GEMOC's research program

GEMOC aims to achieve an integrated understanding of the evolution of the Earth and other planets

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 constrain the processes responsible for the evolution of Earth's chemical reservoirs
- to define the systematics of element redistribution in the mantle and crust during the critical liquid-crystal and vapour-liquid separation events
- to quantify the transport of crustal material into the deep Earth, and its ultimate contribution to mantle plumes and the subcontinental lithosphere
- to advance the modelling of the crust and lithospheric mantle from geophysical datasets, through integration of geophysical, petrological and geochemical information
- to understand from the "bottom-up" the processes that control the generation and modification of the crust-mantle system and to define the tectonic and geochemical processes that have created different crustal and mantle domains through time
- to produce and interpret maps of lithosphere thickness and lithospheric mantle type at the present day and for selected time (and location) slices through Earth's geological evolution
- to produce and interpret chemical tomography sections of lithospheric mantle in time and space where global datasets can be constructed
- to provide a new framework for area selection for a wide spectrum of economic deposits, by linking these models and processes to the formation of metallogenic provinces
- to 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

Thermal 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 Earth's lithosphere can be mapped for rock types and their relationships using fragments of deep materials such as mantle rocks and diamonds, and the compositions of mantle-derived magmas. Timescales can be unravelled 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 contents 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 PROGRAM

The *Research Highlights* section gives an overview of major progress in 2005.

The Research Program for 2006 follows the topics of the funded projects listed in *Appendix 5*. Summaries of funded basic research projects are listed below and some of the collaborative industry research projects are summarised in the section on *Industry Interaction*.

The research program for the first six years focused on four strands: the current Research Program is pushing into new conceptual and technology frontiers, building on our intellectual capital from the first phase of GEMOC.

• Mantle Dynamics and Composition

will form 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, potentially linked to the initiation of subduction. 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.

Lithosphere Mapping provides the fundamental data for defining lithospheric mantle domains in terms of composition, structure and thermal state. Lithosphere profiles

"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."

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

- **Geodynamics**

uses stratigraphic, tectonic, and geophysical data to interpret the history and causes of continental assembly and disruption, with a special focus on Australia, East Asia and major cratons (Siberia, Africa, Canada, South America, India). It provides the fundamental framework to link the research on crustal and mantle processes with the localisation and development of metallogenic provinces. Numerical Modelling is a new direction and is being used to test a range of different Earth models.

- **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 Metallogenesis strands.

- **Metallogenic Provinces**

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

RESEARCH PROJECTS FEEDING MAJOR PROGRAMS

Mantle Dynamics and Composition

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

U-series applications to timescales of lithosphere processes Research Highlights

Experimental studies of mantle minerals: high pressure partition coefficients; 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 Research Highlights

Gravity modelling of lithosphere terranes (regional elastic thickness)

The composition of Earth's core and timing of core formation

Interpretation of deep seismic tomography Research Highlights

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

Diamonds: origin and clues to deep mantle and lithosphere evolution and structure; Canada, Siberia, South Africa Research Highlights

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

Basalts as lithosphere/asthenosphere probes

Plume compositions, sources and origins

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

Lithosphere extension processes and consequences in East Asia: Taiwan and eastern China Research Highlights

Constraints on the timing of depletion and fluid movements in lithospheric mantle of different ages, using a range of isotopic and trace-element methods, including Re-Os in mantle sulfides Research Highlights

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) Research Highlights

U-series analysis of weathering and erosion processes Research Highlights

Dating lower crust domains and tracking extent of Archean crust

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

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

Studies of detrital zircons in Paleozoic sediments: origins of terranes in Lachlan Fold Belt

Metallogenesis

Risk management in exploration

U-series applications to timescales of fluid movement

Metal isotope applications to ore genesis

Geochemistry of mantle sulfides Research Highlights

Area selection and evaluation for diamond exploration

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

Sulfide and PGE budget of the mantle

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

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

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

Trace elements in diamonds - fingerprinting and possible genetic indicators?

Geodynamics

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

Tasman Fold Belt: terrane analysis

Paleomagnetic studies of the northern New England Orogen

Antarctic seismic studies Research Highlights

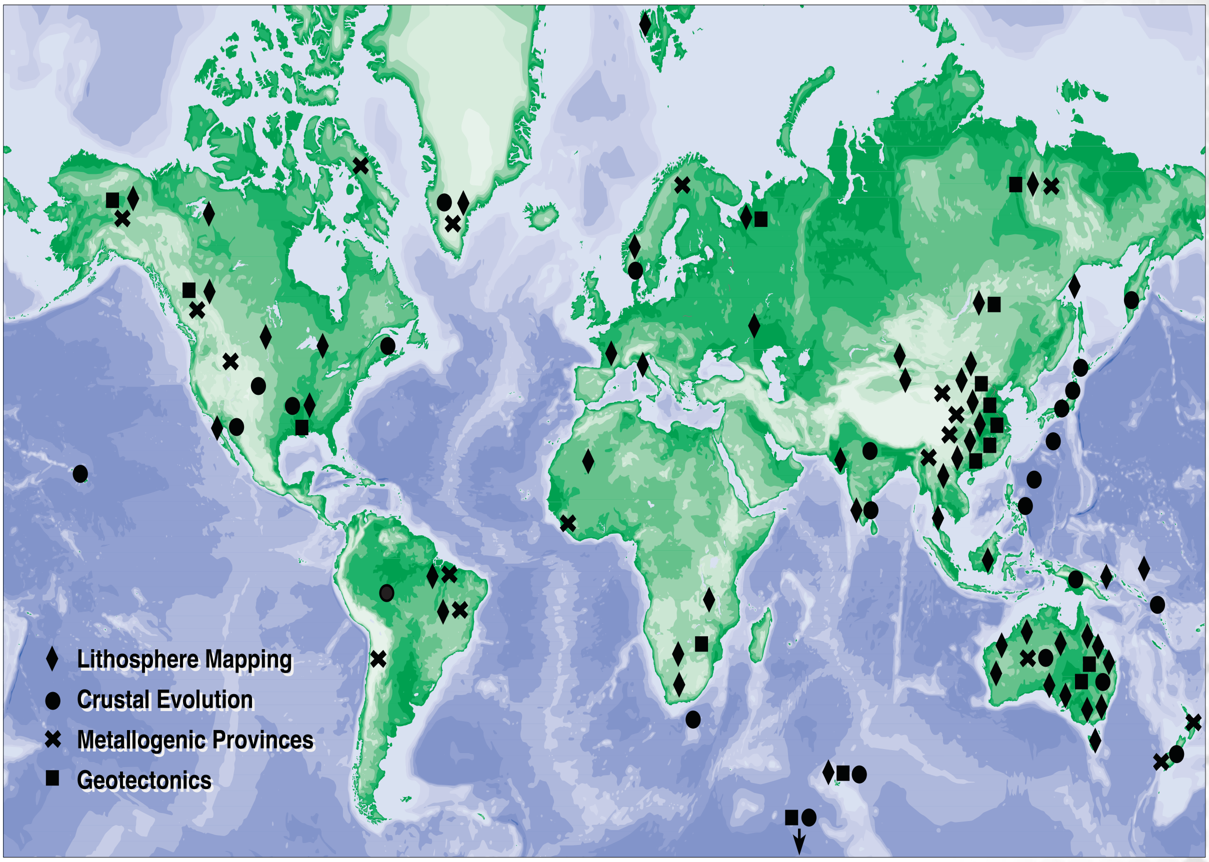
Deep crustal processes (New Zealand)

Plate margin processes (Papua New Guinea, Macquarie Island)

Geodynamic modelling of large-scale processes, integrating constraints from 4-D Lithosphere Mapping

Evolution of lithospheric composition and Earth geodynamics through time

WHERE IN THE WORLD IS GEMOC?



Funded basic research projects for 2006

Funded research projects within GEMOC are formulated to contribute to the long-term, large-scale strategic goals and determine the short-term Research Plan. Summaries of these projects for 2006 are given here.

The behaviour of geochemical tracers during differentiation of the Earth

Bernard Wood: Supported by ARC Discovery

Summary: The aims of this project are to understand the processes by which the Earth separated its metallic core, to test models of how it developed 'enriched' and 'depleted' mantle components and to constrain the nature of continuing interactions between near-surface geochemical reservoirs and Earth's deep interior. These processes have traditionally been followed using chemical tracers, but lack of understanding of chemical behaviour under the conditions of the deep Earth limits their application. This project is aimed at filling the gap, by determining experimentally, at high pressures and temperatures, the chemical behaviour of those trace elements which are central to our understanding of geochemical processes in Earth's interior. The project is aimed at providing fundamental data which Earth Scientists will use to understand the processes by which Earth separated into its chemically-distinct layers (core, mantle, crust, atmosphere, oceans) and to determine the nature of the continuing interactions between the surface environment in which we live and the deep interior.

Episodicity in mantle convection: effects on continent formation and metallogenesis

Craig O'Neill: Supported by Maquarie University Research Fellowship

Summary: Quantitative numerical modelling will be used to evaluate the links between episodes of intense mantle convection and the production of the continental crust that we live on. These models will assess the degree of melt production and crustal generation resulting from different styles of episodic mantle convection, and will determine which types of mantle evolution through time could produce the age distribution observed in the continental crust worldwide. The research addresses a critical shortcoming in our understanding of the formation and evolution of continents, with important implications for the distribution of major mineral and energy resources.

Isotopic fractionation of the ore minerals (Cu, Fe, Zn): A new window on ore-forming processes

Simon Jackson and Bruce Mountain: Supported by ARC Discovery

Summary: Stable isotopes of common ore metals (eg copper and iron) are new tools for investigating ore deposits. Our data suggest that metal isotopic variations can provide new insights into mechanisms operative during formation of ore deposits. Stable metal isotopes also show promise as a new exploration tool for identifying the location of economic mineralisation within large prospective terrains; eg weakly vs strongly mineralised zones in a volcanic belt.
This project will provide fundamental baseline data that will help elucidate the processes that cause metal isotope variations. This will allow stable metal isotopes to be used much more effectively by the mining and exploration industries.

Spreading ridge sedimentation processes: a novel approach using Macquarie Island as a natural laboratory

Nathan Daczko and Julie Dickinson (University of Sydney): Supported by ARC Discovery

Summary: This project is the first that aims to understand the generation, deposition and lithification of sedimentary rocks at mid-ocean spreading ridges. It will improve our understanding of the construction of significant volumes of oceanic crust that commonly host important economic resources such as cupriferous sulfides. The project will examine spreading-related sedimentary rocks, including processes relating to their depositional system, utilising unique exposures on Macquarie Island, where *in situ* oceanic crust still lies within the basin in which it formed.

A new approach to understanding the mechanism and deep crustal controls of continental rifting

Nathan Daczko: Supported by ARC Discovery

Summary: The Papuan Peninsula region of Papua New Guinea represents an active plate boundary on the northern Australian margin that is presently rifting. This project will develop models that detail how the rifting is accommodated in continental rocks and compare and contrast this with oceanic rocks. The project aims to understand the tectonics of rifting by examining this active tectonic region, thus investigating a fundamental plate tectonic process that is critical to understanding Earth evolution. Expected outcomes include a deeper understanding of plate tectonics, with special focus on deep Earth processes.

Global lithosphere architecture mapping

Sue O'Reilly and Bill Griffin: Supported by ARC Linkage Project and WMC Resources

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

Toward the use of metal stable isotopes in geosciences

Olivier Alard: Supported by ARC Discovery

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

Crustal Evolution in Australia: Ancient and Young Terrains

Elena Belousova: Supported by ARC Discovery

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

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

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

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

The timescales of magmatic and erosional cycles

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

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

Mantle Melting Dynamics and the influence of recycled components

Simon Turner: Supported by Macquarie University Development Grant

Summary: This proposal aims to use U-series isotopes to constrain the rates of mantle melting and residual porosity. Precise information on the time scales and rates of change is fundamental to understanding natural processes and central to developing and testing physical models in the earth sciences. 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. By contrasting normal and enriched basalts we will constrain the effect of heterogeneities, including volatiles on mantle melting. This will radically improve our understanding of mantle melting which powers Earth's dynamics.

The oxidation state of the early Earth mantle: new clues from iron isotopes

Helen Williams: Supported by Macquarie University New Staff Grant and Industry (Nu Instruments)

Summary: This project's goal is to understand how the Earth's atmosphere became oxygen-rich. Oxygen stored in the Earth's deep interior (the mantle) was probably released to the surface as water and CO_2, allowing the growth of free oxygen in the atmosphere to a significant level by ~2.4 Ga (billion years ago). These processes, and the distribution of oxygen in the mantle, are poorly understood. This project will use iron and chromium isotopes as oxygen tracers in 3.3-2.1 Ga mantle rocks to understand the evolution of oxygen in the mantle and how this is linked to the development of the Earth's atmosphere.

Thallium isotopes: a novel geochemical tracer to map recycling in Earth's mantle

Sune Nielsen: Supported by a fellowship from the Danish Research Council and subsequently awarded an ARC Discovery Grant

Summary: **The recycling of crustal material back into the mantle at subduction zones is one of the most fundamental Earth processes, but its effect on the evolution of the geochemistry of the mantle, and the ultimate fate of the subducted material, are poorly understood. This project will use the stable isotope geochemistry of thallium as a novel and sensitive tracer to follow subducted oceanic crust through the subduction process, and test for its reappearance in hot-spot volcanoes and the continental lithosphere. The results will provide firm constraints on models of mantle convection, Earth evolution and the generation of continents.**

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

Vladimir Malkovets: Supported by Macquarie University Research Fellowship

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

Enhancing the use of zircon in crustal studies and mineral exploration: trace-element and statistical approach

Elena Belousova: Supported by Macquarie University Staff Grant

Summary: **Zircon is an accessory (low-abundance) mineral present in most rock types and represents a time-capsule carrying significant information about its original host rock, including its age, tectonic origin and composition. Interpretation of the parent rock composition using trace-element signatures of zircons has not been fully exploited. This study will characterise trace-element compositions of zircons from representative rock types and use a robust statistical diagnostic methodology (CART: Classification And Regression Trees) to identify criteria for assigning parent rock types using single zircon grains. Zircons collected from alluvial sources could then be used to unravel regional geology and sediment provenance.**