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This report summarises GEMOC’s 2009 activities including research, technology development, strategic applications, industry interaction, international links and teaching (at both undergraduate and postgraduate levels). The report is required as part of GEMOC’s formal annual accounting to the Australian Research Council (ARC). The ARC acknowledges GEMOC as a continuing ARC National Key Centre while GEMOC attracts sufficient funds to maintain its high research activity and output, achieves its annual goals, and submits an Annual Report fulfilling ARC reporting requirements.

GEMOC’s strategic vision is the integration of geophysical, geochemical and petrological data with tectonic and geodynamic modelling to gain a better knowledge of the whole-Earth system from its accretion to the present day. This has been a logical extension of our progress in addressing the original goal of understanding the evolution of the lithosphere. Significant parts of the large-scale Global Lithospheric Architecture Mapping program (GLAM), in collaboration with Western Mining and subsequently BHP-Billiton, are now published or in press and the results are impacting a broad spectrum of areas including early Earth, lithosphere evolution, interpretation of seismology datasets, and global mineral exploration strategies.

In 2006 GEMOC was designated a Concentration of Research Excellence by Macquarie Vice-Chancellor Steven Schwarz, who has enhanced our expertise with six new academic staff positions across isotopic and trace-element geochemistry, lithosphere and Earth dynamics, geophysical imaging of Earth’s interior, dynamic modelling of Earth’s mantle and rheology of rocks and minerals, as reported in previous Annual Reports. The appointment of a seismologist, Dr Yingjie Yang, due to arrive in 2010, completes the first stage in the strategic plan to build a dynamic group of outstanding early-career researchers (with Juan Carlos Afonso and Craig O’Neill), spanning a broad range of geophysical and geodynamic expertise relevant to understanding deep Earth processes and planetary systems. This provides a critical mass for mutual collaboration, and to interface with the existing depth of geochemical, petrologic and tectonic knowledge on the deep Earth and its processes that exists within GEMOC. The 2009 cover references the ongoing work of Juan Carlos Afonso and co-workers in unravelling the deep structure beneath northern Africa.

A highlight of 2009 was the increase in infrastructure for GEMOC, with a broad funding base including Macquarie University, ARC and industry. Macquarie University supported the purchase of a computing cluster nucleus designed for progressive modular expansion to support the developmental computing requirements of the geophysical and geodynamic modelling projects. Within the Geochemical Analysis Unit, the purchase of a Zeiss scanning electron microscope with cathodoluminescence imaging and energy dispersive analytical capabilities reflects a new direction incorporating more emphasis on mineral imaging linked to microstructure and compositional variations. This initiative was supported by the installation of a new-generation FTIR microscope (ThermoFisher iN10) enabling rapid whole-grain mapping of spectral data. A spectral deconvolution program has been developed in-house to capitalise on the huge array of data embedded in the digital FTIR images.

We also acquired a SelFrag apparatus (installation in early 2010), which uses high-power electrostatic pulses to fragment rocks into individual mineral grains without crushing. This will become the nucleus of a new mineral-separation laboratory, with particular focus on extraction of zircons for the ongoing TerraneChron® program (see Research Highlights).
A successful ARC LIEF application for 2010, built on partner-organisation contributions and Macquarie University support, has provided over $1.6m to leap-frog some of our existing technology, allowing exciting new developments in in situ analytical capabilities that will extend our trace-element and isotopic applications. GEMOC’s world-class geochemical and high-pressure experimental infrastructure (see page 67) is the critical core of most of our research and allows us to maintain a leading profile in geochemical analytical developments. It is timely to reflect that GEMOC has provided the geochemical community with several new and powerful methodologies. For example, we developed the in situ Hf isotope method for zircon (published in 2000; GEMOC Publication 179, GCA 64) that now has wide global uptake and is proving a critical tool for understanding crustal evolution. In situ Re-Os analysis of small sulfide grains, and a range of stable metal-isotope methods are some of the other novel developments.

GEMOC’s success in linking interdisciplinary knowledge and data is also evident in many of the 69 articles published in high-impact journals including Nature Geoscience, Geology, Earth and Planetary Science Letters, Journal of Petrology, Geochimica et Cosmochimica Acta, G-cubed, Lithos and Chemical Geology. Our vigorous postgraduate milieu is evidenced by the publication by postgraduate students of seventeen first-authored papers in high-impact journals.

GEMOC’s leading research profile was again highlighted by a high level of participation at international conferences and workshops, including convening of meetings and sessions, and many plenary, keynote and invited talks at peak international fora (see “GEMOC Communications”). International collaboration provides leverage of our intellectual and infrastructure resources and is evidenced by visits to GEMOC by over 20 international researchers, and postdoctoral fellowships from China, Germany, Taiwan and Spain undertaken at GEMOC.

2010 promises to be another lively year with new challenges, new people, new instrumentation and new contributions to understanding how the Earth works – our ultimate goal.

Signature: J. O’Reilly
Mission

- to define the processes driving Earth’s internal dynamics, and understand how these have generated the present chemical and physical structure of our planet through time, integrating petrological, geochemical and geophysical information
- to provide a leading interdisciplinary research environment for the development of the next generation of Australia’s geoscientists
- to deliver new concepts about the spatial and temporal distribution of Earth resources

This Mission Statement has evolved since GEMOC commenced in 1995, to reflect the evolution of GEMOC’s activities to probe Earth’s geodynamics beyond the lithosphere. Current projects are extending our horizons further to planetary composition and dynamics, and core formation. The postgraduate group is constantly expanding and has developed to reflect strong international research links.

GEMOC’s success and distinctiveness lie in its interdisciplinary approach to understanding the way the Earth works, integrating information across traditional discipline boundaries including geochemistry, geophysics, geodynamics and tectonics. This perspective has made GEMOC a world leader in understanding the complex evolution of the uppermost 200 km of the Earth (the lithosphere), its global geodynamic behaviour, the timing of important Earth episodes, and its origins. The addition in the last two years of six staff resulting from GEMOC’s status within Macquarie University as a Concentration of Research Excellence (CoRE, see page 4) has broadened GEMOC’s horizons, expertise and infrastructure.

GEMOC now has world-class facilities with leading-edge technology in geochemical analysis (including novel laser-sampling capabilities), a state-of-the-art U-series isotope laboratory, and a versatile high pressure/high temperature experimental facility to simulate the physical conditions of the Earth’s interior. These experimental studies can probe the early history and evolution of the Earth’s core, mantle and crust and illuminate planetary analogues.

“GEMOC’s in-house research expertise and capabilities to undertake geodynamic and geophysical modelling has significantly expanded...”

Elena Belousova, Ayesha Saeed and Norman Pearson discussing in situ Hf isotope analysis of zircons by LAM-MC-ICPMS, part of the TerraneChron® methodology (see Technology Development and Research Highlights).
The appointment of three new early-career academic staff (Craig O’Neill, Juan Carlos Afonso and Yingjie Yang (arriving in 2010)) has significantly expanded GEMOC’s in-house research expertise and capabilities to undertake geodynamic and geophysical modelling, and computational Earth simulations. This has created powerful synergy with existing GEMOC programs related to the geochemical and petrologic studies of the deep Earth. A new computer cluster that can be successively upgraded by modular addition was established to support this initiative.

The research foci on the different levels of the deep Earth and on planetary origins in GEMOC are complementary, and pivot on the continuing effective functioning of its unique, internationally recognised Geochemical Analysis Unit to provide geochemical data that underpins their outcomes and outputs.

Extensive international and national collaborations extend our expertise and enhance GEMOC’s resource base.

GEMOC AND THE EARTH AND PLANETARY EVOLUTION CoRE STRATEGY

In 2006, Vice-Chancellor Professor Steven Schwartz designated GEMOC as an existing Concentration of Research Excellence (CoRE) in Earth and Planetary Evolution (EAPE) at Macquarie. The CoRE is being supported by new staff appointed from 2007 to enhance and expand research expertise and performance. GEMOC had built up an interdisciplinary approach to understanding the way the Earth works, integrating the traditional disciplines of geochemistry, geophysics, geodynamics and tectonics. We had developed cutting-edge isotope, geochemical and experimental instrumentation and strong collaborations with national and international researchers and industry. The Earth and Planetary Evolution CoRE seeks to build on these strengths to define the processes driving Earth’s global internal dynamics, and to understand how these have generated the present chemical and physical structure of our planet through time. New and reinforcing expertise from five CoRE recruits will now allow expansion into realistic geodynamic modelling and geologically significant modelling of geophysical datasets by combining new computational expertise with existing geochemical, petrological, tectonic and experimental knowledge bases. It will also enable continuing development of world-leading methodologies and applications in geochemistry (including isotopic) and especially for in situ (laser-ablation) analysis.

Advertisements sought applicants in the fields of rheology of rocks and minerals; geochemical analysis, lithosphere and Earth dynamics; geophysical imaging of Earth’s interior; dynamic modelling of Earth’s mantle; isotope and trace element geochemistry; cosmochemistry and meteoritics. Professor Bill Griffin, Dr Tracy Rushmer, and Dr Craig O’Neill commenced in 2007 and Dr Juan Carlos Afonso, Dr Bruce Schaefer and Professor Simon Turner commenced as CoRE staff in 2008. Dr Yingjie Yang, recruited in 2009, will arrive in 2010.

GEMOC’S STRATEGIC FOCUS

The main targets of GEMOC’s original activities addressed 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 since GEMOC became self-funded in 2002, to involve whole-mantle perspectives of geodynamics, far-field and feedback effects on the lithosphere that shape Earth’s crust, and planetary studies that relate to Earth’s formation, differentiation and geochemical/geodynamic evolution. New ways of measuring the timing of Earth processes are defining the fourth dimension (time) with
increasing clarity for crust, mantle, core and magmatic events. New capabilities in high-pressure experimental work are simulating deep Earth conditions, another complementary approach to probing Earth’s early history and evolution and understanding planetary analogues.

Industry collaboration has increased with funded large-scale collaborative projects related to lithosphere evolution, crustal generation and diamond formation and fingerprinting. The delivery of new tools and a new framework of terrane analysis to the mineral exploration industry has generated much collaboration. Funded projects dealing with magma-related Ni deposits, plume magmatism and PGE deposits, diamond exploration, and deep-lithosphere structure through time capitalise on our depth of intellectual property about deep Earth processes from the lithosphere to the core.

**STRATEGIC OUTCOMES**

Our strategic goal is an integrated understanding of the evolution of the Earth and other planets. In achieving this we will deliver:

- improved understanding of the composition and structure of the Earth from the mantle to the core and the dynamics of the Earth system
- insights on planetary formation, evolution, composition and dynamics from Earth-based analogues
- fundamental insights into the processes that create and modify the continental mantle and crust and the timing and time-scales of these processes
- a better understanding of the assembly of the Australian continent and its geological architecture through work in Australia and global analogues
- results and concepts exportable to other terrains, both globally and to potentially resource-rich areas of interest to Australian exploration companies
- an improved global framework for understanding the localisation of economic deposits
- 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) and the timing of Earth processes and events
- new experimental petrology approaches to probing the nature of the deep Earth (core and lower mantle)
- development of *in situ* analytical methods (including dating) to maximise information encoded in mineral compositions and to enhance interpretation of data using spatial contexts
- development of robust new geodynamic models of Earth’s evolution using constraints provided by geochemical datasets
- strategic and collaborative alliances with technology manufacturers in design and application innovation

*This report documents achievement of these goals in 2009 and aims for 2010.*
SCIENTIFIC PHILOSOPHY

GEMOC's distinctiveness lies in its interdisciplinary and integrated approach to understanding how the Earth works as a 4-dimensional dynamic system (in space and time).

This approach links...

- petrology and geochemistry
- experimental petrology and petrophysics
- geophysics
- petrophysics
- tectonics
- numerical and dynamical modelling

within the important contexts of...

- time
- thermal state

to understand how Earth’s core-mantle system ultimately controls crustal tectonics, and the assembly and destruction of continents through time.

GEMOC is also distinctive in its aim to pursue parallel interlinked basic and strategic/applied research programs with targeted development of new geochemical analytical methodologies, geodynamic modelling protocols and experimental design.
GEMOC is based at Macquarie University (in the Department of Earth and Planetary Sciences).

There is active national collaboration with state Geological Surveys, GA (Geoscience Australia), CSIRO, ANU/RSES and other national universities, and several major industry collaborators, across a broad range of projects related to GEMOC’s strategic goals. A distinctive feature of GEMOC is the high level of active international collaborations and reciprocal links.

Collaborative research, teaching and technology development links have been established with 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 (e.g. some 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 and at www.gemoc.mq.edu.au/

CHANGES IN 2009

2009 arrival in the EAPE CoRE

Dr Juan Carlos Afonso

Dr Juan Carlos Afonso arrived at GEMOC, in the Department of Earth and Planetary Sciences, in early 2009. After graduating with a PhD from Carleton University (Ottawa), he undertook postdoctoral research at the Institute of Earth Sciences Jaume Almera (CSIC, Barcelona) on the development of new methods to study the thermal and compositional structures of the lithospheric/sublithospheric upper mantle. His background is in theoretical and computational geophysics/geodynamics. His current research integrates different disciplines such as mineral physics, potential field modelling, thermodynamics, and physics of the mantle in general, to explore and improve our understanding of plate tectonics. In particular, he is interested in the evolution of the lithospheric mantle, the mechanical and geochemical interactions between tectonic plates and the sublithospheric mantle, and their effects on small- and large-scale tectonic processes.
Other new arrivals and appointments in 2009

**Dr Svetlana Tessalina**

Dr Svetlana Tessalina joined GEMOC in 2009, to work on the PGE and Re-Os systematics of the most depleted mantle xenoliths – dunites and harzburgites – from the South African kimberlites. This project is part of the ARC Discovery Project on “Earth’s internal system: deep processes and crustal consequences”. Svetlana took her PhD in 1997 from Lomonosov Moscow State University, and followed this up with postdoctoral fellowships in France, Italy and England, concentrating mainly on isotopic analysis. Most recently she was Assistant Professor at the University of Pierre and Marie Curie, Paris, and brings expertise in several aspects of research, including the RE-Os systematics of ultramafic rocks.

**Dr Dan Howell**

Dr Dan Howell joined GEMOC in July 2009 as a postdoctoral Research Associate on the ARC Discovery Project “Diamond genesis: cracking the code for deep-Earth processes”. He graduated from University College London with a PhD (March 2009) that investigated the stress related optical properties of both natural and synthetic diamonds. The work, which was part funded by the Diamond Trading Company, discovered a new geobarometry technique for measuring the source pressure and temperature conditions of diamond formation. He also conducted high pressure and temperature experiments to explore relationships between differential stress and diamond colour under simulated mantle conditions. His current work is focusing on developing a new quantitative infrared mapping technique, as well as building on the extensive geochemical databank of diamond trace-element analyses at GEMOC. This work involves collaborations with ARC Partner Investigators including Prof Oded Navon’s group (Jerusalem, Israel), Prof Thomas Stachel’s group (Edmonton, Canada) and Dr Jeff Harris (Glasgow, UK).

**Dr Michael Turner**

Dr Michael Turner arrived at GEMOC in September 2009 assisted by a New Zealand Foundation of Science and Technology three-year Post-Doctoral Fellowship. He graduated with a PhD from Massey University (New Zealand) in 2009, having studied physical volcanology and magma genesis of Mt. Taranaki (New Zealand). This research illustrated recognised cyclic variation in eruption frequency related to the magmatic processes. At GEMOC, he is using U-series isotopic studies to probe variations in magma degassing and its timescales. The isotopic approach will be complemented by continuous FTIR (Fourier Transfer Infrared Spectroscopy) on nominally anhydrous minerals to identify variations in water content. These techniques will allow the greatest potential to record magmatic water/volatile contents over a large range of magmatic conditions and therefore provide further information relevant to the processes that may be responsible for eruption variations.
Dr Norman Pearson

In April 2009 the position held by Dr Norman Pearson was translated from General to Academic Staff. The reclassification recognized Norm’s international research profile and his continuing academic leadership in the development and management of the Geochemical Analysis Unit. Norm is now a Senior Lecturer in the Dept of Earth and Planetary Sciences.
GEMOC’s organisation

GEMOC’s organisation involves four interlinked programs: Research, Teaching and Training, Technology Development and Industry Interaction. Basic research strands are supported by parallel applied collaborative research with industry partners: these provide the impetus for technology development. This development is in turn supported by strategic alliances with front-line instrument designers and manufacturers (e.g. Nu Instruments, Agilent Technologies). 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, core formation and planetary origins in GEMOC.
GEMOC’s research program

**The research aims**

- to understand how Earth’s core-mantle system controls crustal tectonics, and the assembly and destruction of continents through time
- to map the spatial and temporal distribution of elements, rock types and physical and chemical conditions within this system
- to understand the processes responsible for the evolution of Earth’s chemical reservoirs
- to use quantitative modelling to simulate and understand Earth’s geodynamic evolution
- to define the systematics of element redistribution in the mantle and crust
- to define timescales of magmatic and erosional cycles
- to understand mantle melting dynamics, the influence of recycled components and their ultimate contribution to plumes and the subcontinental lithosphere
- to constrain models of the crust and lithospheric mantle from geophysical datasets, through integration of geophysical, petrological and geochemical information
- to define the tectonic and geochemical processes that have created distinct crustal and mantle domains through time
- 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 provide a new framework for area selection for a wide spectrum of economic deposits, by linking deep Earth models and processes to the formation of metallogenic provinces
- to define the timing of events and processes in the crust and mantle to understand crust-mantle linkages
- to develop collaborative links with international institutions and researchers relevant to GEMOC’s goals

**SCIENTIFIC CONTEXT**

**HERMAL ENERGY TRANSMITTED FROM THE DEEP EARTH** (core and convecting mantle) provides the energy to drive lithosphere-scale 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 lithology of the Earth’s lithosphere can be mapped using fragments of deep materials such as mantle rocks and diamonds, and the compositions of mantle-derived magmas. Timescales can be measured from billions of years to tens of years.

What drives the heat engine that powers the Earth’s magnetic field and drives mantle convection? We do not clearly understand this, because we do not know the concentrations of heat-producing
radioactive elements (K, U, Th) in the lower mantle and the core, and how these may have changed with Earth’s evolution. Experimental studies of Earth materials at extreme conditions will provide new constraints for modelling of the mantle and the evolution of the early Earth.

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

- Understanding Earth’s internal dynamics and the generation of the present chemical and physical structure of our planet through time
- 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

**RESEARCH STRATEGY**

The Research Program for 2009/2010 follows the topics of the funded projects listed in Appendix 5; all contribute to the four strands (described below) that were established to achieve GEMOC’s vision and goals. Summaries of funded basic research projects are given 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 focussed on four strands: the current Research Program has extended the scope of these original strands and is pushing into new conceptual and technology frontiers, building on our intellectual capital from the first phase of GEMOC and the new expertise in the Earth and Planetary Evolution CoRE.

**Mantle Dynamics and Composition**

Forms the framework for advancing our knowledge of Earth’s geochemical and physical evolution. The thermal output driving Earth’s “engine” has declined exponentially through time, and the distribution of heat sources must have changed with the geochemical evolution of Earth. How has this secular cooling of Earth affected the internal driving forces, and what does this imply about changes in Earth dynamics through time? When did subduction processes begin? Novel approaches using redox-sensitive metal-isotope systems will be used to examine changes in the mantle’s oxidation state, and potentially provide, in combination with geochemical-petrological-thermomechanical models, constraints for the role and processes of subduction. These models will be used to study the evolution and stability of both oceanic and continental lithosphere.

Modelling of Earth’s thermal history, incorporating information about the present and past distribution of heat-producing elements and processes, will be used to test conceptual models for Earth’s internal dynamics through time. High-pressure experimental approaches will advance our understanding of deep
Earth structure and properties, the nature of the accretion process, and the effects of core differentiation. Lithosphere Mapping provides the fundamental data for defining lithospheric mantle domains in terms of composition, structure and thermal state. It represents the basis for any evolutionary model of the Earth, as well as for understanding the relationships between geophysical observables (e.g. electrical conductivity, seismic velocity, etc) and the physical state of the Earth’s interior. Lithosphere profiles built up from this information are interpreted in the context of geophysical datasets (especially seismic tomography) to extrapolate laterally.

Recent developments towards an internally consistent geochemical-petrological-geophysical methodology to map lithospheric and sublithospheric upper mantle domains link with the other three Research Strands and are helping 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. State-of-the-art numerical techniques that combine realistic rheologies, metamorphic reactions, and partial melting, are being used in 2D and 3D numerical simulations to test a range of different Earth models and understand deep Earth processes. Planetary structure within the solar system and comparisons with Earth parameters are being explored with geophysical datasets and integrated geodynamic modelling.

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 Mantle Dynamics and Composition and Metallogenic Provinces 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.
WHERE IN THE WORLD IS GEMOC?

RESEARCH PROJECTS FEEDING MAJOR PROGRAMS

Mantle Dynamics and Composition

Lithosphere mapping: Geochemical structure and evolution of continental lithosphere and interpretation of geophysical data  (see Research Highlights)

U-series applications to timescales of lithosphere processes  (see Research Highlights)

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

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

Origin of mantle eclogites  (see Research Highlights)

The composition of Earth’s core and timing of core formation; core-mantle interaction  (see Research Highlights)

Interpretation of deep seismic tomography  (see Research Highlights)

Evolution of oceanic lithosphere: Kerguelen Plateau, Hawaii, Crozet Islands, abyssal peridotites  (see Research Highlights)

Diamonds: origin and clues to deep mantle and lithosphere evolution and structure

Basalts as lithosphere/asthenosphere probes  (see Research Highlights)

Plume compositions, sources and origins

Thermal framework of the lithosphere: paleogeotherms, heat production, conductivity, thermal evolution  (see Research Highlights)
Lithosphere extension processes and consequences in East Asia: Taiwan and eastern China
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 (see Research Highlights)
Metal isotopes as tracers of lithosphere processes and Earth evolution

**Crustal Evolution and Crustal Processes**
Timescales and mechanisms of magmatic processes and movement (U-series applications)
U-series analysis of weathering and erosion processes
Dating lower crust domains and tracking extent of Archean crust (see Research Highlights)
Role of oceanic plateaus in the formation of oceanic and continental crust: Kerguelen
Tracers of magmatic processes: trace elements in accessory minerals
HF-isotopic signatures of zircons (in situ LAM-ICPMS) as tracers of crust-mantle interaction in granites (see Research Highlights)
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®, eastern China, South America, Canada, South Africa, Australia, India, Norway (see Research Highlights)
Studies of detrital zircons in Paleozoic sediments: origins of terranes in Lachlan Fold Belt
Formation of Earth's first silicic crust

**Metallogenesis**
U-series applications to timescales of fluid movement
Metal isotope applications to ore genesis
Geochemistry of mantle sulfides
Area selection and evaluation for diamond exploration
Diamond trace elements as clues to diamond formation
Lithosphere domains through time and location of ore deposits
Effect of deep mantle processes on lithosphere evolution and structure
Identification of plume types fertile for Ni and PGE mineralisation
Crust-mantle interaction, granites and metallogenesis through time
Re-Os dating of mantle sulfides in situ and timing of mantle processes
Application of 186Os to geochemistry and cosmochemistry
Highly siderophile element (including PGE) concentrations in sulfides and alloys (LAM-ICPMS)
Stable-isotope ratios of some important commodity elements (e.g. Cu, Fe, Zn, Mo) in a range of ore minerals and deposit types
Trace elements in diamonds - source fingerprinting and genetic indicators
GEMOC’s research program

Geodynamics

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

Tasman Fold Belt: terrane analysis

Paleomagnetic studies of the northern New England Orogen

Hf behaviour in migmatites during granite production, Mt Stafford Central Australia

Subsurface pluton shape: Gravity studies

The role of east Antarctica in supercontinent assembly

Antarctic seismic studies

Nature of the lower continental crust, Fiordland New Zealand

The role of the Bering Sea in climate change over the last five million years

Plate margin processes (Papua New Guinea, Macquarie Island)

Geodynamic modelling of large-scale processes, integrating constraints from 4-D Lithosphere Mapping (see Research Highlights)

Evolution of lithospheric composition and Earth geodynamics through time

Crustal heat flow (see Research Highlights)
Funded basic research projects for 2009/2010

Funded research projects within GEMOC are formulated to contribute to the long-term, large-scale strategic goals and determine the short-term research plan. Research goals for each year are linked to the aims of funded projects. Summaries of these projects are given here.

Probing the composition of the early Solar System and planetary evolution processes
Sue O’Reilly, Bill Griffin, Norman Pearson, Olivier Alard, Benoit Ildefonse, Sylvie Demouchy: Supported by ARC DIISR French-Australian Science and Technology Program (commencing 2010)
Summary: The aim of this project is to understand the origins and history of chondritic meteorites, the most primitive rocks in the solar system, and the stuff from which planets are made. An ongoing controversy about the relative ages and relationships between the different components of these primitive meteorites goes to the heart of models for the evolution of the Solar nebula and the generation of planets, including Earth. This controversy turns on the question of whether the various components of chondritic meteorites have been formed separately in space and time, or have shared a common high-temperature history. To provide new constraints on this problem, we will focus on the chemical and micro-structural relationships between the chondrules and the very fine-grained matrix in which they are embedded. We will use both established and recently developed in-situ microanalytical techniques, to measure the abundances and isotopic compositions of critical elements in the fine-grained minerals of chondrules and their matrix, and to determine the degree of structural alignment between the minerals in the two components. The data will be used to evaluate the degree of high-temperature interaction between chondrules and their matrix, and to assess different models for the formation of chondrites. The results will be compared with equivalent information on samples of the Earth’s deep interior brought to the surface in volcanoes or tectonic uplift; such samples can provide analogues for the differentiation of meteoritic parent materials. The project will use complementary equipment in France and Australia (laser-ablation (LA) inductively coupled mass spectrometry (ICPMS) at GEMOC (Macquarie University); ion microprobe and electron backscatter diffraction (EBSD) at GM (Geosciences Montpellier, UMR 5342).

The evolution of the oceanic lithosphere and upper mantle: a novel petrological-geophysical approach
Juan Carlos Afonso: Supported by MQNS grant (commenced 2010)
Summary: Understanding the evolution of the oceanic mantle, from the creation of oceanic lithosphere at mid-ocean ridges to its destruction at subduction zones, is a cornerstone in Earth Sciences. However, a complete model capable of reconciling all its geophysical and geochemical characteristics is still lacking. The proposed research program will combine novel interdisciplinary methods and powerful computer software to obtain a robust thermo-chemical-mechanical model for the evolution of the Earth’s mantle beneath the oceans. This project will advance our knowledge of the evolution of ocean basins and continental margins, and thus it is directly translatable into predictive exploration methodologies for Australia’s energy sector.
Nature, antiquity and length scales of compositional anomalies in the convecting Earth  
Bruce Schaefer: Supported by MQNS (commenced 2010)  
Summary: The convecting Earth is sampled by volcanic rocks and some ocean island basalts, such those erupted as the Azores, preserve evidence of anomalously ancient material which is chemically and possibly also mineralogically distinct from the rest of the mantle. This project aims to evaluate the nature and role of heterogeneities in the mantle beneath the Azores and how these may influence melting dynamics. Through application of novel isotopic techniques we aim to further constrain geodynamic models for the Azores and inform the current vigorous debate surrounding the age, origin and indeed fundamental nature of the Earth’s convecting interior.

Resurrecting Rodinia? The role of east Antarctica in supercontinent assembly  
Nathan Daczko: Supported by ARC MQRDG (commenced 2010)  
Summary: This project will determine the role of east Antarctica in the Rodinian supercontinent that assembled 1300-900 million years ago. Controversy exists regarding the timing of geological events in east Antarctica and how these relate to the architecture of the Rodinian supercontinent. This project will characterise the age and geochemical signature of key Precambrian rocks in Kemp and MacRobertson lands, which outcrop as islands, isolated nunataks and mountain ranges, and compare their evolution with proposed conjugate regions in India, Australia and broader Antarctica. These rocks will provide a missing link between disparate terranes in recent tectonic reconstructions of Rodinia.

Developing permeability in the Earth’s crust: A coupled experimental and numerical study of geologically important fluids in a dynamic environment  
Tracy Rushmer: Supported by MQRDG (commenced 2009)  
Summary: The development of permeability in host rocks is key to understanding fluid flow and ore formation. However, we have yet to build into fluid transport models realistic evolutionary paths of porosity and permeability with time. While the controls on fluid flow and focusing in the Earth’s crust are conceptually understood, we still need a quantitative approach to their evolution. This project uses a coupled approach between numerical modelling and dynamic experiments on natural crustal rocks to gain quantitative information on the physical and chemical mechanisms of generating enriched mineral zones. The results will seed a CSIRO MDU Collaboration Cluster application.

A novel approach for economic uranium deposit exploration and environmental studies  
Simon Turner, Bruce Schaefer, Geoffrey McConachy: Supported by ARC Linkage and Quasar Resources (commenced 2009)  
Summary: The project proposes the use of a novel approach to prospect for economic uranium ore deposits. The measurement of radioactive decay products of Uranium in waters (streams and aquifers) and sediments will allow us to (i) identify and locate economic uranium ore deposits, and (ii) quantify the rate of release of uranium and decay products during weathering and hence the evolution of the landscape over time. In addition, this project will improve our knowledge on the mobility of radioactive elements during rock-water interaction, which can be used to assess the safety of radioactive waste disposal. Outcomes of this project will be: (i) the discovery of new economic uranium deposits; (ii) development of a new exploration technology allowing for improved ore deposit targeting. Information gained on the behaviour of radioactive elements at the Earth’s surface will be critical for the study of safety issues related to radioactive waste storage and obtaining reliable time constraints on the evolution of the Australian landscape.
Did obesity kill the arc? A model from the Fiordland Arc, New Zealand

Nathan Dazcko: Supported by MQNS grant (commenced 2009)

Summary: This project explores crustal growth in a magmatic arc flare up event, immediately before rapid crustal growth (obesity) and death of the arc. Rare exposures of deep arc crust (>60 km), in the natural laboratory of Fiordland, New Zealand, offer unique insight into crustal growth mechanisms. Our approach is to incorporate field-, petrographic- and isotope-based analysis for a fully integrated model of the evolution-extinction of this arc. We will quantify mantle versus crustal recycling sources and variations in magmatic flux rates, and document the rock types formed at the base of the thickest exposed continental arc, and their petrogenesis.

Diamond genesis: cracking the code for Deep-Earth processes

Bill Griffin, Sue O’Reilly, Norman Pearson, Thomas Stachel, Oded Navon, Jeff Harris: Supported by ARC Discovery (commenced 2009)

Summary: Diamonds carry unique, but cryptic, information on Deep-Earth processes. We will take a new approach to the question of how diamond forms deep in the Earth. We will integrate our recently developed techniques for trace-element analysis and new types of compositional imaging with \textit{in situ} analysis of the isotopic composition of C, O, H and N in a range of diamond types, and in genetically related silicate, sulfide and oxide minerals. This innovative approach will provide new insights into the nature and origin of the fluids that precipitate diamond in the Earth’s lithosphere, the transition zone and the lower mantle. These data and insights will become the basis for new geochemical approaches to diamond exploration and target evaluation.

Partial melting in natural metal-silicate and silicate systems: rheological and geochemical implications for the Earth and other planets

Tracy Rushmer: Supported by ARC Discovery (commenced 2009)

Summary: Differentiation is the separation of a melt or fluid from its host. It is the fundamental mechanism by which the terrestrial planets have evolved both chemically and physically through time and central to how the crust has evolved from mantle, how metallic cores are formed from undifferentiated planetary bodies and how economic elements can be concentrated. This proposal tackles this primary process by using the true (observed) rock textures and compositions as templates uniquely constrained by experiment so that numerical modelling can quantify flow processes and deformation regimes. It provides a basis for understanding fluid migration in dynamically evolving permeable networks.

Application of very short-lived Uranium-series isotopes to constraining Earth system processes

Simon Turner, Tony Dosseto, Mark Reagan: Supported by ARC Discovery (commenced 2009)

Summary: Precise information on time scales is fundamental to understanding natural processes. Uranium series isotopes have revolutionised the way we think about time scales because they can date processes which occurred in the last 10-350,000 years. This proposal will establish new procedures at the recently founded world-class Uranium-series research facility at Macquarie University for analysing very short-lived isotopes (22 years). These new abilities will be utilised to determine the mechanisms of melt/fluid migration and volcano degassing and to ascertain rates of soil production and erosion over time. The methodologies developed will also have application to Uranium exploration and nuclear safeguarding.
**Composition, structure and evolution of the lithospheric mantle beneath Southern Africa: improving area selection criteria for diamond exploration**

*Bill Griffin, Sue O’Reilly, Norman Pearson: Supported by ARC Linkage and De Beers Group Services (commenced 2008)*

**Summary:** Trace-element analyses of garnet and chromite grains from kimberlites distributed across the Kaapvaal craton and the adjacent mobile belts will be used to construct 2D and 3D models of compositional and thermal variation in the lithospheric mantle (to ~250km depth), in several time slices. Regional and high-resolution geophysical datasets (e.g. seismic, magnetotelluric, gravity) will be used to test and refine this model. Links between changes in the compositional structure of the lithospheric mantle and far-field tectonic events will be investigated using 4-D plate reconstructions. The results will identify factors that localise the timing and distribution of diamondiferous kimberlites, leading to new exploration targeting strategies.

**Basin development in Proterozoic South Australia: developing a time-integrated, compositional framework to assist mineral exploration**

*Elena Belousova, Bill Griffin, Anthony Reid (PIRSA), Alsa Schwarz (PIRSA) (commenced 2008)*

**Summary:** This project will generate new geochemical and age information to improve the existing geochronological framework for geologically ancient regions of South Australia. These chemical “fingerprints” and age data will be obtained for zircon (collected from river sands and rocks), that acts as a time capsule allowing us to determine the nature and sources of individual magmatic rocks and also sedimentary sequences. This will provide an integrated understanding of the geological history of the region to aid mineral exploration, and will also add to knowledge of the composition, metallogeny and assembly of this region of the Australian continent.

**The role of supercontinents in Earth’s dynamic evolution**

*Craig O’Neill: Supported by ARC Discovery (commenced 2008)*

**Summary:** The formation and destruction of supercontinents has far-reaching consequences for the evolution of life, the distribution of Earth’s resources, and the shaping of the Earth’s crust and surface that support human society. Tools to investigate these supercontinent processes have only recently been developed to the stage where they can be used to investigate the complex interactions of the continent-mantle system. Mantle convection simulations will be used to assess the thermal and dynamic impact the aggregation and dispersal of supercontinents has on the mantle, with a view to understanding the origin of anomalous volcanism often associated with supercontinent breakup.

**Global lithospheric architecture mapping II**

*Sue O’Reilly, Bill Griffin, Craig O’Neill: Supported by ARC Linkage and BHP Billiton (commenced 2008)*

**Summary:** Domains of different composition in the deep part of Earth’s rigid outer shell (the lithosphere) reflect processes of continent formation and breakup through Earth’s history. The boundaries of domains focus the fluid flows from the deeper convecting mantle that may produce giant ore deposits. We will integrate mantle petrology, tectonic syntheses and geophysics to image the 3-D architecture of the continental lithosphere, and provide a basis for realistic dynamic modelling of the behaviour of these deep continental roots and their response to geodynamic forces through time. This will provide a new approach to identifying predictive relationships between different types of lithosphere domains and structures, and large-scale mineralisation.
Forming Earth's first silicic crust

*Tracy Rushmer: Supported by MQNS (Awarded September 2007)*

**Summary:** Earth's earliest history (the Hadean eon) was a different world, yet we have recently discovered that in this unusual environment Earth's first silicic crust, the portion that forms the continents, began to grow and set the stage for the planet we know today. This experimental project aims to address fundamental issues concerning planetary evolution, early Earth and origin of the Hadean magmatism. The approach combines melting experiments performed on rocks with numerical modelling. The results will help allow us to assess the nature of earliest Earth and conditions necessary to produce crust during the Hadean eon.

Earth’s internal system: deep processes and crustal consequences

*Sue O’Reilly, Bill Griffin, Norman Pearson, Olivier Alard, Klaus Regenauer-Lieb (with 8 partner investigators): Supported by ARC Discovery (commenced 2007, ended 2009)*

**Summary:** New ways of imaging Earth's interior are providing remarkable insights into its structure and opening the way to a new synthesis linking tectonics, mantle structure and the internal transport of material and energy. We will harness the resources of an interdisciplinary, international team with leading expertise in geochemistry, seismic imagery and numerical modelling, and capitalise on new developments in these fields, to explore the internal dynamics of the Earth to understand how these produced the present structure of our planet. The resulting new conceptual framework for the evolution of the continents and their deep roots will be directly translatable into predictive exploration methodologies for Australia's mineral and energy sector.

Outcomes will include significant new information about the structure and formation of the Earth’s crust and the underlying mantle. An improved framework for interpreting the architecture of Australia and other continents will be directly relevant to exploration for world-class economic deposits, the Earth resources on which society depends.

Trace element analysis of diamond: new applications to diamond fingerprinting and genesis

*Sue O’Reilly, Bill Griffin, Norman Pearson: Supported by ARC Linkage and Rio Tinto (commenced 2007)*

**Summary:** As diamond crystals grow, deep in the Earth's mantle, they trap minute inclusions of the fluids from which they crystallise. We will use recently developed laser-ablation microprobe techniques to analyse the trace-element patterns of diamond crystals from the Argyle, Diavik and Murowa mines (Australia, Canada and Zimbabwe). The results will define the nature and evolution of the parental fluids of the diamonds, and thus shed new light on the processes of diamond formation and the nature of fluids in the deep Earth. A better understanding of these processes can lead to improved models and techniques for diamond exploration, enhancing the prospect of finding new deposits in Australia and abroad. The project will test the potential of trace-element microanalysis to fingerprint diamonds by source. If successful, this technology will provide economic benefits by reducing theft and illegal mining, which represent significant losses to legitimate companies. Application of this Australian development could reduce the circulation of "conflict diamonds", which would have real social benefits worldwide, especially in some developing countries.
GEMOC’s context in 2009

A SHORT HISTORY OF GEMOC

The national key centre for the geochemical evolution and metallogeny of continents (GEMOC) formally commenced in January 1996 and was funded under the ARC Key Centre scheme for 6 years. Under the government regulations for this round of Key Centres, there was no provision for extension of Centre funding beyond the original six-year term. A detailed business plan was required in the application to demonstrate how the Centre could continue and maintain its identity after the Commonwealth funding term. This business plan succeeded and the evolved GEMOC started its new phase in 2002 and is continuing with an independent, well-funded base.

GEMOC’S FUNDING BASE FROM 2002

This funding, like a good investment portfolio, has a healthy, risk-minimising diversity ranging across traditional competitive schemes such as those available from the Australian Research Council, to substantial industry collaborative projects. It also includes provision of value-added products to the mineral exploration industry (see the section on Industry Interaction) and one-off opportunities such as the competitive DEST Systemic Infrastructure Initiative in 2002 that granted over $5 million to enable GEMOC’s Technology Development Program to stay at the forefront (see the section on Technology Development). Extensive international collaborations extend our expertise and enhance our resource base.

GEMOC’S LINKAGES AND ALLIANCES

GEMOC has significantly evolved and expanded from its original base with shifts in the original linkages and expansion in collaborations. Strong new national and international collaborative research links and programs have emerged, and robust ongoing engagement with industry (mineral exploration and technology manufacturing) partners through collaborative projects continues to fulfil one of GEMOC’s original goals and extend our intellectual and funding base.
GEMOC’s structure

The organisational structure of GEMOC is designed for efficiency, flexibility and interaction. The financial management operates within Macquarie University’s Finance System and within AccessMQ for commercialised products, some strategic collaborative research projects and for any consulting. The Teaching Program stemming from GEMOC is fully 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.

GEMOC is recognised as a Concentration of Research Excellence within Macquarie University.

2009 MANAGEMENT ROLES

Professor Suzanne O’Reilly: Director of GEMOC.

Mrs Carol McMahon: GEMOC Administrator.

Professor William Griffin: Professor at Macquarie University and GEMOC Program Leader responsible for Technology Development and Industry Interaction.

Dr Kelsie Dadd: Head of the Department of Earth and Planetary Sciences and coordinates the Teaching Programs.

Dr Richard Flood: represents Department Staff.
Professor Simon Turner: leader of the U-Series Geochemical Program.

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

Dr Craig O’Neill: Manager of the GEMOC computing cluster

Ms Sally-Ann Hodgekiss: GEMOC graphics and design consultant at Macquarie; NCRIS administrator

ADVISORY BOARD MEMBERS (2009)

Board Members at Macquarie

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

Dr Kelsie Dadd – EPS Macquarie

Professor Simon Turner and GAU Manager Dr Norman Pearson are ex officio members

External Board Members

Adjunct Professor Michael Etheridge – Company Director

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

Dr Paul Heitherseay – representative of PIRSA

Dr Jon Hronsksy – industry member from Western Mining Services (Australia) Pty Ltd

Dr Simon Shee – industry member (formerly De Beers)

“Annual Reports from 2003 are available as downloadable pdf files on the GEMOC website as well as in html format. All previous Annual Reports are available in html format.”
GEMOC WEB RESOURCES provide past Annual Reports, updated details on methods for new analytical advances and software updates (GLITTER), activities of research teams within GEMOC, synthesised summaries of selected research outcomes and items for secondary school resources. Undergraduate teaching is also web-based. Annual Reports from 2003 are available as downloadable pdf files on the GEMOC website as well as in html format. All previous Annual Reports are available in html format. Strong industry interaction in 2009 ranged from presentations to specific industry groups in their offices to numerous formal and informal workshops at GEMOC, and invited and plenary presentations at peak industry symposia, workshops and conferences nationally and internationally.

GEMOC PUBLICATIONS FOR 2009 ARE GIVEN IN APPENDIX 2

The 69 GEMOC Publications that were published in 2009 are mainly in high-impact international journals as listed by the internationally recognised Thomson ISI Citation data, and designated as A* and A journals by the ARC ERA (Excellence in Research) official journal ranking.

PARTICIPATION IN WORKSHOPS, CONFERENCES AND INTERNATIONAL MEETINGS IN 2009 (AND BEYOND)

GEMOC staff, postdoctoral researchers and postgraduates again had a high profile at peak metallogenic, geodynamic and geochemical conferences as convenors, invited speakers, or presenters, with 83 presentations including:

- International Conference on Arc-Continent Collisions 2009 – “The Macquarie Arc Lachlan Orogen” (Orange, NSW, Australia)
- European Geosciences Union General Assembly 2009 (Vienna, Austria)
- GSA Penrose Conference, Pico, Azores “Plumes and Their Role in Whole Mantle Convection” (The Azores)
- American Geophysical Union Meeting (Toronto, Canada)
- 19th Annual Goldschmidt™ 2009 – “Challenges to our Volatile Planet” (Davos, Switzerland)
- 60th UK Diamond Conference (Warwick, UK)
- Granulites and Granulites 2009, “Granulites, Partial Melting and Rheology of Orogenic Lower Crust” (Czech Republic)
- 72nd Annual Meeting of the Meteorological Society 2009 (Nancy, France)
- AOGS (Asia and Oceania Geological Society), 6th Annual General Meeting 2009 (Singapore)
- SGA2009 – The 10th Biennial Meeting of the SGA (Townsville, Australia)
- International Discussion Meeting on Continental Geology and Tectonics (Northwest University, Xian, China)
- Geotitalia 2009, VII Forum Italiano di Scienze Della Terra (Rimini, Italy)
- 8th International Eclogite Conference (IEC-8) 2009 (Xining City, China)
- GSA Annual Meeting “From Volcanoes to Vineyards: Living with Dynamic Landscapes” 2009 (Portland, USA)
• First Young Earth-Scientist Congress (Beijing, China)
• The 2009 Biennial Conference of the Specialist Group in Geochemistry, Mineralogy and Petrology, Acacia Hotel (Kangaroo Island, South Australia)
• 2009 Australian Geothermal Energy Conference: Geothermal Downunder - Clean Energy From the Ground Up (Brisbane, Australia)
• Geosciences ’09, Geological Society of New Zealand, New Zealand Geophysical Society 26th Joint Conference (Oamaru, New Zealand)
• American Geophysical Union — 2009 Fall Meeting (San Francisco, California, USA)

Plenary Talks in 2009 included O’Reilly, Begg (SGA 10th Biennial Meeting in Townsville).

Keynote talks in 2009 included O’Reilly (Wyllie Symposium, Goldschmidt, Davos), Turner (Goldschmidt, Davos), Griffin (International Discussion Meeting, Xian), Afonso (FIST-Geolalia-2009, Italy).

Invited talks in 2009 included Belousova, Griffin, Rushmer (Goldschmidt, Davos), Belousova, Griffin (SGA, Townsville), Griffin (UK Diamond Conference, Warwick), O’Reilly, Zhang, Griffin (International Discussion Meeting, Xian).

GEMOC research was represented by 26 talks in total at the peak 19th Goldschmidt conference in Davos.

A full list of abstract titles and authors for Conferences and Workshops attended is given in Appendix 4 and on the GEMOC website where full-text versions of many of the abstracts can also be found.

OTHER CONFERENCE ROLES

Tracy Rushmer and Simon Turner were co-convenors for the Penrose Conference “Plumes and their role in whole mantle convection and recycling” held in the Azores in May 2009.

Bill Griffin was co-convenor for the session “Crust Coming of Age: From Accretion to Craton” at the 19th Annual V.M. Goldschmidt Conference held in Davos, Switzerland in June 2009.

Norman Pearson organised and participated in a workshop of the International Working Group for Laser Ablation ICP-MS U-Pb Geochronology at the American Geophysical Union annual meeting (San Francisco) in December 2009.

Bill Griffin is co-convenor for session “Diamond crystallisation under natural and experimental conditions” at the IMA in Budapest (August, 2010).

Norman Pearson is convenor of session “Recent Advance in High Precision Trace Element and Isotopic Analysis, 2010 Western Pacific Geophysics Meeting, Taipei 2010.

Simon Turner and Tracy Rushmer are co-convening the 5th “State of the Arc” meeting to be held on Santorini in September 2010.

Elena Belousova is co-convener of session “Russia and Central Asia” at the 13th IAGOD Quadrennial Symposium, Adelaide, South Aust, April 2010.
ESTEEM FACTORS AND OUTREACH

Sue O’Reilly was awarded a Visiting Professorship at Montpellier University.

Sue O’Reilly was appointed a panel member for the ARC Excellence in Research for Australia (ERA) Initiative trial process for Physics, Chemistry and Earth Sciences.

Bill Griffin was invited to be a founding core member of the new International Precambrian Research Centre of China (IPRCC) at Beijing SHRIMP Centre and the Department of Geology, Chinese Academy of Geological Sciences.

Tracy Rushmer was appointed NSF (National Science Foundation) panel member for Geochemistry and Petrology (2010-2012).

Bruce Schaefer was the AuScope Earth Composition and Evolution Component Leader and coordinated the National Geochemistry Program for the AuScopope NCRIS capability; http://www.auscope.org.au.

Tracy Rushmer was chair, Penrose and Field Forum Committee, Geological Society of America.

Juan Carlos Afonso became Topical Editor of the journal Solid Earth (EGU).

Bill Griffin continued as a member of the Australian Research Council (ARC) Expert Advisory Committee.

Simon Turner was co-editor for a Blackwell volume on the “Time scales of magmatic processes”.

Juan Carlos Afonso was appointed member of the High-Education Degree committee visiting lecturer at the University of Patagonia, Argentina.

Tracy Rushmer continued as a “Member at Large” on the Geological Society of America Penrose Committee, appointed for 2007-2010.

Sue O’Reilly continued as a member of the International Kimberlite Conference Committee. (Vancouver).

Norman Pearson continued as a founding member of the international organising committee of the “Working Group on Data Acquisition, Handling and Interpretation in Laser Ablation U(-Th)-Pb Geochronology”.

Juan Carlos Afonso was an invited speaker at the Dublin Institute for Advanced Science (DIAS).

Craig O’Neill continued as Honorary Secretary of the NSW Division of the Geological Society of Australia.

Sue O’Reilly was an invited editor of a Special Volume of the Geological Society of London on the “Nature of the European Mantle” and one of the Editors of a special Journal of Petrology Volume (50, 7) “Petrological Evolution of the European Lithospheric Mantle: Archean to Present Day”.

Sue O’Reilly is Chief Editor by invitation of the international journal, Lithos, of a Thematic Volume on the Nature of the Lithosphere-Asthenosphere Boundary, with Bill Griffin and Juan Carlos Afonso as co-editors.
Representation on editorial boards include: Lithos (Griffin, O’Reilly, Rushmer); Geological Society of America Bulletin (Griffin); Journal of Petrology (Turner); Chemical Geology (Griffin); Elements (Schaefer); Acta Geologica Sinica (Griffin).

Nathan Daczko continued as chair of the Geological Society of Australia Specialist Group in Tectonics and Structural Geology (SGTSG), and chaired the organising committee for the 2010 Field Conference.

Nathan Daczko co-led a 5-day pre-conference field trip “Overview of the Southeast New England Fold Belt” prior to the SGTSG Field Conference.

Formal industry collaborator on the GLAM (Global Lithospheric Architecture Mapping) project, Dr Graham Begg, was appointed as the International Exchange Lecturer for the Society of Economic Geologists for 2009 in recognition of the leadership position that GEMOC has attained in understanding the nature of the lithosphere and the geodynamic controls on the genesis, location and preservation of ore deposits. This appointment has resulted in a significant transfer of knowledge from GEMOC’s GLAM project to research institutions worldwide, end-users and the public domain through over 30 presentations in 8 countries during 2009.

MEDIA

Kelsie Dadd was the subject of an article in the Australian, in September 2009 titled “Voyage of enlightenment” by Jill Rowbotham. The article highlighted her participation in the IODP JOIDES Resolution voyage to the Bering Sea.

Craig O’Neill was active in media outlets including:

- Volcanic shutdown may have led to ‘snowball Earth’, 09 May 2009
  http://www.newscientist.com/article/mg20227073.800-volcanic-shutdown-may-have-led-to-snowball-earth.html
- Volcano ‘Vacation’ Produced First Glaciers, 14 May 2009
- Early Mars stayed molten, Thursday, 23 July 2009
- Molten Mars kept life at bay, Tuesday, 21 July 2009
- Molten Mars Too Hot to Handle Life, July 21 2009
- Mars breakthrough: Scientists uncover red planet’s hot and steamy secrets, 21 July 2009
- Enceladus episodic overturn, Scientific American, January 2010,
  http://www.scientificamerican.com/article.cfm?id=saturn-enceladus-episodic-overturn
- Saturn’s ice moon shows signs of life, The Australian, 11 January 2010 (Page 5)
Applications from Chinese firms to buy up small Australian companies involved in mining deposits of the Rare Earth Elements attracted considerable media attention, because China already is the dominant source of these strategically important elements. Prof Bill Griffin answered several requests for information on “What are these elements and why are they important?”, and gave a longer interview to the Sky News Business Channel, which was aired during the period when the Foreign Investment Review Board was reviewing the investment applications.

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 partnerships in grants with reciprocal funding from international collaborators.

All 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

Manel Fernandez from the National Research Council of Spain and Juan Carlos working on global lithospheric models during Manel’s visit in July 2009.
ERRANECHRON® is GEMOC’S UNIQUE METHODOLOGY FOR TERRANE EVALUATION. During 2009 a range of new studies, including collaborative research projects with industry, using TerraneChron® expanded our knowledge of crustal evolution and the timing of tectonic events.

**Research highlights 2009**

Visit the TerraneChron® web page at www.gemoc.mq.edu.au/TerraneChron.html

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**What is TerraneChron®?**

The methodology was developed by GEMOC to provide rapid, cost-effective characterisation of crustal history on regional (10-1000 km²) scales. It is based on U-Pb, Hf-isotope and trace-element analysis of single zircon grains by laser-ablation ICPMS (single- and multi-collector) methods.

- **U-Pb ages**, with precision equivalent to SHRIMP
- Hf isotopes trace magma sources (crustal vs juvenile mantle input)
- Trace elements identify parental rock types of detrital zircons

**What kind of samples?**

- Regional heavy-mineral samples (modern drainages: terrane analysis)
- Sedimentary rocks (basin analysis)
- Igneous rocks (dating, specialised genetic studies)

**Applications to mineral exploration**

- Rapid assessment of the geology in difficult or poorly mapped terrains
- “Event Signatures” for comparison of crustal histories from different areas
- Identify presence/absence of key rock types (e.g., Cu/Au porphyries, A-type granites,...)
- Prioritisation of target areas

**Applications to oil and gas exploration**

In provenance studies, the information from Hf isotopes and trace elements provides a more detailed source signature than U-Pb ages alone.

- **TerraneChron®** defines the crustal history of the source region of the sediment
- Changes in direction of basin filling track regional tilting, subsidence
- Stratigraphic markers in thick non-fossiliferous sediment packages
- Proven applications in the North Sea

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**TerraneChron®**

A new tool for regional exploration for minerals and petroleum

- Based on zircon analyses
- Efficient and cost-effective
- Identifies regional tectonic events
- Dates magmatic episodes
- Fingerprint crustal reworking and mantle input (fertility)

**Contact:** Bill Griffin or Suzanne O’Reilly (bill.griffin or sue.oreilly@mq.edu.au)
ARc GEMOC National Key Centre
Department of Earth and Planetary Sciences
Macquarie University,
NSW 2109, Australia
www.gemoc.mq.edu.au/
The determination of the thermal and compositional structures of the Earth’s mantle in space and time is a fundamental goal of modern geophysical modelling. These data are the basis for any evolutionary model of the Earth, as well as for understanding the relationships between geophysical observables (e.g., gravity, seismic velocity) and the physical state of the Earth’s interior. They also provide critical information on how the lithospheric-sublithospheric system would respond to perturbations arising from tectonic shortening, rifting and sublithospheric convection. Much of our current knowledge about the present-day thermal and compositional structure of the lithospheric and sublithospheric upper mantle has been based on three independent approaches: i) modelling of geophysical observables such as gravity, surface heat flow (SHF), elevation, or some combination of these; ii) interpretation of seismic data using an appropriate combination of “observed” seismic velocities (usually shear waves) with mineral physics, laboratory data, and thermodynamic concepts; ii) geochemical and thermobarometry studies of mantle xenoliths (see GEMOC publications #521 and 622). If the assumptions behind all these methods were correct, any modelled section of upper mantle should produce consistent results, no matter which methodology is applied. However, large discrepancies between predictions from these three different methods still are the rule rather than the exception (see GEMOC publication #521).

One way to overcome these difficulties and obtain more consistent and robust models is to fit simultaneously and self-consistently all the available geophysical and petrological observables (i.e., gravity anomalies, geoid height, SHF, electrical conductivity, seismic velocities, xenolith data and elevation). A simultaneous fit of all these observables reduces the uncertainties associated with the modelling of each of them alone, or with the combinations of pairs commonly used in the literature (see above). It also allows us to distinguish, and have a better control on, thermal or compositional density variations at different depths, since these observables are differently sensitive to shallow/deep, thermal/compositional density anomalies. However, an integrated modelling approach that can include all of these parameters in a self-consistent manner represents a major technological and conceptual challenge. Current research at GEMOC attempts to fill this gap by developing and applying a new integrated geophysical-petrological methodology based on a robust and consistent combination of thermodynamic and physical models. The first full 3D forward version has been recently applied to the Atlantic-Mediterranean Transition Region (AMTR, see GEMOC publication #627), and the main results are summarised here.

The AMTR comprises a narrow region along the transition between the western Mediterranean and the Atlantic Ocean along the westernmost segment of the African-Eurasian
plate boundary (Fig. 1). It is characterised by a diffuse transpressive contact between the African and Eurasian plates, including a wide band of active deformation. Traditionally, the AMTR has been considered as a zone comprising the Alboran Basin, the Betic and Rif orogens, and the Gulf of Cadiz (Fig. 1). However, some authors have included the adjacent Atlas Mountains on the basis of the similarities in the type and ages of the lavas in south-eastern Iberia and north-western Africa, including the Atlas.

Maps of the depths to the LAB and the crust-mantle boundary of our final best fitting model are shown in Figure 2. The depth of the crust-mantle boundary shows a very heterogeneous crust in the modelled region, with thickness variations of > 25 km. The resulting LAB topography is characterised by strong lateral gradients in the northern, southern and eastern limits of the thick lithosphere imaged beneath the Gulf of Cadiz, the Betics and the Rif (170-240 km). These regions coincide with the contact between the Iberian Variscan Massif and the Betic chain in the north, the contact between the Middle Atlas and the external Rif domain to the south, and the contact between the Betic-Rif orogen and the Alboran Basin to the east. This lithospheric thickening, with a reduced magnitude, continues to the southwest, encompassing the NW Moroccan margin (140-170 km). The thinnest lithosphere obtained in this model is in the eastern Alboran Basin, where the LAB depth is about 70 km. Moderate lithospheric thicknesses are obtained in the SW Iberian Variscan Massif (90 km) and the Atlas Mountains, particularly in the central High Atlas and eastern Anti Atlas (90 km), and the Middle Atlas (<80 km). The eastern branch of the Atlas does not seem to be affected by a lithospheric thinning. The lack of a spatial correlation between the thicknesses of the crust and lithospheric mantle (Fig. 2) in large parts of the model suggests a previously unrecognised decoupling of these two layers. Whereas the Moho depth map essentially mimics topography, with maximum values beneath the Eastern Betics, Rif and Atlas mountains, the LAB map shows a remarkably different pattern, with NE-SW thickening along the western Betics, Rif, Rharb Basin, and Moroccan Atlantic margin, and thinning along

Figure 3. Thickness map of anomalous mantle layers (i.e. mantle domains with different compositions from the background mantle). All layers are defined from the Moho depth downwards. A) West African Craton/Mobile Belt. B) Atlas Mountains. C) Alboran Basin.
the Eastern Alboran Basin and Middle, High and Anti Atlas. It is therefore likely that this lack of a thickness correlation results from the overlapping of different tectonic processes, which incorporate a sub-lithospheric component (see GEMOC publication #627). Interestingly, most of the Miocene mafic lavas (Fig. 1) seem to be spatially related to regions where the lithospheric mantle has been thinned (Fig. 2), suggesting a causal relationship between mantle upwelling and alkaline magmatism. Geochemical analysis indicates that these magmas have a common mantle source, forming a deep reservoir extending from the Canary Islands to the Western Mediterranean. Therefore mantle melting and alkaline volcanism would be related either to small-scale convection involving the deep reservoir, or to small plumes acting as ‘escape valves’. This implies that the thinning beneath some parts of the High Atlas, Middle Atlas and Anti-Atlas is probably responsible for, or related to, the observed alkaline volcanism rather than acting as an effective corridor through which magma displaces laterally from a unique reservoir located in the Canary Islands.

Our analysis indicates that the average bulk composition of the lithospheric mantle corresponds to that of a typical Tecton (i.e. Phanerozoic) domain, with the exceptions of the Sahara Platform, the Alboran Basin, and Atlas Mountains. The presence of these distinct lithospheric domains (Fig. 3) is required to reduce the residuals between measured and calculated regional observables such as gravity, geoid and elevation. These heterogeneities are related to either secular compositional variations (Sahara Platform) or recent mantle metasomatism (Atlas Mountains and Alboran Basin), and allow a fairly good reproduction of the measured Pn-velocities of the uppermost mantle and the regional travel-time tomography models (Fig. 4).

Although our methodology represents the first petrological-geophysical self-consistent approach in 3D, it still is a forward method (based on a recursive run of user-guided forward models). The non-linearity of the physical problems involved (see GEMOC publication #605) means that any true inversion scheme must be based on either systematic or stochastic exploration of the parameter space, i.e. running several successive forward models. In the 3D case, the high number of degrees of freedom (e.g. the petrophysical and compositional parameters of each body, and the depth of each node defining the limits of the layers), as well as the relatively long time required to run each forward model (~30 min), makes the inversion approach unviable at present. However, preliminary results indicate that a sophisticated combined forward-inversion technique is possible. This will make the modelling process much easier, and will provide a robust means to evaluate uncertainties as well as allowing us to model larger regions of the Earth.

Contact: Juan Carlos Afonso
Funding: Macquarie University

![Figure 4. A) Synthetic P-wave velocity anomalies predicted from our model at 145 km depth. B) Horizontal slice of P-wave velocity anomaly obtained from a seismic tomography study (Villaseñor et al., 2003).](image)
Coal from the Sydney-Gunnedah-Bowen Basin system has been a major resource for Australia’s energy industry for the better part of a century, supplying the largest percentage of NSW’s base-load power. More recently, developments in the extraction of methane and natural gas from coal beds has seen a resurgence of interest in these deposits.

The move from a fossil-fuel based energy system to a renewable energy economy will involve a range of energy solutions, and one of the most promising for delivering base-load power is geothermal energy.

Traditionally, geothermal industries have focussed on the exploitation of obvious, near-surface energy sources, such as active volcanic fields; examples are New Zealand and Iceland. However, advances in scientific drilling have seen deeper levels of the crust become viable heat sources, and some of the most prospective areas in Australia are within sedimentary basins.

While commercial interest recently has been focussed on the extraordinarily hot Cooper Basin in central Australia, many of Australia’s East-coast basins have the advantage of being near the largest population centres. The connected Sydney-Gunnedah-Bowen Basin system is one of the largest tectonic basin systems in Australia, and in places it contains extremely thick sedimentary sequences, ideal areas for trapping crustal heat at depth.

Recent work at GEMOC has been aimed at developing crustal-scale models of the architecture of the Sydney and Gunnedah system. These models, combining information from hundreds of drill cores and detailed gravity modelling, incorporate detailed lithological information on the

Figure 1. Architecture of the Gunnedah Basin, viewed from the south. Stacked model 3D surfaces of the Gunnedah Basin (in mAH), blanked to their approximate extent. (a) Elevation with basin outline; (b) Base of Jurassic sediment; (c) Top and base of the Permian Mullaley Basin coal interval; (d) Top and base of the Permian Maules Creek Coal interval; (e) Top of rift volcanics; (f) Top of Lachlan Fold Belt.
sedimentary pile and have constrained the structure of the basin in 3D at an unprecedented scale. These models have become the basis for thermal models of the sedimentary basin system. Existing geodynamic codes have been ‘rewired’ to import complex geological models; coupled with sparse thermal constraints available in parts of the basin, these show the detailed 3D thermal structure of these systems.

These results have been surprising. Conventional wisdom holds that the highest temperatures would be found directly beneath the thickest sedimentary “blanket”, but these simulations suggest that instead the lateral temperature gradients within a basin cause heat to refract around such layers. Heat preferentially goes around a coal layer, for instance, rather than through it. In addition, large gradients in the basement are also the sites of elevated temperatures at depth, as heat preferentially moves around the thick insulating blanket of basin sediments. The results also show a lower correlation between surface heat flow and temperatures at depth than commonly assumed, often due to these lateral geometric effects. Heat flow measurements over a coal layer, for instance, may be low, despite high temperatures beneath the insulating coal layer. Without detailed thermal modelling, it is difficult to extrapolate shallow temperature measurements to depth.

This project is currently expanding into the Bowen Basin, and will soon be able to address the thermal history of these basins through time, which has clear potential for the coal/gas maturation history. Additionally, such detailed thermo-structural models will enable us to constrain the stress state of these basins in greater detail - relevant to intraplate earthquakes in areas such as Newcastle. The detailed thermal and sedimentary structure models will also enable us to simulate the deep, hot aquifers of such basins - identified as a potential geothermal resource in their own right, and also an important and under-appreciated factor in basin-scale groundwater systems.

Contacts: Craig O’Neill, Cara Danis
Funding: ARC Discovery, APA

Figure 2. Temperature at the top of the Lachlan Fold Belt Basement, draped over basin architecture.
Hot, cold, or different? New constraints to interpret upper mantle seismic data

The seismological structure of the Earth’s upper mantle is highly heterogeneous, and much of this heterogeneity reflects the lithosphere’s thermal and compositional structure. Since lithospheric discontinuities commonly correlate with the location of seismically active zones, major tectonic boundaries, foci of magma intrusion and major ore deposits (see GEMOC Publication #547), their detection is important for ore and energy exploration and natural hazard assessment. However, limitations on resolution, and trade-offs between temperature and composition complicate the seismological characterisation of the small-scale (ca 300 km) distribution of compositional and thermal anomalies in the upper mantle.

A fundamental problem is the lack of reliable quantitative relationships or indicators (derived from seismic data) that can distinguish between compositional and thermal contributions to variations in seismic velocity. In this context, parameters such as the ratio of compressional-wave to shear-wave velocity (Vp/Vs) or the Poisson’s ratio are commonly thought to be reliable indicators of compositional variations in peridotites. Although these parameters have been successfully applied at crustal P-T-X conditions (where X is composition), their extension to general upper mantle conditions has serious limitations due to the effects of temperature-dependent non-elastic behaviour and phase stability.

In order to give some insights into these problems we have carried out a systematic assessment of the effects of temperature and composition on densities and seismic velocities in peridotites, applying thermodynamically self-consistent and hybrid methods, the latest mineral physics databases, and experimental results on the non-elastic behaviour of olivine aggregates at seismic frequencies (see GEMOC Publications #521, 542, 605, 622, 627). We have used a xenolith dataset that spans a range of composition (Mg# values from ~88 to 95) covering most of the expected variability within the lithospheric mantle.

Figures 1d, e and f illustrate the compositional dependence of Vp, Vs, and Vp/Vs within the spinel stability field. Although the general behaviour of both Vp and Vs with Mg# is similar to that observed within the garnet stability field, Vp/Vs shows no apparent correlation. Since spinel is stable in peridotitic rocks to depths of ~50-60 km under most circumstances, and down to ~100 km in strongly depleted rocks, we cannot apply correlations derived for garnet-bearing peridotites in seismic studies of the uppermost mantle.
We have analysed different anomaly ratios from our data set and find that p/Vs (where p is density) displays the best correlation with Mg# (Figs. 2a, b). Furthermore, the ratio between the compositional and thermal (anharmonic) derivatives of p/Vs is similar to, but more reliable than (i.e. less scatter), the Vp/Vs case. Although p/Vp also correlates well with composition (particularly in the case of garnet-bearing assemblages; Figs. 2c, d), our results reveal several previously unrecognised advantages of using p/Vs rather than p/Vp as a general indicator of compositional anomalies. Foremost among these are (i) the greater sensitivity of Vp to temperature variations; (ii) the larger compositional derivative of p/Vs; (iii) the smaller scatter of p/Vs in the spinel field; and (iv) the similarity in the anharmonic derivatives (∂(p/Vs)/∂Mg#) and (∂(p/Vs)/∂T) of both spinel- and garnet-bearing assemblages.

While the first two factors ensure a better response to temperature and compositional variations, respectively, the last two eliminate the problem of phase stability. Despite these advantages, the indicator ∂lnp/∂lnVs is also affected by attenuation, although considerably less than Vp/Vs, as discussed below.

The anelastic behaviour responsible for seismic wave attenuation becomes important in olivine-rich rocks at temperatures ~> 900 °C. Since all of the sublithospheric UM and up to 40% of the subcontinental lithospheric mantle have temperatures above this limit, any attempt at constraining mantle composition from seismic data must include attenuation effects. Shear waves are more strongly affected by anelasticity than compressional waves, and therefore both Vp/Vs and Poisson’s ratio become strongly dependent on temperature at T ~> 900 °C. Figure 3 shows that a change of 300 °C within the anelastic regime translates into a fictitious change of ~ 6-7 units in Mg#. If anharmonic estimates are used for the conversion. This change covers the entire range of common peridotitic compositions in the UM. The ratio p/Vs is appreciably less sensitive to anelastic effects and therefore gives a smaller fictitious Mg# change (Fig. 3b). However, due to the non-linear effects of temperature on shear modulus, the graphs for both Vp/Vs and p/Vs steepen with increasing temperature. Therefore, the common practice of interpreting observed variations of Vp, Vs, and/or Vp/Vs in the UM in terms of compositional variations with no consideration of anelasticity and phase stability is likely to produce erroneous conclusions.

In the light of the above considerations, can we distinguish thermal from compositional anomalies in the UM? The data presented here show that previous models based on seismic parameters produce results that are not meaningful for spinel-bearing peridotites or for olivine-rich assemblages at T ~> 900 °C. On the other hand, the ratio p/Vs is a more robust compositional indicator, but requires bulk density as an independent input. Since both density
and elastic moduli depend on bulk composition, any model (inverse or forward) of these properties requires a framework that guarantees a self-consistent coupling among P, T and X (bulk and phase). Current joint inversion methods are not well suited because they rely on long-period normal-mode observations, while studies based on the combination of short-period body waves and gravity anomalies model these two geophysical fields through scaling factors and therefore are not self-consistent. Recently-developed techniques that combine geophysical and petrological modelling within a consistent thermodynamic framework (see GEMOC Publications #605 and 622) are particularly promising, although more detailed studies on the effects of intrinsic attenuation, fluid content and thermodynamic modelling of mantle assemblages are needed.

Contact: Juan Carlos Afonso

Funded by: Macquarie University, Spanish research projects, NSERC, ARC

Figure 3. A) Vp/Vs versus temperature for two representative samples with Mg# = 88.9 (red colour) and 93.3 (green colour) within the garnet stability field. Reference pressure is Po = 4 GPa. The envelopes enclose Vp/Vs values for grain sizes between 1 and 10 mm. The anharmonic approximation is shown with dashed lines. The black circles denote Vp/Vs values for the same sample (i.e. no change in composition) separated by ΔT = 300 °C (1300 °C – 1000 °C) and 100 °C (1400 °C – 1300 °C) within the anelastic regime. B) ρ/Vs [kg s m⁻¹] versus temperature for the same samples shown in A). The anharmonic behaviour is shown with dashed lines.
Our understanding of differentiation events occurring early in the solar system has been greatly enhanced by using short-lived radioisotopes. The rapid decay in these systems gives us fine-scale temporal resolution of melting and differentiation events. Data from the short-lived radioisotope systems suggest that planetary differentiation (represented by iron meteorites which are considered to represent the cores of planetesimals) must have started within ~1.5 Myr of the beginning of the solar system. The results also require that the physical segregation of the core(s) was very rapid. Both percolative flow and deformation-driven flow have been shown to be important in core formation. For a more robust analysis of the speed at which metallic liquid migrated, we need to perform additional numerical studies. We have examined the preserved textures in the Kernouve meteorite (an H6 ordinary chondrite) before and after experimental deformation. The original, static state provides a snapshot of porous flow at the beginning of melting with no applied stress; after experimental deformation the textures show that focused metallic liquid flow has occurred, producing veins of metal in the silicate matrix.

Our modeling results show that the textures in the undeformed rock reflect migration of the metallic liquid by porous flow into high-permeability and low-pressure sites of initial melting and the flow velocity becomes position-dependent. If we modify the matrix permeability in the numerical model, we find that the highest average migration velocities ($10^{-5}$ m/s) correspond to the highest permeability ($10^{-9}$ m$^2$). When deformation textures are included in the modeling, channel flow becomes important and most liquid metal moves through channels (Fig. 1), as demonstrated by the experiments. Under these conditions flow velocities are higher ($10^{-3}$ m/s). For a planetesimal 200 km across, metallic iron can segregate within 30 (channel) to 30,000 (porous flow) years, providing flow is continuous. Another important aspect is the production of silicate melt as the planetesimal continues to heat. When silicate melt is produced, the porous-flow mechanism of segregation shuts off, unless impacts can produce stresses high enough to trigger deformation at high strain rates. High strain rates can overcome the strength of the silicate mush matrix, and deformation would shift back to fracture (albeit transient) rather than plastic flow.

Contact: Tracy Rushmer
Funded by: ARC Discovery

Figure 1. Numerical result of a simulation of the 2D velocity field made using a geometry in which melt flow is confined largely to a vein formed during sample deformation in the laboratory. Some background matrix flow also takes place. The implication is that this geometry reflects textures likely to dominate in an environment where planetesimals are in frequent collision. For this calculation, matrix permeability $= 10^{-10}$ m$^2$ using a liquid metal viscosity in vein $10^{-3}$ Pa s corresponding to 14 wt% S at $T = 1500$ K and 1 GPa.
Geological swap meet: transforming geochemical data into geophysical observables in southern Africa

The Kaapvaal Craton in Southern Africa is one of the most-studied fragments of Archean crust and mantle in the world. Detailed seismic and geochemical surveys of the craton provide an unprecedented view of this ancient system from different perspectives. However, the question remains: how well do these perspectives agree with one another?

The “4-D” lithosphere-mapping methodology developed at GEMOC provides a framework to convert geochemical data directly into seismic data in order to compare these data sets. Lithosphere mapping principles were applied to two sets of peridotitic garnet xenocrysts collected from the heavy mineral concentrates of kimberlites along a transect through southern Africa (Fig. 1). The first set of garnet xenocrysts comes from 33 Group II kimberlites with a median age of ~119 Ma and records the thermal and compositional state of the lithosphere after a long period of quiescence. The second set of garnet xenocrysts comes from 31 Group I kimberlites with a median age of ~90 Ma and records major metasomatism and heating of the lithosphere, particularly near the craton margins (for details see GEMOC publication #578).

Using the geochemical information contained in the two sets of garnets, a whole-rock bulk composition was calculated and converted into modal mineral estimates using a Gibbs free-energy minimisation algorithm. Anharmonic seismic velocities were then calculated from pressure, temperature, and mineral elasticity data and corrected for anelastic effects due to grain size, temperature, and seismic wave frequency (see GEMOC publication #521). The seismic velocity images resulting from each set of garnets are shown in Figure 2.

The seismic images echo the changes in the thermal and compositional data described above. Seismic velocities derived from garnets hosted in the older kimberlites are uniformly higher than those from garnets hosted in the younger kimberlites. The reduction in velocity is primarily related to a rising geotherm and thermal disequilibrium at the base of the lithosphere resulting from metasomatic activity preceding the eruption of the second set of kimberlites. Comparison of the garnet-derived velocities with modern seismic observations (Fig. 3) indicates that the localised thermal anomaly causing the low velocities 90 Ma years ago has dissipated to form a broad low-velocity zone between 175 and 250 km depth beneath the...
Figure 2. Shear wave velocities calculated from garnet xenocrysts hosted in the older set of kimberlites (bottom panel) and the younger set of kimberlites (top panel). Diamond symbols on the profiles indicate the depth range of garnet data from each kimberlite. The heavy vertical black line indicates the location of the craton boundary as mapped at the surface.

Kaapvaal Craton. Ongoing thermal modeling at GEMOC aims to reveal the timing and extent of the thermal perturbation and related metasomatism beneath southern Africa from the Late Mesozoic to the present.

Contacts: Alan Kobussen, Juan Carlos Afonso, Bill Griffin, Sue O’Reilly
Funded by: ARC Discovery, ARC Linkage, DeBeers Exploration, Macquarie University

Figure 3. Seismic tomography model of velocities along the same profile as Figure 2 using modern seismic observations in southern Africa (S. Fishwick, personal communication). The colour scale is the same as Figure 2.
The Cape Verde Islands lie in the Atlantic Ocean off west Africa, in a clearly oceanic setting. The lavas of some islands carry mantle-derived xenoliths of depleted peridotites (low in Ca, Al, Fe and other basaltic components), petrologically similar to those derived from cratonic lithospheric mantle. Oceanic lithospheric mantle, in contrast, consists mainly of less-depleted peridotites (lherzolites and harzburgites) formed by the extraction of mid-ocean ridge basalts. In situ Re-Os analyses of individual sulfide grains from depleted xenoliths from the island of Sal yield Re-depletion model ages ranging mainly from Neoproterozoic to Archean. Their age distribution mirrors the tectonic history of the western margin of the West African Craton and the corresponding continental margin of Brazil. These data suggest that part of the Cape Verde Archipelago is underlain by a fragment of ancient subcontinental lithospheric mantle (SCLM), left stranded in the oceanic lithosphere during the opening of the Atlantic Ocean (GEMOC Publication #625). Contamination of magmas by this ancient continental root can explain the unusual isotopic characteristics of some Cape Verde lavas without recourse to recycled continental material in the sources of mantle plumes.

The sulfide Re-Os age data from the Cape Verde mantle xenoliths (Fig. 1) broadly reflect the timing of events characterising the tectonic history of the Atlantic suture, and especially of the West African margin. The oldest Archean ages correlate with the ancient rocks of the West African Craton; the peak around 2 Ga correlates with the Birrimian volcanism and the Eburnian orogeny along the margins of the craton. The major Neoproterozoic peak (ca 1 Ga) matches the collision of the West African and Sao Luis Cratons and related volcanism; the youngest group of ages (550-800 Ma) corresponds to the breakup of the continent along the earlier suture, and the opening of the Iapetus Ocean. The dominance of Neoproterozoic ages is consistent with the position of the Cape Verde Archipelago closer to the inferred former suture between Africa and South America, where pre-existing SCLM would have been most strongly modified.

The broad spread of model ages between ca 1800-1300 Ma (ca 30 % of the data) may reflect either reactions between successive sulfide generations (i.e. mixed ages), or episodic metasomatism of the SCLM. In any case, the existence of possible “mixed ages” requires the presence of an older (cratonic) component. This possibility is also suggested by recent global tomographic mapping which show a high-velocity region below the Cape Verde Archipelago (Fig. 2).

The presence of a domain of Archean-Proterozoic SCLM beneath the Cape Verde Islands suggests that the opening of the ocean basin did not involve a clean break, with generation of new oceanic lithosphere directly overlying the underlying convective mantle. Depleted Archean to Proterozoic SCLM is buoyant relative to the convecting mantle (see GEMOC Publication #228), and detached fragments are thus unlikely to sink; instead they may “surf
the convecting mantle” (see GEMOC Publication #411) as the ocean opens. Such fragments of relict SCLM may be widespread in the ocean basins.

We suggest that during rifting, before true oceanic crust has been formed, rising MOR-like melts impregnate the pre-existing SCLM, causing a progressive heating and rheological weakening. A combination of rifting and ductile extension could produce an intermingling of old pieces of SCLM and new oceanic lithosphere. Geological and geochemical studies of the Lanzo peridotite massif (Piccardo et al., Lithos, 94, 181-209) provide a possible analogue. Lanzo may represent a transition between old SCLM and oceanic lithosphere; extending SCLM was modified by magmas, causing a progressive thermo-chemical erosion of the SCLM.

The presence of an SCLM remnant beneath the Cape Verde islands also can explain the complex isotopic signatures of the magmatic rocks. Geochemical signatures typical of ancient SCLM components have been recognised in some lavas on Sal (Holm et al., J Petrology, 47, 145-189) and the interaction of rising magmas (derived from the convecting mantle) with the SCLM could impart these signatures.

If such SCLM remnants are widespread in the ocean basins, they offer an alternative interpretation of the origin of EM1 and EM2 components (geochemical signatures of recycled crust) in ocean-island basalts. Further studies indicate contamination of rising magmas by relatively shallow SCLM remnants (see GEMOC Publication #576).

The new Re-Os data resulting from this study, coupled with those from abyssal peridotites, suggest that the traditional picture of oceanic lithosphere as the residues of basalt extraction at mid-ocean ridges is probably an oversimplification. Instead, the development of ocean basins may involve disruption of continental lithosphere and incorporation of relict SCLM domains in oceanic regions (Fig. 3). The repeated opening and closing of oceans, commonly along older sutures, must have left many SCLM remnants of different ages within the ocean basins. This process will produce significant compositional and geochronological heterogeneity in the oceanic lithosphere over time.

Contacts: Sue O’Reilly, Bill Griffin, Massimo Coltorti, Norman Pearson, Costanza Bonadiman
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**Figure 2.** Seismic tomography (Vs) image of northern Africa and the adjacent Atlantic Ocean at 0-100 km (after GEMOC Publication #547) showing high-velocity regions in the ocean basin. (Note colour reversal with hot colours indicating high velocity).

**Figure 3.** Cartoon showing possible oceanic rifting mechanism with listric faulting at cratonic margins and stranding of ancient subcontinental lithospheric mantle remnants in the ocean basin (after GEMOC publication #576).
A translithospheric suture in the vanished 1-Ga
lithospheric root of South India

GARNET XENOCRYSTS AND ECOLIGTE XENOLITHS from 15 kimberlites (1.0–1.1 Ga in age) have been used to map the composition and structure of the subcontinental lithospheric mantle (SCLM) along an 80-km traverse across the eastern margin of the Closepet Granite in Andhra Pradesh, southcentral India (see GEMOC Publication #567; Fig. 1, 2). The SCLM at the SW end of the traverse is more depleted (abundant harzburgites, mean XMg of olivine = 93.5, mean whole-rock Al₂O₃ ≈ 1.5%) than that at the NE end (fewer harzburgites, XMg ≈ 92, Al₂O₃ > 2%) (Fig. 3). The depleted layer thins from ca 195 km thick in the SW, to ca 170 km in the NE, although geotherms derived from the xenocrysts are similarly low (ca 35-37 mW/m²). The middle of the traverse is underlain by a strongly refertilised SCLM with a higher geotherm (ca 40 mW/m²) and extensive evidence of metasomatism (high Ti, Zr, lower Mg#; Fig. 4). At the SW end of the traverse, the kimberlites contain abundant eclogites; P-T estimates show that these are tightly concentrated in a layer from 175-190 km depth, and coincide with a zone of melt-related metasomatism. In the central part of the section, the eclogites also are abundant, but are distributed through the highly metasomatised section from 90-160 km depth.

These data suggest that the kimberlites at either end of the traverse sampled two distinct lithospheric blocks, perhaps coinciding with the Eastern and Western blocks of the Dharwar Craton. The zone of refertilised SCLM between them is interpreted as the cratonic suture, metasomatised by mafic melts (now eclogites). At either end of the traverse, such melts ponded at the base of the SCLM, but they were able to penetrate higher into the SCLM along the ancient suture. If this suture dips 70-80° to the east, its surface outcrop would lie within the area now intruded by the Closepet Granite. The “tilt” of the proposed cratonic suture may reflect overthrusting of the Eastern Dharwar Craton crust up to 100 km to the west.

Recent geophysical data (seismic, MT) suggest that the depleted lithospheric root beneath the Dharwar Craton...
that was sampled by the 1.1 Ga kimberlites is no longer present. The removal or major modification of this root could have occurred during the breakup of Gondwanaland, and may help to explain India’s rapid northward drift before it collided with Asia. India thus joins the North China Craton as an example of the destruction of an Archean continental keel.

Contacts: Bill Griffin, Sue O’Reilly, Alan Kobussen
Funded by: ARC Discovery, MQRESIndia

Figure 3. Chemical Tomography sections, illustrating the vertical distribution of geochemical signatures in peridotitic garnets. The mean X_{Mg} of coexisting olivine and the mean whole-rock Al_2O_3 content are calculated from garnet data.

Figure 4. Lithosphere mapping. Diamonds, individual data points. Circles, eclogites (numbers show >1 sample with similar depth estimate). Contour filtering blocks are 20 km wide by 5 km deep. (a) Median calculated X_{Mg} of olivine coexisting with Cr-pyrope garnets. (b) Distribution of Ti in peridotitic garnets. (c) Distribution of Zr in peridotitic garnets.
CLOGITE (THE HIGH-PRESSURE METAMORPHIC EQUIVALENT OF MAFIC ROCKS SUCH AS BASALT) is an important constituent of the subcontinent lithospheric mantle (SCLM) although its abundance is low (1-3 vol%). A clear picture of its origin will help us to understand the origin of the ancient SCLM, one of the key questions in Earth Sciences. Extensive studies of these rocks have generated two contradictory hypotheses about their origin; one regards eclogites as deep-seated magmatic rocks, while the other regards them as components of subducted oceanic slabs. Eclogite xenoliths are very abundant in the Roberts Victor kimberlite in South Africa, and previous studies have provided many observations and analyses. These provide a basis for a new approach to the “eclogite problem”, using a large collection of samples housed at GEMOC.

The Roberts Victor eclogites can be divided into two types based on differences in microstructure and mineral composition; the abundance of Type II is low, about a quarter of Type I. Type II eclogites have low Na in gnt and low K in cpx, while Type I have high values. Type II eclogites are generally fresh and show equilibrated microstructures. Rutile exsolution in gnt and cpx, and gnt exsolution in cpx, are only found in Type II eclogites. Type I eclogites, in contrast, are not in textural equilibrium, have many fluid inclusions and contain altered cpx. Only Type I eclogites contain diamond, graphite, sulfides and apparently-primary phlogopite.

All the minerals are homogenous within each sample. The depth of each sample was estimated by projecting the P-T locus calculated from the gnt-cpx thermometer to the local geotherm derived from peridotitic xenoliths and garnets. Type II eclogites are homogeneously distributed from 170-200 km depth, but Type I are strongly concentrated in a layer at 180-190 km depth, just beneath the lithosphere-asthenosphere boundary (180-200 km).

Reconstructed whole-rock compositions show that Type I eclogites are richer in Mg and K than Type II; there are also significant differences in trace-element patterns between the two types. Type II garnets have higher mean ∑REE than those of Type I, but Cpx from Type II has lower REE concentrations than those from Type I, and ∑LREE/∑HREE is much lower (Fig. 1).

O- isotope ratios also show differences between the two types of eclogites. Type II eclogites have δ18O < 4.3‰ and those of Type I have mantle values (ca 5.4) or higher (Fig. 2).

Sr, Nd and Hf isotopes of gnt and cpx were analysed in small acid-leached grains. Although Eu anomalies are absent or very small in gnt and cpx (Fig. 1), they are pronounced in the leachates from both phases in both types of eclogites. Previous reports of Eu anomalies in such eclogites probably represent contamination on grain boundaries or in cracks within the minerals.

The Nd-Hf data for Type I eclogites define two-point isochron ages (Sm-Nd 127±21 Ma; Lu-Hf
128±13 Ma; Fig. 2) that are identical to the kimberlite eruption age (128 Ma). Lu-Hf isochron ages for three Type II eclogites (1354±9 Ma; Fig. 3) may suggest a connection to the Namaqua-Natal Orogenic Belt south of the Kaapvaal Craton; other Type II eclogites show more obvious partial re-equilibration. These differences immediately suggest that Type II eclogites have retained their initial isotopic compositions (modified by radioactive decay) whereas the isotopic systems of the Type I eclogites were actively re-equilibrating at the time of their entrainment in the kimberlite. This is consistent with the petrographic and mineralogical evidence of fluid metasomatism in the Type I eclogites. Initial isotopic ratios at the time of kimberlite eruption also show marked differences between Type II and Type I; initial $^{87}\text{Sr}/^{86}\text{Sr}$ is 0.7060-0.7064 in Type I and 0.7013-0.7030 in Type II.

These data and observations, combined with the detailed study of sulfide minerals suggest that Type I eclogites were being actively metasomatised at the time of the kimberlite eruption. Inter-element correlations suggest that the metasomatism was adding Mg, K, Na, Ti, S, C (diamonds) and LREE. Some samples from the same depth range (the present Type II eclogites) appear to have escaped this process and preserved their original characteristics.

The calculated fluid in equilibrium with Type I eclogitic gnt and cpx is LREE-enriched and shows trace-element patterns similar to those of fibrous diamonds and carbonatitic/kimberlitic melts. The Sr- and O-isotope values are also consistent with reaction between Type II eclogites and carbonatitic melt (typical $\delta^{18}\text{O} \approx 6 - 7, ^{87}\text{Sr}/^{86}\text{Sr} \approx 0.706 -0.707$) to form Type I eclogites. Type II eclogites therefore are the key samples for studying the origin of this eclogite suite, since they may represent the protoliths. Type I, in contrast, are heavily metasomatised rocks, and retain little evidence of their primary origin.

Contacts: Jinxiang Huang, Yoann Greau, Bill Griffin, Sue O’Reilly
Funded by: ARC Discovery (O’Reilly and Griffin), MQRES, EPS Postgraduate Fund...
Imberlites, our main source of natural diamonds, are notoriously difficult to date, because they are chaotic mixtures of foreign mineral and rock material, enclosed in a (usually altered) magmatic matrix. Perovskite (CaTiO₃) grains in the groundmass of kimberlites are usually interpreted as having crystallised from the kimberlite during its rapid cooling after emplacement in the shallow crust. The perovskites have high contents of uranium, and potentially can be used to date the emplacement of the kimberlite by U-Pb isotopic analysis. This approach could avoid the complications of inheritance or mixed ages associated with traditional zircon and mica dating methods. The drawback to perovskites is that (unlike zircon) they also soak up lead (“common Pb”) from the magma, so that they contain a mixture of common Pb and radiogenic Pb produced by the decay of U and Th, which complicates the dating.

In recent years the use of laser ablation microprobe-inductively coupled plasma mass spectrometry (LAM-ICPMS) U-Pb analysis to date kimberlitic perovskite has become increasingly popular (see 2009 Annual Report). It can provide very precise ages in a fraction of the time used by other techniques, allowing its widespread application. For these analyses, it is assumed that perovskite is concordant in the U-Pb system. A linear regression is calculated through the data points; the upper intercept of this line with the Concordia curve on a Tera-Wasserburg plot (Fig. 1) gives the common-Pb composition and the lower intercept gives the inferred crystallisation age (Fig. 1a).

This procedure works well as long as the data points show sufficient spread in U/Pb ratios and common-Pb contents to define a line. If this is not the case, a common-Pb correction is required for each analysis. In TIMS (thermal ionisation mass spectrometry) or SIMS (secondary ion mass spectrometry, or “ion-probe”) analysis this can be done by measuring the abundance of the non-radiogenic isotope ²⁰⁴Pb, assuming an isotopic composition for the common-Pb component, and subtracting the calculated common-Pb abundance from the analytical data. However, the LAM-ICPMS method cannot accurately measure the ²⁰⁴Pb contents due to an interference with ²⁰⁴Hg in the Ar carrier gas. This problem became apparent during our attempts to obtain more precise emplacement ages for some old kimberlites, in the Kuruman field of South Africa.

The non-diamondiferous Kuruman Kimberlite Province is comprised of 16 small pipes and dikes that were intruded across the western edge of the Archean Kaapvaal Craton (Fig. 1). Despite being recognised as some of the oldest kimberlites in the world (~1.6-1.7 Ga), there are only limited geochronological data for the Kuruman Province. Unfortunately, the Kuruman perovskites are relatively homogenous in terms of U and common-Pb contents, which results in a limited range of data points on the Concordia plot. Furthermore, the Kuruman perovskites commonly show evidence of mild, fine-scale alteration and LAM-ICPMS U-Pb analyses of these grains typically scatter results to younger discordant ages. Regression of such data results in large errors in the lower-intercept ages and unrealistically low upper-intercept common-Pb compositions (Fig. 1b). As such, for the Kuruman perovskites, a common-Pb correction is required for each analytical spot.
This may suggest that perovskite is not as resistant to weathering and alteration as was previously thought and that the U-Pb isotopic system in perovskite may be reset by alteration. The LAM-ICPMS analysis uses volumes ca 30 microns across and 30-40 microns deep, and we suspected that the analysed volumes were including altered material, even if the grains looked good on the surface. An alternative approach clearly was required, and was made possible by our collaborator (Jin-Hui Yang) in the SIMS lab at the Chinese Academy of Sciences, Beijing.

The application of SIMS to U-Th-Pb perovskite geochronology has been relatively limited. However, recent developments in calibration protocols using well-characterised standards (see Li et al., Chemical Geology, 269, p. 396-405, 2010) have allowed the smaller analytical sampling volume used by SIMS to be combined with precise measurements of $^{204}$Pb, providing a promising tool for detailed in situ perovskite geochronology.

Perovskites from the Kuruman kimberlites were re-analysed using SIMS to target only the most pristine parts of each grain and the results were then corrected for $^{204}$Pb. The Bathlaros kimberlite yielded a $^{206}$Pb/$^{238}$U age of 1594±27 Ma (n=7; MSWD=0.22; Fig. 3a); this is younger than the 1694± 42 Ma phlogopite isochron age, upon which the age of the Kuruman Province is currently defined. The Elston (Fig. 3b) and Helpmekaar (Fig. 3c) kimberlites have $^{206}$Pb/$^{238}$U perovskite ages within error of each other at 1689±26 Ma and 1651±21 Ma, respectively. The Zero kimberlite yielded an older emplacement age of 1832±37Ma (Fig. 3d). The SIMS results thus show a considerable range (~200 Ma) in emplacement ages within the Kuruman Province and reveal a previously unrecognised trend of increasing kimberlite age from east to west across the Province.

The recent LAM-ICPMS dating of kimberlite perovskite has produced many precise and apparently accurate ages, but these have all been from relatively young kimberlites (≤1 Ga; GEMOC publication #505; Wu et al., 2010, Lithos, 115, 205-222). The failure of this method in the case of the Kuruman kimberlites, even when “unaltered” grains were analysed, suggests that the U-Pb system in older perovskites may be disturbed by metamictisation – the breakdown of the crystal structure under α-particle bombardment as U and Th decay – as is seen in many zircons.

Contacts: Cara Donnelly, Bill Griffin, Sue O’Reilly, Jin-Hui Yang
Funded by: ARC Discovery (O’Reilly and Griffin), MQRES, EPS Postgraduate Fund, Industry
Short-lived isotopes reveal off-axis magmatism at the East Pacific Rise

More than 70% of global volcanism consists of basalts erupted at mid-ocean ridge ridges (MORB) and this is generally thought to be confined to a narrow axial zone due to efficient magma focusing from a much broader, triangular melting volume. However, the dynamics of melting and melt transport remain a subject of debate. In this regard, studies of short-lived U-series isotopes have proven especially useful because of their potential to constrain melting rates and melt extraction porosity.

One of the most intensively studied ridges is the fast-spreading (11.1 cm/yr) East Pacific Rise (EPR) which appears to be underlain by axial magma chambers. The EPR axial summit trough is only 10-100 m wide, yet geophysical surveys indicate that the oceanic crust continues to thicken (by a factor of ~ 2) away from the ridge axis. This demands the occurrence of off-axis magmatism either by intrusion or by volcanism. This inference has been supported by observations from submersible vessels, and by earlier U-series dating that yielded ages younger than those predicted by combining the distance of the sample from the axis with the local spreading rate. For example, in the region 9-10°N, U-series data demonstrate the persistence of volcanism up to 4 km from the ridge axis.

In order to explore these substantial matters further, we have undertaken U-series analyses of samples from traverses across the EPR at 9°30’N, 10°30’N and 11°20’N. The results show that about 50% of the 34 samples analysed must have erupted off-axis and at least 14 formed within a few km of their current position. Thus, the data confirm geophysical suggestions that magmatism extends significantly off axis (up to 30-50 km). The implication is that magmatism is not as efficiently focused beneath the ridge as is generally believed. There is a decrease in "primary" U-series disequilibria in samples inferred to have formed off-axis and simple modeling suggests that this can be explained by a decrease in melt-column length and fertility as the overlying lithosphere thickens with age (Fig. 1).

Contact: Simon Turner
Funded by: ARC Discovery

Figure 1. True-scale illustration of the melting model explored in light of the East Pacific Rise traverse data, showing schematic mantle flow lines. The oceanic crust thickens away from the ridge axis following the thermal plate model (age is given in italics). Shown are the location of the spinel to garnet transition and the melting region that is required to dip into the garnet peridotite zone on the basis of the large 230Th excesses observed in erupted lavas. It is also assumed the melt extraction in the central upwelling region results in more depleted peridotite moving away from the axis. The location of a melt lens identified from seismic observations is also shown. Ship not to scale.
Accessory minerals, though tiny and sparse, concentrate specific geologically-interesting trace elements such as rare earth elements and can give critical constraints on the details of igneous processes in magma chambers. This approach provides information about igneous petrogenesis that is not accessible through conventional bulk-rock analysis. Apatite, although less intensively studied than zircon, may be the next candidate for such expanded applications. In terms of its common occurrence, stability during magma evolution and chemical diversity, apatite is comparable with zircon and even better in some respects.

To get a better idea of the relationships between magmatic processes and the geochemical characteristics of apatite, we have analysed minor- and trace elements in apatites from a range of plutonic rocks in the Lhasa terrane of southern Tibet. The Lhasa terrane consists primarily of Paleozoic to Mesozoic sedimentary rocks, intruded by ubiquitous igneous rocks. These may be categorised into three principal rock types on the basis of geochemistry and/or occurrence: (1) S-type granites, (2) I-type Gangdese granitoids, (3) (collision-type) adakites, with uniquely high Sr/Y ratios and heavy-REE depletion.

Apatite retains geochemical information about the host magma through the course of magmatic evolution: F, Mn, Sr and rare earth elements in apatite systematically vary with the composition of its host magma and thus have high potential as petrogenetic tracers. More specifically, F and Mn contents in apatite can be used as an indicator of magma aluminium content or differentiation index. Combined with Sr and REE data, which also show significant variations in apatite from different rock types as well, these elements are useful for constructing “discrimination diagrams” (Fig. 1). The variations of Sr and REE in apatite with bulk rock aluminium content reflect competition with other major and accessory minerals in silicate melts, including plagioclase and monazite. These variations therefore are useful for more detailed investigations of petrogenetic processes such as fractional crystallisation and magma mixing (see GEMOC Publication #609). Magma mixing is signaled by inconsistent Eu anomalies, Sr abundances and REE patterns relative to bulk rock composition.

Contacts: Mei-Fei Chu, Norman Pearson, Bill Griffin, Sue O’Reilly
Funded by: ARC Discovery

Figure 1. Two examples of “discrimination diagrams.” (a) F and (b) heavy REE, e.g. Yb, abundances in apatites generally increase with aluminositities of host plutonic rocks, e.g. the aluminum saturation index (ASI: molecular Al₂O₃/(Na₂O+K₂O+CaO)). In host rocks of similar aluminosity, apatite from an adakite has higher Sr and lower heavy REE than one from a granite.
The Gawler Craton, South Australia: Unexpected discoveries and mysteries

Irccon grains from modern and ancient drainages of the Gawler Craton, South Australia have been studied to unravel the evolution of this craton. The study has defined the relative contributions of juvenile sources and recycled crust to magmatic activity as a function of time, and constrained the role of mantle inputs during the Proterozoic rejuvenation of the Archean Gawler Craton (see GEMOC Publication #600).

The integration of Hf-isotope data with U-Pb age spectra showed that the crustal evolution was dominated by long periods of crustal reworking, and that crust generated in the Paleoarchean (3.2–3.5 Ga) was largely reworked during Proterozoic time (Fig. 1). There were three periods with some juvenile mantle input at ca 2540 Ma, 1853 Ma and 1595 Ma. However, these juvenile mantle inputs provided a minor contribution to the crustal volume, compared to the major role played by the reworking of older crust.

Modelling of the composite age spectrum derived from the detrital zircons allows definition of six major geological events in the Gawler Craton, spanning the period 2550-1550 Ma (Fig. 2). Besides those previously well-recognised events, we identified a minor age peak at ~3152 Ma. This Archean age is also strongly supported by Hf-isotope data – many zircons have model ages ca 3.2 Ma. This conclusion was later confirmed by the Geosience Australia discovery of the oldest rocks reported from the Gawler Craton; an outcrop in the Eyre Peninsula has been dated to 3150 Ma.

We also found a major peak at 1169 ± 48 Ma represented by a prominent zircon population (Fig. 2). This appeared to be the only event that had not been reported previously in the Gawler Craton and is a mystery remaining to be resolved. There is a possibility that this age population might represent zircons that were transported from the Musgrave Province, where a Grenville-age event is well documented. However, zircons of this age are found not only in the samples...
from drainages situated near the Musgrave Province, but across the Gawler Craton as far as the Gawler Range Volcanics Domain and the southern part of the Olympic Domain, over 700 km SE of the Musgrave Block. Moreover, other age populations, and especially the 1300-1400 Ma event that is prominent in the Musgrave Province, are not found in the Gawler samples. This observation alone makes it improbable that the 1169 Ma age population is derived from the Musgrave province. Further investigations to find rocks of this age within the Gawler Craton will be necessary to resolve this ambiguity.

Contacts: Elena Belousova, Bill Griffin, Sue O’Reilly
Funded by: PIRSA, ARC Linkage

TerraneChron® sampling in the Gawler Craton
The Yangtze craton of South China is usually regarded as a Proterozoic block with minor Archean remnants, but this interpretation is based mainly on inference, because most of the craton is obscured by much younger sediments. However, there are several late Proterozoic basins lying around the edge of the craton, and the detritus in these is believed to be derived from its now-covered interior. A Nanjing University-GEMOC collaboration has been investigating these basins, using integrated U–Pb dating, Hf-isotope and trace-element analysis of detrital zircons to identify ancient crustal remnants and the provenance of clastic sediments, and to provide an overview of crustal evolution in the now-covered parts of the Yangtze Block.

The Fanjingshan and Xiajiang sediments in the southeastern part of the Yangtze Block have been studied during 2009. The zircon dating indicates that the Fanjingshan Group, which previously was regarded as 870 Ma old, actually was deposited in a ~800 Ma rift basin similar to other contemporaneous basins in the Yangtze Block. The regional unconformity separating the Fanjingshan Group from the overlying Xiajiang Group is dated to 800~740 Ma and is probably related to rifting processes during the breakup of Rodinia (830~740 Ma).

Detrital zircons from these two sedimentary groups have different age populations. We have identified seven main age populations in the Fanjingshan Group: 0.85~0.8 Ga, 0.95~0.86 Ga, 1.3~1.1 Ga, 1.6~1.5 Ga, 1.8~1.7 Ga, 2.1~2.0 Ga, 2.4~2.2 Ga and 2.6~2.5 Ga. There are fewer age peaks in the Xiajiang Group: ~760 Ma, ~800 Ma, ~880 Ma, ~2000 Ma and ~2500 Ma (Fig. 1).

The trace-element analysis indicates that most zircons in the Fanjingshan Group were derived from granitoids, with a few from mafic rocks. However, the dominant source rock of zircons from the Xiajiang Group changes from the lower to the upper part of the group. The proportion of mafic rocks increases upward through the sequence, suggesting bimodal magmatism in the region.

Based on the zircon U-Pb dating and Hf-isotope results for the Fanjingshan and Xiajiang groups, the distinguishing features of Precambrian crustal evolution in their respective source regions are summarised in the Event Signature curves of Figure 2a. They have similar Archean origins. The oldest continental crust in the Yangtze Block may have started to form in early Archean or even Hadean time. A previously unrecognised source (~4.3 Ga) is suggested by the Hf model ages of the oldest zircons. During late Archean time (2.4~2.6 Ga), some juvenile material was added to the crust in the source areas for both the Fanjingshan and Xiajiang groups. After this time the two source regions have followed different evolutionary paths.

In the source regions of the Fanjingshan Group, the juvenile Archean crust was reworked during Paleoproterozoic time (2.1~1.7 Ga). An important input of juvenile mantle-derived material occurred in the early Mesoproterozoic (1.6~1.4 Ga). This is the first documentation of early Mesoproterozoic juvenile crust in South China. Afterwards, both reworking and some
juvenile growth of crust took place from Mesoproterozoic (~1300 Ma) to mid-Neoproterozoic (~800 Ma) time.

In the source area of the Xiajiang Group, the Archean crust was reworked in Paleoproterozoic time (2.0-2.1 Ga), but the 1.6-1.4 episode is essentially absent. The most significant input of juvenile crust occurred in early Neoproterozoic time (850-1000 Ma). This episode of juvenile-crust formation was followed by crustal reworking until ~800 Ma. The last magmatic activity in this area involved a new juvenile contribution at 790-740 Ma. The curves show that crustal evolution of the source area of the Xiajiang Group is quite similar to that of the Yichang area reported by Liu et al. (2008; AJS, 308, 421-468).

The possible source areas for these sedimentary rocks are the Yangtze Block and the adjacent Cathaysia Block (Fig. 2b). Although similar mid-Neoproterozoic and Paleoproterozoic age populations (0.85-0.8 Ga, 1.8-1.7 Ga) are found within both the Yangtze Block and the Cathaysia Block, the detrital zircon spectra in this study show remarkably little material of Grenvillian age (0.95-1.0 Ga) whereas rocks of this age are abundant in the Cathaysia Block. The crustal event signature summarised in Figure 2b shows a different geological evolution than the one recorded by the zircons studied here (see GEMOC Publications #615 and 477).

The euhedral morphology of zircons in all age windows from the Fanjingshan and Xiajiang sediments also suggests that their primary sources were not far from their site of deposition. Therefore, the (now unexposed) Yangtze Block is considered to be the main source for the sediments in the Fanjingshan and Xiajiang groups. The differences in the sources for some detrital material between these two groups, and with exposed basement in the Yangtze Block that the sources for these zircons lie within different, now-covered, parts of the Yangtze Block.

Contacts: Lijuan Wang, Sue O’Reilly, Jin-Hai Yu
Funded by: ARC Discovery (O’Reilly and Griffin), MQRES, EPS Postgraduate Fund
Platinum-group elements nobly unravel komatiites

PLATINUM-GROUP ELEMENTS (PGE: Ru, Rh, Pd, Os, Ir, Pt) are important as petrogenetic tracers in the study of Earth’s accretion history, core-mantle interaction, mantle differentiation processes, and the Re-Os isotopic system that is widely used to date mantle depletion events. They are industrially important commodities in their own right, and have been identified as potential pathfinders for Ni-Cu-sulfide mineralisation. However, owing to their low abundance and complex behavior, PGEs remain among the least understood elements in geochemistry, mainly because of the difficulties of producing accurate and precise analyses. Research at GEMOC has developed novel analytical approaches for low-level PGE analysis in order to investigate the behaviour of PGEs during the fractionation of komatiites and komatiite-derived magmas, with a particular focus on the role of chromite in the fractionation and concentration of Ru.

In sulfide-saturated systems, the behaviour of the strongly chalcophile PGE is well established; it is dominantly controlled by their strong partitioning into sulfide melts relative to silicate magmas. However, little is known about the fractionation of PGEs in sulfide-undersaturated systems, mainly because the PGE contents of mineral phases that record the magmatic evolution of a system are generally below the detection limit of conventional analytical techniques. Accordingly, most studies have been limited to using whole-rock PGE signatures from S-poor rocks. Although this gives a rough idea about the PGE behavior, it leaves a lot of questions unanswered, particularly as primary magmatic whole-rock signatures can be overprinted by metamorphism, alteration, and weathering. Moreover, the presence of minute platinum-group minerals can distort the whole-rock PGE signatures of S-poor rocks (Fig. 1).

A more informative way to investigate PGE behaviour is to determine the PGE signatures and/or concentrations of primary mineral phases as these signatures are less likely to be overprinted by secondary processes. However, it has been widely debated over the past decades if PGE can exist in solid solution in non-sulfide phases at all, or if measured PGE concentrations in oxides and silicates are exclusively related to the presence of inclusions. This needs to be established, as only PGE in solid solution will record the evolution of a magmatic system, and therefore can be used to better understand...
the behaviour of PGE during fractionation. The analytical approach for low-level PGE analysis in mineral phases at GEMOC combines (1) in situ laser ablation (LA) ICP-MS analysis of chromite and silicate grains to determine PGE concentrations at low ppb levels and the spatial distribution of PGE within the grains; and (2) Carius-tube digestion and isotope-dilution ICP-MS analysis of mineral concentrates to confirm the accuracy of the in situ studies. The study has demonstrated that Ru can exist in solid solution in chromite with concentrations up to several hundred ppb and that the fractionation of Ru in S-poor systems is controlled by the crystallisation of chromite. The laser ablation ICP-MS data show that Ru concentrations in chromite grains in individual samples are, within analytical uncertainty, the same on sample- and grainscale (Fig. 2). These results suggest that Ru is bound as solid solution in the crystal lattice of chromite, as the occurrence of Ru-bearing micro-inclusions would produce a greater variability within and among grains of the same sample. This hypothesis is supported by the fact that time-resolved LA-ICPMS analyses show a uniform distribution of Ru in komatiitic chromite indicated by a constant signal intensity of approximately 40-50 cps above background, whereas it was possible to establish the presence of Ir-inclusions distinctly smaller than 1 μm using the same analytical procedures (Fig. 3). This indicates that the absence of Ru-bearing micro-inclusions in the analysed chromites is a real feature and not the result of sampling bias. It could be argued that Ru may be evenly distributed as nano-particles in chromite – and not necessarily bound in the crystal lattice as solid solution. However, our data give similar results for many samples from different localities. If Ru was hosted as nanoparticles rather than being in solid solution, a greater variability would be expected. Therefore, we suggest that Ru can exist in solid solution in chromite with concentrations up to several hundred ppb.

These outcomes are the first of their kind and open up new avenues of research related to the role of chromite in the fractionation and concentration of Ru in mafic and ultramafic systems.

Contacts: Marek Locmelis, Norman Pearson
Funded by: ARC Discovery (O’Reilly, Griffin and Pearson), MQRES, EPS Postgraduate Fund

Figure 2. Ruthenium in chromite from the Murphy Well komatitite flow in Western Australia as analysed by laser ablation ICP-MS. The solid line shows the average Ru concentration obtained by Carius-tube digestion and isotope-dilution ICP-MS analysis and confirms the accuracy of the in-situ studies.

Figure 3. Time resolved analysis record obtained by LA-ICP-MS illustrating (A) the absence of any PGE-bearing micro-inclusions in chromite from Murphy Well, and (B) the presence of an iridium-bearing micro-inclusion in a chromite grain from a komatiitic basalt flow at Collurabbie (Western Australia).
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

THE TEACHING HIGHLIGHTS 2009

- All of our units ran successfully in 2009. Student numbers increased from 2008, as did our retention of students from first year. GEOS226 Introduction to Field Geology attracted 60 students.

This has been a year of preparing for change with many of our units changing from 4 credit points to 3 credit points in line with the University’s new curriculum. We are also introducing two new units that will be ready for 2011: Geology of Australia - Global Perspectives that will investigate interdisciplinary perspectives on the origin and geological evolution of Australia and its plate margins; and Liquid Fuels and Energy Security that will combine geological and geophysical approaches to investigate exploration and production methods for crude oil, natural gas and coal bed methane.

- EPS successfully ran another GEOS307 field trip to Olary (200 km west of Broken Hill) together with the University of Sydney. With combined enrolments of over 60 students this year, the unit was run twice. The dual offering was welcomed by the students as it offered flexibility and two lots of smaller groups reduced the strain on the Plumbago Station shearer’s quarters, otherwise known as the “Plumbago Hilton”. Postgraduate tutors Luke Milan, Ryan Portner, Matt Pankhurst, James Watton and Andrew Frost ably assisted the students with their field mapping. 2009 saw some of the best maps ever produced of the area. This year also saw Steve and Jan Craven lead the camp management for the second trip with
enthusiastic feedback from the students. The field trip will be relocated to Alice Springs in Central Australia in 2010. The students will enjoy mapping two locations in the red centre at Ormiston Gorge and Aileron.

- Kelsie Dadd and Jenny George (Environment and Geography) presented the results of their Work-Integrated Learning in Environmental and Life Sciences project at the Faculty of Science Learning and Teaching Forum. Kelsie also presented aspects of her research on problem-based learning and its use in undergraduate classes at the Australian Learning and Teaching Council Education Roundtable.

- Kelsie Dadd participated in IODP Leg 323 to the Bering Sea in July and August and Simon George participated in the Canterbury Basin Sea Level Expedition, Leg 317, off the coast of New Zealand in December and January 2010. This research will be incorporated into the teaching of marine science units and will probably form the basis for “tailored problem-based learning” modules. These prepare the students for employment by ensuring they master a range of generic skills such as problem-solving, teamwork and critical thinking as well as technical content. Where possible we integrate computers into the coursework using both our portable computer laboratory and more traditional computer labs. Students are introduced to a number of computer packages used in industry.

Geophysics teaching progress 2009

The geophysics curriculum was updated throughout the year in readiness for the new curriculum, which will take effect in 2010. A new unit dealing with petroleum geophysics and geology will be introduced in 2011.

Extended use of seismic, gravity, GPS (including the ASHTECH Z-Xtreme Differential GPS system) and resistivity (DUALEM Frequency Domain EM System) electrical (TerraTEM em equipment) and the new GPR equipment for student field projects in exploration, groundwater, environmental and engineering geophysics was implemented.

Equipment upgrades funded by Macquarie University over the last five years have resulted in an excellent array of new instrumentation.

- Software such as GEOSOFT, MODELVISION, EMVISION, ERMAPPER, SeisImager, Profile Analyst, Discover, Discover3D, Maxwell, Quickmag and Reflexw have been maintained, while teaching packages such as SurfSeis and SeisImagerSW were purchased to upgrade the software suite.

- A set of low frequency geophones (4.5Hz) were purchased for environmental studies.
The following honours projects in GEMOC were completed in 2009:

**Andrew Frost:** Petrogenesis, modelling and characterisation of layered mafic intrusion White Hill and Peculiar Knob North within the Mount Woods Inlier, South Australia

**Rosanna Murphy:** The major and trace-element composition and isotope geochemistry of garnet in silicic volcanic and plutonic rocks

**Sophie Ratcliff:** Breccias of the Wasp Head Formation, southern Sydney Basin

**Elyse Schinella:** Convergence within the Wedges Region, Europa

**James Watton:** Petrogenesis and geochemical characterisation of the Breaksea Orthogenesis, Fiordland, New Zealand

The following honours projects are relevant to GEMOC in 2010:

**Mid year submission**

**Andrew Buchel:** Geophysical delineation of impact structures: an investigation of impact origin of the Borealis Basin, Mars

**Eileen Dunkley:** Geochemical evolution of the Median Batholith magmatic arc, Fiordland, New Zealand

**Elizabeth Teague:** The application of in-situ zircon and monazite geochronology to understanding the tectonic evolution of the Wongwibinda Complex, Southern New England Fold Belt

**End of year submission**

**Trent Bowman:** Salinity of groundwater in various vineyards in the Hunter region, NSW

**Glen Cathers:** The Devils Playground Volcanics: A Late Archaean calc-alkaline complex?

**Chris Firth:** Magma geochemistry and petrogenesis of Ambrym and Yasur Volcanoes, Vanuatu Arc
Tom Harris: Gravity modelling of the Bundarra Plutonic Suite, New England Batholith, NSW: Implications for pluton geometry during transtensional tectonics

Troy Hewitt: 3-D structure and lithospheric evolution of the Myall Syncline, NSW: Application of magnetic and gravity modelling

Tim Jones: The D" layer

Matthew Robertson: Characterisation of the source for Solander Island volcanics using in-situ REE, U-Pb and Hf-isotope analysis of zircon

Max Milz: Thermo-tectonic history of the Carnarvon Basin

Susie Schartz: Controls on the chemistry and petrography of IOCG mineralisation in the Eastern Gawler Craton, SA

Teaching and training program -
GEMOC postgraduate

**COMPLETED**

**Olivier Alard (PhD):** Chalcophile and siderophile elements in the mantle: Geochemical characteristics and distribution; *IPRS with MUIPRA stipend* (graduated 2001)

**Kari Anderson (PhD):** Palaeozoic Eastern Gondwana: palaeomagnetic investigations of Queensland; *IPRS with MUIPRA stipend* (graduated 2003)

**Sonja Aulbach (PhD):** Evolution of the lithospheric mantle beneath the Slave Craton and Alberta Canada; *IPRS with MUIPRA stipend* (graduated 2004)

**Jacques Batumike (PhD):** Origin of kimberlites from the Kundelungu region: Lithospheric mapping, diamond potential and crustal evolution in southern Democratic Republic of the Congo; (graduated 2009)

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

**Eloise Beyer (PhD):** Evolution of the lithosphere beneath Tasmania and Western Norway; *Field assistance from Ashton Mining* (graduated 2003)

**Heather Cunningham (PhD):** Using short-lived U-series isotopes to constrain the time scales of magmatic processes in an active caldera, Rabaul, Papua New Guinea; *iMURS* (graduated 2009)

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

**Guillaume Delpech (PhD):** Trace-element and isotopic fingerprints in ultramafic xenoliths from the Kerguelen Archipelago (South Indian Ocean); *Co-tutelle with University of Jean Monnet, IPRS with GEMOC stipend and EURODOC scholarship* (graduated 2005)

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

**Bin Guo (PhD):** An integrated geophysical investigation of the Tamworth Belt and its bounding faults; *IPRS with MUIPRA stipend* (graduated 2005)

**Véronique Le Roux (PhD):** Melt-rock interactions and melt-assisted deformation in the Lherz peridotite: Implications for the structural, chemical and isotopic evolution of the lithospheric mantle; (graduated 2009)

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See advertisement for GEMOC postgraduate opportunities, Appendix 6.
| **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) |
| **Valeria Murgulov (PhD)**: Lithosphere evolution and metallogeny in the Georgetown Inlier and adjacent Tasman Fold Belt, North Queensland, Australia; *APA* (graduated 2007) |
| **Mark Pirlo (PhD)**: Australian groundwater geochemistry; applications to heat flow and exploration; *APA and Queen’s Trust for Young Australians Award* (graduated 2003) |
| **Will Powell (PhD)**: Geochemically diverse domains in lithospheric mantle, eastern Australia; *APA* (graduated 2006) |
| **Sonal Rege (PhD)**: Trace-element geochemistry of diamond; *IPRS with iMURS scholarship* (graduated 2006) |
| **Stéphanie Touron (PhD)**: Geochemical fingerprints of mantle metasomatism beneath the Massif Central, France; *IPRS with MURAACE scholarship* (graduated 2006) |
| **Esmé van Achterbergh (PhD)**: Geochemical fingerprints of mantle metasomatism; (graduated 2005) |
| **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) |

**CURRENT**

| **Brad Bailey (PhD)**: Law Dome: Ice and crust mass balance studies; *RAACE* (commenced 2004) |
| **Stephanie Carroll (PhD)**: The mechanisms and deep-crustal controls on continental rifting; *RAACE* (commenced 2005) |
| **John Caulfield (PhD)**: Nature and timing of magma genesis at Tofua volcano, Tonga; *iMURS* (commenced 2006) |
| **June Chevet (PhD)**: Gabbros, dolerites and associated ultramafic cumulates from the thickened oceanic crust of the Kerguelen Archipelago; *iMURS* (commenced 2005) |
| **David Child (PhD)**: Characterisation of Actinide particles in the environment for nuclear safeguards using mass spectrometric techniques; (commenced part time 2007) |
| **David Clark (PhD)**: Contributions to integrated magnetics - applications to the Earth Sciences; (commenced 2006) |
Teaching and training program: postgraduate

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

**James Cowlyn (PhD):** Growth of evolved continental crust in the primitive Tonga Arc: A study of the island of Fonualei; MQRES (EAPE CoRE) (commenced 2008)

**Stephen Craven (PhD):** The structural and metamorphic evolution of the Wongwibinda Complex, NSW, Australia; (commenced 2006)

**Cara Danis (PhD):** Geothermal structure of Eastern Australian Basins; APA (commenced 2008)

**Cara Donnelly (PhD):** Mantle xenoliths, kimberlites and related rocks of the Kuruman Kimberlite Province, Kaapvaal Craton, South Africa; iMURS (commenced 2007) (see Research Highlights, p48)

**Fiona Foley (PhD):** Generation of continental crust during subduction initiation; iMQRES (commenced 2009)

**Anne Fonfrege (PhD):** Geochemical and isotopic characterisation of magma mixing: comparative studies in volcanic and plutonic settings; Co-tutelle with Jean-Monnet University, France (commenced 2008)

**Felix Genske (PhD):** Assessing the heterogeneous source of the Azores mantle plume; iMQRES (commenced 2009)

**Yoann Gréau (PhD):** Elemental and isotopic fractionation of siderophile and chalcophile elements: A new perspective on eclogite origin; iMURS and Co-tutelle with Montpellier University, France (commenced 2007)

**Jinxiang Huang (PhD):** Origin of eclogite and pyroxenite xenoliths in kimberlites and basalts; China Government Scholarship and co-tutelle with China University of Geosciences, Beijing (commenced 2008) (see Research Highlights, p46)

**Alan Kobussen (PhD):** Composition, structure and evolution of the lithospheric mantle beneath Southern Africa; iMURS (commenced 2006) (see Research Highlights, p40)

**Weiqiang Li (PhD):** Copper isotope geochemistry of the Northparkes porphyry Cu-Au deposit; iMURS (commenced 2006)

**Marek Locmelis (PhD):** Understanding nickel deposits using platinum group element geochemistry; iMURS (commenced 2006) (see Research Highlights, p56)

**Kathleen McMahon (PhD):** Fracturing and deformation along the Amery Ice Shelf: A seismic study; (commenced 2004)

**Luke Milan (PhD):** The emplacement, pressure-temperature-time path and structural evolution of lower crustal gneisses in Fiordland, New Zealand; (commenced 2004)
**Melissa Murphy (PhD):** A novel U-series isotopic approach for investigation of the Beverley U mine, South Australia; APA (commenced 2009)

**Nenad Nikolic (PhD):** Evolution of crust-mantle systems near a young rift: NW Spitsbergen, Norway; iMURS (commenced 2004)

**Matt Pankhurst (PhD):** Geodynamic significance of shoshonitic magmatism within the Andean Altiplano; MQRES (commenced 2009)

**Ryan Portner (PhD):** Sedimentary and volcaniclastic record of a mid-ocean spreading ridge: Macquarie Island, Southern Ocean; iMURS (commenced 2006)

**Suresh Puthiyaveetil Othayoth (PhD):** Timescales of soil evolution and sediment transport in a small catchment in SE Australia; (commenced 2009)

**Lijuan Wang (PhD):** Crustal evolution of the Yangtze Block using zircons in sediments; China Government Scholarship (commenced 2008) (see Research Highlights, p54)

**Yamei Wang (PhD):** Evolution of the subcontinental lithospheric mantle beneath the Western Block of the North China Craton: a mantle xenolith approach; China Government Scholarship, iMQRES (commenced 2009)

GEMOC PhD students presented posters at the Faculty of Science Research Day, held in October 2009

Felix Genske, Jinxiang Huang and Lijuan Wang

Daniel Howell and Matt Pankhurst

Jinxiang Huang

Lijuan Wang

Marek Locmelis and Suresh Puthiyaveetil Othayoth

Cara Danis
COMMENCING 2010

Ekaterina Rubanova (PhD): Fluid processes in the deep mantle: Geochemical studies of diamonds and related minerals

Edward Saunders (PhD): Gold distribution and mobility within the mantle and its significance to mineralised provinces

Elyse Schinella (PhD): Processes shaping the Venusian landscape

Rajat Taneja (PhD): Origin of intraplate volcanism in the east Indian Ocean

Yao Yu (PhD): The evolution and tectonic dynamics of the subcontinental lithospheric mantle, SE China
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 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.

In 2009 a new strand of Technology Development commenced with the acquisition of a nucleus of a computer cluster for computational analysis, part of the strategic plan to develop strong capabilities in geodynamic and geophysical modelling. This new development is detailed on p. 73.

The analytical instrumentation and support facilities of the Macquarie University Geochemical Analysis Unit (GAU) represent a state-of-the-art geochemical facility.

- The GAU contains:
  - a Cameca SX-50 electron microprobe
  - a Cameca SX-100 electron microprobe (installed January 2003)
  - three Agilent 7500 ICPMS (industry collaboration; two installed October 2004)
  - a custom-built UV laser microprobe, usable on the Agilent ICPMS
  - five New Wave/Merchantek laser microprobes (two 266 nm, three 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 Thermo Finnigan Triton TIMS (installed March 2005)
  - a Spectro XLAB2000 energy-dispersive XRF with rocker-furnace sample preparation equipment
  - a LECO RC412 H₂O-CO₂ analyser (delivered September 2003)
  - an Ortec Alpha Particle counter
  - a New Wave MicroMill micro-sampling apparatus
  - a ThermoFisher iN10 FTIR microscope
clean labs and sampling facilities provide infrastructure for ICPMS, XRF and isotopic analyses of small and/or low-level samples

Experimental petrology laboratories include 4 piston-cylinder presses (pressure to 4 GPa), hydrothermal apparatus, controlled atmosphere furnaces, Griggs apparatus and a multi-anvil apparatus for pressures to 27 GPa.

The Centre for Isotope Studies has provided access to extraction lines and gas-source mass-spectrometers for stable-isotope analysis of fluids and minerals; it is planned that these facilities will be moved to GEMOC at Macquarie.

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 were 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. In late 2009 GEMOC was awarded an ARC LIEF grant to integrate the two existing multi-collector inductively-coupled-plasma mass spectrometers (MC-ICPMS) with 3 new instruments: a femtosecond laser-ablation microprobe (LAM); a high-sensitivity magnetic-sector ICPMS; quadrupole ICPMS. The new equipment will be purchased and installed in 2010.

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. A further upgrade in 2004 involved the replacement of the Sun-based operating system with the PC-based SAMx software. In early 2003 a new CAMECA SX100, with a similar configuration of spectrometers, was installed and the SX50 was used mainly for the imaging and analysis of zircons, in connection with TerraneChron® applications and basic research. The CAMECA SX100 carries the workload of the routine major and minor element analyses for the majority of GEMOC’s research projects. It is fitted with large-area diffracting crystals for improved sensitivity and lower limits of detection.

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 has been 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 ELAN 5100 ICPMS was replaced by a Hewlett Packard 4500, and in 2000 an Agilent 7500S ICPMS was added. In 2004 two new Agilent 7500CS instruments were purchased (one primarily for solution work), and the 7500S replaced the HP4500 for zircon analysis at the end of the year. The 7500S and one 7500CS 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 266 nm or 213 nm light, a New Wave UP-266 nm system, and a New Wave UP-213 nm system. In November 2005 the New Wave UP-193 nm system (based on a Lambda Physik OPTex excimer laser) was moved from the Nu Plasma to...
provide an additional option for in situ analysis of transparent minerals on the 7500CS. Spatial resolution varies with the application, but typically is on the order of 30-40 µm. Each 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 through AccessMQ.

**Laser Ablation Multi-collector ICPMS microprobe (LAM-MC-ICPMS):** The Facility has two Nu Plasma MC-ICPMS. The first was installed in November 1998 and the other in November 2003. The second Nu Plasma instrument has high-resolution capabilities and a retardation filter to enable U-series work. The instruments combine a laser ablation micro-sampler, 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 instruments use either a New Wave 193 nm system based on an Lambda Physik OPTex excimer laser, a New Wave UP-266 nm Nd:YAG laser, or a New Wave UP-213 nm Nd:YAG laser depending on the application. 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 Triton thermal ionisation mass spectrometer (TIMS):** The Triton was purchased in 2004 following a successful ARC LIEF application led by Professor Simon Turner and Dr Bruce Schaefer (Monash University), and was installed in March 2005. Following an intensive period of testing the Triton quickly became the primary source of Sr, Nd and Os isotope analyses in the Facility, relieving the MC-ICPMS of this aspect of the analytical workload. The instrument represents the state-of-the-art in thermal ionisation mass spectrometry and its capabilities have contributed to the developments in Ra isotope analysis.

**Applications in use and under development include:**

**Laser Analysis (in situ point analysis)**

- U-Pb geochronology of zircons from igneous and metamorphic rocks
- U-Pb dating of groundmass perovskite and xenocrystal rutile in kimberlites
- Hf isotope analysis in zircon and rutile 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, including kimberlitic perovskite
- Sr isotope analysis of carbonates, feldspars, apatites, pyroxenes and kimberlitic perovskite
- Pb isotope analysis of sulfides, silicates and perovskite
- Stable isotope ratios of Fe, Mg, Zn, Cu and other cations in appropriate minerals from ore systems and mantle rocks
- Multi-element trace element analysis of silicates, sulfides, oxides and diamond

**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 – MC-ICPMS and TIMS
• 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 2009

1. Facility for Integrated Microanalysis

   a. Electron Microprobe: During 2008 the SX50 developed a range of problems and these continued to restrict its usage through 2009. A decision was made to decommission the SX50 and an order was placed for a Zeiss EVO MA15 SEM to carry the electron imaging workload. The installation of the Zeiss SEM is scheduled for January 2010. The SX100 serviced all projects including analysis of perovskite in kimberlites; analysis of platinum group minerals; minor and trace element analysis of metals.

   b. Laser-ablation ICPMS microprobe (LAM): During 2009, the LAM laboratory produced large volumes of data for fourteen 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. As in the recent years more than 7000 U-Pb analyses of zircons were carried out, related to projects (including TerraneChron® applications) from Congo, Russia, Norway, Burkina Faso, Mongolia, China, Papua New Guinea, Indonesia, New Zealand, France, Ghana and Australia (NSW, SA, WA). 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 (see Research Highlights).

   U-Pb dating of zircons was carried out on the Agilent 7500S, while one of the two Agilent 7500CS instruments was dedicated to laser-probe applications, and the other set up for solution analysis. The addition of a third ICP-MS has allowed uninterrupted periods of time for method development without disrupting the productivity of the laboratory.

   c. MC-ICPMS: 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, continued to produce severe competition for instrument time on the MC-ICPMS.

   In 2005 significant advances were made in the analysis of ‘non-traditional’ stable isotopes and included the development of separation techniques and analytical protocols for Ti, Fe and Ni isotopes. In 2009 an emphasis was placed on the on-going development for the separation and analysis of Li isotopes. Major applications during 2009 using in situ techniques continued to centre on the high-precision analysis of Hf in zircons to trace lithosphere evolution, magma-mixing histories in granitic rocks and Re-Os dating of single grains of Fe-Ni sulfides and alloys in mantle-derived rocks. In situ Hf isotopes were measured in zircons from Australia, Congo, Russia, Norway, Burkina Faso, Mongolia, China, Papua New Guinea, Indonesia, New Zealand, France and Ghana. We carried out Re-Os studies on xenoliths from the USA, South Africa, eastern China and Siberia. Sr and Nd isotopes were measured in situ in kimberlitic perovskites from South Africa.

   d. Laboratory development: The new clean-room facility, which is being used primarily for isotope separations, opened in April 2004. It provides an ultra-clean environment within a
3-stage pressurised volume; it contains 6 Class 3500 work areas, three for radioactive isotopes and three for other activities.

**e. Software:** GLITTER (GEMOC Laser ICPMS Total Trace Element Reduction) software is our on-line interactive program for quantitative trace element and isotopic analysis and features dynamically 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. An arrangement by which New Wave Research marketed the software together with their laser microprobe equipment was terminated late in 2007. Sales are now handled by AccessMQ (formerly Macquarie Research Limited) and GEMOC provides customer service and backup. During 2009 a further 22 full licences of GLITTER were sold bringing the total number in use to 171 worldwide, in forensics and materials science, as well as earth science applications. During 2005, Will Powell, Norm Pearson and Chris Ryan began updating GLITTER to version 4.4 and version 4.4.3 is currently available without charge to existing customers and accompanies all new orders. Will Powell continued in his role in GLITTER technical support and software development through 2009.

2. Laser development

For more than a decade GEMOC benefited from an industry partnership with New Wave Research (formerly Merchantek EO), a major US manufacturer of laser ablation systems. 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, delivered in March 2002 has been decommissioned. Three more New Wave laser systems, acquired during 2004 (a UP-266 nm and two UP-213 nm), represented a major upgrading of the instrument park and giving redundancy to limit downtime. The 213 nm lasers are now used for most of the zircon analytical work including both U-Pb and Hf isotope analyses, especially where small grains are being analysed. The 266 nm systems have proven most useful for analysis of sulfides, and for other stable-isotope applications.

3. Energy dispersive XRF


A LECO RC412 H2O-CO2 analyser, installed in September 2003 to replace an outdated unit, is providing high-quality analyses to complete whole-rock analyses by XRF and solution-ICPMS.

4. Solution analysis

An Agilent 7500CS 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 (e.g. 87Rb on 87Sr), 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 was developed for the dissolution of rocks and mineral separates, to enable the separation of Sr, Nd and Hf from the same sample digestion. Prior to the installation of the Triton TIMS the isotopic analyses were performed using the MC-ICPMS in solution mode. Subsequently the analysis of Sr and Nd has been moved on to the Triton but Hf continues to be run on the MC-ICPMS. An additional clean-up column has also been added to the Nd separation method to remove Ba and LREE from samples with LREE-enriched compositions. This step has been found to be necessary in order to run these samples on either the MC-ICPMS or TIMS.

During 2009 further developments were made in the separation of ‘non-traditional’ isotopes, with significant improvements in the separation of Fe from silicate rocks and oxide minerals and Li from silicate rocks. The permanent availability of one of the Agilent 7500CS for solution analysis greatly benefited the development of the separation techniques. Advances were also made in the U-series chemistry with the development of separation methods for Ra and $^{210}$Pb.

5. Diamond preparation and analysis

In 2008 Argyle diamonds donated to GEMOC a laser-cutting installation, which will allow us to cut thin plates of single diamond crystals, allowing detailed spatial analysis of trace elements, isotopic ratios and the abundance and aggregation state of nitrogen. Refurbishment of the laboratory to house the laser cutter was completed in late 2009 and installation of the equipment is now planned for early 2010. GEMOC also took delivery of a new-generation FTIR microscope, the ThermoFisher iN10. This will allow the spatial mapping of whole diamond plates at high resolution with very short acquisition times.

6. SelFrag – a new approach to sample preparation

GEMOC ordered a SelFrag installation, the first in Australia, and it was to be delivered early in 2009. This instrument uses high-powered electrical pulses to disaggregate rocks and other materials along the grain boundaries. It removes the need to crush rocks for mineral separation, and provides a high proportion of unbroken grains of trace minerals such as zircon. The installation will be used for zircon separation, the analysis of grain size and shape in complex rocks, and the liberation of trace minerals from a range of mantle-derived and crustal rocks.

The installation of the SelFrag was delayed until early 2010 while a new laboratory space was prepared to house the equipment and for mineral separation.

7. Computer cluster

GEMOC has received funding to purchase a 24 node computer cluster to enhance its high-performance computing capabilities, and allow the development and maintenance of massively parallel geodynamics and geophysics computer codes. The machine will possess 3GHz Xeon quad core processors, and will enable full global 3D simulations of mantle convection and lithospheric deformation. The machine will be integrated with existing high-performance computing infrastructure within the geophysics group, and will run a Linux operating system (Ubuntu) allowing easy upgrades and maintenance by the geophysics group.

The machine arrived late in 2009 and is expected to be up and running early in 2010.
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 collaborative research on industry problems involving national and international partners
- provision of high quality geochemical analyses with value-added interpretations in collaboration with industry and government organisations, extending our industry interface
- use of AccessMQ consultancies and collaborative industry projects, 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, has been successfully commercialised and is available from GEMOC through AccessMQ (http://www.gemoc.mq.edu.au/); the software is continually upgraded
- collaborative relationships with technology manufacturers (more detail in the section on Technology Development). GEMOC (Macquarie) is the Australian demonstration site for Agilent Technologies LAM-ICPMS applications

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 and support for GIS platforms
- logistic support for fieldwork for postgraduate projects
- collaborative research programs through ARC Linkage Projects and the Macquarie University External Collaborative Grants (MUECRG) and PhD program support
- assistance in the implementation of GIS technology in postgraduate programs
- participation of industry colleagues as guest lecturers in undergraduate units
- 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 2009

4 Industry Reports were completed for collaborative industry projects. 

_TerraneChron®_ studies (see Research Highlights) have enjoyed continued uptake by a significant 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 (www.gemoc.mq.edu.au/TerraneChron.html).

The ARC Linkage Project titled “Global Lithosphere Architecture Mapping” (GLAM) continued with full industry partner support following the takeover of WMC Resources by BHP Billiton. A successful bid for an ARC Linkage grant in 2008 ensured the continuation of the project despite key players leaving BHP Billiton. A sub-licencing agreement was executed with Minerals Targeting International to accommodate Dr Graham Begg’s new role (in relationship to Macquarie, BHPB and the GLAM project) as Director of this company. Planning and workshop sessions at Macquarie with participants from BHP Billiton and GEMOC were key activities in 2009. Dr Begg spent significant research time at GEMOC through 2009 as part of the close collaborative working pattern for this project.

Graham Begg was the Society of Economic Geologists International Exchange Lecturer for 2009. The role of the lecturer is to share insights involving research into ore deposit science and/or exploration methodology. A total of 34 talks in 8 countries were given to groups of geoscientists from academia, industry and government and highlighted GEMOC’s GLAM project. Talks focused on the relationships between planet- and lithosphere- scale processes, lithospheric architecture and composition, geodynamic history, and ore deposit genesis in space and time.

GEMOC’s development of a method to analyse trace elements in diamond has opened up potential further developments and applications relevant to industry, ranging from diamond fingerprinting for a range of purposes to improving the knowledge framework for diamond exploration. An ARC Linkage Project on Diamond Fingerprinting supported by Rio Tinto finished in mid-2009 with a final report. Dr Debora Araujo was employed as a Research Associate on the project and has carried out an extensive program of method development and diamond analysis.

In 2007-2008 GEMOC developed a technique for dating the intrusion of kimberlites and lamproites using LAM-ICPMS U-Pb analysis of groundmass perovskite (see _GEMOC Publication #505_). This rapid, low-cost application has proven very attractive to the diamond exploration industry, and has led to several small collaborative projects; it also is being applied in a new ARC Linkage project sponsored by De Beers.

During 2009, GEMOC increased its collaboration with CERCAMS, the Centre for Russian and Central EurAsian Mineral Studies at the Natural History Museum, London, that serves the international mineral deposits community as a centre for research into the geodynamics and metallogenesis of the Former Soviet Union and neighbouring territories. The final report entitled “Western Altaids Module 2: Hf-Isotope Data” was delivered to CERCAMS in March, 2009 and the results were presented for the industry collaborators at the Final Reporting Meeting CERCAMS Altaids Project Module-2 at the University of Toronto in February 2009.
During 2009 a new initiative was the application of U-series isotopes to the investigation of groundwater studies for both exploration and investigation of palaeoclimate. Collaboration with Heathgate Resources at the Beverley Uranium mine in South Australia has investigated these processes using a well constrained aquifer system in both a mining and exploration context.

Modelling capabilities have now been extended to industry related projects. An ongoing collaboration with Granite Power Ltd continues, which has led to important data exchange and ongoing consulting projects through AccessMQ. An Honours project funded by Chevron Australia Ltd. is underway, studying the thermal evolution of the Carnarvon Basin, and Chevron is covering the direct costs of the project (data acquisition and processing, flights to Western Australia and accommodation for student and supervisor). An ongoing collaboration with Hydrolex Ltd. has also led to important data exchange across the Sydney Basin region.

Studies on the controls of fractionation and concentration of platinum-group elements (PGE) in ultramafic magmas continued in 2009 as part of PhD project of Marek Locmelis, funded by AMIRA Project P710a. The research goal is to develop reliable geochemical indicators that can guide the exploration for magmatic nickel-sulfide deposits with a particular focus on the role of chromite and olivine in the concentration and fractionation of PGE in komatiites. Industry partners are BHP Billiton, Independence Group NL, Norilsk Nickel, MERIWA and ARC. The project is in collaboration with the Centre for Exploration Targeting / University of Western Australia, CSIRO Exploration and Mining and the Australian National University.

Industry interaction

A continuing collaborative research relationship with New South Wales Geological Survey is applying TerraneChron® to investigations of the provenance of targeted sequences in Paleozoic sedimentary terranes of eastern Australia, and the development of the Macquarie Arc.

Industry visitors spent varying periods at GEMOC in 2009 to discuss our research and technology development (see visitor list, Appendix 3). This face-to-face interaction has proved highly effective both for GEMOC researchers and industry colleagues.

DIATREEM continued to provide LAM-ICPMS analyses of garnets and chromites to the diamond-exploration industry on a collaborative basis.

GEMOC publications, preprints and non-proprietary reports are available on request for industry libraries.

GEMOC was prominent in delivering keynote and invited talks and workshop modules at national and international industry peak conferences in 2009, including 2 Plenary Addresses. Sue O’Reilly was a member of the organising committee for the SGA Conference in Townsville in 2009. See Appendix 4 for abstract titles and GEMOC Publications.

A new collaborative research project aimed at developing an integrated approach to understanding the formation of mineral sand deposits using Australian deposits as a world benchmark, and to improve exploration strategies employed in Australia and in Russia was initiated in collaboration with Professor Alexandr Kremenetsky from Institute of Mineralogy, Geochemistry and Crystal Chemistry of Rare Elements (IMGRE), PIRSA and Iluka Resources. The results were discussed during the meeting at the Iluka Resources office in Adelaide in August, 2009 and presented at the 13th IAGOD Symposium, Adelaide 2010.

A new collaborative research project was started with the Geological Survey of Western Australia, in which GEMOC is carrying out in-situ Hf-isotope analyses of previously SHRIMP-dated zircon grains from across the state. This is a part of the WA government’s Exploration Incentive Scheme.
CURRENT INDUSTRY-FUNDED COLLABORATIVE RESEARCH PROJECTS

These are brief descriptions of current GEMOC projects that have direct cash support from industry, with either formal ARC or Macquarie University Grant status and timeframes of at least one year. Projects are both national and global. In addition to these formal projects, many shorter projects are directly funded by industry alone, and the results of these feed into our basic research database (with varied confidentiality considerations). Such projects are administered by AccessMQ, Macquarie’s commercial entity.

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 use of mantle sulfides to date mantle events, and the characterisation of crustal terrane development using U-Pb dating and Hf isotopic compositions of zircons provide more information for integration with geophysical modelling. TerraneChron® (see Research Highlights) is an important tool for characterising the tectonic history and crustal evolution of terranes on the scale of 10 – 100 km and delivers a cost-effective exploration tool to the mineral (and potentially petroleum) exploration industry.

The breakthrough in developing a robust methodology to quantitatively analyse the trace elements in diamonds is another world-first for GEMOC. In addition to providing unique knowledge about the nature and compositions of deep mantle fluids that has led to a new hypothesis for how diamonds form in the Earth’s mantle (see Research Highlights 2007, p. 27, 30), it has potential practical applications to diamond fingerprinting for forensic applications and to better prediction of targets for diamond exploration.

Formal projects newly funded for 2009:

A novel approach for economic uranium deposit exploration and environmental studies

**Supported by ARC Linkage**

**Industry Collaborator: Heathgate Resources**

**Summary:** The project proposes the use of a novel approach to prospect for economic uranium ore deposits. The measurement of radioactive decay products of uranium in waters (streams and aquifers) and sediments will allow us to (i) identify and locate economic uranium ore deposits and (ii) quantify the rate of release of uranium and decay products during weathering and hence the evolution of the landscape over time. In addition, this project will improve our knowledge of the mobility of radioactive elements during rock-water interaction, which can be used to assess the safety of radioactive waste disposal. Outcomes of this project will be: (i) the discovery of new economic uranium deposits; (ii) development of a new exploration technology allowing for improved ore deposit targeting. Information gained on the behaviour of radioactive elements at the Earth’s surface will be critical for the study of safety issues related to radioactive waste storage and obtaining reliable time constraints on the evolution of the Australian landscape.
Global Lithosphere Architecture Mapping II

Supported by ARC Linkage
Industry Collaborator: BHP Billiton

Summary: Domains of different composition in the deep part of Earth’s rigid outer shell (the lithosphere) reflect processes of continent formation and breakup through Earth’s history. These boundaries focus the fluid flows from the deeper convecting mantle that may produce giant ore deposits. We will integrate mantle petrology, tectonic syntheses and geophysics to image the 3-D architecture of the continental lithosphere, and provide a basis for realistic dynamic modelling of the behaviour of these deep continental roots and their response to geodynamic forces through time. This will provide a new approach to identifying predictive relationships between different types of lithosphere domains and structures, and large-scale mineralisation. The continents have been broken up and re-assembled along major zones of weakness many times through Earth’s history. Boundaries between such continental domains focus large-scale movements of fluids that can produce giant ore deposits. This study will provide new perspectives on the localisation of world-class economic deposits, the Earth resources on which society depends.
Trace element analysis of diamond: new applications to diamond fingerprinting and genesis

**Supported by ARC Linkage**

**Industry Collaborator: Rio Tinto**

**Summary:** As diamond crystals grow deep in the Earth’s mantle, they trap minute inclusions of the fluids from which they crystallise. We will use recently developed laser-ablation microprobe techniques to analyse the trace-element patterns of diamond crystals from the Argyle, Diavik and Murowa mines (Australia, Canada and Zimbabwe). The results will define the nature and evolution of the parental fluids of the diamonds, and thus shed new light on the processes of diamond formation and the nature of fluids in the deep Earth. The data will be used to test the potential for fingerprinting diamonds by source; such fingerprinting can be used as a tool in controlling the flow of stolen and illegally mined diamonds. The project will provide new insights into the processes by which diamond crystallises in the Earth’s mantle. A better understanding of these processes can lead to improved models and techniques for diamond exploration, enhancing the prospect of finding new deposits in Australia and abroad. If successful, this technology will provide economic benefits by reducing theft and illegal mining, which represent significant losses to legitimate companies. Application of this Australian development could reduce the circulation of “conflict diamonds”, which would have real social benefits worldwide, especially in some developing countries.

Lithosphere evolution across a craton margin, southern Africa

**Supported by Industry and a matching Macquarie University Collaborative Grant**

**Industry Collaborator: De Beers**

**Summary:** The margins of cratonic blocks extend to 150-300 km depth, and exert a strong control on crustal tectonics. Kimberlite magmas intruded across the southern margin of the Kaapvaal Craton (S. Africa) provide detailed sampling of the lithospheric mantle. We will use these samples to map the composition and structure of the mantle in two time slices (120 Ma, 90 Ma), providing new information on how the craton margins channel fluids. Linkages between crustal tectonics and mantle events are being constrained by comparing TerraneChron® analyses of zircons from modern streams, and the kimberlites themselves, with existing Re-Os ages for mantle rocks.

Mechanisms of PGE fractionation and concentration in mafic and ultramafic melts

**Supported by AMIRA and MERIWA and an international postgraduate scholarship from Macquarie University**

**Industry Collaborators: BHP Billiton, Independence, LionOre**

In collaboration with Dr Marco Fiorentini from UWA with shared PhD student Marek Locmelis

**Summary:** A long-standing goal of research on nickel-sulfide (NiS) deposits has been the development of reliable lithogeochemical indicators that can act as guides for exploration. In order to better constrain how platinum-group element (PGE) signatures may be utilised as pathfinders for those NiS deposits, this project focusses on the processes that control the fractionation and concentration of PGE in mafic and ultramafic magma types. The study looks into a range of variables controlling the PGE geochemistry, including the role of sulfides (i.e. pentlandite, millerite), oxides (i.e. chromite), silicate phases (i.e. olivine, pyroxene) and platinum-group minerals (i.e. alloys, antimonides, arsenides, tellurides) in the concentration and fractionation of PGE in mineralised and barren sequences. Furthermore, the study investigates the spatial relationship between the PGE signature of mafic and ultramafic rocks and the occurrence of various types of NiS mineralisation, thus optimising the use of the PGEs as vectors towards mineralised environments. See 2007 Research highlights p. 34.
GEMOC’s international links

BACKGROUND

GEMOC’s international links provide leverage of intellectual and financial resources on a global scale, and an international network for postgraduate experience. International activity includes funded projects and substantial collaborative programs with exchange visiting programs in France, Norway, Germany, United Kingdom, New Zealand, Canada, USA, Taiwan, Italy, Spain, South Africa, South America, China, Brazil, Japan, Thailand and Russia.

FUNDED COLLABORATIVE PROJECTS COMMENCED OR ONGOING IN 2009 INCLUDE:

- Collaboration in the CERCAMS project (www.nhm.ac.uk/research-curation/projects/cercams/gallery.html) as part of the ARC Discovery project “Earth’s internal system: deep processes and crustal consequences” (see section on Funded Research Projects). The CERCAMS project is a major study of crustal evolution across the Altaiides, led by the Centre for Russian and Central EurAsian Mineral Studies at the Natural History Museum, London (Dr Richard Herrington, PI on the Discovery Project, and Dr Reimar Seltman) and involving Russian research groups, a number of industry sponsors and GEMOC.

- A new collaboration with the China Academy of Science, (Beijing) commenced involving both the Institutes of Geochemistry and Geophysics. Exchange visits for geochemical programs involved complementary analytical work on perovskite dating and in situ analyses of oxygen isotopes in zircon and apatite.

- A formal visit by executive from the China University of Geosciences resulted in a MOU with GEMOC, Macquarie University. A formal co-postgraduate project also commenced.

- Trace elements and fluids in diamonds and relevance to mantle fluids and processes with Professor Oded Navon (Hebrew University, Israel), Professor Thomas Stachel (Edmonton, Canada) and Dr Jeff Harris (University of Glasgow, UK).

- Shear-induced metal segregation in ordinary chondrites, a collaborative project with Professor N. Petford 2007-2009 (Bournemouth University, UK).

- The first million years of our solar system – stellar nucleosynthetic inputs, solid formation and planet building with Professor Joel Baker (Victoria University, New Zealand).

- Core formation and degassing of the Earth, a collaborative project with Dr S. Nielsen and Professor A. Halliday (University of Oxford) and Dr M. Rehkamper (Imperial College, London).

- Partitioning of chalcophile elements between metal, sulfide and silicate, a collaborative project with Dr D. Frost and Professor D. Rubie (Bayreuth University, Germany).

- Detailed 2-D and 3-D structure of the Kaapvaal Craton in several time slices, using mantle-derived xenocrysts, a collaborative project with De Beers.
Global Lithosphere Architecture Mapping, involving analysis of crustal evolution, the composition of the lithospheric mantle and the interpretation of seismic tomography, a collaborative project with BHP Billiton and Professor Steve Grand (University of Texas at Austin).

Dr Kelsie Dadd was one of a team of 50 international scientists who participated in a nine-week Integrated Ocean Drilling Program (IODP) expedition in the Bering Sea that recovered sediment cores showing evidence of past climate change. The drilling has shown the history of the climate and water circulation in the basin over the last five million years reflected in the type of sediment recovered, the degree to which it has been mixed by burrowing organisms, and the distribution of biogenic material.

Collaboration with Professor Massimo Coltorti and Dr Costanza Bonadiman from the University of Ferrara on the geochemistry of amphiboles, mantle metasomatism, and the age and origin of the lithospheric mantle beneath the Cape Verde Islands and Antarctica.

A TerraneChron® study to unravel the timing and tectonic history of regions in Tibet continued as a collaborative program with the National University of Taiwan (led by Professor Sun-Lin Chung), and has expanded to include collaboration with Nanjing University and the Tibet Institute, Beijing.

The nature of the lithosphere in Mongolia, and lithosphere extension in the Taiwan region, with Dr Kuo-Lung Wang (Institute of Earth Sciences, Academia Sinica, Taiwan).

Collaboration with colleagues at the University of Jean Monnet, St Etienne, including Professor Jean-Yves Cottin, Dr Bertrand Moine and Dr Marie-Christine Gerbe (with reciprocal funding from both sides) expanded. 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 the Hoggar region of Algeria. In addition, studies on magma mixing in granites commenced with a new co-tutelle agreement (Anne Fonfrege).

Collaboration with colleagues at the University of Montpellier continued with two co-tutelle PhD projects (Véronique Le Roux and Yoann Gréau) and projects on the mantle budget of platinum group elements, microstructures of meteorites and mantle rocks, and ophiolites.

Trace elements in mineral inclusions in lower mantle diamonds from Juina, Brazil with Dr Felix Kaminsky (KM Diamond Exploration, Vancouver, Canada).

Dr Farida Ait-Hamou from the Université des Sciences et de la Technologie Houari Boumediene (USTHB), Algeria, undertook fieldwork in Algeria to collect mantle xenoliths from the Hoggar region as part of the Hoggar strand of the Discovery Project “Earth’s Internal System: deep processes and crustal consequences”. Analyses of these xenoliths will be integrated with geophysical datasets to understand the origins of the Hoggar Swell, a major topographic feature of North Africa.

Igneous rocks, mineral deposits, lithosphere structure and tectonic setting: southeastern China and eastern Australia. This collaboration with Nanjing University has expanded from an AusAID grant under the ACILP scheme with Professor Xisheng Xu (Nanjing University).
- Collaboration with Professor Yuri Kostitsyn from the Vernadsky Institute of Geochemistry and Analytical Chemistry (GEOKHI), Russian Academy of Science includes studies on continental crust formation in the modern subduction zone: Kamchatka Peninsula. Professor Kostitsyn is also involved in the GEMOC project testing models for continental crustal growth using the TerraneChron® database.

- Studies with Professor Jianping Zheng (China University of Geosciences, Wuhan) on the evolution of the lithosphere beneath several parts of China, crustal evolution in the North China Block, the Yangtze Block and southeastern China, and the UHP metamorphism of Dabie-Sulu peridotites. Dr Yuping Su from this Institute visited for 6 months’ research work on related studies.

- Studies on Cathaysia’s place in Rodinia, crustal evolution of southeast China, and crustal evolution of the Yangtze Block with Professor Jinhai Yu and Ms Lijuan Wang (collaborative project with Nanjing University and cotutelle program).

- Studies continued with Dr Rendeng Shi (University of Science and Technology, Hefei, China) on the age and origin of platinum group alloy phases in podiform chromitites in ophiolites from Tibet, including a research visit by Dr Shi and his postgraduate student, Mr Qiashuai Huang.

- TerraneChron® analysis of Proterozoic terrains in Africa, North America and Europe, with BHP Billiton and several other mineral-exploration companies.

- A new study on the granite magmatism, basement ages and provenance indicators in the Malay Peninsular using U-Pb and Hf isotopes from detrital zircons commenced with a research visit by Inga Sevastjanova (a postgraduate student from Imperial College)

- Age and magma sources of Chilean Cu-porphyries, with Codelco (Chile) and the CSIRO Division of Exploration and Mining (Perth).

- Several collaborative projects continued with Dr Kreshimir N. Malitch (Department of Geochemistry, All-Russia Geological Research Institute (VSEGEI), St Petersburg) including: (1) the nature and origin of zircons from the intra-continental palaeorift-related ultramafic intrusions of the Noril’sk area (northern Siberia, Russia). The latter include world-class PGE (platinum-group element)-Cu-Ni sulphide deposits related to Noril’sk-1, Taldykon and Kharaelakh ultramafic-mafic intrusions, subeconomic PGE-Cu-Ni deposits related to Chernogorsk, Zub-Marksheider and Vologochan intrusions, prospective Mikhangia intrusion and non-economic Nizhny Taldykon, Zelyonyaya Griva and Kruglogorsk intrusions; (2) analysis of Os-(Ir-Ru) alloy grains derived from two world-class Au-PGE placer deposits associated with the Guli clinopyroxenite-dunite massif (northern Siberia, Russia) and the Evander Goldfield within the Witwatersrand Basin (South Africa). The main aim of this study is to place further constraints on osmium-isotope signatures of the mantle sources for Os-rich alloy grains at Guli and Evander, which (along with Witwatersrand grains) represent the oldest terrestrial platinum-group minerals known so far.

- Formal visits to three Chinese institutions strengthened or initiated collaborative research projects and agreements: Nanjing University; China Academy of Sciences, Geophysical and Geochemical Institutes; China University of Geosciences (Beijing)
GEMOC’S BUSINESS PLAN HAS PROVED TO BE A SUCCESSFUL blueprint, resulting in viable funding to continue and evolve GEMOC’s activities beyond the Commonwealth Centre funding period that ended in 2001.

Key elements of funding continuation include:

- Recognition as Centre of Concentration of Research Excellence at Macquarie by the new Vice-Chancellor in 2006 and award of seven new, funded academic positions
- Macquarie University provides Postgraduate Scholarships for Australian and international students
- ARC Discovery and Linkage successes
- Award of two Federation Fellowships (Professors Simon Turner and Bernard Wood)
- Industry funding has increased through substantial collaborative ventures supporting basic research
- Commercialisation of GLITTER software through AccessMQ
- Independent Research Fellowships to support Postdoctoral Fellows (Australian and International sources)
- LIEF successes for infrastructure with co-investment by industry and other universities
- DEST Systemic Infrastructure Initiative Grant 2002-2004
- Success in Macquarie University competitive funding schemes for research, postgraduate studies, and teaching development for undergraduate studies
- 3 academic staff positions created for GEMOC in 1995, 1996 and 2003 are continuing (Dadd, Daczko and one under recruitment)

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 was designated as one of the National Geochemistry Nodes in the AuScope (www.auscope.org.au) award in the NCRIS round in 2007 and will receive a funding contribution to staff and small equipment items for five years from 2007
- Macquarie University’s guarantee of a strategic plan to ensure the integrity, maintenance and appropriate staffing of the Geochemical Analysis Unit
GEMOC Funding

- 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 and with partner co-investment
- Industry capital investment in return for access equity, negotiated intellectual property and collaborative rates

GEMOC INCOME 2009

This is a summary of 2009 income. A full, audited statement of detailed expenditure and income is prepared by Macquarie University. *No in-kind support is included here.*

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Scientific innovation relevant to National Priority Areas

*Research Priority 1: An Environmentally Sustainable Australia*
- Goal 1: Water – a Critical Resource
- Goal 2: Water – Transforming existing industries and
- Goal 6: Developing Deep Earth Resources and

*Research Priority 3: Frontier Technologies for Building and Transforming Australian Industries*
- Goal 1: Breakthrough Sciences and
- Goal 2: Frontier Technologies

- Enhanced international links

- Excellence in training of our future generation of geoscientists

- Enhanced industry links nationally and internationally

- Improved exploration tools and strategies for Australian mineral exploration companies both on- and off-shore

- Technological innovation (scientific advances, intellectual property, commercialisation, value-added consulting services)
Appendix 1: Participants

GEMOC PARTICIPANTS 2009/2010
MACQUARIE UNIVERSITY
Department of Earth and Planetary Sciences

Academic and GEMOC Managerial Staff
(Teaching and Research)
Dr Juan Carlos Afonso (Geodynamic modelling, CoRE)
Dr Nathan Daczko (Structural and metamorphic geology, tectonics, geodynamics)
Dr Kelsie Dadd (Physical volcanology, geochemistry, tectonics)
Dr Richard Flood (Volcanic geology, application of magnetic fabrics to reconstruction of volcanic terrains)
Professor W.L. Griffin, Program Leader (Technology development and industry liaison, CoRE)
Dr Mark Lackie (Rock magnetism, paleomagnetic reconstructions)
Dr Craig O’Neill (Geodynamic modelling, CoRE)
Professor Suzanne Y. O'Reilly, Director (Crust and mantle evolution, lithosphere modelling)
Dr Norman Pearson (Director, GAU)
Dr Tracy Rushmer (Experimental rock deformation and experimental petrology, CoRE)
Dr Bruce Schaefer (Geodynamics, isotope geochemistry, CoRE)
Professor Simon Turner (Isotopic geochemistry, CoRE)

Research Staff
Dr Debora Araujo
Dr Jaques Batumike
Dr Elena Belousova
Dr Mei-Fei Chu
Dr John Caulfield
Dr Beverley Coldwell
Dr Alex Corgne
Dr Anthony Dosseto
Dr José María González Jiménez
Dr Kevin Grant
Emeritus Professor Trevor Green
Dr Jacqueline Halpin
Dr Heather Handley
Dr Daniel Howell
Dr Claudio Marchesi
Dr Laure Martin
Dr Lev Natapov
Dr Svetlana Tessalina
Dr Michael Turner
Emeritus Professor John Veevers
Emeritus Professor Ron Vernon

Adjunct Professors
Dr Anita Andrew
Professor Bruce Chappell
Professor Mike Etheridge
Dr Richard Glen
Dr Jingfeng Guo
Dr Jon Hronsky (BHP Billiton)
Professor Else-Ragnhild Neumann
Professor Xisheng Xu

Visiting Fellows
Dr Christoph Beier
Associate Professor Ian Metcalfe
Professor Jianping Zheng

Honorary Associates
Dr John Adam
Dr Farida Ait-Hamou
Dr Olivier Alard
Professor Tom Andersen
Dr Sonja Aulbach
Dr E.V.S.S.K. Babu
Dr Graham Begg
Dr Eloise Beyer
Dr Phillip L. Blevin
Professor Hannes Brueckner
Dr Robert Bultitude
Dr Gilles Chazot
Professor Massimo Coltorti
Professor Kent Condie
Dr Michel Grégoire
Dr Bin Guo
Dr Bram Janse
Dr Felix Kaminsky
Dr Hans-Rudolf Kuhn
Dr Kreshimir Malich
Dr Valeria Murgulov
Dr Alison Ord
Dr Geoff Nichols
Prof Nick Petford
Dr Yvette Poudjom Djomani
Dr Peter Robinson

Appendix 1:
Participants
Dr Chris Ryan  
Dr Giovanna Sapienza  
Dr Stirling Shaw  
Dr Simon Shee  
Dr Kuo-Lung Wang  
Professor Xiang Wang  
Professor Jin-Hai Yu  
Dr Ming Zhang

FORMAL COLLABORATORS

University of Wollongong  
Associate Professor Paul Carr (LIEF partner)  
Professor Allan Chivas (DEST Systemic Infrastructure partner)

University of Newcastle  
Victoria University of Wellington, New Zealand  
Professor Joel Baker (LIEF partner)

University of Sydney  
Professor G. Clarke (DEST Systemic Infrastructure partner; 2010 LIEF)

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

University of Western Australia  
Dr Marco Fiorentini

Australian National University  
(Research School of Earth Sciences)  
Professor Geoff Davies  
Dr Masahiko Honda (LIEF partner)  
Professor Brian Kennett  
Professor Gordon Lister  
Professor Hugh O’Neill

PIRSA (South Australian Geological Survey)  
Dr Anthony Reid  
Mr Martin Fairclough

OTHER COLLABORATORS ON PROJECT BASIS

Dr Farida Ait-Hamou (Université des Sciences et de la Technologie Houari Boumediene (USTHB), Algiers)  
Professor Joel Baker (Victoria University, NZ)  
Dr Christoph Beier (Erlangen, Germany)  
Kim Berlo (McGill University, Canada)  
Dr Bernard Bingen (Geological Survey of Norway, Trondheim)  
Professor J.-L. Bodinier (Université Montpellier, France)  
Dr Costanza Bonadiman (University of Ferrara)  
Professor Sun-Lin Chung (National Taiwan University)  
Dr Yuriy Erinchek (VSEGEI)  
Dr Marie-Christine Gerbe (Université Jean Monnet, St Etienne)  
Dr Julie Dickinson (Sydney University)  
Professor Steve Grand (University of Texas at Austin)  
Dr Jeff Harris (University of Glasgow, Glasgow)  
Dr Richard Herrington (Natural History Museum, London)  
Professor Yuri Kostitsyn (Vernadsky Institute of Geochemistry and Analytical Chemistry and Geochemistry Department at Moscow State University, Moscow)  
Dr J.-P. Lorand (Museum National d’Histoire Naturelle)  
Professor Oded Navon (The Hebrew University, Jerusalem)  
Dr Sune Nielsen (University of Oxford)  
Professor Nick Petford (Bournemouth University, UK)  
Professor Richard Price (Waikato University, NZ)  
Professor Elisabetta Rampone (Genoa University, Genoa, Italy)  
Professor Mark Reagan (University of Iowa, USA)  
Klaus Regenauer-Lieb (CSIRO Exploration and Mining and the University of Western Australia)  
Dr Patrice Rey (University of Sydney)  
Professor Marco Scambelluri (Genoa University, Genoa, Italy)  
Dr Rendeng Shi (University of Science and Technology, Hefei, China)  
Dr Reimar Seltmann (Natural History Museum, London)  
Professor Ian Smith (University of Auckland)  
Professor Thomas Stachel (University of Alberta, Edmonton)  
Dr Csaba Szabo (Eotvos University, Budapest)  
Dr Qin Wang (Nanjing University)  

Technology Partners

Agilent Technologies  
Nu Instruments
Appendix 2: Publications 2009/2010

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


Appendix 2: Publications


Appendix 3: Visitors/GAU users

GEMOC VISITORS 2009
(Excluding Participants in Conferences and Workshops)

Macquarie

Prof Tom Andersen (University of Oslo, Norway)
Dr Graham Begg (Minerals Targeting International Pty Ltd)
Dr Christoph Beier (GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Erlangen, Germany)
Dr Kim Berlo (McGill University, Canada)
Prof Mike Brown (University of Maryland)
Dr Hannes Brueckner (Queens College, USA)
Mr Buddy Doyle (CEO, Amarillo Gold Corp, Canada)
Prof Yangsong Du (Assoc Dean of the Graduate School, China University of Geosciences)
Prof Manel Fernandez (National Research Council of Spain)
Daniel Frick (ETH Zurich)
Mr Fred Fryer (Agilent Technologies)
Prof John Gamble (University of College Cork, Ireland)
Dr Damon Green (New Wave Research, Huntington, Cambridgeshire, UK)
Prof Huaming Guo (School of Water Resources and Environment, China University of Geosciences)
Dr Heather Handley (University of Munich)
Dr Richard Herrington (British Museum)
Prof Greg Houseman (University of Leeds, UK)
Mr Qishuai Huang (The Chinese Academy of Sciences)
Prof Trevor Ireland (RSES, ANU)
David Kelsey (University of Adelaide)
Prof Yuri A Kostitsyn (Vernasky Institute of Geochemistry and Analytical Chemistry)
Prof Yalin Lei (Vice President for International and Financial Affairs, China University of Geosciences)
Prof Liao, Libing (Dean of School of Material Sciences, China University of Geosciences)
Dr Guilherme Mallmann (ANU)
Prof Stephen Miller (Professor of Geodynamics/Geophysics, University of Bonn, Germany)
Dr Gabriele Morra (Geology Department, University Roma, Tre, Rome, Italy)
Prof Hugh O’Neill (RSES, ANU)
Dr Justin Payne (University of Adelaide)
Prof Nick Petford (University of Bournemouth, UK)
Prof Richard Price (University of Waikato, NZ)
Prof Mark Reagan (University of Iowa, USA)
Ms Inga Sevastjanova (Royal Holloway University of London)
Siri Lene Simonsen (University of Oslo)
Dr Simon Shee (Shee and Associates Pty Ltd)
Assoc Prof Rendeng Shi (The Chinese Academy of Sciences)
Prof Ian Smith (University of Auckland)
Dr Christopher Tye (Agilent Technologies, Singapore)
Dr Yuping Su (China University of Geosciences)
Prof Hongbing Wang (Chairman of the Uni Council, China University of Geosciences)
Dr Yingjie Yang (Center for Imaging the Earth’s Interior, Department of Physics, University of Colorado at Boulder, USA)
Dr Kuo-Lung Wang (Institute of Earth Sciences, Taiwan)
Prof Chuanheng Zhang (Dir, International Cooperation, China University of Geosciences)
Prof Zhaocheng Zhang (School of Earth Sciences, China University of Geosciences)
Dr Sergio Zlotnik (Monash University)
EXTERNAL USERS OF THE GEOCHEMICAL ANALYSIS UNIT FACILITIES IN 2009

(Note: this does not include contract work through AccessMQ)

Dr Chris Adams (Institute of Geological and Nuclear Science)
Prof Tom Andersen (University of Oslo, Norway)
Prof Joel Baker (Victoria University of Wellington)
Dr Christoph Beier (GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Erlangen, Germany)
Ms Rachel Brick (Adelaide University)
Prof Hannes Brueckner (Queens College, City University of New York, USA)
Mr Daniel Cronin (University of Sydney)
Marco Fiorentini (University of Western Australia)
Brian Gulson (Graduate School of the Environment, Macquarie University)
Ms Zarah Heyworth (School of Earth Sciences, University of Queensland)
Ms Katie Howard (Adelaide University)
Mr Qishua Huang (The Chinese Academy of Sciences)
Ms Carissa Isaacs (University of Western Australia)
Mr David Mole (University of Western Australia)
Ms Inga Sevastjanova (Royal Holloway University of London)

Mr Martin Schiller (Victoria University of Wellington)
Ass Prof Rendeng Shi (The Chinese Academy of Sciences)
Dr Siri Simonsen (University of Oslo, Norway)
Dr Yuping Su (China University of Geosciences)
Dr Nicholas Thebaud (University of Western Australia)
Appendix 4: Abstract titles

TITLES OF ABSTRACTS FOR CONFERENCE PRESENTATIONS IN 2009

Full abstracts available at http://www.gemoc.mq.edu.au/


Refertilization of oceanic mantle by old depleted melts beneath a slow spreading ridge: An Os isotope study of the peridotites drilled at ODP Site 1274 (15°20 FZ, Mid-Atlantic Ridge)

O. Alard, Y. Géreau, M. Godard, J.-P. Lorand and S.Y. O’Reilly
1. CNRS - Université Montpellier, 2. Géosciences Montpellier, Montpellier, France, 2. GEMOC, Macquarie, 3. Laboratoire de Minéralogie, CNRS & Muséum National d’Histoire Naturelle, Paris, France

A wide angle upper mantle reflector in SW Iberia: some constraints on its nature

P. Ayarza, I. Palomeras, R. Carbonell, J.C. Afonso and F. Simancas
1. Geology Department, Pza. de la Merced, Salamanca University, 2. Institute of Earth Sciences J. Almera, Barcelona, 3. GEMOC, Macquarie, 4. Geodynamics Department, Campus de Fuentenueva. Granada University

The nature of the Moho beneath the Iberian peninsula

1. Institute of Earth Sciences J. Almera, Barcelona, 2. Geology Department, Pza. de la Merced, s/n. Salamanca University, 3. GEMOC, Macquarie, 4. Geodynamics Department, Campus de Fuentenueva. Granada University

Disrupted subcontinental mantle in an ocean basin: Sal Island, Cape Verde Arcipelago

M. Coltorti, C. Bonadiman, S. O’Reilly, W. Griffin and N. Pearson
1. Department of Earth Science, Ferrara, Italy, 2. GEMOC, Macquarie

A LA-HR-ICPMS study of abyssal peridotites from ODP Sites 920 and 1274 (23°N and 15°20N, Mid-Atlantic Ridge): New insights on the (re-)distribution of highly incompatible elements in the mantle during magmatic processes and serpentinisation

M. Godard, M. Andreani, O. Alard and Y. Géreau
1. CNRS - Université Montpellier, 2. Géosciences Montpellier, Montpellier, France, 2. GEMOC, Macquarie

Different scales of Os isotopic heterogeneity in ophiolite chromitites from Sagua de Táñamo and Mayari mining districts (Eastern Cuba)

1. University of Granada, Mineralogy and Petrology, Granada, Spain, 2. Instituto Andaluz de Ciencias de la Tierra, Universidad de Granada-CSIC (Spain), 3. GEMOC, Macquarie, 4. Departamento de Cristalografía, Mineralogía e Dipósits Minerals, Facultat de Geològic, Universitat de Barcelona, Spain

Core segregation mechanism and compositional evolution of terrestrial planets

N. Petford and T. Rushmer
1. Bournemouth University, Poole, United Kingdom, 2. GEMOC, Macquarie

The composition of Yakutian diamond-forming liquids

D.A. Zedgenizov, V.S. Shatsky, D. Araujo, W.L. Griffin and A.L. Ragozin
1. Institute of Geology and Mineralogy, Novosibirsk, Russian Federation, 2. GEMOC, Macquarie

A new model for the evolution of diamond-forming fluids

Y. Weiss, R. Kessel, W.L. Griffin, I. Kiflawi, O. Klein, D.R. Bell, J.W. Harris and O. Navon
1. The Hebrew University, Institute of Earth Sciences, Jerusalem, Israel, 2. GEMOC, Macquarie, 3. School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, 4. Geographical and Earth Sciences, University of Glasgow, Scotland

Trace elements of fibrous diamonds

Y. Weiss, W.L. Griffin and O. Navon
1. The Hebrew University, Institute of Earth Sciences, Jerusalem, Israel, 2. GEMOC, Macquarie


Basement to the Ordovician Macquarie Arc, Lachlan Orogen, NSW: constraints from zircon data

A. Saeed, R.A. Glen, C.D. Quinn, E. Belousova and W. Griffin
1. GEMOC, Macquarie, 2. Geological Survey of New South Wales Department of Primary Industries, Australia

GSA PENROSE CONFERENCE, PICO, AZORES “PLUMES AND THEIR ROLE IN WHOLE MANTLE CONVECTION”, THE AZORES, 11-15 MAY 2009

Recycling of ancient subducted material through the mantle: Os and stable isotope evidence from the Azores

B.F. Schaefer, S. Turner, S. Tonarini, I. Bindeman and W. Leeman
1. GEMOC, Macquarie, 2. Istituto di Geoscienze e Georisorse, Pisa, Italy, 3. Department of Geology and Geophysics, University of Wisconsin, Madison, USA, 4. National Science Foundation, Arlington, Virginia, USA

Recycling of ancient subducted material through the mantle: Os and stable isotope evidence from the Azores

B.F. Schaefer, S. Turner, S. Tonarini, I. Bindeman and W. Leeman
1. GEMOC, Macquarie, 2. Istituto di Geoscienze e Georisorse, Pisa, Italy, 3. Department of Geology and Geophysics, University of Wisconsin, Madison, USA, 4. National Science Foundation, Arlington, Virginia, USA
AMERICAN GEOPHYSICAL UNION MEETING, 2009 JOINT ASSEMBLY: THE MEETING OF THE AMERICAS, TORONTO, CANADA, 24-27 MAY 2009

Fabric development in a late-Hercynian magmatic strike-slip shear zone in southern Corsica: indications of melt-supported large-scale deformation localization
J.H. Kruhl1 and R.H.Vernon2
1. Tectonics and Material Fabrics Section, Technische Universität Muenchen, Muenchen, Germany, 2. GEMOC, Macquarie

Nd isotopic constraints on the provenance of cover sequences in the southern Australian Palaeoproterozoic:
K.E. Howard1, M. Hand1, K.M. Barovich1, M.A. Szpunar1 and J.L. Payne2
1. Continental Evolution Research Group, School of Earth and Environmental Sciences, University of Adelaide, Adelaide, SA 5005, Australia, 2. GEMOC, Macquarie

GOLDSCHMIDT™2009 - "CHALLENGES TO OUR VOLATILE PLANET", DAVOS, SWITZERLAND, 21-26 JUNE 2009

Back-arc melting: Fluid or source induced?
C. Beier1,2, S.P. Turner2, W. Bach1, D. Niedermeier1, J. Sinton1 and J. Gill1
1. GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Germany, 2. GEMOC, Macquarie, 3. Petrologie der Ozeankruste, Department of Geosciences, University of Bremen, Bremen, Germany, 4. Department of Geology and Geophysics, University of Hawaii, Honolulu, USA, 5. Earth and Planetary Sciences, University of California, Santa Cruz, USA

Continental versus crustal growth: Resolving the paradox
G. Begg1,2, E. Belousova1, W.L. Griffin1, S.Y. O’Reilly1 and L. Natapov1

Testing models for continental crustal growth: A TerraneChron® approach
E.A. Belousova1, Y.A. Kostitsyn2, W.L. Griffin1 and S.Y. O’Reilly1
1. GEMOC, Macquarie, 2. Vernadsky Institute of Geochemistry and Analytical Chemistry RAS, Moscow, Russia

Isotopic data (Sr-Nd-Hf-O) of intrusive rocks from the Kerguelen Islands (Indian Ocean)
J. Chevet1,2, M-C. Gerbe1, M. Grégoire3, S.Y. O’Reilly1, J-Y. Cottin2 and W.L. Griffin1
1. GEMOC, Macquarie, 2. UJM LTL UMR 6524 Magmas et Volcans, Université Jean Monnet, Saint-Étienne, France, 3. DTP, CNRS-UMR 5562, Observatoire Midi Pyrénées, Université Toulouse III, Toulouse, France

Deep lithosphere processes recorded for the West Antarctic Rift System
M. Coltorti1, C. Bonadiman1, B. Faccini1, M. Melchiore1, S. O’Reilly1, W. Griffin2 and N. Pearson2
1. Department of Earth Sciences, Ferrara University, Ferrara, Italy, 2. GEMOC, Macquarie

A new perspective on the 2.7 Ga event on Earth
K.C. Condle1 and C. O’Neill2
1. Department of Earth and Environmental Science, New Mexico Tech, Socorro, USA, 2. GEMOC, Macquarie

Long residence time of sediments in small catchments
A. Dosseto1,2, S.P. Turner1, F. Chabaux3 and H. Buss4

Refertilization of oceanic mantle by old depleted melts: An in situ trace element and Os isotope study of ODP Site 1274 peridotites
M. Godard1, O. Alard1, Y. Greau1, J.-P. Lorand1, W.L. Griffin1 and S.Y. O’Reilly2
1. Geosciences Montpellier, CNRS and UM2, Montpellier, France, 2. GEMOC, Macquarie, 3. Laboratoire de Minéralogie, CNRSMNHN, Paris, France

Paleo-Archean generation of the continental lithosphere
W.L. Griffin1, G. Begg2, S.Y. O’Reilly1 and J.C. Afonso1
1. GEMOC, Macquarie, 2. Minerals Targeting International PL, West Perth, WA, Australia

U-Pb dating and HF isotope analysis of zircon from young magmatic rocks of the Mid-Atlantic ridge
Y. Kostitsyn1, E. Belousova1, N. Bortnikov1, S. Silantiev1 and E. Sharkov2
1. GEOKHI RAS, Moscow, Russia, 2. GEMOC, Macquarie, 3. IGEM RAS, Moscow, Russia

In situ laser ablation ICP-MS analysis of Ruthenium in chromite
M. Locmelis1, N.J. Pearson1, M.L. Fiorentini1 and S.J. Barnes1
1. GEMOC, Macquarie, 2. Centre for Exploration Targeting, School of Earth and Geographical Sciences, University of Western Australia, 3. CSIRO Exploration and Mining, Western Australia

U/Pb dating of zircons from the lower crustal xenoliths from Siberian kimberlites
V.G. Malkovets1, E.A. Belousova2, W.L. Griffin1, L.V. Buzukova1, V.S. Shatsky1, S.Y. O’Reilly2 and N.P. Pokhilenko1
1. Institute of Geology and Mineralogy SB RAS, Novosibirsk, Russia, 2. GEMOC, Macquarie

Persistence of mantle lithospheric Re-Os signature during lithosphere-asthenosphere interaction: Insights from in situ isotopic analysis of sulfides from the Ronda peridotite (S. Spain)
C. Marchesi1, W.L. Griffin2, C.J. Garrido3, J.-L. Bodinier1, S.Y. O’Reilly1 and N.J. Pearson2
1. Géosciences Montpellier, Montpellier, France, 2. GEMOC, Macquarie, 3. Instituto Andaluz de Ciencias de la Tierra, Granada, Spain
Evolution and stabilization of a juvenile crust: Zircon U-Pb and Hf isotopic perspectives from the northern Arabian-Nubian Shield
N. Moragi, D. Avigad, A. Gerdes, E. Belousova and Y. Harlavan
1. Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel, 2. Institut für Geowissenschaften, Johann Wolfgang Goethe Universität, Germany, 3. GEMOC, Macquarie, 4. The Geological Survey of Israel, Jerusalem, Israel

Geochemical signatures of arc and back-arc magmatism in the Eastern Manus Basin
D. Niedermeier, W. Bach and C. Beier
1. Petrologie der Ozeankruste, Department of Geosciences, Universität Bremen, Bremen, Germany, 2. GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Erlangen, Germany, 3. GEMOC, Macquarie

Ultradeep continental roots and their stranded oceanic remnants: A solution to the geochemical ‘crustal reservoir’ problem?
S.Y. O’Reilly, M. Zhang and W.L. Griffin
Keynote
GEMOC, Macquarie

Shallow slab melting at the start of Western Pacific subduction: Geochemical and experimental evidence
J. Pearce, D. Peate and T. Rushmer
1. School of Earth and Ocean Sciences, Cardiff University, Cardiff, Wales, UK, 2. Department of Geoscience, University of Iowa, USA, 3. GEMOC, Macquarie

The accuracy and precision of in situ Re-Os isotopic measurements by laser ablation MC-ICPMS
1. GEMOC, Macquarie, 2. CNRS, Geosciences Montpellier, Université Montpellier 2, Montpellier, France

Mesozoic dekratonization of the North China Block: Evidence from Hf-Os isotopes
J.-H. Yang, F.-Y. Wu and W.L. Griffin
1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, 2. GEMOC, Macquarie, 3. The Institute for Geoscience Research, Curtin University of Technology, Perth, Western Australia

Formation of Precambrian crust in the Cathaysia Block, South China
1. State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing, China, 2. GEMOC, Macquarie

60th UK DIAMOND CONFERENCE, WARWICK, JULY 2009
Diamond-forming fluids and their origins: Direct evidence from quantitative LAM-ICPMS microanalysis
W.L. Griffin, D.P. Araujo, N.J. Pearson and S.Y. O’Reilly
Invited
GEMOC, Macquarie

Timescale of Martian mantle overturn recorded in Nakhlite martian meteorites
V. Debaillie, A.D. Brandon, C. O’Neill, B. Jacobsen and Q.-Z. Yin
1. Université Libre de Bruxelles, Brussels, Belgium, 2. NASA-Johnson Space Center, Houston, TX, 3. GEMOC, Macquarie, 4. University of California, Davis, CA

Unraveling a protracted history in the hot seat: Charnockitic magmatism in the Proterozoic Rayner Orogen, east Antarctica
J.A. Halpin1,2, L.A. Milan1, N.R. Daczko1 and G.L. Clarke3
1. GEMOC, Macquarie, 2. ARC Centre of Excellence in Ore Deposits, University of Tasmania, TAS, Australia, 3. School of Geosciences, The University of Sydney, NSW, Australia

Metastable persistence of pelitic assemblages during high-P granulite facies metamorphism of intermediate-mafic orthogneiss, Fiordland, New Zealand
N.R. Daczko1, L.A. Milan1, J.A. Halpin1,2, A. Allibone3 and G.L. Clarke4
1. GEMOC, Macquarie, 2. ARC Centre of Excellence in Ore Deposits, University of Tasmania, TAS, Australia, 3. Rodinian Pty Ltd, Queanbeyan, NSW, Australia, 4. School of Geosciences, The University of Sydney, NSW, Australia

AOGS (ASIA AND OCEANIA GEOLOGICAL SOCIETY) 2009 | 6TH ANNUAL GENERAL MEETING, SINGAPORE, 11-15 AUGUST 2009

Existence of microcontinent in the Central Asia Orogenic Belt: Evidence from the lithospheric mantle beneath the North Hangai Region, Central Mongolia
K.-L. Wang1,2, S.Y. O’Reilly2, W.L. Griffin2 and N.J. Pearson2
1. Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, 2. GEMOC, Macquarie


TerraneChron*: application to crustal evolution studies and terrane-scale metallogenic potential assessments
E. Belousova, W.L. Griffin and S.Y. O’Reilly
Invited
GEMOC, Macquarie

Plumes, cratons and nickel sulphide deposits
G. Begg1,2, J. Hronsky3, S.Y. O’Reilly2, W.L. Griffin2 and N. Hayward4
Plenary Keynote
1. Minerals Targeting International PL, West Perth, WA, Australia, 2. GEMOC, Macquarie, 3. Western Mining Services (Australia), West Perth, WA, Australia, 4. BHP Billiton Ltd, Perth, WA, Australia

Diamonds: How they form where they are
W.L. Griffin1, S.Y. O’Reilly1, D. Araujo1, J.C. Afonso1 and G. Begg2
Invited
1. GEMOC, Macquarie, 2. Minerals Targeting International PL, West Perth, WA, Australia

Platinum-Group Element mineralisation in sulfide-poor komatiites – a case study from Mt. Clifford, Western Australia
M. Locmelis1, S.J. Barnes2, M.L. Fiorentini3 and N.J. Pearson1
1. GEMOC, Macquarie, 2. CSIRO Exploration and Mining, Western Australia, 3. Centre for Exploration Targeting, School of Earth and Geographical Sciences, University of Western Australia

Global lithospheric domains: a multidimensional framework to enhance mineral exploration targeting
S.Y. O’Reilly1, W.L. Griffin1, M. Zhang1, E. Belousova1, N. Pearson1 and G. Begg2 and J. Hronsky3
Plenary Keynote
1. GEMOC, Macquarie, 2. Minerals Targeting International PL, West Perth, WA, Australia, 3. Western Mining Services (Australia) Pty Ltd, West Perth, WA, Australia

Genesis of the Urals VHMS deposits inferred from coupled Pb-Os isotope systematics
S. Tessalina1,2 and J.-J. Orgeval3
1. Institute de Physique du Globe, Paris, France, 2. GEMOC, Macquarie, 3. BRGM, Orleans, France

INTERNATIONAL DISCUSSION MEETING ON CONTINENTAL GEOLOGY AND TECTONICS, NORTHWEST UNIVERSITY, XI’AN, CHINA, 6-12 SEPTEMBER 2009

Growth of continental crust from the Archean to now
W.L. Griffin1, E. Belousova1, G.C. Begg1,2 and S.Y. O’Reilly1
Keynote
1. GEMOC, Macquarie, 2. Minerals Targeting International PL, West Perth, WA, Australia

Archean lithospheric mantle: formation, composition and fate through time
S.Y. O’Reilly1, W.L. Griffin1, G. Begg1,2 and M. Zhang1
Invited
1. GEMOC, Macquarie, 2. Minerals Targeting International PL, West Perth, WA, Australia

Highly siderophile elements in mantle sulfides: constraints on Archean mantle evolution and Ni-PGE mineralization
M. Zhang1, S.Y. O’Reilly1, W.L. Griffin1 and K-L. Wang1,2
Invited
1. GEMOC, Macquarie, 2. Institute of Earth Sciences, Academia Sinica, Taipei, Republic of China

GEOITALIA 2009, VII FORUM ITALIANO DI SCIENZE DELLA TERRA, RIMINI, ITALY, 9-11 SEPTEMBER 2009

Characterizing the lithospheric-sublithospheric upper mantle system from internally consistent petrological-geophysical-geochemical modelling: why and how?
J.C. Afonso
Keynote
GEMOC, Macquarie
Appendix 4: Abstract titles

8th INTERNATIONAL ECLOGITE CONFERENCE (IEC-8) 2009, XINING CITY, CHINA, 25 AUGUST - 3 SEPTEMBER 2009

Type I and Type II eclogites from Roberts Victor, South Africa: A metasomatic model
J. Huang1,2, Y. Gréau1, W.L. Griffin1, S.Y. O’Reilly3
1. GEMOC, Macquarie, 2. School of Earth Sciences and Resources, China University of Geosciences, Beijing, China

2009 PORTLAND GSA ANNUAL MEETING, 18-21 OCTOBER 2009

How does degassing in an active caldera differ from other systems? U-series isotopes constrain the time scales of gas transfer at Rabaul Caldera, PNG
H. Cunningham and S. Turner
GEMOC, Macquarie

Continental versus crustal growth: understanding the paradox
G.C. Begg, E.A. Belousova, W.L. Griffin, S.Y. O’Reilly and L. Natapov
GEMOC, Macquarie

FIRST YOUNG EARTH-SCIENTIST CONGRESS, BEIJING, CHINA, 25-28 OCTOBER 2009

Mantle eclogites from Roberts Victor, South Africa: A Metasomatic model
J. Huang, Y. Gréau, W.L. Griffin and S.Y. O’Reilly
GEMOC, Macquarie

THE 2009 BIENNIAL CONFERENCE OF THE SPECIALIST GROUP IN GEOCHEMISTRY, MINERALOGY AND PETROLOGY, KANGAROO ISLAND, SOUTH AUSTRALIA, 8-13 NOVEMBER 2009

Hadean boninites and TTG genesis
J. Adam and T. Rushmer
GEMOC, Macquarie

Influence of subducted components on back-arc melting dynamics in the Manus Basin
C. Beier1, S. Turner1, J. Sinton2 and J. Gill3
Invited
1. GEMOC, Macquarie, 2. Department of Geology and Geophysics, University of Hawaii, 3. Department of Earth Sciences, University of California, Santa Cruz

Evolution of two contrasting subduction zones from late stage adakitic rocks
B. Coldwell1, T. Rushmer1, C. Macpherson2 and N. Petford3
1. GEMOC, Macquarie, 2. Department of Earth Sciences, University of Durham, Durham, UK, 3. School of Conservation Sciences, Bournemouth University, Dorset, UK

A-type granites: Nature or nurture?
J. Foden1, K. Kromkhun1 and S. Turner2
1. TRAX, School of Earth and Environmental Science, University of Adelaide, Adelaide, SA, 2. GEMOC, Macquarie

Did plate tectonics shut down for 250 Myr in the Early Proterozoic?
C. O’Neill1, K. Condie2 and R. Aster2
Invited
1. GEMOC, Macquarie, 2. Department of Earth and Environmental Science, New Mexico Tech, New Mexico, USA

Metallic-liquid segregation mechanisms during core formation and implications for the compositional evolution of terrestrial planets
T. Rushmer1, N. Petford2 and J. Adam1
Invited
1. GEMOC, Macquarie, 2. Bournemouth University, Poole, UK

The 187Re–187Os isotopic system in silicate systems: constraints on closure temperature and its viability as a chronometer
B.F. Schaefer1 and K.W. Burton2
Invited
1. GEMOC, Macquarie, 2. Department of Earth Sciences, Oxford University, UK

2009 AUSTRALIAN GEOTHERMAL ENERGY CONFERENCE: GEOTHERMAL DOWNUNDER - CLEAN ENERGY FROM THE GROUND UP, BRISBANE, AUSTRALIA, 10-13 NOVEMBER 2009

The 3D basement and thermal structure of the Gunnedah Basin
C.R. Danis and C. O’Neill
GEMOC, Macquarie

GEOSCIENCES ’09. GEOLOGICAL SOCIETY OF NEW ZEALAND NEW ZEALAND GEOPHYSICAL SOCIETY JOINT CONFERENCE, OAMARU, NEW ZEALAND, 23-27 NOVEMBER 2009

Metastable persistence of pelitic metamorphic assemblages during high-P granulite facies metamorphism of intermediate-mafic orthogneiss, Fiordland, New Zealand
N.R. Daczko1, L.A. Milan1, J.A. Halpin1, A.H. Allibone1 and G.L. Clarke2
1. GEMOC, Macquarie, 2. CODES, University of Tasmania, TAS, Australia, 3. Rodinian Pty Ltd, Queanbeyan, NSW, Australia, 4. School of Earth Sciences, The University of Sydney, NSW, Australia

Complexity of U-Pb-Hf isotope patterns in zircon during arc magma genesis: evidence from a high-P Cretaceous granulite/eclogite facies arc root, Fiordland, New Zealand
L.A. Milan1, N.R. Daczko1, G.L. Clarke2, A.H. Allibone1, I.M. Turnbull4 and R. Sutherland4
1. GEMOC, Macquarie, 2. School of Earth Sciences, The University of Sydney, NSW, Australia, 3. Rodinian Pty Ltd, Queenbeyan, NSW, Australia, 4. Institute of Geological and Nuclear Sciences, Dunedin, NZ

100 GEMOC 2009 ANNUAL REPORT
Autochthonous inheritance of zircon in the Arthur River Complex, Fiordland, New Zealand
A. Tulloch1, T. Ireland2, J. Ramezani3, D. Kimbrough4 and W.L. Griffin5
1. GNS Science, Dunedin Research Centre, Dunedin, NZ, 2. RSES, ANU, Canberra, Australia, 3. Earth, Atmospheric and Planetary Sciences, MIT Cambridge, USA, 4. Geological Sciences, San Diego State University, San Diego, USA, 5. GEMOC, Macquarie

AMERICAN GEOPHYSICAL UNION- 2009 FALL MEETING, SAN FRANCISCO, CALIFORNIA, UNITED STATES, 14-18 DECEMBER 2009

Hadean boninites and TTG genesis
J. Adam1, T. Rushmer1, J. O’Neill2 and D. Francis
1. GEMOC, Macquarie, 2. McGill University, Montreal, QC, Canada

The crust mantle transition beneath the Variscan Domain of the Iberian Peninsula
R. Carbonell1, J. Diaz2, D. Brown1, I. Palomeras1, D. Marti1, P. Ayarza1, J.C. Afonso1, F. Simancas1, A. Perez-Estau1 and J. Gallart1
1. Institute of Earth Sciences J. Almera, Barcelona, 2. GEMOC, Macquarie, 3. Geodynamics Department, Campus de Fuentenueva, Granada University

Relative roles of fluid fluxed and decompression melting within the Tonga Arc-Lau Basin system: Insights from the Fonualei spreading centre
J.T. Caulfield1, S. Turner1 and R.J. Arculus2
1. GEMOC, Macquarie, 2. Research School of Earth Sciences, Australian National University, Canberra, ACT

The role of eclogite in the metasomatism and Cenozoic magmatism of Northern Victoria Land, Antarctica
M. Coltorti1,2, C. Bonadiman1,2, B. Faccini1, W. Griffin1, M. Melchiorre1, S. O’Reilly2 and N. Pearson3
1. Earth Sciences Department, University of Ferrara, Italy, 2. GEMOC, Macquarie

(230Ra/234Th) excesses and the formation of high Mg andesitic lavas in the Western Bismarck arc, Papua New Guinea
H.S. Cunningham1, S. Turner1, J.B. Gill2 and S.J. Day1,1
1. GEMOC, Macquarie, 2. UCSC, Santa Cruz, CA, USA, 3. UCL, London, UK

Catching in flagrante mantle unrooting beneath the Alpine-Himalayan Belt: Evidence from Atlas, Zagros and Tibet
M. Fernández1, I. Jiménez-Munt1, A. Villaseñor1, J. Vergés1, D. García-Castellanos1, E. Saura1 and J.C. Afonso2
1. Institute of Earth Sciences J. Almera, Barcelona, 2. GEMOC, Macquarie

Geophysical modelling of the lithosphere-asthenosphere boundary beneath the Atlantic-Mediterranean Transition Region: integrating potential field, surface heat flow, elevation, seismological and petrological data
J. Fullea1, M. Fernández2, J.C. Afonso2, J. Vergés2 and H. Zeyen4
1. Dublin Institute for Advanced Studies, 2. Institute of Earth Sciences J. Almera, Barcelona, 3. GEMOC, Macquarie, 4. Département des Sciences de la Terre, Université Paris, France

Sediment residence time and landscape evolution in arid Australia
H.K. Handley1, A. Dosseto2, P.O. Suresh3, T.J. Cohen2 and S. Turner1
1. GEMOC, Macquarie, 2. GeoQuEST Centre, School of Earth and Environmental Science, University of Wollongong, NSW, Australia, 3. Department of Environment and Geography, Macquarie

Decoupled accommodation of convergence between Africa and Eurasia: modeling the lithospheric structure across the Gorringe Bank and the NW Moroccan Margin
I. Jiménez-Munt1, M. Fernández2, J. Vergés3, D. García-Castellanos1, M. Pérez-Gussinyé4, J.C. Afonso2 and J. Fullea1
1. Institute of Earth Sciences J. Almera, Barcelona, 2. GEMOC, Macquarie, 3. Dublin Institute for Advanced Studies

Metallic liquid segregation mechanisms: texturally-based models for estimating timescales of core formation
T. Rushmer1, N. Petford2 and P. Treolar2
1. GEMOC, Macquarie, 2. Bournemouth University, Poole, United Kingdom, 3. Kingston University, Kingston upon Thames, UK

Re-Os isotopes on the timing and origin of the Giles Complex, South Australia
B.F. Schaefer1, B.P. Wade2 and K. Barovich3

The origins of large volume, compositionally-zoned volcanic eruptions – new constraints from U-series isotopes and numerical thermal modeling for the 1912 Katmai-Novarupta eruption
S. Turner1, M. Sandiford2, M.K. Reagan3, C.J. Hawksworth4 and E.W. Hildreth4
1. GEMOC, Macquarie, 2. School of Earth Sciences, University of Melbourne, Australia, 3. Department of Geoscience, University of Iowa, IA, USA, 4. Department of Earth Sciences, University of Bristol, UK, 5. United States Geological Survey, Menlo Park, CA, USA

Polygenetic magmatism in a monogenetic field: an isotopic investigation from the Auckland Volcanic Field, New Zealand
L. McGee1, C. Beier1, I.E. Smith1 and S. Turner1
1. University of Auckland, Auckland, New Zealand, 2. GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Erlangen, Germany, 3. GEMOC, Macquarie
### Appendix 5: Funded research projects

#### GRANTS AND OTHER INCOME FOR 2009

<table>
<thead>
<tr>
<th>2009 Funding Source</th>
<th>Investigators</th>
<th>Project Title</th>
<th>Amount</th>
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<td>ARC Discovery</td>
<td>Griffin, O'Reilly, Pearson, Stachel, Navon, Harris</td>
<td>Diamond genesis: cracking the code for deep-Earth processes</td>
<td>$157,000</td>
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<td>Turner, Dossetto, Reagan</td>
<td>The application of short-lived Uranium-series isotopes to constraining Earth system processes</td>
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<td>Daczko, Clark</td>
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<td>Developing permeability in the Earth's crust: A coupled experimental and numerical study of geologically important fluids in a dynamic environment</td>
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<td>Did obesity kill the arc? A model from the Fiordland Arc, New Zealand</td>
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<td>iMURS</td>
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<td>Tofua Volcano, Tonga Arc, eruption history and timescales of magma chamber processes</td>
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<td>iMURS</td>
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<td>Mantle xenoliths, kimberlites and related rocks of the Kuruman Kimberlite Province, Kaapvaal Craton, South Africa</td>
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<td>Gréau</td>
<td>Elemental and isotopic fractionation of siderophile and chalcophile elements: A new perspective on eclogite origin</td>
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## Appendix 5: Funded research projects

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<tr>
<th>2009 Funding Source</th>
<th>Investigators</th>
<th>Project Title</th>
<th>Amount</th>
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<tr>
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<td>Origin of eclogite and pyroxenite xenoliths in kimberlites and basalts</td>
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<td>Locmelis</td>
<td>Understanding nickel deposits using platinum group element geochemistry</td>
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<td>APA</td>
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<td>A novel U-series isotopic approach for investigation of the Beverley U mine, South Australia</td>
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<td>MQRES</td>
<td>Pankhurst</td>
<td>Geodynamic significance of shoshonitic magmatism within the Andean Altiplano</td>
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<td>Portner</td>
<td>Spreading ridge sedimentation processes: a novel approach using Macquarie Island as a natural laboratory</td>
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<tr>
<td>PGRF</td>
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<td>Precambrian crust evolution of the Yangtze Block</td>
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## FUNDED RESEARCH PROJECTS FOR 2010

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<th>2010 Funding Source</th>
<th>Investigators</th>
<th>Project Title</th>
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<tr>
<td>ARC Discovery</td>
<td>Griffin, O’Reilly, Pearson, Stachel, Navon, Harris</td>
<td>Diamond genesis: cracking the code for deep-Earth processes</td>
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<td>ARC Discovery</td>
<td>Turner, Dossetto, Reagan</td>
<td>The application of short-lived Uranium-series isotopes to constraining Earth system processes</td>
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<td>Partial melting in natural metal-silicate systems: rheological and geochemical implications for the Earth and other planets</td>
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<td>ARC Linkage Infrastructure</td>
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<td>Frontiers in integrated laser-sampled trace-element and isotopic geoanalysis</td>
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<td>A novel approach for economic uranium deposit exploration and environmental studies</td>
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<td>Australian Antarctic Division</td>
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<td>The tectonic significance of regional flat-lying fabrics in rocks (logistic support)</td>
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<td>Did obesity kill the arc? A model from the Fiordland Arc, New Zealand</td>
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<td>IMQRES</td>
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<td>APA</td>
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<td>MQRES</td>
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<td>iMQRES</td>
<td>Wang</td>
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</table>
GEMOC has a flourishing postgraduate research environment with postgraduate students from many countries (including France, Germany, China, Russia, USA, Canada and Australia). Scholarships funding tuition fees and a living allowance are available for students with an excellent academic record or equivalent experience. These include:

- **Australian Postgraduate Awards (APA):** available for Commonwealth citizens to cover tuition fees and living allowance, with a closing date in late October annually

- **Macquarie University Research Excellence Scholarship (MQRES) scholarships:** available for Australian citizens and international students who wish to undertake a postgraduate program in a Centre of Excellence at Macquarie University (e.g. GEMOC)

- **International Postgraduate Research Scholarships (E-IPRS Endeavour Scholarships):** available to overseas students to cover tuition fees with a closing date in late August annually

Macquarie University also provides research funding through a competitive internal scheme and GEMOC’s funded projects (see Appendix 5) provide further resources to support postgraduate research projects.

Postgraduate projects are tailored to your expertise and interests within the framework of GEMOC’s research goals. GEMOC carries out interdisciplinary research across the boundaries of petrology, geochemistry, tectonics, metallogenesis, geodynamics and geophysics to explore the nature and evolution of the lithosphere and global geodynamics. Current funded projects are based in Australia, Antarctica, Canada, China, Taiwan, Italy, France, Siberia, Norway, North America, South America, Africa, Kerguelen Islands and other global locations (see the section on GEMOC’s Research Program).

GEMOC postgraduate programs have opportunities through access to our outstanding analytical facility (see Technology Development section) with currently unique technologies and instrumentation configurations to tackle exciting large-scale problems in the Geosciences.

Examples of broad PhD project areas include:

- Lithosphere structure and geochemistry: mantle provinciality and tectonism
- Granitoid and mineralised provinces along western Pacific convergent margins
- Fluid-vapour transfer of elements in the crust and mantle
- Heat production and evolution of the crust: crust-mantle interaction
- Geophysical applications to lithosphere studies
- Isotopic and trace element geochemistry: mantle and crustal systems
- Metal isotopes: applications to ore formation
- Magma genesis and crustal evolution: includes trace elements of accessory minerals, isotopic fingerprints
- High-pressure experimental studies

Potential applicants should discuss possible projects with a potential supervisor and the Director of GEMOC before applying.
Contact details

http://www.gemoc.mq.edu.au/
gemoc@mq.edu.au

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

Carol McMahon
Administrator
Phone: 61 2 9850 8953
Fax: 61 2 9850 8943 or 6904
Email: carol.mcmahon@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: norman.pearson@mq.edu.au

GLOSSARY

ACILP  Australia China Institutional Links Program
AMIRA  Australian Mineral Industry Research Association
ANU  Australian National University
APA (I)  Australian Postgraduate Award (Industry)
ARC  Australian Research Council
BHPB  BHP Billiton
BSE  Backscattered Electrons
CERCAMS  Centre for Russian and Central EurAsian Mineral Studies
CNRS  French National Research Foundation
CoRE  Concentrations of Research Excellence
CSIC  Consejo Superior de Investigaciones Científicas (Spanish National Research Council)
CSIRO (EM)  Commonwealth Scientific Industrial Research Organisation (Exploration and Mining)
DEST  Department of Education, Science and Training (from 2002)
DIATREEM  Consulting company within AccessMQ
DP  Discovery Project
EAPE CoRE  Earth and Planetary Evolution Concentration of Research Excellence
EMP  Electron Microprobe
(DEPS)  (Department of) Earth and Planetary Sciences
ERA  Excellence in Research for Australia
EURODOC  The council for postgraduate students and junior researchers in Europe
FIM  Facility for Integrated Microanalysis
FTIR  Fourier Transfer Infrared Spectroscopy
GA  Geoscience Australia (formerly AGSO)
GAU  Geochemical Analysis Unit (DEPS, Macquarie University)
GIS  Geographic Information System
GLAM  Global Lithospheric Architecture Mapping
GLITTER  GEMOC Laser ICPMS Total Trace Element Reduction software
GPS  Global Positioning System
HIAP  Heavy Ion Analytical Facility
ICPMS  Inductively Coupled Plasma Mass Spectrometer
iMURS  International Macquarie University Research Scheme
IODP  Integrated Ocean Drilling Program
IPRS  International Postgraduate Research Scholarship
LAM-ICPMS  Laser Ablation Microprobe - ICPMS
LIEF  Linkage Infrastructure, Equipment and Facilities
MC-ICPMS  Multi-Collector - ICPMS
MDU  “Minerals Down Under” CSIRO Flagship program
MERIWA  The Minerals and Energy Research Institute of Western Australia
MQNS  Macquarie University New Staff Research Grants Scheme (formerly MUNS)
MQRDG  Macquarie University Research Development Grant
(i)MQRES  (International) Macquarie University Research Excellence Scholarships
MORF  Macquarie University Research Fellowship (formerly MURF)
MUIPRA  Macquarie University International Postgraduate Research Award
MURAACE  Macquarie University Research Award for Areas and Centres of Excellence
NCRIS  National Collaborative Research Infrastructure Scheme
NSERC  Natural, Sciences and Engineering Research Council of Canada
PGE  Platinum Group Element
PIRSA  Primary Industries and Resources, South Australia
RAACE  Research Areas and Centres of Excellence Postgraduate Scholarships
RIBG  Research Infrastructure Block Grant
RES  Research School of Earth Sciences at ANU
SEM  Scanning Electron Microscope
UWA  University of Western Australia
XRF  X-Ray Fluorescence