Contents

Director’s preface 1
Introducing GEMOC *2
GEMOC participants *4
GEMOC programs 5
GEMOC structure see web
GEMOC communications 2003 6
Is GEMOC making a difference? 8
GEMOC’s research program 9
Funded basic research projects for 2004 15
Research highlights 2003 17
Teaching and training program: undergraduate 42
GEMOC honours 45
GEMOC postgraduate 46
Technology development program *49
Industry interaction 52
- Current industry-funded collaborative research projects 55
GEMOC’s international links 59
GEMOC funding 62
Benefits to Australia 63
Appendices
1 Participants 64
2 Publications 66
3 Visitors 72
4 Abstract titles 73
5 Funded research projects 77
6 Flowsheets for courses in geology and geophysics see web
7 GEMOC postgraduate and honours opportunities see web
Contact details 81
Glossary 81
* Additional material available on web version at www.es.mq.edu.au/GEMOC/

Contact details
http://www.es.mq.edu.au/GEMOC/ gemoc@mq.edu.au

GEMOC
Department of Earth & Planetary Sciences
Macquarie University NSW 2109 AUSTRALIA

Leigh Newton
Administrator
Phone: 61 2 9850 8853
Fax: 61 2 9850 8943 or 6904
Email: lnewton@laurel.ocs.mq.edu.au

Professor Suzanne Y. O’Reilly
Director
Phone: 61 2 9850 8382
Fax: 61 2 9850 8943
Email: sue.oreilly@mq.edu.au

Professor W.L. Griffin
Program Leader
Phone: 61 2 9850 8954
Fax: 61 2 9850 8943
Email: bill.griffin@mq.edu.au

Dr Norman Pearson
Manager, Geochemical Analysis Unit
Phone: 61 2 9850 8384
Fax: 61 2 9850 8943 or 6904
Email: npearson@laurel.ocs.mq.edu.au

GLOSSARY

ACILP Australia China Institutional Links Program
AGSO Australian Geological Survey Organisation (now GA)
AMIRA Australian Mineral Industry Research Association
ANU Australian National University
APA (D) Australian Postgraduate Award (Industry)
ARC (LGS) Australian Research Council (Large Grant Scheme)
ARC (LIEF) Australian Research Council Linkage Infrastructure Equipment & Facilities
AWI Alfred Wegener Institute for Polar and Marine Research
CNRS French National Research Foundation
CSIRO (EM) Commonwealth Scientific Industrial Research Organisation (Exploration and Mining)
DEST (SIID) Department of Education, Science and Training (from 2002) (Strategic Infrastructure Initiative)
DETYA Department of Education, Training and Youth Affairs (from 1998)
DIATEEM Consulting company within ML@IR
EMP Electron Microprobe
EPS Earth and Planetary Sciences
EURODOC The council for postgraduate students and junior researchers in Europe
GA Geoscience Australia (formerly AGSO)
GAU Geochemical Analysis Unit (Department of Earth and Planetary Sciences, Macquarie University)
GEMOC Research Center for Marine Geosciences
GIS Geographic Information System
GLITTER GEMOC Laser ICPMS Total Trace Element Reduction software
GPS Global Positioning System
ICPMS Inductively Coupled Plasma Mass Spectrometer
IMURS International Macquarie University Research Scheme
IPFV The French Polar Institute Paul Emile Victor
IFRS International Postgraduate Research Scholarship
IREE International Research Exchange Program of ARC
LAMICTMS Laser Ablation Microprobe Inductively Coupled Plasma Mass Spectrometer
MC-ICPMS Multi-Collector ICPMS
MRL Macquarie Research Limited
MUECRG Macquarie University External Collaborative Research Grants
MUPFA Macquarie University International Postgraduate Research Award
MUNS Macquarie University New Staff Scheme
MUPGRF Macquarie University Postgraduate Research Fund
MURAACE Macquarie University Research Award for Areas and Centres of Excellence
MURD/F/G Macquarie University Research Development (Fund/Grant)
MURF Macquarie University Research Fellowship
NERC Natural Environment Research Council
NSF National Science Foundation (USA)
NSWG New South Wales Geological Survey
ODP Ocean Drilling Program (International Consortium)
PGRF Postgraduate Research Fellowship
QMDE Queensland Department of Minerals and Energy
RAACE Research Areas and Centres of Excellence Postgraduate Scholarships
RBIG Research Infrastructure Block Grant
RSES Research School of Earth Sciences at ANU
SFPT Strategic Partnership with Industry - Research and Training
USC University of Southern California
XRDI X-Ray Diffraction

Front Cover: This year’s cover emphasises the scope of GEMOC’s strategy to understand the way the Earth works: from fieldwork to geochemical analysis to technology development to geodynamic modelling – and from the micron to the global.
This report is required as part of GEMOC’s formal annual accounting to the Australian Research Council. It summarises our activities for 2003 over the broad range of GEMOC activities, including research, technology development, strategic applications and industry interaction, international links and teaching (at both undergraduate and postgraduate levels). We invite you to read the sections of interest to you and would welcome your feedback.

This year we are experimenting with new ways of presenting our Annual Report. The hard copy no longer contains our complete report. The full version is available on our website (www.es.mq.edu.au/GEMOC/) by following the links to the 2003 Annual Report, which can be read online or downloaded as a pdf file. Sections that are only available electronically are highlighted in the Table of Contents and through the text. We enclose a survey to gauge your reaction to different presentation formats, and you can also email your opinion from the website.

As reported last year, GEMOC became self-supporting in 2002 (Commonwealth Key Centre funding for the 1995 round of Key Centres was limited to six years, with no extensions). Our funding now comes from a broad range of sources including the Australian Research Council schemes, industry collaborative projects, delivery of novel exploration methodologies and value-added products to industry, strategic partnerships with technology manufacturers, non-ARC government sources, and international links and alliances that provide reciprocal resources. A $5 million DEST Systemic Infrastructure grant (2002-2004) is allowing GEMOC to maintain its technological edge and develop new analytical applications in geochemistry.

A highlight of 2003 was the construction (to be completed early 2004) of high-quality serviced spaces to house instruments purchased under the DEST Systemic Infrastructure grant and to provide ultra-clean geochemical facilities; these include infrastructure for the development of the U-Series facility by Simon Turner and co-workers. This work will double the original laboratory space and, with the new instrumentation, will provide a unique national resource in integrated geochemical analysis. Large building projects always provide interesting scenarios both logistically and financially and the support of Macquarie University and especially of the Vice-Chancellor have been outstanding. The management talents and construction knowledge of Peter Squibb (from Macquarie Buildings and Grounds) have solved many problems.

Research highlights for 2003 include the broadening of our programs beyond the original goals of understanding the lithosphere and the role of the lithospheric mantle in lithosphere evolution and metallogenesis. This has taken our research both deeper into the Earth, to address geodynamic processes below the lithosphere, and up into the crustal regime. Both of these directions have synergies with industry collaborative projects, illustrating GEMOC’s philosophy of addressing fundamental “big questions” through basic research with parallel strategic and applied goals and with support from relevant technology development.

In addition, new ways of measuring the timing and rates of geological processes have provided more exciting possibilities. The maturing of the application of the Re-Os system for dating important mantle events (including lithosphere stabilisation times) using in situ analyses of tiny mantle sulfide grains now provides a method, currently unique to GEMOC, for understanding the timing of mantle processes. The TerraneChron™ methodology (see Research Highlights) is allowing us to track large-scale crustal tectonism, test styles of crust-mantle linkage and probe the nature and formation age of the hidden lower crust. The processes and time scales of magma formation, transport and differentiation beneath western Pacific island arc volcanoes, and the time scales and relative roles of physical and chemical erosion in Australian river basins are being evaluated with U-series methodologies.

GEMOC’s wide-ranging contributions to national and international conferences and workshops by many staff and postgraduate students again emphasise our continuing multifaceted approaches to understanding the way the Earth works.

GEMOC continues to be strongly supported by the Vice-Chancellor and the Executive at Macquarie.

We look forward to another year of exciting new advances.

[Signature]

O’Reilly
GEMOC’S STRATEGIC FOCUS

The main targets of GEMOC’s founding activities were defined to be large-scale problems related to lithosphere evolution and understanding the relevance of different types of crust-mantle domains to area selection for mineral exploration. These have broadened during 2003 to involve whole-mantle perspectives of geodynamics, and far-field and feedback effects involving the lithosphere.

Despite the coincidence of GEMOC’s term with a time of increasingly contracting activities in the mineral exploration climate, our industry interaction has steadily increased and now forms a significant part of the ongoing funding. Our industry interaction is largely based in strong collaboration; interchange of concepts and discussions on GEMOC strategies relevant to industry needs is invaluable in maintaining our focus on industry relevance.

The increasing industry collaboration with funded projects related to lithosphere evolution and crustal generation studies has fulfilled one of our major strategic goals of delivering new tools and a new framework of terrane analysis to the minerals exploration industry. Some of these new tools and concepts are summarised in the Research Highlights, and the Technology Development section.
Mission

- to create a new paradigm for the formation of metallogenic provinces by undertaking fundamental research on the evolution of the upper 200 km of the Earth’s crust-mantle system, integrating petrological, geochemical and geophysical information
- to give the Australian minerals exploration industry a competitive edge into the 21st century by transferring this new knowledge base and the methodologies to the industry and to the next generation of students

This Mission Statement is being revised to reflect the evolution of GEMOC’s activities to consider Earth Geodynamics beyond the Lithosphere.

Scientific Philosophy

GEMOC’s distinctiveness lies in its interdisciplinary and integrated approach to interpreting Earth’s lithosphere as a 4-dimensional dynamic system (in space and time).

This approach links...
- petrology & geochemistry – geophysics – petrophysics – tectonics – numerical modelling
- within the important contexts of...
- time (the 4th dimension) and thermal state
- to understand the significance of large-scale mantle and crustal domains and the processes that have formed and modified them.

The front cover for this 2003 Report emphasises this integration from field to laboratory to the global scale of our lithosphere studies as well as the interface with geophysical datasets. The present-day timeslice of the seismic character of the deep Earth cannot give us the time perspective to unravel over 4 billion years of Earth’s evolution. However, this is provided by the petrological samples of the mantle delivered to the Earth’s surface at different (and measurable) times by tectonism or magmatism.

Parallel advances in the integration of geophysical and geochemical information to model and image the lithosphere and its properties continue to be driven by our desire to solve more of the intriguing questions about how the Earth has evolved, especially now that we have developed many novel geochemical tools to date important events in the mantle and crust and have made so many fundamental new discoveries about the life and times of lithospheres (see Research Highlights and Technology Development sections). These advances mesh with end-user needs and the knowledge required to solve major geological problems.

“GEMOC’s founding activities ... have broadened during 2003 to involve whole-mantle perspectives of geodynamics and far-field and feedback effects involving the lithosphere.”

GEMOC Board meeting 2003 (details available at www.es.mq.edu.au/GEMOC/).
STRATEGIC OUTCOMES

These were the founding strategic aims in 1995 and are still serving GEMOC well even though there has been much evolution in our understanding and much development of novel methodologies to address these aims.

- fundamental insights into the processes that create and modify the continental mantle and crust through time
- a better understanding of the assembly of the Australian continent and its geological architecture to 100-200 km depth through work in Australia and global analogues
- results and concepts exportable to other terrains, including Southeast Asia and other potentially resource-rich areas of interest to Australian exploration companies
- a new conceptual framework for understanding the localisation of economic deposits, that will influence exploration strategies for world-class ore deposits, and improve the competitiveness of the Australian exploration industry both on- and off-shore
- a realistic 3-D geological framework for the interpretation of lithospheric-scale geophysical datasets
- a training program for senior undergraduate and postgraduate students (and continuing education) that will help maintain the technological edge of the Australian mineral industry and improve the industry’s ability to rapidly assimilate new concepts and methodologies
- new analytical strategies for determining the chemical and isotopic compositions of geological materials (including fluids)
- development of in situ analytical methods (including dating) to maximise information encoded in mineral zoning and to enhance interpretation of data using spatial contexts
- strategic and collaborative alliances with technology manufacturers in design and application innovation

This report documents achievements of these goals
The Host Institution for GEMOC is Macquarie University (in the Department of Earth and Planetary Sciences).

There is a close collaboration with CSIRO Exploration and Mining (EM) (North Ryde) and GA (Geoscience Australia) across an increasingly broad range of projects. Collaborative research, teaching and technology development links have been established with other universities nationally and internationally and these evolve as new alliances become relevant to new directions.

GEMOC has developed ongoing collaborative relationships with national and international industry and end-users such as Geological Surveys globally (eg Australian states, Canada, Norway).

GEMOC has a wide network of international research and teaching development partners and collaborators.

A full list of GEMOC participants and their affiliations is given in Appendices 1 and 3 at www.es.mq.edu.au/GEMOC/

Changes in 2003

Dr Elena Belousova commenced an ARC Postdoctoral Fellowship, and
Dr Vladimir Malkovets commenced his Macquarie University Research Fellowship (MURF).

Professor Simon Turner commenced a Federation Fellowship. He is setting up
a new laboratory and instrument facility to explore new frontiers related to time scales and rates of change that are fundamental to understanding natural processes and the development and testing of quantitative physical models in the Earth Sciences. Uranium decay-series isotope studies are revolutionising this field by providing time information in the range 100 -100,000 years, similar to that of many important Earth processes (see Research Highlights). This work will be relevant to eruption cycles of volcanoes, the Earth’s carbon cycle, time scales and relative roles of physical and chemical erosion in Australian river basins as well as other environmentally important systems and processes.

Three other experienced geochemists, **Dr John Ketchum** (from the Royal Ontario Museum Geochronology Laboratory, Canada), **Dr Rhiannon George** (from Bristol University) and **Dr Kirsty Tomlinson** (with experience from the Canadian Geological Survey) also joined GEMOC in 2003 to enhance the geochemical expertise available and to assist in industry collaborative projects.

**Dr Nathan Daczko** was appointed to the academic staff of the Department of Earth and Planetary Sciences and is an active member of GEMOC. His expertise includes structural and metamorphic geology and geodynamics. Since his PhD at the University of Sydney, he spent 2 years as a postdoctoral Research Fellow at the Department of Geological Sciences and Institute for Geophysics, Jackson School of Geosciences, University of Texas (Austin) where he studied the geodynamic setting of the Australian Plate Margin using integration of petrologic, structural and geophysical datasets (see Research Highlights).

---

**Dr Nathan Daczko** camping at Lake Grave, Fiordland National Park, New Zealand - sandflies love the place (geologists think it is OK too).
THE ORGANISATIONAL STRUCTURE of GEMOC is designed for efficiency, flexibility, and interaction. The financial management operates within Macquarie University’s Finance System and within Macquarie Research Limited for commercialised products, consulting and some strategic collaborative research projects. The Teaching Program is incorporated into the teaching activities and strategies of the Department of Earth and Planetary Sciences at Macquarie to ensure that GEMOC interfaces in a positive way with the existing structures while retaining a clear identity and funding unit.

GEMOC has been reconfirmed as a Centre of Excellence and research concentration within Macquarie University, and three designated Areas of Excellence within Macquarie University’s Research and Research Teaching Management Plan lie within GEMOC:

- lithosphere and planetary evolution and metallogeny
- isotopic and global geochemistry
- paleomagnetism, geodynamics and geophysical modelling

All of these align with GEMOC’s mainstream foci. This University recognition allows for ongoing appropriate staffing and support arrangements.
2003 MANAGEMENT ROLES

Professor Suzanne O’Reilly is Director of GEMOC.

Ms Leigh Newton is GEMOC Administrator.

Dr Richard Flood is the coordinator of Teaching Programs at Macquarie and Head of the Department of Earth and Planetary Sciences from December 1999 (re-elected in 2002).

Professor William Griffin is seconded (80%) to GEMOC (through Macquarie University) from CSIRO in 2003. He is Adjunct Professor at Macquarie University and is the Program Leader responsible for Technology Development and Industry Interaction.

Professor Simon Turner leads the development of the U-Series Geochemical Program.

Dr Norman Pearson is Manager of the Geochemical Analysis Unit at Macquarie.

Dr Kelsie Dadd is responsible for implementation of GIS-based teaching methodology in the Teaching Program and for promotional activities to attract students.

Dr Simon Jackson assists with ICPMS and laser microprobe development at Macquarie.

Ms Sally-Ann Hodgekiss is the GEMOC graphics and design consultant at Macquarie.

ADVISORY BOARD MEMBERS 2003

Changes were made to the Advisory Board in December 2002 to commence in 2003.

Professor Suzanne O’Reilly (Director) - EPS Macquarie  
Professor William Griffin (Program Leader: Technology Development) - EPS Macquarie  
Dr Richard Flood (Program Leader: Teaching) - EPS Macquarie  
Professor Jim Piper – Deputy Vice-Chancellor (Research), Macquarie  
Professor John Loxton – Deputy Vice-Chancellor (Academic), Macquarie  
Dr Kelsie Dadd – GEMOC, EPS Macquarie  
Adjunct Professor Michael Etheridge – Leader, Risk Assessment Group, interfaces with GEMOC’s Tectonic Research program and the Predictive Mineral CRC, links with the Exploration Industry and Management Roles, EPS Macquarie
GEMOC’s programs were set up to be interactive. Basic research strands are supported by parallel applied collaborative research with industry partners: these provide the impetus for technology development. This is, in turn, supported by strategic alliances with front-line instrument designers and manufacturers (e.g., Nu Instruments, Agilent, New Wave Research). Teaching and training benefit directly from these new advances. Technology development has been transferred to relevant end-users, applied in postgraduate research programs, and is the essential core that provides the data underpinning the conceptual advances about lithosphere architecture and evolution in GEMOC.

**Dr Russell Korsch** – representative of Geoscience Australia (GA)

**Dr Richard Glen** – representative of Geological Survey of New South Wales

**Dr Paul Heithersey –** representative of PIRSA

**Dr Jon Hronsky** – industry member WMC (Perth)

**Dr Steve Walters** – industry member GeoDiscovery

**Dr Simon Shee** – industry member DeBeers Australia Exploration Ltd

**Dr Terry Mernagh** – from GA was invited as an observer to the 2003 Board meeting.
EMOC WEB RESOURCES include details of this 2003 Annual Report, past Annual Reports, updated details on methods for new analytical advances and software updates (GLITTER), synthesised summaries of selected research outcomes (eg studies of eastern China lithosphere) and items for secondary school resources on the lithosphere and on diamond occurrence. In addition, undergraduate teaching is web-based.

AWARDS

Dr Nathan Daczko was awarded the inaugural Chris Powell Medal by the Structural Geology Specialist Group of the Geological Society of Australia.

Professor Bill Griffin was Logan Club Distinguished Lecturer, Geological Survey of Canada in February 2003 with the title “Continental Roots: their life and times” and also gave the Keynote address at the Lithoprobe Workshop in Canada in February 2003.

Professor Bill Griffin was elected to the Royal Norwegian Society of Sciences and Letters in 2003. He has been a Fellow of the Norwegian Academy of Science and Letters for nearly 20 years.

GEMOC Director, Professor Sue O’Reilly was inducted into the Australian Academy of Science in May 2003 and gave a presentation “Journey to the Centre of the Earth”. She was also awarded the position of visiting “Director of Research” by CNRS (France) and took this up as a 3 month research visit to the University Jean Monnet, St Etienne.

GEMOC was a Chief Investigator on a funded ARC Network Seeding Grant to foster further national networking (led by ANU, RSES).

PARTICIPATION IN WORKSHOPS AND CONFERENCES IN 2003

GEMOC staff and postgraduates were again convenors or invited speakers or presenters at peak geodynamic and geochemical conferences with over 30 presentations. International fora included: the West Norway Eclogite Field Symposium, the 8th International Kimberlite Conference, the 3rd State of the Arc Conference, the 13th V. M. Goldschmidt Conference, the 5th Hutton Symposium and the American Geophysical Union Fall Meeting. Sonja Aulbach, Sonal Rege and Stuart Graham received full travel grants from the Organising Committee to present papers at the 2003 8th International Kimberlite Conference in Vancouver in June. A full list of abstract titles for Conferences and Workshops attended is given in Appendix 4 and on the GEMOC website where full-text versions of most of the abstracts can also be found.

A major achievement in 2003 was the successful bid by Australia to host the 2006 International Goldschmidt Conference, led by Professor Simon Turner.
The International Workshop and Symposium “Granites and Associated Metallogenesis” was held at Macquarie in July 2003, organised by Professor Bruce Chappell (see p 58 for more details).

Professor Simon Turner was a co-presenter, co-author and co-editor of the volume for the Mineralogical Society of America Short Course on Uranium Series Geochemistry.

The recognition of GEMOC’s expertise in linking the micron with the global is evidenced by the co-convening by Sue O’Reilly of the session “Composition, Processes and Structure of the Mantle” for the 2003 Goldschmidt Conference in Japan and her co-editing of a Lithos issue (to be published in 2004) recording results from the session “Trace-element fingerprinting: laboratory studies and petrogenetic processes” which she co-convened for the 2002 Goldschmidt Conference.

Bill Griffin and Sue O’Reilly were appointed by the IUGG (International Union of Geology and Geodesy) to be co-convenors for a Special Session “Geophysical and geochemical imaging and modelling of continental roots and beyond: implications for the formation and evolution of continents” at the International Geological Conference in Florence in 2004.

**SERVICE ROLES**

In addition to another year on the Physics, Chemistry and Geosciences ARC Expert Advisory Committee, Professor Sue O’Reilly was also a member of the Academy of Science National Committee for Earth Sciences that prepared the *National Strategic Plan for the Geosciences in Australia*.

GEMOC participants are well-represented on editorial boards of international journals, on international expert panels for research evaluation (Canada, Sweden, UK) and on Boards of Geoscience Department and Centres nationally and internationally.

**VISITORS**

GEMOC fosters links nationally and internationally through visits of collaborators to undertake defined short-term projects or short-term visits to give lectures and seminar sessions. Formal collaborative arrangements are facilitated by ARC Linkage grants with reciprocal funding from international collaborators.

Australian and international visitors are listed in Appendix 3.

They have participated in:

- collaborative research, technology exchange,
- seminars, discussions and joint publications,
- collaboration in postgraduate programs.
Highlights of research program outcomes:

- Unique methodology for geochemical imaging of the lithosphere (4-D Lithosphere Mapping) developed to maturity and now being extended to whole-mantle perspectives
- New understanding of lithosphere formation mechanisms and changes through time (eg see “The Deviant Archean” Research Highlight)
- Unique methodologies developed for dating and fingerprinting regional crust and mantle events to test mantle-crust coupling through Earth’s history - also a key to new exploration methods (see Research Highlights)
- Integration of petrological, geochemical and tectonic syntheses with geophysical data is revealing a unique image of the deep Earth (see Research Highlights 2002). This is emphasised by this year’s cover image showing the sweep from fieldwork to laboratory geochemical and technological applications to interpretation of deep Earth architecture and composition.

Highlights of technology development outcomes:

- Focus on in situ analysis of important elements to parts per billion
- Unique method (in situ Re-Os) to date mantle events
- Unique method to track crustal histories (U-Pb dating and Lu-Hf and trace-element fingerprinting of zircons, rutiles): TerraneChron™
- Delivery of rapid, cost-effective and user-friendly new methodologies and software in geochemical analysis
- Establishing the rates of geological processes both for the deep Earth and for surface processes using Uranium decay series dating

Highlights of teaching outcomes:

- Industry-standard training with development of new degree programs (eg Exploration Geoscience, Environmental Geoscience, Marine Geoscience)
- Hands-on undergraduate training in use of state-of-the-art techniques (GIS databases, imaging, geochemical techniques, geophysical measurements) with industry-standard instrumentation
- Vigorous postgraduate group with active international postgraduate exchange programs: (eg Nanjing University, University Jean-Monnet (St Etienne), University of Clermont-Ferrand, University of Oslo, University of Siena, Université Paris 7)
- Short-course programs for end-user information and technology exchange

Highlights of industry interaction outcomes:

- Changing the mineral exploration paradigm by delivering new concepts for exploration globally and in Australia derived from basic research and technology development
- Development of active partnerships in strategic and applied research with industry (exploration companies and technology manufacturers)
- Development of value-added consultancies and collaborative research programs using GEMOC’s geochemical technologies and database

Other sections of this report provide the details of performance indicators and GEMOC’s visibility
SCIENTIFIC CONTEXT

THERMAL ENERGY transmitted through the mantle provides the energy to drive lithosphere processes. Mantle-derived fluids and the tectonic environment control element transfer across the crust-mantle boundary and control commodity distribution in the accessible crust. The nature of mantle heat transmission reveals information on fundamental deep Earth processes from the core-mantle boundary to the surface. The Earth’s interior can be mapped for rock types and their relationships using fragments of deep materials such as mantle rocks and diamonds, and the compositions of mantle-derived magmas.

The focus of GEMOC’s research programs is the driving role of the mantle in Earth processes and its control of element concentration and distribution in the accessible crust. This bottom-up approach involves:

- Understanding the location of different types of metallogenic provinces by defining the links between:
  - mantle evolution, type and processes
  - crustal generation
  - large-scale tectonics
  - heat, fluid and element transport
- Integration of information across disciplines, especially petrology, geochemistry, geodynamics, geophysics and tectonics

The research aims

- to understand from the “bottom-up” the processes that control the generation and modification of the crust-mantle system and to define the tectonic and geochemical processes that have created different crustal and mantle domains through time
- to map the spatial and temporal distribution of elements, rock types and physical and chemical conditions within this system
- to define the systematics of element redistribution in the mantle and crust during the critical liquid-crystal and vapour-liquid separation events
- to advance the modelling of the crust and lithospheric mantle from geophysical datasets, through integration of geophysical, petrological and geochemical information
- to produce and interpret maps of lithosphere thickness and lithospheric mantle type at the present day and for selected time (and location) slices through Earth’s geological evolution
- to produce and interpret chemical tomography sections of lithospheric mantle in time and space where global datasets can be constructed
- to provide a new framework for area selection for a wide spectrum of economic deposits, by linking these models and processes to the formation of metallogenic provinces
- to develop collaborative links with international institutions and researchers relevant to GEMOC’s goals
- to define the timing of events and processes in the crust and mantle to understand crust-mantle linkages
RESEARCH PROGRAM

The Research Highlights section gives an overview of major progress in 2003. The Research Program for 2004 follows the topics of the funded projects listed in Appendix 5. Summaries of funded basic research projects are listed below and some of the collaborative industry research projects are summarised in the section on Industry Interaction.

The research program for the first six years focused on four strands: the current Research Program is pushing into new conceptual and technology frontiers, building on our intellectual capital from the first phase of GEMOC. Additional details on the Research Programs are given at www.es.mq.edu.au/GEMOC/

- **Lithosphere Mapping**
  provides the fundamental data for defining mantle domains in terms of composition, structure and thermal state. Lithosphere profiles built up by this information are interpreted in the context of geophysical datasets (especially seismic tomography) to extrapolate laterally. Relating lithospheric domains to refined models of tectonic evolution will help to define the large-scale evolution of mantle processes through time, and their influence on the development of the crust and metallogenic provinces. The nature of mantle fluids and the mantle residence and abundances of siderophile, chalcophile and noble elements, sulfur, carbon, oxygen and nitrogen and timescales of magmatic processes are keys to understanding the transfer of mineralising elements into the crust.

- **Geodynamics**
  uses stratigraphic, tectonic, and geophysical data to interpret the history and causes of continental assembly and disruption, with a special focus on Australia, East Asia and major cratons (Siberia, Africa, Canada, South America, India). It provides the fundamental framework to link the research on crustal and mantle processes with the localisation and development of metallogenic provinces.

- **Crustal Generation Processes**
  seeks to understand the large-scale processes that have created and modified continental crust, how these processes may have changed through time, and how crustal processes influence the concentration and localisation of economically important elements. The role of crust-mantle interaction in granite genesis, coupled crust-mantle formation and its influence on tectonism, and transport of elements across the crust-mantle boundary link to the Lithosphere Mapping and Metallogenesis strands.

- **Metallogenic Provinces**
  seeks to define the mantle and crustal reservoirs of economically important elements, the mechanisms by which elements can be extracted from the mantle and transported into the crust, and the mechanisms of fluid transfer in the crust and mantle. The emphasis is on understanding processes of regional scale, and relating these processes to the tectonic framework and the processes of mantle and crustal generation.
STRENGTHENING GEOPHYSICS

A major strategic goal of GEMOC is strengthening geophysics and bridging the geology/geophysics interface. During 2003 the following activities addressed this goal.

- Ms Tara Deen continued a Research Fellowship in geodynamic modelling at Macquarie University. This strengthens connections with Dr Dietmar Muller and Dr Patrice Rey at the University of Sydney.
- The strategic alliance with Dr Karsten Gohl of the Alfred Wegener Institute, Bremerhaven proceeded as planned on the mutually funded project collaboration “Structure and dynamics of a submarine continent: evolution of the Campbell Plateau”, involving research cruises by the vessel RV Sonne that commenced in January 2003. Tara Deen was the GEMOC representative on the cruise and GEMOC will be involved in interpretation of mantle structure and composition and basalt geochemistry and origin with German colleagues. Dr Karsten Gohl made arrangements to spend 3 months at Macquarie in 2004 to advance this project.
- GEMOC had continuing access to the pool of seismic detectors, which formed part of the ARC Seismic Consortium (headed by the University of Adelaide/Flinders University with Macquarie, Monash, Sydney, Queensland and ANU as partners and with strong support from GA) and which are now located in the ANSIR facility.
- Dr Yvette Poudjom Djomani, GEMOC Postdoctoral Fellow, continued her work in potential field geophysics (including gravity, magnetic and thermal modelling) in collaborative projects including the SPIRT project on Australian lithosphere studies with WMC. She will also be involved in the new ARC Linkage Project with WMC (Global Lithosphere Architecture Mapping) funded for 2004-2006.
- Collaboration with Professor Paul Morgan (Northern Arizona University, Flagstaff) continued in geophysical modelling.
- The published interpretation and documentation of the results of Global Geoscience Transect 21 (from the Philippine Sea to the Barents Sea) with the Geological Survey of China and the Institute for Gravity, Xi’an continued through 2003.
- Major advances were again made in understanding the interpretation of geophysical signatures of some types of large-scale lithosphere domains (eg Publications #322, 348 and presentations at conferences (see Appendix 4)).
- Professor Bill Griffin was invited as Keynote Speaker for the Copenhagen Symposium in February 2004 on Seismic Heterogeneity in the Earth’s Mantle: Thermo-Petrologic and Tectonic Implications – with the title “Imaging petrological and thermal heterogeneity in the lithospheric mantle: implications for interpretation of geophysical data.”
- Investigation of the paleomagnetism and rock magnetism of rocks from the Lachlan Fold Belt continued.
- Modelling of the density of different types and compositions of lithospheric mantle to assess mechanisms of mantle overturn and thinning in regions of
GEMOC’s research program

different age, thermal structure and tectonic environment continued (eg Publication #303).

• Investigation of the Mooki and Peel Faults, and the Tamworth Belt using gravimetry continued (postgraduate project by Bin Guo).

• Investigation of the 3D shape of a stitching pluton in the New England Fold Belt was undertaken by Mark Lackie.

• Seismic studies of the Amery Ice Shelf in Antarctica continued in collaboration with Associate Professor Richard Coleman of the University of Tasmania.

• SPIRT funding continued on the project with WMC on recognition of lithospheric domains in Australia and integration with thermal and magnetic signatures and datasets: this work was also extended to southern Africa.

• A new ARC Linkage Project with WMC (Global Lithosphere Architecture Mapping) was funded for 2004-2006 and will extend integration of geophysics, geochemistry and geodynamics to interpretation of global tomography datasets.

RESEARCH PROJECTS FEEDING MAJOR PROGRAMS

Lithosphere Mapping

Geochemical structure and evolution of continental lithosphere and interpretation of geophysical data Research Highlights

U-series applications to timescales of lithosphere processes Research Highlights

Mantle terranes and cratonic roots: Canada, USA, southern Africa, Siberia, eastern China, Australia, Brazil, India Research Highlights

Gravity modelling of lithosphere terranes (regional elastic thickness)

Evolution of oceanic lithosphere: Kerguelen Plateau, Hawaii, Crozet Islands Research Highlights

Diamonds: origin and clues to lithosphere evolution and structure; Canada, Siberia, South Africa

Seismic imaging of Moho structure and integration with petrological data: Indian Ocean, Kerguelen Plateau

Basalts as lithosphere/asthenosphere probes

Thermal framework of the lithosphere: paleogeotherms, heat production, conductivity, thermal evolution

Experimental studies of mantle minerals: high pressure partition coefficients; role of accessory minerals in controlling mantle fluid compositions

Lithosphere extension processes and consequences in East Asia: Taiwan and eastern China regions Research Highlights
Constraints on the timing of depletion and fluid movements in lithospheric mantle of different ages, using a range of isotopic and trace-element methods, including Re-Os in mantle sulfides Research Highlights

The nature of lithospheric mantle in arc regions (Japan, Kamchatka, Philippines, Solomon Islands)

Tracking mantle plumes through time

Metal isotopes as tracers of lithosphere processes and Earth evolution

**Crustal Evolution**

Role of oceanic plateaus in oceanic and continental crustal formation: Kerguelen

Crustal evolution and metallogensis, southeastern China

Evolution of continental crust: central Queensland; San Francisco Volcanic Field, Arizona; Peninsular Ranges batholith of Baja California, Mexico Research Highlights

Origin of granites and crustal genesis at continental margins: eastern Australia, southeastern China Research Highlights

Metamorphic reactions and mineral growth; microstructural processes in metamorphic rocks

Tracers of magmatic processes; trace elements in accessory minerals

Integrated U-Pb, Hf-isotope and trace-element *in situ* analysis of detrital zircons to characterise the magmatic history of major crustal terrains (“Event Signatures”): applications of TerraneChron™, South America, South Africa, Australia, India Research Highlights

Timescales of magmatic and erosional processes (U-series applications)

Hf-isotopic signatures of zircons (*in situ* LAM-ICPMS) as tracers of crust-mantle interaction in granites Research Highlights

**Metallogenesis**

Risk management in exploration

U-series applications to timescales of fluid movement

Metal isotope applications to ore genesis

Geochemistry of mantle sulfides Research Highlights

Chromite chemistry in mantle-derived magmas and residues

Resistate minerals and mineral exploration Research Highlights

Area selection and evaluation for diamond exploration

Lithosphere domains through time and location of ore deposits

Crust-mantle interaction, granites and metallogensis through time Research Highlights

Sulfide and PGE budget of the mantle Research Highlights
WHERE IN THE WORLD IS GEMOC?

GEMOC’s research program

Re-Os dating of mantle sulfides in situ and timing of mantle processes
Research Highlights

Highly siderophile element (including platinum group element) concentrations in sulfides (LAM-ICPMS) Research Highlights

Zircon composition in mineral exploration Research Highlights

Groundwater geochemistry and aquifer lithology

Stable-isotope ratios of some important commodity elements (eg Cu, Fe, Zn, Mo) in a range of ore minerals and deposit types

Trace elements in diamonds - possible genetic indicators?

Geodynamics

Influence of mantle processes on crustal geology and topography: regional geotectonic analysis: Slave Craton (Canada), Siberia, eastern China, Australia, Kaapvaal Craton Research Highlights

Neoproterozoic earth history of Australia: Tectonics, isotope-, volcanic- and bio-stratigraphy

Tasman Fold Belt tectonism and regional volcanology: Tumut-Gundagai region; Louth area; central western NSW; central Queensland

Paleomagnetic studies of the northern New England Orogen

Geodynamic modelling of large-scale processes using constraints from 4-D Lithosphere Mapping results Research Highlights

Evolution of lithospheric composition and Earth geodynamics through time Research Highlights
Toward the use of metal stable isotopes in geosciences

Olivier Alard: Supported by ARC Discovery

Summary: Metal stable isotopes (MSI: Mg, Fe, Cu, Zn, Ga) have enormous potential applications (basic and applied) in Geosciences and beyond. However the use of these elements as geochemical tracers and petrogenetic tools requires: (i) the definition of their isotopic composition in Earth’s key reservoirs and in reference materials such as the chondritic meteorites; (ii) understanding and quantification of the causes of MSI fractionations during geological processes. By a unique combination of *in situ* and solution geochemical analytical techniques available now through frontier technology and method development, we aim to establish a conceptual and theoretical framework for the use of metal stable isotopes in Geosciences.

Crustal Evolution in Australia: Ancient and Young Terrains

Elena Belousova: Supported by ARC Discovery

Summary: The mechanisms of crustal growth and the processes of crust-mantle interaction will be studied in selected Archean, Proterozoic and Phanerozoic terrains in Australia, using a newly developed approach: the integrated, *in situ* microanalysis of Hf and Pb isotopic composition and trace-element patterns in zircons from sediments and selected igneous bodies. The results will provide new information on the evolution of the Australian crust, with wider implications for the development of global crust and mantle reservoirs. The outcomes will define crustal evolution signatures related to regional-scale mineralisation, and thus will be highly relevant to mineral exploration in Australia and offshore.

How has continental lithosphere evolved? Processes of assembly, growth, transformation and destruction

Sue O’Reilly and Bill Griffin (with 5 partner investigators): Supported by ARC Discovery and Linkage International

Summary: We will use new *in situ* analytical techniques, developed in-house, to date the formation and modification of specific volumes of the subcontinental lithospheric mantle, and to define the temporal and genetic relationships between mantle events and crustal formation. Quantitative modelling will investigate the geodynamic consequences of spatial and temporal variations in lithosphere composition and thermal state. Magmatic products will be used to assess the roles of mantle plumes and delamination in construction of the lithosphere, and xenolith studies will investigate the evolution of oceanic plateaus. The results will provide a framework for interpreting the architecture of lithospheric terranes and their boundaries.

The timescales of magmatic and erosional cycles

Simon Turner (with 4 partner investigators): Supported by ARC Discovery

Summary: Precise information on time scales and rates of change is fundamental to understanding natural processes and the development and testing of quantitative physical models in the Earth Sciences. Uranium decay-series isotope studies are revolutionising this field by providing time information in the range 100-100,000 years, similar to that of many important Earth processes. This project is to establish a dedicated Uranium-series research laboratory and to investigate (1) the processes and time scales of magma formation, transport and differentiation beneath western Pacific island arc volcanoes, (2) the time scales and relative roles of physical and chemical erosion in Australian river basins.
Funded basic research projects for 2004

Isotopic fractionation of the ore metals (Cu, Zn, Fe): Mechanisms and significance

Simon Jackson: Supported by Macquarie University Research Development Grant
Summary: Utilising recent advances in laser and mass spectrometric technologies, it has been determined that the stable isotope ratios of important metals (eg Cu) exhibit significant variations in ore systems. However, little is known of the fractionating processes. The proposed project will determine the mechanisms that fractionate isotopes of Cu, Fe and Zn by: (a) building a data-base of isotopic signatures for rock types commonly associated with mineralisation, (b) study of selected active and ancient hydrothermal systems, (c) experimental studies. This information will allow metal isotopes to be applied to determining the genesis of, and, potentially, exploration for, ore deposits.

Evolution of the upper mantle beneath the Siberian Craton and the southern margin of the Siberian Platform

Vladimir Malkovets: Supported by Macquarie University Research Fellowship
Summary: This project will contribute new information and concepts about the formation of Earth’s continents over the last 4 billion years. It will use geochemical techniques recently developed with state-of-the-art instrumentation in the GEMOC laboratories, and apply these techniques to unique suites of mantle-derived samples (xenoliths) from volcanic rocks across Siberia to investigate differences between mantle domains of different age and tectonic setting. The results will provide direct analogues for better understanding of mantle structure and mantle evolution beneath Australia, and will contribute to development of tectonic models relevant to the area selection process in mineral exploration.

Lithosphere extension in East Asia: tectonic mechanisms and geochemical consequences

Kuo-Lung Wang: Supported by Macquarie University Research Development Grant
Summary: This project seeks to better understand how continents pull apart (extend) and how the mantle part of the lithosphere (~200 km depth) responds. Novel Re-Os techniques will date mantle samples delivered to the surface in magmas; geochemical fingerprints of processes related to extension will be established. Integration of new geophysical data with geochemical results will constrain the lithosphere architecture. The East Asia region is an ideal natural laboratory and the results will be applicable to analogous tectonic scenarios globally and throughout geological time. The results will have particular relevance for unravelling the geological evolution of Phanerozoic eastern Australian lithosphere.

Melt escape and trace element partitioning during high-pressure partial melting in the lower crust, northern Fiordland, New Zealand

Nathan Daczko: Supported by Macquarie University Early Career Research Grant
Summary: This project aims to derive new constraints on processes of lower crustal (>30 km depth) melting and melt escape. It will test and expand upon the proposed hypothesis that the efficient segregation and transport of magma from the lower crust is controlled by fracture propagation, not just slow upwelling. It is impossible to directly observe active ascent mechanisms at such depths. This, as well as the heterogeneity and structural complexity of lower crustal source regions, has led to controversy. Integration of field relationships, petrological and geochemical analyses will define the parameters of lower crustal melting and improve our understanding of deep-Earth processes.
The ultimate goal of GEMOC’s 4D Lithosphere Mapping Program is to link petrology and geophysics to map the lateral and vertical heterogeneity of the subcontinental lithospheric mantle (SCLM) worldwide. The petrological data derived from studies of xenolith suites in volcanic rocks give baseline data on the distribution of rock types and composition through individual mantle sections, which ultimately can be correlated in detail with geophysical data. But good xenolith suites are scarce and widely scattered on Earth’s surface, and time-consuming and expensive to study. On the other hand, many volcanic rocks contain suites of mantle-derived xenocrysts – the debris from disaggregated mantle wall rocks – that can be easily collected and rapidly analysed in statistically useful numbers. GEMOC has therefore invested considerable resources in extracting petrological data from this abundant reservoir of material, and relating it to geophysical properties like density and seismic velocity.

The most useful mineral in these suites is chrome-pyrope garnet: stable in most mantle peridotites at depths greater than 50-80 km, resistant to weathering, and easily recovered from heavy-mineral concentrates. The ambient temperature where each grain was sampled in the mantle can be estimated from its nickel content, and the information contained in the garnet’s major- and trace-element composition can be put into a depth context by projecting this temperature to a local paleogeotherm, which also can be derived from the garnet concentrates themselves (Publication #92).

Over recent years the information content of garnet concentrates has been expanded in several steps. A statistical analysis of the GEMOC database (now >40,000 garnets) has defined compositional populations that can be identified with specific rock types and processes (Publication #299), and the relative abundances of these can be plotted against depth. Such a “Chemical Tomography” column for the mantle beneath the Kimberley area in South Africa (Fig. 1a) shows that the top of the section (80-120 km) is dominated by relatively fertile lherzolites. The proportion of harzburgites and depleted lherzolites increases with depth, but so does the influence of metasomatism, related to asthenosphere-derived melts infiltrating the base of the lithosphere. Rocks affected by this type of metasomatism become dominant at about 170 km, marking the base of the depleted lithosphere.

The composition ($X_{Mg} = 100 \text{Mg}/(\text{Fe+Mg})$) of olivine that coexisted with each garnet grain can be calculated (Publication #222), and the mean composition plotted with depth. The results for the Kaapvaal section (Fig. 1b) compare well with data obtained from a large sample of xenoliths analysed at GEMOC. The highly metasomatised part of the section around 110 km shows a low in $X_{Mg}$ whereas the lower part, dominated by depleted rocks, has higher $X_{Mg}$ near the median values in xenoliths taken from the literature. The $X_{Mg}$ decreases rapidly toward the base of the lithosphere, giving values like those seen in high-temperature sheared peridotite
xenoliths from many kimberlites. These X\textsubscript{Mg}-depth curves are important because olivine is the dominant phase of the SCLM, and its properties are a major control on density and seismic velocities.

Algorithms have been developed that relate the \Al2O3 content of a peridotite to the composition of its garnet (Publications #90, 132). Figure 1c shows the results based on the Y contents of the garnets. Near the top of the section, the estimated \Al2O3 values are close to the median of published whole-rock analyses of lherzolites, consistent with the abundance of lherzolites in that part of the section. From 125-165 km, the \Al2O3 values are closer to the median of published harzburgite analyses, consistent with the distribution of these depleted rocks in Figure 1a.

In peridotite suites, major oxides are well-correlated with \Al2O3 contents, reflecting processes of melt depletion and re-fertilisation. This lets us calculate the mean bulk composition of the mantle for each point on the \Al2O3-depth curve in Figure 1c (Publication #132). Since we know the X\textsubscript{Mg} of the olivine from Figure 1b (and thus the coexisting orthopyroxene) at each point, the average modal composition of each point also can be derived, using a least-squares mixing equation and average compositions for the minor clinopyroxene and garnet components.

So now we have the temperature, pressure, rock composition, mineral mode and mineral compositions at any depth in the mantle column in Figure 1a. By applying experimental data on the density and elastic properties of the constituent minerals, we can then calculate the density and seismic velocities (V\textsubscript{p}, V\textsubscript{s}) as a function of depth – this is the basic information needed to interpret seismic tomography, and use it to map the mantle.

Figure 2 shows the variation of these parameters with depth for the SW Kaapvaal section, calculated using the algorithms of Hacker et al. (2004; G\textsuperscript{3} 5, #QO1005). These are compared with data calculated by James et al. (2004; G\textsuperscript{3} 5, #QO1002),...
using a suite of 56 xenoliths, and adjusted to the temperature-depth profile used for the garnet data. The similarities between the garnet-derived and xenolith-derived curves are encouraging, especially for the Vp and Vs data. The differences also are instructive; some reflect the choice of elastic constants in the two sets of calculations, and others the nature of the sampling. The xenolith suite specifically excludes samples with significant metasomatic effects, while these are inevitably included in the garnet data. This may explain the lower Vs and Vp predicted by the garnet data for the deeper part of the section (150-170 km). The garnet concentrates indicate a high proportion of strongly depleted rocks in the 130-150 km range, and this probably is a minimum estimate, as such depleted rocks will contribute less garnet to the sample than a similar volume of fertile (and hence garnet-rich) rocks. These depleted (low-density) rocks are not as well represented in the xenolith data, and the difference is reflected in the gap between the density curves over this depth range.

Both sets of data suggest that Vs varies more regularly and more strongly with depth in this cratonic section than Vp, so that the base of the SCLM might be more easily recognised in Vs tomography than in Vp tomography. The success of these calculations in reproducing, from garnet concentrates, the basic chemical and modal data on well-studied xenolith suites means that such petrological data can be derived for many sites worldwide, providing a network of “control points” for the interpretation of seismic tomography and other geophysical data, and the use of those data to map the SCLM.

Contact: Bill Griffin, Sue O’Reilly
Funded by: ARC Large, Industry

Figure 2. Density and seismic velocity beneath the Kaapvaal craton, calculated from garnet concentrate data, and from xenoliths (James et al., 2004).
UNIFORMITARIANISM is a driving force in modern geology; linked with the plate tectonics paradigm, it has provided a powerful tool for the analysis of ancient tectonic regimes. However, there are possible problems with extending the Uniformitarian model into Deep Time. To what extent can we assume that Archean tectonic processes were analogous to Phanerozoic ones? How far back in time can the plate tectonic paradigm, derived from modern observations, be extended before it breaks down?

The composition of the subcontinental lithospheric mantle (SCLM) varies in a systematic way with the age of the last major tectonothermal event in the overlying crust (Fig. 1). This secular evolution in SCLM composition implies quasi-contemporaneous formation (or modification) of the crust and its underlying mantle root, and indicates that crust and mantle in many cases have remained linked through their subsequent history. The differences in SCLM composition also imply a secular change in the mechanisms that have produced the SCLM; this implies, in turn, an evolution in the mechanisms by which continents have formed.

Archean SCLM is distinctively different from younger mantle; it is highly depleted, commonly is strongly stratified, and contains rock types (especially subcalcic harzburgites) that are essentially absent in younger SCLM (Fig. 2). Some, but not all, Archean SCLM also has higher Si/Mg than younger SCLM. Attempts to explain the formation of Archean SCLM by reference to Uniformitarian processes, such as the subduction of oceanic mantle (“lithospheric stacking”), founder on the marked differences in geochemical trends between Archean xenolith suites and Phanerozoic examples of highly depleted mantle, such as abyssal peridotites, island-arc xenolith suites and ophiolites (Fig. 3).

In Archean xenolith suites, positive correlations between Fe, Cr and Al imply that no Cr-Al phase (i.e. spinel or garnet) was present on the liquidus during the melting. This situation is in direct contrast to the geochemical patterns observed in highly depleted peridotites from modern environments, which are controlled by the presence of spinel during melting.

It is more likely that Archean SCLM represents residues and/or cumulates from high-degree melting at significant depths, related to specifically Archean

Figure 1. CaO vs Al₂O₃ for calculated SCLM compositions, showing the secular evolution in the composition of the SCLM (Publications #132, 234).

Figure 2. Chemical tomography sections constructed from the vertical distribution of garnet classes (see “Garnets: Key to the SCLM” in this Research Highlights section) in representative Archon, Proton and Tecton sections. Full details are given in Publications #299 and 303.
processes involving major mantle overturns or megaplumes (Fig. 4). The preservation of island arc-like SCLM at shallow levels in some sections (e.g., Slave Craton, E. Greenland) suggests that a specifically Archean tectonic regime may have coexisted with a shallow regime more similar to modern plate tectonics. If this two-regime model is correct, the late Archean marks an even bigger change in Earth’s geodynamics than generally thought; it may be when the formation of stable SCLM ended, and modern plate tectonics and lithosphere recycling became the dominant regime.

Preliminary data from in situ Re-Os dating of sulfide minerals in mantle-derived peridotites suggest that most Archean SCLM may have formed in a small number of such major events >3.0 Ga ago. The survival of Archean crust may have been critically determined by the availability of large plugs of very buoyant SCLM (a “life-raft model” of craton formation).

Many Archean SCLM sections have been strongly affected by Proterozoic and Phanerozoic metasomatism, and much of the observed secular evolution in SCLM composition, at least through Proterozoic time, may reflect the progressive modification of relict, buoyant Archean lithosphere (Publications #132, 234, 299, 303).

Contacts: Sue O'Reilly, Bill Griffin, Norm Pearson, Natsue Abe, Sonja Aulbach, Rondi Davies
Funded by: GEMOC, Macquarie University, ARC SPIRT, Large, Discovery, Industry

Figure 4. Model for the thermal evolution of a two-layered Earth, after Davies (1995). In an early hot Earth, heat builds up in the lower mantle faster than it can be lost from the upper mantle, leading to periodic convective overturns in which the rising lower mantle passes through the dry peridotite solidus and undergoes large-scale melting at depths ≥150 km. This provides a mechanism for the generation of Archean-type SCLM and this mechanism would cease to operate after Archean time due to the secular cooling of Earth.

Figure 3. Fe and Cr behave incompatibly at high degrees of melting (low Al contents) in the Archean suites but not in the Phanerozoic suites, implying significant differences in the processes of mantle melting.
Earth’s continents are underlain by “roots” 100-250 km thick of depleted mantle rocks, and the properties and history of these roots affect the long-term stability of the continents. Recent advances in analytical technology make it possible to measure the Re-Os age of single grains of sulfide minerals in mantle-derived rocks, and thus to trace the history of the continental roots. The crust of SE China was stretched and subsided to form the Taiwan Strait about 15 million years ago, following subduction of the Paleo-Pacific plate beneath the continental margin in the Mesozoic. Analysis of fragments of mantle rocks brought up by Miocene intra-plate basalts on the Penghu Islands in the Taiwan Strait (see Research Highlights 2002) has been carried out using GEMOC’s novel high-precision in situ techniques for Re-Os isotopic analysis. The Os isotope compositions of sulfides in the mantle-derived xenoliths reveal the presence of Proterozoic subcontinental lithospheric mantle (SCLM) beneath the highly extended southeast margin of the South China block.

The mantle sulfides from Penghu Islands are mixtures of Fe-rich and Ni-rich monosulfide solid solutions (MSS), pentlandite, millerite and chalcopyrite, exsolved from high-temperature (>900°C) MSS bulk compositions. These sulfides have undergone three types of disturbance in their Os isotope systematics, which might be relevant to mantle metasomatism in the SCLM: (1) addition of Re, and of Os with an isotope composition near the present-day PUM; (2) addition of radiogenic Os, but little or no Re; (3) addition of Re with no apparent addition of Os, or with only lithospheric Os with low $^{187}\text{Os}/^{188}\text{Os}$ ratios (Fig. 1). The highly radiogenic Os in type (2) could be derived from lithospheric sources such as pyroxenites or subducted basalts, and the transporting medium may have been an oxidizing fluid derived from the Mesozoic subducting slab beneath the area. Despite the Os disturbance, both $T_{\text{MA}}$ model ages for individual sulfides and model ages estimated from the initial $^{187}\text{Os}/^{188}\text{Os}$ ratios of Re-Os mixing lines (Fig. 1) require that some volumes of the SCLM formed prior to 2.3-1.9 Ga. Later major events in the SCLM may be recorded by $T_{\text{Rd}}$ model ages of 1.5-1.2 Ga and ca. 0.9 Ga, which are consistent with the ages of reworking events in the area.
with the ages of crustal tectonothermal events on the mainland South China block (Fig. 2). The correlations suggest that in situ sulfide Re-Os ages are dating metasomatic events in the SCLM, related to mantle thermal events that also affected the crust.

The results show that depleted parts of the SCLM beneath the Taiwan Straits retain mid-Proterozoic ages, while other, less depleted parts record only younger ages. The mixture of ages and rock types suggests that during the stretching of the lithosphere (the rigid Earth layer above the convecting mantle), the ancient continental root was partly disrupted and replaced by younger material, but stayed attached to the extending lower crust. The oldest mantle ages for the lithosphere beneath the Taiwan Strait are similar to ages from the interior of the mainland. This implies that the ancient mantle on the continental margin of mainland China survived even where major volcanic activity was constructing new crust above it during Mesozoic time. The results are directly relevant to current debates about the geodynamics of the continents, and the long-term evolution of the upper mantle.

Contacts: Kuo Lung Wang, Sue O’Reilly, Bill Griffin
Funded by: ARC, Macquarie University, National Taiwan University

Photo 2. EMP maps of element distribution in an interstitial sulfide grain from a Penghu xenolith, Taiwan.
The region to the east and southeast of the South Island of New Zealand comprising the Chatham Rise, Bounty Trough, Bounty Rise and the Campbell Plateau (Fig. 1) is the largest area of submerged continental crust in the world. Prior to the breakup of Gondwanaland, the Campbell Plateau and Chatham Rise were attached to the Marie Byrd Land and Thurston Island blocks of West Antarctica. The crustal structure and history of the Campbell Plateau-Bounty Trough-Chatham Rise region are poorly known, but are a key element in understanding the evolution of this Gondwanan margin from a convergent margin to continental breakup and rifted margins.

The Campbell Plateau and Chatham Rise are separated by the Bounty Trough. This trough lies parallel to the former Gondwanan subduction margin, which ran along the northern edge of the Chatham Rise (now a suture between the Chatham Rise and the accreted Hikurangi Plateau). The location of the Bounty Trough may have been dictated by a pre-existing back-arc basin, possibly Permian in age (Davy, 1993). It may have acted as a failed rift related to an early South Pacific opening. The timing of the breakup between the Campbell Plateau region and Marie Byrd Land at 84 Ma is relatively well documented by magnetic lineations off the plateau margin (Eagles et al., 2004). What is not so well understood is the process that led to the breakup. How much extension affected the area before oceanic crust developed? Questions yet to be answered include the processes involved in developing the anomalously steep continental slope on the southern margin of the Campbell Plateau; the composition of the crust-mantle boundary across the plateau; the volume, source and timing of magmatism across the area; and whether there are differences between submarine plateau margins and passive continental margins.

Tara Deen participated in the research cruise of the RV Sonne that surveyed the Campbell Plateau region in January and February of 2003 with Karsten Gohl as cruise leader. This is part of a GEMOC collaboration with GEOMAR (Kiel), to investigate the relationships between the Campbell Plateau and multi-stage rifting between New Zealand and Marie Byrd Land.
Zealand and West Antarctica. Two coincidental Ocean Bottom Seismograph (OBS) refraction and marine reflection seismic surveys as well as two high-resolution reflection seismic lines were completed. Preliminary first-arrival models of the seismic data across the Bounty Trough indicate highly extended crust (Fig. 2).

Marine magnetic and gravity measurements were taken continuously throughout most of the cruise, and help constrain more extensive satellite gravity measurements. Swath multi-beam sonar bathymetry and Parasound sediment echosounding data (Fig. 3) were collected along a number of profiles along with dredged geological samples. Geological samples were collected by dredging at a number of seamounts identified from multi-beam sonar bathymetry.

The coincidental refraction and reflection seismic lines will be integrated with analyses of the rocks dredged from seamounts on the Campbell Plateau to develop a 3-dimensional image of the crust of the Campbell Plateau/Bounty Trough region. Rock compositions will be used to calculate seismic velocities for the upper crust, which in turn can be used to interpret the seismic profiles and constrain the composition of the lower crust as well.

Contacts: Tara Deen, Sue O’Reilly, Bill Griffin
Funded by: ARC Discovery, Macquarie University, GEOMAR

Figure 2. Preliminary first-arrival seismic tomography for the Bounty Trough. Reflections have not yet been incorporated. (Top) Quality of penetration. (Bottom) Velocity field for the tomographic inversion.

Figure 3. Multi-beam swath bathymetry was used in the identification of dredge sites, such as these seamounts near the Antipodes Islands.
Oceanic transform faults are important features of global tectonics, but they are difficult to study because they are almost entirely under water. Even where they are (rarely) exposed on land within ophiolites, the faults have typically been deformed during obduction. Our knowledge of oceanic transform faults therefore comes mainly from bathymetry and other geophysical data, dredge samples and a few areas surveyed and sampled by submersibles.

Macquarie Island, located approximately 1200 km southwest of New Zealand in the Southern Ocean (Fig. 1), forms the apex of the Macquarie Ridge Complex (MRC). The MRC is a system of ridges and troughs along the currently active Australian-Pacific oceanic transform plate boundary between the Alpine Fault of New Zealand and the Australian-Pacific-Antarctic triple junction. The island exposes the eastern side of a ~5 km high, ~50 km wide submarine ridge and lies ~4.5 km east of the major active plate boundary fault zone. It is the only subaerial exposure of non-plume-related oceanic crust that still lies within the basin in which it formed, and the transform-related structures on the island can be put in a relatively well-constrained present-day plate tectonic setting. This situation makes Macquarie Island a globally unique opportunity to examine an active oceanic transform plate boundary.

The Australian-Pacific transform plate boundary fault zone, south of New Zealand, is characterised by dominantly normal faults and pull-apart basins, in apparent conflict with the regional transpressional tectonic setting.

Daczko et al. (GJI 125(9),1080) proposed that the present day curvature of the transform is inherited from a pre-existing divergent plate boundary, and that the overall extensional kinematics shown by faults along the main plate boundary trace and exposed on Macquarie Island result from local stresses related to right-lateral, right-stepping, *en echelon* plate boundary faults and not to the current transpressional setting.

Mapping of recent faults affecting the topography of Macquarie Island (Fig. 1) shows the island is extensively cut by high angle normal faults forming pull-apart basins. Furthermore, evidence
for reverse motion is rare. Using marine geophysical data, including swath bathymetry (Fig. 2), reflectivity and seismic reflection data, collected along the Australian-Pacific plate boundary north and south of the island, we have defined a 5-15 km wide plate boundary zone. A series of right-stepping en echelon faults within this zone lies along the main plate boundary trace. At the right-stepping fault terminations, elongate depressions (≤10 km wide and 1.2 km deep) parallel the plate boundary, which we interpret as extensional relay zones or pull-apart basins. We propose that transpression is partitioned into en echelon strike-slip faults at the plate boundary and a convergent component that flexes the crust, causing the anomalous bathymetric ridge and trough morphology of the McDougall and Macquarie segments of the MRC.

Contacts: Nathan Daczko (work done at Department of Geological Sciences and Institute for Geophysics, Jackson School of Geosciences, University of Texas, Austin, Texas)
Funded by: Australian Antarctic Division, University of Texas

Figure 2. 3D perspective view of the MRC (see Daczko et al., G3 4(9), 2003).
GEMOC researchers have obtained a detailed picture of the composition, architecture, and temporal evolution of the subcontinental lithospheric mantle beneath the Slave craton (see GEMOC Annual Reports 2000-2002, Publications #121, 137, 144, 348). Provided that crustal evolution can also be well characterised, the combined data should provide valuable clues to crust-mantle genetic links. Fortunately the Slave craton is well exposed and amenable to field-based research. Detailed mapping of key areas supported by extensive U-Pb dating of zircon, baddeleyite, titanite, and monazite has allowed us to significantly advance our knowledge of crustal evolution.

The western part of the craton is underlain by a Hadean to Mesoarchean basement complex and Neoarchean supracrustal assemblages and plutons, whereas the eastern part is dominated by juvenile Neoarchean crust (Fig. 1). The largely plutonic basement block (the Central Slave Basement Complex of Bleeker et al., Canadian Journal of Earth Sciences, 1999) contains Earth’s oldest rocks, the 4.03 Ga Acasta gneisses (Fig. 2). This basement block is unconformably overlain by a <200 m thick package of quartzite and banded iron formation (the Central Slave Cover Group). Widespread occurrences of this distinctive 2.85-2.80 Ga package (Fig. 1) outline the regional extent of the unconformity, which developed following volumetrically significant basement magmatism between 2.99-2.90 Ga.

The Central Slave Basement Complex evolved through a series of tectonomagmatic episodes that are constrained by U-Pb data (Fig. 3). In all mapped areas we found inherited zircon evidence of older crust-building/recycling events, even though this crust is no longer (and in some cases likely never was) exposed at the surface. The distribution of maximum crustal age, determined from igneous and inherited zircons, suggests outward growth of the basement complex from a nucleus containing the Acasta gneisses, with present-day size reached by ca. 3.3 Ga (Fig. 4). This growth pattern is broadly consistent with existing Nd and Pb isotopic data. Possible tectonic settings for basement growth have yet to be fully evaluated, but episodic magmatism is certain to have played an important role.

The basement complex is underlain by a highly-depleted mantle layer extending to 150 km depth. The western boundary of this layer is relatively unconstrained due to an absence of kimberlite pipes, but the layer thins or terminates toward the northern and southern (younger) edges of the craton.
Beneath this layer, a more fertile mantle layer extending from 150 to ~220 km depth underlies much of the craton. Emplacement of this lower layer during mantle plume activity at 3.3 Ga is indicated from a variety of data. An older age is therefore inferred for the shallow mantle layer, consistent with its location beneath similarly ancient crust. Plume emplacement of the lower layer suggests that mantle-derived magmas may have invaded the basement complex at 3.3 Ga. We are in the process of characterising crustal and mantle contributions to the magmatic episodes shown in Figure 3 by in situ laser ablation analysis of Hf isotopes in zircon, using GEMOC’s Nu Plasma multicollector ICP-MS.

Contacts: John Ketchum, Bill Griffin, Sue O’Reilly, (Wouter Bleeker, Geological Survey of Canada)
Funded by: ARC Discovery, Lithoprobe, Geological Survey of Canada, Natural Science and Engineering Research Council of Canada

Figure 3. Histogram of all U-Pb ages for the western Slave craton. Most of the data represent igneous protolith ages. Ten age groupings have been defined; each corresponds to one or more discrete geological events.

Figure 4. Contoured distribution of maximum protolith age based on the data in Figure 3, with additional input of whole-rock Nd and Pb isotopic data. Maximum age of crust appears to young outward from a central core. Heavy dashed line outlines the extent of a highly-depleted upper mantle layer (western boundary relatively unconstrained; see Publications #121, 137, 144, 348) that likely predates 3.3 Ga and may represent the original mantle lithosphere of the Central Slave Basement Complex.
ROGENIC PERIDOTITE bodies are widespread in the Western Gneiss Region (WGR) of western Norway. These bodies typically occur as small garnet-bearing volumes within larger masses of garnet-free dunite. In situ Re-Os analysis of mantle sulfides from the garnet peridotites has demonstrated that at least some of these fragments are Archean (see Research Highlights 2001). In fact, there is growing evidence indicating that all of these bodies have an Archean origin, despite being surrounded by gneisses that appear to be no older than Proterozoic.

Dunite comprises the great bulk of the WGR peridotite massifs. The Almklovdalen peridotite in southern WGR is one of the larger bodies in the region with an estimated volume of 70-80 billion tonnes and approximately 90% of this is highly refractory dunite. Unfortunately the dunite contains very little sulfide and therefore conventional whole-rock methods have been employed to date this material. Whole-rock Re-Os analysis of the dunites yields model ages that range from 2.7 to 3.1 Ga, similar to the range seen in the sulfide data for the garnet peridotites (see Research Highlights 2001), suggesting that these rocks experienced an Archean partial melting event.

Previously, Proterozoic ages for the garnet-bearing peridotites and the basement crustal rocks of the WGR led to the suggestion that the mantle and crust in the southern Caledonides of Norway, as well as other terrains adjacent at the time, were coupled throughout much of the Proterozoic (Brückner and Medaris, 1998). However, the Archean Re-Os ages now established for the Almklovdalen peridotite body provide evidence for a much older depletion event in the mantle beneath the Baltic Shield. This is intriguing as there is no geochronological evidence for the presence of Archean crust in the WGR, although the possibility has been discussed in the literature. It is possible that the peridotite bodies reflect a mantle depletion event that predated crustal growth in this part of the Baltic Shield. Alternatively, the Archean crust corresponding to this mantle depletion event may have been reworked in Proterozoic time, to the point of being unrecognisable. A third possibility is that Archean crust exists at deeper levels than those presently exposed.

A potential tool to help in determining the presence, or absence, of Archean crust in the WGR is GEMOC’s TerraneChron technique (see Research Highlights 2002). TerraneChron utilises detrital zircon to provide timing and tectonic style information for inaccessible crustal terranes, and may prove the key to unlocking the Archean history of this part of the Baltic Shield.

Contacts: Eloise Beyer, Bill Griffin, Sue O’Reilly
Funded by: GEMOC Macquarie, MUPGRF, ARC Large
Spinellite lherzolite xenoliths hosted by Tertiary basaltic magmas have been used to characterise the composition, architecture and evolution of sub-continental lithospheric mantle beneath the New England Orogen, Eastern Australia. Studies of their detailed mineralogy and geochemical characteristics reveal regional variations in the degree of melt extraction and the type and extent of metasomatism that has affected the lithosphere.

At the Allyn River locality (Fig. 1), two distinct populations of xenoliths can be identified on the basis of microstructure, whole-rock and mineral major-element chemistry, and clinopyroxene trace-element chemistry. One group is granoblastic and shows no evidence of deformation; the other group is generally more coarse-grained, with common exsolution in pyroxene and kink-banding in olivine. These coarse-grained xenoliths contain trails of small sulfide grains (< 10 µm) along fracture planes in the silicate phases. These sulfide-bearing trails are absent in the granoblastic xenoliths: instead sulfides are found as relatively large polyminalic aggregates (~ 100 µm across) within melt pockets interstitial to the silicate phases (Fig. 2). These melt pockets have not been observed in the coarse-grained xenoliths. Equilibration temperatures calculated for the granoblastic xenoliths are lower than those of the coarse-grained samples, suggesting they represent a shallower mantle volume.

In addition to the sulfide patches, the melt patches contain variable proportions of secondary olivine ± clinopyroxene, plagioclase, K-feldspar, Mg-rich carbonate, Ca-rich carbonate, glass, ilmenite, apatite, and a titanium and chrome-rich oxide phase (spinel?). Mg-carbonates are dolomitic, suggesting a high-pressure origin. The melt patches are interpreted to represent crystallised volatile-bearing melts rich in CO₂, and would be highly mobile at mantle pressure and temperature. The close association between the sulfides and the melt patches indicates that sulfides can be highly mobile under some mantle conditions. This implies that pre-existing sulfides may be mobilised or deposited during metasomatic episodes, changing the abundance of chalcophile elements such as Re and Os, which would modify the original age information from the Re-Os system. Any Re and Os data from mantle rocks need to be interpreted within a detailed mineralogical context and a knowledge of the nature of sulfides within the rock.

Contacts: Will Powell, Sue O’Reilly
Funded by: GEMOC, MUPGRF, ARC Large

Figure 1. Melt patch in sample AR-10. The bright region in the centre of the back-scattered electron image (bse) which is black in the Si map is the sulfide patch. Beside it is a Ca-Mg-carbonate, which is also black in the Si map. Secondary clinopyroxene, some apatite, and Ti-rich chrome spinel are present also.
Fluid fronts surge through the Kerguelen lithospheric mantle

The Kerguelen Islands are the exposed part of the Kerguelen oceanic plateau, a Large Igneous Province in the Antarctic plate domain. Its birth is related to both the spreading of the South East Indian Ridge (SEIR) overprinted by the long-lived Kerguelen plume. It provides a unique opportunity to study plume-ridge interactions and their implications for the composition of the oceanic mantle. Mantle xenoliths from the Kerguelen Islands are common in dykes or pipes of young alkaline lavas. The major and lithophile trace elements have been well-characterised over the last decade. The platinum group elements (PGE; Os, Ir, Ru, Rh, Pd, Pt) and chalcophile elements (S, Se, Cu) provide different information on the geological processes that operate in the lithosphere. This is because they are almost exclusively partitioned into a sulfide-rich melt, whereas major and lithophile trace elements have a greater affinity for silicate melts.

The PGE, S, Se and Cu were analysed in representative mantle xenoliths (harzburgites and dunes) for which data on major elements and lithophile trace elements in bulk-rock and separate mineral grains were already available. The harzburgites do not contain obvious sulfide grains and therefore have low S, Se, Cu contents and high Os, Ir, Ru and Rh relative to (Pd + Pt). These features indicate that these pieces of Earth's mantle are residues after a large degree of melt extraction, during which the sulfide phase was exhausted.

Some harzburgites show microstructural and geochemical evidence of refertilisation by percolation of basaltic to alkaline melts but still have concentrations of the compatible PGE (Os, Ir, Ru, Rh) lower than expected from partial melting models. This suggests a decoupling between the PGEs, major elements and lithophile trace elements during melt/rock reactions in the upper mantle. The major elements and lithophile trace elements are re-introduced into the harzburgites, while the PGE are further depleted during the melt/rock reactions. Dunite samples formed through extensive melt/rock reactions and have about the same concentrations of PGE as the harzburgites.

Some dunes were further impregnated by small volumes of highly evolved volatile-rich silicate melts, which precipitated carbonate and sulfide grains disseminated through the olivine matrix. The bulk-rock and sulfide chalcophile and PGE abundances of these rocks display unusual fractionations that suggest different sulfidation mechanisms. A group of samples with broadly chondritic S/Se and Os/Ir ratios and no enrichment in Pd over Pt (Pd/\(\text{Pd}_{\text{N}}\) = 1) contains Cu-Fe-Ni-rich sulfide melt droplets, apparently unmixed from metasomatic carbonate melt patches. In contrast, some dunes with abundant Fe-Ni sulfides have superchondritic S/Se ratios (up to 10000), coupled with superchondritic Os/Ir\(_{\text{N}}\) and Pd/\(\text{Pd}_{\text{N}}\). This correlated behaviour of Os, Pd and S suggests transport in a S- and Cl-bearing CO\(_2\) vapour phase.

Chalcophile and platinum group elements are proving to be useful tracers of metasomatic agents in the mantle, providing further geological information that is not easily accessible from major and lithophile trace elements alone.

Contact: Guillaume Delpech, Sue O’Reilly
Funded by: GEMOC, MUPGRF, IPRS, ARC IREX, ARC Large
The rates of plate tectonic processes and the vastness of geological time have led to a sense that many changes take place very slowly on Earth. However, processes ranging across melt formation and migration, volcanic eruptions (Fig. 1), erosion and water flow (Fig. 2) all occur on time scales of days to thousands of years. Thus, if we wish to study these processes and to constrain their mechanisms via detailed knowledge of their time scales, we need to apply chronometers that have very short half lives. The nuclides of the U and Th decay chains provide such tools and their application is one of the most rapidly growing areas in modern isotope geoscience.

The continental crust has been formed by partial melting and magma differentiation. In principle, magma differentiation could occur via a number of different processes including cooling, decompression and degassing. Research carried out by Simon Turner and Rhiannon George (now at GEMOC) with Chris Hawkesworth and Georg Zellmer has shown that the activity ratio of $^{226}$Ra to $^{230}$Th decreases systematically as magmas become differentiated from basalt to andesite to dacite to rhyolite. This appears to be true in a number of tectonic settings including island arcs and in continental rifts and both at the scale of a whole island arc and within individual volcanoes. $^{226}$Ra and $^{230}$Th are nuclides within the $^{238}$U decay chain and $^{226}$Ra has a half life of 1600 years. Thus, the decreases in $^{226}$Ra with increasing silica in young lavas strongly suggest that differentiation of the magmas occurred within several half lives or 1600-5000 years. Such time scales are similar to numerical estimates for the cooling and crystallisation of moderate sized magma bodies in the lower to middle crust and so the Ra isotope data suggest that magma differentiation in the volcanoes studied occurs in response to cooling rather than decompression or degassing, both of which are likely to occur in weeks to a few years at most.

Greater detail can be obtained by measuring the U-series nuclides in crystals from lavas and these reveal many complexities. Results indicate that crystal grains are commonly older then their enclosing volcanic glass and many are likely to show age zoning. When the isotope data are combined with microstructural information such as grain size distributions, it can be shown that many of the grains did not grow in situ but were entrained by the host magma from cumulates left behind by previous magma batches. One implication is that the grains observed in a volcanic rock may often not be the ones responsible for its bulk compositional evolution. Such data also inform models for the longevity and past history of a volcano and will ultimately help in the development of better predictive models for volcano hazards.

Contacts: Simon Turner, Rhiannon George
Funded by: NERC + Royal Society at the Open University and University of Bristol (where this work was done with co-workers)
The Slave Craton and the Buffalo Head Terrane (BHT) in northwestern Canada are two ancient entities in the mosaic of provinces and terranes that make up the North American Craton. They are currently juxtaposed, which raises the question of whether this spatial relationship is accidental or whether they were part of a single larger craton. Studies of the lithospheric mantle can help answer this question.

The subcontinental lithospheric mantle (SCLM) beneath Lac de Gras (central Slave Craton) is strongly layered, with an ultra-depleted shallow and a less depleted plume-related deep layer (see Research Highlights 1997, 2000; Publications #137, 303). Some sulfides from the deep SCLM layer lie on a $3.27 \pm 0.34$ Ga isochron with a supra-chondritic initial Os isotopic composition that may be interpreted as the signature of a high-Re/Os source, such as the lower mantle or outer core. This age exceeds that of the overlying crust, part of the Contwoyto terrane, but coincides with a period of major crust formation in the neighbouring Central Slave Basement Complex (CSBC), suggesting that CSBC-type deep SCLM was thrust under the younger Contwoyto terrane during 2.7 Ga collision (Publication #346; Fig. 1A-C).

Proterozoic metasomatism by possibly asthenosphere-derived melts that evolved from silicate to small-volume residual melts similar to carbonatite is indicated by high Lu/Hf, but low Sm/Nd in garnet, resulting in highly radiogenic Hf and unradiogenic Nd. Interaction with melts that originated from a source similar to that of the host kimberlites preceded 50 Ma kimberlite magmatism and led to variable resetting of Nd and Hf isotope ratios (Fig. 1E).

The BHT consists
mostly of Proterozoic basement rocks, but there are indications that this basement was continuous with the Rae province in Archean times (Fig. 2A). Peridotites from Buffalo Hills have a range in FeO, MgO and SiO$_2$ similar to those in the deeper layer of the central Slave craton section and this may suggest that the mantle beneath the BHT and the central Slave craton formed under similar conditions, i.e. plume subcretion. Lower mantle inclusions in diamonds from the Buffalo Hills kimberlites strengthen the plume connection (Publication #346).

As in the Slave Craton, a later (in this case Proterozoic) metasomatic event is recognised, involving silicate melts that evolved to small-volume volatile-rich melts through interaction with garnet-bearing mantle, but the importance of different metasomatic styles and their distribution with depth are different. This metasomatism may have occurred during 2.4 to 2.3 Ga rifting of the Buffalo Head Terrane from the neighbouring Rae province (Fig. 2B) and may be responsible for the evolution of some samples toward unradiogenic Nd and Hf isotopic compositions. No metasomatic processes related to subduction beneath the BHT during collision with the Chinchaga domain at 2.0-1.9 Ga are evident in mantle rocks from the BHT (Fig. 2C). However, an additional metasomatic event around 1.9 Ga may be documented by sulfide in one peridotite that has unradiogenic $^{187}$Os/$^{188}$Os and gives a model age of 1.89 ± 0.38 Ga (Fig. 2D). This age coincides with the inferred emplacement of mafic sheets in the crust and suggests that the melts parental to the intrusions interacted with the lithospheric mantle. A young metasomatic event is indicated by the occurrence of sulfide-rich melt patches, unequilibrated mineral compositions, and overgrowths on spinel that are Ti-, Cr- and Fe-rich but Zn-poor (Fig. 2E; Publication #352).

In summary, there are definite differences between the two cratons: the strong layering of the SCLM beneath the central Slave craton is absent beneath the BHT, and metasomatic signatures in different depth intervals differ in style. However, there are also some parallels in the evolution of the SCLM beneath the two areas. This may indicate that plume-influenced SCLM growth and repeated metasomatism, including metasomatism precursory to kimberlite magmatism, are common milestones in the genesis and evolution of Archean to Proterozoic SCLM.

Contacts: Sonja Aulbach, Bill Griffin, Sue O’Reilly
Funded by: GEMOC, IPRS, MUIPRA, MUPGRF, ARC Large, ARC Spirit, Industry
The Old Soak – Hf in MARID rutile unravels mantle metasomatism

Research highlights 2003

The Group I Kimberlites of the Kaapvaal Craton in South Africa carry many types of mantle-derived xenoliths, providing a snapshot of mantle composition at the time of eruption (ca 90 million years ago). The xenolith suite contains rare but spectacular samples of rocks known as MARID (from their mineral assemblage Mica-Amphibole-Rutile-Ilmenite-Diopside), some of which are altered to Phlogopite-Ilmenite-Clinopyroxene (PIC) assemblages. The origin of these rocks – whether metasomatic or magmatic – has been widely debated, and several detailed isotopic studies have been inconclusive. These rocks are difficult to study isotopically, because their complex history means that mineral separates may record only the average of several different processes. In situ isotopic analysis, with better spatial resolution, might resolve these processes, but most of the elements of traditional isotopic systems are too dilute in the main minerals to be analysed in situ.

However, preliminary studies showed that the rutile in MARID and PIC rocks contains 900-1500 ppm Hf, which is enough to get analyses of useful precision for $^{176}$Hf/$^{177}$Hf (±0.0002, 2 sigma) using GEMOC’s LAM-MC-ICPMS techniques. The rutiles are very refractory, and they have very low Lu/Hf ratios, so that the Hf-isotope composition of the rutiles can be regarded as “frozen in” at the time of crystallisation. We therefore have analysed Hf isotopes in large (0.5-5 mm) rutile grains in 9 xenoliths, showing the full range from typical MARID, through intermediate MARID-PIC samples to PIC.

The rutiles proved to be isotopically very heterogeneous. $^{176}$Hf/$^{177}$Hf ranges from 0.2812-0.2858 (Fig. 1); much of this range is found within single samples and even within single grains. The lowest values represent Hf that has been isolated from the Depleted Mantle source for about 3 Ga, similar to ages derived for the formation of the SCLM under the Kimberley area (see 2002 Research Highlights). The highest values lie far above the mean value for the present-day Depleted Mantle, and represent Hf that has resided in a rock or mineral with high Lu/Hf for a long time. One possible reservoir is mantle garnet; with typical $^{176}$Lu/$^{177}$Hf ratios of ca 0.085, such garnets could “grow” the most radiogenic Hf seen in the MARID rutiles over ca 2.8 Ga (Fig. 1).

We therefore suggest that the MARID rocks initially resulted from the interaction of an asthenospheric melt with ancient harzburgitic mantle, which has dominated their Hf budget (giving the low Hf isotopic signatures). They were later metasomatised by a fluid/melt that had caused the breakdown of eclogitic or lherzolitic garnet with high Lu/Hf, providing a source of highly radiogenic Hf (explaining the range to high Hf isotopic signatures).

During the analytical work, a single large (1.5 mm) zircon was found in one of the MARID samples. Its Hf isotope composition ($^{176}$Hf/$^{177}$Hf = 0.28224±2) lies near the mean value for the rutiles, linking it to related metasomatic activity. It gave a LAM-ICPMS U-Pb age of 112±4 Ma, which corresponds to the age of the older (Group II) kimberlite magmatism in the area, and is consistent with a genetic link between MARID and Group II kimberlites (Gregoire et al., 2002. Contrib. Mineral. Petrol. 142, 603-625).

---

Figure 1. Hf isotope evolution plot showing composition of Hf in rutiles from MARID and PIC samples, and evolution of Hf isotopes in mantle peridotites and eclogites.
The low \(^{176}\text{Hf}/^{177}\text{Hf}\) preserved in MARID rutiles also helps to resolve one of the minor controversies about the origin of kimberlites. In plots of Nd-Hf isotopes (Fig. 2), the Group I and Group II kimberlites define long trends pointing to low values. Nowell et al. (1999, Proc. VII\(^{th}\) Int. Kimberlite Conf., 2, 616-624) argued that these data require a “hidden reservoir”, probably located in the very deep mantle, while Griffin et al. (2000, Publication #179) suggested that this reservoir was simply the lithospheric mantle. The new \textit{in situ} rutile data, combined with published data on MARID rocks (Fig. 2) show that the Nd-Hf isotopic systematics of kimberlites and lamproites also can be explained by contamination of asthenospheric melts with the ancient subcontinental lithospheric mantle, without any mysterious hidden reservoirs.

\textbf{Contact: Mathieu Choukroun, Sue O'Reilly, Bill Griffin}

\textbf{Funded by: ARC Discovery}

\textbf{A Wide Variety of Granitoid Rocks was Generated in the Georgetown Inlier (Fig. 2) during three major events in Mid-Proterozoic, Siluro-Devonian and Permo-Carboniferous time. Contemporaneous mafic and felsic magmatism during these events could reflect the underplating of the continental crust by basaltic magmas (Black and McCulloch, 1990). As part of a study of the evolution of the crust-mantle system beneath this region, three detrital zircon samples were taken from the Etheridge Province, where Siluro-Devonian I-type granites and Permo-Carboniferous I-, S- and A-type granites intruded the Proterozoic Einasleigh Metamorphics. The zircons were analysed by \textit{in situ} LAM-ICPMS (Laser Ablation Microprobe Inductively Coupled Plasma Mass Spectrometry) for U-Pb ages, trace element patterns and Hf isotope composition (the \textit{TerraneChron}™ approach: see Research Highlights p39).

U-Pb dating yielded Mesoproterozoic, Siluro-Devonian and Permo-Carboniferous ages comparable to those recognised from existing SHRIMP U-Pb zircon data. The modelling of \textit{in situ} LAM-ICPMS trace-element data indicates that the majority of zircons are derived from granitoids with 65-75 % SiO\(_2\), consistent with the known geology. Many of the zircons, especially in one sample, are characterised by resorbed cores of Proterozoic age overgrown by oscillatorily-zoned rims of Siluro-Devonian age (Fig. 1), offering an opportunity to study magma sources and evolution in two time slices.
The Proterozoic cores in Siluro-Devonian zircons, and single grains with Proterozoic ages, are characterised by a wide spread of $\epsilon_{\text{Hf}}$ values, from 11.2 to -9 (Fig. 3). The lowest values give model ages (assuming an average crustal source) of more than 3 Ga, while the highest lie near the value for the Depleted Mantle at the time. This suggests mixing between magmas derived from Archean crust (low $\epsilon_{\text{Hf}}$) and magmas of juvenile origin (high $\epsilon_{\text{Hf}}$). The Siluro-Devonian rims, and single grains with Siluro-Devonian ages, also show a large range in $\epsilon_{\text{Hf}}$ from 2 to -26.5. This spread could reflect either mixing of crustally-derived and juvenile magmas, or the remelting of a heterogeneous Proterozoic crust. The observation that high-$\epsilon_{\text{Hf}}$ rims are found on high-$\epsilon_{\text{Hf}}$ cores (Fig. 3) tends to favour the latter model, and does not indicate a large juvenile contribution to the crust in Siluro-Devonian time. However, some zircons have $\epsilon_{\text{Hf}}$ too high to be derived from Proterozoic sources, and their trace-element chemistry indicates they are derived from mafic rocks. Basaltic underplating thus may have provided a heat source for remelting of the Archean to Proterozoic lower crust to generate most of the Siluro-Devonian granitoids.

The zircons from the Permo-Carboniferous granitoids show a much narrower range in $\epsilon_{\text{Hf}}$ and a higher mean value (+7), indicating a much larger contribution of juvenile material than occurred in either Proterozoic or Siluro-Devonian time. These preliminary results suggest that the Georgetown Inlier is underlain by Archean crust, although the surface geology is dominated by Mesoproterozoic basement rocks and Paleozoic granitoids. Its crustal evolution has involved at least three stages of strong heating, possibly associated with basaltic magma underplating and/or overplating, and reflecting the complex tectonic history of north Queensland. However, the most significant juvenile additions to the crust, after the Archean, may have occurred in Permo-Carboniferous time.

Contact: Valeria Murgulov, Sue O’Reilly, Bill Griffin
Funded by: Macquarie University, BHP Billiton, APA

Figure 3. Plot of $\epsilon_{\text{Hf}}$ vs age for Georgetown zircons from three samples (circle, triangle and cross). Zircons lying below the CHUR (Chondritic reservoir) line are derived largely from crustal sources; those lying between CHUR and Depleted Mantle contain material derived from both crustal and juvenile sources. The arrows connect the Proterozoic core and Siluro-Devonian rim in representative grains.
**TerraneChron™**: a competitive edge in exploration and understanding crustal evolution

**ERRANECHRON™** is GEMOC’s unique methodology for terrane evaluation and studies of crustal evolution. It is based on the integrated *in situ* analysis of zircons for U-Pb ages, Hf-isotopic composition and trace-element compositions using GEMOC’s laser-ablation-microprobe ICPMS technology. It can be applied to zircons from single rocks or to zircons separated from drainage samples judiciously collected within a defined catchment (on scales of 10 - 1000 km depending on terrane and terrain).

The zircon *U*-Pb analyses provide rapid and cost-effective age determinations with accuracy comparable to the ion microprobe; the Hf-isotopic data provide information on the source characteristics of the magmatic parent rock to the zircon - whether it was generated by crustal reworking or from young mantle (“juvenile”) sources. The trace elements provide information about the composition of the magmatic rock that precipitated the zircon.

The combination of age, composition and sources of magmas for a large number of grains from drainage samples yields an “Event Signature” providing a clear fingerprint of crustal evolution events (Fig. 1).

In this “Event Signature” diagram, trends toward the lower left (see key on Fig. 1) indicate tectonic events dominated by *reworking of pre-existing crustal material*. Juvenile (young mantle) input is shown by trends towards the upper left. Trends of intermediate slope imply contributions from both juvenile and pre-existing crustal sources.

Figure 1 shows results for the Mt Isa Eastern Succession (Australia) and southern Norway. **Mt Isa’s tectonic history**, as shown by these zircons, starts with a short episode of Late Archean crustal reworking, followed by several episodes of juvenile addition and mixing with reworked crust up to about 1.8 Ga, a short period dominated by crustal reworking, then a significant juvenile input at ca 1650 Ma, associated with the main Mt Isa mineralisation. This was followed by crustal reworking over a period of about 200 Ma, producing rocks such as the Williams Batholith and minor later intrusives. This pattern reflects *repeated extensional tectonism and magmatism superimposed on a pre-existing old crustal environment*.

In contrast, the Event Signature for **southern Norway** (a poorly mineralised area) shows no Archean prehistory, but is dominated by juvenile input from 1.6-1.4 Ga; and by crustal reworking from 1.4-1.3 Ga. This pattern reflects the *continual buildup of new crust at a convergent margin*. The Sveconorwegian (Grenville) episode started with pulse of juvenile input at ca 1.2 Ga, but the later magmatism (1.1- 0.9 Ga) was dominated by crustal reworking.
The TerraneChron™ methodology thus:
• Yields a synthesis of the tectonic history in the region sampled and identifies relative crust- and mantle contributions to specific magmatic episodes
• Can be used as a cost-effective reconnaissance tool in remote, inaccessible or complex terranes for evaluation of exploration potential
• Can potentially fingerprint the tectonic signatures associated with different styles of mineralisation
• Defines the timescales for crustal reworking and thermal relaxation after major crustal-generation events

Contacts: Bill Griffin, Sue O’Reilly, Elena Belousova
Funded by: ARC Discovery, Industry, Macquarie University Collaborative Grants

The Kerguelen Archipelago is located in the southern part of the Indian Ocean. Along with Heard Island 500 km to the south, the islands lie on the huge Kerguelen-Heard oceanic plateau (25 x 10⁶ km²), which is the second largest in the world after the Ontong-Java plateau. Numerous occurrences of ultramafic to mafic xenoliths (24 outcrops) have been described in the Kerguelen archipelago with a higher concentration in the southeastern province (Ronar’ch and Jeanne d’Arc peninsula; see p. 32). The Kerguelen archipelago has provided the largest diversity of xenoliths ever observed in an oceanic setting (Grégoire et al., Eur. J. Min., 9, 1996).

Some mantle-derived Kerguelen harzburgite and dunite xenoliths have bulk-rock and mineral trace-element compositions that provide evidence of carbonatitic metasomatism similar to that described in some continental and other oceanic settings. Rare xenoliths contain carbonates that are highly enriched in rare-earth elements (REE), interpreted to be quenched, evolved carbonatitic melts. One amphibole-bearing dunite xenolith containing carbonates in small interstitial pockets (100-500 µm across; Fig. 1) has been studied in detail. Mg-bearing calcite (MgO: <1.4 wt%, XCa = 0.96) with unusually high REE abundances and strong LREE enrichment occurs in the pockets; the trace element contents of these carbonates are similar to those of common carbonatite magmas (Fig. 2). The REE-rich carbonate is sometimes associated with euhedral carbonates (dolomite and Mg-free calcite), mafic silicate glass (low in alkalis) and small grains of spinel, sulfides and magnesio-
wüstite concentrated near the boundaries of the carbonate pockets (Fig. 1).

The unusual metasomatic mineral assemblage, together with the microstructural features and the chemical composition of the carbonates, suggests that the pockets of Mg-bearing calcite represent quenched carbonate melts rather than crystal cumulates from carbonate-rich melts. The associated mafic silicate glass may represent the immiscible silicate fraction of an evolved fluid produced by the dissolution-percolation of the original carbonate melt through the dunitic matrix. Unmixing of the silicate and carbonate fractions would be expected to occur as the xenoliths ascended to the surface.

During the percolation, carbonate melt dissolves olivine and reacts with preexisting amphibole and spinel to produce clinopyroxene. This pyroxene is therefore inferred to be in chemical equilibrium with the carbonate melt. This allowed calculation of clinopyroxene/carbonate melt partition coefficients for a large set of trace elements at relatively low pressure (1 GPa). The results indicate a significant pressure control on REE partitioning between carbonate melt and clinopyroxene (Fig. 3) as was observed experimentally by Adam and Green (see Research Highlights 2001) for clinopyroxene and basanitic melt.

These data, and the recent discovery of zircon-bearing dolomitic tuff on the Kerguelen archipelago (IPEV field campaign 2002; another occurrence is known on the Cape Verde Islands) provide a new understanding of carbonate melt genesis in the oceanic mantle and the implications of these melts for mantle metasomatism.

Contact: Bertrand Moine (Univ. Jean Monnet, St. Etienne), Sue O’Reilly
Funded by: CNRS (France), ARC Discovery

Figure 3: Plot of REE partition coefficients ($D_i$) between cpx and carbonate melt (Mg-bearing calcite) versus VIII-fold co-ordinated ionic radius ($r_i$, Shannon, 1976). Data from this study are compared with experimental results at 2 GPa (Klemme et al., 1995) and 3 GPa (Blundy & Dalton, 2000).
GEMOC’s teaching program aims to:

- provide undergraduate and postgraduate students with a broad, integrative understanding of Earth architecture and processes, bridging the discipline boundaries of geology and geophysics
- train undergraduate and postgraduate students in new conceptual approaches and the applications of advanced technology, including geochemical analysis techniques and the integrated field and laboratory use of geographic information systems (GIS)
- develop international links in teaching programs (especially postgraduate) relevant to GEMOC’s goals
- develop formal tailored course work components at postgraduate level which also can be packaged for distance education delivery and as short courses available to the mining industry
- enhance the pool of high quality geoscience graduates by restructuring academic programs to attract a new clientele

HIGHLIGHTS 2003

Curriculum Development

- Our tailored problem-based learning units GEOS116 Marine Geoscience and GEOS115 Earth Dynamics, Materials and the Environment continue to be well received by students. The format includes lectures, problem-based workshops and traditional skill-based practicals. The workshops are completed as group work projects and are modeled on real-life scenarios with the students adopting a role as part of a geoscience team. The success can be judged by comments from the end of year evaluation such as:

  “the only subject where you get to discuss ideas in a group and come up with team decisions which is important because it is how the real world works. I think it develops important skills”

[Best aspect of the unit] “studying real life/actual problems of today”
A team from the department, lead by Kelsie Dadd, was awarded $5928 under the Macquarie University Teaching Development Grant program for a project entitled “Bringing the workplace into the classroom – the redesign of GEOS377 using Tailored Problem-based Learning and real workplace scenarios”. GEOS377 Environmental Geology is a core unit of the new Bachelor of Environmental Science in Environmental Geology.

Nathan Daczko co-ordinated two units in 2003 - GEOS307 and GEOS389. GEOS307 Field Geology and Mapping was run in the Broken Hill region in conjunction with the University of Sydney for the first time in 2003. Field studies in the Broken Hill region allow students to gain experience mapping in a geological province not encountered before in their course. The unit attracted 10 students from the Department of Earth and Planetary Sciences in 2003 and current enrolments indicate an increase to 20 students in 2004. GEMOC’s John Ketchum attended as a demonstrator.

GEOS389 Special Interest Seminar was run under the name “Tectonics along the Pacific margin of the Australian plate in the last 100 or so million years” in New Caledonia. This type of unit is an excellent opportunity for students to experience first hand world-class exposures of a broad range of interesting rocks in an area of recent tectonic activity. The unit attracted 12 second and third year students. Nathan is currently developing our new unit GEOS230 Field and Laboratory Studies in Geoscience introduced after a review of second-year units.

Simon Jackson revised GEOS314 Magmas, Fluids and Ore Deposits in 2003 around a new teaching team that included Simon Turner, Rhiannon George and Kirsty Tomlinson from GEMOC. The new team brings GEMOC’s world-class research into the third-year teaching curriculum.

The use of computer packages and web interfaces in Earth and Planetary Sciences continues as a routine feature of content and skills delivery. Both geology and geophysics units incorporate packages used by industry into classroom and field teaching. Our portable computer lab allows students access to up-to-date computer software for use in both the classroom and field.

Teaching Infrastructure changes 2003

- The existing aged XRD instrument was replaced using University equipment funds
- Field equipment was upgraded
Teaching and training program: undergraduate

Geophysics teaching progress 2003

- Collaboration in teaching and research between GEMOC and Geophysics at the University of Sydney continues.
- The named degree, Bachelor of Geophysics, continued in 2002 after its inception in 1998 to increase the visibility of Geophysics. It has evolved into the advanced geophysics stream in the Bachelor of Science degree.
- The Bachelor of Technology in Exploration Geoscience has a Geophysics strand initiated in 1999, streamed from second year level (see flow sheet in Appendix 6).
- Use of an extensive pool of GPS units for undergraduate (and postgraduate) fieldwork continued.
- Extended implementation of new seismic, gravity GPS and resistivity equipment for student field projects in exploration, groundwater, environmental and engineering geophysics.
- Equipment upgrades funded by Macquarie University over the last five years have resulted in an excellent array of new instrumentation. Acquisitions include:
  - GEOMETRICS G856 Proton Precession Magnetometer
  - GEOSOFT, MODELVISION, EMVISION, ERMAPPER and Claritas software was either purchased or upgraded
  - Seismic trigger cable modifications
  - ABEM SAS4000 Resistivity System and an ABEM LUND system
  - ASHTECH Z-Xtreme Differential GPS system

OUTCOMES AT MACQUARIE

The introduction of new units and restructuring of existing undergraduate units at Macquarie as described in each Annual Report has achieved the goals of attracting new clientele. However, this is within an environment of a contracting pool of science undergraduates. Despite this, GEMOC core units at 100 level have maintained average enrolments. Reorganisation of course structures and acquisition of teaching infrastructure (computers, high-technology instruments, GIS units) have increased the visibility of geoscience and have resulted in the presentation of geoscience with an interdisciplinary and innovative approach using state-of-the-art technology and concepts.
The following honours projects in GEMOC were completed in 2003:

**Daniel Galda:** Determination of the elastic properties of alluvium

**Lachlan Gibbins:** A geophysical investigation of two upland swamps, Woronora Plateau, NSW Australia

**Kathleen McMahon:** Seismic reflection studies of the Amery Ice Shelf, East Antarctica

**Dan Nielsen:** A geological, geochemical and geophysical investigation of the Paleroo Creek area near Narrabri

The following Honours projects are relevant to GEMOC in 2004:

**Stephanie Carroll:** Cretaceous Granulites in Fiordland, New Zealand (mid-year)

**Kirsty Liddicoat:** Chemical and isotopic signatures of opal genesis at Lightning Ridge, NSW
EMOC postgraduate students once more provided a high profile for our postgraduate training through 2003, including the Goldschmidt Conference in Kurashiki (Japan), the West Norway Eclogite Symposium in Selje (Norway), the 8th International Kimberlite Conference in Victoria (Canada) and the Hutton Symposium in Japan. Sonja Aulbach and Sonal Rege received travel grants from the Organising Committee to present papers at the peak mantle forum, the 8th Kimberlite Conference. 

GEMOC’s international exchange program with the University of Jean Monnet, St Etienne continued. Stephanie Touron spent 3 months working in the stable isotope laboratory at St Etienne while her Macquarie supervisors (Sue O’Reilly and Bill Griffin) were there for 3 months’ research. Guillaume Delpech was in the final stages of thesis writing in anticipation of completion early in 2004.

completed

Olivier Alard (PhD): Trace element geochemistry and mantle domains, emphasis on PGE and Re/Os; IPRS with MUIPRA stipend (graduated 2001)

Sonja Aulbach (PhD): Depletion and metasomatic processes in cratonic mantle; IPRS with MUIPRA stipend (submitted October 2003) (see Research Highlights)

Kari Anderson (PhD): Defining the APWP for early to mid Palaeozoic eastern Gondwanaland: paleomagnetic pole information from the northern Tasman Orogen; IPRS with MUIPRA stipend (graduated 2003)

Elena Belousova (PhD): Zircon and apatite geochemistry: applications to petrology and mineral exploration; APA and sponsorship by Rio Tinto (graduated 2000)

Eloise Beyer (PhD): Contrasting characteristics of Proterozoic and Phanerozoic mantle types; Field assistance from Ashton Mining (graduated 2003) (see Research Highlights)

Rondi Davies (PhD): East Australian Diamonds: Characterisation and origin; Sponsored by Rio Tinto, Kennecott Canada (graduated 1999)

Oliver Gaul (PhD): Composition of the lithospheric mantle beneath Australia; APAI collaborative with Stockdale Prospecting, CSIRO EM (graduated 2000)

Joanne McCarron (MSc): Mantle xenoliths from Queensland and South Australia (graduated 1997)
Bertrand Moine (PhD): The role of fluids in the genesis, segregation and crystallisation of intraplate oceanic mantle magmas: implications for crustal accretion; Co-tutelle with University of Jean Monnet (graduated 2000)

Mark Pirlo (PhD): Australian groundwater geochemistry; applications to heat flow and exploration; APA and Queen’s Trust for Young Australians Award (graduated 2003)

Shixin Yao (PhD): Chromite as a petrogenetic indicator in ultramafic rocks; Collaborative with Rio Tinto (graduated 2000)

Xu Xisheng (PhD): The lithospheric mantle beneath eastern China; Formal exchange PhD, Nanjing and Macquarie (graduated 2000)

Steven Cooper (PhD): Diamonds and mantle-derived minerals, NW Australia and South Australia (commenced part-time 2003)

Guillaume Delpech (PhD): Isotopic characteristics of lithosphere processes beneath Kerguelen; Co-tutelle with University of Jean Monnet, IPRS with GEMOC stipend and EURODOC scholarship (commenced 2000)

Raynald Ethien (PhD): Origin of differentiated magmas from an oceanic island: petrology and geochemistry of volcanic and plutonic silicic rocks from Kerguelen Island (Indian Ocean); Co-tutelle with University of Jean Monnet, St Etienne (commenced 2001)

Bin Guo (PhD): An integrated geophysical investigation of the Hunter-Mooki and Peel Fault; IPRS with MUIPRA stipend (commenced 2001)

Valeria Murgulov (PhD): Crust-mantle evolution and metallogeny, eastern Australia; APA (commenced 2003)

Kathlene Oliver (MSc): Depth and subsurface shape of the Dundee Ignimbrite (part-time, commenced 2001)

Will Powell (PhD): Nature of the lithospheric mantle in the New England Region, NSW; APA (part-time, commenced 1997)

Sonal Rege (PhD): Trace-element geochemistry of diamonds; IPRS with iMURS scholarship (commenced 2002)

Stephanie Touron (PhD): Geochemical fingerprints of the mantle beneath the Massif Central; IPRS with MURAACE scholarship (commenced 2001)
Teaching and training program: postgraduate

Esmé van Achterbergh (PhD): Trace-element fingerprints of metasomatic processes in lithospheric mantle (part-time, commenced 1998)

commencing 2004

Brad Bailey (PhD): Law Dome: Ice and Crust Mass Balance Studies

Kathleen McMahon (PhD): Fracturing and deformation along the Amery Ice Shelf: A seismic study

Luke Milan (PhD): The emplacement, pressure-temperature-time path and structural evolution of lower crustal gneisses in Fiordland, New Zealand

Nenad Nikolic (PhD): Evolution of crust-mantle systems near a young rift: NW Spitsbergen, Norway
Background

GEMOC’s research, training and Industry Interaction programs require a high level of geochemical analytical technology, which is provided by the state-of-the-art facilities available to the Key Centre. Continual development of both technology and innovative analytical and microanalytical approaches is required to meet our research aims and the needs of our industry collaborators. GEMOC develops new analytical strategies as required, to determine the chemical and isotopic composition of geological materials (both solid and fluid) in solution and in situ. Special emphasis is being placed on the development of advanced in situ microbeam methods. These developments are transmitted to industry via open and collaborative research, through technology exchange visits and workshops, and as an integral part of the training program.

The analytical instrumentation and support facilities of the Macquarie University Geochemical Analysis Unit (GAU) represent a state-of-the-art geochemical facility. In 2004 this will be enhanced by the relocation of the stable-isotope operations of the former Centre for Isotope Studies, previously housed at CSIRO, North Ryde, to GEMOC.

- The GAU contains:
  - a Cameca SX-50 electron microprobe
  - a Cameca SX-100 electron microprobe (installed January 2003)
  - a Hewlett Packard 4500 ICPMS (dedicated to U-Pb analysis)
  - an Agilent 7500 ICPMS (industry collaboration)
  - a custom-built UV laser microprobe, usable on either ICPMS
  - two New Wave/Merchantek laser microprobes (266 nm and 213 nm) for the MC-ICPMS and ICPMS laboratories (industry collaboration)
  - a New Wave/Merchantek excimer (193 nm) laser microprobe, based on a Lambda Physik OPTex laser
  - a Nu Plasma multi-collector ICPMS
  - a Nu Plasma high resolution multi-collector ICPMS (installed November 2003)
  - a Spectro XLAB2000 energy-dispersive XRF with rocker-furnace sample preparation equipment
• a LECO RC412 H₂O-CO₂ analyser (delivered September 2003)
• clean labs and sampling facilities provide infrastructure for ICPMS, XRF and isotopic analyses of small and/or low-level samples
• Experimental petrology laboratories in GEMOC include piston-cylinder presses (9, 15 and 40 kb), hydrothermal apparatus, and controlled atmosphere furnaces.
• The Centre for Isotope Studies has provided access to extraction lines and gas-source mass-spectrometers for stable-isotope analysis of fluids and minerals; these facilities will be moved to GEMOC during 2004.

THE GEMOC FACILITY FOR INTEGRATED MICROANALYSIS (FIM) AND MICRO GIS DEVELOPMENT

GEMOC is continuing to develop a unique, world-class geochemical facility, based on in situ imaging and microanalysis of trace elements and isotopic ratios in minerals, rocks and fluids. The Facility for Integrated Microanalysis now consists of four different types of analytical instrument, linked by a single sample positioning and referencing system to combine spot analysis with images of spatial variations in composition (“micro-GIS”). All instruments in the FIM have been operating since mid-1999. Major instruments are being replaced or upgraded in 2002-2004 through the $5.125 million DEST Infrastructure grant awarded to Macquarie University with the Universities of Newcastle, Sydney, Western Sydney and Wollongong as partners.

the facility provides:

• The capability to image both major- and trace-element distribution in a sample, as an interpretive tool and as the basis for higher precision spot analysis of trace-element concentrations and isotopic ratios
• Co-registration of images and spot data from different instruments, and use of digitised images to locate spots with a precision of better than 5 µm
• Analytical capability for most elements of the periodic table at ppm to sub-ppb levels
• In situ isotopic-ratio measurement for a range of elements, at the precision required for geologically useful results
• New approaches to data interpretation through application of micro-GIS principles

Electron Microprobe: for imaging and point analysis of major and minor elements
Scanning Nuclear Microprobe: for imaging and point analysis of trace elements at ppm levels
**Laser-ablation ICPMS Microprobes:** for point analysis of a wide range of trace elements at low ppb levels

**Multi-collector Sector ICPMS with laser microprobe:** for high-precision *in situ* analysis of isotopic ratios

**Micro-GIS system:** A key aspect of the Facility is the co-registration of images and point analyses collected on all instruments. All data for a sample, from any of the instruments or from a bench microscope, are in the same coordinate system and can be overlaid in the computer to enhance interpretation.

When fully developed, images from one instrument will be read into the computer of another instrument and used to guide the analysis. Major-element maps from EMP, or trace-element maps from the nuclear microprobe, can be linked directly to images from petrographic or cathodoluminescence microscopes, BSE or SEM, or to spot analyses.

**CURRENT STATUS**

**Electron microprobe (EMP):** The original GEMOC EMP is a CAMECA SX50, installed in 1993; it routinely produced high-precision analyses of major and minor elements with a spatial resolution of one micron, as well as high-quality images of major-element (> 0.1 wt%) distribution over areas up to 45 x 45 mm, by stage-scanning with five fixed wavelength-dispersive spectrometers. In early 1999 the EMP was upgraded with an energy-dispersive X-ray detector to allow rapid and simultaneous mapping of all major elements. In early 2003 a new CAMECA SX100, with a similar configuration of spectrometers, was installed and the SX50 is now used almost entirely for the imaging and analysis of zircons, in connection with TerraneChron™ applications and basic research.

**Scanning nuclear microprobe (SNMP):** This instrument was built by Dr C. G. Ryan (with GEMOC funding contribution) as a separate beam line on the HIAF particle accelerator at CSIRO, North Ryde. The design incorporates several complementary types of detector, a new high-resolution probe-forming system and an innovative optical system, and provides both images of trace-element distribution and spot analyses, with a lateral resolution of 1-3 µm. Current capabilities cover micro-PIXE, micro-PIGE and quantitative element imaging. Due to the closure of CSIRO’s North Ryde site during 2004, the SNMP beam line will be relocated to the accelerator facility at the University of Melbourne.

**Laser Ablation ICPMS microprobe (LAM-ICPMS):** The original GEMOC LAM was installed in December 1994 using a Perkin-Elmer ELAN 5100 ICPMS (later replaced by an ELAN 6000), attached to a UV laser ablation microprobe built for GEMOC by Memorial University, Newfoundland. In 1999 the ICPMS was replaced by a Hewlett Packard 4500, and in 2000 an Agilent 7500 ICPMS was added. These two instruments now routinely provide quantitative analyses of > 30 elements at sub-ppm levels in minerals, glasses and metals, as well as precise U-Pb dating of zircons. The laboratory currently uses three Nd:YAG LAM systems: a Quantel Brilliant laser that can deliver beams of either 266nm or 213nm light, a Merchantek LUV 266nm system, and a Merchantek/New Wave LUV213 nm system. Spatial resolution varies with the application, but typically is on the order of 30-40 µm. The LAM is fitted with a computer-driven sample stage to provide co-registration
of X-Y coordinates with the other instruments. On-line data reduction with the GEMOC-developed “GLITTER” software enhances laboratory productivity and data interpretation; the software is marketed internationally by New Wave Research.

Multi-collector LAM-ICPMS microprobe (MC-LAM-ICPMS):
A fully-equipped Nu Plasma MC-ICPMS is an integral part of the Facility. This instrument combines a laser ablation microsampler, an Ar-plasma ionisation source, and a multi-collector magnetic-sector mass spectrometer, to provide high-precision in situ analysis of isotope ratios in geological materials. The current laser is a New Wave 193nm system based on a Lambda Physik OPTex excimer laser. The MC-ICPMS also can be used in solution mode, with either a standard nebuliser or a desolvating nebuliser, to provide high-precision isotopic analysis of a wide range of elements, including many not accessible by standard thermal ionisation mass spectrometry. A second Nu Plasma instrument, with high-resolution capabilities and a retardation filter to enable U-series work, was installed late in 2003.

Applications in use and under development include:

Laser Analysis (in situ point analysis)

- U-Pb geochronology of zircons from igneous and metamorphic rocks
- Hf isotope analysis in zircon for studies of crustal generation, mantle evolution and crust-mantle interaction
- Re-Os dating of sulfides in mantle-derived xenoliths
- Nd isotope analysis in apatites, titanites and other REE-rich minerals
- Sr isotope analysis of carbonates, feldspars, apatites, pyroxenes
- Pb isotope analysis of sulfides and silicates
- Stable isotope ratios of Fe, Mg, Zn, Cu and other cations in appropriate minerals from hydrothermal systems and mantle rocks
- Multi-element trace element analysis of silicates, sulfides, oxides and diamonds

Solution Analysis

- Re-Os — determination of mantle depletion ages and isochron ages in whole rocks, ilmenites and chromites; dating of sulfide assemblages in ore bodies
- Lu-Hf — crustal genesis, mantle metasomatism; Lu-Hf dating of garnet peridotites, eclogites, granulites; basalt genesis
• Rb-Sr, Sm-Nd, U-Pb, Pb-Pb — faster and simpler than TIMS; simplified low-blank chemistry, no time-dependent mass fractionation, hence greater precision
• U, Th-series analysis – for dating of young processes, ranging from magma genesis to weathering and erosion
• Multi-element analysis of trace elements in whole-rock samples

PROGRESS IN 2003

1. Facility for Integrated Microanalysis

a. **Electron Microprobe**: A fully optioned Cameca SX-100 electron microprobe with five crystal spectrometers and an energy-dispersive spectrometer, to replace GEMOC’s aging but still highly functional SX-50 instrument, arrived in late December 2002, and was installed in January 2003. The energy-dispersive spectrometer has been returned for repairs, but the instrument is otherwise performing well.

b. **Laser-ablation ICPMS microprobe (LAM)**: During 2003, the LAM laboratory produced large volumes of data for eight Macquarie PhD thesis projects, several projects carried out by international visitors and Honours students, in-house funded research projects and industry collaboration. These projects included the analysis of trace elements in the minerals of mantle-derived rocks, in sulfide minerals and in a range of unusual matrices. *Over 5000 U-Pb analyses of zircons were carried out, related to projects (including TerraneChron™ applications) in South America, Scandinavia, Mongolia, Turkey, China and Australia.* The LAM laboratory also routinely provides data for projects related to mineral exploration (diamonds, base metals, Au), as a value-added service to the industry. New developments included further improvements in the quantitative *in situ* analysis of diamonds, as part of Sonal Rege’s PhD project, supported by DeBeers, on the trace-element signatures of diamonds (see Research Highlights).

The 4500 instrument is now dedicated primarily to U-Pb dating of zircons, where its stability and ease of operation provide a high throughput.

c. **MC-ICPMS**: A multi-collector magnetic sector ICPMS for *in situ* (laser-ablation) and solution analysis of isotopic ratios was installed in November 1998. The instrument is the Nu Plasma, designed and manufactured by Nu Instruments of Wrexham, UK. The instrument was producing good data only a few days after installation, and has continued to do so. Merchantek EO (now New Wave Research) has provided a 266 nm UV laser microprobe (under a collaborative agreement; see "Over 5000 U-Pb analyses of zircons were carried out, related to projects (including TerraneChron™ applications).")

*Tin Tin Win from CSIRO using the LAM-ICPMS for zircon dating.*
below) for use with the MC-ICPMS and a 213 nm laser microprobe was purchased in 2000. During 2002 the MC-ICPMS was fitted with a New Wave/Merchantek excimer (193 nm) laser microprobe, based on a Lambda Physik OPTex laser. This has been used mainly for the analysis of Hf isotopes in zircon, where its different absorption characteristics have provided somewhat greater spatial resolution and beam intensity than were available using the 213 nm laser.

Major applications during 2003 (see Research Highlights) included the high-precision analysis of Hf in zircons to trace lithosphere evolution and magma-mixing histories in granitic rocks, the analysis of copper and iron isotope compositions in minerals from ore bodies, the analysis of Sr isotopes in clinopyroxene phenocrysts from lavas, and Re-Os dating of single grains of Fe-Ni sulfides in mantle-derived rocks.

We carried out Re-Os studies on alpine-type peridotites from the Norwegian and Swedish Caledonides and xenoliths from the Kerguelen oceanic plateau, S. Africa, eastern China and Taiwan. A study of U-Pb and Hf-isotope systematics of zircons in late-Proterozoic sediments in southern Norway, continued from 2002, is providing a new view of the tectonics of southern Scandinavia.

Further developments were made in 2003 for the in-situ analysis of Mg isotope compositions in mantle olivine and other phases in mantle peridotites. This involved the characterisation of potential standard materials and the investigation of the matrix effects on isotopic fractionation. Detailed studies were undertaken on olivine, pyroxene and amphibole in spinel peridotites from the Massif Central (France) and from Western Victoria (Australia), with the results providing further evidence of significant Mg isotopic fractionation in metasomatised samples.

The rapid growth in the use of the TerraneChron™ application (see Research Highlights), coupled with the demand for in situ Re-Os analysis and stable isotope analysis, has led to severe competition for instrument time on the MC-ICPMS. An order was placed early in 2003 for a second instrument, funded by the DEST infrastructure grant, and this instrument was installed late in 2003.

d. Scanning Nuclear Microprobe: The pending closure of the CSIRO North Ryde site forced the shutdown of the SNMP in late 2003. While the removal of the accelerator to the Clayton (Melbourne) site has been discussed, little progress has been made. The beam line has been dismantled, and will be re-installed on the University of Melbourne accelerator during 2004. It is anticipated that it will be able to operate for 2-3 days/week, and negotiations regarding access for GEMOC projects will take place once the SNMP is operative again.
e. Laboratory development: Funding from the DEST infrastructure grant contributed toward the building of a new suite of clean-room laboratories on the second floor of building E5B, which include facilities for the work on U-series chemistry to be carried out by Dr Simon Turner and his group starting in 2003. Construction began in September 2003, and the facilities are scheduled for completion by the end of March 2004.

f. Software: Chris Ryan further refined the GLITTER (GEMOC Laser ICPMS Total Trace Element Reduction) software, our on-line interactive program featuring linked graphics and analysis tables. This package provides the first real-time interactive data reduction for LAM-ICPMS analysis, allowing inspection and evaluation of each result before the next analysis spot is chosen. Its capabilities include the on-line reduction of U-Pb data. The use of GLITTER has greatly increased both the flexibility of analysis, and the productivity of the laboratory. New Wave Research now market the software together with their laser microprobe equipment; GEMOC provides customer service and backup through Macquarie Research Limited. Eleven copies of GLITTER were sold worldwide in 2003, and the software appears to have achieved industry-standard status; more than 30 copies are in use worldwide, in forensics and materials science, as well as earth science applications.

2. Laser development

GEMOC continues to benefit from an industry partnership with New Wave Research (formerly Merchantek EO), a major US manufacturer of laser ablation systems, which has made Macquarie its Alpha Test Site. New Wave donated their 266 nm Nd:YAG UV laser ablation sampling system to GEMOC and their new 213 nm system was delivered early in 2000. Both lasers can be coupled to the Nu Plasma MC-ICPMS, allowing high precision isotope ratio determinations to be performed on minerals \textit{in situ}. The mobility of the probes has allowed them to be used on the quadrupole ICPMS instruments as well, in a range of applications. A Merchantek/New Wave Research 193 nm excimer system based on a Lambda Physik OPTex laser was delivered in March 2002 and was finally commissioned late in the year. The 213 nm laser is now used for most of the U-Pb work, especially where small grains are being analysed, while the excimer system is used mainly for Hf-isotope analysis. A major upgrading of the laser park will take place in 2004, with the purchase of three new systems.
3. Energy Dispersive XRF

A Spectro XLAB2000 energy-dispersive X-ray spectrometer was installed in November 2000 in a joint venture with Tasman Resources. This instrument utilises the polarisation of scattered X-rays to substantially reduce backgrounds and enhance detection limits. The XLAB2000 uses a specially designed 300 W palladium X-ray tube that improves its performance for the lighter trace elements, and also for major elements, relative to the earlier instrument. In addition, this spectrometer is fitted with a silicon detector, of a type recently developed, that eliminates the low-energy “tail” from the lightest elements, and enables all major elements to be measured in a fused glass to levels below 0.01%. The capability of the instrument to provide major element analyses of a quality at least comparable to the more expensive conventional crystal spectrometers has been thoroughly evaluated and confirmed. This instrument provides highest-quality data for major elements and for most trace elements to sub-ppm levels. The operation of the equipment is enhanced by a 100 position sample loader, one of the first to be installed on a Spectro instrument, and the purchase of a rocker furnace for sample preparation. During 2003 over 5000 samples were analysed for major and trace elements, providing data to student theses, in-house research projects, and industry collaborators.

4. Solution analysis

The Agilent 7500 ICPMS is regularly used to provide trace-element analyses of dissolved rock samples for the projects of GEMOC researchers and students, and external users, supplementing the data from the XRF.

The in situ analysis of the Rb-Sr, Lu-Hf, Sm-Nd and Re-Os systems by laser ablation microprobe has required the development of corrections for isobaric overlaps (eg $^{87}$Rb on $^{87}$Sr), and has demonstrated that these corrections can be done with very high precision in the Nu Plasma MC-ICPMS. This has allowed us to simplify the ion-exchange chemistry traditionally used to obtain clean element separations for standard mass-spectrometry analysis. A new scheme for the dissolution of rocks, separation of Sr, Nd, Hf and Pb, and isotopic analysis using the MC-ICPMS in solution mode provides precise whole-rock isotopic analyses that are faster, simpler and ultimately cheaper than those obtained by traditional methods.

During 2003 we further developed methods for extracting Re and Os from rock samples and the analysis of the Os samples on the MC-ICPMS by sparging the oxidised Os directly into the ICPMS torch. The method now routinely provides analyses with a precision and accuracy comparable to the best TIMS analyses, but much more rapidly. The technique was applied to suites of mantle-derived peridotite and eclogite xenoliths from several localities, and to the Re-Os dating of sulfide-rich rocks from ore deposits.

A new LECO RC412 H$_2$O-CO$_2$ analyser (delivered September 2003) replaces an outdated unit, and will provide high-quality analyses to complete whole-rock analyses by XRF and solution-ICPMS.
5. Centre for Isotope Studies (CIS)

The Centre for Isotope Studies (CIS) was a consortium operated by the geoscience departments of the New South Wales Universities, CSIRO Exploration and Mining, and Petroleum Resources using jointly-purchased mass-spectrometers housed at the CSIRO in North Ryde. The facility allowed staff and students to obtain both radiogenic and stable isotopic analyses and used technical staff jointly funded by the University members; Dr Richard Flood of GEMOC has been University Consortium Convenor.

GEMOC has developed its own clean laboratories to prepare solutions for radiogenic isotope analysis by MC-ICPMS, but has used the stable isotope separation facilities at North Ryde. CIS was one of the rare laboratories where staff and students could obtain C, O, N, S and D analyses including the routine determination of O in silicates. Dr Anita Andrew developed techniques for C-isotope analysis of diamonds using very small sample sizes (0.1 mg), which allows analysis of microdiamonds or multiple fragments of different zones of small stones. This is now an essential part of GEMOC capabilities.

With the closure of the CSIRO’s North Ryde site in 2004, Dr Andrew will move the stable isotope facilities to GEMOC, where they will form a self-funded entity, and GEMOC will continue to benefit from this collaboration.

GEMOC continues to benefit from strategic alliances with Agilent, Nu Instruments and New Wave Research.
Industry interaction

INDUSTRY INTERACTION, TECHNOLOGY TRANSFER AND COMMERCIALISATION PROGRAM

GEMOC relies on a vigorous interaction with the mineral exploration industry at both the research and the teaching/training levels. The research results of the Centre’s work are transferred to the industry and to the scientific community by:

- collaborative industry-supported Honours, MSc and PhD projects
- short courses relevant to the industry and government sector users, designed to communicate and transfer new technologies, techniques and knowledge in the discipline areas covered by the Key Centre
- one-on-one research collaborations and shorter-term consultancies on industry problems involving national and international partners
- provision of high quality geochemical analyses with value-added interpretations to industry and government organisations, extending our industry interface
- use of Macquarie Research Limited consultancies, which employ and disseminate the technological developments carried out by the Centre
- GLITTER, an on-line data-reduction program for Laser Ablation ICPMS analysis developed by GEMOC and CSIRO GEMOC participants, is available commercially through New Wave Research
- collaborative relationships with technology manufacturers (more detail in the section on Technology Development):
  - GEMOC (Macquarie) is the Agilent Technologies ICPMS Australian demonstration site
  - GEMOC (Macquarie) is the international Alpha test site for New Wave Research Lasers

SUPPORT SOURCES

GEMOC industry support includes:

- direct funding of research programs
- “in kind” funding including field support (Australia and overseas), access to proprietary databases, sample collections, digital datasets
• collaborative research programs (eg ARC SPIRT (now Linkage) Projects, APA Industry and PhD program support)
• assistance in the implementation of GIS technology in postgraduate programs
• participation of industry colleagues as guest lecturers in senior courses (eg Bachelor of Technology)
• extended visits to Macquarie by industry personnel for interaction and research
• ongoing informal provision of advice and formal input as members of the Advisory Board

ACTIVITIES IN 2003

TerraneChron™ studies (see Research Highlights) have been adopted by a large segment of the global mineral exploration industry. This methodology, currently unique to GEMOC, requires the integration of data from three instruments (electron microprobe, LAM-ICPMS and LAM-MC-ICPMS) and delivers fast, cost-effective information on the tectonic history (with ages) of regional terranes.

Collaborative research with Kennecott Canada Inc., continued within the Lithosphere Mapping strand, following the very successful SPIRT project “Lithosphere Mapping and Diamond Exploration”. This involved the synthesis of results from analysis of heavy mineral concentrates from more than 25 localities scattered around North America, and the correlation of the data with seismic tomography and other geophysical data (Publication #348). Results of the SPIRT project were released as planned at the 8th International Kimberlite Conference in Vancouver in June 2003.

Nine Industry Reports were completed for collaborative and consulting projects.

An ARC SPIRT project (2001-2003) sponsored by WMC used gravity data to interpret effective elastic thickness and integrate this with tectonic analysis and geochemical data across Australia.

A new ARC Linkage Project with WMC was funded for 2004-2006. This project is titled “Global Lithosphere Architecture Mapping”. Planning and workshop sessions at Macquarie with participants from WMC and GEMOC, and a visit by Macquarie staff to WMC in Perth, were key activities in 2003. Dr Graham Begg spent significant research time at GEMOC through 2003 as part of the close collaborative working pattern for this project.
Professor J. Harris (on behalf of de Beers) provided samples for the PhD project of Sonal Rege aimed at developing a methodology for the trace-element analysis of diamonds.

The exploration consulting group GeoDiscovery continued to work with GEMOC to develop TerraneChron™, a novel approach to terrane analysis (see Research Highlights). A GeoDiscovery/Macquarie collaborative project supported the initiation of this project, and another collaborative project, supported by BHP-Billiton, began early in 2003 (see summaries of current industry projects below).

Dr Steve Walters visits Macquarie to participate in this collaboration.

Many companies have provided high levels of in-kind support in the form of samples: these include access to diamonds and xenoliths through Rio Tinto and Kennecott Canada, suites of xenoliths from Ashton Mining of Canada and heavy mineral concentrates from numerous sources including BHP, DeBeers Australia, Monopros and several small companies.

Rio Tinto supplied samples for pilot studies of garnets, chromites and pyroxenes from kimberlites on the Dharwar Craton of India; the results were used to support a successful proposal for a Macquarie University Collaborative Grant (2004).

A pilot study on detrital zircons from Paleozoic sediments was carried out with the New South Wales Geological Survey; the results were used to support a successful proposal for a Macquarie University Collaborative Grant (2004).

Numerous industry visitors spent varying periods at GEMOC in 2003 to discuss our research and technology development (see visitor list, Appendix 3).

DIATREEM continued to provide LAM-ICPMS analyses of garnets and chromites to the diamond-exploration industry on a routine basis, in cooperation with CSIRO, North Ryde.

GEMOC publications, preprints and non-proprietary reports are available on request for industry libraries.
CURRENT INDUSTRY-FUNDED COLLABORATIVE RESEARCH PROJECTS

These are brief descriptions of current GEMOC projects that have direct cash support from industry and timeframes of at least one year. Projects are both national and global.

GEMOC’s industry collaborative projects are designed to develop the strategic and applied aspects of the basic research programs based on understanding the architecture of the lithosphere and the nature of Earth’s geodynamic processes that have controlled the evolution of the lithosphere and its important discontinuities. Most of the industry collaborative projects rely on geochemical information from the Geochemical Analysis Unit in GEMOC and especially on novel methodologies developed by (and some unique to) GEMOC.

Geochemical data on crustal and mantle rocks are being integrated with tectonic analyses and large-scale datasets (including geophysical data) to understand the relationship between lithosphere domains and large-scale mineralisation.

The new methodologies of using mantle sulfides to date mantle events, and of characterising crustal terrane development using U-Pb dating and Hf isotopic compositions of zircons provides more information for integration with the geophysical modelling. TerraneChron™ (see Research Highlights) is proving an important new approach to characterising the tectonic history and crustal evolution of terranes on the scale of 10 – 100 km as well as delivering a cost-effective exploration tool to the mineral (and potentially petroleum) exploration industry.

Proterozoic crustal evolution: Development of a global comparative library of Event Signatures linked to mineral endowment

Supported by a matching Macquarie University Collaborative grant (2002-2003)
Industry Collaborator: BHB-Billiton
Summary: This project is aimed at understanding processes of Proterozoic crustal formation. We will measure the U-Pb ages, Hf isotope ratios and trace-element patterns of detrital zircons from selected Proterozoic terranes to study the timing, nature and sources of magmatic rocks. The Event Signature for each region will be compared with our data from geologically similar districts, eg Mt Isa block (Australia) and Aravalli Craton (India), and event styles will be correlated with differences and similarities in known mineralisation styles. The project will contribute to a unique global ‘library’ of Event Signatures with application to area selection for mineral exploration.
Lithosphere mapping beneath the Dharwar Craton, India  
**Supported by a matching Macquarie University Collaborative grant (2004)**  
**Industry Collaborator: Rio Tinto**  
**Summary:** The project uses major- and trace-element analysis of mantle-derived minerals in kimberlites to map vertical and lateral variations in the composition and thermal state of the lithospheric mantle across the Archean Dharwar Craton in central India. The kimberlites are 900-1200 million years old, and may provide information on a relatively unmodified lithospheric root. Comparison with geophysical data (today’s situation) will help to define the fate of this root during India’s northward movement after its separation from Gondwanaland. The results will be directly relevant to diamond exploration models for the Dharwar Craton, and for other areas in India.

Global Lithosphere Architecture Mapping  
**Supported by ARC Linkage (2004-2006)**  
**Industry Collaborator: WMC**  
**Summary:** Compositional domains in the subcontinental lithospheric mantle reflect the processes of continental assembly and breakup through Earth’s history. Their boundaries may focus the fluid movements that produce giant ore deposits. Mapping these boundaries will provide fundamental insights into Earth processes and a basis for the targeting of mineral exploration. We will integrate mantle petrology, tectonic synthesis and geophysical analysis to produce the first maps of the architecture of the continental lithosphere, to depths of ca 250 km. These maps will provide a unique perspective on global dynamics and continental evolution, and on the relationships between lithosphere domains and large-scale mineralisation.

Continental Flood Basalts: geochemical discrimination with relevance to exploration for nickel and platinum-group elements  
**Supported by a matching Macquarie University Collaborative grant (2004)**  
**Industry Collaborator: WMC**  
**Summary:** A major proportion of magmatic Ni- platinum group element (PGE) deposits are hosted in mantle-plume-derived continental flood basalts (CFB). Therefore, geochemical discrimination of CFB from other mantle-derived rocks and identification of Ni-PGE-prospective CFB are significant for Ni-PGE exploration. This project is exploring existing geochemical databases for mantle-derived rocks to provide user-friendly practical discrimination parameters to identify CFB-related mafic rocks and to evaluate their Ni and PGE economic potential. The research will also further constrain the role of mantle plumes in formation and evolution of subcontinental lithosphere and the behaviour of sulfides during the process of mantle evolution.
Where was Baltica? Testing continental reconstructions with TerraneChron™

Supported by a matching Macquarie University Collaborative grant (2003-2004)
Industry Collaborator: University of Oslo and Norwegian Geological Survey

Summary: Norway represents the western margin of the ancient landmass of Baltica, which was partly destroyed in the Caledonian Orogeny ~550-400 million years (Ma) ago. Its position before 600 Ma is debated. This project is using U-Pb dating and Hf-isotope analysis of zircons in basement rocks in SW Norway and in far-transported thrust sheets (nappes) derived from the vanished western margin of Baltica, to reconstruct the geological history of this margin. The results will allow evaluation of models for continental assembly, and will be relevant to studies of the provenance of sediments in the oil/gas basins of the North Sea.

Testing Ordovician-Devonian tectonic models for the Lachlan Orogen

Supported by a matching Macquarie University Collaborative grant (2004)
Industry Collaborator: NSW Geological Survey

Summary: This project combines the TerraneChron™ technology developed at GEMOC with tectonic and structural concepts developed at the Geological Survey of NSW, to understand the plate-tectonic evolution of SE Australia. U/Pb dating and Hf-isotope analysis of detrital and primary zircon grains will shed light on potential terrane accretion and on the timing of crustal growth and will be used to test published models of the Ordovician–Devonian tectonic development of Eastern Australia. This in turn will help to understand the nature of the interaction between the Australian plate and the proto-Pacific margin of the Gondwana supercontinent.

Crustal evolution in southern Norway: U-Pb and Hf-isotope analysis of zircons from bedrock, sediments and modern drainages

Supported by a matching Macquarie University Collaborative grant (2002-2003)
Partners: Geological Survey of Norway and the University of Oslo

Summary: The broad-scale evolution of the Proterozoic crust of southern Norway is being investigated, using U-Pb, Hf-isotope and trace-element analysis of zircons from selected bedrock units and the overlying Neoproterozoic Sparagmite sedimentary sequence. The results will provide an “Event Signature” for comparison with similar data from more strongly mineralised Proterozoic crust elsewhere. Signatures from small modern drainages in the study area will be compared with those from the rock samples to test the usefulness of this approach for the study of crustal evolution in glaciated areas. The results will enhance the technique’s applications to mineral and energy exploration.
Lithospheric architecture of Australia: relevance to location of giant ore bodies

Supported by an ARC SPIRT grant (2001-2003)

Industry Collaborator: WMC

Summary: This research project is designed to test the concept that giant magmatic and hydrothermal ore bodies are localised by major structural discontinuities that extend through the Earth’s lithosphere. Modelling of geophysical data across the Australian continent is defining regional trans-lithospheric domains and their boundaries. Tectonic analysis and geochemical data on crustal and mantle rocks are defining the age and composition of the upper mantle beneath each domain, and the history of crust-mantle interaction (magmatism, extension, compression). This history will be integrated with information on the timing and style of large ore deposits to understand the relationship between lithosphere domains and large-scale mineralisation. The focus of this project was expanded in 2002 to include the detailed analysis of lithosphere structure and evolution worldwide, using seismic tomography and other geophysical datasets.

Igneous metallogenic systems of eastern Australia

Supported by AMIRA (Project P515)

Industry Collaborators: Newcrest, Rio Tinto, Delta, GA, NSWGS, QDME, Triako Normandy

Summary: The research part of this project was completed in 2002. The final outcome in 2003 was a three-day symposium on granites, “The Ishihara Symposium: Magmas to Mineralisation”, held at Macquarie from 22-24 July 2003. The initial suggestion for this meeting came from representatives of the companies and surveys that sponsored AMIRA projects of Phil Blevin and Bruce Chappell. The symposium was named in honour of Dr Shunso Ishihara who has been at the forefront of developing ideas on the relationships between granites and mineralisation. More than 100 participants included academics, students, survey geologists and mineral exploration geologists. Abstracts for the symposium were published as Geoscience Australia Record 2003/14 and GA is also making available adaptations of PowerPoint presentations of many of the talks. The Ishihara Volume from the Conference will be published as an issue of the Japanese journal Resource Geology in September 2004.
BACKGROUND

GEMOC has strong international links and these increased and changed significantly through 2003. These links were based dominantly in Asia for the first three years, including China, Japan, Mongolia, Myanmar, Thailand and the former USSR, but have since broadened to include substantial collaborative programs in France, Norway, Germany, United Kingdom, Canada and the USA.

EXAMPLES OF ACTIVE FUNDED PROJECTS IN ASIA

- geophysical analysis of China Geotraverses (including gravity modelling)
- nature and geophysical signature of the lithosphere in southeastern China
- crust-mantle interaction in southeastern China: the origin of the Yanshanian Granites and evolution of southeastern China
- trace element and isotopic characteristics of zircon as indicators of granite magma evolution
- nature of the lithosphere in northwestern China (Tienshan Mountains in Xinjiang)
- metallogenesis of southeastern China
- crustal evolution, basaltic volcanism and basin development, north China
- mantle processes in the mantle wedge above the subduction zone in Japan
- thermal contrasts and paleogeotherms in Siberia, Mongolia, eastern China
- diamond exploration, tectonism, and geophysical nature of the lithosphere, Siberia and East Asia
- mantle terranes and tectonic analysis, Siberia
- lithosphere extension and geodynamic processes in east Asia (including the Taiwan region)

FUNDED COLLABORATIVE PROJECTS COMMENCED OR ONGOING IN 2003 INCLUDE:

- The time scales of magmatic and erosional cycles, with Professor C. Hawkesworth (Bristol University), Dr M. Reagan (University of Iowa) and Dr J. Kirchner (University of California).
- The nature of lithosphere extension in the Taiwan region and implications for geodynamics in eastern China, with Professor S-L Chung, National University of Taiwan, relevant to the research project of Dr Kuo-Lung Wang (Macquarie University Research Fellow)

- Analysis of off-craton lithospheric mantle in East Central Asia Orogenic Belt, with Dr V. Malkovets, Novosibirsk

- TerraneChron™ analysis of the Amazon Craton, with WMC Resources

- Canary Islands lithosphere and volcanism with Prof. E.-R. Neumann (Oslo)

- Tectonic domains in southern Norway using TerraneChron™ with Prof. T. Andersen (University of Oslo) and Dr B. Bingen (Norwegian Geological Survey)

- Participation in the RV Sonne cruises to investigate the nature of the Campbell Plateau, Southern Ocean with Drs Karsten Gohl and Kaj Hoernle (Alfred Wegener Institute, Bremerhaven)

- Characteristics of the lithospheric mantle wedge in the Luzon-Taiwan subduction zone

- Collaboration continued with Professors A. Giret and J.-Y. Cottin of the University of Jean Monnet, St Etienne (with reciprocal funding from both sides). A formal agreement between the two universities includes PhD exchange, academic exchange and research collaboration relevant to the nature of the lithosphere in the Kerguelen Archipelago, Crozet Islands and Hoggar. Three PhD programs related to this project are ongoing with Guillaume Delpech and Stephanie Touron (both funded by an International Postgraduate Research Scholarship (IPRS) and a French government Co-tutelle Scholarship) and Raynald Ethien (funded by a Co-tutelle Scholarship).

- Lithosphere studies in the Massif Central of France commenced in collaboration with the Universities of Jean Monnet (St Etienne) and Blaise Pascal (Clermont-Ferrand). The postgraduate program of Stephanie Tournon (funded by an IPRS, a RAACE award and a Co-tutelle Scholarship) addresses this topic. Sue O’Reilly and Bill Griffin visited the University of Jean-Monnet for 3 months collaborative research in 2003 while Sue O’Reilly was a recipient of a CNRS Visiting Director of Research Award.

- Hf isotopic composition of rutiles in the South African lithosphere with M. Choukroun (Ecole Normale Supérieure, Paris) and Prof. J.B. Dawson (University of Edinburgh)
- Sulfides and the PGE budget in the mantle beneath the Massif Central with Prof. J.-L. Bodinier (Université Montpellier) and Prof. J.-P. Lorand (National Natural History Museum, Paris)

- Composition and crystal chemistry of mantle amphiboles with Dr M. Tiepolo, Dr R. Vance and Prof. R. Oberti from the University of Pavia, Italy

- \textit{In situ} Sr isotope analysis of marine fossils to constrain stratigraphic/tectonic reconstruction of terranes in New Zealand, with Dr C. Adams (Institute of Geological and Nuclear Sciences, New Zealand)

- Interpretation of the lithosphere structure of the Global Geoscience Transect 21 with Professor Yuan Xuecheng of the China Geological Survey

- Igneous rocks, mineral deposits and tectonic setting: southeastern China and eastern Australia. This collaboration with Nanjing University has expanded from an AusAID grant under the ACILP scheme.

- Lithosphere Mapping and crustal evolution in southeastern China (with Professor Xu Xisheng, Nanjing University, funded by the Chinese National Science Foundation)

- Lithosphere studies in China (with Professor Jianping Zheng). This follows on from a project with a consortium of participating institutions in a 5-year National Priority Program funded by China NSF from 1997.

- Lithosphere structure of North America (with Kennecott Canada)

- Inclusions in diamonds from Canadian lithosphere (with Kennecott Canada Exploration Inc.)

- Trace elements in diamonds from the South African lithosphere (with de Beers)

- Lithosphere Mapping and crustal evolution in the Dharwar Craton, India (with Rio Tinto and Dr E. Babu (National Geophysical Research Institute, Hyderabad) funded by a Boyscast fellowship from India)

- Age and magma sources of Chilean Cu-porphyries, with Codelco (Chile)

- Collaboration continued with Dr Scott E. Johnson at the University of Maine, funded by an NSF grant to Johnson, with Ron Vernon as collaborator, working on the San Jose pluton, Baja California, Mexico, and with Dr Scott R. Paterson at the University of Southern California, working on metamorphic-deformation problems in the Cascade Range, Washington. This project is being funded by an NSF grant to Vernon at USC, which also supports an MS student (Luke Jensen).

Refer to the \textit{Research Program} and \textit{Postgraduate} sections of this Report for details of other projects.

\textit{GEMOC participants also have a wide range of other research collaborations with colleagues in UK, USA, Europe (France, Germany, Norway, Italy) as described in the section on Research Programs and in Appendix 5.}
WAS THE FUNDING STRATEGY FOR GEMOC CONTINUATION AFTER 2001 SUCCESSFUL?

GEMOC’s business plan has proved to be a successful blueprint, resulting in viable funding to continue GEMOC’s activities beyond the Commonwealth funding period that ended in 2001.

Key elements of funding continuation include:

- Macquarie University support of $100,000 per annum
- Macquarie Vice-Chancellor’s grant to support Geophysical Modelling development
- ARC Program Grant 2002-2006 for basic research component
- DEST Systemic Infrastructure Initiative Grant ($5.125 million) for 2002-2004
- Industry funding is increasing through substantial collaborative ventures and value-added consulting
- Independent Research Fellowships to support Postdoctoral Fellows
- Continuation of existing funding sources for other ongoing activities such as postgraduate scholarships, undergraduate teaching development and pilot research projects.

Summary of strategy outcomes

- Staff: 2 new academic staff members continuing, new academic staff appointment
- Postgraduate funding strategy exceeded goals
- Strategy for equipment and analytical funding exceeded goals

Macquarie University support has been exceptional in all areas including cash, in-kind and space guarantees, and in policy support. Macquarie’s Research Strategic Plan recognises GEMOC’s research programs as Areas of Excellence (lithosphere and planetary evolution and metallogeny; isotopic and global geochemistry; and paleomagnetism, geodynamics and geophysical modelling) and GEMOC as a Centre of Excellence.

Strategy for ongoing Geochemical Analysis Unit funding

GEMOC’s outstanding analytical facilities are vital to our innovative research programs and to attracting research and industry income. This technology concentration also represents a high-budget item in terms of maintenance, running costs, replacement and especially for new purchases to maintain frontline developments. Funding strategies in place include:

- User-pays system for running, maintenance and development costs
- University annual contributions through competitive schemes and capital equipment allocations
- Annual contribution from the Department of Earth and Planetary Sciences
- Macquarie University’s guarantee of a strategic plan to ensure the integrity, maintenance and appropriate staffing of the Geochemical Analysis Unit
- Collaborative project building with industry partners
• Delivery of new exploration tools to industry through novel analytical methodologies
• Research and Development ventures with manufacturers leading to equipment replacement
• Applications to funding schemes for matching funds for new purchases
• Provision of services to external clients including industry
• Industry capital investment in return for access equity, negotiated intellectual property and collaborative rates

GEMOC INCOME 2003

This is a summary of 2003 Income. A full audited statement of detailed expenditure and income is provided to DETYA every March. *No in-kind support is included.*

<table>
<thead>
<tr>
<th>Source</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC</td>
<td>$814.2</td>
</tr>
<tr>
<td>Discovery, SPIRT, Fellowships</td>
<td></td>
</tr>
<tr>
<td><strong>OTHER COMMONWEALTH</strong></td>
<td></td>
</tr>
<tr>
<td>Postgraduate awards</td>
<td>$122.5</td>
</tr>
<tr>
<td>DEST Systemic Infrastructure</td>
<td>$1900.0</td>
</tr>
<tr>
<td><strong>INDUSTRY</strong></td>
<td></td>
</tr>
<tr>
<td>Collaborative Research grants (MUECRG, AMIRA)</td>
<td>$275.3</td>
</tr>
<tr>
<td>Collaborative and commercial through MRL</td>
<td>$324.5</td>
</tr>
<tr>
<td>Other Industry</td>
<td>$312.9</td>
</tr>
<tr>
<td><strong>INTERNAL UNIVERSITY</strong></td>
<td></td>
</tr>
<tr>
<td>Annual Key Centre Contribution</td>
<td>$150.0</td>
</tr>
<tr>
<td><strong>Internal competitive schemes</strong></td>
<td></td>
</tr>
<tr>
<td>Fellowships</td>
<td>$153.6</td>
</tr>
<tr>
<td>Research grants</td>
<td>$168.8</td>
</tr>
<tr>
<td>Vice-Chancellor Development Grant</td>
<td>$100.0</td>
</tr>
<tr>
<td>Postgraduate awards</td>
<td>$73.9</td>
</tr>
<tr>
<td>Postgraduate research grants</td>
<td>$6.5</td>
</tr>
<tr>
<td>Infrastructure (RIBG)</td>
<td>$61.1</td>
</tr>
<tr>
<td>Capital Equipment</td>
<td>$133.3</td>
</tr>
<tr>
<td>GAU maintenance (Department)</td>
<td>$30.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$4626.6</td>
</tr>
</tbody>
</table>

BENEFITS TO AUSTRALIA

- Scientific innovation relevant to National Priority Areas 1 (Goal 3: Developing Deep Earth Resources) and 3 (Goal 1: Breakthrough Sciences)
- Excellence in training of our future generation of geoscientists
- Enhanced industry links nationally and internationally
- Improved criteria for exploration by Australian mining companies both on- and off-shore
- Technological innovation (scientific advances, intellectual property, commercialisation, value-added consulting services)
- Enhanced international links
Appendix 1: Participants

GEMOC PARTICIPANTS 2003
MACQUARIE UNIVERSITY
Department of Earth and Planetary Sciences

Academic Staff (Teaching and Research)
Dr Kelsie Dadd (Physical vulcanology, geochemistry, tectonics) 100%
Dr Nathan Daczko (Structural and metamorphic geology, tectonics, geodynamics) 100%
Dr Richard Flood (Volcanic geology, application of magnetic fabrics to reconstruction of volcanic terrains) 100%
Professor W. L. Griffin, Program Leader (Technology development and industry liaison) 80%
Dr Simon Jackson (Trace element geochemistry, metallogeny) 100%
Dr Mark Lackie (Rock magnetism, paleomagnetic reconstructions) 30%
Professor Suzanne Y. O’Reilly, Director (Crust and mantle evolution, lithosphere modelling) 100%

Research Staff
Dr John Adam 40%
Dr Elena Belousova 100%
Ms Tara Deen 100%
Dr Lev Natapov 100%
Dr Yvette Poudjom Djomani 100%
Dr Rhianne George 100%
Dr Vladimir Malkovets 100%
Emeritus Professor Trevor Green 100%
Professor Simon Turner 100%
Emeritus Professor John Veevers 30%
Emeritus Professor Ron Vernon 20%
Dr Kuo-Lung Wang 100%
Dr Ming Zhang 100%

Adjunct Professors
Professor Bruce Chappell (Granite petrogenesis, geochemistry)
Professor W. L. Griffin
Dr John Hronsky (WMC Resources Ltd)
Professor Paul Morgan (University of Northern Arizona, Geophysics and tectonics)
Professor Mike Etheridge Professor Else-Ragnhild Neumann Professor Xisheng Xu

Visiting Professors
Professor Tom Andersen (University of Oslo)
Professor Jean-Yves Cottin (University Jean-Monnet, St Etienne)
Dr Yong-Joo Jwa
Associate Professor Ian Metcalfe (Tectonic reconstructions in Asia: Gondwana breakup)
Professor Nicholas Fisher (Statistics, quality management)
Dr Phil Schmidt (see CSIRO)

Visiting Fellows
Dr Gilles Chazot (University of Clermont-Ferrand)
Associate Professor Ian Metcalfe (Tectonics, Asian terrain reconstructions, Gondwana breakup)

Honorary Associates
Dr Natsue Abe
Dr Kari Anderson
Ms Sonja Aulbach
Dr Graham Begg
Dr Phillip L. Blevin (Igneous metallogeny, ore deposit studies)
Ms Rosa Maria Bomparola
Professor Hannes Brueckner
Dr Robert Bultitude
Dr Gilles Chazot
Mr David Clark (CSIRO)
Professor Kent Condie
Dr Richard Glen
Dr Karsten Gohl (Seismic studies and RV Sonne Cruise program)
Dr Michel Grégoire (Geochemistry)
Dr Jingfeng Guo (Mineral exploration in Asia; mantle sulfides, sapphire origin)
Dr Bram Janse (Diamond exploration)
Dr Mel Jones
Dr Felix Kaminsky
Associate Professor Ian Metcalfe
Dr Bertrand Moine
Dr Geoff Nichols
Dr Boris Panov
Dr Mark C. Pirlo
Dr Peter Robinson
Dr Chris Ryan (CSIRO)
Dr Stirling Shaw (Granitoids and crustal genesis)
Dr Simon Shee
Dr Zdislav Spetsius
Dr Nancy van Wagoner
Dr Steve Walters (Crustal terranes)
Dr Xiang Wang
Mr Bruce Wyatt (Mantle petrology, diamond exploration)
Ms Chunmei Yu
Professor Jin-Hai Yu
Professor Jianping Zheng (Geochemistry, China lithosphere)

Professional Staff
Ms Manal Bebbington (rock preparation) 50%
Ms Eloise Beyer (Geochemist) 40%
Ms Suzy Elhlou (Scientific Officer) 100%
Dr Oliver Gaul (Research Officer) 80%
Dr Stuart Graham (Geochemist until July 2003) 100%
Ms Sally-Ann Hodgekiss (Research Officer, Design consultant) 50%
Dr John Ketchum (Geochemist) 100%
Ms Carol Lawson (XRF, Laboratories) 100%
Ms Valeria Murgulov (Geochemist) 40%
Ms Leigh Newton (Administrator) 100%
Dr Norman Pearson (Manager, GAU) 100%
Dr Ayesha Saeed (Geochemist) 100%
Dr Kirsty Tomlinson (Geochemist) 100%
Mr Peter Wieland (Geochemist) 100%
Mr William Powell (Research Assistant) 40%

FORMAL COLLABORATORS

University of Wollongong
Professor Allan Chivas (DEST Systemic Infrastructure partner)

Monash University
Dr Peter Betts
Dr David Giles
Dr Bruce Schaefer

University of Newcastle
Dr W. Collins (DEST Systemic Infrastructure partner)

University of Sydney
Dr G. Clark (DEST Systemic Infrastructure partner)
Dr Dietmar Muller

University of Western Sydney
Professor Peter Williams (DEST Systemic Infrastructure partner)

CSIRO Division of Exploration and Mining
Dr Anita Andrew (Stable isotopes)
Mr D. Clark (Paleomagnetism, magnetic modelling)

Dr N. Evans (PGE geochemistry and Re/Os systematics)
Dr Brent McInnes (Cu/Au metallogeny)
Dr C. G. Ryan (Proton microprobe, fluid analysis)
Dr P. Schmidt (Rock magnetism, terrane evolution)
Ms Tin Tin Win (Hydrothermal systems, mantle petrology)

Australian National University
(Research School of Earth Sciences)
Professor Brian Kennett
Professor Gordon Lister

AGSO
Dr Barry Drummond (Geophysics)
Dr L. Wyborn (Crustal evolution, metallogeny through time, implementation of GPS/GIS)

Geological Survey of Western Australia
Dr D. Nelson (zircon U-Pb/Hf isotopes)
Dr I. Tyler (zircon U-Pb/Hf isotopes)

OTHER COLLABORATORS ON PROJECT BASIS

Dr Bernard Bingen (Geological Survey of Norway, Trondheim)
Professor J.-L. Bodinier (Université Montpellier, France)
Professor Chen-Hong Chen, (National Taiwan University)
Professor Chen Daogong (University of Science and Technology of China, Hefei)
Dr Sun-Ling Chung (National Taiwan University)
Mr B. Doyle (Kennecott Canada)
Dr Yuriy Erinchek (VSEGEI)
Professor Weiming Fan (Resource and Environment Department, Chinese Academy of Sciences)
Professor A. Giret (Université Jean Monnet, St Etienne)
Mr K. Kivi (Kennecott Canada)
Dr T.-L. Knudsen (Geologisk Museum, Norway)
Dr Lai Shaocong (Northwestern University, Xi'an)
Dr L. M. Larsen (Greenland Geological Survey)
Dr J.-P. Lorand (Museum National d'Histoire Naturelle)
Professor Fengxiang Lu (China University of Geosciences at Wuhan)
Professor Ma Hongwen (China University of Geosciences at Beijing)
Professor Boris Panov (Donetsk State Technical University)
Professor S. R. Paterson (University of Southern California)
Dr Patrice Rey (University of Sydney)
Dr Peter Robinson (Geological Survey of Norway, Trondheim)
Dr Z. Spetsius (ALROSA, Mir)
Professor O. T. Tobisch (University of California, Santa Cruz)
Associate Professor Wang Xiang (Nanjing University)
Professor P. F. Williams (University of New Brunswick)
Professor Xue Jiyue (Nanjing University)
Professor Yuan Xuecheng (China Geological Survey)
Professor Zhou Xinmin (Nanjing University)

Technology Partners
Agilent Technologies (Hewlett Packard)
New Wave Research
Spectro Instruments
Nu Instruments
Appendix 2: Publications

A full list of GEMOC Publications is available at http://www.es.mq.edu.au/GEMOC/


244. Grégoire, M., Jackson, I., O’Reilly, S.Y. and Cottin, J.-Y. 2001. The lithospheric mantle beneath the Kerguelen Islands (Indian Ocean): petrological and petrophysical characteristics of mantle rock types and correlation with seismic profiles. Contributions to Mineralogy and Petrology, 142, 244-259.


Appendix 2: Publications


Appendix 2: Publications


Appendix 3: Visitors

GEMOC VISITORS 2003
(Excluding Participants in Conferences and Workshops)

Macquarie

Dr Chris Adams (Institute of Geological & Nuclear Sciences, New Zealand)
Prof. Tom Andersen (University of Oslo)
Dr Graham Begg (Western Mining Resources Limited, Perth)
Mr Robert Bills (Western Mining Resources Limited, Perth)
Dr Jon Blundy (University of Bristol, U.K.)
Mr Nigel Brand (Anglo American, WA)
Mr Mathieu Choukroun (PhD student, Universite St Etienne, France)
Dr Richard Glen (Geological Survey of NSW, New South Wales, Australia)
Dr Chris Hatton (De Beers South Africa)
Dr Yong-Joo Jwa (Gyeongsang National University, Korea)
Mr Chris Lay (New Wave Research Co. Ltd)
Prof. T. M. Mahadevan (DST-DCS Newsletter Editor, India)
Dr Suzanne McEnroe (Geological Survey of Norway, Trondheim)
Mr Malcolm Norris (Western Mining Resources Limited, Perth)
Dr Chris Oates (Anglo American, Canada)
Prof. Boris Panov (Donetsk State Polytechnic University, Ukraine)
Dr Peter Robinson (Geological Survey of Norway, Trondheim)
Dr Bruce Schaefer (Monash University, Melbourne, Australia)
Mr Bryce Healy, Department of Geology, University of Newcastle
Dr Florence Le Hebel, Dept of Geosciences, University of Sydney
Ms Panatree Lomthong, Dept of General Science, Kasetsart University, Bangkok, Thailand
Dr Suzanne McEnroe, Geological Survey of Norway
Dr Terry Mernagh, Geoscience Australia, Canberra
Dr Bruce Mountain, Institute of Geological and Nuclear Sciences, Taupo, New Zealand
Dr Niels Munksgaard, School of Science, Charles Darwin University
Ms Kylie Prendergast, School of Earth Sciences, James Cook University, Townsville
Mr Anthony Reid, School of Earth Sciences, Melbourne University
Dr Peter Robinson, Geological Survey of Norway
Mr Florian Schr"uter, Dept of Geosciences, University of Sydney
Dr Keith Sircombe, School of Earth and Geographical Sciences, University of Western Australia
Ms Tin Tin Win, CSIRO Exploration and Mining, North Ryde
Dr Xiaolin Xiong, Guangzhou Institute of Geochemistry, China Academy of Sciences, Guangzhou, China
Ms Chunmei Yu, China University of Geosciences
Prof. Jianping Zheng, China University of Geosciences

Dr Simon Shee (DeBeers Exploration Australia Ltd)
Dr Steve Walters (GeoDiscovery Group, Queensland, Australia)
Dr Xiaolin Xiang (Chinese Academy of Sciences, P. R. China)
Prof. Xisheng Xu (Nanjing University, P. R. China)
Ms Chunmei Yu (China University of Geosciences)
Prof. Jianping Zheng (China University of Geosciences)

EXTERNAL USERS OF THE GEOCHEMICAL ANALYSIS UNIT FACILITIES IN 2003
(Note: this does not include commercial or contract work through Macquarie Research Limited)

Dr Chris Adams, Institute of Geological & Nuclear Sciences, Lower Hutt, New Zealand
Prof. Tom Andersen, University of Oslo, Norway
Mr Manish Arora, Faculty of Dentistry, University of Sydney
Dr Tim Baker, School of Earth Sciences, James Cook University, Townsville
Ms Rosa-Maria Bomparola, Università degli Studi di Siena, Italy
Dr Graziella Caprarelli, Dept of Environmental Sciences, University of Technology, Sydney
Mr Michael Carew, School of Earth Sciences, James Cook University, Townsville
Mr Raynal Ethien, Université Jean Monnet, St Etienne, France
Mr Mathew Greentree, School of Earth and Geographical Sciences, University of Western Australia
ALICE WAHN MEMORIAL WEST NORWAY ECLOGITE FIELD SYMPOSIUM 2003, SELJIE, WESTERN NORWAY, 21-28 JUNE 2003

Origin of Western Gneiss Region garnet peridotites: refterilisation of Archean lithosphere? Evidence from the Almklovdalen peridotite body
E. E. Beyer, W. L. Griffin, S. Y. O’Reilly and N. J. Pearson
GEMOC, Macquarie

8th INTERNATIONAL KIMBERLITE CONFERENCE, VICTORIA, CANADA, 22-27 JUNE 2003

The lithospheric mantle beneath the Buffalo Head Terrane, Alberta: xenoliths from the Buffalo Hills kimberlites
S. Aulbach1, W. L. Griffin1,2, S. Y. O’Reilly4 and T. E. McCandless3.1. GEMOC, Macquarie, 2. CSIRO Exploration and Mining, North Ryde, 3. Ashton Mining Canada Inc., North Vancouver, Canada

Origins of eclogites beneath the Central Slave Craton

Inclusions in diamonds from the K10 and K14 kimberlites, Buffalo Hills, Canada: Diamond growth in a plume?
R. M. Davies1,2, W. L. Griffin3, S. Y. O’Reilly4 and T. E. McCandless4.1. American Museum of Natural History, New York, USA, 2. GEMOC, Macquarie, 3. CSIRO Exploration and Mining, North Ryde, 4. Ashton Mining of Canada, Canada

Geological characteristics of microdiamonds from kimberlites at Lac de Gras, Central Slave Craton

Geochemistry and Ar-Ar dating of upper Holocene volcanic rocks from Kerguelen islands (Indian Ocean)
R. Ethien1,2, G. Feraud1, M. C. Gerbe1, J. Y. Cottin1, S. Y. O’Reilly3 and A. Giret1.1. Dpt. de Petrologie, Minerologie et Geochimie, UMR-CNR “Magma set Volcans”, Universite Jean Monnet-Saint-Etienne, France, 2. GEMOC, Macquarie, 3. CNRS, “Geosciences Azur”, Universite de Nice Sophia-Antipolis, France

Mineralogical and geochemical characteristic of a unique mantle xenolith from the Udachnaya kimberlite pipe
S. Kuligina1, V. Malkovets1, N. Pokhilenko1, M. Vavilov1, W. L. Griffin2 and S. Y. O’Reilly2.1. Institute of Mineralogy and Petrography SB RAS, Russia, 2. CSIRO Exploration and Mining, North Ryde, 3. GEMOC, Macquarie

Geochemical and isotopic evidence of a kimberlite-melnoite-carbonatite genetic link
S. Graham1, D. Lambert1,2 and S. Shee1,4.1. VIEPS, Monash University, Australia, 2. GEMOC, Macquarie, 3. NSF, USA, 4. De Beers Australia Exploration Limited, Australia

Lithospheric mapping beneath the North American plate
W. L. Griffin1,2, S. Y. O’Reilly1, B. J. Doyle1, K. Kivi1 and H. G. Coopersmith1.1. GEMOC, Macquarie, 2. CSIRO Exploration and Mining, North Ryde, 3. Kenneecott Canada Exploration Inc., Vancouver, Canada, 4. Great Western Diamond Co., Fort Collins, USA

GEOLOGICAL SOCIETY OF AMERICA 38TH NORTHEASTERN SECTION MEETING, HALIFAX, NOVA SCOTIA, CANADA, 27-29 MARCH 2003
Emplacement-related microstructures in the deformed carapace of a tonalite pluton: evidence for fast chamber con 
struction
S. E. Johnson1, R. H. Vernon2 and P. Upton1.1. Dept. of Geological Sciences, University of Maine, Orono, USA, 2. GEMOC, Macquarie
Evidence for fast magma chamber construction: the deformed carapace of the San Jose tonalite pluton, Mexico
S. E. Johnson1, R. H. Vernon2 and P. Upton1.1. Dept. of Geological Sciences, University of Maine, Orono, USA, 2. GEMOC, Macquarie

5TH INTERNATIONAL SYMPOSIUM ON APPLIED ISOTOPE GEOCHEMISTRY, HERON ISLAND, QUEENSLAND, AUSTRALIA, 26-30 MAY 2003
In-situ determination of high precision isotope ratios by Laser Ablation-Multicollector-Inductively Coupled Plasma Mass Spectrometer (LA-MC-ICP-MS): Application to Cu and Fe isotopes in ore minerals
S. E. Jackson1, S. Graham1 and D. Gunther2.1. GEMOC, Macquarie, 2. Laboratory for Inorganic Chemistry, ETH Honggerberg, Zurich, Switzerland
Appendix 4: Abstract titles

Peridottes from the Grib kimberlite pipe, Arkhangelsk, Russia
V. G. Malkovets1,2, L. A. Taylor3, W. L. Griffin1, S. Y. O’Reilly1, N. J. Pearson1, N. Pokhilenko1, E. M. Verichev1, N. N. Golovin1 and K. D. Litasov6
1. Institute of Mineralogy and Petrography, Novosibirsk, Russia, 2. Planetary Geosciences Institute, University of Tennessee, Knoxville, USA, 3. GEMOC, Macquarie, 4. Arkhangelskgeolrazvedka, Arkhangelsk, Russia, 5. Arkhangelskgeoldobycha, Arkhangelsk, Russia, 6. Dept. Mineral. Petrol. Econ. Tohoku University, Sendai, Japan

Taking the pulse of the Earth: lithosphere events tracked by in-situ geochronology
S. Y. O’Reilly and W. L. Griffin
GEMOC, Macquarie

Magnesium isotopic composition of olivine from the lithospheric mantle
N. J. Pearson1, W. L. Griffin1,2, S. Y. O’Reilly1 and G. Delpech1
1. GEMOC, Macquarie, 2. CSIRO Exploration and Mining, North Ryde

Pyrope and chromites of the Snap Lake/King Lake kimberlite dyke system in relation to the problem of the southern Slave Craton lithospheric mantle structure and composition
N. Pokhilenko1,2, W. L. Griffin1,2, N. Shimizu1, C. McLean1, V. Malkovets2,3, L. Pokhilenko2 and E. Malygina1
1. Diamondex Resources Ltd, Canada, 2. Institute of Mineralogy and Petrology, Russia, 3. GEMOC, Macquarie, 4. CSIRO Exploration and Mining, Australia, 5. Woods Hole Oceanographic Institution, USA

Geophysical analysis of the lithosphere beneath the Slave Craton
Y. H. Poudjom Djomani2, S. Y. O’Reilly1, W. L. Griffin1,2 and B. J. Doyle3
1. GEMOC, Macquarie, 2. CSIRO Exploration and Mining, North Ryde, 3. Kennebec Exploration Canada Exploration Inc., Vancouver, Canada

Diamond formation and mantle metasomatism: A trace element perspective
T. Stachel1, S. Aulbach2, G. P. Brey3, J. W. Harris1, I. Leost1, R. Tappert1,2 and K. S. (Fanus) Viljoen3

Melt inclusions from the deep Slave lithosphere: Constraints on the origin and evolution of mantle-derived carbonatite and kimberlite
E. van Achterbergh1,2, W. L. Griffin1,2, S. Y. O’Reilly1, C. G. Ryan1, N. J. Pearson1, K. Kivi3 and B. J. Doyle4
1. GEMOC, Macquarie, 2. CSIRO Exploration and Mining, North Ryde, 3. Department of Geosciences, National Taiwan University, Taipei, Taiwan R. O. C., 4. Department of Geology, National Museum of Natural Science, Taichung, Taiwan R. O. C.

Trace element analysis of diamond by IAP LCPMS: preliminary results
S. Rege1, R. M. Davies1,2, W. L. Griffin1,3, S. E. Jackson1 and S. Y. O’Reilly1

Late Vendian aerial alkaline volcanism in Winter Coast kimberlite area (Arkhangelsk Diamondiferous Province)
V. S. Shchukin1, S. M. Sablukov2, L. I. Sablukov2, E. A. Belousova1 and W. L. Griffin1
1. JSC Arkhangelsk Diamonds, Russia, 2. Central Research Institute of Geological Prospecting (TsNIGRI), Russia, 3. GEMOC, Macquarie
Natural trace element distribution between immiscible silicate and carbonate melts imaged by nuclear microprobe
E. van Achterbergh1,2, C. G. Ryan2, W. L. Griffin1,2 and S. Y. O'Reilly3
1. GEMOC, Macquarie, 2. CSIRO Exploration and Mining, North Ryde

Geochemical characteristics of mantle xenoliths from Penghu Islands, Taiwan Straits, SE Asian Margin
K. Wang4, S. Y. O'Reilly1, W. L. Griffin1,2, S. Chung3 and W. Juang4
1. GEMOC, Macquarie, 2. CSIRO Exploration and Mining, North Ryde, 3. Department of Geosciences, National Taiwan University, Taipei, Taiwan R. O. C., 4. Department of Geology, National Museum of Natural Science, Taichung, Taiwan R. O. C.

The Brockman Creek kimberlite, East Pilbara, Australia
B. A. Wyatt1, M. Mitchell1, S. R. Shee1, W. L. Griffin1, N. Tomlinson1 and B. White1

Granites of the southern New England orogen
C. J. Bryant1, B. W. Chappell2 and P. Blevin2
1. Dept. of Geology, Australian National University, Canberra, Australia, 2. GEMOC, Macquarie

From Tuttle and Bowen onwards
B. W. Chappell
GEMOC, Macquarie

Causes of variation in granite suites
B. W. Chappell
GEMOC, Macquarie

High and low-temperature granites
B. W. Chappell
GEMOC, Macquarie

Towards a unified model of granite petrogenesis
B. W. Chappell
GEMOC, Macquarie

Granites of the Lachlan Fold Belt
B. W. Chappell
GEMOC, Macquarie

Mesozoic granites and associated mineralisation in South Korea
Y. J. Iwa
GEMOC, Macquarie

Gravity and granites
M. A. Lackie1, B. T. Bailey1,2 and M. A. Edmiston1,3
1. GEMOC, Macquarie, 2. Gmomic Exploration Services, Townsville, QLD, 3. Coffey Geosciences, North Ryde, NSW

THE 5th HUTTON SYMPOSIUM ON THE ORIGIN OF GRANITES AND RELATED ROCKS, TOYOHASHI, JAPAN, 2-6 SEPTEMBER 2003

Lithium isotopes and granite petrogenesis
C. Bryant1, B. W. Chappell2, V. Bennett1 and M. McCulloch1
1. Research School of Earth Sciences, ANU, Canberra, 2. GEMOC, Macquarie

Towards a unified model for granite genesis
B. W. Chappell
GEMOC, Macquarie

Silica-oversaturated volcano-plutonic association in the Rallier du Baty Peninsula, Kerguelen Island: time and space relations and magma genesis
R. Ethien1, M. C. Gerbe1, J-Y. Cottin1, G. Feraud2, S. Y. O'Reilly1 and B. Moine1
1. Universite Jean Monnet & UMR CNRS “Magmas et Volcans”, Saint Etienne, France, 2. Université de Nice-Sophia Antipolis, Geosciences Azur, Nice, France, 3. GEMOC, Macquarie

A reconnaissance Lu/Hf investigation of the New England batholith Eastern Australia
R. H. Flood and S. E. Shaw
GEMOC, Macquarie

Preservation of zircon U-Pb ages through high-grade metamorphism and magma genesis
I. S. Williams1, B. W. Chappell2, D. W. Maidment1 and I. S. Buick3
1. Research School of Earth Sciences, ANU, Canberra, 2. GEMOC, Macquarie, 3. Department of Earth Sciences, La Trobe University, Bundoora, VIC

MAGMAS TO MINERALISATION: THE ISHIHARA SYMPOSIUM, MACQUARIE UNIVERSITY, NORTH RYDE, AUSTRALIA, 22-24 JULY 2003

Metallogeny of granite rocks
P. Blevin
GEMOC, Macquarie

Paleozoic granite metallogenesis of eastern Australia
P. Blevin
GEMOC, Macquarie

Granites of the southern New England orogen
C. J. Bryant1, B. W. Chappell2 and P. Blevin2
1. Dept. of Geology, Australian National University, Canberra, Australia, 2. GEMOC, Macquarie

From Tuttle and Bowen onwards
B. W. Chappell
GEMOC, Macquarie

Causes of variation in granite suites
B. W. Chappell
GEMOC, Macquarie

High and low-temperature granites
B. W. Chappell
GEMOC, Macquarie

Towards a unified model of granite petrogenesis
B. W. Chappell
GEMOC, Macquarie

Granites of the Lachlan Fold Belt
B. W. Chappell
GEMOC, Macquarie

Mesozoic granites and associated mineralisation in South Korea
Y. J. Iwa
GEMOC, Macquarie

Gravity and granites
M. A. Lackie1, B. T. Bailey1,2 and M. A. Edmiston1,3
1. GEMOC, Macquarie, 2. Gmomic Exploration Services, Townsville, QLD, 3. Coffey Geosciences, North Ryde, NSW

THIRD STATE OF THE ARC CONFERENCE (SOTA III), MOUNT HOOD, OREGON, 16-21 AUGUST 2003

Experimentally-determined trace element characteristics of aqueous fluid from partially dehydrated mafic oceanic crust at 3.0 GPa, 650-700°C
T. H. Green and J. Adam
GEMOC, Macquarie
Appendix 4: Abstract titles

13th V. M. Goldschmidt Conference, Kurashiki, Japan, 7-12 September 2003

LA-ICP-MS: a mature technology?
S. E. Jackson
GEMOC, Macquarie

Paleozoic upper mantle of the southern frame of the Siberian platform: Structure and composition
V. G. Malkovets1, A. A. Gibsher1, Y. D. Litasov3, S. Y. O’Reilly1 and W. L. Griffin1
1. Institute of Mineralogy and Petrography, Novosibirsk, Russia
2. Institute of Geology, Novosibirsk, Russia, 3. GEMOC, Macquarie

New data on mantle metasomatism beneath the Deves, France
S. Tourron1,2, S. Y. O’Reilly1, C. Renac2, C. Chazot3, J. Y. Cottin2
1. GEMOC, Macquarie, 2. Universite Jean Monnet St-Etienne, France, 3. CNRS, Clermont-Ferrand, France

Proterozoic mantle lithosphere beneath the extended margin of the South China block: In situ Re-Os evidence
K.-L. Wang1, S. Y. O’Reilly1, W. L. Griffin1,2, S.-L. Chung3 and N. J. Pearson1
1. GEMOC, Macquarie, 2. CSIRO Exploration & Mining, North Ryde, 3. Department of Geosciences, National Taiwan University, Taiwan, R. O. C.

Re-Os isotopes in sulfides of mantle peridotites from SE China: age constraints and evolution of lithospheric mantle
X. Xu1,2, W. L. Griffin3, S. Y. O’Reilly2 and N. J. Pearson2
1. State Key Laboratory for Mineral Deposits Research, Department of Earth Sciences, Nanjing University, Nanjing, China, 2. GEMOC, Macquarie

Trace element partitioning between natural clinopyroxene, garnet and plagioclase under liquid condition
J. Yu1 and S. Y. O’Reilly2
1. Dept. Earth Sciences, Nanjing University, Nanjing, China, 2. GEMOC, Macquarie

SGTSG Field Meeting Kalbarri 2003, Kalbarri, Western Australia, 22-26 September 2003

Extension along the Australian-Pacific transpressional transform plate boundary near Macquarie Island
N. Daczko1,2, K. L. Wertz1,2, S. Mosher1, M. F. Coffin1,2 and T. Meckel1,2
1. Department of Geological Sciences, University of Texas at Austin, 2. Institute for Geophysics, University of Texas at Austin, 3. Ocean Research Institute, University of Tokyo & Institute for Frontier Research on Earth Evolution, Japan Marine Science & Technology Centre

American Geophysical Union Fall Meeting, San Francisco, USA, 8-12 December 2003

Constraints on the mechanism and timing of sediment recycling beneath the Tonga-Kermadec arc from Be isotopes
R. George1, S. Turner1, J. Morris2, C. Hawkesworth1 and J. Ryan3
1. GEMOC, Macquarie, 2. Department of Earth & Planetary Sciences, Washington University, Saint Louis, USA, 3. Department of Geology, University of South Florida, Tampa, USA

Calculating Upper Mantle Heat Flow Values Using Xenolith P-T Data and Temperature-Dependent Thermal Conductivity Estimates
P. Morgan1 and S. Y. O’Reilly2
1. Northern Arizona University, Dept. Geology, USA, 2. GEMOC, Macquarie

Constraints on melting processes beneath subduction zones from U-Pa disequilibria
M. Regelous1, S. P. Turner2, C. J. Hawkesworth2, T. Elliot1 and K. Rostami2
1. Dept. of Earth Sciences, University of Bristol, UK, 2. GEMOC, Macquarie

Navajo garnetites and rock-wall interaction in the mantle
D. Smith1 and W. L. Griffin2
1. University of Texas at Austin, USA, 2. GEMOC, Macquarie

Extreme Pb-Ra disequilibria observed in arc lavas: Implications for the time scales of magma degassing
S. Turner
GEMOC, Macquarie

Extreme Re-Os disequilibria observed in arc lavas: Implications for the time scales of magma degassing
S. Turner
GEMOC, Macquarie
### Appendix 5: Funded research projects

**GRANTS AND OTHER INCOME FOR 2003**

<table>
<thead>
<tr>
<th>Funding Source</th>
<th>Investigators</th>
<th>Project Title</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macquarie University Host Institution Support</td>
<td>O'Reilly</td>
<td>GEMOC Matching</td>
<td>$100,000</td>
</tr>
<tr>
<td>Macquarie University Vice Chancellor’s Special Fund</td>
<td>O'Reilly</td>
<td>Geodynamic Modelling</td>
<td>$100,000</td>
</tr>
<tr>
<td>ARC Discovery</td>
<td>O'Reilly, Griffin, Gohl, Morgan, Cottin, Neumann, Xu</td>
<td>How has the continental lithosphere evolved? Processes of assembly, growth, transformation and destruction</td>
<td>$329,926</td>
</tr>
<tr>
<td>ARC Discovery</td>
<td>Walter</td>
<td>Palaeobiology of hydrothermal mineral deposits</td>
<td>$73,317</td>
</tr>
<tr>
<td>ARC Discovery</td>
<td>Belousova</td>
<td>Crustal evolution in Australia: Ancient and young terrains</td>
<td>$101,695</td>
</tr>
<tr>
<td>ARC Discovery</td>
<td>Veevers</td>
<td>Mapping under ice – crustal evolution in Antarctica &amp; the assembly of Gondwanaland</td>
<td>$61,419</td>
</tr>
<tr>
<td>ARC LIEF</td>
<td>O'Reilly, Griffin, Braun et al.</td>
<td>An inference engine for complex earth systems (ANU lead institution)</td>
<td>$190,000</td>
</tr>
<tr>
<td>ARC SPIRT</td>
<td>O'Reilly, Griffin, Hronsky, WMC</td>
<td>Lithospheric architecture of Australia: relevance to location of giant ore bodies (with industry contribution)</td>
<td>$125,601</td>
</tr>
<tr>
<td>ARC</td>
<td>Turner</td>
<td>Federation Fellowship</td>
<td>$296,934</td>
</tr>
<tr>
<td>DEST SII</td>
<td>O'Reilly</td>
<td>Advanced technology for a clever geoscience future in Australia</td>
<td>$1,900,000</td>
</tr>
<tr>
<td>MURF</td>
<td>Wang</td>
<td>Geochemical characteristics of mantle xenoliths from Taiwan and Penghu Islands, SE China: Implications for mantle process and geodynamics</td>
<td>$83,685</td>
</tr>
<tr>
<td>MURF</td>
<td>Malkovets</td>
<td>Evolution of the upper mantle beneath the Siberian Craton and the Siberian Platform</td>
<td>$69,998</td>
</tr>
<tr>
<td>MURDG</td>
<td>Wang</td>
<td>Lithosphere extension in East Asia: tectonic and geochemical consequences</td>
<td>$19,900</td>
</tr>
<tr>
<td>MURDG</td>
<td>Jackson</td>
<td>Isotopic fractionation of the ore minerals (Cu, Zn, Fe): Mechanisms and significance</td>
<td>$13,000</td>
</tr>
<tr>
<td>MURDG</td>
<td>Green</td>
<td>Behaviour of antimony, molybdenum and tungsten in Earth’s crust-mantle system - an experimental examination of their geochemical character</td>
<td>$4,024</td>
</tr>
</tbody>
</table>
## Appendix 5: Funded research projects

<table>
<thead>
<tr>
<th>Funding Source</th>
<th>Investigators</th>
<th>Project Title</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>MURDF</td>
<td>Etheridge</td>
<td>Risk and value management in mineral exploration</td>
<td>$130,451</td>
</tr>
<tr>
<td>RIBG</td>
<td>O’Reilly</td>
<td>A high pressure asher</td>
<td>$61,126</td>
</tr>
<tr>
<td>Capital Equipment</td>
<td>Lackie</td>
<td>Upgrade of teaching PC lab</td>
<td>$16,133</td>
</tr>
<tr>
<td>Capital Equipment</td>
<td>Lackie</td>
<td>Real-time differential GPS total station</td>
<td>$85,300</td>
</tr>
<tr>
<td>EPS</td>
<td>GEMOC</td>
<td>GAU Maintenance contribution</td>
<td>$30,000</td>
</tr>
<tr>
<td>PGRF</td>
<td>Aulbach</td>
<td>Depletion and metasomatic processes in the lithosphere mantle</td>
<td>$1,500</td>
</tr>
<tr>
<td>PGRF</td>
<td>Touron</td>
<td>Mapping geochemical domains in the mantle beneath the Massif Central (France)</td>
<td>$4,000</td>
</tr>
<tr>
<td>PGRF</td>
<td>Rege</td>
<td>Trace elements in diamond</td>
<td>$4,000</td>
</tr>
<tr>
<td>IPRS</td>
<td>Delpech</td>
<td>Isotopic characteristics of lithosphere processes beneath the Kerguelen Plateau</td>
<td>$18,009</td>
</tr>
<tr>
<td>IPRS and MUIPRA</td>
<td>Guo</td>
<td>An integrated geophysical investigation of the Hunter-Mooki and Peel Faults</td>
<td>$38,809</td>
</tr>
<tr>
<td>IPRS and MUIPRA</td>
<td>Aulbach</td>
<td>Depletion and metasomatic processes in the cratonic mantle</td>
<td>$38,809</td>
</tr>
<tr>
<td>IPRS and MURAACE</td>
<td>Touron, O’Reilly</td>
<td>Geochemical fingerprinting of the Massif Central (France) mantle</td>
<td>$38,809</td>
</tr>
<tr>
<td>IPRS and iMURS</td>
<td>Rege, O’Reilly</td>
<td>Trace elements in diamonds: genetic and forensic implications</td>
<td>$38,809</td>
</tr>
<tr>
<td>APA</td>
<td>Murgulov</td>
<td>Crust-mantle evolution and metallogeny, E. Australia</td>
<td>$18,009</td>
</tr>
<tr>
<td>8IKC Conference Travel Grant</td>
<td>Aulbach</td>
<td>The lithospheric mantle beneath the Buffalo Head Terrane, Alberta: Xenoliths from the Buffalo Hills kimberlites</td>
<td>$2,765</td>
</tr>
<tr>
<td>8IKC Conference Travel Grant</td>
<td>Rege</td>
<td>Trace element analysis of diamond by LAM ICPMS: preliminary results</td>
<td>$2,765</td>
</tr>
<tr>
<td>8IKC Conference Travel Grant</td>
<td>Graham</td>
<td>Geochemical and isotopic evidence of a Kimberlite-melnoite-carbonatite genetic link</td>
<td>$2,765</td>
</tr>
<tr>
<td>EURODOC</td>
<td>Touron</td>
<td>Isotopic studies of the French Massif Central ultrabasic-basal xenoliths: source of the Tertiary-Quaternary volcanism, mantle metasomatism and 4D Mapping of the continental lithosphere</td>
<td>$6,250</td>
</tr>
<tr>
<td>EURODOC</td>
<td>Delpech</td>
<td>Isotopic studies of Kerguelen ultrabasic-basal xenoliths: characterisation of the sources of magmatism and metasomatism beneath an oceanic plateau</td>
<td>$6,250</td>
</tr>
<tr>
<td>Funding Source</td>
<td>Investigators</td>
<td>Project Title</td>
<td>Amount</td>
</tr>
<tr>
<td>----------------</td>
<td>---------------</td>
<td>------------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>MUECRG</td>
<td>Griffin, University of Oslo, Norwegian Geological Survey</td>
<td>Where was Baltica? Testing continental reconstruction with TerraneChron™ (including industry contribution)</td>
<td>$85,308</td>
</tr>
<tr>
<td>MUECRG</td>
<td>Griffin, O'Reilly, Walter, BHP</td>
<td>Proterozoic crustal evolution: Baseline development of a global comparative library of Event Signatures linked to mineral endowment (including industry contribution)</td>
<td>$100,000</td>
</tr>
<tr>
<td>MUNS</td>
<td>Daczko</td>
<td>Melt escape and trace-element partitioning during high-pressure partial melting in the lower crust, northern Fiordland, New Zealand</td>
<td>$18,615</td>
</tr>
</tbody>
</table>

### FUNDED RESEARCH PROJECTS FOR 2004

<table>
<thead>
<tr>
<th>Funding Source</th>
<th>Investigators</th>
<th>Project Title</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macquarie University Host Institution Support</td>
<td>O'Reilly</td>
<td>GEMOC Key Centre Contribution</td>
<td>$120,000</td>
</tr>
<tr>
<td>ARC Discovery</td>
<td>O'Reilly, Griffin, Gohl, Morgan, Cottin, Neumann, Xu</td>
<td>How has the continental lithosphere evolved? Processes of assembly, growth, transformation and destruction</td>
<td>$285,000</td>
</tr>
<tr>
<td>ARC Discovery</td>
<td>Belousova</td>
<td>Crustal evolution in Australia: Ancient and young terrains</td>
<td>$99,345</td>
</tr>
<tr>
<td>ARC Discovery</td>
<td>Turner</td>
<td>The time scales of magmatic and erosional cycles</td>
<td>$100,000</td>
</tr>
<tr>
<td>ARC Discovery</td>
<td>Alard</td>
<td>Toward the use of metal stable isotopes in geosciences</td>
<td>$140,000</td>
</tr>
<tr>
<td>ARC Linkage International</td>
<td>O'Reilly, Griffin, Cottin, Gregoire, Xu</td>
<td>How has the continental lithosphere evolved? Processes of assembly, growth, transformation and destruction</td>
<td>$40,000</td>
</tr>
<tr>
<td>ARC Linkage Projects</td>
<td>O'Reilly, Griffin, WMC</td>
<td>Global lithosphere architecture mapping (including industry contribution)</td>
<td>$190,000</td>
</tr>
<tr>
<td>ARC</td>
<td>Turner</td>
<td>Federation Fellowship</td>
<td>$290,000</td>
</tr>
<tr>
<td>ARC</td>
<td>Daczko</td>
<td>The environmental and tectonic implications of volcanioclastic sedimentary deposits on Macquarie Island</td>
<td>$79,000</td>
</tr>
<tr>
<td>DEST SII</td>
<td>O'Reilly</td>
<td>Advanced technology for a clever geoscience future in Australia</td>
<td>$1,830,000</td>
</tr>
<tr>
<td>MUECRG</td>
<td>O'Reilly, Zhang, WMC</td>
<td>Continental flood basalts: geochemical discrimination with relevance to exploration for nickel and platinum-group elements (including industry contribution)</td>
<td>$60,000</td>
</tr>
<tr>
<td>MUECRG</td>
<td>Griffin, O'Reilly, Rio Tinto</td>
<td>Lithosphere Mapping beneath the Dharwar Craton, India (including industry contribution)</td>
<td>$60,800</td>
</tr>
</tbody>
</table>
### Appendix 5: Funded research projects

<table>
<thead>
<tr>
<th>Funding Source</th>
<th>Investigators</th>
<th>Project Title</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUECRG</td>
<td>Griffin, Pearson, O'Reilly, Daczko, NSWGS</td>
<td>Testing Ordovician-Devonian tectonic models for the Lachlan group (including industry contribution)</td>
<td>$50,000</td>
</tr>
<tr>
<td>MURIF</td>
<td>Smith, O'Reilly, Parfitt, Esselle</td>
<td>Inversion scattering, remote sensing and data inversion</td>
<td>$247,681</td>
</tr>
<tr>
<td>MURF</td>
<td>Malkovets</td>
<td>Evolution of the upper mantle beneath the Siberian Craton and the Siberian Platform</td>
<td>$66,949</td>
</tr>
<tr>
<td>MURF</td>
<td>Wang</td>
<td>Geochemical characteristics of mantle xenoliths from Taiwan and Penghu Islands, SE China: Implications for mantle process and geodynamics</td>
<td>$32,482</td>
</tr>
<tr>
<td>MURDG</td>
<td>Wang</td>
<td>Lithosphere extension in East Asia: tectonic and geochemical consequences</td>
<td>$19,555</td>
</tr>
<tr>
<td>MURDG</td>
<td>Jackson</td>
<td>Isotopic fractionation of the ore metals (Cu, Fe): Mechanisms and significance</td>
<td>$16,700</td>
</tr>
<tr>
<td>MURDF</td>
<td>Etheridge</td>
<td>Mineral exploration risk</td>
<td>$100,000</td>
</tr>
<tr>
<td>Nu Instruments</td>
<td>Griffin, O'Reilly</td>
<td>Postdoctoral Fellowship from Nu Instruments</td>
<td>$312,929</td>
</tr>
<tr>
<td>Capital Equipment</td>
<td>Lackie</td>
<td>Frequency FM Equipment</td>
<td>$42,000</td>
</tr>
<tr>
<td>Capital Equipment</td>
<td>Flood</td>
<td>Precision lapping &amp; polishing machine</td>
<td>$90,000</td>
</tr>
<tr>
<td>EPS</td>
<td>GEMOC</td>
<td>GAU Maintenance contribution</td>
<td>$30,000</td>
</tr>
<tr>
<td>IPRS and MUIPRA</td>
<td>Guo</td>
<td>An integrated geophysical investigation of the Hunter-Mooki and Peel Faults</td>
<td>$39,284</td>
</tr>
<tr>
<td>IPRS and MUIPRA</td>
<td>Touron</td>
<td>Geochemical fingerprinting of the Massif Central (France) mantle</td>
<td>$39,284</td>
</tr>
<tr>
<td>IPRS and IMUPRA</td>
<td>Rege</td>
<td>Trace elements in diamonds: genetic and forensic implications</td>
<td>$39,284</td>
</tr>
<tr>
<td>RAACE and iMURS</td>
<td>Daczko, Milan</td>
<td>The emplacement, pressure-temperature-time path and structural evolution of lower crust gneisses in Fiordland, New Zealand</td>
<td>$39,284</td>
</tr>
<tr>
<td>APA</td>
<td>Murgulov</td>
<td>Crust-mantle evolution and metallogeny, E. Australia</td>
<td>$18,484</td>
</tr>
</tbody>
</table>

ARC Research Projects initiated prior to 2003 are available at our website: [http://www.es.mq.edu.au/GEMOC/](http://www.es.mq.edu.au/GEMOC/) Follow the Annual Report Link to Appendix 5 of the previous Annual Reports.
Established and supported under the Australian Research Council's Research Centres Program

GEMOC information is accessible on WWW at: http://www.es.mq.edu.au/GEMOC/

Contact GEMOC via email at: gemoc@mq.edu.au

Contents
Director's preface 1
Introducing GEMOC *2
GEMOC participants *4
GEMOC programs 5
GEMOC structure see web
GEMOC communications 2003 6
Is GEMOC making a difference? 8
GEMOC's research program 9
Funded basic research projects for 2004 15
Research highlights 2003 17
Teaching and training program: undergraduate 42
GEMOC honours 45
GEMOC postgraduate 46
Technology development program *49
Industry interaction 52
- Current industry-funded collaborative research projects 55
GEMOC's international links 59
GEMOC funding 62
Benefits to Australia 63
Appendices
1 Participants 64
2 Publications 66
3 Visitors 72
4 Abstract titles 73
5 Funded research projects 77
6 Flowsheets for courses in geology and geophysics see web
7 GEMOC postgraduate and honours opportunities see web
Contact details 81
Glossary 81
* Additional material available on web version at www.es.mq.edu.au/GEMOC/

Contact details
http://www.es.mq.edu.au/GEMOC/

GEMOC
Department of Earth & Planetary Sciences
Macquarie University NSW 2109
AUSTRALIA

Leigh Newton
Administrator
Phone: 61 2 9850 8953
Fax: 61 2 9850 8943 or 6904
Email: lnewton@laurel.ocs.mq.edu.au

Professor Suzanne Y. O'Reilly
Director
Phone: 61 2 9850 8362
Fax: 61 2 9850 8943
Email: sue.oreilly@mq.edu.au

Professor W.L. Griffin
Program Leader
Phone: 61 2 9850 8954
Fax: 61 2 9850 8943
Email: bill.griffin@mq.edu.au

Dr Norman Pearson
Manager, Geochemical Analysis Unit
Phone: 61 2 9850 8361
Fax: 61 2 9850 8943 or 6904
Email: npearson@laurel.ocs.mq.edu.au

Glossary
ACILP Australia China Institutional Links Program
AGSO Australian Geological Survey Organisation (now GA)
AMIRA Australian Mineral Industry Research Association
ANU Australian National University
APA D Australian Postgraduate Award (Industry)
ARC (LGS) Australian Research Council (Large Grant Scheme)
ARC LIEF Australian Research Council Linkage Infrastructure Equipment & Facilities
AWI Alfred Wegener Institute for Polar and Marine Research
CNRS French National Research Foundation
CSIRO (EM) Commonwealth Scientific Industrial Research Organisation (Exploration and Mining)
DEST (SIP) Department of Education, Science and Training (from 2002) (Strategic Infrastructure Initiative)
DETYA Department of Education, Training and Youth Affairs (from 1998)
DIATEEM Consulting company within MRL
EMP Electron Microprobe
EPS Earth and Planetary Sciences
EUGODOC The council for postgraduate students and junior researchers in Europe
GA Geoscience Australia (formerly AGSO)
GAM Geochronological Analysis Unit (Department of Earth and Planetary Sciences, Macquarie University)
GEOMAR Research Center for Marine Geosciences
GIS Geographic Information System
GLITTER GEMOC Laser ICPMS Total Trace Element Reduction software
GPS Global Positioning System
ICPMS Inductively Coupled Plasma Mass Spectrometer
IMOURS International Macquarie University Research Scheme
IFP The French Polar Institute Paul Emile Victor
IFRS International Postgraduate Research Scholarship
IREX International Research Exchange Program of ARC
LAMACPMAS Laser Ablation Microprobe Inductively Coupled Plasma Mass Spectrometer
MC-ICPMS Multi-Collector ICPMS
MRL Macquarie Research Limited
MUECRG Macquarie University External Collaborative Research Grants
MUPFA Macquarie University International Postgraduate Research Award
MUNI Macquarie University New Staff Scheme
MUPGRF Macquarie University Postgraduate Research Fund
MURACIE Macquarie University Research Award for Areas and Centres of Excellence
MURDF/G Macquarie University Research Development (Fund/Grant)
MURF Macquarie University Research Fellowship
NERC Natural Environment Research Council
NSF National Science Foundation (USA)
NSWGS New South Wales Geological Survey
ODP Ocean Drilling Program (International Consortium)
PGRF Postgraduate Research Fellowship
QDME Queensland Department of Minerals and Energy
RAACE Research Areas and Centres of Excellence Postgraduate Scholarships
RBIG Research Infrastructure Block Grant
RSES Research School of Earth Sciences at ANU
SPWRT Strategic Partnership with Industry - Research and Training
USC University of Southern California
XRD X-Ray Diffraction

Front Cover: This year’s cover emphasises the scope of GEMOC’s strategy to understand the way the Earth works: from fieldwork to geochemical analysis to technology development to geodynamic modelling – and from the micron to the global.