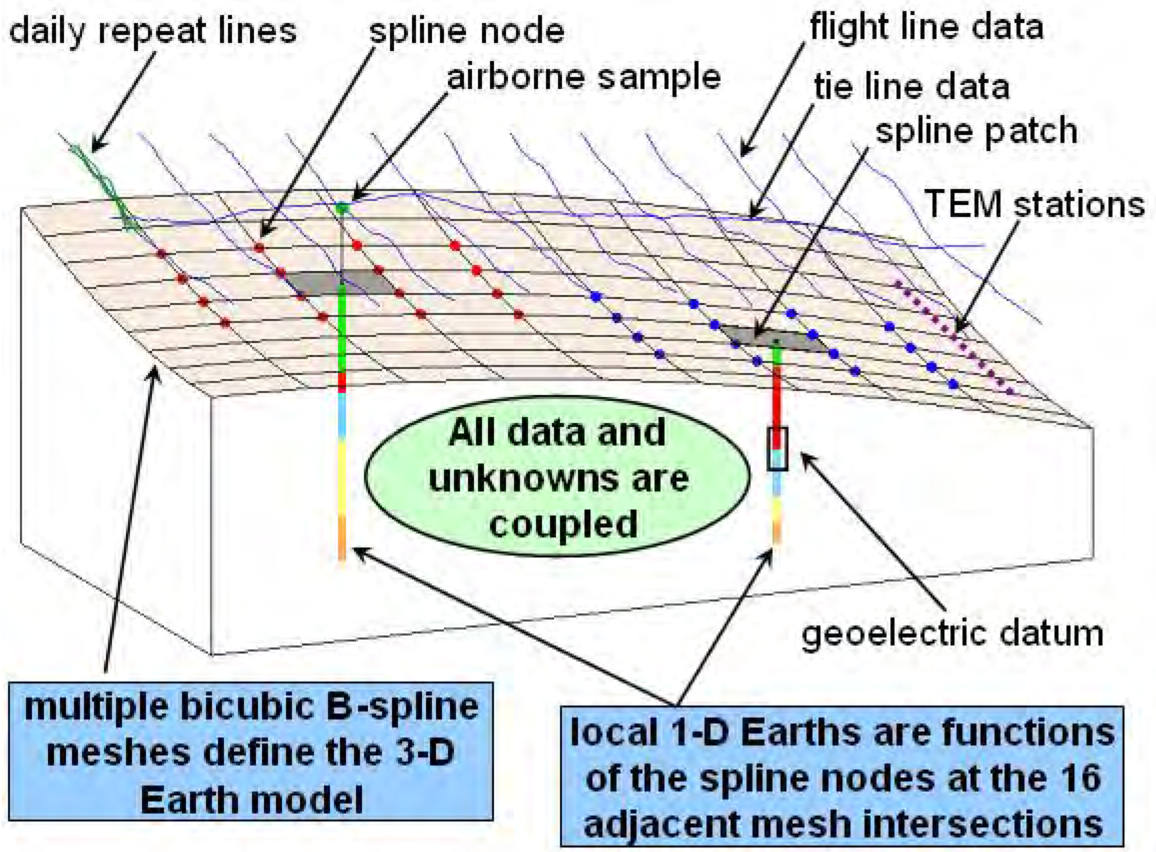

Figure 1:   Schematic representation of the main elements of the holistic inversion formulation.

The key differences from previous processing and inversion techniques are:

- The calibration model concept of Deszcz-Pan et al. (1998) is adopted to account for systematic calibration error, however we invert for calibration model parameters and conductivity-thickness model parameters simultaneously;
- A single continuous 3-D conductivity-thickness model, represented by locally-supported bicubic B-spline basis functions, is estimated as opposed to independently estimating then later stitching together many separate 1-D conductivity-thickness models;
- All of the airborne samples (including those along tie-lines and daily-repeat-lines) are inverted together, instead of in separate sample-by-sample inversions;
- In addition to the airborne data, we use independent observations of conductivity and interface depths as input data in the inversion algorithm.

Through consideration of calibration, processing and inversion together the propagation of errors through a sequence of processing steps that often occurs is eliminated. It also avoids the manual, time-consuming and often costly correction-inversion-correction iteration paradigm of conventional techniques. The B-spline parameterisation allows a choice of scale length of conductivity variation that reflects the airborne system's footprint size and any a priori perceptions about the scale length of geological variation. In this way subsurface conductivity can be represented with as few parameters as necessary - there are more independent data per unknown and hence inversion stability is improved. The new approach also exploits the most useful feature of airborne geophysical data - the coherency that exists in the data. This cannot be capitalised upon by conventional inversion methods that deal with each airborne sample independently.

A synthetic conductivity model and calibration model were used to generate synthetic uncalibrated data, to which Gaussian random noise was added. These synthetic observed data were then inverted with the holistic inversion algorithm. Figure 2 shows that the inversion algorithm accurately estimated the parameters of the synthetic models.

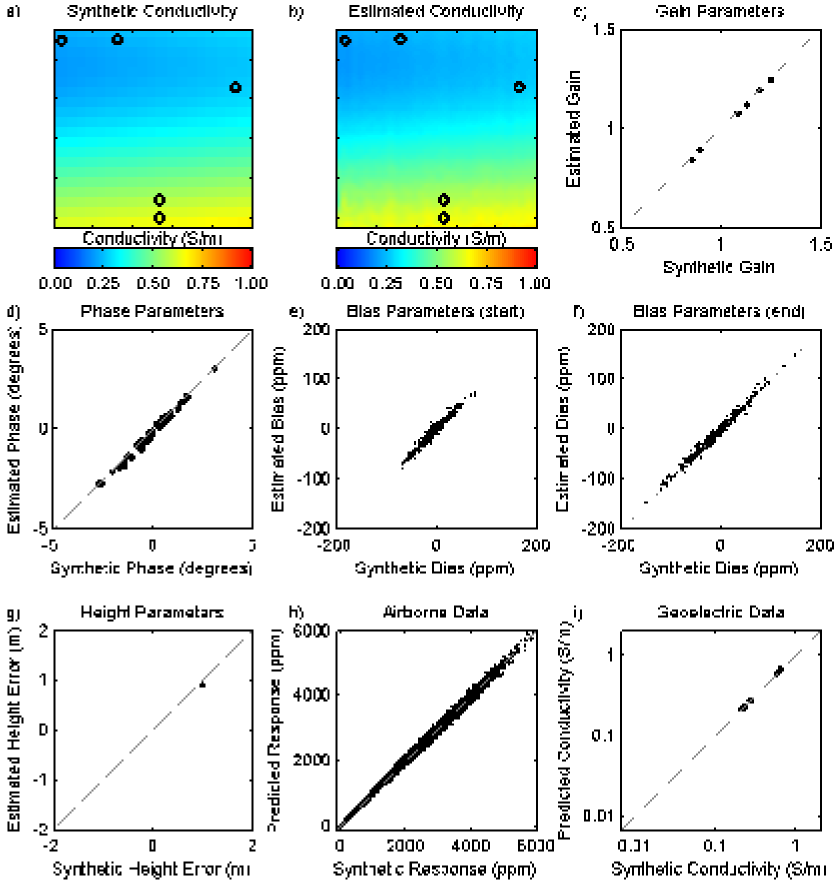

Figure 2:   Comparison of actual parameters with estimated parameters and synthetic with predicted data from a synthetic test.

The method was tested on a ten kilometre square subset the Riverland Airborne Survey from South Australia. The real raw data were inverted with the holistic inversion algorithm to produce a constrained five layered conductivity-thickness model and the parameters of a calibration model. Data from five downhole conductivity logs and observation of watertable depth (depth to bottom of third layer) were also included in the inversion. There were 254214 data in total and 30553 unknowns to be estimated. The resultant conductivity thickness model is shown in Figure 3.

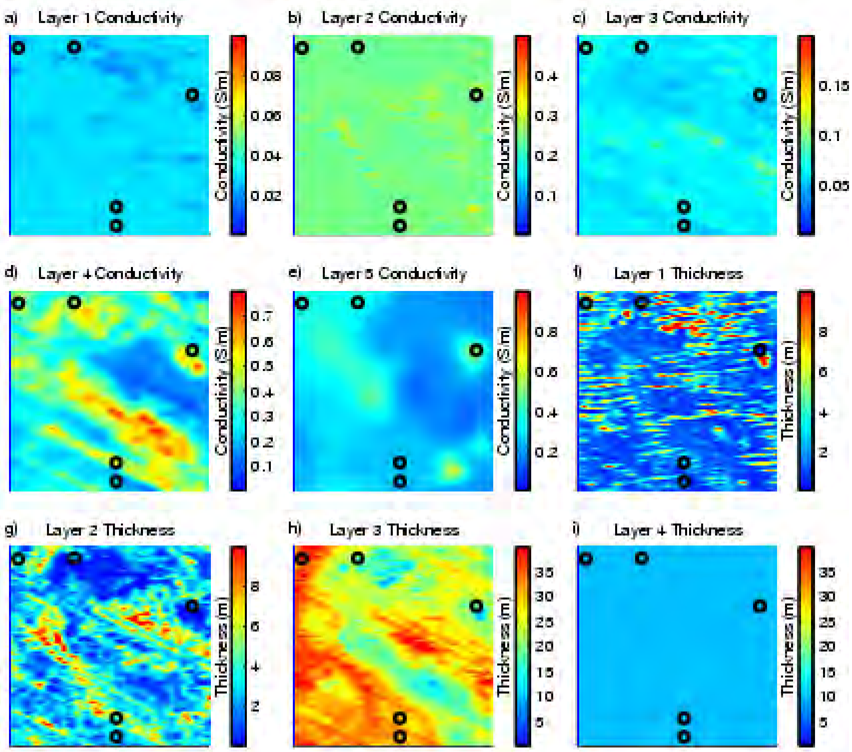

Figure 3:   Conductivity-thickness model resulting from the holistic inversion of part of the Riverland Survey dataset. Circles represent the location of the downhole conductivity logs included in the inversion.

The results shown in Figure 3 are free of features that are symptomatic of systematic calibration error, like artefacts elongate in the north-south flight line direction. This is a very satisfying outcome for the inversion of raw airborne survey data. The images are also consistent with our a priori expectation of the geological variation and published studies relating to the same dataset. For example Figure 4 shows a comparison of the estimated gain values for all six frequencies of the airborne system with equivalent (reciprocal) values from a separate study.

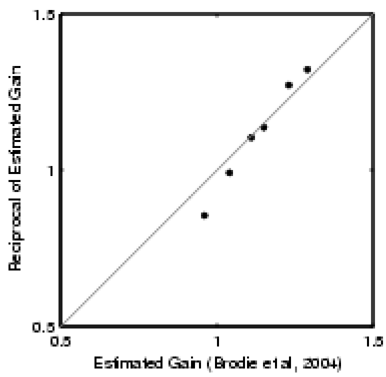

Figure 4:   The reciprocal of gain values for the six frequencies estimated by the holistic inversion compare favourably with gain correction (i.e. reciprocal of gain) values estimated by Brodie et al (2004) for the same dataset.

It is expected that the holistic approach will be able to be applied to the calibration of time domain airborne electromagnetic systems as well, particularly in the estimation of unknown elements of the system geometry in towed bird fixed wing systems. It is also anticipated that bird manoeuvre noise can be accounted for in towed rigid boom helicopter systems with the holistic approach. These possibilities will be researched during 2005.

References

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Deszcz-Pan, M., Fitterman, D.V., and Labson, V.F., 1998, Reduction of inversion errors in helicopter EM data using auxiliary information: Exploration Geophysics, **29**, 142-146.

A Thermal and Reheological model for the Australian Continent

A. Pulford, J. Braun &amp U. Faul

The strength of the continental crust is predominantly controlled by temperature and crustal thickness, with composition playing a minor role. We have investigated the deformation of the Australian continent using a 1D uncoupled mechanical model with vertically varying rheology and temperature. Due to the strong role played by temperature, we have employed a new method to constrain the thermal structure of the continent by using laboratory measurements of shear wave speeds to interpret the a tomographic seismic model (basd on the results of the SKIPPY experiment), observed surface temperature and estimates of surface heat flow. The results we obtain are consistent with those of other studies: hotter geotherms are predicted for eastern Australia compared to central and western Australia. Using these temperature estimates we were able to construct a rheological model for the Australian continent which can be tested against independent estimates of stress and strain rate. The strain rate estimates were derived from a statistical analysis of a continental-scale earthquake database.

Our results show that the distribution of current deformation in the Australian continent can be explained in terms of lateral variations in strength resulting from horizontal temperature gradients in the crust and mantle lithosphere. There are, however, discrepancies between the predicted strain pattern from our `best fitting' rheological model and that derived from the earthquake database. In Western Australia, regions that are characterized by cold geotherms, and should therefore be strong, are currently deforming at noticeable strain rate. We postulate that in these regions the crust and mantle parts of the lithosphere are mechanically decoupled. This hypothesis cannot, however, be tested by our current one dimensional model and will need the use of a more advanced three-dimensional model of lithospheric deformation being currently developed. The depth of the brittle-ductile transition can also be extracted from our model and indicates that this transition is uniformly shallow (i.e. <$10 km depth).

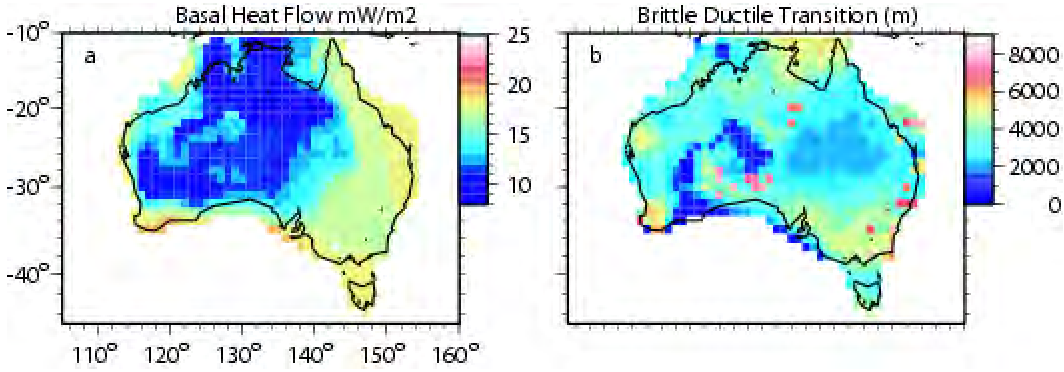

Figure 1: Predictions of the thermo-rheological model: the depth to the brittle-ductile transition and the mantle contribution to the vertical heat flow.

Constraints on the rate of post-orogenic erosional decay from low-temperature thermochronological data

J. Braun &amp X. Robert (Ecole Normale SupÃ©rieure de Lyon, France)

We have used Pecube, a numerical method to solve the heat transport equation in the Earth's crust, including the effects of a changing, finite-amplitude topography and the resulting flexural isostatic rebound, to investigate whether low temperature thermochronological datasets can be used to constrain the rate of surface evolution during the post-orogenic phase of a mountain belt. We demonstrated that accurate estimates of the amount of relief loss can be obtained by applying the spectral method developed by Braun (2003) based on the relationship between age and surface elevation as a function of topographic wavelength. We also showed that the rate at which topography decays with time following cessation of tectonic activity can be constrained from estimates of exhumation rate derived from the slope of age-elevation profiles collected across short wavelength topography.

Using the Neighbourhood Algorithm (Sambridge, 1999) to perform a thorough search through parameter space, we were able to find a tectono-morphic scenario that predicts age distributions compatible with a thermochronological dataset collected in the Dabie Shan of eastern China by Reiners et al, (2003). We demonstrated that, in the Dabie Shan, the mean topograhic relief has decreased by a factor of 2.5 to 4.5 during the last 60-80 Myr, while the mountain belt experienced a mean exhumation rate of 0.01 to 0.04 km/Myr. We confirm the conclusions of Reiners et al (2003) that there is no need to invoke a discrete Cenozoic tectonic event to explain the observed age distribution. The thermochronological dataset can also be used to put constraints on the effective elastic thickness of the lithosphere underlying the orogen (10 to 30 km). There is however a trade-off between elastic thickness, mean exhumation rate and amount of topographic relief loss. The most likely scenario also predicts that the topography has decresed at a constant rate since the end of orogenic activity about 100 Myr ago.

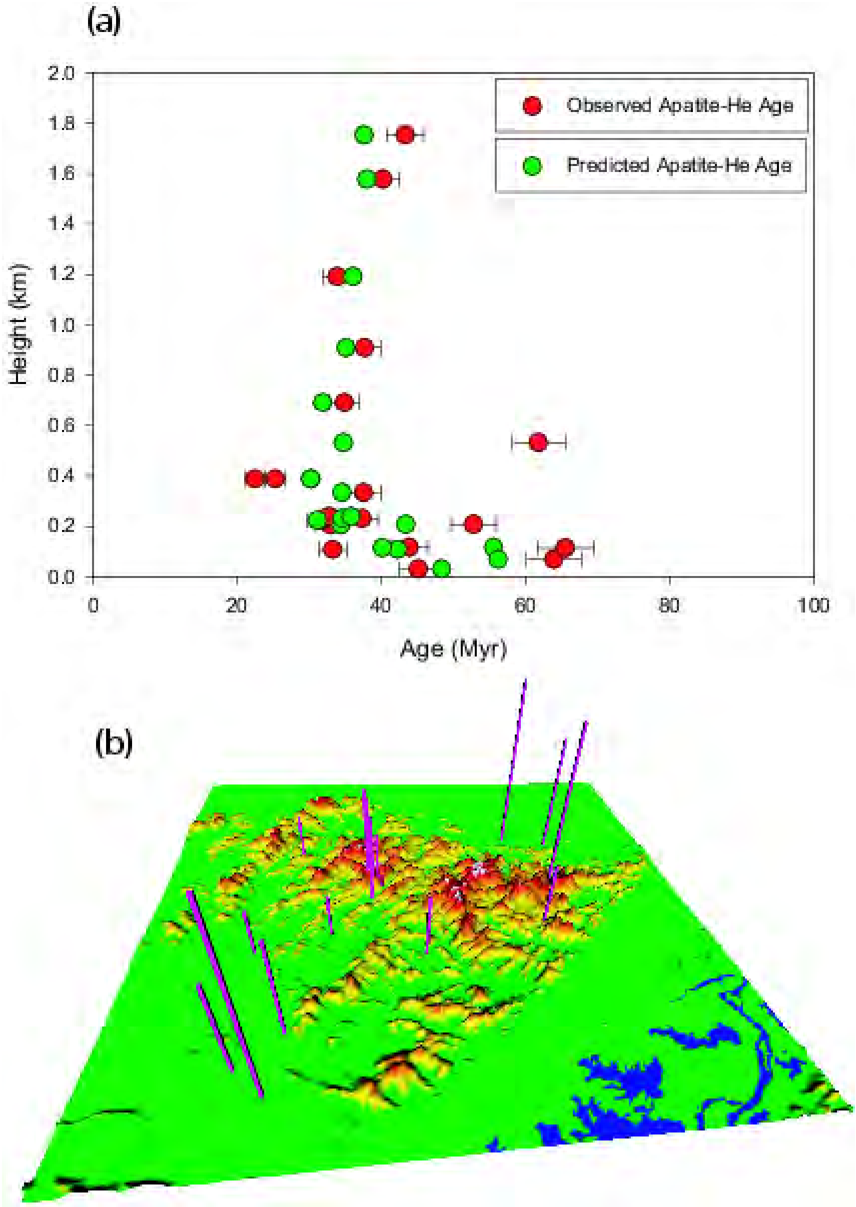

Figure 1: (a) Comparison between observed and predicted ages obtained from the best fitting model run. (b) Relationship between age and elevation across the Dabie Shan of eastern China; each column correspond to a (U-Th)/He apatite age; the height of the column is proportional to the age.

Gcube, a new three-dimensional model of lithospheric deformation and mantle flow

J. Braun, P. Fullsack &amp M. DeKool

In the last 12 months, we have developed a new finite element code, which we called ***Gcube,*** **to solve the equations of quasi-static force force balance in three dimensions that will allow us to simulate the deformation of the lithosphere and its coupling to flow in the underlying mantle. Of particular interest to us is the strong interactions between the**

solid lithosphere and the hydrosphere through the process of erosion, transport and sedimentation.

The method differs from classical finite element based approaches in several aspects

> **it allows for the accurate tracking of the free surface, internal boundaries and clouds of points on which the history of the flow can be stored; this is achieved by using a combination of particle-based methods and level set functions;**
>
> **it is based on a non-uniform, yet regular discretization of three-dimensional space through the use of an octree structure; octrees are also used to communicate information between the finite elements and the tracked interfaces;**
>
> **the solution of the large system of algebraic equations is performed by a parallelized version of a direct Cholesky solver developed by the IBM Watson Labs.**

So far, predictions of the model have been tested against the results of laboratory experiments in which a solid body (a pÃ©tanque ball) is slowly sinking in a highly viscous silicon oil, deforming the surface of the fluid. The comparison demonstrated the accuracy and efficiency of the method.

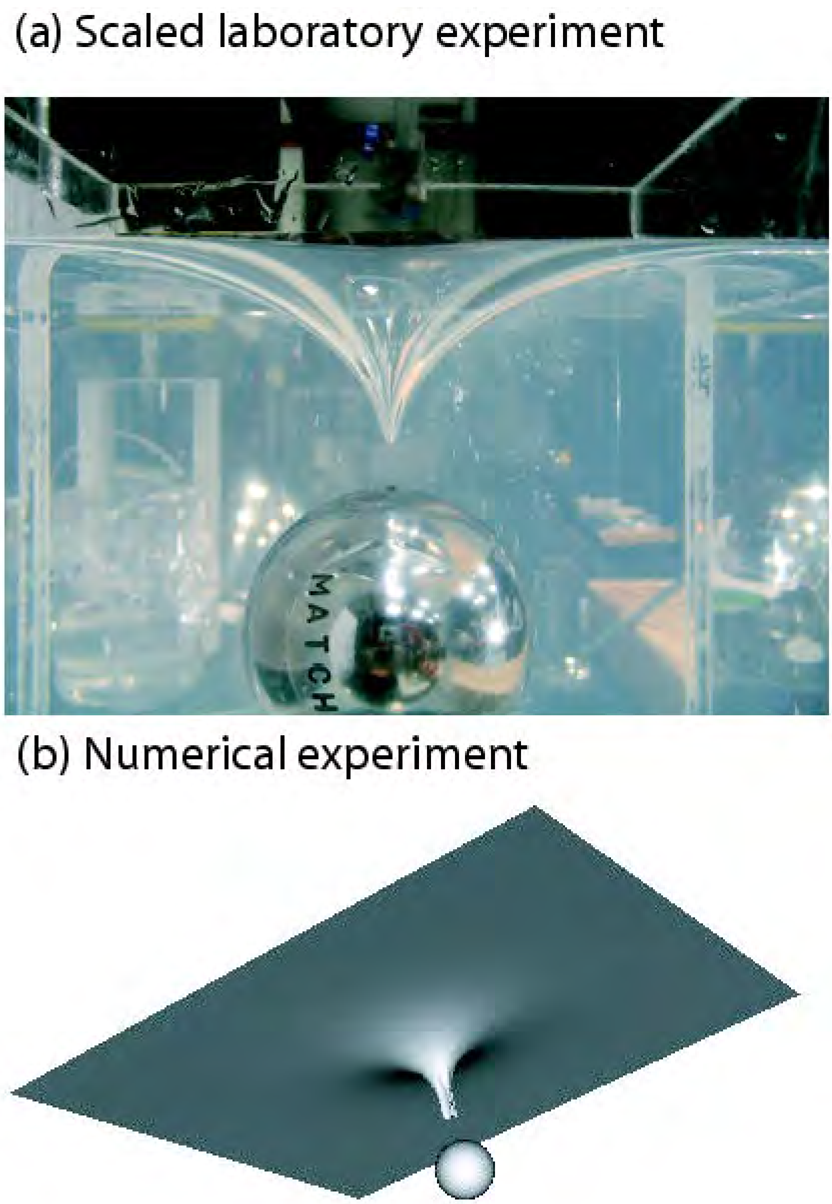

Figure 3: (a) Results of the laboratory experiment after the pÃ©tanque ball has sunk to a depth approximately equal to its own diameter. (b) Numerical simulation using Gcube in which the ball has sunk to a depth greater than twice its diameter.

A parametric study of soil transport mechanisms.

F. Herman and J. Braun

We have used numerical models to help constrain empirical parameterizations of soil production and transport mechanisms on soil-mantled hillslopes. The neighbourhood algorithm (NA) is used to invert soil thickness vs.~surface curvature data to provide not only more rigourous estimates of model parameter values but determine which of the model parameters are constrained by cosmogenic exposure ages [Heimsath et al., 2000]. Our experiments enabled us to show that linear and depth-dependent creep constants can be constrained by simple geomorphometric measurements such as the distribution of soil thickness on the landform and its relationship to surface curvature. We also showed that this unique dataset cannot be used on its own to constrain the parameterization of overland flow, another transport mechanism that is thought to play an important role on soil-mantled hillslopes, or to determine if a soil distribution has reached local steady-state. We also demonstrate that, to explain the data, soil production must be a function of soil thickness. These conclusions have important implications for our understanding of landscape evolution on medium to long time-scales.

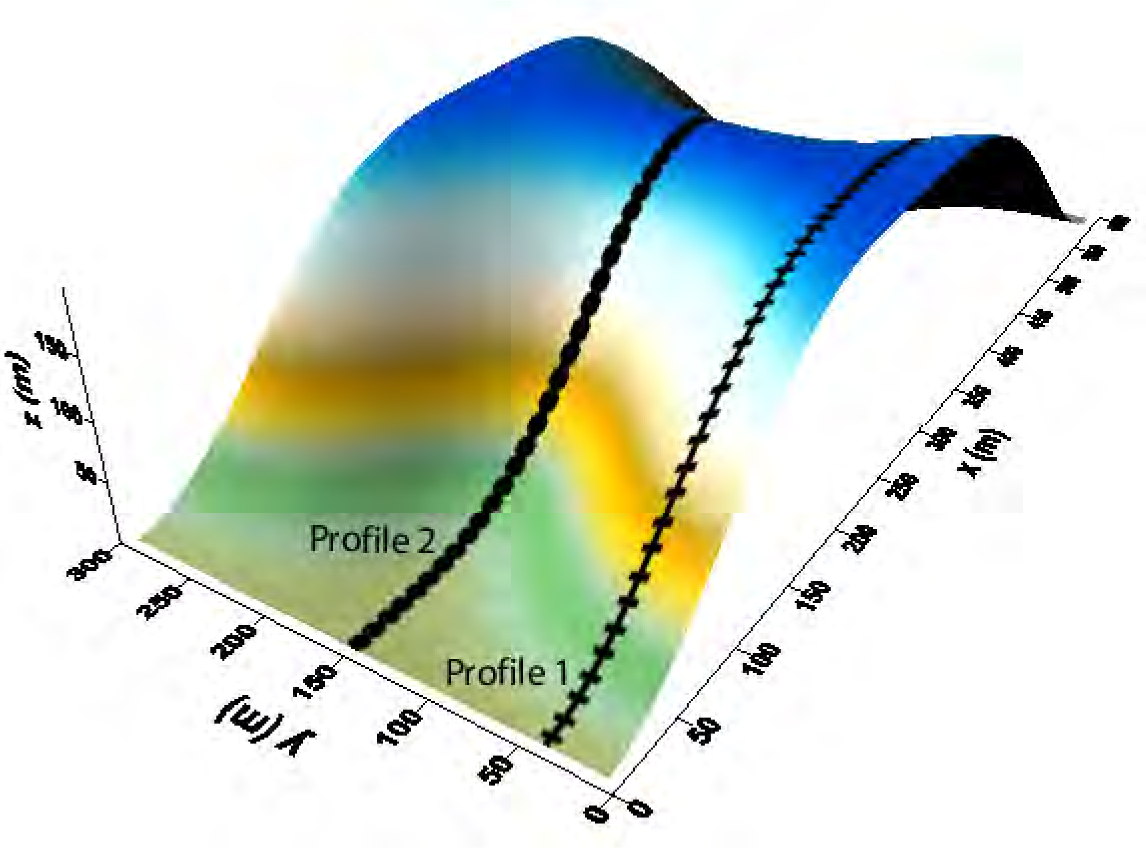

Figure 1: Hillslope model

Fluvial response to horizontal shortening and glaciations: a study in the Southern Alps of New Zealand.

F. Herman and J. Braun

Surface processes play a critical role in the dynamical evolution of compressional orogens. It has been postulated that a steady-state between erosional and tectonic processes may develop in continental collision. However, it is not clear whether steady-state conditions can be reached for all components of the landscape. Our study shows, using landscape evolution models and field evidence, that a true geomorphic steady-state may never be reached in the Southern Alps of New

Zealand. The strong asymmetry in tectonic uplift, tectonic advection and the onset of glaciations constantly interact to prevent the landscape from reaching a topographic steady-state. Field evidence suggests that the first-order geomorphology on the western side of the Southern Alps is controlled by strong orographic precipitation combined with extreme rates of tectonic uplift, whereas the development of deep glacial valleys on the eastern side is controlled by differential uplift along large faults. We have developed a first order equation governing the dynamics of the main divide to show that both tectonic advection and fluvial erosion efficiency control the position and the height of the main drainage divide. Then we predicted, using a 2D landscape evolution model and inversion techniques (e.g. Neighbourhood Algorithm), that the transition from glacial to fluvial conditions at the end of the last glaciation led to substantial modifications of the landscape: while the main trunk channels get slowly uplifted, ridges are leveled down which causes the relief to decrease. Hillslopes appear to be strongly affected by fluvial processes which seem to be mostly driven by incision of river tributaries. This reduction of relief will most likely never reach a steady state since warmer, inter-glacial periods are substantially shorter than glacial period.

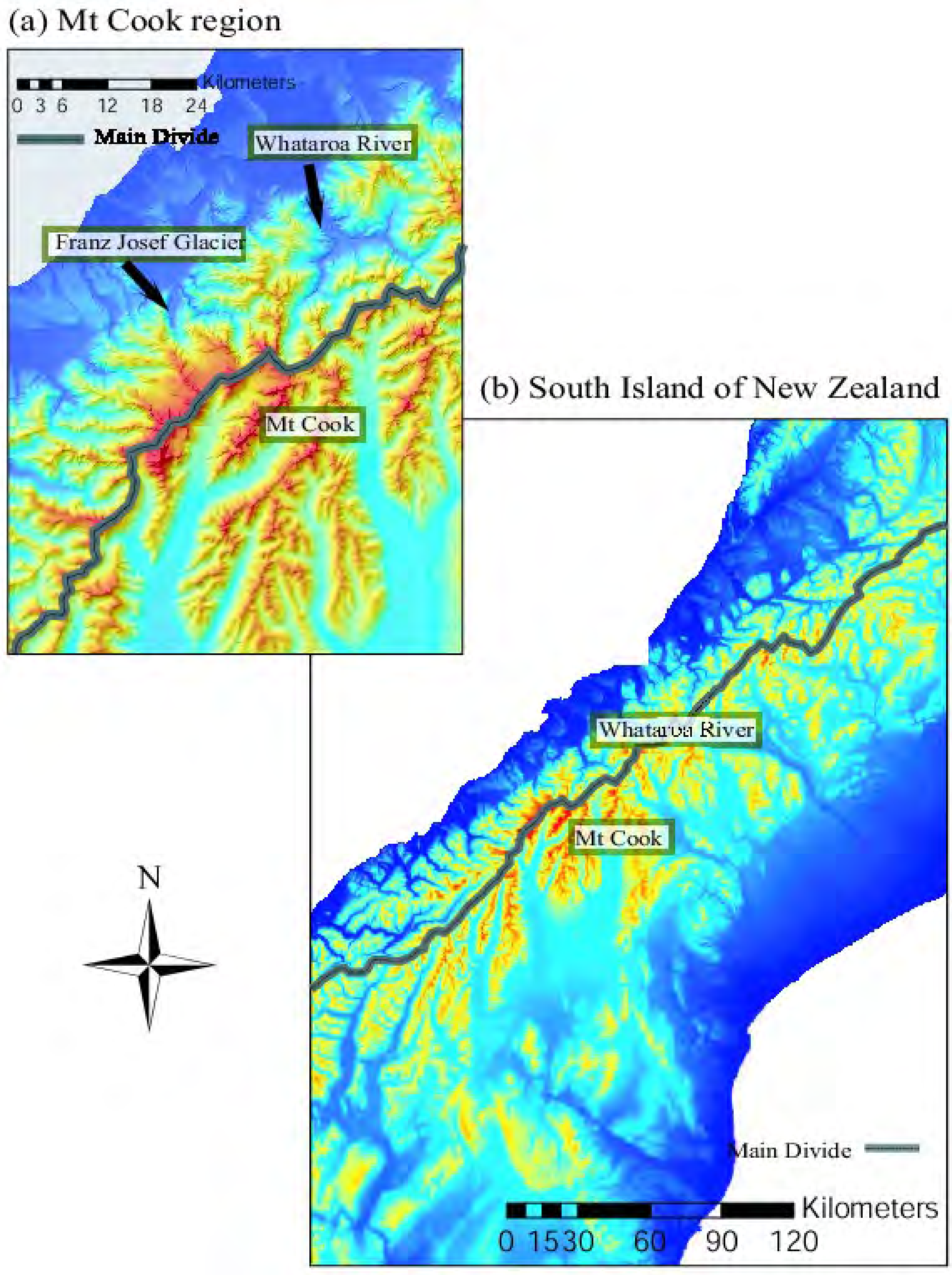

Figure 1: Location of the main divide in the Southern Alps of New Zealand. The western flanks experience high precipitation rate and strong climatic variations, whereas on the eastern side climatic conditions are much drier and mostly glaciated.

Tectono-morphic scenarios in the Southern Alps of New Zealand.

F. Herman, J. Braun, J. Dunlap and S. Cox (Institute of Geological and Nuclear Survey, New Zealand)
Temperature-time histories of rocks can be used to constrain tectonic and/or geomorphic scenarios in tectonically active areas. However, this inference is not always straightforward and relies on several interdependent mechanisms such as heat conduction, heat advection or transient topography, that must be taken into account. Using a 3D finite element code [Braun, 2003] that solves the transient heat transfer equation with an evolving topography, one can define accurate Temperature-time histories to interpret thermochronological datasets. Inversion methods (Monte Carlo type, e.g. Neighbourhood Algorithm) can in turn be used to constrain the tectono-morphic development of an orogen. Existing thermochronological datasets (K-Ar and FT) complemented by new low-T termochronometer data ((U-Th)/He and FT) from the Southern Alps of New Zealand are used here to derive information on the tectono-morphic development of the orogen during Pliocene and Pleistocene periods. Doing so, we can constrain the rate of horizontal advection and vertical uplift as well as the geometry of the main structural boundaries, i.e. the Alpine Fault and Main Divide Fault Zone. Our results strongly suggest that the relief on the West Coast of the Southern Alps has increased. This augmentation of relief could have occurred in 1.5 Ma as well as in 100 ka, whereas any reduction of relief during this period must be discarded. This would suggest that relief can substantially increase during glacial times or that relief has increased consequently to the transport of surface topography across the main divide towards the side of the orogen where precipitation is focused. On the other hand, early results show that major glacial valleys of the eastern side, where precipitation and uplift are much smaller, appear to be controlled by reverse, west-dipping faults, i.e. Main Divide Fault Zone.

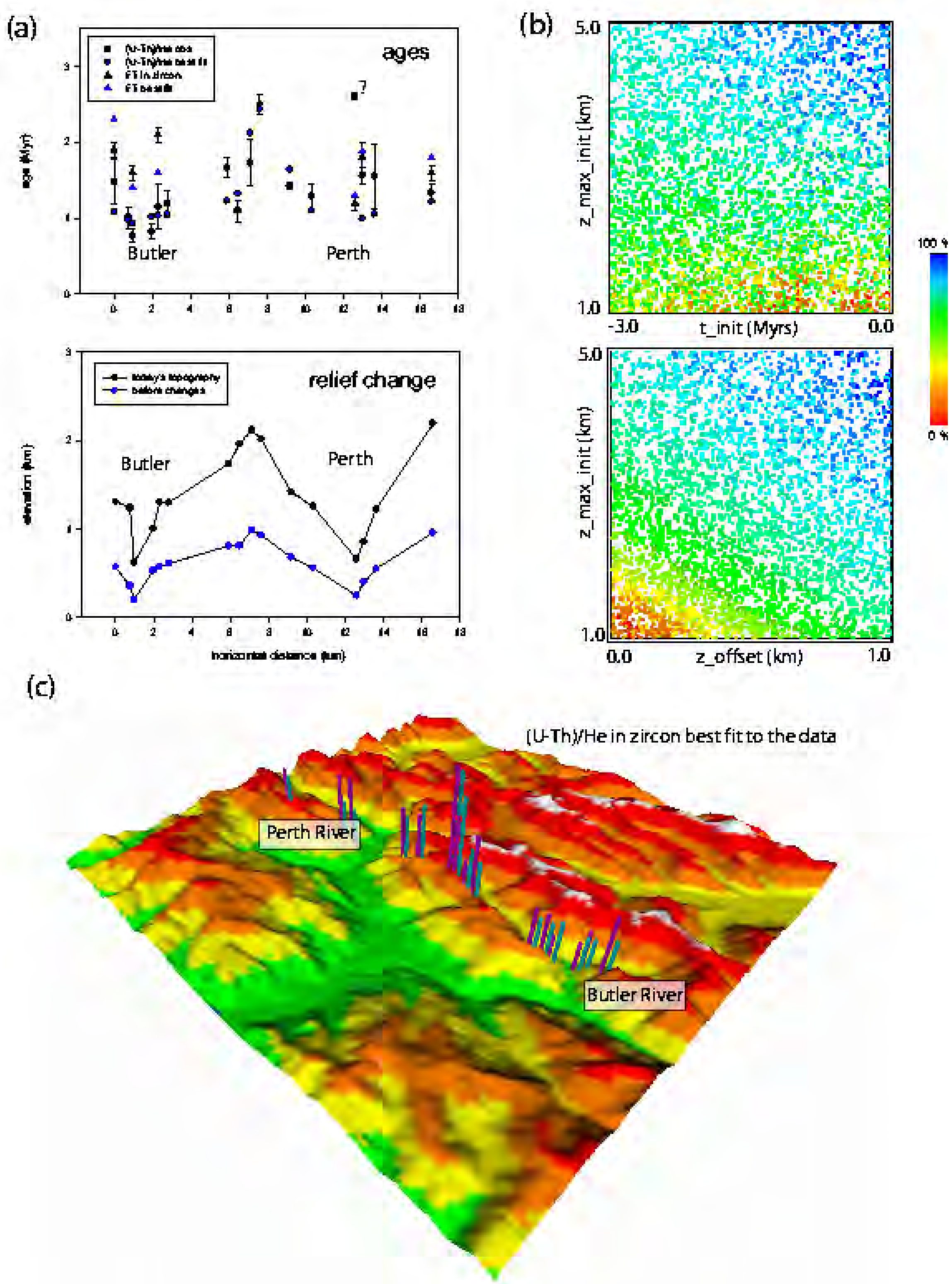

*Figure 1:*Results from simulation using a finite element model (Pecube) and inversion techniques to quantify relief changes from low-temperature thermo-chronometry. (a) Predicted and observed ages for bestfit model and relief change for bestfit model. (b) Parameter search (t_init: time in the past from which the topography starts evolving to today's

topography; z_offset: base-level of topography at time t_init; z_max_init: maximum elevation at time t_init).(c) 3D view of observed and predicted ages.

PRISE

This report is not available.

RESEARCH SUPPORT

Electronics and Engineering Groups

ELECTRONICS GROUP

Demand for Electronics support was strong during 2004, with resources allocated as shown:

	Budgeted	Actual	Comment
Total hours worked	10010	11573	Staff did not take leave as forecast
Hours billed	8008	8658	Surplus because more hours worked
Billable	80%	74.8%	Higher administration % due to the nature of tasks undertaken (numerous small projects)

Human resources were utilized as follows:

Task	Percentage of total hours
Development	64%
Maintenance	12.5%
Administration & Group Support	23.5%

The group should carry a budget surplus into 2005 due to a combination of higher hours worked and billed than forecast, and restrained capital expenditure. There may, however, be a significant shortfall ($18,000) in recharge earnings due to the incapacity of a major client to pay. Should this occur, the group might enter 2005 with a deficit.

The Electronics group enjoyed its first full year in the renovated facilities, which have proven to be effective and comfortable. Notable developments undertaken include:

- Design, implementation and installation of an upgraded 3-channel furnace control system for the Attenuation Apparatus for Earth Materials (Mr A. Forster and Mr D. Cassar).
- Substantial upgrade of the Multi-Anvil Apparatus, incorporating updated pressure and furnace control systems, together with automation software for Earth Materials (Mr D. Cassar, Mr A. Forster, Mr P. Lanc [Earth Chemistry]).
- Commissioning of a precision data acquisition and high resolution (22-bit) magnet control and housekeeping system for the 61cm Mass Spectrometer used by Earth Environment, together with user software for instrument control, data acquisition and preliminary data reduction (Mr A. Latimore).
- Design, installation and commissioning of updated high voltage control and diagnostics hardware on SHRIMP II, incorporating fibre-optic control (Mr A. Welsh).
- Design, development, construction and commissioning of a source pumping and sample insertion system for the renovated 61 cm mass spectrometer for Earth Environment (Mr D. Corrigan, Mr A. Cooper [RSPhySE], Mr N. Schram).
- Completion and testing of 9 “Tesla Tamer” precision magnetic field probes for ASI and the SHRIMP group, and fabrication of electron suppressors for the SHRIMP SI (Mr J. Arnold).

- Design, manufacture and commissioning of a motorised Cryogenic Head Controller and a specialised microcomputer-firmware-based GPIB interface for an existing electrometer, both on the VG5400 Mass Spectrometer used by Earth Chemistry (Mr D. Cassar, Mr D. Cummins).
- The generation of preliminary specifications and estimates for the electronics associated with the proposed SHRIMP SI (Mr N. Schram).
- Design, development, fabrication, firmware support and installation of versatile electrometer control cards and cabling to interface Keithley 642 and RSES-INSB electrometers to the automation facilities of the renovated 61cm mass spectrometer used by Earth Environment (Mr A. Welsh, Mr A. Latimore, Mr N. Schram, Mr D. Cummins, Mr D. Cassar, Mr J. Arnold).
- Formal testing and documentation against benchmark comparators of the performance of the prototype RSES-Finnigan-INSB precision electrometer, optimized for 'charge mode' data acquisition on the 61 cm mass spectrometers used by Earth Environment (Mr N. Schram).
- Design, construction and assembly of a filament degasser to support the renovated 61cm Mass Spectrometer (Mr D. Corrigan, Mr D. Cassar).
- Design, construction, installation and commissioning of innovative 'power-control' and automation system to improve reliability and product quality of diamond composite materials produced by the 4 kilotonne press operated by Ringwood Abrasives (Mr A. Forster, Mr D. Cassar, Mr P. Lanc [Earth Chemistry]).

Staffing

The group comprises an Electronics Engineer and five Technical Officers supplemented by two Trainee Technical Officers, both of whom have proven to be capable, independent and self-motivated technicians. Mr D. Corrigan continues to specialise in engineering design, working closely with both Engineering and Electronics staff. His primary focus for 2004 was the upgrade of the existing 61cm Mass Spectrometer.

Outlook

2005 promises to be another interesting year, as we turn our attention to the SHRIMP SI, the commissioning of several degasser units and further mechanical design for the NG61 Mass Spectrometer. The strategic budget model arranged for 2004 proved accurate and useful for monitoring operational efficiency and expenditure and a similar model will be implemented for 2005. There is clear evidence that the 'internal recharge' system of cost recovery has affected the flow of spontaneous and low cost projects and it has challenged the abilities of our clients to raise funds to match their aspirations . Changes to the administrative and management processes used by the group, stemming from the RSES Administration restructure, will undoubtedly frustrate group efficiency during 2005, but the resulting changes should both improve operations from mid-year onwards and further facilitate the group's drive towards independence, transparency and accountability. The SHRIMP SI will pose technical challenges to the group, which it is well positioned to address via its broad staff profile. The year will see increased responsibility passed to younger members, as several senior members move into or towards retirement. With an age-balanced and enthusiastic staff profile and a professional culture and client focus, the group is well positioned to meet school requirements within the foreseeable future.

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Engineering Group

In 2004 the Engineering Workshop was occupied with an abundance of short-term work, a few major projects and the usual amount of external work.

Administration, including Occupational Health and Safety, workshop maintenance and training accounted for 30% of human resources. External work comprised 5%, with the remaining 65% committed to jobs for RSES.

Prominent work in 2004 included:

- A New coral coring rig for Prof M. McCulloch (Mr C. Were, Mr D. Thomson, Mr G. Woodward)
- Preparation of tungsten carbide cubes and iron/iridium capsules for use in the multi-anvil press (Mr G. Woodward, Mr B. Taylor, Mr C. Were, Mr A. Wilson and Mr V. Baek-Hansen)
- Refurbishment of high pressure vessels (Mr G. Woodward, Mr C. Were)
- A lapping jig to obtain optical flatness on ceramic pistons used for seismic property measurements in the Rock Physics laboratories (Mr B. Taylor, Mr V. Baek-Hansen)
- A Micro-Drill for precision sampling under an optical microscope for Prof G. Lister (Mr V. Baek-Hansen, Mr B. Taylor)
- Secondary Column test bench for SHRIMP (Mr G Woodward)
- New lid and faraday cup modifications to SHRIMP 2 Multi collector (Mr D. Thomson, Mr A. Wilson, Mr B. Taylor and Mr C. Were)

Staffing

The group comprises four full time technical officers (Mr A. Wilson, Mr D. Thomson, Mr C. Were and Mr G. Woodward), one part time technical officer (Mr V. Baek-Hansen), and a third year apprentice (Mr B. Taylor).

An additional full time technical officer will join our team early in 2005.

Outlook

The proposed SHRIMP SI will be a major commitment for the Engineering workshop in 2005 and beyond. Prior to the commencement of SHRIMP SI we hope to be involved with another multi collector, for the SHRIMP 2 at Curtin University.

As usual plenty of general school activity is expected.

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Note: The two 2003 papers included were not in the 2003 Annual Report.

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NEW GRANTS

Australian Research Council Grants (commenced in 2004)

Discovery Project Grants

Dr A. Berry: The Geochemistry of Trace Elements with Variable Oxidation States. $120,000 (2004 – 2006)

Dr E. Calvo: The Key Role of the Southern Ocean in Atmospheric CO2 Sequestration. $235,000 (2004 – 2006)

Prof S. Cox: Time and Temperature - Dependence of the Fluid Transport Properties, Strength and Mechanical Behaviour of Faults - An Experimental and Modelling Study. $295,000 (2004 – 2006)

Dr G. Davies: Dynamics and Chemical Evolution of the Earth's Early Mantle. $210,000 (2004-2006)

Dr A. Hogg: A Laboratory Study of Ocean-Atmosphere Coupling in the Antarctic Circumpolar Wave. $235,000 (2004-2007)

Prof I. Jackson and Dr J. Fitzgerald: Grain-Boundary Sliding in High-Temperature Ceramics: Mechanical Spectroscopy of High-Purity Magnesium Oxide. $230,000 (2004 – 2006)

Prof K. Lambeck: Growth and Decay of Ice Sheets During Glacial Cycles. $290,000 (2004–2006)

Prof G. Lister, Dr M. Forster and Dr J. Dunlap: Revisiting the Alpine Paradigm - The Role of Inversion Cycles in the Evolution of the European Alps . $565,000 (2004 – 2008)

Dr M. Norman: Early Evolution of the Solar System - A Planetary Perspective. $120,000 (2004 – 2006)

Dr J. Mavrogenes: Determining Metal Complexation in Supercritical Fluids using Synthetic Fluid Inclusions. $5,980 (2004)

Dr H. O'Neill: The Geochemical Role of Iron in Basaltic Magnetism and Planetary Differentiation: An Experimental Study. $105,000 (2004 – 2006)

Dr N. Rawlinson and Dr M. Sambridge: Multi-arrival Wavefront Tracking for Improved Seismic Imaging of the Earth's Interior. $255,000 (2004-2006)

Dr W. Schellart: Integrated Dynamic Models of Subduction Initiation, Slab Evolution, Arc - Back-Arc Deformation and Mantle Convection. $235,000 (2004-2007)

Dr E. Tenthorey: The Role of Hydrous Fluids in Fault Processes - An Experimental Study. $206,000 (2004 – 2007)

Linkage International

Prof R. Griffiths: Three-Dimensional Flow Temperature and Melting Distributions in Mantle Subduction Zones. $37,800 (2004 - 2007)

Other Grants commenced in 2004

Dr A. Berry: An in Situ Study of the Oxidation State of U in Silicate Melts – ASRP. $4,480 (2004)

Dr A. Berry: Micro-Xanes Determination of the Oxidation State of Fe in Komatiite Melt Inclusion – ANSTO. $6,195 (2004)

Dr A. Berry: The Speciation of Cu in Fluid Inclusions from Alumbrera , Argentina– ANSTO. $5,980 (2004)

Dr D. Christie: Detection of Nuclear Explosions using Infrasound Techniques – US Air Force. $446,082 (2004-2007)

Dr J. Dunlap: VG Isotopes Analyses Fund - Noble Gas Analyses – AINSE. $13,353 (2004)

Ms K. Lilly: Use of Cosmogenic Nuclides to Constrain the Glacial History of the Lambert-Amery Basin , East Antarctica – AINSE. $14,300 (2004 – 2006)

NATIONAL AND INTERNATIONAL LINKS

COLLABORATION WITH AUSTRALIAN UNIVERSITIES, CSIRO & INDUSTRY

Earth Chemistry

Dr C.ALLEN with Dr S. Bryan (University of Queensland , now Yale University), What amount of crustal recycling has occurred in the Carboniferous volcanic rocks of central coastal Queensland ?.

Dr I.H. CAMPBELL and Dr C. ALLEN with Dr R. Squire and Dr C. Wilson (The University of Melbourne), Dating detrital zircons from sandstones from the Stawell gold mine in Victoria .

Dr I.H. CAMPBELL and Dr C. ALLEN with Mr G. Phillips and Dr C. Wilson (The University of Melbourne), Dating detrital zircons from Precambrian sandstones, Antarctica .

Dr I.H. CAMPBELL and Dr C.ALLEN with Mr M. Paine (CSIRO and Curtin University), Provenance of heavy mineral deposits in South Australia .

Dr I.H. CAMPBELL and Ms A.STOLTZE with Placer Granny Smith Pty. Ltd , Ore-fluid pathways around the mesothermal gold deposits in the Laverton region, WA using alkali elements and stable isotopes.

Prof M. HARRISON with Dr N. Phillips (CSIRO), Geoscience Research & Development Initiative related to exploration and including various state universities.

Prof M. HARRISON with the Tectonics Special Research Centre (School of Earth and Geographical Sciences, University of Western Australia , Perth), Board member Science Advisory Council.

Prof M. HARRISON with Prof S. Turner (Macquarie University) and others, Board member for planning of Goldschmidt 2006 Conference in Melbourne .

Dr M. HONDA with Dr D. Phillips (The University of Melbourne), Noble gas studies on diamonds.

Dr M. HONDA with Dr J.D. Woodhead (The University of Melbourne), A primordial solar-neon enriched component in the source of EMI-type ocean island basalts from the Pitcairn Seamounts, Polynesia .

Dr T.R. IRELAND with Dr P. Vasconselis (University of Queensland), SHRIMP project on stable isotopes.

Dr I.S. WILLIAMS with Dr M. Hand (Adelaide University), Collaborative work towards thesis by Mr D. MAIDMENT.

Dr I.S. WILLIAMS with Australian Scientific Instruments Pty Ltd (25% appointment as Applications Scientist - SHRIMP development, marketing, testing, operator training, applications consultant), SHRIMP commercialisation.

Dr I.S. WILLIAMS with Dr M. Hand (Adelaide University) and Dr I. Buick, (Monash University), Geologic evolution of the Arunta.

Dr I.S. WILLIAMS with Prof B.W. Chappell (Macquarie University), Genesis of SE Australian granites.

Dr I.S. WILLIAMS with Dr P. Lennox (University of New South Wales), Chronology of Wyangala granites.

Dr I.S. WILLIAMS with Dr J. Hergt, Dr J. Woodhead and Mr R. Kemp (The University of Melbourne), Age and origin of S-type granite zircon.

Earth Environment

Ms S.BURGESS with Prof R. Arculus (Department of Earth and Marine Sciences, ANU), participated as a biologist on the North Tonga Vents Expedition (NOTOVE) of the *RV* Southern Surveyor SS11/2004, which was investigating submarine hydrothermal plume activity and petrology of the northern Tofua Arc, Tonga

Dr E. CALVO and Dr C. PELEJERO with Dr P. DeDeckker (Department of Earth and Marine Sciences, ANU), Reconstruction of past oceanic and climatic conditions using deep sea sediments.

Dr E. CALVO and Dr C. PELEJERO with Dr W. Howard and Dr A. Moy (Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania), Comparison of different proxies of past ocean chemistry.

Dr E. CALVO and Dr C. PELEJERO with Prof A. Chivas (School of Geosciences , University of Wollongong), Geochemistry of sediments from Gulf of Carpentaria .

Dr S. EGGINS and Prof R. GRÜN with Dr C. Murray-Wallace (University of Wollongong), Open-system U-series dating of molluscs.

Prof R. GRÜN and Dr M. GAGAN with Dr R. Wells (Flinders University) and Dr D. Bowman (Northern Territory University), ARC Discovery grant, Stable isotopes in marsupials: reconstruction of environmental change in Australia.

Prof R. GRÜN with Dr P. White (Dept of Anthropology, University of Sydney) and Dr J. Field (Dept of Archaeology, University of Sydney), Dating of the archaeological and megafauna site of Cuddie Springs.

Prof R. GRÜN with Dr J. Dorth (Dept of Archaeology, University of Sydney) and Dr M Cupper (School of Earth Sciences , University of Melbourne), Dating of the megafauna site of Lancefield.

Prof R. GRÜN with Dr R. Wells (Flinders University), Dating of a series of South Australian sites with faunal remains including Naracoorte Cave and the Rocky River Site on Kangaroo Island .

Prof R. GRÜN with Prof R. Twidale (University of Adelaide), Onset of dune formation in the Stretzlecki Desert .

Dr B. PILLANS with Prof A. Chivas (University of Wollongong), Dr B. Kohn (The University of Melbourne), Dr G. Humphries and Mr M. Wilkinson (Macquarie University) and Prof R. Bourman (University of South Australia), Regolith dating.

Dr E. RHODES with Dr J. Nott (James Cook University), Dating of palaeoflood and storm surge deposits in Northern Australia

Dr E. RHODES with Dr K.-H. Wyrwoll (University of Western Australia), Dating of fluvial deposits, aeolian deposits and former lake levels.

Dr E. RHODES with Dr P. Hearty (University of Wollongong), Dating of coastal sand dunes.

Dr E. RHODES with Prof R. Twidale (University of Adelaide), Onset of dune formation in the Stretzlecki Desert .

Dr E. RHODES with Dr R. Wells (Flinders University), Dating a series of South Australian sites with faunal and mega-faunal remains including the Rocky River Site on Kangaroo Island.

Earth Materials

Prof S.F. COX and Dr S. MICKELTHWAITE with geoscientists from five industrial gold mining companies (Goldfields St Ives, Placer Dome, Anglogold, Newmont, KCGM), Development and Application of Stress Transfer Modelling for Area Selection in Mesothermal Gold Systems; ARC-Linkage Project P718.

Dr A.J. BERRY and Prof H.St.C. O'NEILL with Dr G.J. Foran (ANSTO), An *in situ* study of the oxidation state of U in silicate melts.

Dr J. DUNLAP with Dr A. Harris and Dr B. Jones (CODES, University of Tasmania), Argon dating.

Mr. J. FREEMAN with Dr D. Stegman (Monash University) working on two- and three-dimensional numerical subduction simulations.

Prof I. JACKSON and Dr J.D. FITZ GERALD collaborated with Mr Gang Wang (visiting student from Harbin University , China) and Dr Z. Stachurski (Faculty of Engineering and Information Technology, ANU) on the mechanical behaviour of bulk metallic glass.

Dr J. MAVROGENES with Dr S. Hageman (University of Western Australia), Study of granite-hosted melt inclusions associated with west Australian Au deposits.

Dr J. MAVROGENES and Dr D. McFARLANE with CSIRO, Ongoing project on metamorphism and ore deposits.

Mr D. WOOD with AngloGold Australia , Tectonic evolution of the Anakie Inlier and implications for the early Palaeozoic in eastern Australia .

Earth Physics

Prof K. LAMBECK with Assoc Prof R. Coleman (University of Tasmania), Looking Back to See the Future; ARC Discovery Project.

Dr W.P. SCHELLART with Dr D. Stegman (Monash University) working on two- and three-dimensional numerical subduction simulations.

Dr W.P. SCHELLARTt with Prof M. Sandiford (The University of Melbourne) on mechanical coupling and stress transfer between the slab and the trailing plate, in particular looking at stresses in the Indo-Australian plate and their relation to the Sunda subduction zone.

Dr P. TREGONING with Dr R. Coleman (University of Tasmania), Monitoring of vertical movements of tide gauges, TIGA-PP Analysis Centre.

Australian National Seismic Imaging Resource (ANSIR)

Prof B.L.N. KENNETT is Director of the Australian National Seismic Imaging Resource (ANSIR). RSES has responsibility for the reflection equipment and vibrator sources, as well as the portable instruments that are housed at RSES.

The ANSIR equipment is available via a competitive proposal scheme. During 2004 instrumentation was provided as follows:

- To University of Western Australia for studies of the use of mine blasts for seismic refraction
- 20 sets of broad-band equipment to RSES for the Tasman Line experiments
- 4 sets of broad-band equipment to pmd*CRC for crustal studies in the Yilgarn craton and Gawler craton
- 8 sets of broad-band equipment to Geoscience Australia for imaging of active faults in the Flinders Ranges
- 20 sets of short period equipment for detailed structural studies in SE Australia

Reflection experiments carried out in 2004:

- Curnomona Craton , South Australia (100 km of profile – to be resumed in 2004),
- Darling Basin , NSW, (300 km of profiles)
- a number of smaller experiments using the mini-vibrator

PRISE

Dr R. ARMSTRONG with Prof M. Barley and B. Krapez (University of Western Australia) on research into the Late Archaean – Early Proterozoic timescale relevant to the emergence of the Earth’s atmosphere.

Dr R. ARMSTRONG with Prof D. Gray (University of Melbourne) on research projects in Oman and Namibia .

Dr R. ARMSTRONG with Dr B. Kohn (University of Melbourne) on the geochronology of Macquarie Island .

Dr R. ARMSTRONG has completed a number of geochronological projects for Australian and international exploration companies and consultants during the year and new projects were commenced.

Mr C.M. FANNING with Associate Prof C. Fergusson (University of Wollongong) and Prof R. Henderson (James Cook University) on Tectonics of the Neoproterozoic – Early Palaeozoic margin in eastern Australia .

Mr C.M. FANNING with Prof J. Roberts (University of New South Wales) on the timing of Carboniferous-Permian volcanic rocks in the Tamworth belt NSW.

Mr C.M. FANNING with Dr K. Knesel (Univerity of Queensland) on the timing and protolith history of Cenozoic volcanic rocks from Chile.

Mr C.M. FANNING with Dr M. Rubenach (James Cook University) on the geochronology of granitic rocks in north west Queensland .

Dr G.M. YAXLEY and Dr M.D. NORMAN with Dr V. Kamenetsky (University of Tasmania), Dr M. Kamenetsky (University of Tasmania) and Prof. D. Francis, (McGill University), Compositional heterogeneity in olivine-hosted melt inclusions from the Baffin Island picrites.

INTERNATIONAL COLLABORATION

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Earth Chemistry

Dr V.C. BENNETT with Prof M. Garcia (University of Hawaii), Pb isotope compositions of melt inclusions determined by multi-collector SHRIMP analysis.

Dr V.C. BENNETT with Prof D. DePaolo and Ms K. Weaver (University of California , Berkeley), Measurement of Sr isotopic compositions of zircons.

Dr I.H. CAMPBELL and Dr C. ALLEN with Dr M. Palin (University of Otago), Dating zircons from the two youngest caldera-forming ignimbrites of the Yellowstone volcanic field, using the laser ablation ICP-MS.

Dr I.H. CAMPBELL and Dr C. ALLEN with Prof P. Reiners (Yale University , USA), Double-dating [U/Pb and (Th + U)/He)] of detrital zircons in sedimentary provenance studies.

Dr I.H. CAMPBELL and Dr C. ALLEN with Dr M. Brandon and his research group (Yale University , USA), What percentage of sediments are first cycle? Case study in Olympic Mounts, Washington.

Dr I.H. CAMPBELL and Dr C. ALLEN with Dr S. Bryan (Yale University, USA), Geochronology and geochemistry of the long-lived, large-volume silicic magmatism of the Sierra Madre Occidental, Mexico.

Dr I.H. Campbell and Dr C. ALLEN with Dr P. Zeitler (Lehigh University , Pennsylvania , USA), What are the U-Pb age profiles for zircons in recent sediments in NE Himalaya.

Dr I.H. CAMPBELL and Dr C. ALLEN with Dr H-Y. Liang (Guangzhou Institute of Geochemistry, Guangzhou , P.R. China), The geochronology and geochemistry of shoshonites from eastern Tibet .

Mr J. CELERIER with Prof An Yin and Mr A. Webb (UCLA, USA), Ongoing collaboration including two months of fieldwork in India with Mr Webb .

Mr J. CELERIER with Prof J.-P. Avouac and Dr O. Beyssac (California Institute of Technology, Pasadena) , Collaborative research visit.

Prof T.M. HARRISON with Prof K.D. McKeegan (UCLA , USA). Ion Probe Lab Review UCLA, NSF Instrumentation and Facilities Panel.

Prof T.M. HARRISON with Dr J. Blichert-Toft and Prof F. Albarede , (Laboratoire des Sciences de la Terre, Ecole Normale Superieure de Lyon, France), Continuation of collaboration on old zircons analysis.

Dr M. HONDA with Dr J.W. Harris (University of Glasgow), Noble gas studies on diamonds.

Dr T.R. IRELAND with Dr S. Weaver (Canterbury University , New Zealand), SHRIMP project on Antarctic granites and detrital rocks.

Dr T.R. IRELAND with Prof K. McKeegan (UCLA , USA), Collaborative research.

Dr T.R. IRELAND with Mr B. Ito (Stanford University , USA), Collaborative work on SHRIMP analyses.

Dr A.P. NUTMAN with Dr J. Hollis and Dr A.A. Garde (Geological Survey of Denmark and Greenland), New collaborative research into the Archaean geology in the Kapisillit area of Greenland that will last for 3 years and entail the Survey providing support for up to 2 RSES PhD students.

Dr A.P. NUTMAN with Dr C.R.L. Friend (British Museum , UK), Long-standing research into Archaean crustal evolution using Greenland rocks.

Dr A.P. NUTMAN with Dr B. Chadwick (freelance geologist, UK), Archaean crustal evolution in southern India .

Dr A.P. NUTMAN with Prof U.G. Cordani, and Dr M. Basei (University of Sao Paulo , Brazil), Precambrian evolution of South America .

Dr A.P. NUTMAN with Dr M. Basei (University of Sao Paulo , Brazil), Timescale of sedimentation and volcanism in the Parana basin of S. America .

Dr A.P. NUTMAN with Mr O. Christiansen (Nunaminerals A/S, Greenland), Timing of Archaean gold mineralisation in the Nuuk district, Greenland .

Dr A.P. NUTMAN with Prof H. Hidaka and Mr K. Horie (Hiroshima University , Japan), Dating of early Archaean rocks in Greenland .

Dr A.P. NUTMAN with Dr P.R. Dawes (Geological Survey of Denmark and Greenland , Denmark), Dating of the Inglefield mobile belt of NW Greenland.

Prof R.W.R.RUTLAND and Dr I.S. WILLIAMS with Dr K. Korsman and Dr J. Kousa (Geological Survey of Finland) and Dr T. Schiöld (Swedish Museum of Natural History), Svecofennian evolution.

Ms A. STOLTZE with Dr E. Nakamura (Institute for the Study of the Earth's Interior, Okayama University , Misasa , Japan), Radiogenic isotopes from the Wallaby Gold Deposit.

Dr I.S. WILLIAMS with Dr J. Wiszniewska and Ms E. Krzeminska (Polish Geological Institute, Warsaw , Poland), Evolution of the Polish basement.

Dr I.S. WILLIAMS with Dr R. Findlay and Mr G. Kopi (Geological Survey of Papua New Guinea), Provenance of the Owen Stanley metamorphics.

Dr I.S. WILLIAMS with Prof J.W. Goodge (University of Minnesota, Duluth, USA) and Prof P. Myrow (Colorado College, Colorado Springs, USA), Provenance of east Antarctic metasediments.

Dr I.S. WILLIAMS with Prof D. Mossman (Mount Allison University , Sackville , Canada), Baddeleyite dating in thin section.

Dr I.S. WILLIAMS for Geological Survey of Canada (Ottawa), Hiroshima University (Japan), National Institute of Polar Research (Japan), Chinese Academy of Geological Sciences (Beijing), and All Russian Geological Research Institute (St. Petersburg), SHRIMP technical and applications consultancy.

Earth Environment

Dr E. CALVO and Dr C. PELEJERO with Dr R. Simó, Dr M. Ribes, Dr C. Marrasé, Prof M. Estrada and Prof J.M. Gili (Institut de Ciències del Mar, CMIMA-CSIC, Barcelona), Cultures of marine organisms for paleoceanography proxy calibration.

Dr E. CALVO, Dr C. PELEJERO, and Dr S. EGGINS with Dr I. Cacho and Mr L. Pena (GRC Geociències Marines, Dept Estrat. Paleont. i Geoc. Marines, Facultat de Geologia, Universitat de Barcelona , Spain), LA-ICPMS analysis of foraminifera for the assessment of cleaning protocols.

Dr D. FABEL with Prof J. Harbor (Purdue University , USA), Dr A. Stroeven (Stockholm University , Sweden), Cosmogenic nuclide-base boundary conditions for numerical ice sheet models: a simulation of the Fennoscandian Ice Sheet through a glacial cycle.

Dr D. FABEL and Prof K. LAMBECK, with Dr A Hubbard (University of Edinburgh), Dr A. Stroeven (Stockholm University , Sweden), Prof J. Harbor (Purdue University , USA), and Dr C. Hättestrand (Stockholm University , Sweden), Cosmogenic nuclide-based boundary conditions for numerical ice sheet models: a simulation of the Fennoscandian Ice Sheet through a glacial cycle.

Dr D. FABEL with Prof S. Björk (Lund University , Sweden), Cosmogenic exposure dating of Baltic Ice Lake drainage deposits.

Dr D. FABEL with Dr C. Hättestrand (Stockholm University , Sweden), Deglaciation history of the Kola Peninsula , Russia .

Dr S. EGGINS with Dr. M. Ellwood and Dr. M. Kelly (National Institute for Water (NIWA), Hamilton , New Zealand), *In-situ* analysis of the elemental and stable isotope composition of siliceous sponges.

Dr S. EGGINS and Prof P. DeDeckker (Dept of Earth and Marine Science, ANU) with Prof D. Kroon, Dr P. Anand and Dr F. Peeters , (Department of Earth Science, Free University, Amsterdam, Netherlands), Mg/Ca geochemistry of live-collected and core-top samples foraminifera shells from the Indian Ocean.

Prof R. GRÜN investigated ‘The timing of modern human evolution’ with numerous international scholars. He has collected hominid samples from the anthropological sites Cave of Hearths and Hutjiespunt, South Africa with Prof V.A. Tobias and Dr L. Berger (University of the Witwatersrand) and Prof J. Parkington (University of Cape Town), Skhul, Qafzeh, Tabun, Kebara and Amud, Israel with Prof Y. Rak (Haifa University) and Prof C.B. Stringer (Natural History Museum, London), Banyoles, Spain with Prof J. Maroto (Universitat de Girona, Spain) and Irhoud, Sale and Thomas Quarry, Morocco with Prof J.J. Hublin (Max Planck Institute for Evolutionary Anthropology, Leipzig).

Prof R. GRÜN with Dr J. Brink, (Florisbad Quaternary Research Department, National Museum , Bloemfontein , South Africa), Dating of a range of sites in South Africa , including the newly discovered human site of Cornelia.

Prof R. GRÜN with Dr A. Pike (University of Bristol), Uranium uptake of bones.

Prof R. GRÜN with Prof T. de Torres (Escuela Tecnica Superior de Ingenieros de Minas de Madrid), Calibration of amino acid racemisation in bones, cave bear evolution and dating human material from Sidron.

Prof R. GRÜN with Prof U. Radtke and Dr A. Hilgers (Universität zu Köln , Germany), The onset of dune formation in the Stretzlecki Desert .

Prof R. GRÜN with Dr A. Gurbanov (Institute of Geology of Ore Deposits, Moscow) and Dr D. Koshchug (Department of Geology, Moscow State University) on the reconstruction of cooling and denudation rates of the Greater Caucasus.

Dr B. PILLANS continued his appointment as a Research Associate of the New Zealand Institute of Geological & Nuclear Sciences (IGNS), facilitating collaborative studies of Quaternary sedimentary sequences in the North Island of New Zealand with Dr T. Naish, Dr A. Beu and Dr B. Alloway .

Dr E. RHODES with Prof C. Stringer (Natural History Museum , London), Prof. N. Barton (University of Oxford , UK), Dr C. Finlayson (Gibraltar Museum) and Dr Jalil Bouzaggar (Rabat Museum , Morocco), Dating of palaeolithic archaeology and hominid remains from southern Iberia and Morocco .

Dr E. RHODES with Dr C. Sancho and Dr J-L. Pena (University of Zaragoza , Spain) and Dr G. Benito (University of Madrid , Spain), Dating of fluvial and glacial deposits in N. Spain .

Dr E. RHODES with Dr S. Doerr, Dr R. Shakesby and Ms V. Farwig (University of Wales , UK), Reconstructing past heating events to understand past bush fire magnitude and frequency.

Mr A. SADEKOV and Dr S. EGGINS with Dr A.D. Russell and Prof H. Spero (University of California , Davis , USA), Investigation of Mg partitioning in calcite precipitated under controlled laboratory conditions by the planktonic foraminifer *Orbulina universa* (d'Orbigny).

Earth Materials

Dr A.J. BERRY and Prof H.St.C. O'NEILL with Dr S.R. Sutton and Dr M. Newville (University of Chicago, USA) and Dr L. Danyushevsky (CODES, University of Tasmania), Micro-XANES determination of the oxidation state of Fe in komatiite melt inclusions.

Dr A.J. BERRY with Dr S.C. Wimperis (University of Exeter) and Dr S.E. Ashbrook (University of Cambridge), High resolution 17 O NMR studies of high-pressure silicate phases.

Dr A.J. BERRY and Prof H.St.C. O'NEILL with Dr N. Metrich (CEA-CNRS , France), A XANES study of sulfur speciation in synthetic glasses and melt inclusions.

Dr A.J. BERRY and Dr J.A. MAVROGENES with Dr S.R. Sutton and Dr M. Newville (University of Chicago, USA) and Dr A.C. Harris (University of Tasmania), The speciation of Cu in fluid inclusions from Alumbrera, Argentina.

Prof S.F. COX with Dr N. Mancktelow (ETH-Zurich , Switzerland), Dr A.-M. Boullier (Universite Joseph Fourier, Grenoble , France), Dr Y. Rolland (Universite de Nice , France) and Dr G. Pennachioni (Universita di Padova , Italy), continued collaboration as part of an ARC grant.

Prof S.F. COX with Dr S. Miller (ETH-Zurich , Switzerland), ARC Discovery Grant on modelling of fluid flow in fault networks.

Dr J. DUNLAP with Dr C. Teyssier (University of Minnesota, USA), Dr H. Fossen (Bergen University, Norway), Dr N. Mortimer and Dr A. Tulloch (Institute of Geological & Nuclear Sciences , Dunedin, New Zealand), collaborative argon dating.

Dr J. DUNLAP with Dr P. van der Beek (France) and Dr S. Cox (Institute of Geological & Nuclear Sciences , Dunedin , New Zealand), collaborative helium dating.

Dr J. HERMANN with Dr A. Korsakov, (Geophysics and Mineralogy, Novosibirsk , Russia), Evidence for carbonatite and silicate melt involvement in the genesis of micro-diamonds in subducted continental crust.

Dr J. HERMANN with Prof M. Scambelluri (University of Genova , Italy), Constraints on subduction zone fluids from high pressure ultramafic rocks.

Dr J. HERMANN with Prof V. Trommsdorff (ETH-Zurich , Switzerland), Alpine zircon growth in a garnet-peridotite by infiltration of crustal fluids

Prof I. JACKSON continued an ARC Linkage-funded collaboration with Prof. R. Liebermann's group (Stony Brook University , New York) and Dr G. Gwanmesia (Delaware State University , USA) on the high-temperature measurement of elastic wave speeds.

Prof I. JACKSON, Dr J.D. FITZ GERALD and Dr U.H. FAUL with Prof S. Morris (University of California , Berkeley) continued a collaboration on grain-boundary sliding in MgO.

Prof I. JACKSON, Dr J.D. FITZ GERALD and Dr U.H. FAUL with Prof K. Itatani (Sophia University, Tokyo) and Prof. F. Bejina (Université Paul Sabatier, Toulouse, France) on grain-boundary diffusion in olivine.

Prof I. McDOUGALL with Dr F.H. Brown (University of Utah , USA) and Dr J.G. Fleagle (Stony Brook University , New York), Geological history of the Turkana Basin, Ethiopia and Kenya .

Earth Physics

Prof R.W. GRIFFITHS and Dr R.C. KERR with Prof K. V. Cashman (University of Oregon , USA) on the dynamics of channelized lava flows, a project funded by an ARC Discovery grant.

Prof R.W. GRIFFITHS with Prof C. Kincaid (University of Rhode Island , USA) on the three-dimensional flow and temperature distribution in slab subduction zones, with funding from NSF and an ARC Linkage International grant.

Prof R.W. GRIFFITHS and Dr G.O. HUGHES with Prof R. Watts (University of Rhode Island, USA) on the processes governing the convective overturning and density stratification in the Sea of Japan.

Dr A.McC. HOGG with Prof P. D. Killworth (Southampton Oceanography Centre, UK) and Prof W. K. Dewar (Florida State University , USA) relating to ocean-amtosphere dynamics in the mid-latitudes.

Dr A.McC. HOGG with Dr A. Engqvist (Stockholm University , Sweden) on flow through ocean straits.

Dr A.McC. HOGG with Dr J. Nycander (Stockholm University , Sweden) on numerical simulation of internal hydraulic flows.

Prof B.L.N. KENNETT is Past-President of the International Association for Seismology and the Physics of the Earth's Interior (IASPEI).

Prof B.L.N. KENNETT and Mr S. FISHWICK with Dr E. Debayle (University of Strasbourg , France), Dr M. Ritzwoller (University of Colorado , USA) and Dr K. Yoshizawa (University of Hokkaido , Japan) on surface wave tomography.

Prof B.L.N. KENNETT with Dr T. Furumura (Earthquake Research Institute, University of Tokyo , Japan) on a variety of issues in seismic wave propagation, particularly propagation of high frequency waves in subduction zones from deeper earthquakes.

Prof B.L.N. KENNETT with Prof H.-P. Bunge (University of Munich , Germany) on the nature of heterogeneity within the Earth.

Prof K. LAMBECK with Drs M. Anzidei (Instituto Nazionale di Geofisica e Vulcanologia (INGV), Italy) and F. Antonioli (Ente per le Nuove Tecnologie, L'Energia e L'Ambiente (ENEA), Rome) Sea level change in the Mediterranean.

Prof K. LAMBECK with Dr D. Sivan (Haifa , Israel) Flooding of the Black Sea .

Prof K. LAMBECK with scientists from Universities of Lund, Copenhagen and Kiel and with the Norwegian Geological Survey on a range of glacial rebound and climate issues in Scandinavia , Greenland , and arctic Russia .

Prof K. LAMBECK with Dr Y. Yokoyama (University of Tokyo), Sea level change during and before the Last Glacial Maximum.

Dr H. McQUEEN and Prof K. Lambeck with Prof T. Sato (National Astronomical Observatory of Japan), Operating and analyzing a Superconducting Gravimeter at Mt Stromlo to monitor dynamic processes inside the Earth.

Dr H. McQUEEN with Prof Y. Fukuda, T. Higashi and S. Iwano (Kyoto University, Japan) and Y. Hiraoka (Geographical Survey Institute, Japan), Absolute Gravity measurements at the Mt Stromlo gravity station, Perth and Tidbinbilla.

Dr M. SAMBRIDGE with Dr T. Nicholson (University of Wellington , New Zealand) on aspects of global heterogeneity and its influence on seismic travel times.

Dr M. SAMBRIDGE with Prof K. Creager (University of Washington , USA), a school visitor during the year, on seismic travel times.

Dr M. SAMBRIDGE with Dr K. Gallagher (Imperial College , UK) on statistical approaches to inverse problems.

Dr M. SAMBRIDGE with Prof M. Christie (Heriot-Watt University , UK) on uncertainty quantification in reservoir engineering.

Dr W.P. SCHELLART with Ms V.G. Toy (Otago University , New Zealand), primarily working on a reconstruction of the Southwest Pacific region since 65 Ma.

Dr P. TREGONING with Dr T. van Dam (European Centre for Geodynamics and Seismology), Atmospheric pressure loading effects in GPS data analysis.

Dr P. TREGONING with Dr A. Niell (Haystack Observatory, Massachusetts) and Dr J. Boehms (Technische Universität Wien, Austria), New mapping functions implemented in the GAMIT GPS software.

Dr P. TREGONING with Drs R. King, T.A. Herring and S. McClusky (Massachusetts Institute of Technology, USA), Development of the GAMIT/GLOBK GPS software.

Dr P. TREGONING, Dr H. MCQUEEN, Prof K. LAMBECK, Mr R. DECREVEL with Mr S. Hasiasta (Papua New Guinea University of Technology, Lae), Mr R. Rosa (Papua New Guinea National Mapping Bureau), Mr I. Itikarai and Mr S. Saunders (Rabaul Volcano Observatory, Papua New Guinea), Tectonic studies in Papua New Guinea.

Dr P. TREGONING with Dr J. Virieux (Geosciences Azur, Nice, France) and Dr A. Walpersdorf (Universite Joseph-Fourier, Grenoble, France), REGAL: GPS studies in the French Alps.

PRISE

Dr. R.A. ARMSTRONG with scientists from the Geological Surveys of Brazil, Botswana, Namibia, South Africa, South Korea and Swaziland on a number of collaborative projects.

Dr R.A. ARMSTRONG with C. Lana, Prof W.U. Reimold and Dr R. Gibson (University of the Witwatersrand , RSA), Geochronology of the Vredefort impact structure.

Dr R.A. ARMSTRONG with Dr J.Ward and J. Jacob (De Beers Exploration) and A. van der Westhuizen (University of Stellenbosch, RSA), The provenance and history of diamond-bearing sediments from the Orange River, southern Africa.

Dr R.A. ARMSTRONG with R. Baillie, Prof N. Beukes and Prof J. Gutzmer (Rand Afrikaans University, RSA), Geochemistry and geochronology of the Koras Sequence, South Africa.

Dr R.A. ARMSTRONG with C McClung (Rand Afrikaans University , RSA), The provenance and geochronology of metasediments from the Aggeneys region, Namaqualand , South Africa , and possible regional correlations.

Dr R. A. ARMSTRONG with J. Mukhopadhyay (Presidency College , India) and Professor N. Beukes (Rand Afrikaans University , RSA) The geochronology of Archaean Banded Iron Formations from the Bailadila Region, Bastar Craton , Central India .

Dr R.A. ARMSTRONG with Dr B. Eglington (University of Saskatchewan), Development of a geochronological database for Africa .

Dr R.A. ARMSTRONG with Dr P. Macey and Dr G. Grantham (Council for Geoscience, RSA), A SHRIMP U-Pb study of the main magmatic, metamorphic and tectonic events of central Mozambique .

Dr R. A. ARMSTRONG with Dr Deung-Lyong Cho (Korea Institute of Geology, Mining and Materials, South Korea), Geochronology and stratigraphy of the Korean peninsula.

Dr R.A. ARMSTRONG with Dr M. Pimentel and Dr M. Escayola (University of Brasilia , Brazil), Geochronology and provenance studies of various sequences in Brazil and Argentina .

Dr R.A. ARMSTRONG with Dr Jean-Paul Liégeois (Africa Museum, Belgium), The geochronology, structure and tectonic history of the Aïr and Hoggar regions (SE Taureg shield) in Niger.

Dr R.A. ARMSTRONG with Dr M Bröcker (Institut für Mineralogie , Munster , Germany), SHRIMP U-Pb zircon geochronology of jadeitites from Greece .

Mr C.M. FANNING with Prof P. K. Link (Idaho State University , USA) on changes in provenance of sandstones in the Snake River plain and environs with the passing of the Yellowstone hot-spot.

Mr C.M. FANNING with Dr B.J. Mahoney (University of Wisconsin-Eau Claire , USA), The Baja-BC conundrum.

Mr C.M. FANNING with Prof F. Hervé (University of Chile , Santiago , Chile), Geochronology and tectonic evolution of the southern Patagonian batholith and outboard accreted terranes.

Mr C.M. FANNING with Dr R.J. Pankhurst (British Geological Survey & the NERC Isotope Geosciences Laboratory, UK), Evolution of the north Patagonian massif and the Sierras Pampeanas.

Mr C.M. FANNING with Dr C.W. Rapela (Universidad de la Plata , Argentina), Evolution of the north Patagonian massif and the Sierras Pampeanas.

Mr C.M. FANNING with Dr A. Cocherie & Dr P. Rossi (Bureau de Recherche Geologique et Miniere, Orleans , France), Evolution of Corsica and beyond.

Mr C.M. FANNING with Dr J.A Aleinikoff (US Geological Survey, Denver USA), Timing of events in the New England region, North America .

Mr C.M. FANNING with Dr C. Smith-Siddoway (Colorado College, USA), Geochronology of granites in the Ross Sea and the timing of metamorphism in Marie Byrd Land, Antarctica.

Mr C.M. FANNING with Dr K. Shiraishi and Dr K. Misawa (National Institute for Polar Research, Tokyo , Japan), U-Pb reference zircons.

Mr C.M. FANNING with Dr J. Goodge (Southern Methodist University, USA), The geochronology and tectonic evolution of the East Antarctic Craton, Transantarctic Mountains.

Mr C.M. FANNING with Dr J. Jacobs (University of Bremen , Germany), Geochronology and tectonic evolution of Dronning Maud Land.

Mr C.M. FANNING with Prof D. Gebauer and Dr A. Liati (ETH Zürich, Switzerland), Geochronology and trace element geochemistry of zircons from Alpine eclogites.

Mr C.M. FANNING with Dr A. Morton (HM Associates, UK), Detrital zircon provenance of Palaeozoic basins in North Sea region.

Mr C.M. FANNING with Prof C. Casquet and Dr C.Galindo (Universidad Complutense, Madrid, Spain), Sierras Pampeanas and the evolution of the Argentine PreCordillera.

Mr C.M. FANNING with Prof F. Munizaga and Dr Victor Maksaev (University of Chile , Santiago , Chile), Timing of mineralisation in the Collahuasi & Atacama regions.

Dr M. NORMAN with Drs. L. Nyquist and D. Bogard (both NASA Johnson Space Center , Houston), Prof. L. Taylor (University of Tennessee , Knoxville), and Prof. R. Duncan (Oregon state University, Corvallis), Age, Origin, and Impact History of the Lunar Crust.

Dr M. NORMAN with Prof. M. Garica (University of Hawaii , Honolulu), Dr. A. Pietruszka (San Diego State University , San Diego), and Prof. M. Rhodes (University of Massachusetts , Amherst), Magmatic Processes at Hawaiian volcanoes.

Dr M. NORMAN with Dr. M. Humayun (Florida State University, Tallahassee) A. Brandon (NASA Johnson Space Center, Houston), Prof. T. Elliott, Prof. C.J. Hawkesworth, and Dr. A. Scherstén (University of Bristol, Bristol), Core-Mantle Interaction and Origin of Mantle Plumes.

Dr G.M. YAXLEY and Dr A.J. BERRY with Dr A.B. Woodland (Johann Wolfgang Goethe-Universität, Frankfurt, Germany) and Dr G.J. Foran (Australian National Science and Technology Organization), The oxidation state of Fe in mantle garnets: implications for diamond stability during metasomatic events.

Dr G.M. YAXLEY with Dr A.J. BERRY, Prof A.B. Woodland (University of Frankfurt) and Prof G.P. Brey (University of Frankfurt), Application of XANES to determination of $Fe^{3+}/\sum Fe$ in garnet.

Dr G.M. YAXLEY with Prof A. Sobolev (Max-Planck-Isntitut für Chemie, Mainz), Interactions between high pressure partial melts of gabbro and peridotite upper mantle – an experimental investigation.

COOPERATION WITH GOVERNMENT AND INDUSTRY

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Dr R. ARMSTRONG with Dr I. Graham (Australian Museum , Sydney) on sapphire-bearing volcanics in eastern Australia .

Dr E. CALVO and Dr C. PELEJERO with Dr G.A.Logan (Geoscience Australia) on o rganic geochemistry of marine sediments.

Mr C.M. FANNING with Mrs S. DALY, Mr M. SCHWARZ and others (Geological Survey of South Australia) on a geochronological synthesis of South Australia

Mr C.M. FANNING with Mr L. Hutton and Mr I. WITHNALL (Geological Survey of Queensland) on the geochronology of a number of key provinces in Queensland.

Prof T.M. HARRISON, Member of the Australian Research Council College of Experts reviewing ARC Discovery, LIEF, Linkage and Federation Fellowship applications.

Prof T.M. HARRISON, Member of National Committee for Earth Sciences at Australian Academy of Science.

Prof T.M. HARRISON, Member of the Board of the Australian National Seismic Imaging Resource (ANSIR), a Major National Research Facility operated as a joint venture of GA and RSES.

Prof B.L.N. KENNETTt has continued to provide support to the Comprehensive Nuclear-Test-Ban Treaty (CTBT) Organisation in Vienna through the operation of the Warramunga Seismic and Infrasound Research Station near Tennant Creek in the Northern Territory . The seismic and infrasound arrays have been very ably supported by Mr Peter Biggs and Mr Jingming Duan. Very high reliability has been achieved with data transmitted continuously to the International Data Centre in Vienna via satellite link.

Prof K. LAMBECK, Chair, Antarctic Science Advisory Committee, Department of the Environment and Heritage

Prof K. LAMBECK, Member of AUSAID Technical Advisory Group on South Pacific sea level and climate monitoring.

Prof K. LAMBECK, Member of the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE-CRC)

Prof K. LAMBECK, Member working group for the Prime Minister’s Science, Engineering and Innovation Council on Opportunities for Antarctic and Southern Ocean Science

Prof K. LAMBECK, Foreign Secretary, a member of the Council and a member of the Finance Committee of the Australian Academy of Science

Prof K. LAMBECK, Board Member , Australia 21

Prof K. LAMBECK, Consultant, Geoscience Australia

Dr H. McQUEEN with R. Tracey (Geoscience Australia) Gravity ties and gradient measurements at the Mt Stromlo gravity and seismic stations in support of Absolute Gravity determinations.

Dr H. McQUEEN with Dr R. Govind and G. Luton (Geoscience Australia), Coordination of Absolute Gravity measurements at the Mt Stromlo and Tidbinbilla.

Dr M. NORMAN with Dr R. Hough (CSIRO) on the siting of gold and significant pathfinder elements in regolith samples.

Dr A.P. NUTMAN with Dr G. Gibson (Geoscience Australia , Canberra), Tectonothermal evolution of the Broken Hill area and its relevance to mineralisation.

Dr E. RHODES with Dr R. Torrence (Australian Museum , Sydney), Dating of Pleistocene tephras associated with Palaeolithic artefacts in PNG

Dr M. SAMBRIDGE with Dr. P Cummins (Geoscience Australia) on seismic source studies in the Australian continent.

Mr D. WOOD with Queensland Geological Survey, Tectonic evolution of the Anakie Inlier and implications for the early Palaeozoic in eastern Australia .

Dr G.M. YAXLEY has completed several consultative projects for Australian and international diamond exploration companies and for Australian state geological surveys .

STAFF ACTIVITIES

CONFERENCES AND OUTSIDE STUDIES

Earth Chemistry

Mr A.B. AIKMAN, 17th Australian Geological Conference, Hobart, Tasmania, 10-11 February, presented a paper entitled " Structural dislocations in perthitic K-feldspar: from reaction rates to the origin of life".

Mr A.B. AIKMAN, Himalaya-Karakorum Tibet workshop, Niseko , Japan , July, presented a paper entitled "Preliminary results from the Yala- Xiangbo Dome , SE Tibet ".

Dr C. ALLEN, 17th Australian Geological Conference, Hobart , Tasmania , 10-11 February, presented a paper entitled "The stories a single zircon can tell".

Dr C. ALLEN, Spring Meeting of the American Geophysical Union, Montreal, Canada, May, presented a paper entitled "Identifying and dating metamorphic zircons in clastic rocks and river sediment and the technique of U-Pb dating fine overgrowths".

Dr V.C. BENNETT, participated in fieldwork in southwest Greenland from 20 June to 3 August.

Dr V.C. BENNETT, visiting scientist at the Lunar and Planetary Institute, Houston , Texas from 13 November to 10 December.

Dr V.C. BENNETT, The Elizabeth and Frederick White Conference, "Planetary Timescales: from Stardust to Continents", Australian Academy of Sciences, Canberra , 16-19 February, presented a paper entitled " Direct age constraints on planetary differentiation: observations and prospects".

Dr V.C. BENNETT , American Geophysical Union, San Francisco , California , 13-17 December, presented a paper entitled "Evolving Mantle Regimes Revealed by 143Nd Compositions of 3850Ma to Modern Mafic rocks", in the interdisciplinary Union session, The Deep Earth Engine: Geophysics and Geochemistry.

Dr I.H. CAMPBELLl, attended a Council meeting of the International Mineralogical Association at the 32 nd International Geological Congress, Florence, Italy, 20-28 August and presented a paper entitled "Testing the plume hypothesis: prediction and observations" at the Congress.

Mr J. CELERIER, 19th Himalayan-Karakoram Tibet Workshop, 10-12 July, Niseko , Japan .

Mr J. CELERIER, Channel flow, Ductile Extrusion and Exhumation of Lower-mid Crust in Continental Collision Zones, London, 6-7 December.

Prof W. COMPSTON, SHRIMP Workshop, Hiroshima, Japan, 8-12 November, oral presentations entitled "New SHRIMP ages from the P-T boundary at Meishan, China" and

“Direct evidence for within-session variation in SHRIMP 206Pb/ 238 U age-calibration and its numerical correction”.

Mr A.J. CROSS, SHRIMP workshop, Hiroshima , Japan , 8-12 November, oral presentation entitled “ Detrital zircon from the early Palaeoproterozoic sediments of the Tanami Basin : A record of orogenesis”.

Ms T.A. EWING, SHRIMP workshop, Hiroshima , Japan , 8-12 November, oral presentation entitled “ The Kakapo Granite – Complex ages from a complicated granite”.

Dr J.J. FOSTER, SHRIMP workshop, Hiroshima , Japan , 8-12 November, oral presentation entitled “ SHRIMP SI: What is it?”.

Mr T. FUJIOKA, 11th Australian and New Zealand Geomorphology Group (ANZGG), Mount Buffalo , Victoria , Australia , 15-20 February, oral presentation entitled “Evaluation of nucleogenic component in cosmogenic 21Ne surface exposure dating”.

Prof T.M. HARRISON, 17th Australian Geological Convention, Hobart, Tasmania, 8-13 February, presented a paper entitled “The >3.83 ga Akilia quartzite: the oldest known marine sediment containing evidence for life?”.

Prof T.M. HARRISON, The Elizabeth and Frederick White Conference, “Planetary Timescales: From Stardust to Continents”, Australian Academy of Science , Canberra 16-19 February, presented a paper entitled “The Mission to Really Early Earth: When did conditions appropriate for Life emerge?”.

Prof T.M. HARRISON, Goldschmidt Geochemistry Conference, Copenhagen , Denmark , 5-11 June, presented a paper entitled "When Did Conditions Appropriate for Life Emerge? Further Results of the Mission to Really Early Earth".

Prof T.M. HARRISON, 32nd International Geological Congress, Florence , Italy , 20-28 August, presented papers entitled "Did Lower Crustal Channel Flow Create the Himalaya ?" and "Documenting Deep Exhumation using Th-Pb Dating of Monazite".

Prof T.M. HARRISON, A NASA Specialized Center of Research and Training (NSCORT) Seminar, New York, 7-8 November, presented a paper entitled "The Mission to Really Early Earth: When did Conditions Appropriate for Life First Appear on Earth?".

Prof T.M. HARRISON visited Dr Bruce Watson, Rensellaer Polytechnic Institute, New York .

Prof T.M. HARRISON, Geological Society of America Annual Meeting, Denver , 9-11 November.

Prof T.M. HARRISON, Plate Tectonics, Plumes, and Planetary Lithospheres Conference in honour of Dr Kevin Burke’s 75th birthday, Houston , Texas , 12-15 November, presented a paper entitled "The Mission to Really Early Earth".

Prof T.M. HARRISON, Geological Society of London Channel Flow Conference, London 6-7 December, presented a paper entitled "Did molten Tibetan middle crust create the Himalaya via channel flow?"

Dr P. HOLDEN, SHRIMP workshop, Hiroshima , Japan , 8-12 November, oral presentations entitled “Automated multicollector SHRIMP geochronology, Part 1: Data acquisition” and “Problems with zircon U-Pb fractionation on SHRIMP RG”.

Dr M. HONDA, The Elizabeth and Frederick White Conference, “Planetary Timescales: From Stardust to Continents”, Australian Academy of Science, Canberra , 16-19 February, presented a paper entitled “The origin and evolution of planetary atmosphere – implications from noble gases”.

Dr T.R. IRELAND , 17th Australian Geological Conference, Hobart , Tasmania , 10-11 February, presented a paper entitled “Developments in SHRIMP analysis”.

Dr T.R. IRELAND, 35th Lunar & Planetary Sciences Conference, Houston, USA, 13-17 March, oral presentation on oxygen isotopes in lunar metal grains.

Dr T.R. IRELAND, Lunar & Planetary Institute workshop “Oxygen in the Terrestrial Planets”, Santa Fe , USA , 20-24 July, oral presentation entitled “Oxygen isotopes in lunar metal grains: A natural genesis experiment”.

Dr T.R. IRELAND, SHRIMP workshop, Hiroshima, Japan, 8-12 November, oral presentations entitled “Solar wind oxygen isotopes in lunar metal grains” and “Automated multicollector SHRIMP geochronology, Part 3: Results”.

Mr B. JENKINS, SHRIMP workshop, Hiroshima , Japan , 8-12 November, oral presentation entitled “ Field distributions of homogeneous magnetic sectors”.

Ms F. JENNER, 17th Australian Geological Conference, Hobart , Tasmania , 10-11 February, presented a poster entitled “ A 3.0 Ga mafic/ultramafic pillow basalt sequence from Ivisartoq, Southwest Greenland : New insights into late Archean tectonics”.

Mr A.P. KALLIO, SHRIMP workshop, Hiroshima , Japan , 8-12 November, oral presentation entitled “ Rb and Cs as indicators of continental crustal growth”.

Mr P. LANC, SHRIMP workshop, Hiroshima , Japan , 8-12 November, oral presentation entitled “ Automated multicollector SHRIMP geochronology, Part 2: Automated data acquisition”.

Mr D. MAIDMENT, Annual Geoscience Exploration Seminar (AGES) , Alice Springs , 22-23 March, presented a paper entitled “ The Irindina Province – a Neoproterozoic-Cambrian rift in the eastern Arunta” .

Dr A.P. NUTMAN, The Elizabeth and Frederick White Conference, “Planetary Timescales: From Stardust to Continents”, Australian Academy of Science, Canberra , 16-19 February, oral presentation on extracting useful information from the Earth’s oldest rocks.

Dr A.P. NUTMAN, Australian Geological Congress, Hobart, 10-11 February, oral presentation s on Archaean and Palaeoproterozoic tectonics.

Dr A.P. NUTMAN, Workshop on Early Life (sponsored by the Astrobiology Institute), Nuuk, Greenland , June, oral presentation and discussion on early Archaean geology and mineralogy of Akilia Island , Greenland .

Dr A.P. NUTMAN, Chinese Academy of Geological Sciences , Beijing , August, oral presentation on Palaeoproterozoic tectonics and metamorphism and searching for evidence of life in the world's oldest rocks.

Ms R.A. PETCH, SHRIMP workshop, Hiroshima , Japan , 8-12 November.

Ms A. STOLZE, 32nd International Geological Congress, Florence , Italy , 20-28 August, presented a paper entitled "A genetic link between carbonatite magmatism and gold mineralisation at the Wallaby Gold Deposit, Eastern Goldfields, Western Australia".

Dr I.S. WILLIAMS, Invited Lecturer, Polish Geological Institute, Warsaw, 14 June, oral presentations entitled "An introduction to the SHRIMP ion microprobe", "Measuring the ages of granites is not always as easy as it might seem" and "The response of zircon, monazite and their U-Pb isotopic systems to high grade metamorphism and magma genesis".

Dr I.S. WILLIAMS, Invited Lecturer, International Seminars of Petrology (ISPET) II, Granada, 28 March to 3 April, oral presentations entitled "Dating high temperature metamorphic rocks, Part 1 The problem", "Dating high temperature metamorphic rocks, Part 2 The solution", and "Dating high temperature metamorphic rocks, Part 3 Anatexis".

Dr I.S. WILLIAMS, Invited Lecturer, Silesian University, Sosnowiec, Poland, 16 June, oral presentation entitled " An introduction to the SHRIMP ion microprobe".

Dr I.S. WILLIAMS, Invited Lecturer, Mining Academy, Krakow, Poland, 18 June, oral presentation entitled " An introduction to the SHRIMP ion microprobe".

Dr I.S. WILLIAMS, SHRIMP workshop, Hiroshima , Japan , 8-12 November, oral presentation entitled " Towards the analysis of oxygen isotopes in insulators using the SHRIMP II".

Earth Environment

Ms B. AYLING, Robertson Workshop on Environmental Geochemistry and Geochronology: Quaternary Chronologies, Robertson, NSW, 30 April - 2 May, oral presentation entitled "Marine Isotope Stage 9 (300-320ka) climate records utilizing fossil *Porites* corals from Henderson Island , SE Pacific".

Ms B. AYLING, 32nd International Geological Congress, Florence, Italy, 20-28 August, oral presentation entitled "Fossil *Porites* and *Tridacna* d 18 O records of Marine Isotope Stage 9 climate at Henderson Island, SE Pacific".

Ms B. AYLING, 8th International Conference on Paleoceanography, Biarritz , France , 5-10 September, presented a poster entitled "High resolution records of MIS 9 and MIS 11 interglacial climates utilizing fossil *Porites* corals (Henderson Island , SE Pacific) and *Tridacna* clams (Huon Peninsula , PNG)".

Ms S.N. BURGESS, 10th International Coral Reef Symposium, Okinawa, Japan, 28 June – 2 July, presented a poster entitled "Geochemical ecology of *Plesiastrea versipora*: Hermatypic coral at its southern latitudinal limit".

Dr E. CALVO, 8th International Conference on Paleoceanography, Biarritz , France , 5-10 September, presented a poster entitled "Decadal climate variability in the western Coral Sea since 1710 A.D.".

Dr T.M. ESAT, Invited Participant at a Workshop on Evolution and Predictability of Earth System, University of Tokyo , July, "Climate and sea-level correlated variations in U isotopes in the oceans".

Dr T.M. ESAT, The 21st century Earth Science COE Program, University of Tokyo, July, "Climate and sea-level correlated variations in U isotopes in the oceans" and "Potassium isotope fractionation during condensation in the early solar nebula".

Dr T.M. ESAT, Invited Participant, The International Science Symposium on Sample Returns from Solar System Minor Bodies, Kangawa, Japan, October, "Viability of Mg and Si isotope measurements in samples expected from the Hayabusa mission to asteroid Itokawa".

Dr S. EGGINS, Robertson Workshop on Environmental Geochemistry and Geochronology: Quaternary Chronologies, Robertson, NSW, 30 April - 2 May, "In-situ U-series dating of Quaternary".

Dr S. EGGINS, 8th International Conference on Paleoceanography, Biarritz , France , 5-10 September, presented a poster entitled "More from Less, Laser ablation ICPMS microanalysis of foraminifera tests" and oral presentation entitled "Laser ablation ICPMS analysis of Mg/Ca heterogeneity in planktonic foraminifera" at a Conference Workshop on Mg/Ca chemistry of Foraminifera.

Dr D. FABEL, 11th Australia and New Zealand Geomorphology Group Conference, Mt Buffalo, Victoria, 15-20 February, oral presentation entitled " Do different geomorphic features created by the same glaciation give the same exposure age?".

Dr D. FABEL, CRC LEME Regolith Symposium, Canberra , 24-26 November, "Cosmogenic burial dating of shallow deposits – a preliminary study".

Dr D. FABEL, Joint International Geomorphology Conference, Glasgow, 17-20 August, "Constraints on basal thermal regimes of ice sheets from cosmogenic radionuclides".

Dr D. FABEL, Robertson Workshop on Environmental Geochemistry and Geochronology: Quaternary Chronologies, Robertson, NSW, 30 April - 2 May, " Cosmogenic burial dating – Complexities and limitations".

Ms R.A. FRASER, 4th International Conference on Applications of Stable Isotope Techniques to Ecological Studies, Wellington, New Zealand, 19-23 April, presented a poster entitled "Sequential micro-analyses of δ13C in wombat incisors: records of rainfall distribution and seasonality of C3 and C4 plant growth".

Ms R.A. FRASER visited the Research Laboratory for Archaeology, University of Oxford , May-June, to undertake carbon and nitrogen stable isotope analysis of bone collagen and discuss future collaborative projects with Prof R. Hedges, Dr T. O'Connell and Dr P. Ditchfield.

Prof R. GRÜN, Geoscience Africa, Johannesburg , 12-16 July, oral presentation entitled " Progress in dating hominid remains".

Prof R. GRÜN, Robertson Workshop on Environmental Geochemistry and Geochronology: Quaternary Geochronology, Robertson, NSW, 30 April - 2 May, oral presentation entitled " Advances in ESR and U-series dating of human remains".

Dr C. PELEJERO, 8th International Conference on Paleoceanography, Biarritz , France , 5-10 September, presented a poster entitled "Alkenone paleothermometry and phytoplanktonic evolution of the South Tasman Sea during the last four glacial/interglacial cycles".

Dr B. PILLANS, 32nd International Geological Congress, Florence, Italy, 20-28 August, Keynote Speaker: "Definition of the Lower-Middle Pleistocene boundary" and Invited oral presentation entitled "Paleomagnetic dating of Cenozoic, Mesozoic and Paleozoic weathering profiles in Australia".

Dr B. PILLANS, 11th Australian and New Zealand Geomorphology Group Conference, Mt Buffalo, Victoria, 15-20 February, oral presentation entitled "Dating long-term landscape evolution in Australia: Highlights from the LEME Geochronology Project".

Dr B. PILLANS, CRC LEME Regolith Symposium , Canberra , 24-26 November, oral presentations entitled "Talking about time: The Geological Time Scale 2004", and "Tektites as chronostratigraphic markers in Australian regolith".

Dr E. Rhodes, Australia and New Zealand Geomorphology Group meeting, Mount Buffalo, Victoria, 16-20 February, oral presentation entitled "OSL dating of sediments: a tool for developing models of fluvial activity and deposition".

Dr E. RHODES May, oral presentation entitled "Getting the most from Quaternary chronologies".

Dr E. RHODES, 80th Birthday meeting in honour of Prof. John Prescott, Adelaide , South Australia , 31 May, oral presentation entitled "OSL of old samples".

Dr E. RHODES, CRC LEME Regolith Symposium, Canberra , 22 – 24 November, oral presentations entitled "The History of Aridity in Australia : Preliminary Chronological Data".

Dr E. RHODES, Australasian Quaternary Association meeting, Cradle Mountain , Tasmania , 6-10 December, oral presentation entitled "Discreet periods of Aeolian activity during the last glacial cycle in Australia ".

Mr A. SADEKOV, 8th International Conference on Paleoceanography, Biarritz , France , 5-10 September, presented a poster entitled “ Within test Mg/Ca ratio banding and shell morphology variation in a population of *Orbulina universa* (d’Orbigny)”.

Mr M. SMITH, 17th Australian Geological Conference, Hobart , Tasmania , 10-11 February.

Mr M. SMITH, CRC LEME Eastern Regolith Symposium, Canberra , 24-26 November.

Mr T. WYNDHAM, visited the Department of Oceanography, University of Hawaii as part of a project investigating the influence of phytoplankton blooms and trace metal compositions of the coastal ocean, June - November.

Earth Materials

Mr M . BELTRANDO, 32nd International Geological Congress, Florence, Italy, 20-28 August, “Rollback-induced barrovian metamorphism in the Lepontine Alps” and “First results of K-Feldspar multidomain analysis of the cooling path during exhumation of the Gran Paradiso Massif, Italy”.

Dr A.J. BERRY , 17th Australian Geological Convention, Hobart , Tasmania , 8-13 February, “The oxidation state of trace elements in magmas”.

Dr A.J. BERRY , Experimental Mineralogy, Petrology and Geochemistry, Frankfurt , Germany , 4-7 April, “The *in situ* determination of redox states in silicate melts”.

Dr A.J. BERRY , Goldschmidt Geochemistry Conference, Copenhagen , Denmark , 5-11 June, “The water site in mantle olivine”.

Prof S.F. COX, 17th Australian Geological Convention, Hobart , Tasmania , 8-13 February, “Controls on permeability and flow paths in fracture-controlled hydrothermal systems”.

Dr J. DUNLAP, 17th Australian Geological Convention, Hobart , Tasmania , 8-13 February, “Vagaries of a quadrupole mass spectrometer used for helium isotope analysis”.

Dr G. FRASER, Annual Geoscience Exploration Seminar (AGES), Alice Springs , March, “Defining the “footprint” of tectonothermal events in the North Australian Craton: Recent 40Ar/ 39Ar results from the Davenport Ranges and Barrow Creek regions”.

Mr A. HACK, 17th Australian Geological Conference, Hobart, Tasmania, 8-13 February, “Activity-Composition Relations in the SiO 2 – H 2O System at Deep Crust and Upper Mantle Conditions: Fluid density measurements” and “The Origin of Porphyry Copper Deposits: *In Situ* Determination of Copper Speciation and Solubility in Hydrothermal Fluids XANES Spectroscopy and LA-ICP-MS of Individual Fluid Inclusions”.

Dr J. HERMANN, Invited Lecturer at the International Seminars of Petrology (ISPET) III summer school, Padova, Italy, June, “Experimental and natural constraints on trace element recycling in subduction zones”.

Dr J. HERMANN, 10 days of field work in the Alps related to projects on water incorporation into mantle minerals and Alpine high-grade metamorphism.

Prof I. JACKSON, Australian Institute of Physics annual Condensed Matter Physics and Materials, Wagga Wagga, NSW, February.

Prof I. JACKSON, visited Stony Brook University , New York , December, to lecture and hold discussions with research collaborators.

Prof I. JACKSON, visited University of California , Berkeley for discussions with research collaborators.

Prof I. JACKSON, Fall Meeting of the American Geophysical Union , San Francisco , 13-17 December.

Prof G. LISTER, 17th Australian Geological Convention, Hobart, Tasmania, 8-13 February, "Three-dimensional slab structure of the Northwest Pacific".

Prof G. LISTER, 32nd International Geological Congress, Florence , Italy , 20-28 August, "Rollback-induced barrovian metamorphism in the Lepontine Alps " and "First results of K-Felspar multidomain analysis of the cooling path during exhumation of the Gran Paradiso Massif, Italy ".

Dr J.A. MAVROGENES,17th Australian Geological Convention, Hobart , Tasmania , 8-13 February, "Copper chloride species high temperature brines and vapours: Spectroscopic evidence from fluid inclusions ".

Dr J.A. MAVROGENES attended the Spring Meeting of the American Geophysical Union, Montreal , Canada , May.

Dr J.A. MAVROGENES spent six months on sabbatical at CNRS, Orleans , France .

Prof I. McDOUGALL, 17th Australian Geological Convention in Hobart , Tasmania , 8-13 February, presented a paper on some of his East African work.

Dr S. McLAREN, 17th Australian Geological Convention in Hobart , Tasmania , 8-13 February, "A hot-plate tectonic model for Proterozoic crustal evolution in Australia ; Continent-scale spatial analysis of the regional setting of iron-oxide-copper-gold mineral systems in Australia " and "The Cooper Basin Argon Laboratory: Nature's test of the K-feldspar MDD model"

Dr S. MICKLETHWAITE, American Geophysical Union, San Francisco , U.S.A. , 12-17 December, presented a poster entitled "Fault-segment rupture and mineralisation during aftershock focused fluid flow".

Ms M. MILLER, 17th Australian Geological Convention, Hobart , Tasmania , 8-13 February, "Three-dimensional slab structure of the Northwest Pacific".

Mr C. SPANDLER, 17th Australian Geological Convention, Hobart, Tasmania, 8-13 February, oral presentation entitled "The subduction blender – the role of slab-derived hybrid rock-types for volatile and trace element recycling in subduction zones".

Mr D. WOOD, 17th Australian Geological Convention, Hobart , Tasmania , 8-13 February. “Age and implication of core-complex formation in central East Queensland ”.

Earth Physics

Mr R. BRODIE, Australian Society of Exploration Geophysics meeting, Sydney, August, oral presentation on his holistic approach to Airborne Electromagnetic inversion.

Dr D.R. CHRISTIE, Infrasound Technology Meeting, Hobart , Tasmania 29 November to 6 December, presented a paper entitled “Observations of Infrasound in Central Australia ”

Ms M.A. COMAN, 15th Australasian Fluid Mechanics Conference, Sydney, NSW, 13-17 December, oral presentation entitled “Convective exchange between two connected chambers”.

Dr G.F. DAVIES, International Geological Congress, Florence , Italy , 20-28 August, presented a paper entitled “Dynamics of the Archaean Mantle, with geochemical and tectonic implications”.

Dr G.F. DAVIES took Outside Studies leave from April - August. Much of that time was spent at the University of California , Santa Cruz , where he wrote about mantle plumes, taught and interacted with seismologists, petrologists and modellers of the geodynamo. He also visited and consulted with Professor P. Bunge at Ludwig-Maximillians University in Munich .

Mr. S. FISHWICK, 17th Australian Geological Convention, Hobart, Tasmania, 8-13 February, oral presentation entitled “Contrasts in Lithospheric Structure in the Australian Craton”.

Prof R.W. GRIFFITHS , 17th Australian Geological Convention, Hobart , Tasmania , 8-13 February, presented a paper on solidification and formation of lava tubes and channels.

Prof R.W. GRIFFITHS, International Congress of Theoretical and Applied Mechanics, Warsaw , August, presented papers on the ocean overturning circulation.

Prof R.W. GRIFFITHS, 32nd International Geological Congress, Florence , 20-28 August, presented a paper on the solidification in lava channels.

Prof R.W. GRIFFITHS, American Physical Society/ Division of Fluid Dynamics meeting, Seattle, November, presented a paper on the ocean overturning circulation.

Prof R.W. GRIFFITHS, Scientific Committee on Oceanic Research Working Group 121 Symposium on Ocean Mixing, Victoria , Canada , October, presented a poster entitled “A ‘recycling box’ model of the global overturning circulation: replacing the missing mixing with a missing process”.

Prof R.W. GRIFFITHS, 15th Australasian Fluid Mechanics Conference, University of Sydney , 13-17 December, invited lecture on “The energetics of horizontal convection”.

Prof R.W. GRIFFITHS lectured at the University of Sydney and the Graduate School of Oceanography, University of Rhode Island .

Dr M. HEINTZ, 17th Australian Geological Convention in Hobart , Tasmania , 8-13 February.

Dr A. McC. HOGG, 11th National Australian Meteorological and Oceanographic Society (AMOS) conference (held as part of the International Conference on Storms), Brisbane, 5-9 July, oral presentation entitled " Decadal Variability of the Wind-Driven Ocean Circulation".

Dr A. McC. HOGG, 16th Australia New Zealand Climate Forum, Lorne , Victoria , November, oral presentation entitled "Ocean-atmosphere dynamics and decadal variability in the Southern Ocean".

Dr A. McC. HOGG, 15th Australasian Fluid Mechanics Conference, University of Sydney, 13-17 December, oral presentation entitled "Exchange flow between continuously stratified reservoirs".

Dr G.O. HUGHES, American Geophysical Union Ocean Sciences Meeting, Portland , Oregon , January, oral presentation entitled "Plumes, turbulent entrainment and the thermohaline circulation of the oceans".

Dr G.O. HUGHES visited colleagues and presented seminars on a new model for the global overturning circulation of the oceans at the University of Cambridge , Imperial College , Southampton Oceanography Centre, University of Rhode Island and the University of Canterbury .

Dr G.O. HUGHES, Scientific Committee on Oceanic Research Working Group 121 Symposium on Ocean Mixing, Victoria , Canada , October, presented a poster entitled "A 'recycling box' model of the global overturning circulation: replacing the missing mixing with a missing process ".

Dr G.O. HUGHES, 15th Australasian Fluid Mechanics Conference, University of Sydney, 13-17 December, oral presentation entitled "A steady 'filling box' solution with zero net buoyancy flux".

Prof B.L.N. KENNETT, 17th Australian Geological Convention, Hobart, Tasmania, 8-13 February, oral presentation on the current state of understanding of 3-D seismic structure beneath Australia.

Prof B.L.N. KENNETT, Australian Society of Exploration Geophysicists meeting, Sydney, August, oral presentation on the current state of understanding of 3-D seismic structure beneath Australia .

Prof B.L.N. KENNETT, Summer School on Geophysical Inversion, Boulder , Colorado , June, Key Lecturer.

Prof B.L.N. KENNETT paid a short visit to Strasbourg , presenting a seminar on the structure beneath Australia .

Prof B.L.N. KENNETT, 9th Symposium on the Study of the Earth's Deep Interior, Garmisch Partkenkirchen , Germany , 4-9 July.

Prof B.L.N. KENNETT, Fall Meeting of the American Geophysical Union, San Francisco, 13-17 December, presentations on guided waves in subduction zones and the use of joint-body wave tomography in upper mantle studies, as well as contributing to a number of posters.

Dr R.C. KERR, 32nd International Geological Congress, Florence, Italy, 20-28 August, oral presentation entitled "The structure and dynamics of sheared mantle plumes, with implications for the geographical distribution of geochemical heterogeneities in hotspot magmas".

Dr R.C. KERR, International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) General Assembly, Chile, November, oral presentation entitled "Convection and surface solidification in laminar channel flows: lava tubes or a'a' flows". He also participated in two field trips which examined volcanism in the central Andes .

Dr A. KISS, 15th Australasian Fluid Mechanics Conference, University of Sydney , 13-17 December, presented a paper entitled "Response of ocean circulation to variable wind forcing".

Dr A. KISS, Joint Asia Oceania Geosciences Society First Annual Meeting and Asia Pacific Association of Hydrology and Water Resources Second Conference, Singapore, 5-9 July, presented an invited keynote address entitled "Separation of western boundary currents: New insights from barotropic models".

Dr A. KISS presented seminars in the Complex Systems Network Workshop, ANU, 16 - 17 February and the Marine Geochemistry and Ocean Modelling Meeting, ANU, 5 March.

Prof K. LAMBECK, European Union of Geosciences meeting, Nice, France, 25-30 April, oral presentations: "Glacial rebound of Scandinavia: Implications for the ice sheet dimensions since the last glacial maximum and mantle rheology" and " Sea level in Roman time in the Central mediterranean and the timing of the onset of the recent rise in eustatic sea level".

Prof K. LAMBECK, International Geological Congress, Florence , Italy , 20-28 August, oral presentation entitled "The MIS 5.5 Shoreline in the Mediterranean : Isostatic and tectonic causes for spatial variability in its elevation above present sea level".

Prof K. LAMBECK, Canadian Institute of Advances Studies, Earth Science Evolution program, Toronto , Canada , September.

Prof K. LAMBECK also visited and gave seminars at the Universities of Lund and Stockholm and Imperial College London.

Dr F.E.M. LILLEY, Australian Society of Exploration Geophysicists – Petroleum Exploration Society of Australia Geophysical Conference, Sydney 16-18 August, presented a paper entitled "Snapshots from fifty years of geophysics".

Mr A.W. LYMAN, International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) General Assembly , Chile , November, oral presentation entitled “The effects of interior yield strength and surface solidification on the emplacement of lava flows”. He also participated in two field trips, which examined volcanism in the central Andes .

Ms J.C. MULLARNEY, American Geophysical Union Ocean Sciences Meeting in January in Portland , Oregon , January, oral presentation entitled “The meridional overturning circulation: some insights from simple models”.

Dr N. RAWLINSON, 17 th Australian Geological Convention, Hobart, Tasmania, 8-13 February, oral presentation entitled “Three-dimensional structure of the lithosphere beneath northern Tasmania from seismic traveltimes” and poster entitled “ A deeper look at the terranes of southern Victoria and Tasmania: constraints from the broadband stations of the TIGGER seismic network”.

Dr N., RAWLINSON, Fall Meeting of the American Geophysical Union, San Francisco, 13-17 December, oral presentation entitled “3-D teleseismic tomography of the crust and upper mantle beneath northern Tasmania, Australia” and poster entitled “Seismic applications of the fast marching method: traveltime prediction in complex layered media and 3-D tomographic imaging”.

Dr A.M. READING, XXVIII Scientific Committee for Antarctic Research, Open Science Meeting, Bremen, Germany, 26-28 July, Invited oral presentation entitled “SEAP and new international initiatives in Antarctic Seismology” and poster entitled “Seismic structure and tectonics of the Lambert Glacier region: first results from the SSCUA broadband seismic deployment, East Antarctica”.

Dr A.M. READING, Mineral Resources Tasmania, Hobart , 30 June, presented a Research Seminar on “The deep structure of Tasmania from broadband seismic data.

Dr M. SAMBRIDGE, Australian Society of Exploration Geophysics meeting, Sydney, August, presented a poster entitled “Wavefront propagation with Fast Marching methods”, and contributed to the special session to honour the career of Ted Lilley.

Mr E. SAYGIN, Summer school Mathematical Geophysics & Uncertainty in Earth Models, Golden, USA, 14-25 June.

Dr W.P. SCHELLART, 17th Australian Geological Convention, Hobart, Tasmania, 8-13 February, oral presentation entitled “The role of the effective slab pull force in driving tectonic plates” and two posters entitled “Reconstruction of the South 8 June, 2005 s of slab subduction in the upper mantle”.

Dr W.P. SCHELLART, American Geophysical Union Western Pacific meeting, Hawaii , August, two oral presentations: “Three-dimensional fluid dynamic modelling of subduction and mantle flow” and “Episodic migration of the Australian-pacific plate boundary during the Cenozoic” and was invited to present the latter at the AGU press conference. Dr SCHELLART convened and chaired a session entitled “Geoscience software frameworks II: Three-dimensional modeling of subducting slabs” and chaired a session entitled “ Plate Boundary Transitions of the Western Pacific: Observations and Models I”.

PRISE

Dr R.A. ARMSTRONG, 17th Australian Geological Convention, Hobart , Tasmania , 8-13 February, presented a paper on the geochronology of Macquarie Island .

Dr R.A. ARMSTRONG, 20th Colloquium of African Geology in Orléans , France , June, co-authored four papers.

Dr R.A. ARMSTRONG, Geoscience Africa, Johannesburg, South Africa, July, delivered two invited papers entitled “Facing up to heterogeneities in geological samples: some recent advances in geochronology and isotope microanalysis” and “The birth, growth and changes to the Kaapvaal Craton through time” and co-authored another eight papers.

Dr R.A. ARMSTRONG, Geological Society of America Annual meeting, Denver, USA, November, contributed to a Special Session on the “Early Proterozoic (2.5-2.0 Ga) Events and Rates: Bridging Field Studies and Models”.

Mr C.M. FANNING, 17th Australian Geological Convention, Hobart, Tasmania, 8-13 February, presented a paper entitled “Detrital zircon provenance of the Mesoproterozoic Pandurra Formation, South Australia: Gawler Craton derived age spectra and implications for the source of the Belt Supergroup, USA” co-authored two other presentations.

Mr C.M. FANNING, field work in Patagonia, 20-29 February, with Dr R. Pankhurst (UK) and Dr C. Rapela (La Plata, Argentina) related to the project entitled "Chronology of deposition and provenance of Late Palaeozoic sedimentary basins, Argentine Patagonia".

Mr C.M. FANNING, field work in southern Chile , 1-13 March, with Professor Hervé (University de Chile) to examine a section through the southern Patagonian Batholith and the Madre de Dios metamorphic complex.

Mr C.M. FANNING, field work in Minnesota , USA , 8-20 May, with Dr J. Goodge (University of Minnesota , Duluth , USA) to carry out further sampling of the Duluth Complex for use as a SHRIMP reference zircon. Mr C.M. FANNING also presented a seminar at the University of Minnesota on SHRIMP methods and applications.

Mr C.M. FANNING, 2nd International Symposium on Polar Sciences of China, Beijing, 16-17 October, two invited oral presentations entitled “The "Mawson Continent": East Antarctica and southern Australia as a cornerstone for ?Rodinia and Gondwana” and “New insights into the development of the Palaeo Pacific margin of East Gondwana”.

Mr C.M. FANNING, Geological Society of America Annual meeting, Denver , USA , 7-10 November, assisted with four presentations, meetings with numerous international collaborators.

Dr M. NORMAN, 17th Australian Geological Convention, Hobart, Tasmania, 8-13 February, co-convenor of session on New Technologies in Mineralogy, Petrology and Geochemistry and presentation on “Improved Methods for Re-Os Dating of Molybdenite using Multi-collector ICPMS”.

Dr M. NORMAN, Tectonics to Mineral Discovery - Deconstructing the Lachlan Orogen, MORE-SGEG Conference, Orange, NSW, 6–8 July, poster presentation on “New Re-Os Ages of Molybdenite from Granite-related Deposits of Eastern Australia Using an Improved Multi-collector ICP-MS Technique”.

Dr M. NORMAN, Lunar and Planetary Science Conference, Houston, Texas, 15-19 March, Chaired session on “The Lunar Crust as Sampled by Basins and Craters”, and presentations on “Identifying Impact Events Within the Lunar Cataclysm from 40Ar-39Ar Ages of Apollo 16 Impact Melt Rocks” and “Magnesium isotopes in the Earth, Moon, Mars, and pallasite parent body: high-precision analysis of olivine by laser-ablation multi-collector ICPMS”.

Dr M. NORMAN, Visiting Scientist, Lunar and Planetary Institute, Houston, 19 October to 18 December. The purpose of this travel was to conduct geochronological studies of lunar samples at the NASA Johnson Space Center .

Dr G.M. YAXLEY, Goldschmidt Geochemistry Conference, Copenhagen, Denmark, 5-11 June, oral presentation entitled “High-pressure partial melting of gabbro and the preservation of ‘ghost plagioclase’ signatures”.

Dr G.M. YAXLEY, 17th Australian Geological Convention, Hobart, Tasmania, 8-13 February, two oral presentations: “Compositional heterogeneity in olivine-hosted melt inclusions from the Baffin Island picrites” and “Novel techniques for the discrimination of diamond indicator chromian spinel based on major, minor and trace element compositions”.

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EDITORIAL RESPONSIBILITIES

Dr C.M. ALLEN, Associate Editor, Australian Journal of Earth Sciences.

Dr. R.A. ARMSTRONG, member of the Editorial Board of the Journal of African Earth Sciences.

Mr M. BELTRANDO, Chief Editor, Virtual Explorer, vol 16.

Dr V.C. BENNETT, Associate Editor, Journal of Geophysical Research.

Prof S.F. COX, member of the Editorial Advisory Boards for Geofluids and Journal of Structural Geology.

Dr J. DUNLAP, Associate Editor, Australian Journal of Earth Sciences.

Dr S. EGGINS, member of the Editorial Board of Geostandards and Geoanalytical Research.

Prof R.W. GRIFFITHS, member of the Editorial Committee of the Annual Reviews of Fluid Dynamics.

Prof R. GRÜN, Editor of Quaternary Geochronology (Quaternary Science Reviews); member of the Editorial Boards of Quaternary International and Radiation Measurements; Member of reviewers' panel of Ancient TL; standing member of the scientific committee and editor of the proceedings of the International Conferences on Luminescence and Electron Spin Resonance Dating.

Dr J. HERMANN, Associate Editor, Lithos.

Prof B.L.N. KENNETT , Editor-in-Chief of Physics of the Earth and Planetary Interiors, Associate Editor of Earth and Planetary Science Letters and Journal of Geophysical Research (Solid Earth).

Prof K. LAMBECK, member of the Editorial Advisory Boards of Quaternary Science Reviews and Earth and Planetary Science Letters.

Dr F.E.M. LILLEY, Associate Editor, 2004 Conference papers, Brazilian Journal of Geophysics Exploration.

Dr A.P. NUTMAN, member of the Editorial Board of Precambrian Research.

Dr B. PILLANS, member of the editorial boards of Catena, Quaternary Science Reviews and Geology

Dr E. RHODES, member of the Editorial Board of Quaternary Science Reviews, jointly edited a special issue of the Journal of Quaternary Science with Prof R. Hedges (University of Oxford), "Constructing Quaternary Chronologies".

Dr M. SAMBRIDGE finished his term as Pacific Region Editor for Geophysical Journal International. The Pacific Editorial Office, which has been run out of the School since 1984, closed down during the year with editorial activities handled through the World Wide Web.

OUTREACH AND WORKSHOPS

The Elizabeth and Frederick White Conference was held in February at the Australian Academy of Sciences to celebrate the birth of the Planetary Science Institute (PSI), a collaboration between RSES and RSAA. The theme of the conference was "Planetary timescales: from stardust to continents". The meeting was opened by the Science Minister Mr Peter McGauran and included public lectures. The conference was attended by 80 invited delegates from nine countries.

Ms B. Ayling presented a seminar entitled "Fossil Porites d 18 O and trace element records of Marine Isotope Stage 9 climate at Henderson Island , SE Pacific" at the School of Earth Sciences , Victoria University of Wellington, New Zealand.

Dr V.C. BENNETT, co-convener and co-organizer of the Elizabeth and Frederick White Conference, "Planetary Timescales: from Stardust to Continents", Australian Academy of Sciences , Canberra , 16-19 February.

Dr A. BERRY, Member of the Instrument Advisory Team (IAT) for the powder neutron diffraction beamlines (HRPD and HIPD) at the new Replacement Research Reactor at Lucas Heights .

Dr A. BERRY, Co-ordinator of a special interest group called GEOSYNC designed to educate, inform and represent Australian geoscientists on all matters relating to synchrotron science.

Dr A. BERRY, Member of the Beamline Advisory Panels for the X-ray absorption spectroscopy (BL 5) and microfocus spectroscopy (BL 9) beamlines of the Australian Synchrotron Project.

Dr S. EGGINS was interviewed on 13 October by ABC Television News for comment on recent volcanic activity.

Dr S. EGGINS presented a seminar entitled “Mg/Ca heterogeneity in foraminifera shells” to the Department of Earth Science, Free University, Amsterdam , Netherlands , March .

Dr D. FABEL was part of the organising committee of the 11 th Australia and New Zealand Geomorphology Group conference, Mt Buffalo, Victoria, 15-20 February.

Mr S. FISHWICK attended a seismological workshop as part of a WMC Ltd. meeting held at GEMOC, Macquarie University, Sydney, 23 June, oral presentation entitled “Surface Wave Studies of Australia: An Improved Model”.

Prof R. GRÜN organised the Robertson Workshop on Environmental Geochemistry and Geochronology: Quaternary Geochronology, 30 April - 2 May, Robertson, NSW.

Dr A. KISS visited Monash University , Melbourne , 25th May and gave a seminar entitled “Dynamics of wind-driven ocean circulation”.

Dr S. MICKLETHWAITE and Prof S.F. COX organised and ran two workshops on the implications of seismological observations and the application of advanced structural techniques to mineral exploration at Kalgoorlie , WA , for geoscientists from Newmont , Australia , KCGM, Goldfields St Ives, Placer Dome and Anglogold (July and November).

Dr S. MICKLETHWAITE, seminar convener for the Research School of Earth Sciences, which involved organizing and promoting weekly lectures for the geological community across Canberra. In March he organized the Jaeger-Hales public lecture presented by Prof F. Albarede, which involved raising funding from the National Institute of Physical Sciences and advertising around campus, in the Canberra Times and on local radio stations.

Dr S. MICKLETHWAITE is a member of the Geological Society of Australia's committee (ACT division), in which capacity he has arranged and organized seminars for the wider public and geological community and promoted geoscience amongst students.

Dr C. PELEJERO gave the seminar “An Interhemispheric Tour through Different Compartments of the Earth System” in the Instituto Andaluz de Ciencias de la Tierra (CSIC) in Granada , Spain , 5 October.

Dr B. PILLANS was invited to give a public lecture “New tests for old theories: Dating Australian Landscapes” to a joint meeting of the Royal Society of South Australia and the Field Geology Club of South Australia, University of Adelaide, 9 September.

Dr B. PILLANS is a member of the Subcommission on Quaternary Stratigraphy (SQS) and the Working Group on the Lower-Middle Pleistocene Boundary, both for the International Commission on Stratigraphy (ICS). He is also president of the Stratigraphy & Chronology Commission of the International Union for Quaternary Research (INQUA), and Vice President of the joint INQUA-ICS Task Force to define the Quaternary.

Dr A.M. READING gave an outreach seminar at Australian Antarctic Division, Kingston , Tasmania entitled 'Deep structure of East Antarctica from broadband seismic observations'.

Dr A.M. READING gave an invited presentation entitled '5 years of Antarctic Geoscience 1999-2003' to an audience of government and interdisciplinary science policy makers as part of the joint National Committee on Antarctic Research/Australian Antarctic Division Symposium, 11-12 November.

Dr E. RHODES presented a talk entitled " Luminescence Dating in Australasian and Pacific Archaeology", to staff of the Research School of Pacific and Asian Studies, ANU, 26 February and presented a seminar entitled "Luminescence Dating at the Limits: Broch Construction at 60ºN" to the ANU Centre for Archaeological Research, 19 March.

Dr E. RHODES is the secretary to the ACT division of the Geological Society of Australia.

Dr I.S. WILLIAMS, hosted a laboratory tour for students from the Australasian Institute of Mining and Metallurgy Summer School, 16 January.

Dr I.S. WILLIAMS with Dr J. HERMANN and Dr R. Rubatto (Department of Earth and Marine Sciences, ANU), constitute the Organizing Committee for the International Seminars of Petrology (ISPET) IV workshop on Advanced Analytical and Experimental Techniques in Petrology, to be held in February 2005 at RSES.

Dr I.S. WILLIAMS and Dr I.H. CAMPBELL met a delegation from the National Taiwan University visiting the ANU to interview highly cited researchers, 24 February.

TEACHING ACTIVITIES

Prof S.F. COX taught structural geology at 2 nd year level and contributed to three other courses at 1 st to 3 rd year levels, as part of his joint appointment at RSES and the Department of Earth and Marine Science.

Dr G.F. DAVIES taught the Physics of the Earth Honours course Plate Tectonics and Mantle Dynamics (PEAT 8001). Dr Davies also led a graduate seminar course on Mantle Dynamics while on leave at the University of California , Santa Cruz .

Dr J. DUNLAP supported laboratory work by a number of visiting French academics and students associated with Dr J. Braun.

Dr D. FABEL gave two lectures on surface exposure dating in the Chemistry of the Earth course (Geol 2015) at the Department of Earth and Marine Sciences, ANU.

Prof R.W. GRIFFITHS taught one half of the third year undergraduate physics unit "Physics of fluid flows" (PHYS 3034).

Prof R. GRÜN gave a lecture series on Quaternary geochronology to students of the Department of Archaeology and Anthropology.

Dr A.M.C.Hogg was a student supervisor for a third year physics unit (PHYS 3038), " Case Studies in Advanced Computation".

Prof I. JACKSON presented a short course entitled “Elasticity and Anelasticity of Earth Materials: Theoretical Background, Laboratory Measurements and Selected Seismological Applications” as part of the Physics of the Earth Honours program.

Dr R.C. KERR, Dr A.McC. HOGG , Dr G.O. HUGHES , Dr A.E. KISS and Prof R.W. GRIFFITHS taught the Physics of the Earth Honours course (PEAT8004 Current Topics in GFD – a Practical Introduction).

Dr J. MAVROGENES taught one third of “Resources and Environmental Geochemistry” in the Department of Earth and Marine Science, ANU.

Dr C. PELEJERO gave the lecture "The Ocean and the Carbon Cycle" of the undergraduate course, GEOG2016: Introduction to Greenhouse offered in the School of Resources, Environment & Society, ANU, 17 March.

Dr B. PILLANS presented a lecture on regolith geology in the Department of Earth and Marine Sciences, ANU.

Dr N. RAWLINSON was involved in teaching the Earth Physics honours course in seismology.

Dr A.M. READING co-lectured an intensive course on Seismology as part of the Earth Physics Honours course.

Dr M. SAMBRIDGE was an invited lecturer at the Colorado School of Mines Summer school on Mathematical Seismology and Uncertainty in Earth Models, where he presented a tutorial on nonlinear inverse problems, June.

HONOURS SUPERVISION

Dr J. MAVROGENES supervised the honours project of Mr N. Tailby on the Spitskopf carbonatite and of Mr M. Stevens on the Plattreef, South Africa .

Dr N. RAWLINSON co-supervised 4th year software engineering student (Tom Kobialka) together with Dr. M. Sambridge on a wavefront construction project

OTHER MATTERS

Dr V.C. BENNETT, Hon. Secretary, ACT Division of the Geological Society of Australia .

Dr I.H. CAMPBELL, Secretary General of the Commission for the Evolution of the Solid Earth, a subcommission of the International Union of Geological Sciences; councillor of the International Mineralogical Association; and co-leader of the Commission for Large Igneous Provinces (LIP).

Dr G. F. DAVIES has been appointed to the Fellows Committee of the American Geophysical Union for a term of two years.

Prof R.W. Griffiths served as a member of the Sectional Committee for Earth, Ocean and Atmospheric Sciences, Australian Academy of Science.

Prof R.W. GRIFFITHS served as a member of the Fellows Committee for the Volcanology, Petrology and Geochemistry Section, American Geophysical Union.

Prof B.L.N. KENNETT is chair of the Committee for the Elizabeth and Frederick White Conference Series. He completed his term as chair of the Academy Committees for Postdoctoral Opportunities in Japan and exchange arrangements with N.E. Asia (China , Japan , Korea , Taiwan).

Dr B. PILLANS is a member of the Cooperative Research Centre for Landscape Environments & Mineral Exploration (CRC LEME).

Dr M. SAMBRIDGE continued to provide his nonlinear inversion software package, implementing the Neighbourhood Algorithm, to researchers around the world. During the year, 43 requests for the packages were received.

Investigating Rock Surface Coatings – an integrated environmental and archaeological approach

Maxine Aubert, Malcolm McCulloch, Graham Mortimer, Alan Watchman[1] and Sue O'Connor[2]

A fundamental problem confronting archaeologists specialising in rock art is the need for a reliable method for dating. Our research aims to test the reliability of the uranium-series method for dating ancient rock art that is naturally covered by mineral coatings (rock varnish and travertine deposits), and to examine the biogeochemical mechanisms under which rock varnishes form.

For rock varnishes, selective extraction techniques (as well as total dissolution and laser ablation) have been used to determine the type and concentration of metals (such as U and Th) that are retained in each mineral phase, and also their potential environmental significance. Results indicate that some trace and major elements are considerably enriched in rock varnish and that these elements may serve as important tools for environmental monitoring in arid and semi-arid regions. Preliminary results further indicate that the amorphous Fe-oxyhydroxides/Mn-oxides phase could form a closed system for U and Th. However, U-series dating has been inconclusive because of interfering molecular species that have been incorporated during the chemical treatment and subsequent MC-ICPMS analysis of samples. Future work is planned to source and eliminate these interferences.

For travertine deposits, a test art sample was collected from Lene Hara cave in East Timor. Previous archaeological excavations at this site have revealed two levels of human occupation; a lower level dating to between 35,000 ka and ~30,000 ka and an upper level with Neolithic deposits containing pottery dating to ~3,000 ka. Recent excavation and dating of other areas within this extensive cave indicate that a more complete occupation sequence is likely to be forthcoming. Rock paintings are visible today in the cave and are attributed to the second, younger phase of occupation. They occur on a relatively thick (~2.5 mm) and heavily layered travertine deposit, which partly covers some of the paintings. The results of U-series dating indicate the visible paintings are younger than 6,800 ka. A distinctive red layer was also observed within the deposit beneath the younger red paintings. This red layer may be related to an earlier painting episode, and has been bracketed in age to between 25,600 and 30,300 ka. Laser ablation ICPMS analyses of trace metals further indicate that the chemistry of the heavily layered travertine deposit could be used to understand palaeoenvironmental changes.

1. Department of Archaeology and Natural History, RSPAS (ANU)

Trace elements in *Tridacna* clams from Huon Peninsula, PNG - indicators of palaeoclimate and potential for U-series dating?

Bridget Ayling, Malcolm McCulloch, John Chappell, Stephen Eggins, Mary Elliot[1], and Michael Gagan

Giant *Tridacna* clams have the potential to be excellent archives of past tropical climate, similar to massive hermatypic corals. Fast growth rates combined with laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) facilitate the generation of high resolution records of shell geochemistry. *Tridacna* clams have a dense aragonitic skeleton which may be less susceptible to diagenesis than the more porous *Porites* corals that are often used in paleoproxy studies.

This aims of this study are:

1. to determine if *Tridacna* clams can be dated using U-series techniques, by exploring how uranium uptake occurs (both temporally and spatially), and identifying shell parts with greatest potential for such dating; and
2. to investigate how clam trace element and stable isotope compositions relate to changing climatic conditions and to apply this knowledge to fossil *Tridacna* collected from several fossil reef units on the Huon Peninsula.

Fossil *Tridacna* were collected in March 2004 from paleoreef units at the Huon Peninsula that correlate with Marine Isotope Stage (MIS) 11c (420-395ka) and MIS 5e (130-115ka). These represent two contrasting interglacial periods in terms of both duration and Earth's orbital parameters. MIS 11c experienced lower longterm insolation variation at 65°N (30 Wm^2 - similar to modern-day conditions), whereas MIS 5e and 9c experienced amplitudes up to 110 Wm^2.

Inspection of fossil *Tridacna* using SEM and petrographic techniques indicates good preservation for samples of this age, apart from uncommon zones of calcite diagenesis that are very distinctive and easily avoided.

Samples of modern *Tridacna* have very low uranium contents – typically less than 10ppb. Consequently, higher levels of uranium present in fossil *Tridacna* are interpreted to result from postmortem uptake. The rate at which the U-uptake process proceeds is unknown in clams, as is the effect of clam physiological architecture and geometry on U distribution through the clam.

A fossil *Tridacna* believed to be of MIS 11 age was selected for preliminary investigations, using LA-ICPMS to determine the U concentration in different shell growth zones. Figure 1A illustrates a section through this clam and the location of the measured trace element concentration profile. Uranium and other trace element concentrations are non-uniform within the clam, with substantial variations occurring between the hinge, inner and outer growth zones (Figure 1B). The high values and variability in uranium concentrations indicates large differences in the amount of post-mortem U-uptake that may reflect differences in crystal structure between the zones and in turn the available surface area upon which U may be adsorbed. Similar patterns of U distribution, with higher concentrations occurring in hinge and outer zones (consistently around 5 ppm), have been observed in several other MIS 11 clams.

The next stage of our investigations will be to micro-sample different parts of this transect and determine U-series ages using MC-ICPMS, comparing the apparent ages to known (or estimated) age, and assessing U-uptake history based on how the apparent ages vary spatially across the shell.

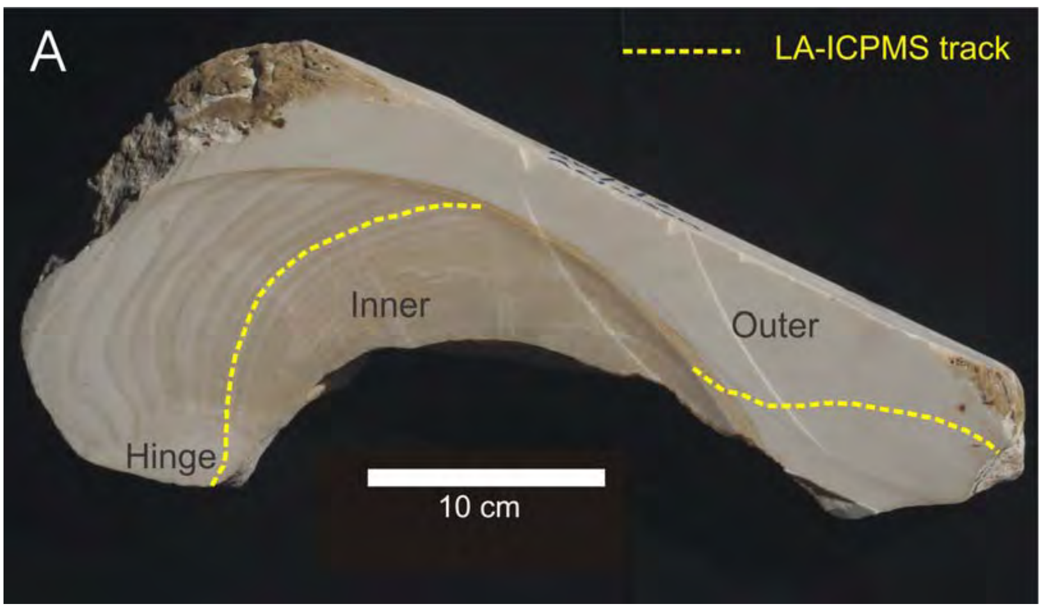

Figure 1A. Photograph of Tridacna RW/1/2, MIS 11 clam from the Huon Peninsula, PNG. The three growth zones are indicated in addition to the transect that has been analysed for trace elements by LA-ICPMS

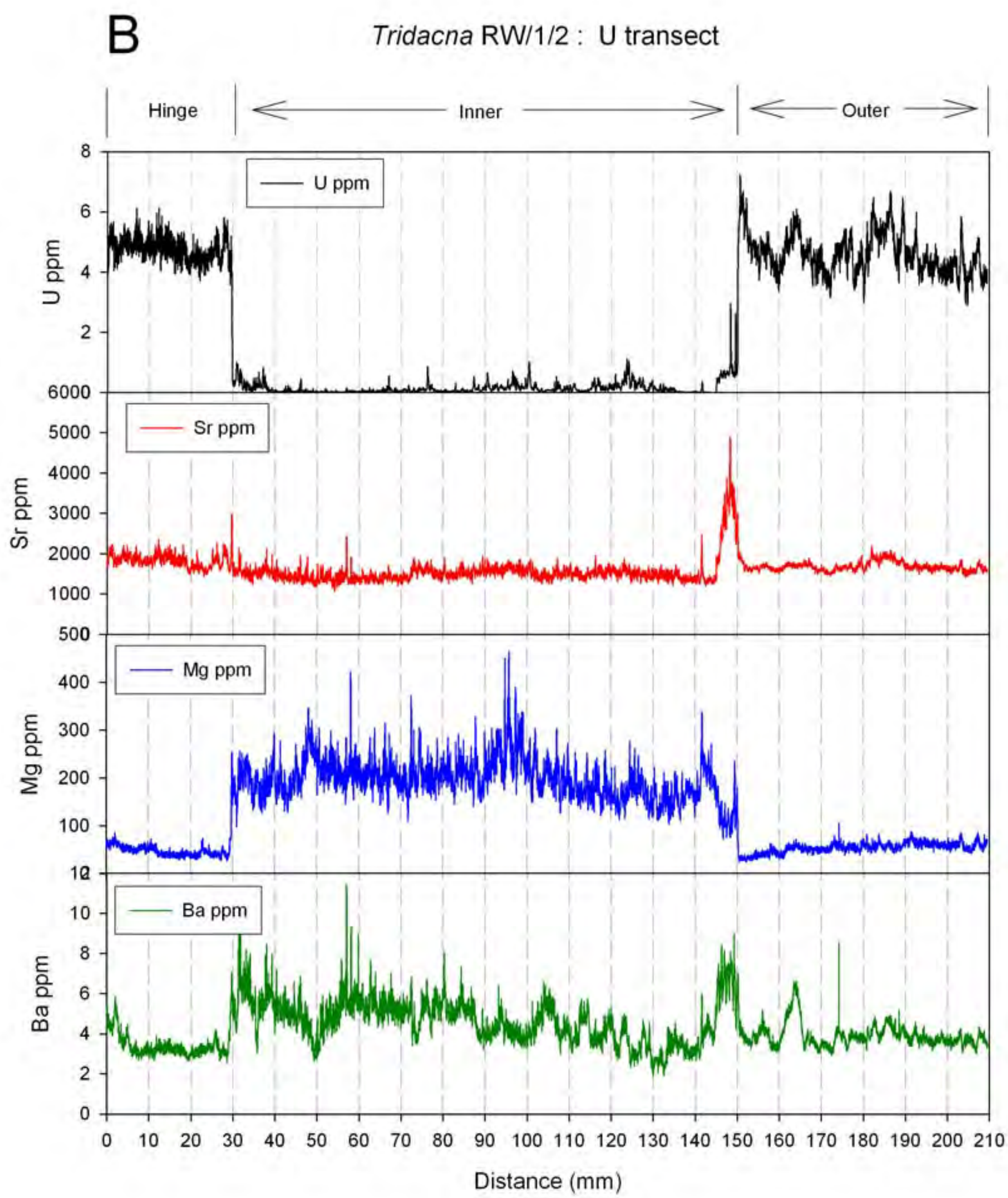

Figure 1B. U, Sr, Mg and Ba concentration profiles for the LA-ICPMS transect shown in Figure 1A.

1. School of Geosciences, University of Edinburgh, UK.

High-resolution palaeoclimate reconstruction of Holocene and modern corals in the Philippines, northern western Pacific warm pool

Rose D. Berdin and Michael K. Gagan

The Philippines is a key site for studying past climate variability. Located between 5°N and 21°N, and bounding the northern edge of the western Pacific warm pool, the archipelago's present climate is greatly influenced by the monsoons, tropical cyclones and ENSO. Modern and Holocene coral reefs that fringe most of the islands provide a wealth of material for studying changes in tropical climate during particularly interesting time periods in the Holocene.

Modern and Holocene *Porites* corals, sampled along the eastern coast of Samar, Philippines (11.5°N/125.5°E), were analyzed for $\delta^{18}O$ and $\delta^{13}C$. Almost 11 years of record (1994-2004), at fortnightly resolution, has been obtained from the modern coral (SM04-01). Oxygen and carbon isotope ratios range from -5.2 to -6.2‰ (mean -5.7‰) and -1.2 to -5.5‰ (mean -3.1‰), respectively. Annual $\delta^{18}O$ profiles are generally defined by a double peak in summer, typically a sharp peak followed by a smaller but broader peak (Figure 1A). These features are very similar to the $\delta^{18}O$ profile obtained from another modern coral (not shown), signifying the reproducibility of the $\delta^{18}O$ data. In the absence of Sr/Ca values, the weekly IGOSS SST data (centered at 11.5°N/ 125.5°E) were used to approximate the SST signal from the coral $\delta^{18}O$ record. Sea-surface temperature in the vicinity of the study site has an annual oscillation of approximately 3°C with well-defined seasonal fluctuations (Figure 1B). Comparison between the SST data and the $\delta^{18}O$ profile indicate a strong salinity component to the coral $\delta^{18}O$ values.

ENSO events, as indicated by the SOI (Figure 1C), are clearly manifested in the coral record. The strong 1997/98 El Niño produced relatively high $\delta^{18}O$ values (up to -5.2‰) towards the end of 1997, that coincide with higher $\delta^{13}C$ values. The relatively weaker El Niños in 1994/95 and 2002/03 also exhibit the same signature in $\delta^{18}O$ but with smaller amplitude; however, no change in $\delta^{13}C$ values is discernible. On the other hand, the 1998-2000 cold ENSO phase registered relatively low $\delta^{18}O$ values in the coral record. Rainfall data close to the study site recorded very low precipitation during these El Niño years and relatively high precipitation during the 1999-2001 La Niña. The corals appear to be excellent recorders of ENSO variability.

The Holocene coral (MDL-1), radiocarbon dated at 2560+60y BP, has so far yielded approximately 12 years of stable isotope record at monthly resolution (Fig. 1D). Oxygen isotope ratios vary from -4.9 to -5.8‰ whereas the $\delta^{13}C$ values range from 0.0 to -3.6 ‰. These values are offset from those of the modern coral: the $\delta^{18}O$ mean of -5.3‰ is 0.4‰ higher than the modern value, and $\delta^{13}C$ is also 1.6‰ higher. Furthermore, the late Holocene coral record exhibits clear seasonal oscillations in the $\delta^{18}O$ profile; the cyclical peaks and troughs in MDL-1 appear to reflect seasonal SST variability, similar to that observed in the Philippines today. This, together with the higher $\delta^{18}O$ values, indicates higher salinity and a drier climate at 2.5 ka.

Also discernible in the late Holocene coral record is the inter-annual variability in $\delta^{18}O$ values at frequency similar to the present-day ENSO tempo (2 to 7 years). At least three annual profiles display depressed $\delta^{18}O$ peaks that mimick the El Niño signature (cooler SST and lower rainfall) of the modern coral record (Fig. 1D). These years have anomalously high $\delta^{18}O$ values, approximately 0.2 ‰ higher than the average peak $\delta^{18}O$ value of -5.6 ‰ for the entire 12 years. A La Niña-like condition, marked by relatively low $\delta^{18}O$ values, can also be seen in the Holocene coral. Results from the work of McGregor and Gagan (2004) indicate that the late Holocene period is characterized by large and protracted El Niño events. The 12-year long Samar coral $\delta^{18}O$ record already indicates a 2-year long El Niño (Figure 1D), although not as large and protracted as the El Niño events recorded in the corals of Papua New Guinea (Tudhope et al., 2001; McGregor and Gagan, 2004) and Christmas Island (Woodroffe et al., 2003). A longer record from Samar Island, Philippines, is needed for a more rigorous comparison.

References

McGregor HV and Gagan MK, 2004. Western Pacific coral $\delta^{18}O$ rcords of anomalous Holocene variability in the El Niño-Southern Oscillation. *Geophysical Research Letters* 31 L11204, doi:10.1029/2004GL019972.

Tudhope AW, Chilcott CP, McCulloch MT, Cook ER, Chappell J, Ellam RM, Lea DW, Logh JM and Shimmield GB, 2001. Variability in the El Niño – Southern Oscillation through a glacial-interglacial cycle. *Science* 291, 1511- 1517.

Woodroffe CD, Beech MR and Gagan MK, 2003. Mid-late Holocene El Niño variability in the equatorial Pacific from coral microatolls. *Geophysical Research Letters* 30 (7), 1358, doi:10.1029/2002GL015868.

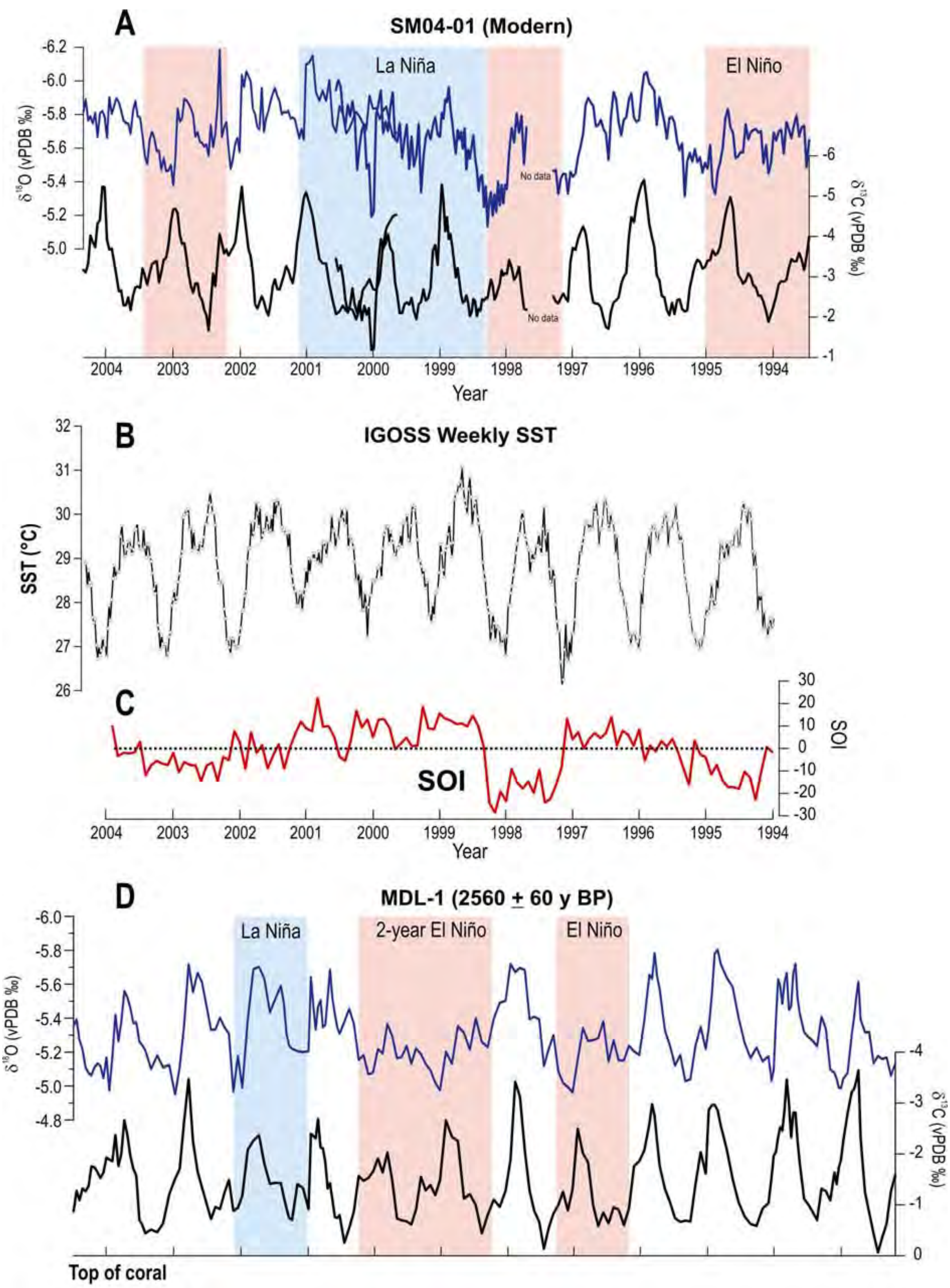

Figure 1. ENSO events are faithfully recorded in the stable isotope records, spanning the period from 1994 to 2004, of a modern coral from eastern Samar, Philippines (11.5°N/125.5°E) (A). Pink and blue bars mark years of El Niño and La Niña, respectively. IGOSS weekly SST data for the area showing an annual range of approximately 3°C and well-defined seasonal oscillation in SST (B). Southern Oscillation Index (SOI) from1994 to 2004 (C). Stable isotope record of a late Holocene coral from the same site exhibits ENSO events at frequency similar to the modern ENSO (D). Also evident in the coral record is a 2-year long El Niño.

Geochemical ecology of a high latitude coral, Gulf St Vincent, South Australia

Samantha Burgess, Malcolm McCulloch and Graham Mortimer

Scleractinian corals record environmental features at high temporal and spatial resolution in the physical, chemical composition of their skeletons. Coral based geochemical proxies provide a means for temporally extending the instrumental record of climate. The lack of long-term environmental information in temperate environments reduces the ability to interpret recent changes in regional oceanographic and climate indices.

X-radiographs of *Plesiastrea versipora* indicate variable growth rates of 1-9 mm per year. Density bands are laid down in annual couplets with low density bands in summer. This interannual variation in extension rate may be due to variability in summer temperature maximums. Luminescent bands are correlated with the high density winter bands. The luminescent bands vary in intensity and width and have become more frequent since 1980. They are likely to be influenced by the higher rainfall and terrestrial runoff in winter.

Of prime concern with the construction of paleo-environmental archive using coral skeletons is the level of reproducibility. Initial LA-ICP-MS analysis has produced varied results. Data obtained for 3 coral colonies from Gulf St Vincent, indicate in the reliability of the record may depend on the extension rate of the individual colony. The temperature proxies Sr/Ca and U/Ca are highly correlated and an inverse correlation between Sr/Ca and Ba/Ca has been observed for a coral from Seacliff Reef. A decadal cycle has been observed in the temperature proxies for Gulf St Vincent from the Seacliff Reef coral, but this decadal scale feature has not been observed in the higher density colonies. Ongoing research is focussing on the calibrate *Plesiastrea* for temperature, terrestrial influence and upwelling to determine intra-colony variation and intra-reef variation.

Coral growth histories based on annual band counts have been validated with preliminary U/Th ages for 4 coral cores, including 2 replicates. The base of the 18 cm long high-density coral core from Gulf St Vincent was 129±2 years old. The base of a 48 cm low-density core from the same reef was 98±2 years old. Continuing research is aimed at elucidating the reasons for such large growth rate differences between coral colonies growing in the same environmental conditions. The base of a 24 cm core that has been analysed from Spencer Gulf has been dated at 151±2 years. This particular coral presents an 'oceanic' signature compared with the 'gulf' signature from Gulf St Vincent corals.

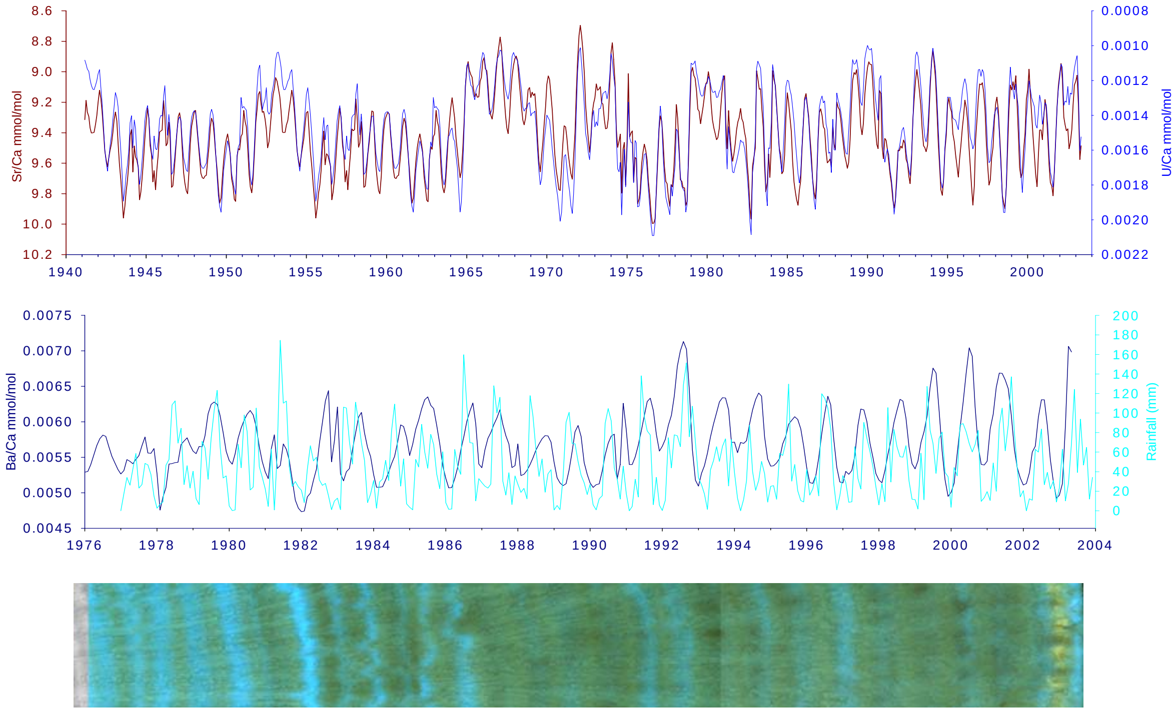

Figure 1. (top) Laser ablation-ICPMS analyses of Sr/Ca and U/Ca. Data has been peak matched to IGOSS SST data. (middle) Ba/Ca compared to monthly rainfall averages for Adelaide (note time-scale difference compared to top panel). Rainfall data supplied by the Bureau of Meteorology. (bottom) Image showing fluorescent banding in the analysed coral core section.

Dust-induced changes in phytoplankton composition in the Tasman Sea during the last four glacial cycles.

Eva Calvo, Carles Pelejero, Graham Logan[1] and Patrick DeDeckker[2]

An increase in iron supply associated with enhanced dust inputs could be responsible for higher marine phytoplankton production leading to the typically lower glacial atmospheric CO_2 concentrations, as suggested by the ‘‘iron hypothesis.’’ The enhanced dust supply may also have provided the oceans with significant amounts of silica, which would have favored the growth of diatoms over coccolithophores, as suggested by the ‘‘silica hypothesis.’’ Here we present new data on molecular biomarkers in a sediment core from the mid latitudes of the Southern Hemisphere (Fr94-GC3, 44º15'S, 149º59'E, 2667m water depth), which reveal dust-induced changes in the relative contribution of the phytoplankton to total productivity. Our results illustrate a shift in the relative abundance of siliceous (see brassicasterol curve in Fig. 1 related to diatoms productivity) over calcareous (see long-chain alkenones curve in Fig. 1, related to Haptophyte algae productivity) organisms during glacial times, when terrestrial aeolian input (see long-chain alkanes curve in Figure 1, related to terrestrial higher plants input) was enhanced. Although we did not detect a significant glacial decrease in coccolithophorid productivity, the decrease in the $CaCO_3/C_{org}$ rain ratio could still have contributed to some extent in lowering atmospheric CO_2 levels. More details of this study can be found in Calvo et al (2004).

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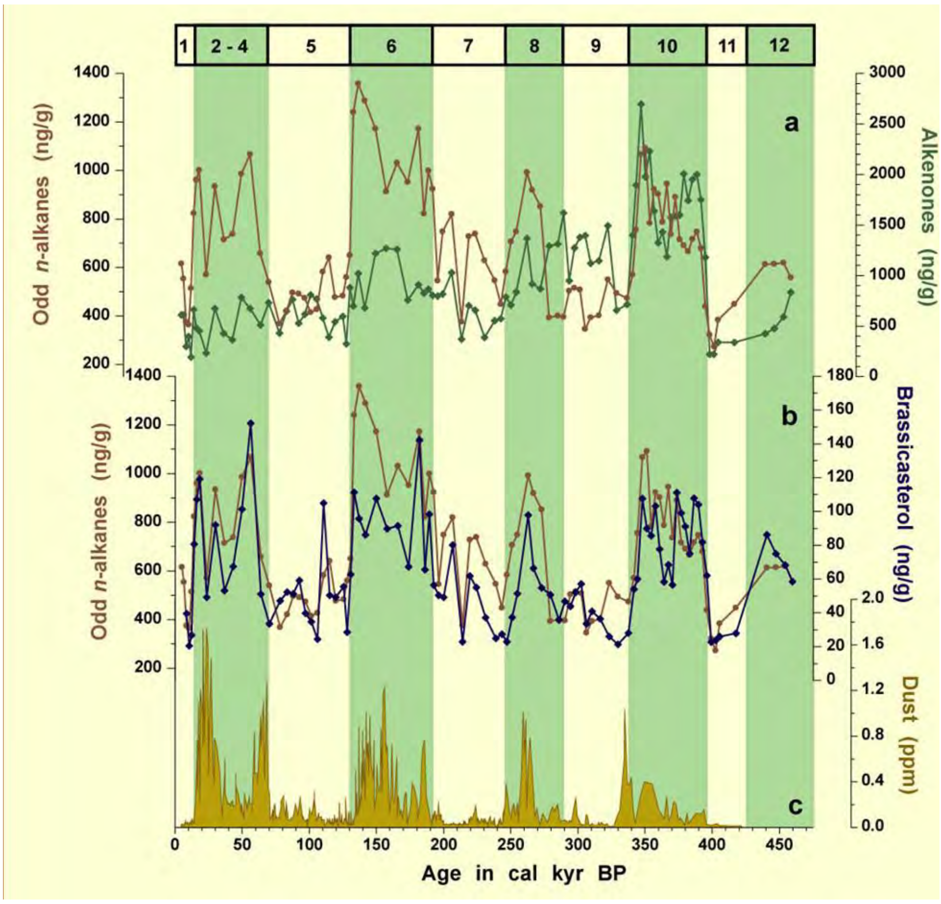

Figure 1. Total odd n*-alkane (brown curve) abundances compared with a) alkenones (green curve) and b) brassicasterol (blue curve). While brassicasterol and total odd* n*-alkanes follow a clear glacial/interglacial pattern, alkenone concentrations show no response to the main orbital parameters. c) Dust concentration as recorded in the Vostok ice core.*

Interdecadal variability in climate and seawater chemistry from a 280-year coral record from Flinders Reef, western Coral Sea.

Eva Calvo, Carles Pelejero, John Marshall, Malcolm McCulloch, Michael Gagan, Janice Lough[1] and Brad Opdyke[2]

Parallel Sr/Ca, $\delta^{18}O$, $\delta^{13}C$ and $\delta^{11}B$ measurements in a *Porites* coral from Flinders Reef (17.5ºS, 148.3ºE) in the western Coral Sea, indicate a close connection between climate variability and ocean chemistry. Low resolution (5-year intervals) Sr/Ca and $\delta^{18}O$ analyses, going back to 1710 AD, show a good correlation with the Interdecadal Pacific Oscillation (IPO). The IPO represents a recurrent pattern of surface temperature variability over the Pacific Ocean, with the most recent and best documented change occurring in 1976. In the Southwest Pacific, the IPO is known to modulate Australian climate, in particular the impact of ENSO events on decadal timescales. When the IPO is negative (tropical Pacific cooler than average), teleconnections between ENSO events and Australia's rainfall and temperature are strong, whereas this relationship barely exists during the positive phase of IPO (Power et al., 1999). In the Flinders coral, negative IPO values correspond with low salinities, due to increased precipitation at these times (enhanced and more frequent La Niña events). The decadal variability observed in our salinity record is closely followed by changes in SST, with cooler temperatures recorded during wet periods. This corresponds to a negative IPO phase when enhanced and more La Niña events bring more precipitation and cooler temperatures to Australia. Using $\delta^{11}B$, we have found surprisingly large variations in pH (~0.3 delta units) in 55-yr cycles that are also well correlated with IPO, probably related to changes in the ventilation of reef waters.

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Regional and continental-scale erosion from cosmogenic nuclides

John Chappell and Keith Fifield[1]

Before the advent of agriculture, erosion and sediment yield depended basically on climate and tectonic uplift. The increase due to human impacts has been debated, particularly in high mountains where natural erosion rates are high. Aiming to determine regional erosion prior to the effects of agriculture, this project uses measurements of cosmogenic nuclides in sedimentary quartz grains. These nuclides are produced by cosmic rays impacting common nuclei in surface rocks; their abundance decreases with increasing erosion, and this signature is preserved in sediment from the eroding surfaces. Terrains being investigated range from extremely slow-eroding landscapes in central Australia to high, actively rising mountains in the Yangtse River catchment in western China. Measured samples range from surface rocks, saprolite and stream sediments in source areas, to sedimentary sinks such as sand deserts in Australia and the Yangtse delta in China. By combining the cosmogenic measurements with digital terrain analysis, erosion rates are reconstructed for different geomorphologic provinces. To evaluate regional human impacts, results are compared with modern erosion measurements from hill slopes and river gauges.

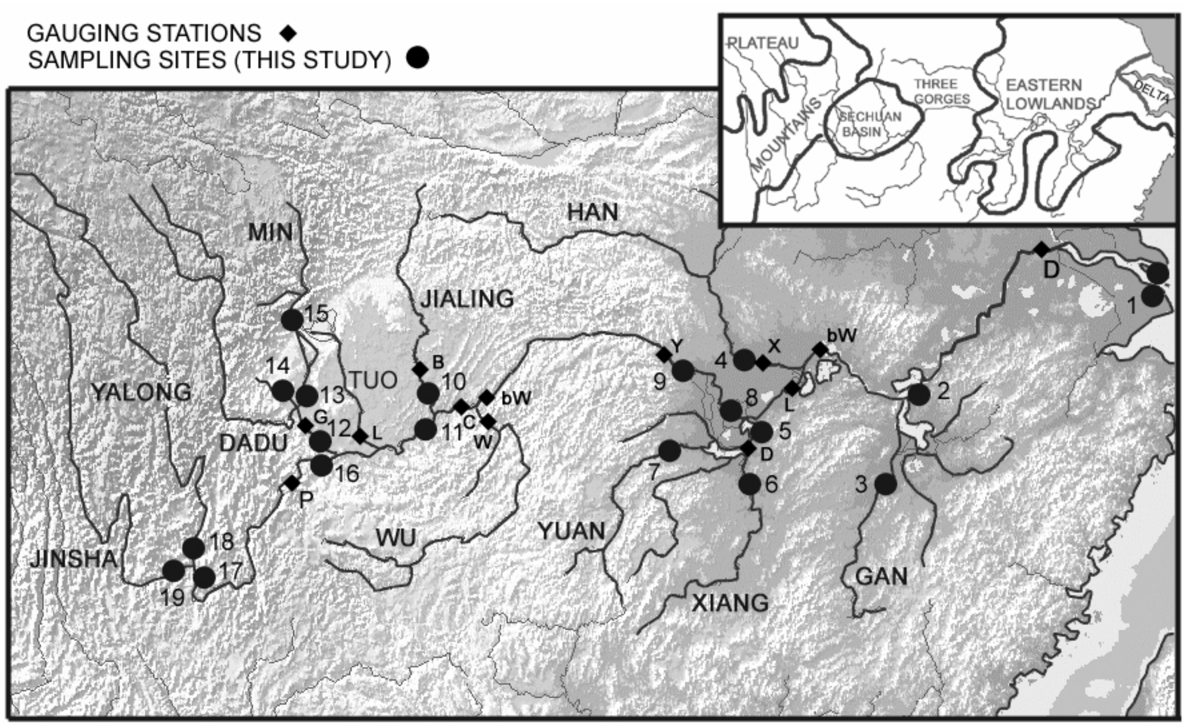

Figure 1. Regional erosion in China – major river sampling sites in China

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The history of aridity in Australia

John Chappell[1], Ed Rhodes[1], Brad Pillans[1], Toshiyuki Fujioka, Masahiko Honda, John Magee[2] and Kath Fitzsimmons[2]

Australia became progressively drier while it drifted northwards in the Cenozoic but the picture is complex and wet periods punctuated the drying trend. Regolith, groundwater and salts actively interact with the landscape and with each other, during these climatic changes. The project is a study of the history of Upper Cenozoic climate in the Australian interior and its effects on the regolith.

Targets include aeolian landscapes (longitudinal dunefields, source-bordering dunes and lunettes), stony desert and dissected silcrete and ferricrete landforms, surfaces with thick regolith and deep weathering with mine-pit access, and palaeochannel systems.

The broad timing of major phases of silcrete and ferricrete formation followed by landscape dissection and falling groundwater are being established by combining palaeomagnetic dating of ferruginous regolith with cosmogenic dating of relict fluvial deposits. A key study concerns the age structure of major dunefields and stony desert, which are the most widespread regolith materials in the arid zone. The ages of other arid-climate deposits including aeolian silt mantles and stony (gibber) pavements also are being determined.

Results from 2004-5 indicate that stony desert began to develop 4 million years ago on Lower Cenozoic silcrete surfaces west of Lake Eyre, and that fluvial dissection declined about 2 million years ago as aridity intensified. OSL dating demonstrated a major disparity in ages from the Strzelecki (<100 ka) and Simpson dunefields (>500 ka), suggesting that episodic arid reworking of sand in the Strzelecki has been repeatedly more intense than in the Simpson – which may also account for colour differences between the dunefields (Strzelecki pale; Simpson red).

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Figure 2. Drilling large longitudinal dunes in the Simpson Desert, for Optically Stimulated Luminescence and cosmogenic nuclide dating

Silica sponges – archives of palaeoseawater pCO_2?

Stephen Eggins, Michael Ellwood[1], Malcolm McCulloch and Michelle Kelly[1]

The occurrence of high boron concentrations in biogenic silica precipitated by diatoms, radiolarians, and sponges has been overlooked since the study of Furst (1980), and earlier reports by Goldschmidt and Peters (1932), and Gross (1967). We have quantified B concentrations by laser ablation ICPMS in a variety of sponges including *Hexactellinid* (glass) sponges, *Lithistid* sponges, and a *Monorhaphis* species, all of which have been taken from intermediate water depths in the southwest Pacific Ocean. The silica skeletons of these sponges contain between 200 and 1,000 ppm boron, consistent with Furst's nuclear track technique results. These elevated boron concentrations most likely reflect the substitution of tetrahedrally co-ordinated boric acid into the opaline silica lattice. Our LA-ICPMS results further reveal that the amount of incorporated boron varies with growth. Subject to the process via which boron is incorporated from seawater, and given the known large $^{11}B/^{10}B$ fractionation between $B(OH)_3$ and $B(OH)_4^-$ species in seawater as a function of pH (Hershey et al., 1986), we suggest that both the boron concentrations and boron isotopic composition of sponge silica may provide a proxy for palaeo-seawater pH and pCO_2. Preliminary B isotope ratio measurements obtained by laser ablation MC-ICPMS at the ANU, indicate $^{11}\delta B$ values in the range +10 to +14. These values lie below both the $^{11}\delta B$ composition of bulk seawater and of the $B(OH)_4^-$ species, indicating a significant biological fractionation of $^{11}\delta B$ occurs during biosilicification.

Figure 1. Fossil (top) and modern (bottom) Hexactellinid sponges from Tasman Sea. The length of the modern sponge is 18 cm.

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Stable isotope analysis of koala bone collagen, enamel carbonate and diet

Rebecca Fraser, Rainer Grün, Michael Gagan, Hillary Stewart-Williams[1],
Joan Cowley and Joe Cali

Stable isotope analyses of terrestrial mammal remains have been widely used to investigate the diet and ecology of modern and fossil species. This is predicated on different dietary sources having distinct isotopic compositions, which are taken up by animals in the environment and recorded in their body tissues (DeNiro and Epstein, 1978). Whilst the use of stable isotopes in palaeodiet research is used extensively overseas in the archaeological, palaeontological and ecological fields, it is currently an underused within Australian palaeoecology. We are examining how stable isotopes in marsupials reflect diet and environmental, with the overriding aim of applying stable isotopes in fossil faunas to investigate past diets and climates in Australia's prehistory.

During 2004 a study was completed of the carbon, nitrogen and oxygen isotope composition of bone collagen, enamel carbonate and diet of modern koalas (*Phascolarctos cinereus*) from populations at six locations in eastern Australia. The koala is an ideal species for this research as they eat a homogenous diet of eucalyptus leaves, inhabit eucalypt forests that grow in variety of climatic zones, and do not migrate seasonally. Moreover, koalas are non-obligate drinkers that obtain the majority of their water from plant leaves (Ellis, Melzer *et al.,* 1995). The homogenous nature of the koala diet can be considered 'a constant', and thus provides a unique opportunity to detect possible climatic influences on the isotopic signatures of bone collagen and teeth.

This study began by characterizing the carbon isotope composition of koala diets based on analyses of eucalyptus leaves and koala faeces undertaken at the ANU Research School of Biological Sciences. The carbon isotope values of faeces and leaves from each site were found to be within 0.5‰ of each other, indicating that koala faeces are a good representation of dietary inputs.

Carbon and nitrogen isotope analysis of bone collagen was undertaken at the Research Laboratory for Archaeology, University of Oxford (with Dr Tamsin O'Connell and Dr Peter Ditchfield), and carbon and oxygen isotope analysis of enamel carbonate was undertaken at the Research School of Earth Sciences, Australian National University.

The carbon isotope compositions of bone collagen and enamel carbonate were compared to the koala diets to calculate the fractionation between diet and these tissues. The average fractionation between diet and bone collagen in koalas is 7‰. This is smaller than the 4‰ fractionation that is commonly observed in other large mammals (Ambrose, 1993). The fractionation observed between diet and enamel in koalas is 10.5‰, which is within the range (9-14‰) observed in other large mammals (Cerling and Harris, 1999). These isotopic fractionations can be applied to accurately reconstruct the carbon isotope values of fossil koala diets.

The second part of the study examined levels of isotopic variability in the each koala population. The mean carbon isotope inter-population variability for bone collagen and enamel was 1.38±0.66‰, and for the combined populations was 1.78± 0.46‰ (1 sd) respectively. Variability in nitrogen isotopes was considerably larger at 4.66±1.6‰ (1 sd), and in oxygen isotopes was 2.89±1.36‰ (1 sd). The range of isotope values at each site was highly variable with, for example, a population from Springsure in Queensland having a 6.85‰ range in nitrogen isotope values. This part of the study indicates that for any comparison of isotopic variability between population averages to be meaningful, the variation within a single population needs to be explored first.

The final part of the study has examined the relationships between the population mean isotope values and a series of environmental variables, including precipitation, humidity, potential evaporation and temperature. Two examples of the correlations for bone collagen nitrogen isotope values and enamel carbonate oxygen isotope values with local precipitation are illustrated in figures 1 and 2. These figures show that the observed relationships between nitrogen and oxygen isotopes in koalas and precipitation in Australia are not strong. The nitrogen isotope results are contrary to observations elsewhere, where nitrogen isotopes in mammals become more positive as precipitation decreases (Sealy, van der Merwe *et al.,* 1987; Gröcke, Bocherens *et al.,* 1997; Handley, Austin *et al.,* 1999).

Figure 1. Koala bone collagen nitrogen isotope values against mean annual precipitation.

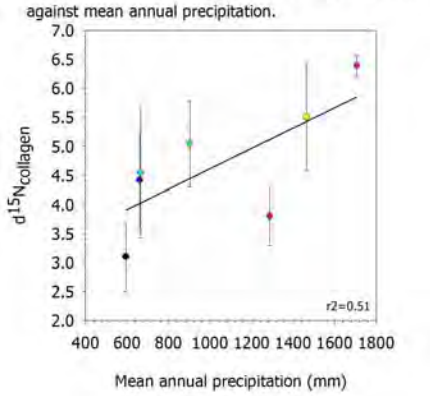
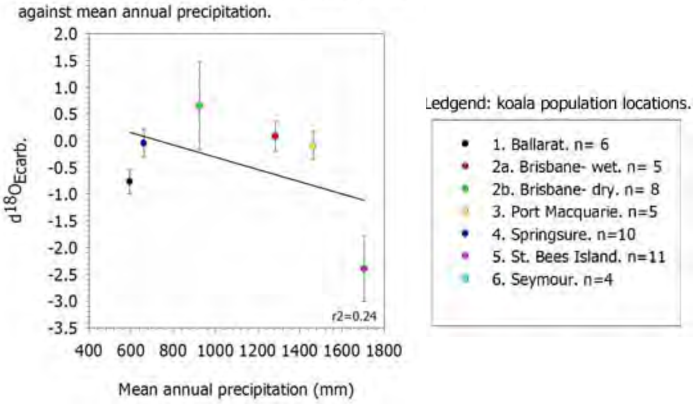


Figure 2. Koala incisor enamel oxygen isotope values against mean annual precipitation.



This study has established the baseline information that is needed to reconstruct koala diets using carbon isotopes and has found that inter-population variability must be considered. The factors affecting the relationships between environmental variables and isotopes in koalas are under further investigation.

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Dating of Australian arid landforms using cosmogenic ^{21}Ne surface exposure dating

Toshiyuki Fujioka, John Chappell, Masahiko Honda, Igor Yatsevich, Keith Fifield[1] and Derek Fabel

Australian climate has dramatically changed from wet to dry during the late Cainozoic period, producing various types of arid landforms such as dune field, gibber plains (stony deserts) and playas. Knowledge of the formation of these landforms stands to enhance our understanding of the late Cainozoic climate change in Australia. This study focuses on dating of sand dunes and silcrete/quartz gibbers in central Australia, using cosmogenic nuclides.

Cosmogenic nuclides are produced by interaction of cosmic rays with elements in Earth's surface rocks. The amounts of cosmogenic nuclides in surface rocks reflect the time for which the rock has been exposed at the surface, and the time-integrated rate at which the rock has been eroded. Radioactive cosmogenic nuclides (e.g., ^{10}Be, ^{26}Al) are limited by their half-lives when applied to samples with long exposure histories (> a few million years). In contrast ^{21}Ne, a stable nuclide, does not have this age limitation, and is able to be applied to samples with relatively long exposure histories.

In cosmogenic ^{21}Ne surface exposure dating, correction of non-cosmogenic neon components including crustal and *in situ* nucleogenic components is critical for accurate determination of the amount of cosmogenic ^{21}Ne in a sample. The crustal neon component is produced by nuclear reactions $^{24}Mg(n, \alpha)^{21}Ne$ and $^{18}O(\alpha, n)^{21}Ne$ in the crust, and is trapped in fluid inclusions when quartz forms. The *in situ* nucleogenic neon component is produced within the crystal lattice by reaction $^{18}O(\alpha, n)^{21}Ne$, where α particles are provided from the decay of uranium and thorium.

Eleven silcrete/quartz gibber samples from central Australia were analysed for the full suite of noble gases (He, Ne, Ar, Kr and Xe) by fusion and crushing experiments, and for U, Th (by ICP-MS) and K (by Flame Photometer). Crustal nucleogenic neon was evaluated from crustal argon and xenon using crustal production ratios, while *in situ* nucleogenic neon was calculated from U and Th contents and the formation ages of the samples. After correction of crustal and *in situ* nucleogenic neon, the amount of cosmogenic ^{21}Ne in the silcrete samples ranged from 68 to 92% of excess ^{21}Ne relative to atmospheric neon (Figure 1). In quartz, the *in situ* nucleogenic neon fraction in the excess ^{21}Ne was insignificant (< 1%) owing to very low U contents (< 5 ppb), whereas those of crustal neon were relatively large (up to 72%, see Figure 1). In order to determine the amount of cosmogenic ^{21}Ne in these samples, it is essential to determine crustal neon isotopic compositions in fluid inclusions by vacuum crushing experiments and to subtract these compositions from total neon isotopic compositions obtained by fusion experiments.

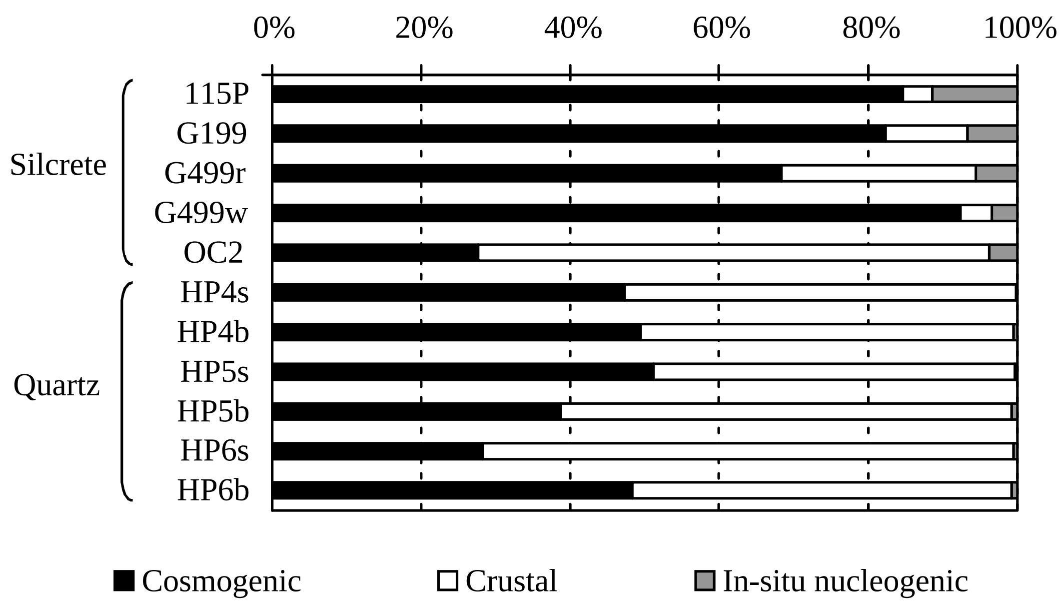

Figure 1. Contributions of cosmogenic, crustal and in situ nucleogenic neon components of excess ^{21}Ne, relative to atmospheric neon, in silcrete/quartz gibber samples from central Australia.

Approximately 30 samples, including sand from various depths and silcrete/quartz gibbers, were collected from longitudinal dune field in the west part of the Simpson Desert in May 2004, and pure quartz samples were prepared for cosmogenic dating. It is planned that these samples will be analysed for noble gases and ^{10}Be in 2005.

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Advances in Understanding the Post-glacial History of Tropical Australasia

Michael Gagan

The Earth Environment area made several advances in 2004 to improve our understanding of the post-glacial history of tropical Australasia. Two synthesis papers were published (Gagan et al., 2004a,b) describing the post-glacial evolution of the Indo-Pacific Warm Pool, the Hadley-Walker circulations, and the El Niño-Southern Oscillation. Gagan et al. (2004a) was published in a special volume of *Quaternary International* summarising outcomes of the IGBP-PAGES *Austral-Asian Pole-Equator-Pole (PEPII) Synthesis* meeting, held at the National University of Singapore in November 2001. Gagan et al. (2004b) is an outgrowth of the meeting, *The Hadley Circulation: Present, Past and Future*, held at the University of Hawaii in November 2002. Together, the papers in these volumes provide excellent overviews of the state of knowledge about past changes in key components of Earth's climate system.

Three publications involving the Earth Environment area provided new contributions to our understanding of past ocean-atmosphere dynamics in Australasia. Bostock et al. (2004) analysed carbon isotope ratios ($^{13}C/^{12}C$) in AMS ^{14}C-dated planktonic and benthic foraminifera from a deep-sea sediment core in the northern Tasman Sea to reveal rapid changes in surface and intermediate water circulation over the last 30 kyr. The new record indicates that ventilation of Antarctic Intermediate Water during the last deglaciation played a role in propagating climatic changes from polar regions to the tropics, and contributed to the post-glacial rise in atmospheric CO_2.

Correge et al. (2004) reported in *Nature* the first high-resolution record of skeletal Sr/Ca and $^{18}O/^{16}O$ for a unique fossil *Diploastrea heliopora* coral preserved on the raised reef terraces of Espiritu Santo, Vanuatu. Uranium-series age determinations show that the specimen lived for at least 700 years during the Younger Dryas interval (~12 ka) established from polar ice cores. Using microanalytical techniques developed at RSES, the team showed that the extent of tropical waters in the SW Pacific was compressed towards the equator during the Younger Dryas, and that rainfall associated with the South Pacific Convergence Zone was reduced.

Also in 2004, analysis of $^{18}O/^{16}O$ in Holocene *Porites* corals from northern Papua New Guinea by McGregor and Gagan (2004) demonstrated a 15% reduction in the amplitude El Niño events during the period 7.6-5.4 ka. In contrast, large and protracted events were identified for 2.5-1.7 ka. Together, the results indicate a non-linear atmospheric response to Holocene changes in El Niño SST anomalies.

Three more publications generated by the Earth Environment area in 2004 provided insight into recent ocean-atmosphere dynamics in the tropics and the ability of corals to record palaeoenvironmental signals. Grumet et al. (2004) completed an ambitious high-resolution study of "bomb spike" radiocarbon (^{14}C from nuclear weapons testing in the 1950s & 1960s) in modern corals from southwest Sumatra and Kenya in the equatorial Indian Ocean. The work was supported by an RSES

Mervyn and Katalin Paterson Fellowship to PhD student Nerilie Abram, and utilised the accelerator mass spectrometer facilities at the University of Arizona and Lawrence Livermore National Laboratory to make several hundred, high-precision AMS C-14 determinations.

Müller et al. (2004) analysed skeletal $^{13}C/^{12}C$, calcification rate, and early marine diagenesis in a long-lived (1830-1994 AD) *Porites* coral from Ningaloo Reef, Western Australia, to investigate the ability of corals to record future decreases in the carbonate saturation state of surface seawater associated with the projected build-up of atmospheric CO_2. Caution is advised for cases where early marine inorganic aragonite has been added to the base of coral colonies. The net effect is to produce changes in bulk skeletal chemistry and calcification which mimic the 20th century decreases in $^{13}C/^{12}C$ (expected from the oceanic Suess effect) and calcification expected from the decrease in carbonate saturation state.

Ayliffe et al. (2004) reported on a 20-year history (1977-1996) of SST, river discharge, and wind-induced mixing of the upper water column, based on high-resolution analysis of Sr/Ca, $^{18}O/^{16}O$, $^{13}C/^{12}C$, and UV fluorescence in a modern *Porites* coral growing offshore from the Sepik and Ramu Rivers in equatorial northern Papua New Guinea. The paper was published in a special issue of *Continental Shelf Research* summarising outcomes of *Project TROPICS (Tropical River-Ocean Processes in Coastal Settings).*

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A cautionary dating tale from down-under: the megafauna site of Rocky River on Kangaroo Island, South Australia

Rainer Grün[1], Stephen Eggins, Rod T. Wells[2] and Malcolm McCulloch

Kangaroo Island, tucked away at the Australian continental fringe, offers an ideal refugium for the megafauna for survival, similar to the survival in Siberia of European glacial megafauna (giant deer and mammoth) for many thousands of years during the last glaciation. Megafauna fossils were first discovered in Black Creek Swamp in 1903 and the site has been investigated intermittently over the next hundred years. Rising sea levels isolated Kangaroo Island from the mainland around 8900 year ago. Yet in spite of abundant Indigenous stone artifact scatters across the island, it was unoccupied at time of first European contact and to date no Aboriginal remains have been discovered on the island. Recent excavations have revealed three distinct megafauna layers at the Black Creek Swamp site with no mixing between strata. Carcasses and partial carcasses remain articulated or are in close association, with some preferred orientation and very low dip angles. Body sizes range from ~2 tonne Diprotodon to 50 g rodents (Figure 1). Many larger bones are highly fragmented from trampling and further disrupted by plant roots. Some also show evidence of scavenging and chewing. No artifacts have been found. Some test pits close by also contained abundant megafauna remains.

Initial ESR dating results of teeth from the Rocky River site were extremely exciting, as they yielded early and linear U-uptake ages on megafauna teeth in the 10,000 to 20,000 years range. Some of the teeth contained several hundreds of ppm of uranium and it would have seemed surprising had these high amounts of uranium accumulated at a very late stage of the burial history (which would allow for older age estimates). The preliminary ESR results were reinforced by some preliminary radiocarbon and OSL dates which were very much in the same age region.

For good measure, we analysed the sediment for radioactive disequilibrium in the U-decay chain as well as all teeth for U-series disequilibrium using laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS).

The sediments of one of the test pits are close to U-series equilibrium. However, the ESR signals of tooth enamel samples from this pit are significantly different to those signals usually used for age determination, and the derived age estimates do not make any sense. We found that the sediments of the flood plain show extreme U-disequilibrium and the teeth show much younger apparent U-series ages than expected. The data indicate some very late accumulation of uranium in the sediments of the site and from there into the megafauna teeth. The overall effect on combined U-series/ESR results is that all samples are older than about 45,000 years.

Conventional dating approaches would all have concluded that the Rocky River megafauna site was the youngest thus far dated in Australia, with severe implications for the hypotheses that are presently being promoted for the demise of the megafauna. However, it is now clear that, at least from the geochronological perspective, the Rocky river joins the numerous > 45,000 years old megafauna sites which are scattered all over Australia.

Figure 1. Megafauna remains at the Rocky River excavation (the strings are set at 1 m intervals). The upper layer shows the remains of Diprotodon, a two tonne wombat (note the large incisors in the centre of the photo). In the foreground middle to left, a lower layer is exposed with bones and teeth of extinct and extant macropods.

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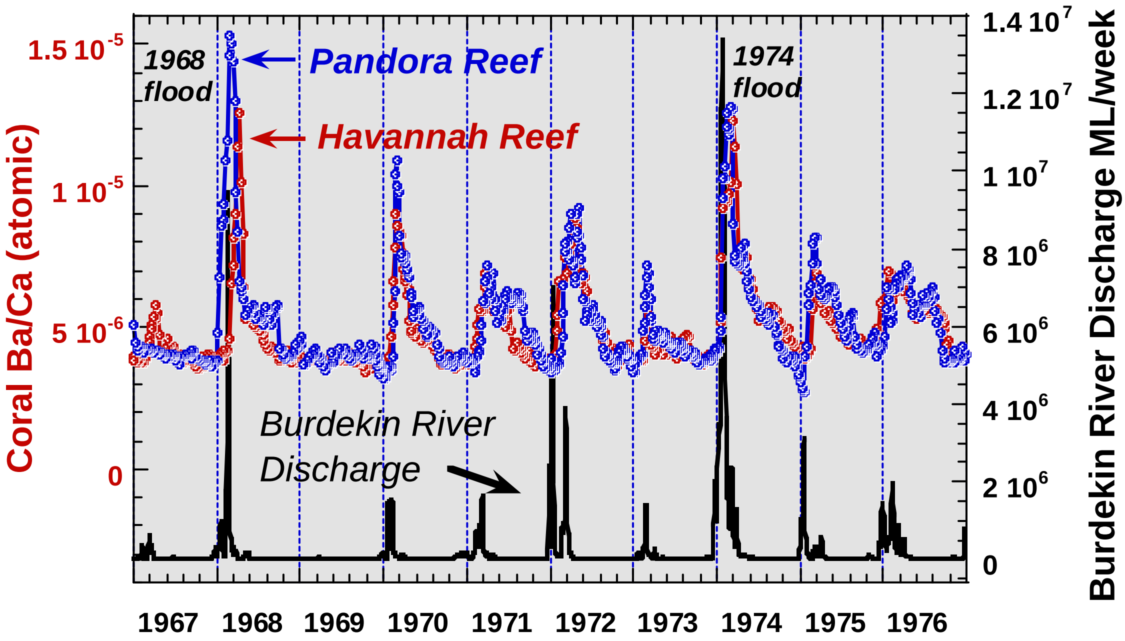
Terrestrial Runoff into the Great Barrier Reef
Direct evidence from corals for major increases in anthropogenic fluxes since European settlement

Malcolm McCulloch, Timothy Wyndham, John Marshall, and Janice Lough[1]

The Great Barrier Reef (GBR) has been described as the world's largest living organism, extending for over 2000 km along the northeastern coastline of Australia and containing immense physical and biological diversity. Although some sections are distal from direct terrestrial influences, inshore regions of the central and northern GBR are regularly impacted by runoff from large rivers. The river flows are highly episodic, being associated with cyclones or occasionally intense monsoon depressions. During these high intensity rainfall events, there can be massive discharges of freshwater and suspended sediments into the GBR lagoon. Longstanding and still highly controversial question are how has the water quality changed within the GBR lagoon since European settlement and what has been the impact of these changes on the ecology and sustainability of the GBR?

Research undertaken at RSES using long-lived (300-400 year old) corals from the inshore region of the GBR, provides a unique long-term quantitative record of suspended sediment loads delivered to the reef by river flood plumes. *Porites* corals from the inshore Pandora and Havannah Reefs, located north of Townsville, experience episodic discharge of freshwater flood plumes from the Burdekin River. It has been shown that barium acts as a monitor for suspended sediment as it is desorbed from suspended particles as the freshwater flood plumes enter the marine environment, and thereafter Ba acts as an essentially conservative dissolved tracer, with Ba being partitioned into the coral carbonate skeleton in proportion to the seawater concentration. Ba/Ca ratios in the coral skeleton therefore provide a proxy of long-term changes in suspended sediment loads and thus nutrients entering the GBR lagoon.

Using the new technique developed at RSES, of laser ablation ICP-MS, Ba/Ca systematics have been examined in ~3-4 m long coral cores (growth rate of ~1-2 cm per year). Two distinctive patterns are present. During the 1770's when Captain Cook explored the east coast of Australia, there is only limited evidence for flood-plume related suspended sediment fluxes entering the inner GBR, although this period is mainly dominated by droughts. From 1800 to 1860, which includes major flood events in the years, 1801, 1811, 1817, 1819 and 1831, the coral flood-bands still do not exhibit any Ba peaks. However, immediately following European settlement in the 1860's, there is a dramatic increase in the Ba/Ca ratios, commencing with the 1870 flood-band. This is indicative of a significant increase in suspended load being delivered to the inner GBR, coincident with the first grazing activities by European settlers in the Burdekin catchment. Thereafter (i.e. post 1870) during all major flood plume events, large Ba/Ca peaks are present in the coral in approximate proportion to the volume of the river discharge, modulated by land-use intensity and weather, principally droughts. These results therefore provide unequivocal evidence for Burdekin River flood-plumes transporting substantially increased fluxes (x4 to x8) of suspended sediment into the inner GBR reef following European settlement. It is clearly imperative that there is a reduction in the fluxes of terrestrial sediment entering coral reefs, if they are to survive the lethal combination of direct anthropogenic impacts and rapid climate change.



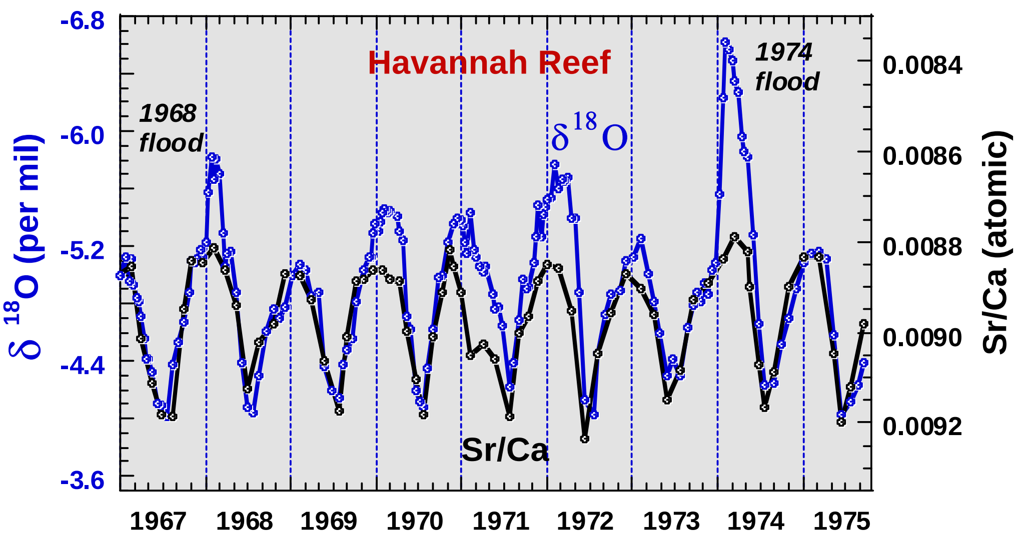


Figure 1. (top) Ba/Ca in coral is applied as a proxy for sediment discharge from the Burdekin River. (bottom) Sr/Ca and $\delta^{18}O$ ratios are used in combination to quantify river flow from the reduction of seawater salinity.

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Mg/Ca variation within the planktic foraminifer *Orbulina universa*

Aleksey Sadekov, Stephen Eggins and Patrick DeDeckker[1]

Mg/Ca composition and test wall profile characteristics have been measured in a population of *Orbulina universa* (a symbiotic planktonic foraminifera) obtained from a core-top sediment sample from off the west Australian coast (20º04 S, 112º66 E). Laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) and electron microprobe have been used to determine the distribution of Mg/Ca and other elements at micron/submicron-scale resolution within individual foraminifera shells. LA-ICPMS profiles and EMPA maps reveal the development of up to 6 alternating low and high Mg/Ca bands that increase in amplitude and Mg/Ca value toward the outer test surface. These results, together with the reported duration of test calcification (e.g. Caron et al., 1987), indicate the Mg/Ca composition of calcite precipitated by *O. universa* is strongly regulated on a diurnal cycle (Eggins et al., 2004). The development of Mg/Ca banding in *O. universa* can be linked to the day-time photosynthetic activity of algal symbionts and night-time respiration of both the host foraminifer and symbionts, which modulate the pH and calcite saturation state within the foraminiferal microenvironment (Wolf-Gleadrow and Riebesell, 1997). We attribute the high and low Mg/Ca bands to night-time and day-time calcification respectively based on previously documented increase in bulk test Mg/Ca composition with decreasing seawater pH (Lea et al., 1999).

'Vital effects' similar to those observed in *O. universa* may affect other symbiont bearing species, and could bias bulk test Mg/Ca compositions and thus derived estimates of palaeo-seawater temperature. Our results provide new insights into the potential importance of such 'vital effects' in controlling the Mg/Ca composition of foraminiferal calcite. They also emphasise the need for a more complete understanding of influences upon the Mg/Ca composition of foraminiferal calcite in order to evaluate both the precision and accuracy of Mg/Ca paleo-seawater thermometry based on bulk test compositions.

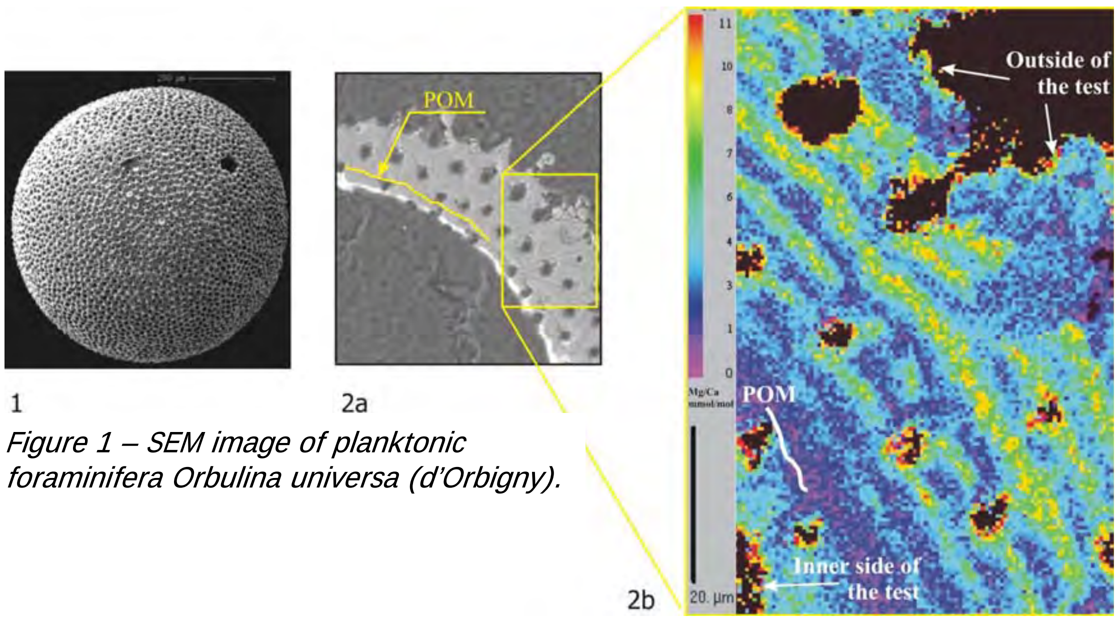

Figure 1 – SEM image of planktonic foraminifera Orbulina universa (d'Orbigny).

Figure 2a-b – SEM image and map of Mg/Ca ratio variation through a test wall cross-section of O. universa with 6 high Mg/Ca-bands (note Mg/Ca-colour scale and length scale). POM indicates the position of the primary organic membrane.

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U–Pb dating of late-stage anatase in silcrete

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and Stephen Eggins

Silcrete is a ubiquitous regolith material found throughout Australia. Despite being the subject of much study, there is still much unknown or debated as to their genesis, age and significance in the Australian landscape. Genetic models range from evaporative processes acting in arid environments to crystallisation in swampy environments similar to those in which coal forms. Silcrete refers to intensely indurated rock composed mainly of quartz clasts cemented by a matrix of crystalline, crypto-crystalline quartz or amorphous silica, where induration occurred at or near the surface, due to inputs or silica from weathering, streams or ground waters. From stratigraphic and fossil evidence, silcretes have been broadly assigned Tertiary ages in Australia.

The Sandstone Tank site is on Fowlers Gap Research Station, ~100km N of Broken Hill, western NSW, where silicified Paleogene palaeochannel sediments contain leaves and twigs of possible Eocene temperate rainforest plants. The outcropping material, about 6 m thick, consists of a basal conglomerate of Adelaidean metasediment gravels, grading up through smaller sized clasts to more massive, tabular silcrete at the top (Figure 1). The basal gravels and larger pebbles are draped by beige-coloured geopetal cappings composed of anatase, iron oxides and silica in varying proportions (Figure 2). Towards the top of the conglomerate, clasts are draped by thicker caps than at lower levels. The anatase is a late stage illuviation feature, commonly as a microcrystalline matrix, as has been noted in other silcretes around the world.

Figure 1. Sandstone tank silcrete, basal conglomerate.

Initial attempts to date the anatase involving Laser Ablation-ICPMS revealed the presence of large amounts of common lead, and the precision of measurements was poor. To remedy these problems, more detailed sampling and analysis was undertaken: 1 – 2mm wafers of the capping material were extracted, crushed and handpicked, to obtain ~10 - 100 mg samples which were then dissolved in HF/HNO_3 dissolution, followed by measurement of spiked and unspiked aliquots, including standards, on a Finnigan Neptune multi-collector ICPMS.

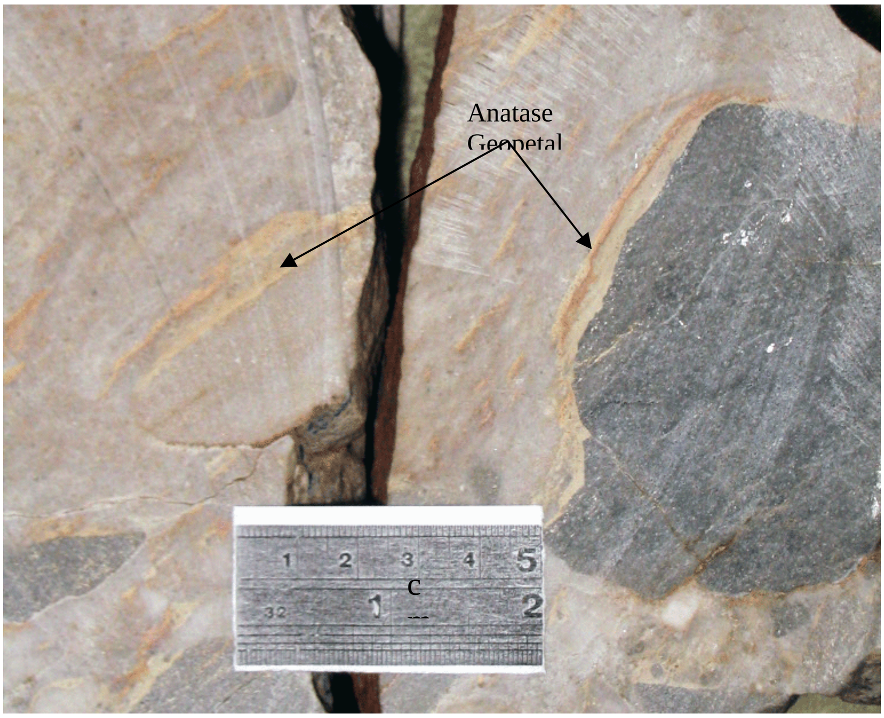

Figure 2. Geopetal cappings on clasts in the Sandstone Tank silcrete.

The common Pb composition for the Sandstone Tank silcrete anatase was obtained from regression on a Tera-Waserburg plot to yield values of $^{207}Pb/^{206}Pb = 0.930$ and $^{204}Pb/^{206}Pb = 0.0593$. The error on the common Pb composition is ~7.7%, owing largely to the tight clustering of the data. This common Pb component has a Stacey-Kramer single stage age of 1430 Ma. The radiogenic Pb component has been established by subtraction of the common Pb component (Figure 3). The U/Pb results for the radiogenic component include two outliers, samples 7.1 and 7.3. The remaining seven samples plot around the concordia curve, and yielding a concordia age of 481±85 Ma (2σ confidence level). This is in agreement with the $^{206}Pb/^{238}U$ age of 477±85 Ma (2σ confidence level). The age errors are large owing to the 7.7% uncertainty in the common Pb value, and the spread of the data.

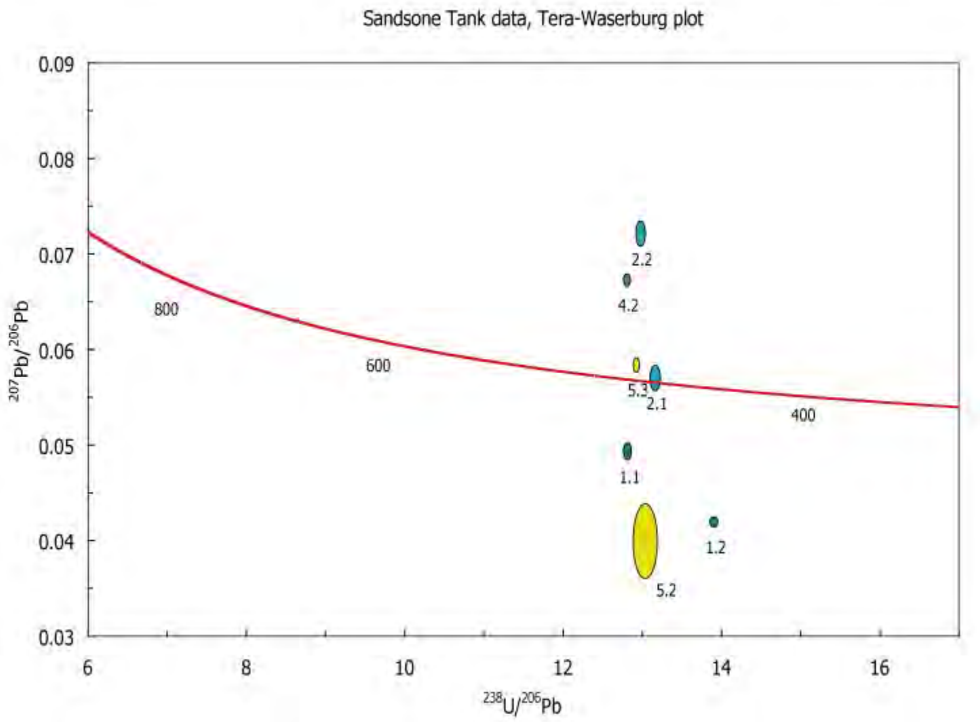

Figure 3. Sandstone Tank U/Pb data

The calculated ages of the anatase are at odds with the Eocene floral age assigned to the silcrete. However, the possibility that the ages represent either mixing of an older component (e.g. from the Delamerian Orogeny), with a younger component brought into the area with the Paleogene sediments, or possibly incomplete resetting of the U-Pb system, cannot be ruled out. Further work is necessary to refine the interpretation of U–Pb results obtained from silcretes in order to date these important deposits and provide improved chronologies for landscape evolution

High resolution coral records of reactive and micronutrient trace metals: Monitoring biological responses to flood plumes.

Tim Wyndham, Malcolm McCulloch, and Eric DeCarlo[1]

The influences of flood plumes on the coastal ocean are difficult to investigate because they are intermittent, transient and highly variable in nature. The application of trace metals in coral carbonates as proxy recorders of marine environmental conditions has been demonstrated to be an excellent method for overcoming these difficulties. Coral records of trace metals have been widely used to provide historical records of the physical impacts of flood plumes, including changes in salinity ($\delta^{18}O$), sediment load (Ba), and anthropogenic inputs such as heavy metal pollution (eg. Pb, Cd). In contrast, the use of coral records to monitor the biologic responses to these changing environmental conditions has proved more difficult. However, with improvements in analytical techniques, it is now possible to investigate coral records of reactive (rare earth elements) and micronutrient (eg Mn, Zn and Cu) trace metals, which can be used to more widely explore the biogeochemical impact of flood plumes on the coastal ocean.

We have obtained high resolution temporal records of rare earth elements, Cu, Zn, Mn and Sn, from corals from two locations; (1) near Townsville on the Great Barrier Reef (GBR), and (2) Kaneohe Bay on Oahu, Hawaii. Both locations often display large phytoplankton blooms following flood events, and therefore provide a good opportunity to test the idea that coral records can be used to monitor the biological response to flood plumes. These coral records show significant responses to flood plumes that can only be attributed to biogeochemical cycling that occurs as a result of the flood plume influence, rather than the flood plume itself. Thus a mechanism for exploring the biological response to flood plumes is provided. It has generally proven difficult, however, to interpret these coral records without a good understanding of the coastal processes. Therefore we have also directly measured the influence of trace metal concentration of a coastal *Trichodesmium* bloom on the GBR and have been investigating the relationship between phytoplankton abundance and trace metal concentrations in Kaneohe Bay. It is hoped that combining these pieces of evidence will make it possible to reconstruct historical records of biologic responses to changing environmental conditions.

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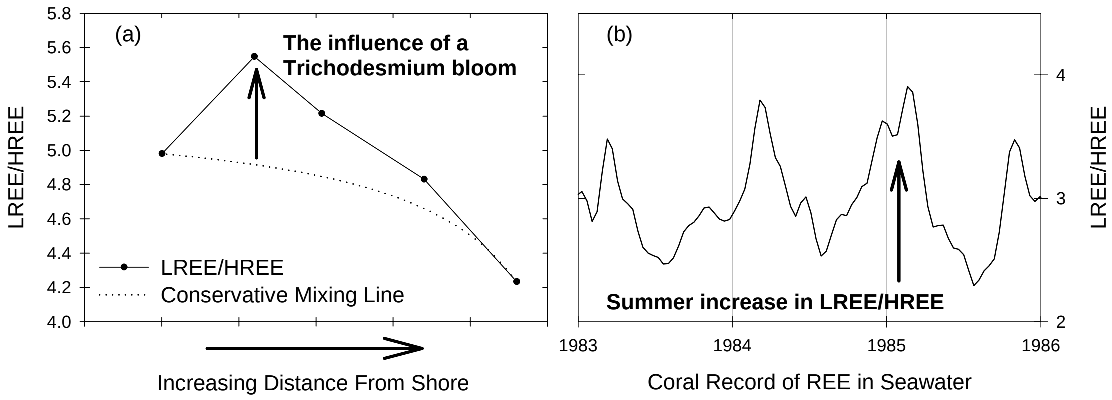

Figure 1. (a) HREE scavenging by a Trichodesmium bloom on the Inner Great Barrier Reef results in an increase in the LREE/HREE ratio. (b) A coral record of REE seawater composition at the same study area shows an annual summer increase in the LREE/HREE that can be attributed to similar processes.

EXPERIMENTAL PETROLOGY GROUP, EARTH MATERIALS

The Experimental Petrology Group uses a laboratory-based experimental approach combined with field observations to study the Earth, its origin, evolution and mineral wealth. The group operates a wide range of experimental apparatuses for generating the high temperatures and pressures that are needed to reproduce the natural conditions within the Earth. The equipment includes: high temperature furnaces capable of reaching 1800ºC, several of which are equipped for precise control of oxygen and sulfur fugacities by gas mixing; eleven solid-media piston-cylinder devices for generating pressures to 6 GPa and temperatures in excess of 2000ºC, a multi-anvil apparatus, which can presently achieve pressures of 26 GPa; and, through collaboration with the Department of Earth and Marine Sciences, the Faculties, a well-equipped hydrothermal laboratory. These high-temperature, high-pressure apparatuses are complimented by an array of microbeam analytical techniques, including a Cameca SX100 electron microprobe; laser-ablation ICP-MS, which is now being used regularly to analyse trace-elements in experimental run products; FTIR spectroscopy for the determination of H_2O, CO_2 and other volatile species in minerals and glasses; and a STOE STADIP powder X-ray diffractometer.

As well as the conventional 1/2 inch and 5/8 inch apparatus for use to 4 GPa, the group's piston-cylinder laboratory also runs a high-pressure device that is now operating regularly at 6.5 GPa; the laboratory also has two large-capacity piston-cylinder devices that take 30 mm and 50 to 65 mm diameter pressure assemblies respectively, enabling pressure to be controlled extremely accurately, and which are capable of synthesising relatively large volumes of high pressure phases for detailed mineralogical studies. A novel diamond composite hard material, developed in these apparatuses and now under commercial production, offers promise as an anvil material to extend the pressure range of the multi-anvil apparatus above 26 GPa, thereby allowing detailed experimental exploration of the pressure-temperature regime of the Earth's lower mantle. To further this research the multi-anvil apparatus has now been refurbished and provided with full computer control of pressure and temperature.

In recent years the group has become increasingly involved in developing methods to characterise geologic materials by X-ray absorption spectroscopy (XANES) and related techniques that use synchrotron radiation. Dr A. J. Berry has adopted a leadership role in this area, setting up a special interest group called GEOSYNC (to educate, advise and represent Australian geoscientists), and is providing input into the design specifications of the planned microprobe and EXAFS beamlines. Research in this area is presently concentrating on oxidation states in silicate melts, including in-situ measurements at temperatures to 1500ºC, and speciation in ore-forming hydrothermal solutions.

Members of the group continue to investigate conditions and processes in the Earth's upper mantle (Professors David Green and Hugh O'Neill), and metamorphism in the continental crust (Drs Joerg Hermann, Chris McFarlane and Carl Spandler), as well as the physical chemistry of ore-forming solutions (Drs John Mavrogenes and Alistair Hack).

A XANES study of Cu speciation in high-temperature brines using synthetic fluid inclusions

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Hydrothermal ore deposits are the world's principal source of copper and gold. To understand the formation of these deposits, it is necessary to determine the speciation of Cu and Au in solution. This can be achieved using X-ray Absorption Near Edge Structure (XANES) spectroscopy - an element specific technique that can provide information on the oxidation state and coordination environment of a metal ion in solution. Cu K-edge XANES spectra were recorded for brines trapped as synthetic fluid inclusions in quartz at GeoSoilEnviroCARS (GSECARS), Advanced Photon Source, Argonne National Laboratory, USA. An example of a typical fluid inclusion at room temperature is given in Figure 1.

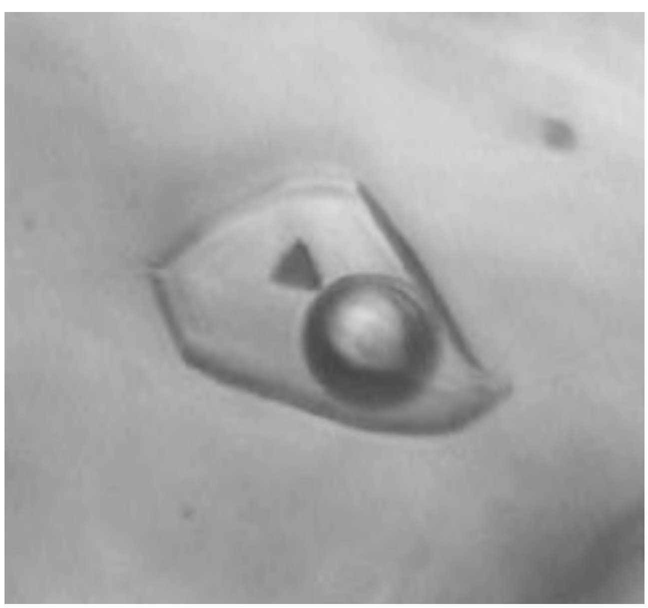

Figure 1: Optical image of a fluid inclusion at room temperature comprising fluid, a shrinkage bubble, and crystal of nantokite (CuCl).

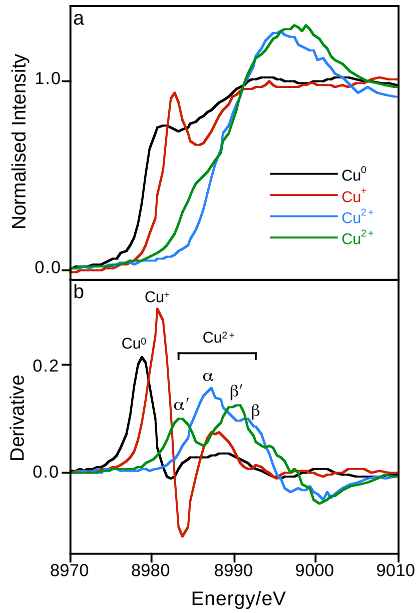

Figure 2: Representative Cu *K*-edge (a) XANES and (b) derivative spectra for different oxidation states. Two spectra are shown for Cu^{2+}, corresponding to different distortions (tetragonal) from octahedral coordination (indicated by the shoulder on the absorption edge). The resulting two peaks in the derivative spectra are labeled a (shoulder) and b (crest).

The energy and intensity of features in the XANES spectra are dependent upon the Cu oxidation state and coordination environment. Example XANES spectra for Cu^{0}, Cu^{+}, and Cu^{2+} are given in Figure 2a. These show an expected shift of the absorption edge to higher energy with increasing oxidation state and differences in the edge shape. Features comprising the absorption edge are often more easily identified in the derivative spectra (*d*(intensity)/*d*(energy)), which shown in Figure 2b.

Fluid inclusions can be heated allowing their use as sample cells for high temperature studies. In this case Cu K-edge XANES spectra were recorded for a number of inclusions containing solutions of different composition at temperatures up to ~ 500 C. Cu^{2+} was observed at room temperature and Cu^{+} at temperatures above ~ 200 C, with the oxidation/reduction being completely reversible. At high temperatures a number of Cu-Cl complexes were identified including $[CuCl_2]^{-}$ and a more highly coordinated $[CuCl_3]^{2-}$ or $[CuCl_4]^{3-}$ species. This is the first time that higher order Cu^{+} complexes have been identified in high temperature brines. The presence of these complexes is not predicted by existing experimental data or thermodynamic models, indicating significant deficiencies in our understanding of the behaviour of Cu in hydrothermal solutions. Further work will focus on identifying the Cu complexes present in natural fluid inclusions.

Large Archean asteroid impacts: implications for the nature of the early crust.

Andrew Glikson

Archean and early Proterozoic impact fallout units, consisting of vapour condensate spherules (microkrystites), microtektites and fragmental tsunami deposits, display high siderophile element (Ni, Co, PGE [platinum group elements]) abundances and, in some instances, high V and Cr levels. The data allow an indirect insight into the composition of crustal regions from which the ejecta were derived, including the contribution of extraterrestrial components and fractionation history of impact-ejected liquid/vapour plumes. The scarcity of shocked quartz grains in recorded Archean and early Proterozoic ejecta and the largely ferromagnesian compositions of the microkrystite spherules, except where heavily altered, are consistent with impacted mafic to ultramafic crust. The PGE data coupled with stratigraphic data are used to estimate the PGE flux and the size of projectiles. PGE patterns relative to chondrite are mostly depleted in volatile low boiling-point species (Au, Pd) and enriched in refractory species (Ir, Ru, Rh), with consequently lower than chondritic Pd/Ir and Pd/Pt ratios (Figure 1), providing useful tracer of microkrystite-rich impact fallout units. First approximations of asteroid and crater sizes based on Ir mass balance and on spherule size-frequencies suggest impact by asteroids 20-30 km large, scaled to oceanic impact basins several hundred kilometre in diameter. A high ratio of sima to sial crust during the Archean is consistent with positive Sm-Nd, Lu-Hf and 87/86Sr isotopic parameters. The evidence suggests post-3.8 Ga geotectonic systems consisting of small sialic granite-greenstone nuclei surrounded by extensive sima crust in which transient Maria-scale impact basins formed during 3.47, 3.26-3.24, 2.63, 2.56, 2.50-2.47 Ga and yet unrecorded impact events.
Criteria allowing diagnostic identification of impact fallout units (impactites), including fragmental ejecta, microtektites and microkrystite spherules (impact vapour condensates) comprise (1) unique mineral fallout phases - shocked quartz grains, coesite and nano-diamonds; (2) unique intra-microkrystite phases - Ni-chromite, Ni-nanonuggets and Ir-nanonuggets, condensed from vapour enriched in meteoritic components; (3) geochemical features such as high abundance and unique ratios of the Platinum Group (PGE) and other siderophile element (Ni, Co); (4) meteoritic isotopic ratios including $^{53}Cr/^{52}Cr$ - $^{53}Cr/^{52}Cr$, $^{182}W/^{183}W$ - $^{182}W/^{184}W$, $^{187}Os/^{188}Os$, $^{17}O/^{16}O$ - $^{18}O/^{16}O$; (5) cometary seeding of

$^{3}He/^{4}He$ and racemic organic molecules (AIB) and possibly fullerenes (C60). Relic Nickel chromites and metasomatically derived sulphides may contain PGE nanonuggets. Alteration, burial metamorphism and open system mobility of uranium in hydrous terrestrial environment renders preservation of meteoritic $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ unlikely. $^{53}Cr/^{52}Cr$ - $^{54}Cr/^{52}Cr$ relations in Barberton Greenstone Belt impact fallout units (3.26-3.24 Ga) identify carbonaceous chondrite composition of the parental asteroids (Kyte et al., 2003). PGE abundances (Ir, Pt) and $^{53}Cr/^{52}Cr$ isotopes allow mass balance estimates of parental projectiles in the order of 20-30 km diameter (Byerly and Lowe, 1994; Shukloyukov et al., 2000)(Figure 2).

Asteroid and comet impacts: effects on the early biosphere

The terrestrial record is punctuated by major clustered asteroid and comet impacts, which affected the appearance, episodic extinction, radiation and re-emergence of habitats. Extraterrestrial effects on microbial habitats includes sterilization by intense asteroid and comet bombardment, supernova and solar flares, impact-triggered volcanic and hydrothermal activity, tectonic modifications and tsunami effects. From projected impact incidence post 3.8 Ga, only ~1.3 percent of craters >100 km and ~4 percent of craters >250 km have to date been identified. Potential relations between asteroid/comet impacts and early habitats include: (1) ~3.5-3.43 Ga - intermittent appearance of stromatolite-like structures of possible biogenic origin on felsic volcanic shoals representing intervals between mafic volcanic episodes in rapidly subsiding basins, accompanied by asteroid impacts; (2) ~3.26-3.24 Ga - impact-triggered crustal transformation from mafic-ultramafic volcanic environments to rifted troughs dominated by felsic volcanics and turbidites, marked by a major magmatic peak, resulting in extensive hydrothermal activity and development of sulphate-reducing microbes around anoxic submarine fumarole ("black smoker") environments; (3) ~2.63-2.47 Ga – impact-triggered tsunami effects in oxygenated carbonate-dominated epicontinental and intra-cratonic environments (Hamersley and Transvaal basins); (4) in at least three instances onset of ferruginous sedimentation closely following major impact events, possibly signifying hydrothermal Fe-enrichment related to impact-triggered volcanic activity. Due to limitations on the phylogenic speciation of Precambrian stromatolite and bacterial populations, major impact-extinction-radiation relations are only identified from the late Proterozoic, beginning with the ~0.59 Ga Acraman impact and continuing with major Phanerozoic extinctions and radiations associated with impact and volcanic events in the late Ordovician, late Devonian, late Jurassic and end Cretaceous.

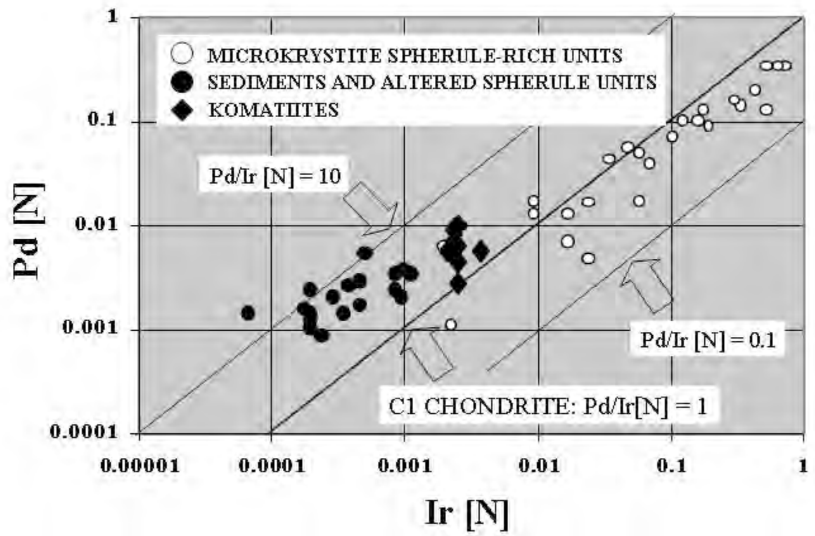

Figure 1 – Pd[N] – Ir[N] plots of microkrystite spherule-rich units (open circles), associated sediments (solid circles) and komatiites volcanics (solid diamonds).

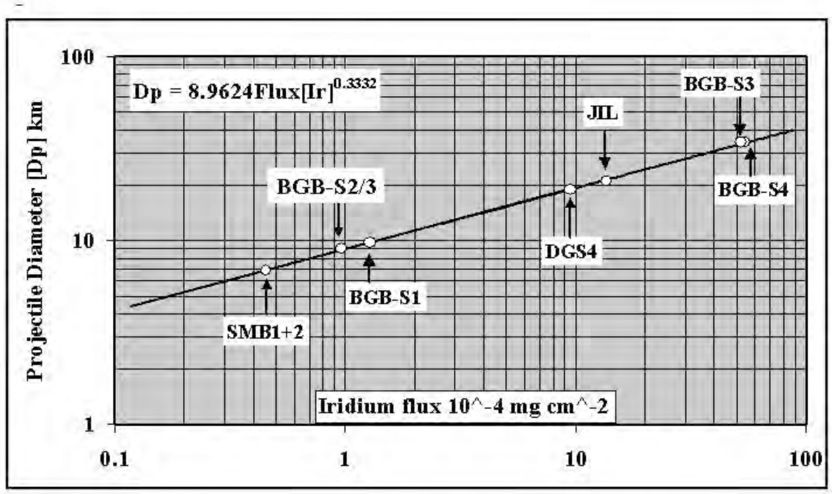

Figure 2 - Correlation between the flux of Iridium (in units of 10^{-4} mg cm^{-2}) and the diameter of chondritic projectile (Dp), based on mass balance calculations assuming mean unit thickness, mean Ir concentration and global distribution of fallout ejecta.

Mineral solubility surfaces at high pressure and temperature and its bearing on the nature of the wet solidus

Alistair Hack, Jörg Hermann and John Mavrogenes

Analysis of available data for SiO_2–H_2O and $NaAlSi_3O_8$(albite)–H_2O reveals that the phase relations in either simple system are not adequately defined in some regions. We have constructed two endmember, internally consistent P–T–X phase relation models for silicate–H_2O, which are consistent with the constraints imposed by the simple systems. Fig. 1 shows one of these endmember P–T–X topologies. Different critical curve behaviour, which describes the P–T limit of silicate melt + aqueous fluid immiscibility, can produce other phase relation forms. Here, however, we focus on data for SiO_2–H_2O, which provides best constraints on the general P–T–X shape of the mineral-saturated supercritical fluid surface and shape of the wet solidus and the nature of its termination at the critical point.

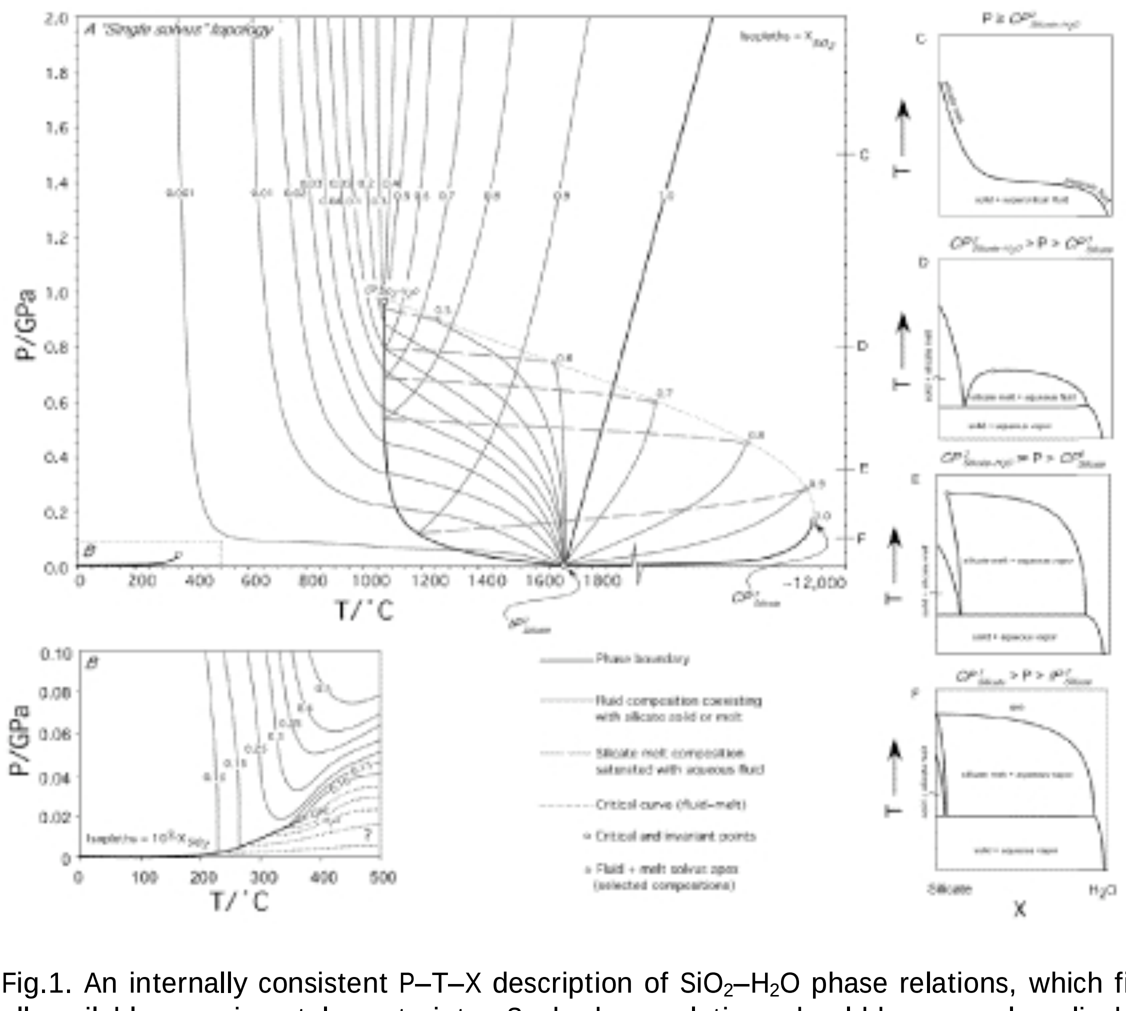

Fig.1. An internally consistent P–T–X description of SiO_2–H_2O phase relations, which fits all available experimental constraints. Such phase relations should be general applicable

to other more complex systems. CP and IP refer to critical and invariant points in the system.

Wet solidi for many rock–H_2O systems are reported as displaying a 'backbend' with increasing pressure. This apparent reversal in the wet solidus slope from negative to positive ∂P/∂T at high pressure, is suspicious as a reversal in slope also accompanies mineral solubility isopleths above the $CP^{2}_{Solid-H_2O}$ (Fig. 1), as does the transition from unquenchable H_2O-rich fluid to quenchable supercritical hydrous melts with increasing temperature. Specifically, 'wet solidi' curves at pressures above the ∂P/∂T inflection may not exist, as this higher pressure part of the curve represents the first appearance of quenchable supercritical melt which presumably occurs at approximately the same composition regardless of pressure and temperature (e.g. fluid/melt containing ~25 wt% H_2O), explaining the similarity in the slope to that expected for a mineral-saturated supercritical melt isopleth. This situation is illustrated in Fig. 2. Ambiguity associated with locating the position of the first quenchable supercritical hydrous melt, would readily explain wet solidi discrepancies between studies.

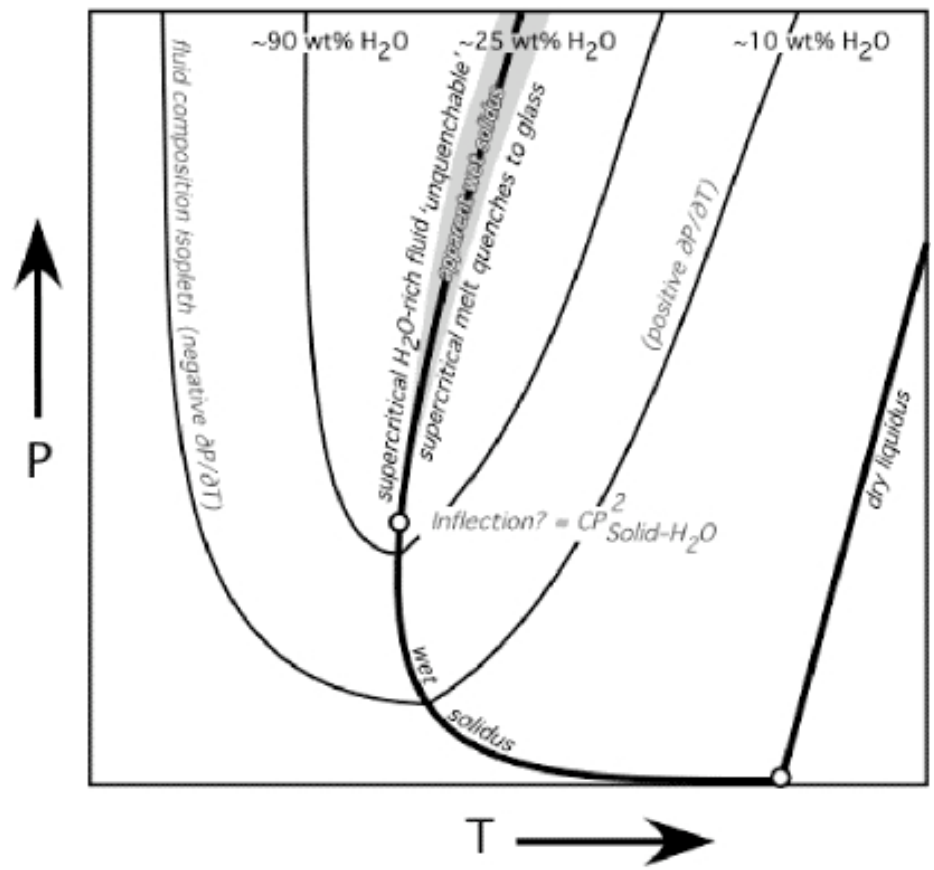

Fig. 2. P–T–X projection illustrating a potential origin for, widely reported, ∂P/∂T inflections in wet solidi curves. The inflection possibly marks the termination of the wet solidus, the apparent extension at high pressure follows a mineral-

saturated fluid isopleth corresponding to the first appearance of a quenchable supercritical fluid/melt composition.

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Experimental determination of zircon/garnet/melt trace element partitioning and implications for geochronology

Jörg Hermann and Daniela Rubatto (EMS, ANU)

Garnet is the most commonly used mineral in thermobarometry, whereas zircon is the most robust chronometer to date high-grade metamorphic rocks. To provide a basis for correlation of zircon and garnet growth, we determined experimentally the trace element partitioning between zircon and garnet ($D^{Zrn/Grt}$) grown from a hydrous, granitic melt at 20 kbar and 800-950°C for P, Y, rare earth elements (REE), Zr, Hf, Th and U.

Large homogeneous garnets coexisting with hydrous granitic melts (Fig. 1) were produced by heating to 1050°C for two hours and then cooling within 15 minutes to the desired temperature between 800 and 950°C. Run products analysed by LA-ICP-MS provide evidence for a significant temperature dependence of garnet/melt partitioning for REE Fig. 2. In contrast, zircon grain size was always very small (Fig. 1). We determined zircon/melt trace element partitioning by analysing a large number of zircon-melt mixtures by Laser Ablation ICP-MS and regressing the data to the known Zr composition of the zircon. The distribution coefficient between zircon and melt ($D^{Zrn/Melt}$) for REE increases with increasing atomic number of the REE and with decreasing temperature. $D_{Yb}^{Zrn/Melt}$ is ~10 at 1000°C but more than an order of magnitude higher at 800°C. $D_{U}^{Zrn/Melt}$ is always significantly higher than $D_{Th}^{Zrn/Melt}$ and both increase with decreasing temperature. One advantage of using LA-ICP-MS for garnet, melt and zircon compositions is that all are compared to the same standard and hence, in the partitioning, uncertainties related to the standard are cancelled out.

Zircon contains significantly more heavy-REE (HREE) than coexisting garnet, whereas middle-REE (MREE) partitioning is close to unity. There is some limited evidence that zircon contains more light-REE than garnet. Zircon/garnet partition coefficients of HREE increase with decreasing temperature from $D_{Lu}^{Zrn/Grt}$ of 2.4 at 950°C to 12 at 800°C. These data provide a tool to establish equilibrium partitioning between garnet and zircon in natural rocks and can assist the construction of detailed pressure-temperature-time paths in high-grade metamorphic rocks.

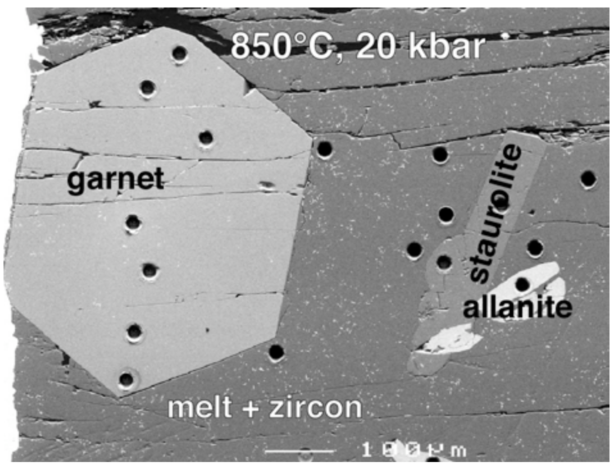

Fig. 1 Backscattered electron image of experimentally produced garnet, melt and zircon. Black holes represent pits from Laser Ablation ICP-MS analysis.

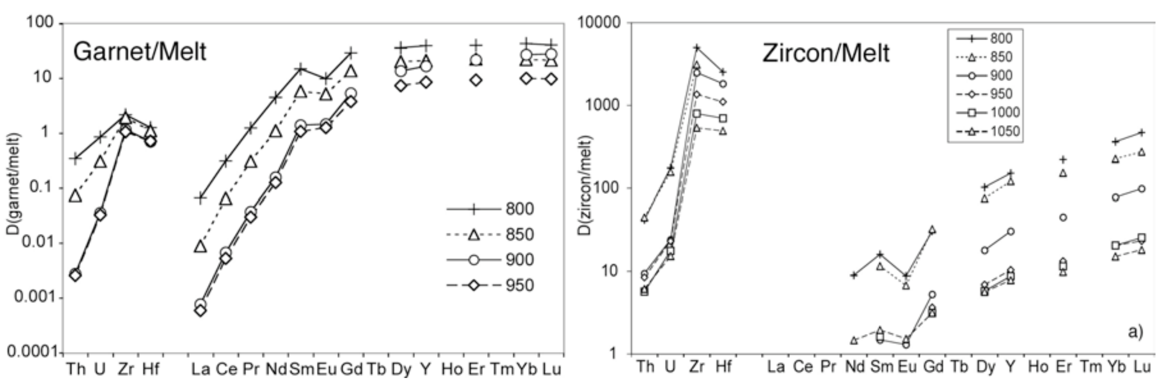

Fig. 2: Experimentally determined trace element partitioning.

H_2O-bearing defects in olivine produced by the breakdown of Ti-rich humite minerals

Jörg Hermann, John Fitz Gerald, Nadia Malaspina and Andrew Berry

We have investigated in detail the breakdown of Ti-clinohumite and Ti-chondrodite in metasomatised mafic-ultramafic rocks from the ultra-high pressure (UHP) province in Dabie-Shan (China). Petrography indicates that the humite minerals are stable at peak UHP conditions (~800°C, ~40 kbar) and coexist with a typical eclogite facies assemblage of garnet, clinopyroxene and orthopyroxene. In thin section we observe that the humite minerals partly break down to olivine+ilmenite (Fig. 1). This reaction must be related to the release of an aqueous fluid since the reactants contain several wt.% of H_2O whereas the solid products are nominally anhydrous minerals. Although this breakdown is related to near isothermal decompression in the studied samples, it can be used as a proxy for what happens when the humite stability field is overstepped during prograde subduction and hence provides information on water redistribution during subduction.

TEM investigation of these newly formed olivine shows the presence of relic Ti-clinohumite layers (Fig. 2). These olivine grains contain significant amounts of H_2O that is associated with Ti in a layer-type defect. Therefore, in subduction zones such olivine might transport water into the mantle beyond the stability fields of the humite minerals. Also it is expected that this defect-rich olivine will have a different (weaker) rheology than normal mantle olivine, with consequences for deformation within the subducted slab and hydrous parts of the overlaying mantle wedge.

So far we were unable to obtain conclusive Infra-Red (IR)-spectra from these small olivine crystals. We will try to get IR-spectra of such olivine in samples that have been ion beam thinned. This will provide an important link between IR-spectroscopy, mineral composition and mineral defects at atomic scale.

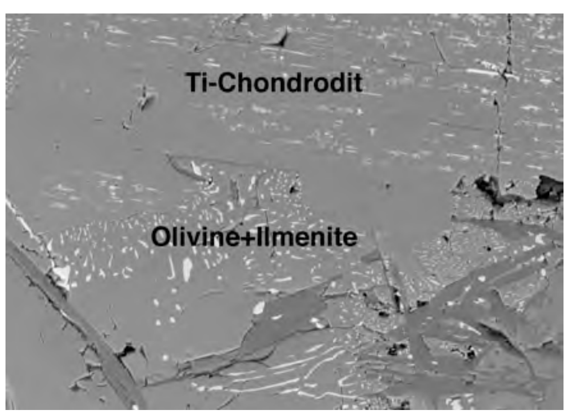

Fig. 1 Back scatter electron image of the partial breakdown of a Ti-chondrodite to olivine+ilmenite. The field of view is 300μm.

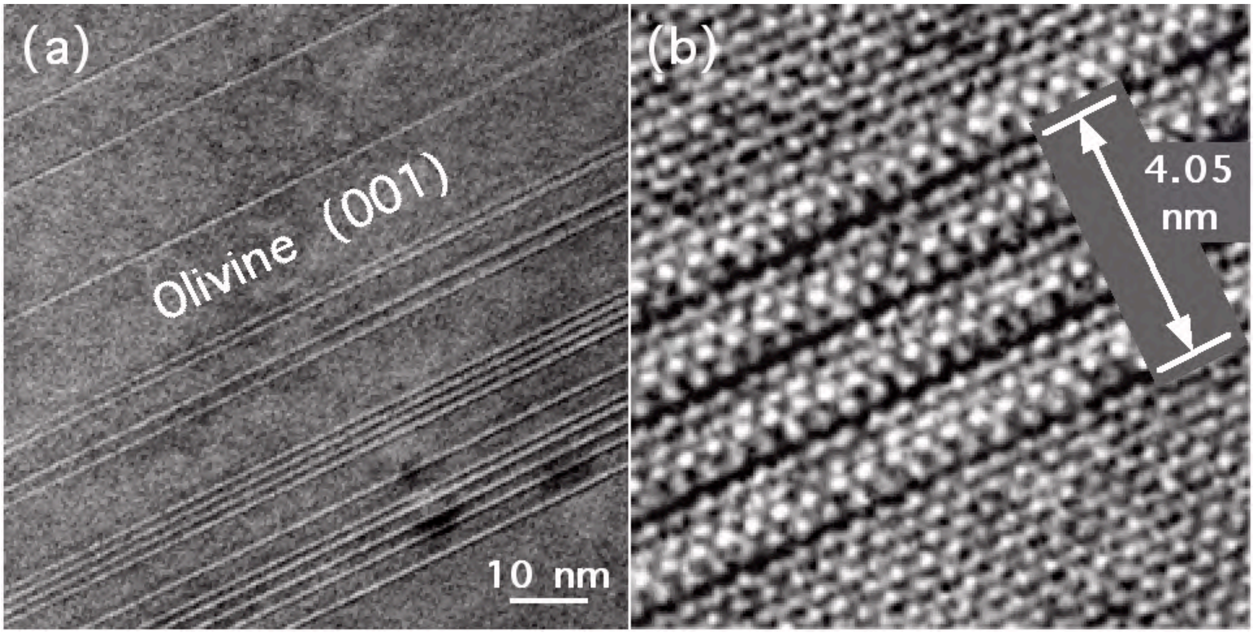

Fig. 2 TEM image of a crystal of newly formed olivine viewed parallel to its crystallographic [b] axis. Figure (a) clearly shows a complex planar intergrowth with (001) sheets viewed edge-on. The lattice image (b) at much higher magnification reveals the regular repeat of the olivine unit cells (top and bottom of image) plus 4 units of a longer-period structure across the centre of the image - this is a thin layer of clinohumite with characteristic 1.35 nm repeat distance.

The role of metamorphism in ore deposition at the Challenger Gold Mine, South Australia

Chris McFarlane

Monazite thermochronology

Studies of the role of metamorphism in ore deposition continued at the Challenger Au Mine, South Australia. Samples taken during field work in February and July 2004 have been used for *in-situ* monazite ([Ce,Th]PO_4) geochronology using the SHRIMP. Several generations of monazite have been identified on the basis of textures, compositional zoning, and isotopic ages (Figure 1) that have been used to reconstruct the prograde, peak, and cooling history of the Challenger Gneiss. The *T-t* history from monazite thermochronology (Figure 2) is defined by rapid heating from garnet-grade conditions at 2460 Ma to granulite conditions (>800ºC) by 2449 Ma. This prograde heating path was followed by slow cooling punctuated by a second partial melting event at ~2434 Ma. Final crystallization of this second melt batch occurred between 2420 and 2415 Ma. A single grain may, therefore, preserve a record of monazite growth and resorption over a ~40 My period. These data will help to constrain the tectonic setting of Au deposition and Au remobilization at Challenger. Reconstruction of this *T-t* path also provides insight into the heat flow and timescales of metamorphism and deformation during the Archaean.

Whole-rock geochemistry

The origin of Au mineralization at Challenger has remained speculative owing to the cryptic nature of its distribution among migmatitic leucosomes and polymineralic quartz-rich veins. Whole-rock geochemistry on a suite a samples taken from individual leucocratic veins from the mine shows that the deposit contains relict quartz veins (>90% SiO2 with negligible trace element concentrations), some of which contain visible gold (Figure 3). Mine geologists at Challenger have also reconstructed the 3D geometry of high-grade zones using grade control logs and have shown that the main ore zone is in fact a planar horizon that has been folded into a series of disharmonic folds. This geometry, together with the presence of relict quartz veins and evidence for preferential partial melting of ore zones, suggests that Challenger is in fact a highly deformed and metamorphosed quartz-gold vein system. Continuing whole-rock geochemical studies will be aimed at augmenting the current geochemical database to look for relict alteration patterns that may help to delineate larger exploration targets.

Silicate/sulfide melting experiments

Ore zones at Challenger show textural evidence for intermingling of silicate and sulfide melts. Piston-cylinder experiments were started in an attempt to reproduce the textures present at Challenger. Experiments comprise mixtures of silicate and sulfide powders that are known to melt at granulite conditions (850ºC, 8 kbar). Preliminary results are very promising. Run products include polymetallic sulfide blebs suspended in a quenched glass matrix. Quench textures of these sulfide blebs (Figure 4) are indistinguishable from heating and quenching experiments on natural inclusions from Challenger.

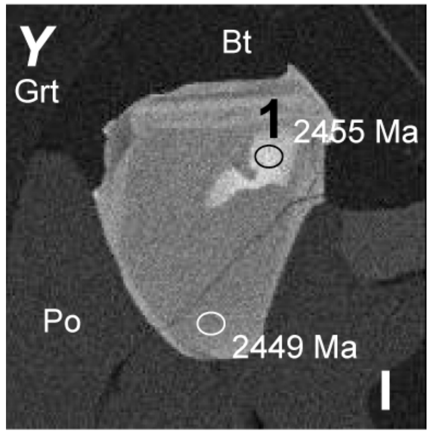

Figure 1. Yttrium X-ray map of monazite from the Challenger Gneiss. Old high-Y cores interpreted to be of prograde origin are surrounded by a large overgrowth that formed during partial melt crystallization at 2449 Ma.

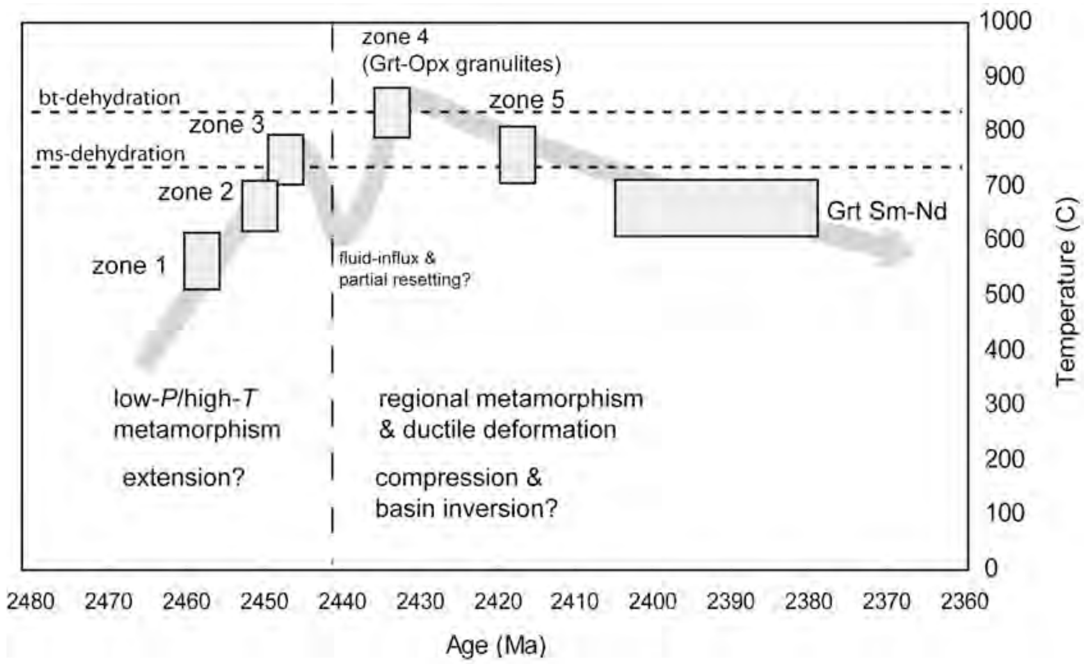

Figure 2. The proposed T-t history of the Challenger Gneiss based on monazite thermochronology. Garnet-WR Sm-Nd ages are from Tomkins (2002)

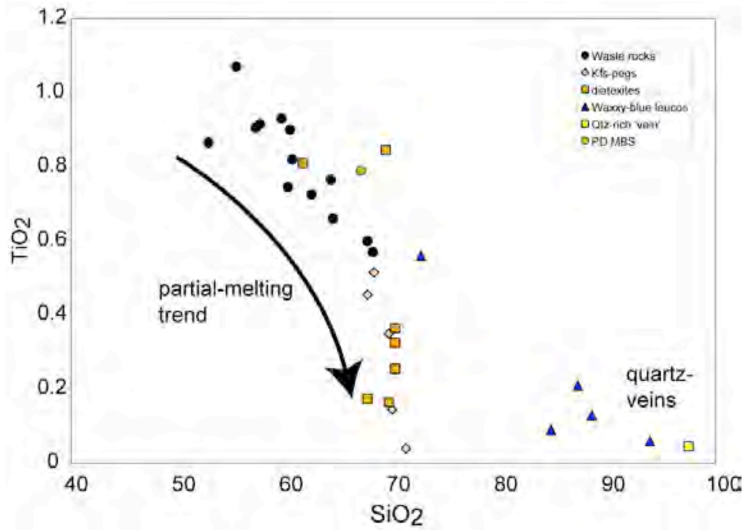

Figure 3. Whole-rock geochemical data from the Challenger Mine. High-SiO_2 veins (blue & yellow symbols) are interpreted as relict quartz veins, some of which contain visible gold. Other lithologies from the migmatite zones display a negative trend towards higher SiO_2 that is typical of partial melting and extraction of granitic melts from a refractory residue.

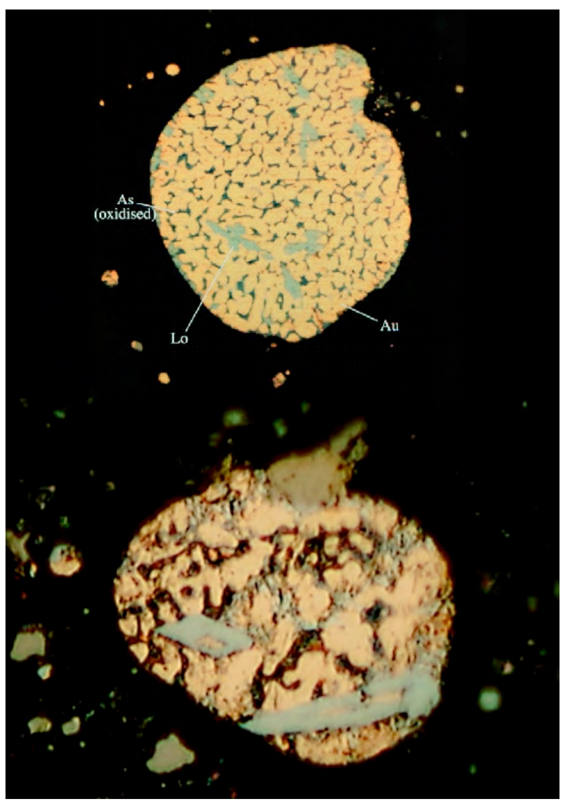

Figure 4. Sulfide melt quench textures in nature (top) and in piston-cylinder experiments (bottom). Natural inclusions were heated to 800°C and 7 kbar and quenched (Tomkins, 2002). Synthetic sulfide melts were heated to 850°C and 8

kbar and quenched. Greenish-brown sulfide in bottom frame is unmelted pyrrhotite.

The oxidation state of iron in silicate melts

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$Fe^{3+}/\Sigma Fe$ ratios were determined from Mössbauer spectra recorded for a series of 17 anorthite-diopside eutectic glasses containing 1 wt% $^{57}Fe_2O_3$ quenched from melts equilibrated over a range of oxygen fugacities from fO_2 ~ 10^5 bars ($Fe^{3+}/\Sigma Fe$ = 1) to 10^{-13} bars ($Fe^{3+}/\Sigma Fe$ = 0) at 1682 K. Fe^{3+}/Fe^{2+} was found to be proportional to fO_2 to the power of 0.245 ± 0.004 in excellent agreement with the theoretical value of 0.25 expected from the stoichiometry of the reaction $Fe^{2+}O + 0.25\ O_2 = Fe^{3+}O_{1.5}$. The uncertainty in the $Fe^{3+}/\Sigma Fe$ ratios determined by Mössbauer spectroscopy was estimated as ± 0.01 (1 s) from the fit of the data to the theoretical expression, which is significantly less than that quoted for previous measurements on silicate glasses; this results from fitting the spectra of a large number of systematically varying samples, which allows many of the ambiguities associated with the fitting procedure to be minimised. $Fe^{3+}/\Sigma Fe$ ratios were then determined for samples of the anorthite-diopside eutectic composition equilibrated at selected fO_2s, to which up to 30 wt% Fe_2O_3 had been added. $Fe^{3+}/\Sigma Fe$ was found to vary with ΣFe (or FeO_{tot}), but both the 1 wt% and high FeO_{tot} data could be satisfactorily fit assuming the ideal stoichiometry (i.e., $Fe^{3+}/Fe^{2+} \propto fO_2^{1/4}$) by the inclusion of a Margules term describing Fe^{2+}-Fe^{3+} interactions. The large negative value of this term indicates a tendency towards the formation of Fe^{2+}-Fe^{3+} complexes in the melt. The resulting expression, using the ideal exponent of 0.25, gave a fit to 289 $Fe^{3+}/\Sigma Fe$ values from the literature of similar quality as previous empirical models which found an exponent of ~ 0.20. While the empirical models reproduce $Fe^{3+}/\Sigma Fe$ values of glasses with high FeO_{tot}, reasonably well, they describe the data for 1 wt% FeO_{tot} poorly. The non-ideal values of the exponent in these empirical models are an artifact caused by not including a term explicitly to describe the Fe^{2+}-Fe^{3+} interactions.

The effect of pressure on the $Fe^{3+}/\sum Fe$ ratio of an anhydrous andesitic melt was determined from 0.4 to 3.0 GPa at 1400°C with oxygen fugacity controlled internally by the $Ru+RuO_2$ buffer. Values of $Fe^{3+}/\sum Fe$ were determined by Mössbauer spectroscopy on quenched glasses with a precision of ± 0.01, one standard deviation. This precision was verified independently by XANES spectroscopy of the same samples. The XANES spectra show a systematic increase in energy and decrease in intensity of the 1s®3d transition with increasing pressure. The results to 2.0 GPa are in good agreement with predictions from density and compressibility measurements fitted to a Murnaghan equation of state, but the datum at 3.0 GPa has higher $Fe^{3+}/\sum Fe$ than predicted from the trend established by the lower pressure data. This might be due to a coordination change in Fe^{3+} at high pressure; while there is no evidence for this in the Mössbauer spectra, such a change could account for the change in intensity of the 1s®3d transition in the XANES spectra with pressure.

A method for controlling alkali-metal oxide activities in one-atmosphere experiments and its application to measuring the relative activity coefficients of $NaO_{0.5}$ in silicate melts.

Hugh St. C. O'Neill

The activity of alkali metal oxides can be controlled in one-atmosphere wire-loop experiments at high temperature by suspending a crucible containing alkali silicate melt beneath the samples. The method has been applied to measuring the activity coefficient of $NaO_{0.5}$ in a series of CMAS-$NaO_{0.5}$ melts relative to that in the anorthite-diopside eutectic composition at 1400 °C, using a reservoir of $NaO_{0.5}$-SiO_2 melt. The results (Figure 1) show that this relative activity coefficient decreases strongly with SiO_2, increases with CaO and MgO, but is insensitive to $AlO_{0.5}$. This latter behavior is inconsistent with "quasi-crystalline" models of melt thermodynamics that hypothesize Na-Al species.

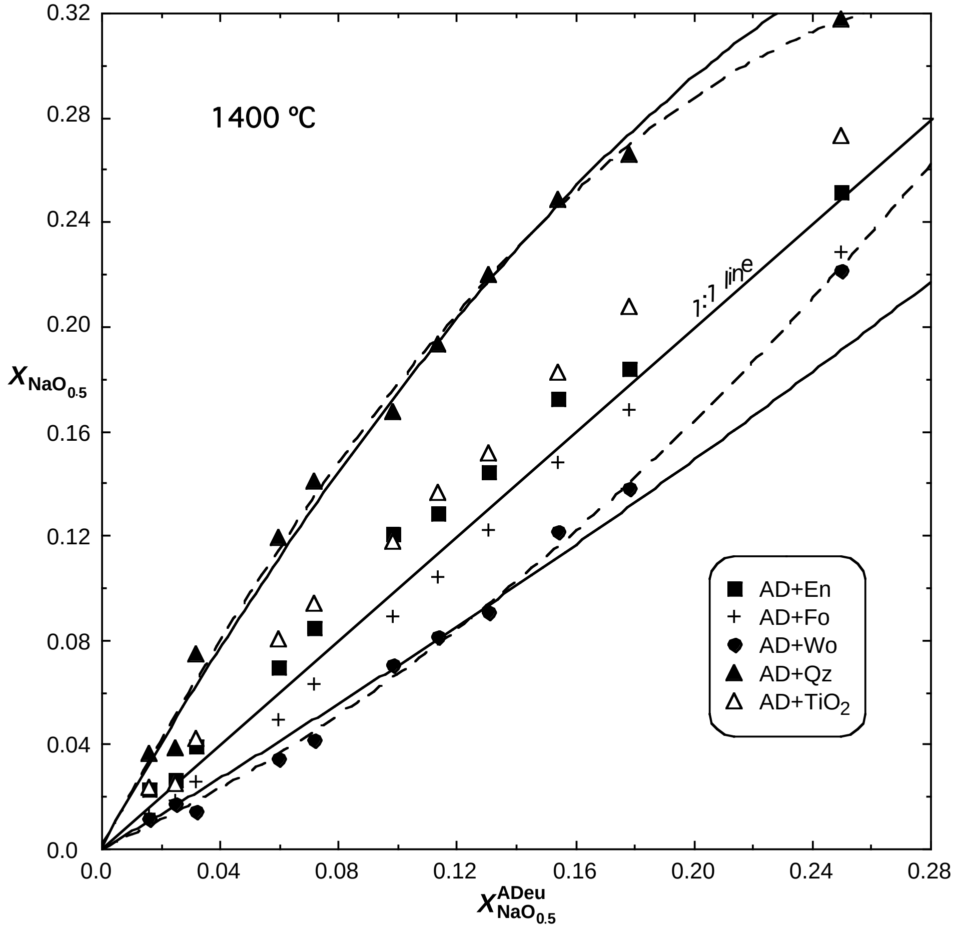


Figure 1. Solubility of $NaO_{0.5}$ in AD6 compositions relative to that in the ADeu "reference" composition. The experiment with the highest $NaO_{0.5}$ was produced with pure Na_2SiO_3 in the reservoir at $fO_2 = 10^{-6.7}$ bars; most other runs were done in air. Solid curves are best fits for AD+Qz and AD+Wo compositions to the equation (omitting the highest Na datum):

$$\ln X_{\mathrm{NaO}_{0.5}} \cong \ln X_{\mathrm{NaO}_{0.5}}^{\mathrm{ADeu}} - (1 - X_{\mathrm{NaO}_{0.5}})^2 \ln(\gamma_{\mathrm{NaO}_{0.5}}^{\infty} / \gamma_{\mathrm{NaO}_{0.5}}^{\mathrm{ADeu},\infty})$$

The dashed curves are a fit to a purely empirical equation:

$$X_{\mathrm{NaO}_{0.5}} = a_1 X_{\mathrm{NaO}_{0.5}}^{\mathrm{ADeu}} + a_2 (X_{\mathrm{NaO}_{0.5}}^{\mathrm{ADeu}})^2$$

and include the highest Na datum.

ROCK PHYSICS, EARTH MATERIALS

Introduction

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

Members of Rock Physics collaborate widely within RSES and beyond. Within the Earth Materials area of RSES, the preparation and characterisation of synthetic rock specimens and their precursors involves intensive collaboration between the Rock Physics and Experimental Petrology Groups. The interest in the structures and microstructures in naturally deformed rocks and related fluid-chemical studies is similarly widely shared – especially with members of the Structure/Tectonics group and the Thermochronology laboratories and the Department of Earth and Marine Sciences, Faculty of Science. Natural links with the Seismology Group, Earth Physics are based on a common interest in the interpretation of seismological models for the Earth's interior.

The group's current research has two main themes: seismic properties and interpretation and the coupling between fluid flow, deformation processes and reaction – led by Professors Ian Jackson and Stephen Cox, respectively. Vital contributions to the group's research effort are provided by postdoctoral/research fellows Drs Ulrich Faul, Stephen Micklethwaite and Eric Tenthorey, and Ph. D. students Shaun Barker and Silvio Giger. The capacity to operate novel equipment, and the further development and timely exploitation of associated experimental techniques, depend heavily upon the skill and commitment of research support staff Messrs Harri Kokkonen and Craig Saint and Ms. Lara Weston along with the staff of the School's Engineering and Electronics Workshops. Mrs Kay Provins provides critical administrative support for the Group, including responsibility for website development and maintenance. The Group pursues this ambitious research agenda using core funding from RSES boosted by several grants from the Australian Research Council.

Within the wider ANU community, the influence of the Rock Physics Group is felt in a variety of forums. For example, the ANU's flagship TEM which serves the needs of the campus materials science community is housed within the School and operated by John Fitz Gerald and Mr. David Llewellyn on behalf of the ANU Electron Microscope Unit.

The group also is committed to undergraduate and graduate teaching, and for many years has participated in the CSIRO Student Research Scheme with students from Canberra secondary colleges.

<u>Seismic properties and interpretation</u>

<u>Coupling between fluid flow, deformation processes and reaction</u>

Seismic properties and interpretation: the structure of the Earth's mantle interpreted through laboratory measurements of seismic wave speeds and attenuation – introduction

Seismic wave speeds typically increase with increasing depth in the Earth's mantle – the generally smooth variation evident in global average models being punctuated by discontinuous increases of 5-10% at depths near 410 and 660 km. Superimposed upon this radial variation is substantial lateral variability especially in the uppermost 300 km of the mantle and near the core-mantle boundary.

Are the discontinuities near 410 and 660 km depth simply the result of known pressure-induced changes in crystal structure or is the mantle sharply stratified in chemical composition? What causes the marked lateral variability of the shear wave speed and attenuation in the upper mantle? Variations in temperature? Compositional heterogeneity? Partial melting?

These questions are central to an understanding of the internal dynamical processes represented at the Earth's surface by continental drift and plate tectonics. Answers require measurements on appropriate materials performed under controlled laboratory conditions of pressure and temperature.

The variation of elastic wave speeds with pressure and temperature, like thermal expansion, arises from asymmetry of the interatomic potential energy. Such 'anharmonic' variations of elastic wave speeds can be conveniently measured in the laboratory on mineral or rock specimens of ~0.1 mm – cm size at sufficiently high frequencies (MHz-GHz) by ultrasonic interferometry and opto-acoustic techniques (Fig. 1a). During the past decade, both single-crystal and coherent polycrystalline specimens of most of the major mantle minerals (including high-pressure phases) have been characterised with these high-frequency methods. Much has been learned about the pressure, and more recently temperature, dependence of their elastic wave speeds. However, substantial uncertainties remain – especially as regards the combined influence of pressure and temperature.

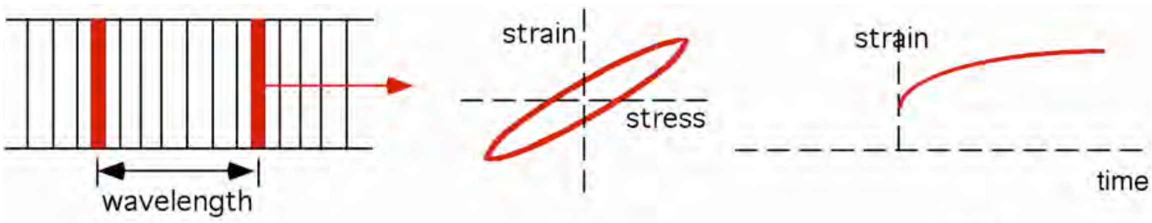


Figure 1(a) (b) (c)

At the much lower frequencies of teleseismic wave propagation (< 1 Hz) the shear modulus and hence both shear and compressional wave speeds may be profoundly altered at high temperature, and in the presence of fluids, by viscoelastic relaxation. The stress-induced migration of crystal defects (vacancies, dislocations and grain boundaries) and/or redistribution of interstitial melt results in additional strain and hence lower wave speeds accompanied by attenuation.

These effects have only recently become amenable to laboratory study through the testing of cm-sized cylindrical specimens at mHz-Hz frequencies with sub-resonant torsional forced-oscillation methods (Fig. 1b). Creep methods (Fig. 1c) probing microstrain deformations in torsion distinguish recoverable (anelastic) from permanent (viscous) strains, whereas axially compressive creep tests constrain the steady-state rheology at moderate strains (~20%).

The development and application of ultrasonic, forced-oscillation/microcreep and compressive creep methods - 2004 highlights:

High-temperature ultrasonic interferometry: applications to pyrope garnet and $ScAlO_3$ perovskite

High-temperature viscoelastic relaxation in olivine-dominated upper-mantle materials and its seismological implications

The moderate-strain rheology of melt-free olivine

High-temperature ultrasonic interferometry: applications to pyrope garnet and $ScAlO_3$ perovskite

Gwanmesia[1], Weston, Jackson & Liebermann[2]

[1] Delaware State University, Dover, Delaware, USA
[2] Stony Brook University, Stony Brook, New York, USA

Elastic wave speeds are precisely measured by ultrasonic interferometry at high temperature and moderate pressure (300 MPa) in gas-medium high-pressure apparatus (Fig. 1).

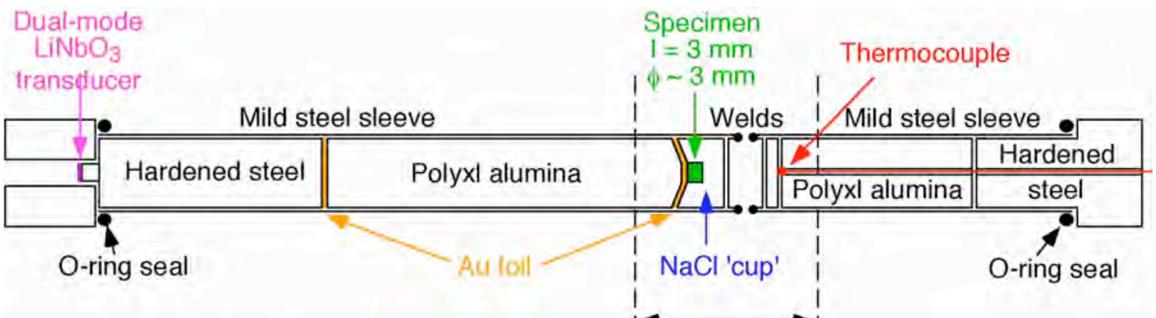


Figure 1

For small specimens and temperatures < 1000 K an alumina buffer-rod tapered to roughly match the specimen diameter and an NaCl pressure-transmitting 'cup' is used. For higher temperatures (to 1600 K), a simple cylindrical buffer-rod and soft Fe cup are employed as in our recently published study of Fo90 olivine (Jackson, Webb, Weston & Boness, *Phys. Earth Planet. Interiors 148*, 85-96, 2005*.*

Elastic wave speeds have recently been measured at high temperature in both solid- and gas-medium apparatus for small polycrystalline specimens of pyrope garnet hot-pressed and characterised at Stony Brook as part of an ARC-NSF funded collaborative research program.

The temperature dependence of the wave speeds is particularly well-constrained by the data from the gas apparatus (Fig. 2a) whereas analysis of the combined dataset (Fig. 2b) yields the pressure derivatives of the elastic bulk and shear moduli and potentially useful constraints on the mixed second derivative d2M/dPdT (Gwanmesia, Jackson & Liebermann, *AGU Fall Mtg*, San Francisco, 12/04).

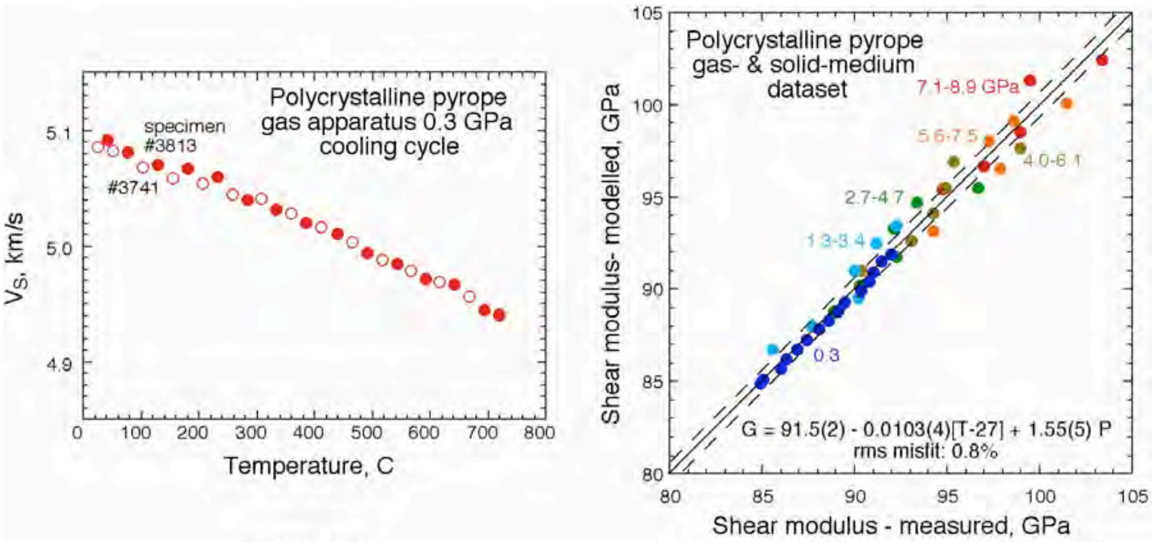


Figure 2(a) (b)

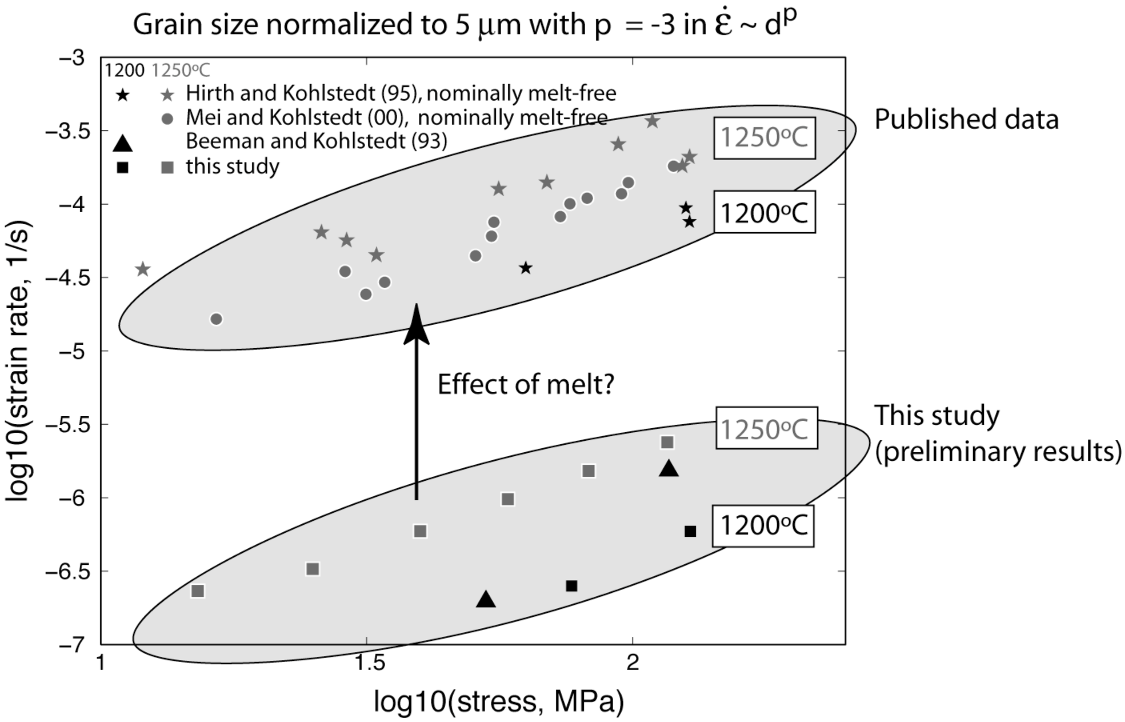
Elastic wavespeeds were successfully measured during 2004 on polycrystalline $ScAlO_3$ – a close structural analogue for the silicate perovskite $MgSiO_3$ – previously measured in the ANU laboratory by Jennifer Kung over a more restricted temperature range. The two datasets are broadly consistent and the analysis and interpretation of the combined dataset is underway.

The moderate-strain rheology of melt-free olivine

Faul, Kokkonen, Saint & Jackson

Our recent measurements of shear modulus and attenuation in pure, fine-grained solution-gelation-derived olivine at seismic frequencies (Jackson et al., JGR, 2002) have highlighted the need to better constrain the finite strain behaviour of these materials. Accordingly we have begun a program to determine the rheology of these materials through triaxial compressive tests in a Paterson-type gas medium apparatus. A particular aim is to determine the activation energy for diffusion creep over a similar temperature range as for the torsional forced oscillation data.

Individual experiments clearly show the transition from diffusion to dislocation creep at stresses of 100 to 150 MPa. When the diffusion creep data are normalized to a common grain size with a grain size exponent of 3, strain rates at a given stress for these genuinely melt-free samples are up to 2 orders of magnitude lower than those observed by Hirth and Kohlstedt (JGR, 1995) for nominally melt-free samples with grain sizes less than 10 micron prepared from natural olivine. However, our strain rates are similar to those reported by Beeman and Kohlstedt (JGR, 1993) for melt-free samples with grain sizes similar to ours. These initial results suggest that the presence of melt has a larger effect on the strength of upper mantle rocks than has previously been reported (Faul and Jackson, AGU Fall Annual Meeting, 2004).



High-temperature viscoelastic relaxation in olivine-dominated upper-mantle materials and its seismological implications

Faul, Fitz Gerald, Jackson, Kokkonen & Saint

In recent years we have applied torsional forced oscillation/microcreep methods in seismic-frequency studies of the high-temperature viscoelastic behaviour of fine-grained materials based on the dominant upper-mantle mineral olivine. Initially we fabricated and tested a suite of dense, high-purity olivine polycrystals – establishing the 'base-line' behaviour in the absence of melt. The variations of both shear modulus G and strain-energy dissipation 1/Q with oscillation period, temperature and mean grain size were quantified. The behaviour is of the type commonly referred to as 'high-temperature background' in which 1/Q varies smoothly and monotonically with period and temperature without any resolvable dissipation peak. Qualitatively different behaviour has been observed for a second suite of olivine specimens containing basaltic melt fractions ranging between 0.01 and 4%. For these specimens, a broad dissipation peak superimposed upon a melt-enhanced background results in the more complicated frequency and temperature dependence displayed in Fig. 1b. The high-temperature dissipation background and associated modulus dispersion are attributed to grain-boundary sliding with diffusional accommodation, whereas the peak seen only in the melt-bearing materials is thought to be caused by elastically accommodated sliding facilitated by the rounding of olivine grain edges at triple-junction melt tubules (Jackson, Faul, Fitz Gerald & Tan; Faul, Fitz Gerald & Jackson, *J. Geophys. Res.*, 2004).

During 2004 we sought to extend to the basaltic melt-bearing olivine polycrystals a parameterisation of the viscoelastic behaviour based on a Burgers-type creep function. The attraction of this approach, already successfully applied to melt-free olivine, is the internally consistent description of the variations with frequency, temperature, grain size and melt fraction of both the shear modulus G and the strain-energy dissipation 1/Q. Torsional forced-oscillation data for individual melt-bearing specimens have been successfully described (Fig. 1) but we are still working towards a satisfactory model for the behaviour of the entire suite of melt-bearing specimens (Jackson, *Frontiers in High-Pressure Research: Geophysical Applications*, in press).

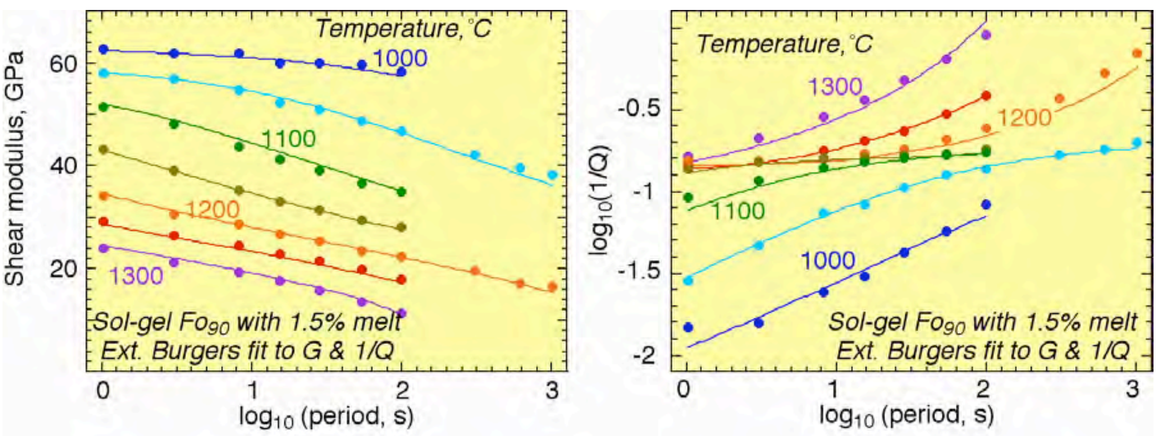


Figure 1(a) (b)

Such models, securely based on an appropriate creep function, provide a robust framework for application of the insights gained in the laboratory to teleseismic wave propagation in the upper mantle. Our model for the behaviour of melt-free olivine, first applied to the structure of the oceanic upper mantle, has this past year also been used to model shear-wave speed versus depth profiles for contrasting tectonic provinces within the continental upper mantle. It is found, for example, that the widely differing structures of the Archaean and Proterozoic terranes of Western and Northern Australia, and the Palaeozoic South-east can be plausibly explained by variations of the depth at which the conductive geotherm meets a common mantle adiabat (Fig. 2). The inference in both oceanic and continental regions is that most of the lateral variability of wave speeds (and attenuation) is of thermal origin (Faul and Jackson, *Earth Planet. Sci. Lett.,* in press).

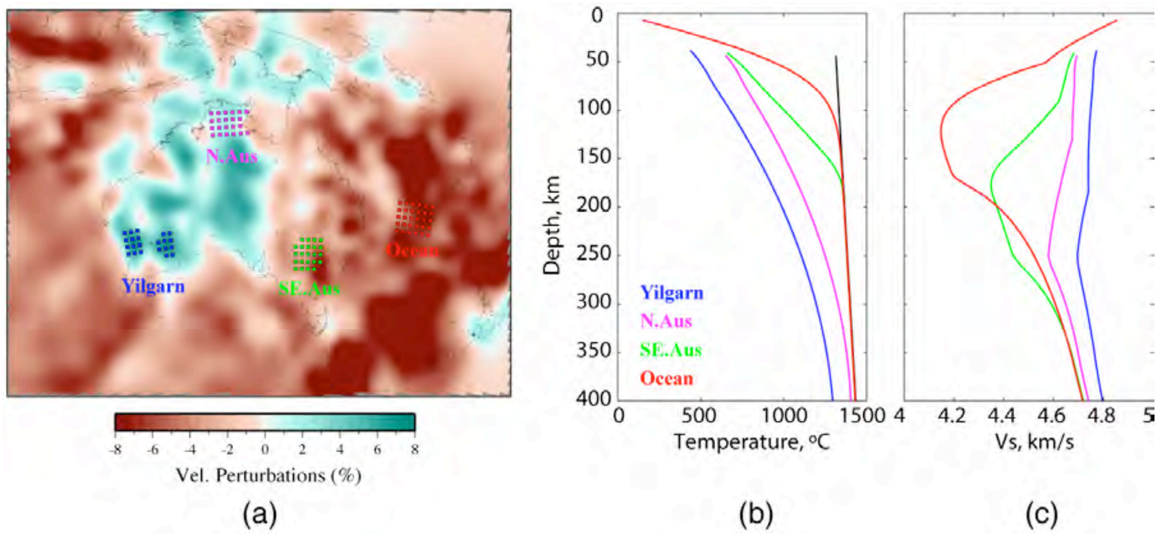


Figure 2. (a) A slice at 200 km depth through the model of Fishwick et al. (EPSL, in press 2005). The squares indicate the locations at which geotherms (b) and corresponding shear velocities (c) are calculated

Coupling Between Fluid Flow, Deformation Processes and Reaction

Experimental, field-based, microstructural and numerical modelling approaches are being used to explore several aspects of coupling between deformation processes, fluid transport, reactions and the strength of earth materials in crustal environments.

Experimental studies have focussed on measuring changes in permeability of simulated fault gouges and cracked granitic materials in hydrothermally-active, isostatic stress regimes, as well as during deformation. In high temperature hydrothermal regimes, the permeability evolution of quartz gouges is found to be strongly dependent on the flow regime and grainsize of the materials. Flow of quartz-undersaturated fluid though the gouge is associated with much more rapid permeability reduction than is the case for a no flow regime. In cracked granite, permeability evolution in the presence of high temperature pore water is sensitive to competition between rates of growth of crack dilatancy and rates of by pore clogging due to growth of micas during hydrothermal breakdown of feldspar. The results have implications for understanding flow in fault zones, ore-producing hydrothermal systems, and in utilisation of geothermal energy resources.

Both *field-based and numerical modelling studies* are being used to further test our new model that mesothermal lode gold systems can develop in faults and related fracture arrays that are repeatedly reactivated during aftershocks following major slip events on nearby crustal-scale faults. New field and modelling case studies, in several well-explored areas in the Eastern Goldfields province of WA, have provided further support for the concept that co-seismic static stress changes associated with mainshocks and large aftershocks on high displacement faults provide a first order control on the distribution of gold deposits in fault systems.

Field-based studies are also using LA-ICPMS trace element studies of vein systems to explore evolution of fluid chemistry and growth of fracture-controlled fluid pathways during upper crustal. Cyclic changes in REE concentrations in vein calcite correlate with individual crack-seal events, and are interpreted as being related to episodic migration of fresh batches of pressurised fluid through the fault/fracture system in response to fault failure events. The work highlights the potential role of migrating pore pressure waves in driving repeated fault slip events and the growth of fracture controlled percolation networks.

Permeability evolution in fault gouges under hydrothermal conditions

Silvio Giger, Stephen Cox and Eric Tenthorey

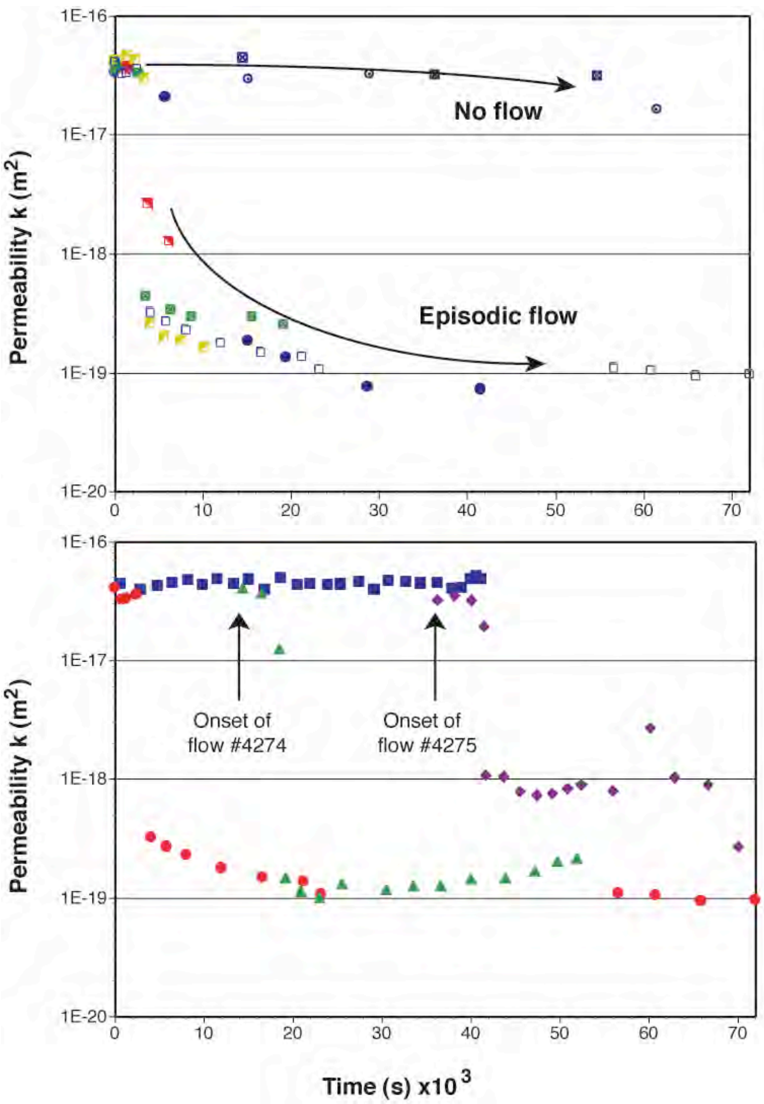
The evolution of permeability (*k*) and porosity (Φ) during rock deformation is of fundamental importance in understanding fluid transport through rocks. In particular, the time evolution of permeability and fluid pressures in active fault zones leads to shear strength being time-dependent, rather than constant, during the seismic cycle. This can play a critical role in controlling rupture nucleation and recurrence.

At depths of 10 –20 km in the normally low permeability continental crust, seismogenic faulting generates permeability, disrupts fluid pressure states, and drives transient redistribution of crustal fluids during and immediately after rupture. In hydrothermally active environments, compaction of fault wear products (gouge), and healing and sealing of fractures, then gradually reduce fault permeability in the interseismic interval. The time-dependence of permeability and thus fluid pressure evolution in fault systems accordingly plays a critical role in governing fault behaviour. In this study, we are exploring the time-dependence of permeability in artificial quartz fault gouges in high temperature, high pressure, hydrothermally active environments. The results will allow us to develop quantitative models of the effects of fluids in driving earthquake nucleation and recurrence.

We have examined the evolution of permeability during simulated interseismic fault healing using hot isostatic pressing (HIP) experiments at temperatures up to 1200K, confining pressures to 250 MPa, and pore water pressures of 150 MPa. To test grain size effects on the compaction process we used fine

(≤37µm), coarse (20-250µm) and intermediate (5-250µm) grainsize quartz powders. We performed two different types of experiments: (1) HIPing the sample for a given time and measuring permeability only at the end of the HIP (i.e. *no fluid flow* during compaction), and (2) HIPing with permeability measurements at many stages during compaction (i.e. *episodic flow*).

The initial *k* of all samples is of the order of $4 \times 10^{-17} m^2$. The *no flow* experiments for all grainsize groups exhibited a *k*-decrease of less than 50% over 2 days (Fig.). Similar results were obtained during HIPping of the coarse gouge during episodic flow. However, during the *episodic flow* experiments on the fine and intermediate grainsize gouges, and initial period of slow permeability decrease in the first hour or so was followed by *k*-decrease of up to two magnitudes within less than 20 minutes. This sudden drop in *k* is followed by a further reduction at much slower rate, ultimately reaching a value around $10^{-19} m^2$ after about 10 hours.



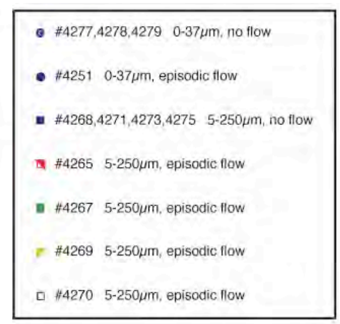
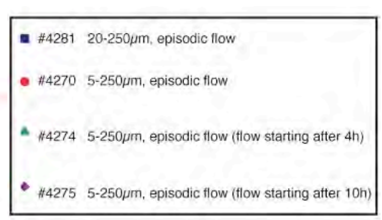


Fig. *Top* No flow vs. episodic flow experiments. Note the dramatic *k*-decrease of two orders of magnitude as an effect of flow.
Bottom Fast *k*-decresae is also predominant even after previous HIPing for several hours. No *k*-decrease is detectable for coarser grained samples



Finally, to test the history-dependence of the fast *k*-drop, we performed experiments in which a *no flow* period was followed by *episodic flow*. HIPing without flow prior to episodic flow had no significant influence on the rate of *k*-decrease once flow started.

Our experiments demonstrate that *k* evolution in grain aggregates can be influenced markedly by fluid flow regimes. Especially at fine grainsizes, flow of silica undersaturated fluid through the gouge drives dissolution-controlled compaction at rates much faster than in the presence of stationary fluid. Accordingly, the time required for faults to shut-off fluid flow following rupture events will be strongly dependent on levels of saturation in the fluid, and also on flow rates. This has implications for rates of post-seismic fluid pressure recovery and rupture recurrence in active fault systems.

Reaction-induced permeability change in thermally cracked and deformed aplite: Importance of reactive surface area and mineralogy.

Eric Tenthorey and John Fitz Gerald

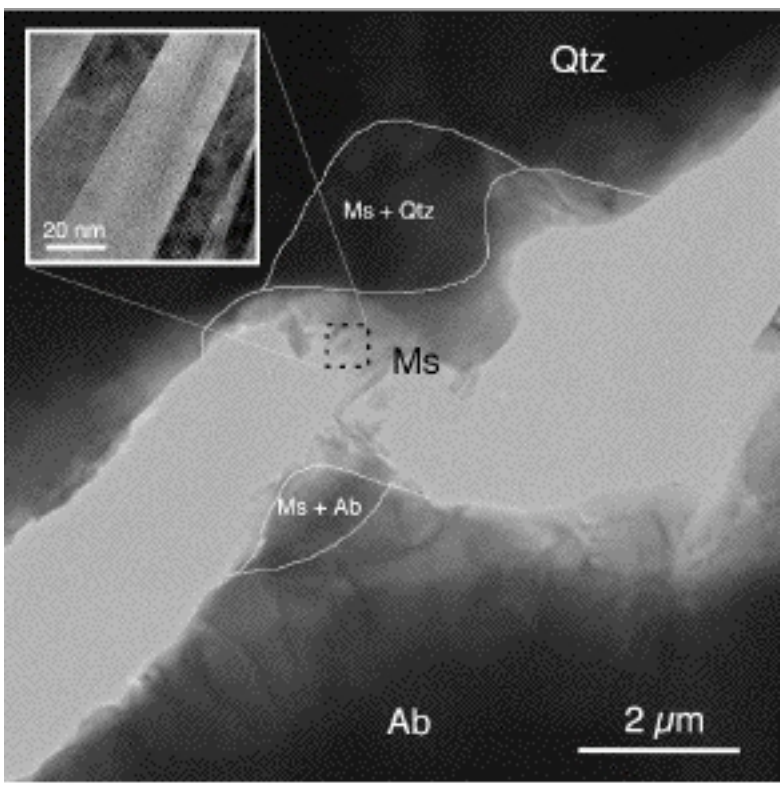


Figure 1. TEM micrograph showing muscovite laths precipitating on primary quartz and albite grains. In the centre of the photo, muscovite actually bridges

the gap between thermally cracked grains, elucidating the mechanism by which permeability reduction occurs.

This experimental program investigates hydrothermal reactions in a granitic system and attempts to quantify how such reactions affect hydrologic properties, namely specimen permeability. Understanding the long-term permeability evolution of rocks is crucial in current times, where environment and the idea of sustainable development are of paramount importance. Geothermal energy, disposal of radionuclides and sequestration of greenhouse gases are all closely reliant on the long-term physics of fluid flow in the Earth. Of specific interest here is the evolution of permeability under variable differential stress conditions, from the compactional and dilatancy regimes to that of shear failure. Under these different stress conditions, reactive surface area will vary, possibly affecting the rate and absolute magnitude of permeability change.

The experiments were conducted using a Paterson gas apparatus capable of independently controlling confining pressure (Pc), pore pressure (Pp) and axial load. Most experiments were conducted at Pc=100 MPa and Pp=50 MPa with temperatures of 200-600°C. Following the initial thermal cracking and permeability increase due to the application of temperature, specimens exhibited a gradual permeability reduction during hydrothermal reaction. We find that permeability decays by an exponential function of the form:

$$k \propto 1-\mu(1-e^{(-rt)})^2$$

suggesting a precipitation type mechanism for the observed permeability change. Microstructural analysis of the post-experiment specimens reveals precipitation of muscovite on primary minerals (see figure).

Permeability was also found to decrease with time when deformed and held either in the compactional, dilatant or shear failure regimes. Overall, the reaction rate constant (r) was enhanced during dilatancy and after rupture, an observation suggesting a negative feedback effect, in which enhanced mineral precipitation moderates permeability generation during episodes of deformation.

As stated above, understanding and quantifying hydrologic behaviour in high temperature granitic systems is of paramount importance to a number of earth science disciplines. In particular, the results presented have important implications for precipitation-induced sealing in granitic fault zones, where hydrologic changes might alter various physical properties of the fault.

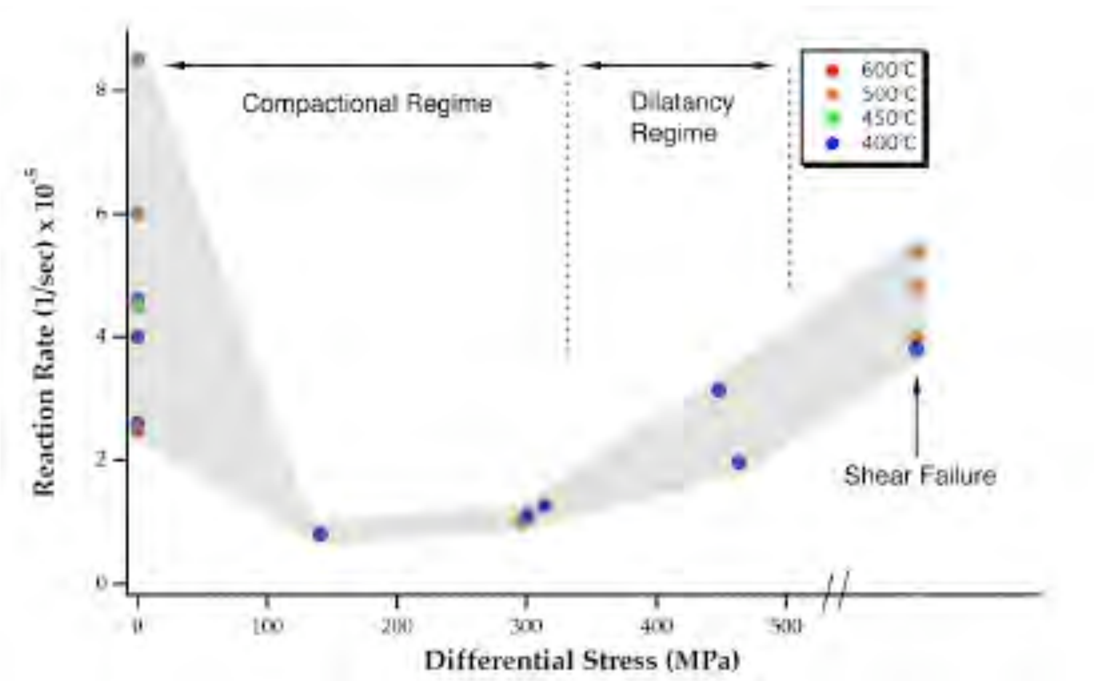


Figure 2. Reaction rate constant (r) plotted against differential stress. The rate constant describes the transient change in permeability as a new chemical equilibrium is attained. The rate is greatest during the dilatant and shear failure regimes, when the mineral surface area is greatest.

Fault-slip, fluid flow and Stress Transfer Modelling for mineral exploration in ancient fault-related gold systems

Steve Micklethwaite and Stephen Cox

Determining where large earthquakes and aftershocks repeatedly developed within ancient mineralised fault systems is proving to be a powerful tool for mineral exploration. The permeability evolution, fluid pathways, and distribution of mineral deposits in fault-controlled hydrothermal systems is dependent on co-seismic permeability enhancement and interseismic fault sealing. Accordingly, exploring what factors influence where the highest permeabilities develop within active fault systems is providing insights about the controls on distribution of mineral deposits in gold-producing regions such as Archaean greenstone-gold provinces.

Stress Transfer Modelling (STM) is an exciting new technology that emerged from earthquake hazard prediction, and is now proving to be a successful tool in mineral exploration. In response to an earthquake on a major fault, the rock volume around the rupture undergoes changes in stress. Those regions where stress states are brought nearer to failure are closely associated with aftershocks or triggered creep on smaller faults. Aftershock networks seem to be particularly important in controlling post-seismic redistribution of hydrothermal fluids in crustal-scale fault systems. The distribution of regions with enhanced aftershock potential can be predicted using STM. In our research, we have applied STM and shown, for the first time, that certain Yilgarn mesothermal goldfields occur where aftershocks and/or creep are predicted to have been triggered by rupture events on nearby crustal-scale faults in the past. STM is able to match distributions of brownfield gold deposits, identify new potential target areas and identify the regional structures responsible for mineralisation. We are able to explain why mineral deposits tend to be hosted by low-displacement faults adjacent to large-displacement regional faults, and why mineral deposits occur in clusters. The ST models also explain why some goldfields occur adjacent to contractional and dilational jogs in the regional fault system and why they are in a range of rock types.

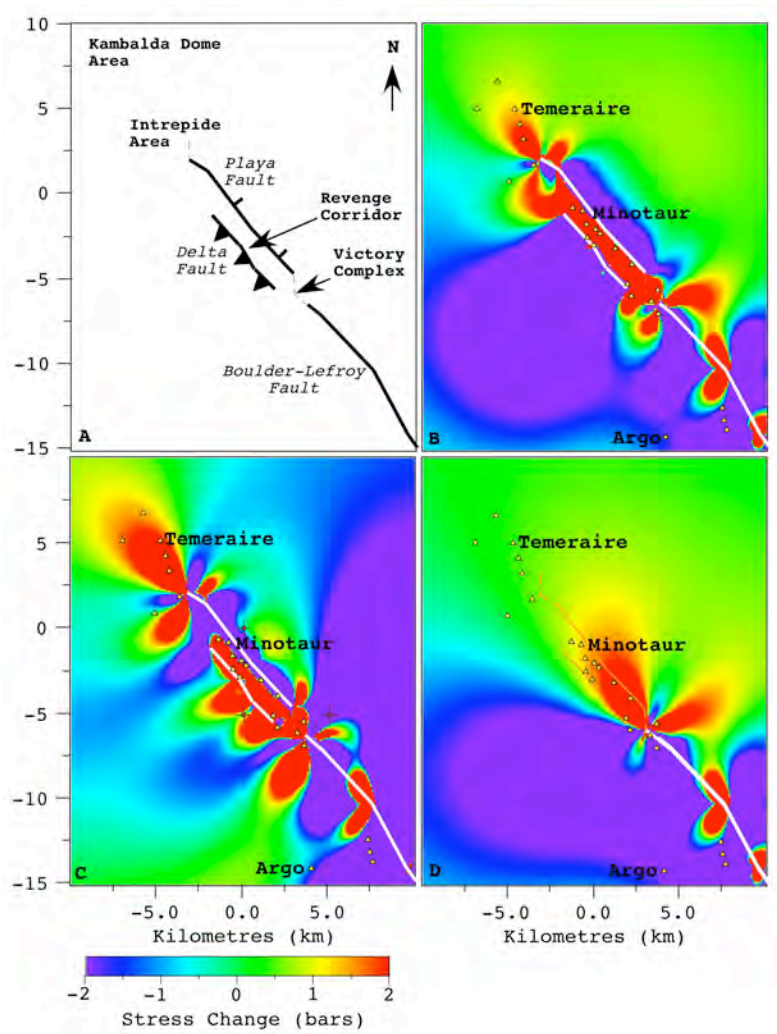


Fig. STM results from the well-constrained St Ives goldfield. (a) Simplified fault map of the modelled area. The Boulder-Lefroy fault is the major first-order driving structure. The Delta and Playa faults are poorly mineralised second-order faults in the goldfield, which are likely to have been triggered following ruptures on the Boulder-Lefroy fault. Mineralisation in the Revenge to Victory area is mainly on reverse faults, but in the Intrepide area it is mainly on strike-slip faults. (b)-(c) Zones of positive stress change for optimally oriented reverse and strike-slip faults respectively. Triangles are deposit locations, which are closely matched by the zones of predicted triggered slip. (d) Model result if the triggering of the Delta and Playa faults is not accounted for, highlighting the improved predictability of STM, if second-order fault slip is modelled.

In 2004 we further tested the application of STM in a number of well-explored brownfield and under-explored brownfield case studies. A major advance was made in the well-explored brownfield areas, where a good knowledge of fault architecture exists. We found that one or two large aftershocks, on second-order faults, can substantially modify the main shock-induced static stress changes. When we account for this behaviour, there is a precise correlation between the distribution of mineralisation on minor faults in the goldfield and modelled co-seismic stress transfer. Application of STM in the two poorly explored brownfield case studies proved useful for identifying which regional structures were important for controlling the distribution of mineralisation, and defining large, goldfield-scale exploration targets.

Links between folding, faulting and fracture-controlled fluid flow – an example from the Lower Devonian Murrumbidgee Group, New South Wales

Shaun Barker and Stephen Cox

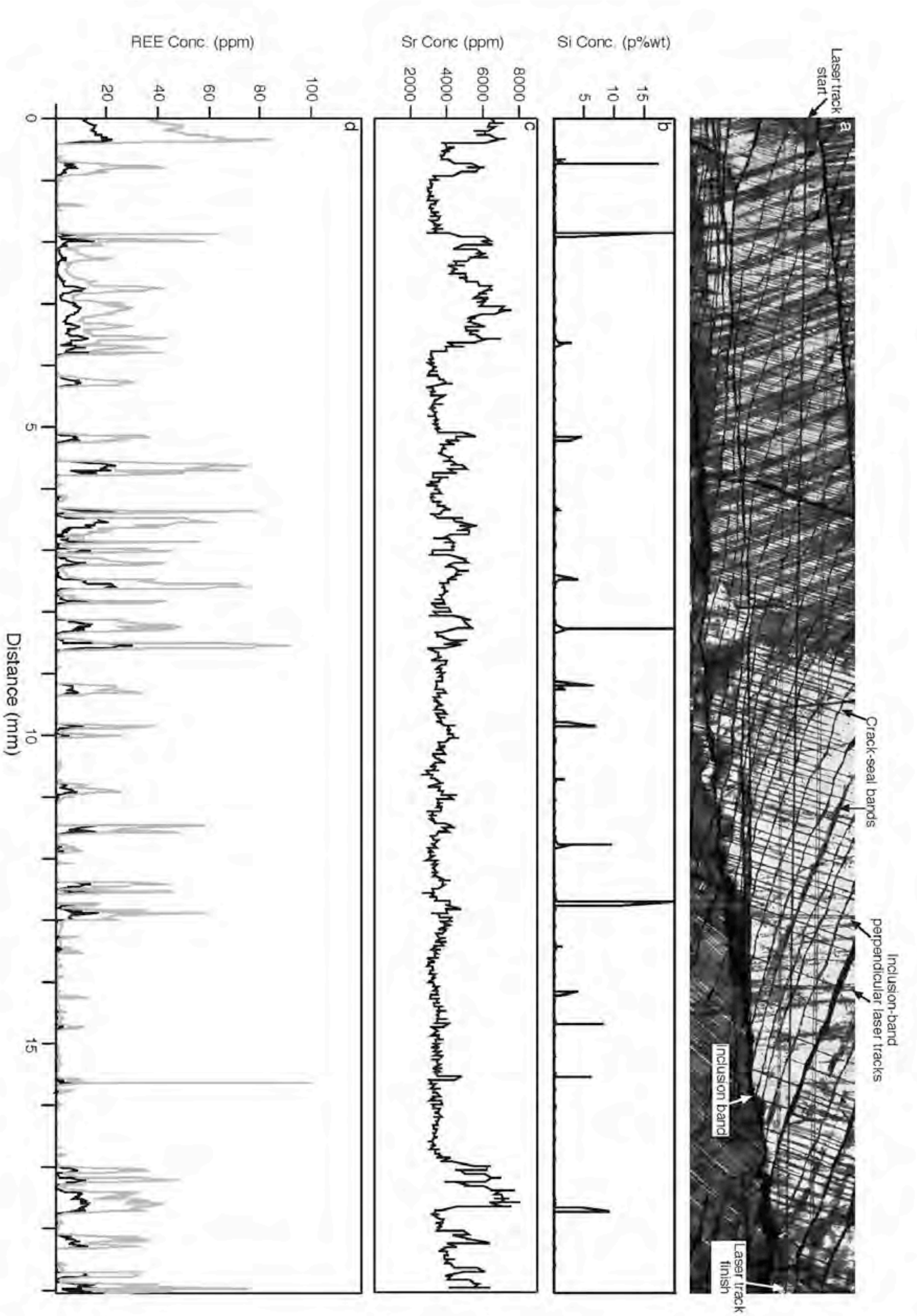
Coupling between deformation processes, fluid flow and fluid pressure states plays a key role in driving the growth of fluid pathways in hydrothermal systems, and also influences the evolution of the strength and mechanical behaviour of the crust. Exhumed vein systems contain a record of where fluid flow was localised, how flow has influenced the mechanical behaviour of the crust, and the nature of chemical fluid-rock interactions along pathways. We are combining field-based structural studies, microstructural and microchemical analysis, stable isotope studies, and fluid inclusion analysis to (1) explore the dynamics of the structural and geochemical evolution of a fracture-controlled hydrothermal system, and (2) examine the role of fluid pressures in driving deformation processes and growth of a fracture-controlled percolation network during folding and faulting in an upper crustal regime. Field studies are focusing on a one kilometre thick, upright folded, Lower Devonian carbonate sequence (Murrumbidgee Group) in the Taemas area of the Lachlan Fold Belt (south-eastern Australia).

Fluid flow during deformation of the Murrumbidgee Group was localised along fold-related and fault-related, high permeability fracture networks, and was associated with widespread development of calcite-quartz veins. Our previous stable isotope studies indicate that systematic vertical changes in O-isotope compositions of veins in the carbonate sequence are related to upwards migration of externally-derived , low $\partial^{18}O$ fluids across the base of the sequence, combined with kinetically-controlled oxygen isotope exchange during reaction with the host rocks along the structurally-controlled fluid pathways.

Major vein types at Taemas include (1) extension veins associated with stretching of fold limbs (dominantly in massive limestone), (2) fault-fill veins and associated extension vein arrays in low displacement, bedding-discordant reverse faults, and (3) bedding-parallel veins associated with flexural slip during fold growth (present in both shale and limestone units). Folding, faulting and veining are closely related. Many low displacement faults are accommodation structures formed during fold growth. Internal textures in many veins indicate growth involved cyclic failure and fracture sealing events (crack-seal), with some centimetre-scale veins recording up to hundreds of crack-seal growth increments.

Analyses of whole calcite veins reveal that the stable isotope composition is generally related to the trace element composition. Calcite veins with fluid-buffered oxygen isotope compositions generally have lower REE concentrations than samples with rock-buffered oxygen isotope compositions. Microscale analyses of bedding-parallel and fibrous calcite, by laser ablation ICPMS, demonstrate variations in trace element and REE concentrations of 100's to 1000's of ppm over distances of < 500 µm. Peak REE concentrations are spatially associated with crack-seal bands (Fig. 1). Regions of high REE concentration probably form due to preferential incorporation of REE into calcite by fractional crystallisation from small fluid batches early during each fracture sealing event, whereas calcite deposited late in the sealing cycle is relatively REE depleted.

These results provide some of the first geochemical evidence to support earlier theoretical arguments that crack-seal events and fault slip events, can be driven by episodic migration of fluid pressure pulses through fault/fracture networks. The geochemical results indicate that each pulse of fluid migration supplied a new batch of fluid which was enriched in REE relative to REE-depleted fluid left over from the previous pulse of fluid migration.



Laser track start
Crack-seal bands
Inclusion-band perpendicular laser tracks
Inclusion band
Laser track finish
Si Conc. (p%wt)
Sr Conc (ppm)
REE Conc. (ppm)
Distance (mm)
a
b
c
d

Figure 1:

(a) Photomicrograph showing the microstructure of the bedding-parallel vein analysed in this study. Note inclusion bands, and multiple crack-seal bands at approximately 25 degrees to inclusion bands. The start and finish of the laser ablation traverses on this specimen are marked (both inclusion band parallel and perpendicular traverses). Photomicrograph is approximately 20 mm wide. Note that the photomicrograph and distance versus concentration graphs (Figures 2b to 2d) are approximately the same scale.\\
(b) Distance versus silica concentration %wt. Peaks represent the locations of c rack-seal bands.
(c) Distance versus Sr concentration (ppm). Note that sudden change in Sr concentration across 2 crack-seal bands at about 2 mm and 4 mm.\\
(d) Distance versus La (black line) and Ce (grey line) concentrations (ppm). Rare-earth element peak concentrations are typically slightly offset from inclusion bands.

STRUCTURE TECTONICS, EARTH MATERIALS

The Structure/Tectonics group at RSES is led by Professor Gordon Lister. It comprises one Research Fellow (Dr Marnie Forster, APD awarded 2004) and two Post-Doctoral researchers (Dr Justin Freeman, PhD awarded 2004, and Mr Simon Richards, PhD submitted, 2004). Dr Joe Kurtz joined the group during 2004 as a Scientific Programmer. During 2004 there were five PhD students in the group (Marco Beltrando, Meghan Miller, and David Wood continuing their studies; Katie Bishop and Anthony Reed joining the group mid-year). Virginia Toy completed her MPhil during 2004, and submitted her thesis for examination. Four Honours students were supervised in conjunction with the department of Earth and Marine Sciences (Katie Bishop, John Clulow, Courtney Gregory and Anthony Reed), and these have now completed. Daniel Viete was a Research Intern. Lidena Carr joined the group as Research Assistant.

The group is closely associated with the 40Ar/39Ar geochronological facility directed by Dr Jim Dunlap, and much of our research is linked to that facility. There are also strong (continuing) interactions with Earth Physics (involving 3D interpretation of tomographic images, and in terms of the study of slab dynamics, with Professor Brian Kennett, and Dr Wouter Schellart). The group also closely interacts with Earth Chemistry, in respect to the use of SHRIMP for analysis of monazite inclusions and metamorphic rims on zircons, allowing us to time processes inferred from field studies.

Our major external interactions are with GEMOC at Macquarie University (with Professor Suzanne O'Reilly and Dr Bill Griffin), the Australian Crustal Research Centre at Monash University (with Dr Peter Betts, and Dr David Giles, with whom an ARC Linkage Grant is being conducted, with BHPBilliton), AngloGoldAshanti Australia supporting a project in central Queensland, and the DeBeers group, supporting research into the tectonic controls on kimberlite emplacement.

In 2004 the Structure/Tectonics group established a Data Visualization Facility (running gOcad and ERmapper) and a Fabric and Microstructure Optical Microscopy Laboratory (with a range of different microscopes and high-resolution digital photographic equipment). The group also operates a Toyota Landcruiser (for outback fieldwork), satellite phones and GPS equipment.

The techniques adopted by the group for its research include: fieldwork (in orogenic belts both within Australia, and overseas), fabric and microstructural analysis ("reading rocks" to ascertain their history of deformation and metamorphism), geochronology (to time deformation and metamorphic events), geophysical data analysis (to plumb the depths for large-scale crustal- and lithospheric-structure), 3D data visualization (to allow structures to be viewed in context, in perspective, and their geometry to be analysed) and numerical simulation (to move towards a geodynamic understanding of large-scale tectonic processes).

There are five interwoven threads amongst the research carried out by the Structure/Tectonics group:

- The Nature of Orogenesis – studies in the Alpine-Himalayan chain
- Planetary-scale Reconstruction – focussed on evolving slab geometries
- Slab Dynamics – using software developed by the ACcESS MNRF
- Geochronology – timing deformation and metamorphic events
- Tectonics and Deep Earth Resources – focussed on gold and diamonds

The key aspect that binds these diverse research themes together is the desire to develop a fundamental understanding of the processes of orogenesis, on the planetary-scale and to determine how these affect the development of energy and mineral resources.

The nature of orogenesis Research focussed on the evolution of the Alpine-Himalayan orogenic belt. Two ARC Discovery projects have been funded that enable this aspect: "Revisiting the Alpine paradigm: the role of inversion cycles in the evolution of the European Alps" (Lister, Dunlap, Forster) and "Tectonic reconstruction of the evolution of the Alpine-Himalayan orogenic chain" (Lister, Harrison). Fieldwork in the classic natural laboratory offered by the European Alps is facilitated by the ready access and vast amount of previous detailed research. Tectonic reconstruction, focussed on the planetary-scale aspect, offers a more regional perspective and provides the overview that allows ready explanation of seemingly complex local variations.

The major result reported during 2004 came from the study of the ultra-high-pressure locality at Lago di Cignana, Val Tournenche, Italy (led by Australian Postdoctoral Fellow Marnie Forster, see Forster et al. 2004). This research has shown that tectonic slices (Figure 1) can be shuffled (even on a crustal-scale) in either of two ways: Mode I involving repeated use of the same movement zones; Mode II involving a vergence change, so that previously extended crust can be thrown into crustal-scale cascades of recumbent folds. Individual shuffles may involve relative movements in excess of 200km. Rocks from ~100km depth are exposed in the "tectonic shuffle zone" studied.

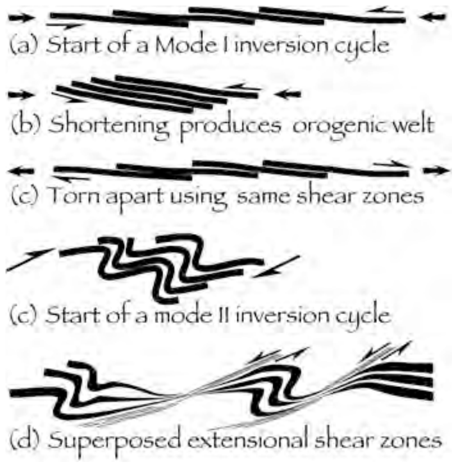


Figure 1. Mode I tectonic mode switches repeatedly juxtapose the same stack of 'nappes' producing a thinly-sliced tectono-metamorphic stratigraphy. The next cycle of shortening (prior to an accretion event) involves a vergence change, so the extended crust is thrown into orogen-scale cascades of recumbent folds. Extension reinitiates (once accretion has taken place) and newly formed extensional shear zones dissect the recumbent fold stack.

The tectonic shuffle zone that has been recognized at Lago di Cignana potentially has a very large areal extent (possibly on the scale of the entire European Alps). Research continues apace tracking this shuffle zone to determine its lateral extent (involving PhD student Beltrando).

The key observation that can be made in any one locality is that there will be a plethora of superimposed faults and ductile shear zones, with a fundamental shuffling of 'exotic' tectonic slices between (Figure 2).

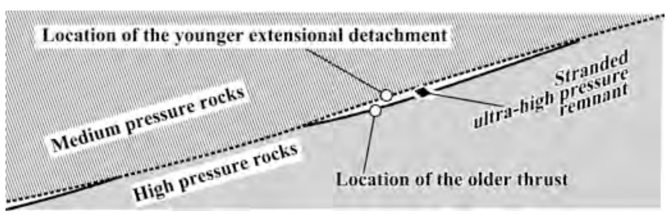
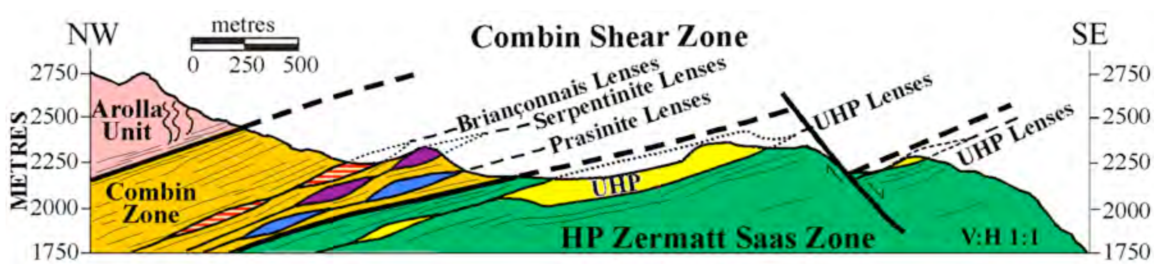


Figure 2. The geometry that leads to a tectonic "shuffle" zone, stranding thin UHP lenses.

Essentially this geometry results because the trajectory of older thrusts is not precisely followed by younger extensional structures, so that remnant higher pressure slices can be stranded. This mechanism provides an explanation for the occurrence of thin-slices of high-pressure rocks between lower-pressure footwall and hanging wall, as observed (Figure 3).



It appears that "tectonic shuffle zones" may be of considerable importance to the orogenic process, and tectonic mode switches associated with this phenomenon may produce pervasive signals though the rock mass, which will be reflected at the microstructural scale. FΔSZ sequences may result.

Therefore, during 2004, PhD student Bishop commenced a PhD on the island of Sifnos, with the intent of elucidating the timing and significance of FΔSZ sequences that have been recognized there, where F denotes a period of recumbent folding, Δ denotes a mineral growth (usually in the form of large overgrowing crystals termed porphyroblasts), and SZ denotes an episode of shear zone formation (in this case usually extensional in character).

Planetary-scale reconstruction The focus initially was to revise major plate motions during the past 150 million years. There have been a number of incremental advances, and when summed, this data points to some significant aspects. For example MPhil candidate Toy (completed during 2005) was able to demonstrate that "slowing" of the advance of India prior to the onset of collision with Asia commenced much earlier than previously considered (at ~65 Ma) (Figure 4).

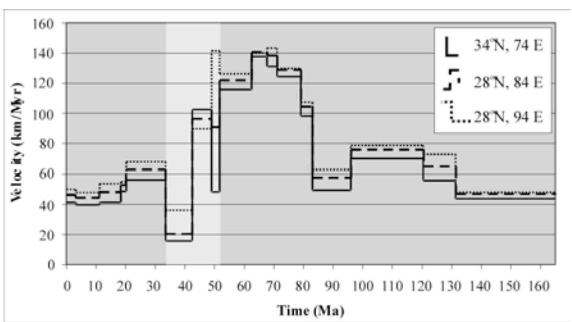


Figure 4 (from Toy, MPhil 2005) shows the advance of India with respect to Asia using the three points shown. From ~70-65 Ma the motion of India begins to slow, with a dramatic decrease from ~45-35 Ma.

Research intern Mr Daniel Viete compiled an extensive database of isochron and rotation pole data, providing a resource for future tectonic reconstruction projects.

The next step is the determination of 3D lithospheric slab geometries, including the identification of possible tears, folds etc. The inferred motions in these zones are of immediate interest, particularly if we are able to reconcile these with the relative movements of the larger plates. Figure 5 shows an accentuated topography (data from NOAA http://ibis.grdl.noaa.gov/) and earthquake hypocentres from the EHB catalogue (after Engdahl, E.R., Van der Hilst, R.D. and Buland, R.P. 1998. *Bull. Seismol. Soc. Amer.* **88**, 722-743). Flow of the material in the over-riding plate may have caused the arc shaped geometries, with movement almost orthogonal to the relative movement of the Indo-Australian plate.

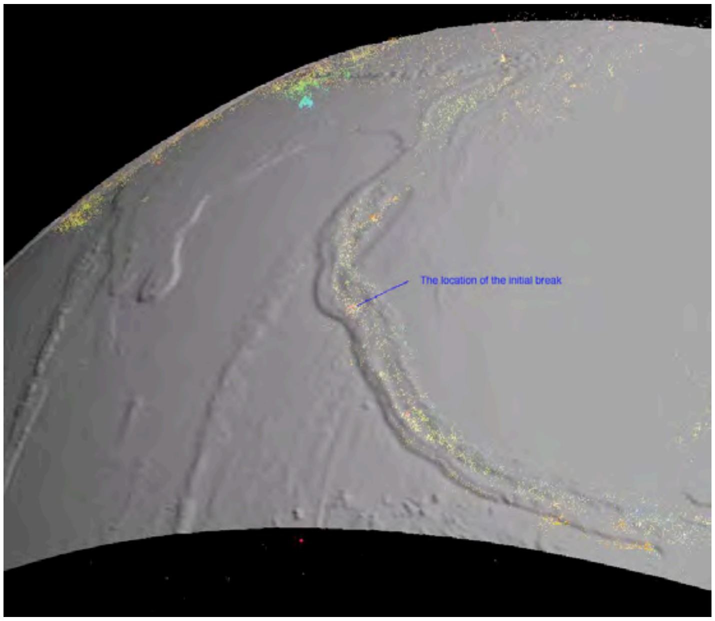


Figure 5. This image was made using the gOcad software. It shows the initial break that triggered the devastating 2004 Sumatran earthquake, at the cusp between the North Sumatran arc to the north, and the Indonesian arc to the south. Further north are the North Andaman Sea arc, and the Burma arc. The Burma arc meets the eastern syntaxis of the Himalaya.

The task of building planetary reconstructions in 3D is complicated – in particular if we aim to include the effects of tearing, folding and stretching lithospheric slabs as they subduct. To this end software development has been undertaken in collaboration with the ACcESS MNRF (the Australian Computational Earth Systems Simulator) based at the University of Queensland. Professor Lister was appointed a "Director-at-Large" within the MNRF, and during 2004 ANU was invited to join in the construction of this facility. The "Tectonics and Geodynamics" project will be the vehicle for the ANU contribution which will include continued development of the Pplates software.

Pplates manipulates clouds of 'mass points' which can be extracted from reconstructed virtual worlds developed for a particular time. Figure 6 shows the 'automatic' generation of mass points in the Southern Ocean in the past 135 Ma as Australia drifted northwards from Antarctica. Each mass point represents a volume of oceanic crust, and it travels with its accumulated history recording increasing submergence, for example, as the lithosphere cools. This will enable automatic generation of hypsometric data for example, allowing prediction of the variation in water depth due to the change in the age of the ocean floor.

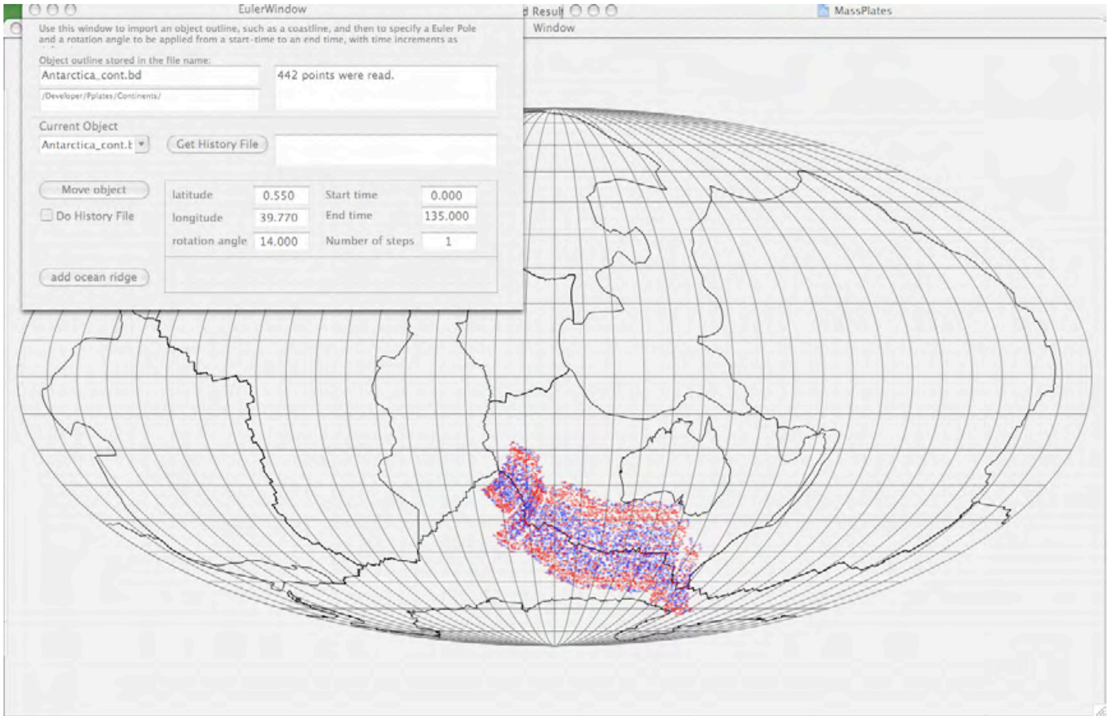
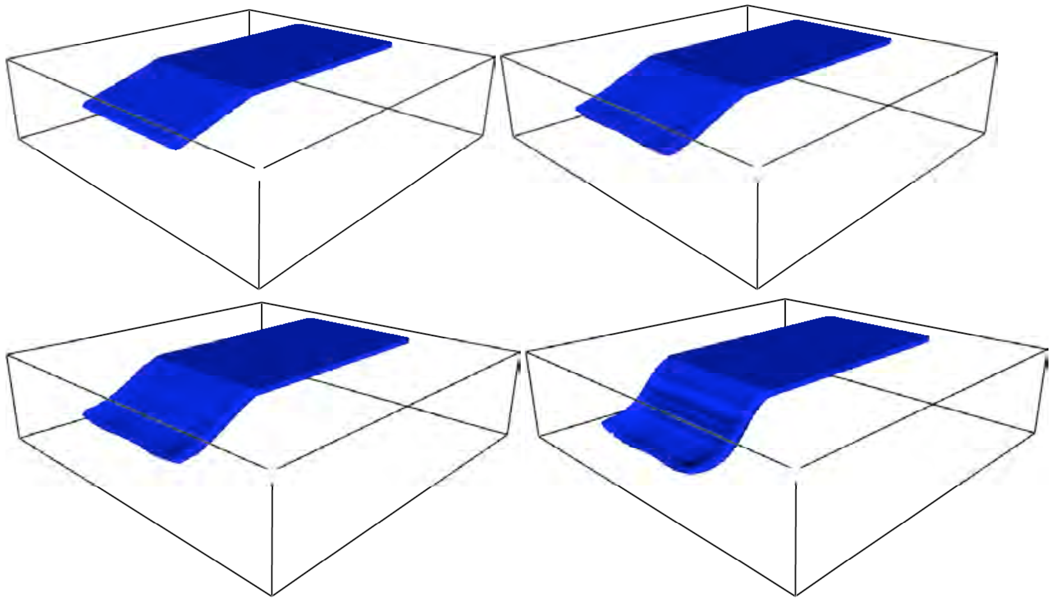


Figure 6 An image prdocued using the Pplates software, developed under the auspices of the ACcESS MNRF. 'Automatic' generation of the sea floor of the Southern Ocean as Australia drifts northward from Antarctica. The age of the ocean floor determines its magnetic polarisation (shown here as red or blue.

Slab dynamics This part of the research program is aimed at developing an understanding of the mechanics of slab roll-back, and how slabs tear in the process, or as a pre-cursor to "roll-back" events. Post-doctoral Research Fellow Dr Justin Freeman is investigating this aspect in 3D, using software developed by the ACcESS MNRF (http://www.access.edu.au/), in collaboration with Dr Wouter Schellart, from the Earth Physics Geophysical Fluid Dynamics laboratory and Dr David Stegman from Monash Cluster Computing at Monash University.

The kinematics of subduction and its influence on mantle convection and plate-scale deformation have been the focus of numerous geodynamic studies, but most of these have considered only two-dimensional aspects of subduction dynamics by incorporating the assumption that subduction zones are infinite in trench-parallel extent. Natural subduction zones are intrinsically three-dimensional, however, due in part to their limited lateral extent. Lateral length scales of natural subduction zones vary from only a few hundred kilometres (e.g. the Calabrian, Hellenic and Scotia slabs) to several thousand kilometres (e.g. the Aleutian, Indonesian, Northwest Pacific and South American slabs).

Figure 7 shows numerical simulations of a 3D subducting lithospheric slab carried out by Post-Doctoral Research Fellow Dr Justin Freeman.



This study is being conducted by systematically varying parameters, so that a ‘phenomenon space’ can be constructed. This allows us to develop some understanding of the types of effects different variables are likely to allow, For example, roll-back of the hinges of subducting slabs begins to take place once visco-plastic rheologies are introduced (Figure 8). These rheologies allow stress to be transmitted horizontally through the slab

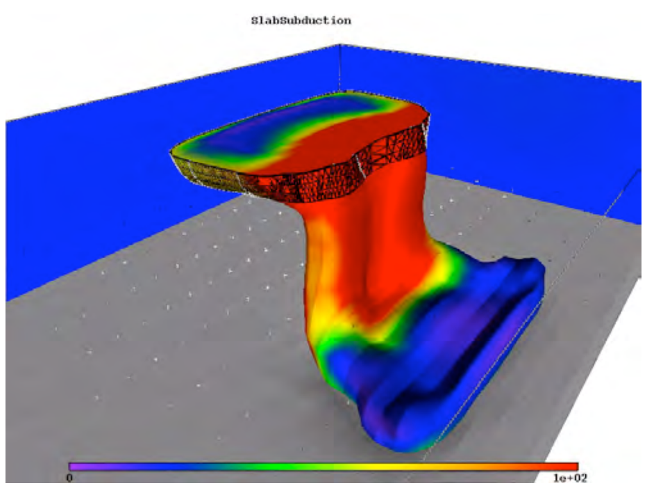
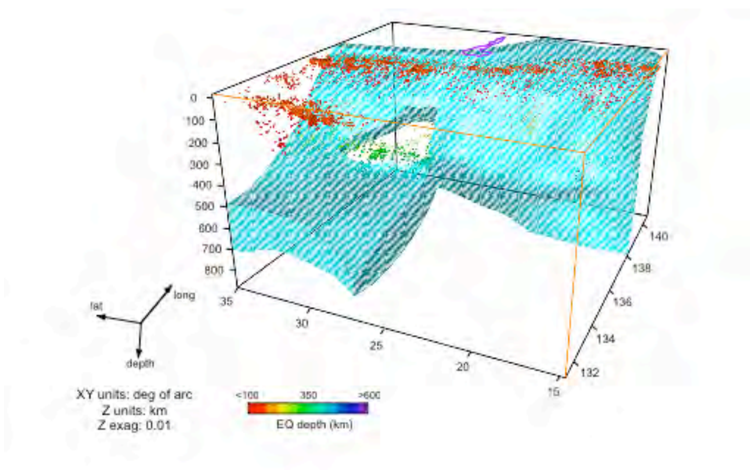


Figure 8 shows a numerical simulation of a subducting lithospheric slab with a visco-plastic rheology. This single factor appears to cause roll-back of the hinge of the subducting slab.

PhD candidate Meghan Miller (in collaboration with Professor Brian Kennett) investigated heterogeneity within the subducting Pacific slab beneath the Izu-Bonin-Mariana arc, building a 3D model using complementing regional bulk sound, shear wavespeed, and P-wave tomographic images. The distribution of seismic anomalies has been used to elucidate a distinct change between the slab beneath the Izu-Bonin and the Mariana arc (Figure 9).

Figure 9. Interpreted morphology and geometry of the subducting Pacific slab beneath the Izu-Bonin arc from P-wave tomography data. The 'hole' illustrates the region where the change in seismic property or "tear" occurs in the P-wave model. The earthquakes acquired from the NEIC catalogue for events from 1967-1995 illustrate a cluster positioned within the anomalous region. The position of the Ogasawara Plateau is depicted in purple.



Changes in physical properties within the slab tear at the southern end of the Izu-Bonin arc, identified as a "gap or thinning" in the tomographic images, could be the result of the distortion of the Pacific plate as its shape transforms between near horizontal to near vertical, a decrease in the rigidity and strength of the lithosphere, the subduction of the Ogasawara Plateau, change in subduction velocity, or a combination of all these factors. A strong, slow anomaly in the mantle wedge between 25-33°N, in contrast to the tear, appears to be a low viscosity region.

Deep Earth Resources This part of the research program is aimed at developing an understanding of the tectonic controls on the formation and location of mineral and energy deposits, exploring the hypotheses that address the ultimate causes of resource accumulation, with attention to the details that determine source fertility, and the traps that temporarily hold the accumulated wealth.

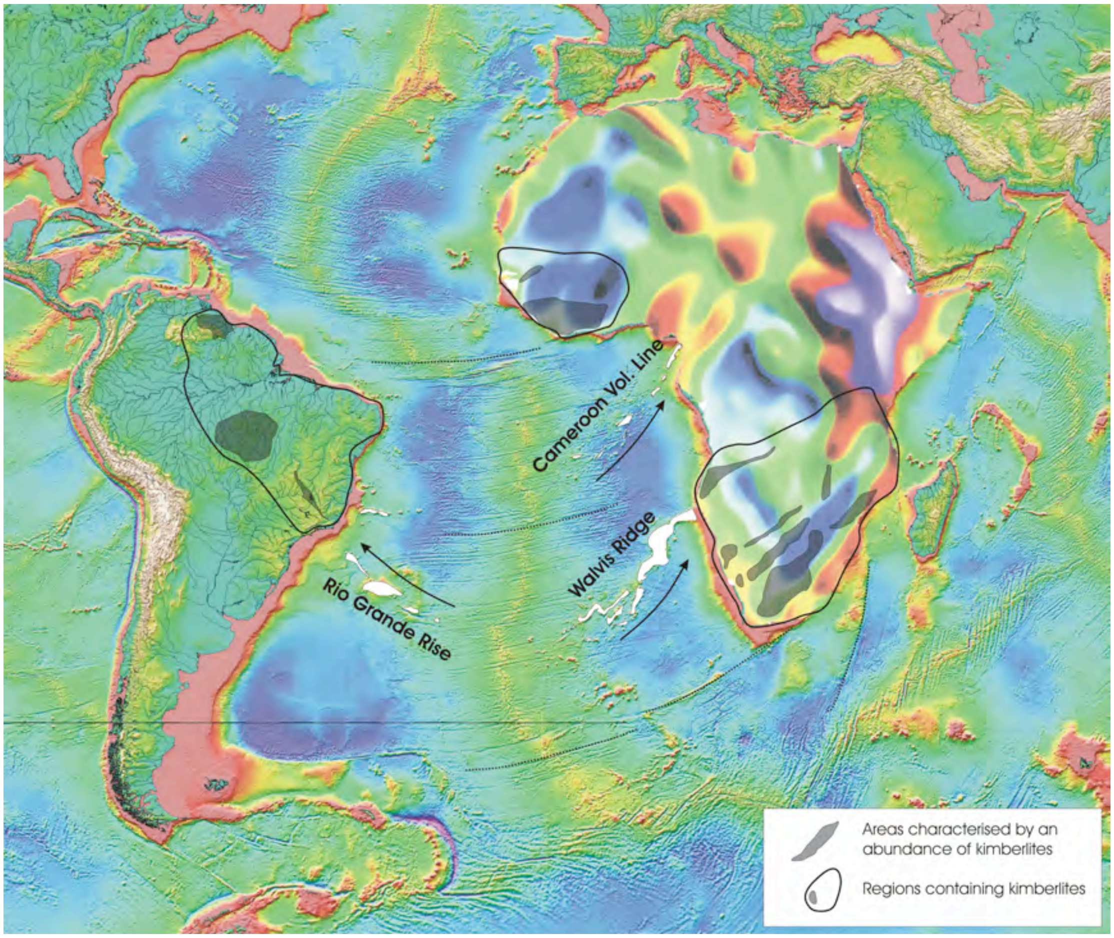


Figure 10 Spatial (as well as temporal) trends in the distribution of kimberlite pipes relate to the orientation of transfer faults during continental extension during the early stages of Gondwana breakup. These may reflect the geometry of movement zones in the deep lithosphere that are analogous to transfer faults and detachment zones, on the continental scale.

Diamonds In 2004 Mr Simon Richards focussed some effort into linking plate tectonics and kimberlite magmatism, showing spatio-temporal controls in the context of global tectonic reconstructions using the emerging P-plates software developed by Dr Joe Kurtz.

A key feature of kimberlites and associated rock types is the preferred orientation of the hypabyssal dyke orientations, implying a tectonic control on their emplacement. However, even though large-scale structures such as faults may locally control kimberlite emplacement, the regional tectonic controls are less well understood (Figure 10).

Another characteristic feature of kimberlite magmatism is the well-documented occurrence of distinct eruption events that are generally specific to a particular region or field. Compilation of over 500 kimberlite ages has revealed a correspondence between major periods of kimberlite eruption and periods of continental extension. A paucity in kimberlite eruption events existed during the life of the Gondwanan continent between ~250 and 340 Ma, during a period of relative plate stability. In contrast, continental fragmentation and breakup at ~250 Ma coincides with the onset of the more recent periods of kimberlite eruption. Rifting at ~120 Ma associated with the formation of the South Atlantic Ocean corresponds with some of the most voluminous and economic kimberlites in South Africa.

Figure 11 Gold mineralization at the boundary between mylonites and sediments in the Miclere gold field (photo by PhD candidate David Wood).

Gold In 2004 Mr David Wood continued with his PhD topic "Tectonic evolution and gold mineralization of the Anakie Inlier, central East Queensland" supported by AngloGold Australia. The ultimate aim of this project is to change the way we assess the evolution of the eastern margin of this part of Gondwana during the Palaeozoic, and to understand large-scale controls on metallogenic fertility. The project will show that architectural studies are necessary to understand the history of a terrane, and that interpolating between terranes is essential for interpretation of tectonic setting. The preliminary results are that changes in geodynamic setting correspond with episodes of gold mineralization, and that in any fertile terrane, the regional setting and rock type are secondary in importance to controls exerted by tectonic setting.

THERMOCHRONOLOGY, EARTH MATERIALS

The protracted cooling history of the Bajo de la Alumbrera porphyry Cu-Au deposit, NW Argentina: a combined U-Pb, $^{40}Ar/^{39}Ar$, K/Ar, and (U-Th)/He study

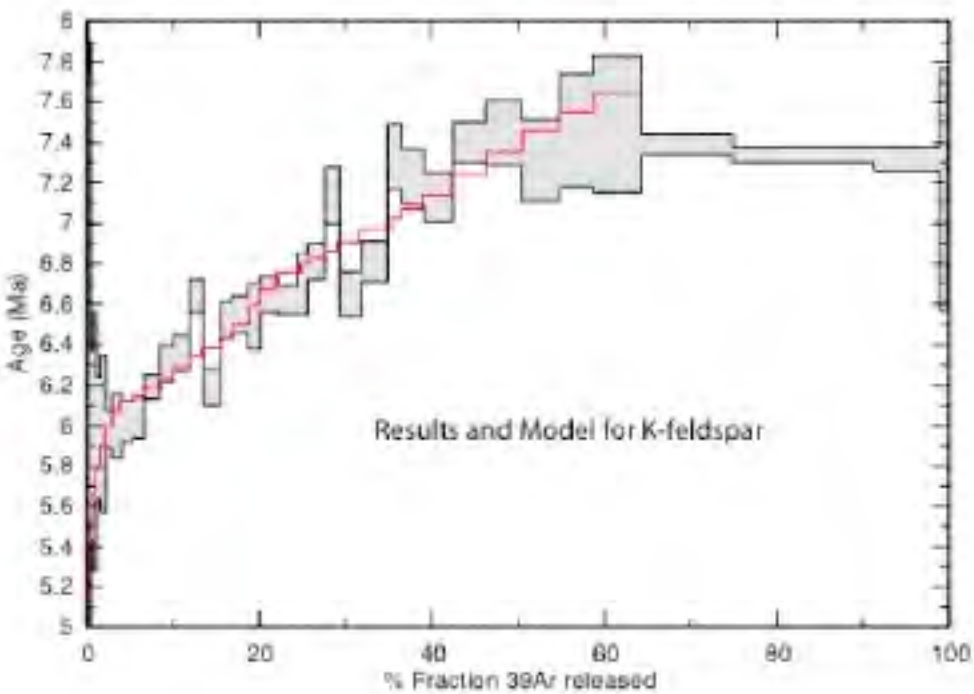
W. James Dunlap, Charlotte M. Allen, Ian H. Campbell and Anthony C. Harris[1]

[1]Centre for Ore Deposit Research, University of Tasmania, 7001, Hobart, Australia

Radioisotopic dating of igneous minerals does not necessarily measure the age of crystallisation of magma. In many cases the measurement can provide estimates on the timing of cooling of minerals, and "closure" of the mineral to parent or daughter isotope loss or gain (losses or gains that are insignificant on the timescale of interest). It may therefore be possible to define the cooling history of an intrusion if several different techniques are used to date multiple minerals from one intrusion. At the RSES, and with help from a number of collaborators abroad, we have applied and assessed several different geochronometers, including the U-Pb, $^{40}Ar/^{39}Ar$, K/Ar and the (U-Th)/ He to porphyry intrusions at the Bajo de la Alumbrera Cu-Au deposit, Argentina. For purposes of this illustration the assumed or calculated closure temperatures of the different techniques are 800°C for zircon U-Pb, the range 350-150°C for $^{40}Ar/^{39}Ar$ on K-feldspar, and ~200 °C for zircon and ~70°C for apatite when applying the (U-Th)/He method.

Our new U-Pb analyses reveal that the last know mineralized magma intruded at Bajo de la Alumbrera at 6.96±0.09Ma. Two new incremental heating $^{40}Ar/^{36}Ar$ age spectra were determined on phenocrysts from the same rock; the biotite spectrum is disturbed, apparently caused by fluid-assisted recrystallisation of the biotite during a brief reheating event (probably not exceeding 300°C). Age spectrum data for K-feldspar also records this thermal event. In the initial heating stages of the masurement ages between 6.3 and 6.1 Ma are resolved, before rising to a plateau-like section at ~7.3 Ma (7.33 ± 0.21Ma). Although the $^{40}Ar/^{36}Ar$ maximum age (measured during melting of the sample) is slightly older than the U-Pb age, both ages are within analytical uncertainty. We explain this spectrum pattern, not in terms of excess argon, but in terms of an apparent diffusion-limited gradient, caused by reheating of the magmatic K-feldspar at some time shortly after crystallization. Based on calculated closure temperatures (~200°C), single-grain (U-Th)/ He age determinations of zircon from the mineralized intrusions (i.e., the ZHe ages are 6.55±0.52 and 5.83±0.52 Ma) confirms that a low temperature thermal event occurred long after the last known intrusion was emplaced at Bajo de la Alumbrera. In other words, we find it unreasonable to think that the intrusion could remain above 200 °C until about 6.5 Ma, given the shallow level of the intrusion.

Our new data, combined with that of other studies (Sasso, 1997; Sasso and Clark, 1998; Harris et al., 2004), reveals that the deposit was reheated and subsequently cooled through 200°C over a million years or more after the emplacement of one of the last known intrusion at Bajo de la Alumbrera. Moreover, these events occurred long after the last igneous emplacement within the Farallón Negro Volcanic Complex. We conclude that the longevity of the hydrothermal system responsible for porphyry Cu deposits is a consequence not only of multiple porphyry intrusions, but also the continued release of magmatic aqueous fluids and heat from deep underlying magma bodies. Meteoric water may be involved in a late stage geothermal system system thermally collapses. At Bajo de la Alumbrera, the exsolution and degassing of metal-rich magmatic fluids may have persisted episodically long after the last volcanic eruptions or shallow intrusions. This confirms the findings of an earlier study (Harris et al., 2003), where the magmatic history determined from geochronology of



subvolcanic intrusions found in and around a porphyry deposit provides only a minimum estimate of the longevity of the hydrothermal system. The complete magmatic history of porphyry ore deposits can only be established from careful consideration of the discrepancies between magmatic ages given by U-Pb zircon geochronology and hydrothermal alteration or cooling ages determined by

$^{40}Ar/^{39}Ar$, K/Ar and (U-Th)/He thermochronology.deposits is a consequence not only of multiple porphyry intrusions, but also the continued release of magmatic aqueous fluids and heat from deep underlying magma bodies. Meteoric water may be involved in a late stage geothermal system as the system thermally collapses. At Bajo de la Alumbrera, the exsolution and degassing of metal-rich magmatic fluids may have persisted episodically long after the last volcanic eruptions or shallow intrusions. This confirms the findings of an earlier study (Harris et al., 2003), where the magmatic history determined from geochronology of subvolcanic intrusions found in and around a porphyry deposit provides only a minimum estimate of the longevity of the hydrothermal system. The complete magmatic history of porphyry ore deposits can only be established from careful consideration of the discrepancies between magmatic ages given by U-Pb zircon geochronology and hydrothermal alteration or cooling ages determined by $^{40}Ar/^{39}Ar$, K/Ar and (U-Th)/He thermochronology.

Age of the metamorphic sole of the Papuan Ultramafic Belt ophiolite, Papua New Guinea

Wilfred Y. Lus, Ian McDougall and Hugh L. Davies

The Papuan Ultramafic Belt (PUB) ophiolite is former oceanic crust and upper mantle emplaced onto continental crust in Papua New Guinea (PNG) in a zone of general convergence between the Pacific and Australian plates (Fig.1). The metamorphic sole beneath the ophiolite is best

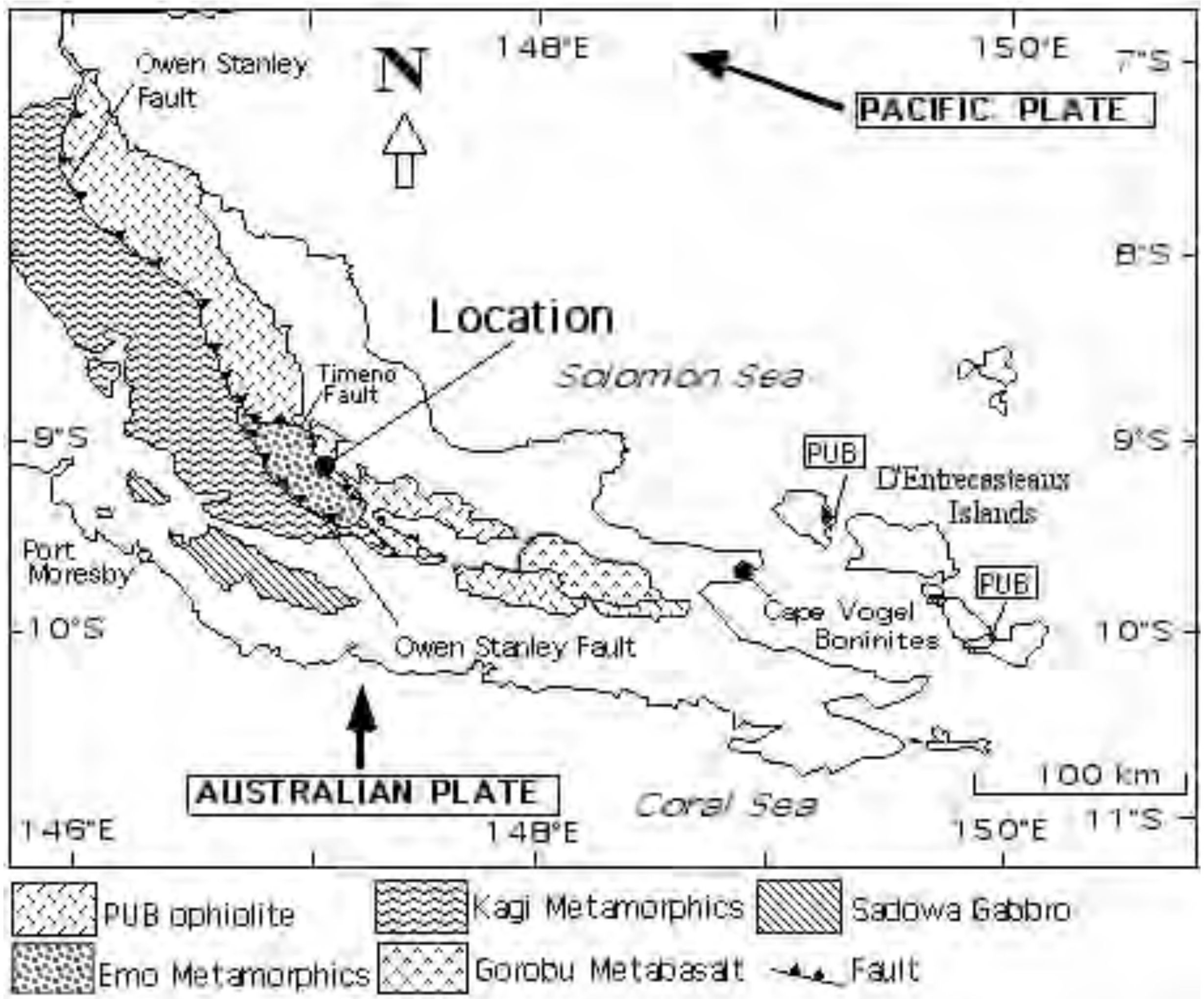


Figure 1. Map of southeastern Papua New Guinea showing the PUB ophiolite and location of the study area. The relative motions of the Australian Plate and the Pacific Plate are shown by the arrows.

exposed in the Musa-Kumusi divide and comprises a 40 to 300 m thick body of granulite and amphibolite facies rocks. Geochronological studies on the metamorphic sole, using amphiboles from the granulites and amphibolites, yield measured K-Ar ages ranging from 65.0 ± 0.7 to 57.2 ± 0.6 Ma and average 40Ar-39Ar direct total fusion ages ranging from 67.0 ± 0.7 to 59.5 ± 0.2 Ma. Five of the six 40Ar-39Ar plateau ages, derived from age spectra, lie between 58.6 ± 0.2 and 57.8 ± 0.2 Ma with an overall mean age of 58.3 ± 0.4 Ma. The large spread in measured K-Ar and 40Ar-39Ar total fusion ages is thought to be caused by the presence of variable amounts of excess argon. The mean plateau age for five samples of 58.3 ± 0.4 Ma is interpreted to mark the time of cooling of the metamorphic sole following peak metamorphism. We suggest that the development of the metamorphic sole and emplacement of the PUB ophiolite onto the PNG crust occurred in a relatively short time interval in the Paleocene.

Lus: Former member of RSES as a PhD student (now University of Papua New Guinea)
McDougall: Visiting Fellow RSES
Davies: Not a member of RSES (University of Papua New Guinea)

Contrasting styles of Proterozoic crustal evolution: A hot-plate tectonic model for Australian terranes

Sandra McLaren

Processes controlling lithospheric evolution on the early Earth are subject to often spirited debate. The popularity of uniformitarian principles has meant that, with the exception of the earliest Archaean, dynamic plate-tectonic models have largely prevailed. These models appear appropriate in many cases, including the Palaeo-Mesoproterozoic evolution of North America (Hoffman, 1989) and the evolution of those Mesoproterozoic terranes related to the assembly of Rodinia, including those in Australia (Myers et al., 1996). However, for the Palaeo-Mesoproterozoic evolution of Australian terranes, there is less consensus, and two end-member models have been proposed. Early work advocated an intraplate, asthenosphere-driven model for lithospheric evolution in which vertical, rather than lateral, accretion was dominant. More recently plate-tectonic models have become popular (Betts et al., 2002; Giles et al., 2002).

There are a number of observations, however, which seem incompatible with these models and we advocate a more general approach to understanding crustal evolution. In particular, these models cannot fully account for: (1) repeated tectonic reactivation (both orogenesis and rifting); (2) large aspect-ratio orogenic belts; (3) mainly high temperature-low pressure metamorphism; (4) rifting and sag giving thick sedimentary basins; (5) the nature and timing of voluminous felsic magmatism, and (6) the general absence of plate-boundary features.

The key to understanding these histories is the observation that Australian Proterozoic terranes are characterized by an extraordinary, but heterogeneous, enrichment of the heat-producing elements. Granites and felsic volcanic rocks in all Australian terranes have average heat production of 4.3 μWm^{-3} when normalized by outcrop area (over 100 000 km^2). This enrichment must contribute to long-term lithospheric weakening and meant that Australian terranes were sensitive to only small applied tectonic forces. This effect is most pronounced when the available heat sources are concentrated in the deep crust rather than the upper crust (Figure 1) and will change as the heat source distribution is modified by ongoing tectonic activity. Thus, we advocate a hybrid lithospheric evolution model with two tectonic switches: (1) plate-boundary-derived stresses and, (2) heat-producing-element-related lithospheric weakening. The Australian Proterozoic geological record is therefore a function of both the magnitude of the plate-boundary stresses, the way in which the heat-producing elements are distributed, and how both of these change with time.

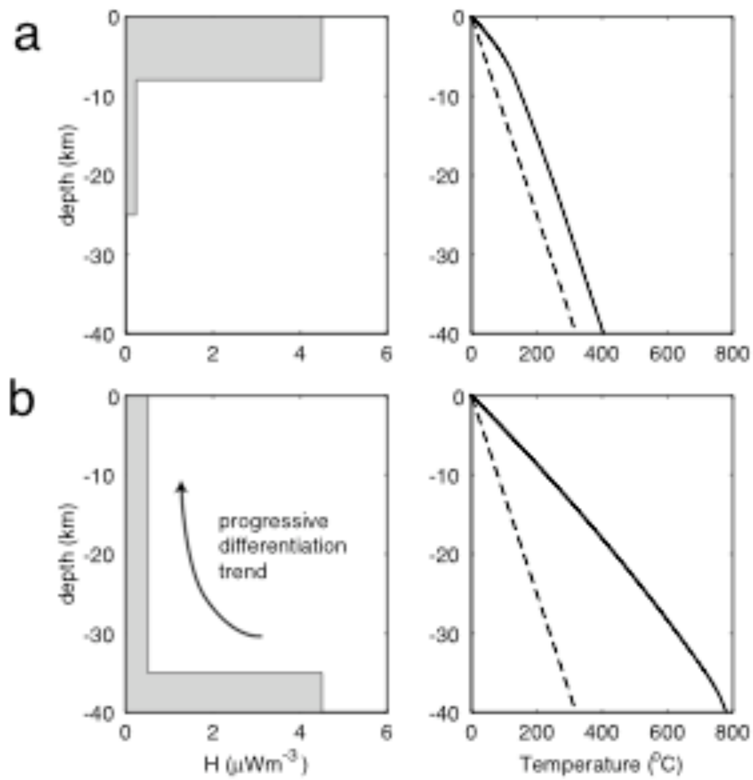


Figure : Crustal heat producing element distributions and the resultant geotherm for: (a) highly differentiated heat-production distributions where the majority of crustal heat sources are located in the uppermost crust; this configuration is appropriate for modern day crust in many Australian terranes; and (b) undifferentiated heat production distributions where the majority of crustal heat sources are located in the lower crust; appropriate for the early Proterozoic crust in many Australian terranes. The dashed line is the geotherm that would apply in crust containing no heat producing elements (i.e., the mantle contribution). Differentiation of crustal heat sources from distribution (a) to distribution (b) through tectonic processing (particularly magmatism) affects a significant increase in crustal strength and is responsible for progressive cratonization of Australian terranes through the Palaeo-Mesoproterozoic. Both distributions give a total crustal contribution to surface heat flow of 40 mWm^{-2}.

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Betts, P.G., Giles, D., Lister, G.S. and Frick, L.R. 2002. Evolution of the Australian lithosphere. Australian Journal of Earth Sciences, 49, p. 661-695.

Giles, D., Betts, P. and Lister, G. 2002. Far-field continental backarc setting for the 1.80-1.67 Ga basins of northeastern Australia. Geology, 30, p. 823-826.

Hoffman, P.F. 1989. Speculations on Lautentia's first gigayear (2.0 to 1.0 Ga). Geology, 17, p. 135-138.

Myers, J.S., Shaw, R.D. and Tyler, I.M. 1996. Tectonic evolution of Proterozoic Australia. Tectonics, 15, p. 1431-1446.

CONFERENCES AND OUTSIDE STUDIES

ARMSTRONG, Dr R.A., 17th Australian Geological Convention, Hobart TAS, 8-13 February. Presented a paper on the geochronology of Macquarie Island.

ARMSTRONG, Dr R.A., 20th Colloquium of African Geology, Orléans, France, January. Co-authored four papers.

ARMSTRONG, Dr R.A., Geoscience Africa, Johannesburg, South Africa, 12-16 July. Delivered two invited papers and co-authored another eight papers.

ARMSTRONG, Dr R.A., Geological Society of America, Annual meeting, Denver 7-10 November. Contributed to a Special Session on the "*Early Proterozoic (2.5-2.0 Ga) Events and Rates: Bridging Field Studies and Models"*.

FANNING, Mr C.M., Australian Geological Convention, Hobart TAS, 8-13 February. Presented paper entitled "Detrital zircon provenance of the Mesoproterozoic Pandurra Formation, South Australia: Gawler Craton derived age spectra and implications for the source of the Belt Supergroup, USA" and was co-author on 2 other presentations

FANNING, Mr C.M., field work in Patagonia, 20-29 February. Together with Dr R. Pankhurst, UK and Dr C. Rapela, La Plata, Argentina conduct field work related to the project entitled "Chronology of deposition and provenance of Late Palaeozoic sedimentary basins, Argentine Patagonia"

FANNING, Mr C.M., field work in southern most Chile, 1-13 March. With Professor Hervé Univeristy de Chile, undertake field work to examine a section through the southern Patagonian Batholith and the Madre de Dios metamorphic complex.

FANNING, Mr C.M., field work in Minnesota, present seminar at Univeristy of Minnesota Duluth, USA, 8-20 May. Together with Dr Goodge, UMD carry out further sampling of the Duluth Complex for use as a SHRIMP reference zircon. Presented a seminar at UMD on SHRIMP methods and applications.

FANNING, Mr C.M., second International Symposium on Polar Sciences of China, Beijing, Oct 16-17. Present two invited keynote talks entitled "The "Mawson Continent": East Antarctica and southern Australia as a cornerstone for ?Rodinia and Gondwana" and "New insights into the development of the Palaeo Pacific margin of East Gondwana".

FANNING, Mr C.M., Geological Society of America, Annual meeting, Denver 7-10 November. Assisted with four presentations, meetings with numerous international collaborators.

NORMAN, Dr M.D., Australian Geological Convention, Hobart TAS, 8-13 February. Co-convenor of session on New Technologies in Mineralogy, Petrology and Geochemistry (with A.J. Crawford) and presentation on 'Improved Methods for Re-Os Dating of Molybdenite using Multi-collector ICPMS'.

NORMAN, Dr M.D., Tectonics to Mineral Discovery - Deconstructing the Lachlan Orogen, MORE-SGEG Conference, Orange, NSW, 6 – 8 July. Poster presentation on

‘New Re-Os Ages of Molybdenite from Granite-related Deposits of Eastern Australia Using an Improved Multi-collector ICP-MS echnique’.

NORMAN, Dr M.D., Lunar and Planetary Science Conference, Houston TX 15-19 March. Chaired session on “The Lunar Crust as Sampled by Basins and Craters”, and presentations on “Identifying Impact Events Within the Lunar Cataclysm from ^{40}Ar-^{39}Ar Ages of Apollo 16 Impact Melt Rocks” and “Magnesium isotopes in the Earth, Moon, Mars, and pallasite parent body: high-precision analysis of olivine by laser-ablation multi-collector ICPMS.”

NORMAN, Dr M.D., Visiting Scientist, Lunar and Planetary Institute, Houston, 19 October to 18 December. The purpose of this travel was to conduct geochronological studies of lunar samples at the NASA Johnson Space Center.

YAXLEY, Dr G.M.; Goldschmidt Meeting, Copenhagen, June 6-11. I presented a talk titled “High-pressure partial melting of gabbro and the preservation of “ghost plagioclase” signatures”.

YAXLEY, Dr G.M, Australian Geological Convention, Hobart, February 9-13. I presented two talks titled “Compositional heterogeneity in olivine-hosted melt inclusions from the Baffin Island picrites” and “Novel techniques for the discrimination of diamond indicator chromian spinel based on major, minor and trace element compositions.”

COOPERATION WITH AUSTRALIAN UNIVERSITIES, CSIRO AND INDUSTRY

Dr R. ARMSTRONG is collaborating with Professor Mark Barley and Brian Krapez from the **University of Western Australia** on research into the Late Archaean – Early Proterozoic timescale relevant to the emergence of the Earth’s atmosphere. He continues to collaborate with Professor David Gray (**University of Melbourne**) on research projects in Oman and Namibia, and with Dr Barry Kohn (**University of Melbourne**) on the geochronology of Macquarie Island.

Mr C.M. FANNING collaborated with Associate Professor C. Fergusson, **University of Wollongong** and Professor R. Henderson, **James Cook University** on Tectonics of the Neoproterozoic – Early Palaeozoic margin in eastern Australia, Professor J. Roberts, **University of NSW** on the timing of Carboniferous-Permian volcanic rocks in the Tamworth belt NSW, Dr Kurt Knesel, **Univerity of Queensland** on the timing and protolith history of Cenozoic volcanic rocks from Chile and Dr Michael Rubenach, **James Cook University** on the geochronology of granitic rocks in north west Queensland

Dr GM YAXLEY and Dr M.D. NORMAN collaborated with Dr V. Kamenetsky and Dr M. Kamenetsky (**University of Tasmania**) and Prof. D. Francis (McGill University) on Compositional heterogeneity in olivine-hosted melt inclusions from the Baffin Island picrites.

COLLABORATION WITH GOVERNMENT & OTHER PUBLIC INSTITUTIONS

Dr R. ARMSTRONG has collaborated on a number of projects with scientists from the Geological Surveys of Brazil, Botswana, Namibia, South Africa, South Korea and Swaziland. He has also participated in joint research with Dr Ian Graham of the Australian Museum, Sydney. A number of geochronological projects for Australian and international exploration companies and consultants were completed during the year and new projects commenced.

Mr C.M. FANNING collaborated with Mrs S. Daly, Mr M. Schwartz and numerous others at the Geological Survey of South Australia on a geochronological synthesis of South Australia; with Mr L. Hutton & Mr I. Withnall, Geological Survey of Queensland on the geochronology of a number of key provinces in Queensland.

Dr G.M. YAXLEY has completed several consultative projects for Australian and international diamond exploration companies and for Australian state geological surveys.

INTERNATIONAL COLLABORATION

Dr R.A. ARMSTRONG with C. Lana, Professor W.U. Reimold and Dr R. Gibson (**University of the Witwatersrand**, South Africa), Geochronology of the Vredefort impact structure.

Dr R.A. ARMSTRONG with Dr J. Ward and J. Jacob (**De Beers Exploration**) and A. van der Westhuizen (**University of Stellenbosch**, South Africa), The provenance and history of diamond-bearing sediments from the Orange River, southern Africa.

Dr R. A. ARMSTRONG with R. Baillie, Prof. N. Beukes and Prof. J. Gutzmer (**Rand Afrikaans University**, South Africa), Geochemistry and geochronology of the Koras Sequence, South Africa.

Dr R.A. ARMSTRONG with C. McClung (**Rand Afrikaans University**, South Africa), The provenance and geochronology of metasediments from the Aggeneys region, Namaqualand, South Africa, and possible regional correlations.

Dr R. A. ARMSTRONG with J. Mukhopadhyay (**Presidency College**, India) and Professor N. Beukes (**Rand Afrikaans University**, South Africa), The geochronology of Archaean Banded Iron Formations from the Bailadila Region, Bastar Craton, Central India.

Dr R.A. ARMSTRONG with Dr B. Eglington (**University of Saskatchewan**, Canada), Development of a geochronological database for Africa.

Dr R.A. ARMSTRONG with Dr P. Macey and Dr G. Grantham (**Council for Geoscience**, South Africa), A SHRIMP U-Pb study of the main magmatic, metamorphic and tectonic events of central Mozambique.

Dr R. A. ARMSTRONG with Dr Deung-Lyong Cho (**Korea Institute of Geology, Mining and Materials**, South Korea), Geochronology and stratigraphy of the Korean peninsula.

Dr R. A. ARMSTRONG with Dr M. Pimentel and Dr M. Escayola (**University of Brasilia**, Brazil), Geochronology and provenance studies of various sequences in Brazil and Argentina.

Dr R.A. ARMSTRONG with Dr Jean-Paul Liégeois (**Africa Museum**, Belgium), The geochronology, structure and tectonic history of the Aïr and Hoggar regions (SE Taureg shield) in Niger.

Dr R.A. ARMSTRONG with Dr M Bröcker (**Institut für Mineralogie**, Munster, Germany), SHRIMP U-Pb zircon geochronology of jadeitites from Greece.

Mr C.M. FANNING with Professor P. K. Link of **Idaho State University**, USA, "changes in provenance of sandstones in the Snake River plain and environs with the passing of the Yellowstone hot-spot".

Mr C.M. FANNING with Dr B.J. Mahoney of **University of Wisconsin-Eau Claire**, USA, "The Baja-BC conundrum".

Mr C.M. FANNING with Professor F. Hervé of **University of Chile**, Santiago, Chile, "geochronology and tectonic evolution of the southern Patagonian batholith and outboard accreted terranes".

Mr C.M. FANNING with Dr R.J. Pankhurst **British Geological Survey** & **the NERC Isotope Geosciences Laboratory**, UK, "evolution of the north Patagonian massif and the Sierras Pampeanas".

Mr C.M. FANNING with Dr C.W. Rapela, **Universidad de la Plata**, Argentina, "evolution of the north Patagonian massif and the Sierras Pampeanas".

Mr C.M. FANNING with Dr A. Cocherie & Dr P. Rossi, **BRGM**, Orleans, France, "evolution of Corsica and beyond".

Mr C.M. FANNING with Dr J.A Aleinikoff of the **US Geological Survey**, Denver USA, "Timing of events in the New England region, North America".

Mr C.M. FANNING with Dr C. Smith-Siddoway, **Colorado College**, Colorado Springs, USA, "Geochronology of granites in the Ross Sea and the timing of metamorphism in Marie Byrd Land, Antarctica".

Mr C.M. FANNING with Dr K. Shiraishi and Dr K. Misawa of the **National Institute for Polar Research**, Tokyo, Japan, "U-Pb reference zircons".

Mr C.M. FANNING with Dr J. Goodge, **Southern Methodist University**, USA, "The geochronology and tectonic evolution of the East Antarctic Craton, Transantarctic Mountains".

Mr C.M. FANNING with Dr J. Jacobs of **University of Bremen**, Germany, "Geochronology and tectonic evolution of Dronning Maud Land".

Mr C.M. FANNING with Professor D. Gebauer and Dr A. Liati, **ETH Zürich**, Switzerland "geochronology and trace element geochemistry of zircons from Alpine eclogites".

Mr C.M. FANNING with Dr A. Morton, **HM Associates**, UK. "detrital zircon provenance of Palaeozoic basins in North Sea region".

Mr C.M. FANNING with Prof. C. Casquet and Dr C.Galindo of **Universidad Complutense, Madrid**, Spain "Sierras Pampeanas and the evolution of the Argentine PreCordillera".

Mr C.M. FANNING with Professor F. Munizaga and Dr Victor Maksaev of **University of Chile**, Santiago, Chile, " timing of mineralisation in the Collahuasi & Atacama regions ".

Dr G.M. YAXLEY and Dr A.J. BERRY with Prof A.B. Woodland (**University of Frankfurt**) and Prof G.P. Brey (**University of Frankfurt**), Application of XANES to determination of $Fe3+/\sum Fe$ in garnet.

Dr G.M. YAXLEY and Prof A. Sobolev (**Max-Planck-Isntitut für Chemie**, Mainz), Interactions between high pressure partial melts of gabbro and peridotite upper mantle – an experimental investigation.

Dr M.D. NORMAN with Drs L. Nyquist and D. Bogard (both **NASA Johnson Space Center**, Houston), Prof. L. Taylor (**University of Tennessee**, Knoxville) and Prof. R. Duncan (**Oregon State University**, Corvallis), Age, Origin, and Impact History of the Lunar Crust.

Dr M.D. NORMAN with Prof. M. Garica (**University of Hawaii**, Honolulu), Dr A. Pietruszka (**San Diego State University**, San Diego), and Prof. M. Rhodes (**University of Massachusetts**, Amherst), Magmatic Processes at Hawaiian volcanoes.

Dr M.D. NORMAN with Dr M. Humayun (**Florida State University**, Tallahassee) A. Brandon (**NASA Johnson Space Center**, Houston), Prof. T. Elliott, Prof. C.J. Hawkesworth, and Dr A. Scherstén (**University of Bristol**, Bristol), Core-Mantle Interaction and Origin of Mantle Plumes.

EDITORIAL RESPONSIBILITIES

Dr R.A. Armstrong is on the editorial board of the Journal of African Earth Sciences.

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RSES ANNUAL REPORT

PRISE RESEARCH HIGHLIGHTS AND SCIENTIFIC CONTRIBUTIONS

PRISE operates as a unique entity within the Research School, with the principal charter to provide external access to the Research School's specialised equipment and expertise in the areas of geochronology, isotope geochemistry and trace element geochemistry. During 2004 ***PRISE*** continued to compete successfully in an increasingly competitive market; the main areas of such activities being SHRIMP projects, with significant LA- and solution ICPMS components and TIMS analyses.

Collaborative research projects have been undertaken with colleagues from Europe, southeast Asia, southern Africa and both North- and South America as well as that conducted with staff of other Australian universities and institutions. A small proportion of purely commercial work has been carried out, mainly for Australian clients.

PRISE staff also conduct their own research and have been successful in obtaining a number of ARC Discovery and Linkage grants. They are also significantly involved with numerous successful grant applications to international funding agencies. ***PRISE*** staff effected 40 publications and hosted 22 visitors to the Research School during 2004.

Research highlights include:

Timing of the Snowball Earth – Mr C.M.**Fanning**
The concept of a Snowball Earth has stimulated much discussion and ongoing research. A fundamental criterion is the absolute timing of the glaciogene events on a global scale. From a study of stratigraphically well constrained rocks near Pocatello Idaho, USA absolute age constraints can be placed on the glaciogene events and so enable one to draw comparisons and contrasts with other correlated horizons. From this and other studies it is clear that some glacigene events are globally coincident, whilst others are clearly outside the bounds of a single coeval, coincident Snowball Earth event.

U-Pb and fission track ages from Oceanic Crust at Macquarie Island

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Macquarie Island is the quintessential ophiolite, being the only exposed oceanic crust within an ocean basin. It is on the Macquarie Ridge, an arcuate topographic high coinciding with the dextral transpressional plate margin between Indo-Australian and Pacific plates. Despite its importance to studies of oceanic crust, the age of Macquarie Island crust formation and subsequent events have not been accurately constrained.

Large (>450 km) transcurrent movements have rendered direct correlation with identified seafloor magnetic anomalies impossible. However, plate reconstructions indicate that Macquarie Island crust may have been generated between 10.5-24 Ma (Sutherland, 1995; Lamarche et al., 1997), immediately prior to the transition of the proto-Macquarie spreading ridge becoming a transcurrent plate margin at 10.5 Ma. The only previous radiometric study (K-Ar and Ar-Ar dating; Duncan & Varne, 1988) on dykes and basalts gave dates ranging from 3.6 – 13.4 Ma, but these are largely considered unreliable or to be cooling ages, with a few Ar-Ar plateau ages and K-Ar hornblende ages ranging 9.7-11.4 Ma possibly indicating crust formation ages.

In a collaborative research effort we have obtained the first U-Pb zircon crystallization ages and apatite and zircon fission track ages from Macquarie Island. Zircons from three late-stage phlogopite pegmatoids give U-Pb dates of 8.4 ± 0.3 Ma, 8.5 ± 0.2 Ma and 8.8 ± 0.2 Ma (95% confidence limits). Fission track ages from the intrusive complex in the north range between 4.2-5.2 Ma (apatite) and 5.5-6.5 Ma (zircon), and a tabular basalt to the southwest yields a fission track age of 4.7 ± 0.7 Ma. These dates indicate rapid Late Miocene-Early Pliocene cooling of the order of ~100°C/myr for the northern part of the island and give new insights into the timing and processes involved in the formation of this section of ocean crust.

Origins of compositional heterogeneity in olivine-hosted melt inclusions from the Baffin Island picrites.

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The Baffin Island picrites erupted onto felsic continental crust about 65 Ma ago. They are highly magnesian (≤22 wt% MgO) olivine tholeiites, and have been extensively studied because of their primitive nature. We have conducted a geochemical investigation of melt inclusions trapped in primitive olivine phenocrysts in these lavas. After correction for post-entrapment modification, the inclusions are systematically slightly lower in Al_2O_3, and significantly higher in SiO_2, K_2O and P_2O_5 than the lavas' fractionation trends. CaO, Na_2O and TiO_2 contents lie within the lavas' fractionation trends. Similarly, most inclusions are higher in Sr/Nd, K/Nb, Rb/Ba, Rb/Sr, U/Nb and Ba/Th than the lavas. These characteristics resulted from up to ≈15% contamination of evolving picritic-basaltic liquids by locally-derived, broadly granitic partial melts of the quartz + feldspar-rich crust through which the picrites erupted. Contamination was minor in the bulk lavas (<1%), suggesting that the inclusions' compositions partly reflect a link between wall rock reaction and precipitation of liquidus olivine. Rapid crystallisation of liquidus olivine from the picrites, along with melting of felsic crustal wall rocks of magma chambers or conduits, were likely during emplacement of hot picritic magmas into cooler felsic crust. Inclusion compositions may thus reflect mixing trends or may be constrained to phase boundaries between olivine and a phase being resorbed, for example, an olivine-plagioclase cotectic. The extent of contamination was probably a complex function of diffusion rates of components in the magmas, and phenocryst growth rates and proximity to wall rock. These results bear on the common

observation that melt inclusions' compositions are frequently more heterogeneous than those of the lavas that host them.

Calibration of a synchrotron-based XANES technique for determination of $Fe^{3+}/\sum Fe$ in garnet.

Gregory M **Yaxley**[1] and Andrew Berry[1]

1. RSES, ANU

Fe is the most common element in the Earth that exhibits a variable oxidation state occurring as both Fe^{2+} and Fe^{3+} in minerals and melts. The $Fe^{3+}/\sum Fe$ ratio of geological samples can be used as an indicator of the redox conditions or oxygen fugacity (fO_2) at which a mineral formed. Garnets are a mineral group which may contain both Fe^{2+} and Fe^{3+}. At depths below ~60 km where garnet bearing peridotites are stable, the Fe^{3+} component in garnet can be used to determine the fO_2 of the mantle. In conjunction with data from geothermometers (e.g. two pyroxene or olivine-garnet) and geobarometers (e.g. Al in orthopyroxene) this allows the fO_2 of the mantle to be profiled as a function of depth. The fO_2 of the mantle is particularly important as an indicator of diamond (as opposed to carbonate) stability. For depths corresponding to pressures greater than the graphite to diamond transition the mantle fO_2 is, as expected, sufficiently reduced for diamond to be stable. However, post formation metasomatic processes may impose significantly higher fO_2 conditions leading to diamond breakdown or resorption. Such events will usually be recorded by the coexisting garnet as oxidised rims. To successfully use garnet as a diamond indicator mineral in exploration, or to predict the potential diamond grade of kimberlites, it is necessary to determine the $Fe^{3+}/\sum Fe$ ratio of these garnets.

The aim of this project is to develop a method for determining the $Fe^{3+}/\sum Fe$ ratio of garnets using the energy of the 1s-3d transition in the Fe K-edge XANES spectrum. A series of well characterised natural and synthetic samples were used as standards (Woodland and O'Neill 1993; Woodland and Koch 2003; Woodland and Ross 1994). $Fe^{3+}/\sum Fe$ has been determined previously for these samples by electron microprobe analysis/stoichiometry and Mössbauer spectroscopy, and varies from 0.0 to 1.0. We collected XANES spectra at the Australian National Beam-line Facility on the sychrotron at Tsukuba, Japan, and used the data to construct a calibration curve relating $Fe^{3+}/\sum Fe$ to 1s-3d energy.

The next step is to apply the calibration to *natural* samples for which garnet $Fe^{3+}/\sum Fe$ has been previously determined by Mössbauer spectrometry, using a micron-scale synchrotron beam at the Advanced Photon Source (Chicago) or the European Synchrotron Radiation Facility (Grenoble).

The XANES method for determining $Fe^{3+}/\sum Fe$ has great potential for the diamond exploration industry. Large numbers of garnets (as diamond indicator minerals) need to be screened as part of the exploration process, however, the only currently available method, Mössbauer spectroscopy, is not practical due to the long (days to weeks) data acquisition times. The comparatively rapid time with which XANES spectra may be acquired (less than 30 minutes) opens up commercial possibilities. Secondly, it is essential to determine the $Fe^{3+}/\sum Fe$ of reaction rims representing metasomatic events, to evaluate the likelihood of diamond preservation. These rims require a technique with micron spatial resolution, which is currently not available. Micro-XANES has great potential to solve this problem.

Detrital apatite geochemistry and its application in provenance studies

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Single-grain laser ablation inductively-coupled plasma mass spectrometry of detrital apatites from Pliocene sandstones in the South Caspian Basin (Azerbaijan) and Devonian-Carboniferous sandstones from west of Shetland (UK) demonstrate that apatite geochemistry has significant potential in provenance analysis. Apatites in Pliocene sandstones deposited by the paleo-Kura river system, which drained the Lesser Caucasus region, were derived largely from mafic/intermediate and alkaline rocks. Apatite populations in Pliocene sediments transported by the paleo-Volga river system, which drained the Russian Platform, show greater compositional diversity, indicating supply from granitoids or other acidic rocks together with subordinate mafic/intermediate and alkaline rocks. Apatites in the Devonian-Carboniferous succession west of Britain were sourced predominantly by acidic rocks, either directly from Archaean gneisses or indirectly from metasedimentary rocks.

Since apatite is stable during burial in sedimentary basins, apatite geochemistry can be used to determine provenance of sandstones from the full range of diagenetic environments, although the instability of apatite during weathering means that the method will be difficult to apply to sandstones with prolonged weathering history. At present, identification of provenance using apatite geochemistry is limited by the lack of a comprehensive database on apatite compositions in some of the potential source rocks, particularly those of metamorphic origin. The role played by sediment recycling is another factor that requires consideration when reconstructing source areas on the basis of apatite compositions.

High pressure partial melting of gabbro and the preservation of “ghost plagioclase” signatures.

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Rare Sr-enriched melt inclusions in olivine phenocrysts from Mauna Loa lavas were interpreted as a “ghost plagioclase” signature derived from partial melting of recycled oceanic gabbro, present as eclogite in the peridotite dominated Hawaiian source.

To test this model, we partially melted gabbro Gb108 at 3.5 and 4.5 GPa. The starting material was the natural powdered gabbro, glassed and ground to fine powder. Run products were analysed by EPMA and SIMS.

The solidus was between 1350°C and 1375°C at 3.5 GPa, and 1450 and 1475°C at 4.5 GPa. The subsolidus assemblage was minor garnet, abundant Jd+CaTs-rich clinopyroxene (cpx), and accessory coesite. Low degree partial melts coexisted with ga+cpx+co and had >60wt% SiO_2. Co-out lay between 1375 and 1400°C at 3.5 GPa and between 1475 and 1500°C at 4.5 GPa. Partial melts at T>co-out were less siliceous (<60wt% SiO_2).

Quenched liquids' trace element patterns exhibited strong positive Sr anomalies, and are very similar to the Sr-rich Mauna Lao inclusions. Mass balance calculations indicate the accuracy of the measured liquid trace element abundances.

Thus, partial melts of discrete gabbroic (eclogite) bodies in intraplate volcanics' sources may generate anomalously Sr-rich liquids. If this feature were preserved during transport from source to magma chamber, Sr-rich inclusions may be trapped by crystallising olivine phenocrysts.

Chalcophile element volatility

Dr. M.D. Norman

The volatility of chalcophile metals rhenium (Re), cadmium (Cd), and bismuth (Bi) during magmatic outgassing of basaltic magma was demonstrated by a study of basaltic glasses using the laser ablation ICPMS facilities at RSES. The behavior of chalcophile metals in volcanic environments is important for a variety of economic and environmental applications, and for understanding large-scale processes such as crustal recycling into the mantle. In order to better define the behavior of chalcophile metals in basaltic magmas, we measured the concentrations of Re, Cd, Bi, Cu, Pb, Zn, Pt, S, and a suite of lithophile trace elements in basaltic glasses from two Hawaiian volcanoes, Ko'olau and Moloka'i.

Correlated variations in the Re, Cd, Bi, and S contents of these glasses demonstrate loss of these elements from the magma as volatile metals during high-temperature outgassing (Figure 1). Rhenium appears to be considerably more volatile during than previously thought, and may be the most volatile chalcophile metal in basaltic magmas.
Key ratios such as Re/Yb and Cu/Re are fractionated significantly from mantle values in the outgassed basalts. Undegassed Hawaiian tholeiites have Re/Yb ratios significantly higher than those of mid-ocean ridge basalts (MORB), with some values greater than that of the primitive mantle.

The low Re contents of many ocean island and flood basalt lavas may be due at least in part to Re loss during outgassing of the magma. Re volatility during eruption, may help explain the surprising combination of radiogenic Os isotopic compositions and low Re/Os ratios in many plume-related magmas. Mantle plumes with high Re/Yb ratios may provide at least a partial complement to the depleted mantle, and help resolve the 'missing Re' problem in which one or more reservoirs with high Re/Yb are required to balance the low Re/Yb of MORB.

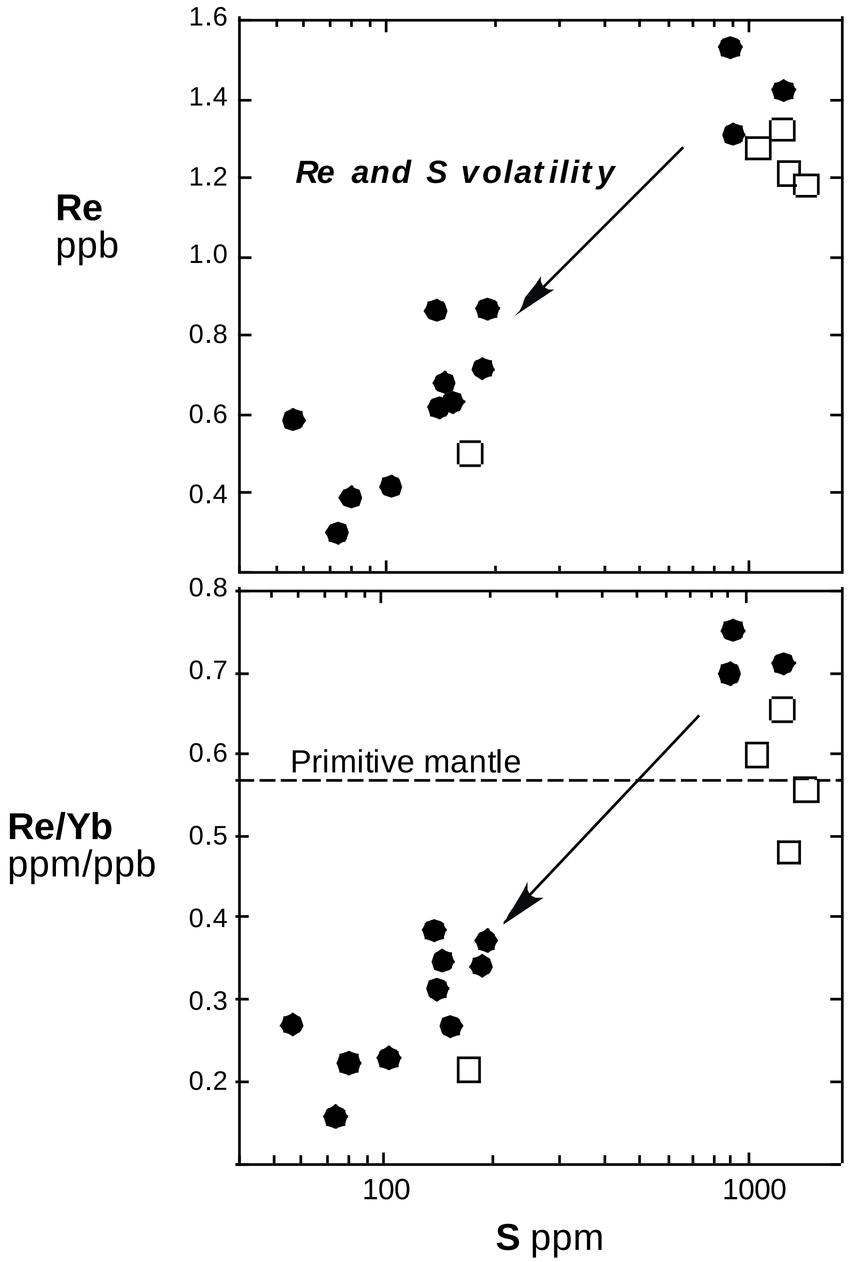

Figure 1. Re contents and Re/Yb ratios of Hawaiian glasses from Ko'olau (filled circles) and Molika'i (open squares) volcanoes, Hawai'i, show strong correlations with sulfur contents indicating loss of these elements as volatiles during high-temperature outgassing of the magmas (Norman et al., 2004).