CCFS

2012 Annual Report

The Australian Research Council Centre of Excellence for Core to Crust Fluid Systems

- CCFS information is accessible on WWW at:

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The CCFS Annual Report is available from our website http://www.ccfs.mq.edu.au/ as a downloadable pdf file or in html format, and by mail on USB on request.

Front Cover: Artist's impression of upwelling, downwelling and mingling fluids in the Earth. Image by Sally-Ann Hodgekiss.

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Australian Government
Australian Research Council

Established and supported under the Australian Research Council's Research Centres Program

Director's preface

This report summarises the activities of the Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS) in 2012 (commenced mid 2011) in accordance with ARC requirements. Activities include research, technology development, industry interaction, international links and research training.

The overarching goal of CCFS is to understand Earth's internal dynamics, evolution and fluid cycles from core to crust. CCFS multiplies the capabilities of three national centres of research excellence in Earth and Planetary Sciences: Macquarie University (Administering Institution), Curtin University and the University of Western Australia (Collaborating Institutions). The Geological Survey of Western Australia is a Partner Institution and researchers from Monash University and the University of New South Wales are formally affiliated.

There are five formal international nodes led by Partner Investigators in France (University of Montpellier), China (Institute of Geology and Geophysics, China Academy of Sciences), Canada (University of Saskatchewan), Germany (Bayreuth University) and the USA (University of Maryland). However, since CCFS commenced, international interaction has blossomed and now includes active projects with 94 international institutions, with 150 international collaborators as co-authors on research articles in 2012. These international collaborations are contributing resources and provide access to a wide variety of complementary expertise, logistics and instrumental capabilities.

CCFS builds on pre-existing centres within the Administering and Collaborating Institutions: the GEMOC Key Centre (http://www.gemoc.mq.edu.au/) at Macquarie University retains its structure and is fully incorporated within CCFS to capitalise on its global recognition; the research and strategic activities of the Centre for Exploration Targeting (http://www.cet.edu.au/) at the University of Western Australia lie within CCFS; and the activities of TiGeR (http://tiger.curtin.edu.au/) at Curtin University are also aligned with CCFS.

A highlight of 2012 was the joint Research Meeting held as part of the visit of the Science Advisory Council (SAC) in August 2012. The SAC presented a comprehensive report praising the Centre

Sue O'Reilly addressing the large crowd at the celebration of 60th Anniversary of the founding of the China University of Geosciences, Wuhan.

structure and activities and providing some very constructive suggestions. Some extracts illustrate the views:

"Advisory Council members considered the standard of presentations to be excellent, and they produced several enthralling sessions..."

"The CCFS Is already doing an excellent job at portraying a "corporate identity", carrying on the fine tradition of the GEMOC group"

"The nodes of the CCFS together form a major, world-leading centre in the in-situ microanalysis of trace elements and isotopes in minerals metal concentrations,"

Recruitment and mentoring of early- and mid-career researchers is a high-level goal in CCFS: early-career researchers and the six Future Fellows are highlighted in the *Participants* section. Research training has expanded rapidly: there are now 69 PhD students undertaking projects aligned with CCFS and Macquarie University has introduced a revolutionary Masters Research (MRES) program commencing 2013 that will be the vehicle for many CCFS research training goals. Four inaugural units directly deliver CCFS related research training and are also being developed as portable short courses.

CCFS is rapidly expanding – including the number of researchers (especially early- to mid-career), postgraduate students, international links, and research horizons. The *Research highlights* in this report evidence a high level of activity with exciting frontline scientific outcomes.

We look forward to an exciting year of new discoveries bringing another level of challenging scientific endeavours, towards better understanding the structure, composition and dynamics of our home planet, Earth, and its geological evolution "*from core to crust*" over 4.5 billion years – ultimately the pathway to securing Australia's future mineral security and ensuring economic health for our society.

S.Y. O'Reilly

The Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS): Background

Vision

A world-leading Centre of Excellence, driving innovative interdisciplinary research toward a new understanding of Earth's origins, fluid budgets and evolution, and delivering outcomes of tangible benefit to society.

GOALS – THE MISSION

- **to reach a new level of understanding of Earth's internal dynamics and fluid cycles, and how these have evolved to generate the hydrosphere, continents and atmosphere**
- **to provide a world-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 to the minerals and energy industries**
- **to develop new educational approaches that can renew and revitalise Australian research in the Earth Sciences**

CONTEXT

Water is essential for human existence, indeed for life's beginning. The circulation of water and other fluids lubricates the deep-seated dynamics that keep Earth geologically alive, and its surface habitable. Several oceans' worth of water may be present inside Earth, and the exchange of water and other fluids between the surface and the deep interior plays a crucial role in most Earth systems, including the evolution of the surface, the hydrosphere, the atmosphere/biosphere, and the development of giant ore deposits.

Subduction - the descent of oceanic plates into the mantle - carries water down into Earth's interior; dehydration of the subducting crustal slabs at high pressure and temperature releases these fluids into the mantle, causing melting and controlling the strength, viscosity, melting temperature and density of rocks in the deep Earth, and the structure of major seismic discontinuities at 410 and 660 km depth. The partial return of some of these materials to the surface through mantle-plume activity provides a mechanism for tectonic cyclicity, which may have varied over geological time. These effects dominate solid-Earth dynamics and make plate tectonics possible, but the origin, abundance, speciation and movements of fluids in the deep interior are largely unknown, and represent key issues in modern geoscience.

Until recently, a real understanding of the workings of Earth's deep plumbing system has been tantalisingly out of our reach. Now, rapid advances in geophysics are producing stunning new images of variations in physical properties such as seismic velocity and electrical conductivity in the deep Earth, but interpretation of these images in terms of processes and Earth's evolution is another key issue. It requires new kinds of data on deep-Earth materials, and especially on the effects of deep fluids and their circulation.

To provide the knowledge needed to reach a new level of understanding of Earth's evolution, dynamics and fluid cycle(s) through time, CCFS will integrate information across geology, tectonics, experimental and analytical geochemistry, petrophysics, geophysics, and petrophysical and dynamical modelling. These disciplines have traditionally represented '*research silos*', but we will bring them together to provide a significant increase in our national research capability.

CENTRE RESEARCH

Research projects within the Centre are focused to provide maximum synergy for the scope enabled by the resource base. As it is not possible to encompass the full range of research about the Earth's fluid cycle and deep Earth dynamics, all applied and mature strategic research will be carried out in parallel, supported by other funding sources. The basic research projects have been selected initially to capitalise on CCFS resources and to fit within the funding base.

The research activity of the CoE is built around three linked interdisciplinary and cross-institutional Themes, each with several Programs. We have structured these to promote synergy and interchange of ideas and information between the Programs, across the Themes, and especially across the three nodes. More detailed information is given in *"Foundation Research Projects"* and *"Research highlights."*

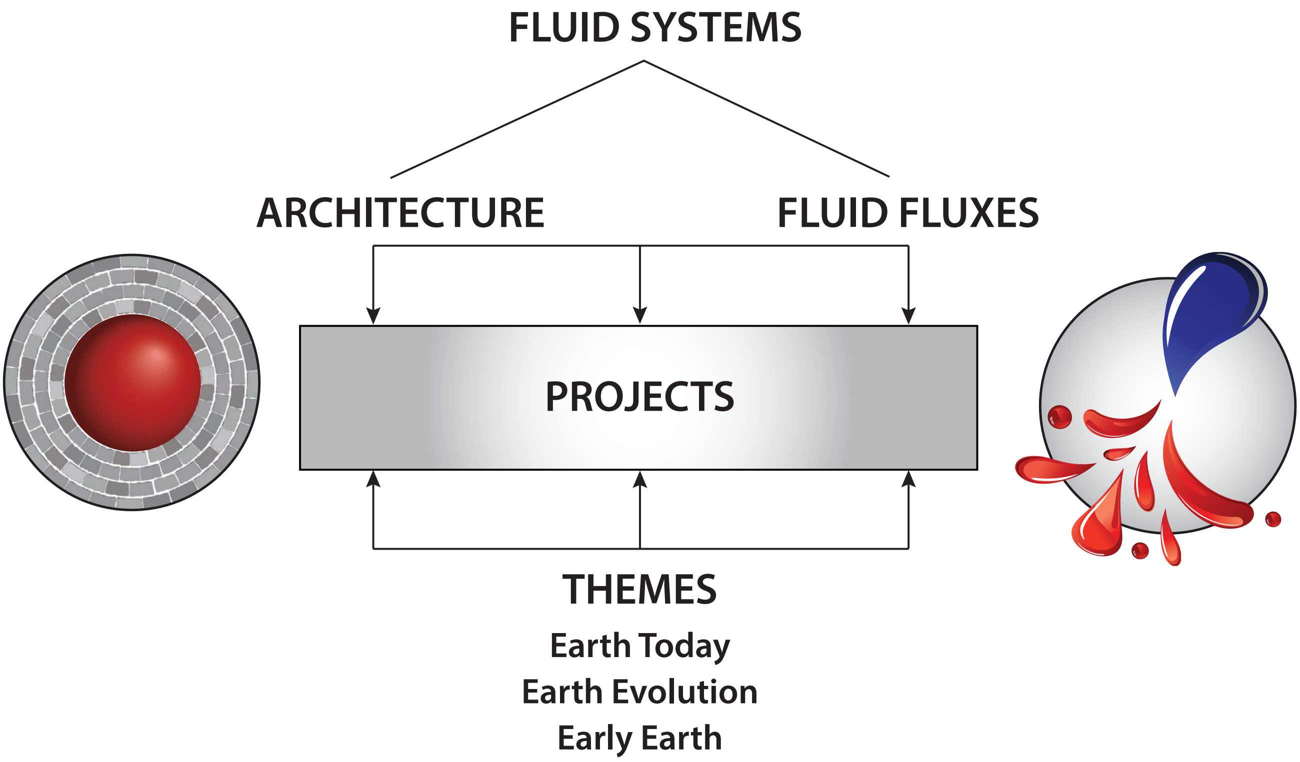
CCFS node leaders Cam McCuaig, Simon Wilde and Sue O'Reilly with representatives of the 2012 Science Advisory Committee, Stephen Foley and Stephen Grand.

In order to address one of the comments by the Science Advisory Committee that "we were sometimes led to pose the question 'what does this have to do with fluids'" the overarching concept of projects contributing to understanding Earth Architecture and/or Fluid Fluxes has now been introduced. This conceptual base arose from very fruitful discussions at the Advisory Board Meeting of December 2012 and encapsulates the relationship of the CCFS projects to "fluids".

"Architecture" is the 'roadmap' for fluids

"Fluid Fluxes" represents the 'traffic report'

All Research highlights and Projects are now keyed to this framework shown diagrammatically below:



Dr Yingjie Yang

SCIENCE ADVISORY COMMITTEE MEETING

A combined meeting of all CCFS national Collaborating Institutions and the Geological Survey of Western Australia Partner was held at Macquarie University on 1-2 August 2012. Presentations were given by senior to early-career researchers and postgraduate students. The presentations were of outstanding quality, especially those of the postgraduates and early-career researchers. The Science Advisory Committee, Professors Stephen Foley, Stephen Grand and Julian Pearce, presented a comprehensive report praising the Centre structure and activities and providing some very constructive suggestions that are being implemented. Eclectic comments from the Report highlight different aspects of CCFS:

"Advisory Council members considered the standard of presentations to be excellent, and they produced several enthralling sessions..."

"The CCFS is already doing an excellent job at portraying a "corporate identity", carrying on the fine tradition of the GEMOC group"

"The nodes of the CCFS together form a major, world-leading centre in the in-situ microanalysis of trace elements and isotopes in minerals... ...attention to these accessory phases such as sulfides and oxide minerals is particularly noteworthy... ...as promising sources of information about geodynamic movements and metal concentrations,"

The Science Advisory meeting provided an excellent oportunity for CCFS members from the various nodes to interact. Above: Sandra Piazolo, Weronika Gorczyk, and Juan Carlos Afonso. Right: Bill Griffin, Yoann Gréau and Laure Martin.

THEMES

THEME 1: EARLY EARTH

The Early Earth - Its formation and fluid budget. This theme focuses on the nature of Earth's early differentiation and the role of fluids. Ancient (>3 Ga) rocks may yield evidence for early life, and analysing the mass-independent fractionation of Fe and S isotopes will allow us to test the involvement of biological processes in ancient deposits.

The earliest record of Earth's magnetic field will provide new information on when the core's geodynamo formed and the geometry and intensity of its field, and will be used to track the movement of Archean tectonic plates. The geochemical nature and dynamic behaviour of the mantle in the early Earth will be assessed using *in-situ* analysis of targeted minerals from a variety of mantle rock types and tectonic environments, coupled with dynamic modelling.

THEME 2: EARTH'S EVOLUTION

Earth's Evolution - Fluids in crustal and mantle tectonics; recycling of fluids into the deep mantle; hydrosphere, atmosphere and the deep Earth. Earth has evolved through cycles of crustal formation and destruction, punctuated by '*tipping points*', when rapid cascades of interlinked events produced dramatic changes in the composition of the oceans, the oxygen levels of the atmosphere, the tectonic behaviour of the crust and mantle, and the distribution of mineral and energy resources. These events changed the distribution and behaviour of fluids in the deep Earth, and each altered Earth's evolution irreversibly.

Key issues are: when did subduction start; how did it contribute to the Earth's cooling; how has this process evolved through time? Isotopic studies will define the rates of continental growth *vs* recycling through time, and test linkages between crust and mantle events. Geophysical imaging and dynamic modelling will be used to build 3D models of subduction dynamics, thermal evolution and geodynamic cycles. Stable-isotope studies will track water and other fluids in their cycles through the Earth and the hydrosphere.

THEME 3: EARTH TODAY

Earth Today - Dynamics, decoding geophysical imaging, and Earth resources. Geophysical imagery gives us a snapshot of the current status of the deep Earth but also carries the imprints of past processes. Realistic interpretation of these data will give us new insights into Earth's internal dynamics and will have practical consequences, e.g. for resource exploration. We will develop thermodynamically and physically self-consistent dynamic codes to model complex processes and their expression in geophysical and geochemical observables. This code will be used to identify the processes that have controlled the fluid cycle through Earth's history.

Measurement of the physical properties of potential deep Earth materials at extreme conditions will feed into petrophysical modelling of seismic data in terms of composition, temperature and anisotropy. Measurements of metal complexing at realistic conditions that mimic real ore-system fluids/melts will provide new ways to interpret observations on fluid/melt inclusions in minerals. We will investigate the role of organo-metallic compounds in metal transport, using the capabilities of the Australian Synchrotron, to understand the role of such compounds in the formation of large mineral systems.

CCFS participants at the Science Advisory Committee Meeting in August 2012.

Structure

CCFS builds on a world-class infrastructure base, and multiplies the capabilities of three internationally recognised centres of research excellence: Macquarie University (lead institution), Curtin University and the University of Western Australia. The Geological Survey of Western Australia is a Partner Institution and researchers from Monash University and the University of New South Wales are formally affiliated. Five overseas nodes led by Partner Investigators in France, China, Canada, Germany and the USA are contributing resources and provide access to a wide variety of expertise and instrumental capabilities. CCFS incorporates several pre-existing centres within the Administering and Collaborating Institutions: the GEMOC Key Centre (http//www.gemoc.mq.edu.au/) at Macquarie University retains its structure and is fully incorporated within CCFS; the research and strategic activities of CET (Centre for Exploration Targeting; http://www.cet.edu.au/) at the University of Western Australia lie within CCFS; and the activities of TiGeR (http://tiger.curtin.edu.au/) at Curtin University are also aligned with CCFS.

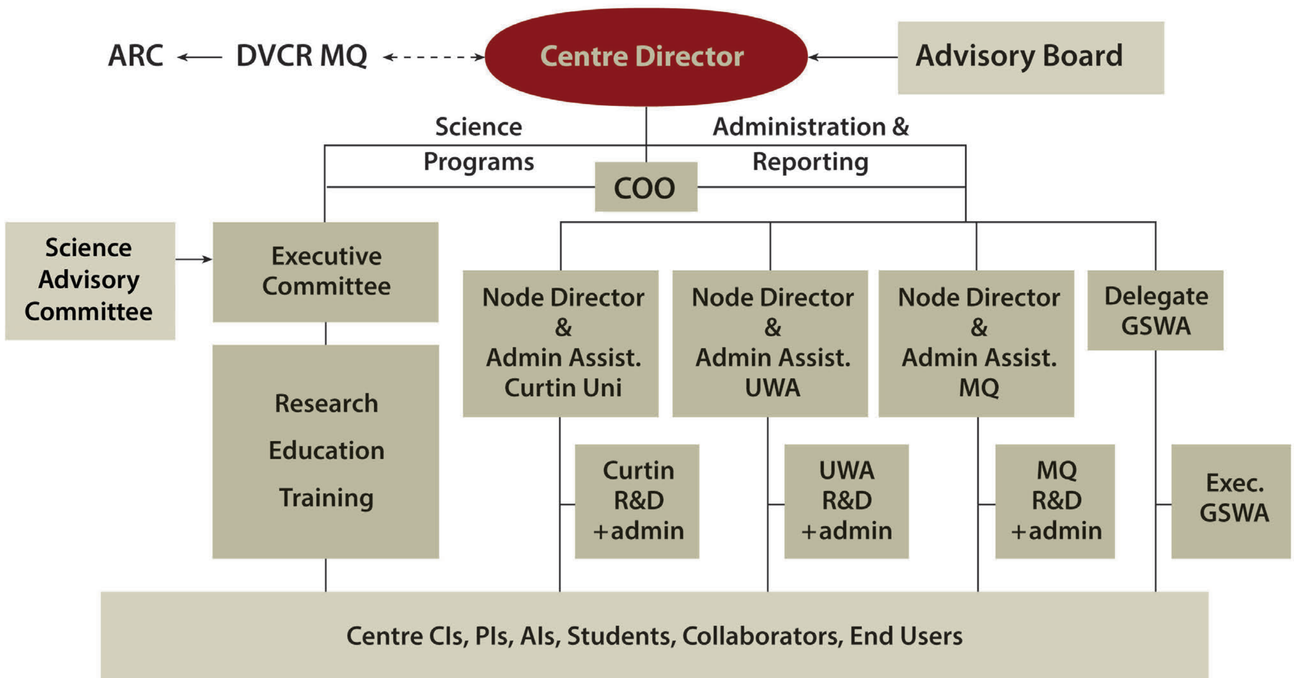
There is active national collaboration with state Geological Surveys, Geoscience Australia (GA), CSIRO, the Australian National University (RSES), Newcastle University, the University of Sydney, the University of Wollongong, the University of Adelaide and several major industry collaborators (national and global), across a broad range of projects related to the CCFS strategic goals. A distinctive feature of CCFS is the high level of active international collaborations and reciprocal links (see the section on *International links* and *Appendix 3*).

MACQUARIE UNIVERSITY

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieve International Excellence

Curtin University

GEOLOGICAL SURVEY WESTERN AUSTRALIA



Governance & management

Centre Director Professor Suzanne O'Reilly is supported by a Chief Operating Officer and a Publicity and Development Officer. Professor O'Reilly provides scientific leadership and strategic direction for the Centre. Node Directors administer the CU and UWA nodes and are responsible for providing leadership in their respective nodes, bringing together researchers to form a coherent team with a shared vision of the whole CoE's aims and objectives. The Geological Survey of Western Australia has a nominated representative.

Professor O'Reilly chairs an Executive Committee, which guides the Advisory Board, and Centre Director on the appropriateness of the research strategies, reports on progress in achieving aims as well as structure and general operating principles, and identifies and protects the Centre IP.

The Advisory Board includes senior representatives from industry and other end users such as Geoscience Australia. This model has proven highly productive during the lifetimes of the GEMOC Key Centre and CET. The Board meets annually to provide advice on the research program and governance, and any other matters relevant to CCFS.

The Science Advisory Committee has a rotating membership and primarily evaluates the Centre's research, in particular its research strategies, structure and outcomes.

Executive Committee

Professor Suzanne Y. O'Reilly - Director
Department of Earth and Planetary Sciences
Macquarie University

Professor William L. Griffin
Department of Earth and Planetary Sciences
Macquarie University

Dr Craig O'Neill
Department of Earth and Planetary Sciences
Macquarie University

Professor Simon Wilde - Node Director
Department of Applied Geology
Curtin University

Professor Zheng-Xiang Li
Department of Applied Geology
Curtin University

Professor Campbell McCuaig - Node Director
School of Earth and Environment
University of Western Australia

Professor Marco Fiorentini
School of Earth and Environment
University of Western Australia

Dr Ian Tyler (Ex Officio)
Assistant Director Geoscience Mapping
Geological Survey of Western Australia

Cate Delahunty (Ex Officio)
Department of Earth and Planetary Sciences
Macquarie University

Advisory Board

Dr Ian Gould
Chancellor
University of South Australia

Dr Paul Heithersay
Deputy Chief Executive, Resources & Energy
DMITRE

Dr Jon Hronsky
Principal
Western Mining Services

Dr Andy Barnicoat
Chief of Minerals & Natural Hazards
Geoscience Australia

plus the Executive Committee

Science Advisory Committee

Professor Stephen F. Foley
Head WG petrology
Johannes Gutenberg University of Mainz

Professor Julian Pearce
School of Earth and Ocean Sciences
Cardiff Univesity

Professor Stephen P. Grand
Jackson School of Geosciences
University of Texas

Participants

Organisations

Administering Organisation

Macquarie University

Collaborating Organisations

Curtin University

University of Western Australia

Partners

Australian Partner

Geological Survey of Western Australia

International Partners

CNRS and University of Montpellier, France

Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

University of Maryland, USA

University of Saskatchewan, Canada

Bayreuth University, Germany

Chief Investigators

Professor Suzanne Y. O'Reilly - Director; Macquarie University

Professor Simon Wilde - Curtin University

Professor T. Campbell McCuaig - University of Western Australia

Professor Mark Barley - University of Western Australia

Professor William Griffin - Macquarie University

Professor Zheng-Xiang Li - Curtin University

Assoc. Professor Norman Pearson - Macquarie University

Professor Simon Turner - Macquarie University

Professor Martin Van Kranendonk - University of NSW

Partner Investigators

Australian Partner Investigator

Dr Klaus Gessner - Geological Survey of Western Australia

International Lead Partner Investigators

Dr David Mainprice - Montpellier

Professor Fuyuan Wu - CAS Beijing

Professor Michael Brown - Maryland

Professor Rob Kerrich - Saskatchewan

Professor Catherine McCammon - Bayreuth

ECSTARS

Dr José María González-Jiménez - Macquarie University

Dr Takako Satsukawa - Macquarie University

Dr Xuan-Ce Wang - Curtin University

Associate Investigators

Dr Juan Carlos Afonso - Macquarie University

Dr Olivier Alard - Universite de Montpellier, France

Dr Elena Belousova - Macquarie University

Dr Christopher Clark - Curtin University, from 2013

Assistant Professor John Cliff - CMCA University of Western Australia

Assoc. Professor Nathan Daczko - Macquarie University

Professor Marco Fiorentini - University of Western Australia

Professor Simon George - Macquarie University

Dr Richard Glen - NSW Geological Survey

Dr Masahiko Honda - Australian National University

Dr Matthew Kilburn - CMCA University of Western Australia

Dr Chris Kirkland - Geological Survey of Western Australia

Dr Louis-Noel Moresi - Monash University

Assoc. Professor Alexander Nemchin - Curtin University

Dr Craig O'Neill - Macquarie University

Dr Sandra Piazolo - Macquarie University

Professor Steven Reddy - Curtin University

Assoc. Professor Tracy Rushmer - Macquarie University

Dr Bruce Schaefer - Macquarie University

Professor Paul Smith - Macquarie University

Dr Michael Wingate - Geological Survey of Western Australia

Dr Yingjie Yang - Macquarie University

Professor Shijie Zhong - University of Colorado, Boulder, USA

ECRs

Dr Marion Grange - Curtin University

Dr Yoann Gréau - Macquarie University

Dr Daniel Howell - Macquarie University

Dr Jin-Xiang Huang - Macquarie University

Dr Yongjun Lu - University of Western Australia

Dr Mary-Alix Kaczmarek - Curtin University

Dr Monika Kusiak - Curtin University

Dr Marek Locmelis - University of Western Australia

Dr Yongjun Lu - University of Western Australia

Dr Michael Turner - Macquarie University

A full list of CCFS participants is given in *Appendix 3* and at http://www.ccfs.mq.edu.au/

NEW STAFF

Dr Takako Satsukawa - ECSTAR and ECR researcher at CCFS Macquarie - See *p. 11, 127.*

Dr Chris Clark received his PhD, on the structural controls on fluid flow in the Curnamona Province of central Australia, from the University of Adelaide in 2006. He then spent 18 months at Adelaide as an ARC postdoctoral research associate investigating the pressure-temperature-time-deformation (P–T–t–d) histories

of high-grade metamorphic terranes in Australia, Antarctica and India. He moved to Perth on a five-year Curtin University Research Fellowship in 2007 where he has continued to work on processes in high-grade metamorphic rocks. In 2012 he was awarded a second Curtin University Fellowship and an ARC DECRA (ARC Discovery Early Career Research Award) grant to investigate the conditions under which crustal rocks reach thermally extreme conditions at a regional scale and the implications this has for the strength of mountain belts and the transfer of heat production within the crust.

Primarily a metamorphic geologist, his research involves the integration of techniques and data from the fields of geochemistry, geochronology, structural geology and tectonics. His principal research interests are fluid flow in mid-crustal rocks, particularly with respect to constraining the timing of fluid ingress and potential fluid sources involved in the rehydration of granulite terranes at the grain-to-terrane scale; high-T and ultrahigh-T metamorphism; the P–T–t–d evolution and tectonics of metamorphic belts, and the application of petrology to understanding orogenic evolution; secular change in styles of tectonics and metamorphism. His work is currently focused on high-grade terranes in India and Antarctica with other collaborative research projects underway in Madagascar, Scotland and central Australia. See *Research highlight p. 53.*

Dr Leon Bagas - Research Associate Professor (Regional Tectonics, Structural Geology, Stratigraphy, Geochronology, Economic Geology) CET, CCFS UWA - See *Research highlight p. 42.*

Dr Laure Martin - Research Associate CMCA, CCFS UWA - See *p. 4, 75.*

CCFS FUTURE FELLOWS

The application for the CoE CCFS foreshadowed that such a Centre of Excellence would become an attractor for rising stars and research leaders in relevant disciplines and fields of interest. The success of CCFS participants in the Future Fellow rounds emphasises this role of our Centre in recruiting high-flyers at early to mid-career levels. Four Future Fellows, Dr Elena Belousova, Professor Marco Fiorentini, Dr Craig O'Neill, and Dr Sandra Piazolo, have projects relevant to CCFS goals and are profiled in our previous report (http://www.ccfs.mq.edu.au/AnnualReport/11Report/Participants.html). Two new Fellowships were awarded in 2012.

Dr Heather Handley completed her BSc (Hons I) at Edinburgh University in 2001 and then completed a PhD on the petrogenesis of Indonesian volcanoes at Durham University. She was awarded an Ogden Trust Teaching Fellowship in 2005 to work for a year with high school students and their teachers to raise the scientific awareness and aspirations of pupils. She continues to strive to enthuse high school students through science outreach activities at Macquarie University.

In 2012 she was invited to bring the excitement and importance of her research area into public view as an invited scientist in

the filming of a documentary on Krakatau Volcano for The Discovery Science Channel. During her PhD she became aware of the importance of Uranium-series (U-series) isotope research, which can uniquely place timescale constraints on a wide range of young geological processes. In 2007 she started as a Post-doctoral Research Associate with Professor Simon Turner in the GEMOC Key Centre at Macquarie University, one of the few laboratories with this capability, and focused on the timescales of young volcanic processes. Heather mastered and helped to further develop and improve methods for U-series isotopic analyses of volcanic rocks, applied to island arc and intra-plate volcanic settings. Heather was awarded a Humboldt Foundation Research Fellowship at LMU in Munich, Germany in 2008 to conduct experiments on magma mixing and contamination. She then returned to Macquarie University in 2009 as a Post-doctoral Research Associate (on an ARC Linkage grant) to work on new, exciting applications of U-series isotopes to constrain sediment weathering and residence timescales.

Heather's Future Fellowship entitled "*The timescales of Earth-system processes: extending the frontiers of uranium-series research*" will capitalise on the recent exposure of a unique volcanic stratigraphy at Merapi Volcano in Indonesia to:
1) advance our understanding of short-lived isotope disequilibria in volcanic rocks and 2) test and develop the U-series comminution method for dating continental sediments and soils (lying between independently datable volcanic deposits). This research will elucidate the driving forces behind geologically rapid transitions in the eruptive behaviour of volcanoes (effusive to explosive) and, via the development of new methodologies, will permit more accurate dating of Quaternary soils and sediments. The outcomes will benefit volcanic hazard mitigation policy and provide crucial knowledge on the rates of the effects of climate change in the landscape. This project is part of CCFS Theme 3, Earth Today, and contributes to understanding Fluid Fluxes in the Earth.

Dr Dorrit Jacob studied mineralogy and geology at the University of Mainz after working at the Max Planck-Institute for Chemistry as a chemical laboratory assistant. She received her Diploma in 1991 and her PhD at the University of Goettingen in 1995 for work on the geochemistry and radiogenic isotopes of mantle eclogites. Following a spell at the University of Greifswald, she moved to Mainz and switched to the new field of biomineralisation from 2006 onwards, building up a research group in the Geocycles Research Centre. This was recently recognised by the award of a nationally funded Heisenberg Chair in Biomineralisation, which she took up at the University of Mainz in 2012. She leaves this full professorship to take up the Future Fellowship at the CCFS in 2013. Dorrit has twice set up laboratories for Laser-ICP-MS, in Greifswald and Mainz, and maintains an interest in diamond formation and the geochemistry of the lithosphere in addition to biomineralisation.

In her Future Fellowship project, she will study the geochemistry and mineralogy of the skeletons of marine organisms as a means to characterise their growth environment. This research will enable the effects of physiological processes on the composition of biominerals to be characterised, thus unlocking the door to palaeoclimate information that can be won from this skeletal material. The project uses a multi-technique approach, combining innovative cutting-edge *in-situ* analytical methods with culture-growth experiments and field studies. Robust links between environmental conditions and biomineral nanostructure will provide new tools for the analysis of palaeoclimate and the monitoring of past environmental change.

EARLY CAREER RESEARCHERS (ECR)

The second primary goal of CCFS (see above) concerns the recruitment, development and mentoring of Early Career Research (ECR) staff "*for the development of the next generation of Australia's geoscientists*".

A Government White Paper in 2010 "*Meeting Australia's research workforce needs*" stated that "*There is a looming gap in the pool of potential leaders in geoscience research and training in Australia; the current crop of leaders is a senior generation, and there are few in the demographic down to people now in their 30s or younger. We need to bring some of this younger group along rapidly, and begin generating a new pool of potential leaders, to avoid a collapse in a research field that is essential to national wealth creation.*"

As part of the solution to this problem, the CCFS proposal specifically targeted funding toward several outstanding ECRs newly employed at the partner institutions. It also foreshadowed that "*the employment of… Centre-funded postdoctoral fellows will bring in young people with targeted expertise and potential, and develop them into the next generation of leaders in research and training.*"

The initial awarded funding framework of CCFS resulted in a revision of the ECR recruitment capacity. However, the ARC provided an opportunity to apply for additional post-award funding dedicated to ECRs. The success of that application allowed CCFS to enhance the ECR training capability. It also represents a strategic intention to further expand our network of overseas investigators and to further enhance strands of research that currently are under-represented in Australia.

The post-award funding allowed the recruitment of four postdoctoral fellows on terms analogous to the DECRA grants (ARC Discovery Early Career Researcher Award). These positions within CCFS have been named "ECSTAR": Early Career Start-up Awards for Research. Three have commenced research in CCFS and one position is under selection.

The following profiles present 2012 ECRs (including the three appointed ECSTARs in CCFS) and summarise their expertise and research areas.

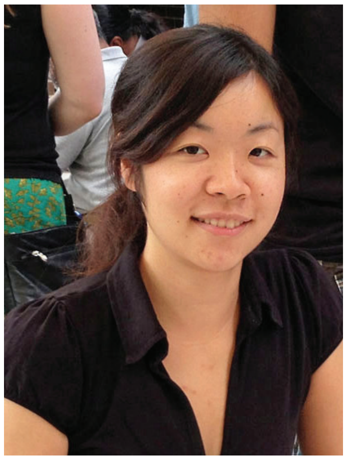
New

Dr Monika A. Kusiak came to Curtin University (Perth) as a Marie Curie Fellow in 2011, following a G08 fellowship at UWA. Monika completed her doctoral thesis in geochronology at the Polish Academy of Science, working mostly on the Bohemian Massif. Monika's research interests focus on the U-Th-Pb geochronology of monazite, zircon and xenotime, including provenance studies, accessory mineral behaviour in evolving magmatic systems, and resetting of isotope systematics by metamorphic, hydrothermal and diagenetic activity. At Curtin, Monika is conducting a worldwide search for traces of early

Earth history preserved in zircon, in localities as widespread as Antarctica, India and Greenland. She is also investigating how such records are disturbed by high-temperature metamorphic events, using ion-beam imaging and other advanced microanalytical technologies. Such techniques have revealed disturbance of isotopic systems by element mobilisation within zircon on a sub-micron scale. This work is part of Theme1, Early Earth. See *Research highlight pp. 59-60.*

Dr Takako Satsukawa joined CCFS/GEMOC in October 2012 as an ECSTAR (Early-Career Startup Award Researcher) funded by an ARC Centre special grant to CCFS for early-career researchers. She completed her PhD jointly at Shizuoka University (Japan) and the Université Montpellier (France). Her dissertation research focused on microstructural and petrological characteristics of mantle-derived peridotite xenoliths in basaltic rocks and their implications for the evolution and seismic anisotropy of the uppermost mantle beneath the back-arc region. She mastered the application of Electron Backscatter Diffraction (EBSD) technology to measure the crystallographic preferred orientations (CPO) of individual grains of minerals. Her current research interests include the rheology of the uppermost mantle and the history of the roots of ancient continents to provide new constraints on the rheological properties of the lithospheric mantle.

"My other interests focus on the discovery of Australian culture! I am pleased to have the opportunity to explore this exciting new research at CCFS/GEMOC."



Her research interests lie in developing a systematic approach to mapping the behaviour of melts and fluids in the upper mantle. Takako approaches this by combining microstructural analysis, analysis of water contents, numerical modelling of the seismic properties of individual samples, and geochemical analyses of xenoliths from different lithospheric levels which have experienced different degrees of melt-rock interaction. Since previous work by GEMOC has used geochemical analysis, a new methodology for mapping '*hidden*' microstructures can be developed by combining these approaches. As this project has just commenced, the characterisation of the microstructural evolution of mantle-derived rocks from the cratonic lithosphere has started to explore the CPO mapping of statistically representative sample sets from key mantle domains representing specific tectonic histories, and which are already geochemically well characterised. This project is part of CCFS Themes 2 and 3, Earth's Evolution, and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Continuing

Dr Marion Grange has been employed by Curtin University since March 2008, and joined the CCFS in 2011. Marion is interested in providing better timing constraints on the early stages of differentiation and the early meteoritic impact history of Earth and Moon by studying isotopic systems of ancient materials from both planetary bodies. Her recent work showed that careful textural characterisation of zircon and apatite in lunar impact melt breccias is necessary to properly interpret *in-situ* geochronological

data of these complex grains. During 2012 her work concentrated on magmatic and alteration minerals in Martian meteorites. She has worked on characterising carbonates from Mars and obtained stable isotopes on these minerals. She has also identified several phosphate grains in other Martian samples, that will be used for U-Pb geochronology.

Dr Yoann Gréau joined GEMOC in 2007 as a PhD candidate (graduated 2011) after obtaining an MSc from the University of Montpellier II (France), where he trained in ultramafic petrology and geochemistry, studying ultra-refractory abyssal peridotites. During his PhD studies, he investigated the origin and history of eclogite xenoliths brought up from the lithosphere-asthenosphere boundary by kimberlitic magmas. His research focused on the petrology and geochemistry of the sulfide phases, looking at siderophile and chalcophile elements (e.g. Cu, Ni, Se, Te, PGEs and S isotopes). He also investigated the relationships between microstructures and mineral geochemistry (e.g. REE, HFSE, LILE and O isotopes) of the main silicate phases, demonstrating strong links between mantle eclogites and metasomatic processes occurring within the sub-continental lithospheric mantle.

In 2012 Yoann co-managed the *TerraneChron*® team in CCFS. *TerraneChron*® uses a specifically developed methodology to study the evolution of the continental crust through time by using integrated *in-situ* analysis of zircons for U-Pb ages and O- and Hf-isotope composition. The methodology, developed at Macquarie University, has had great success with our industrial and geological survey partners; it provides the partners with information useful in their mapping and exploration programs, and gives the team valuable data for large-scale research. In 2012, *TerraneChron*® imaged and analysed 3463 grains of zircons for a total of 23 different projects from different regions of 4 continents.

Dr Dan Howell is a postdoctoral research associate in CCFS working on the structure and origin of diamonds, a unique recorder of mantle fluid activity. By studying fluid and mineral inclusions trapped within them, this robust capsule mineral can provide direct samples from the depths of the Earth. Publications in 2012 utilised the infrared-mapping data-processing technique that he developed with Craig O'Neill *(CCFS publication #168);* he is now focusing on trace element distributions and abundances, especially understanding their partitioning in mixed-habit diamonds. He has been investigating the causes of pink colour in naturally deformed diamonds using the electron backscatter diffraction facility now operational within CCFS (Macquarie University node). See *Research highlight p. 63*.

Dr Jin-Xiang Huang completed her undergraduate study at China University of Geosciences, Beijing, and was one of the top students in her class. She received her PhD at GEMOC (December 2011) with a study of the metasomatism and origins of xenolithic eclogites from the Roberts Victor kimberlite, South Africa. This gave her extensive experience in the clean labs and on state-of-art instruments to get precise geochemical data; and in integrating a wide range of information into one model. She discovered that mantle metasomatism has completely changed the petrography and chemical and isotopic compositions of most eclogites. The evidence from these thus cannot be used to support the popular idea that they represent subducted oceanic crust. Information from primary eclogites favours their origin from deep-seated magmas.

After her PhD, she joined CCFS as a post-doctoral research associate, to work on the Mg and Oxygen isotopes of mantle rocks (both eclogites and peridotites) and in different mantle

processes (e.g. magma crystallisation, mantle metasomatism). This will provide a better understanding of mantle processes and further constraints on geodynamics.

In 2012, she developed high-Cr garnet standards for *in-situ* O-isotope analysis by ion probe. Combined with the low-Cr standards, garnets of any composition can now be measured; the fine-scale homogeneity/heterogeneity of $\delta^{18}O$ can be mapped and used as one important piece of information for understanding geological processes. See *Research highlight pp. 34-35*.

Dr José María González-Jiménez is a geologist/mineralogist specialising in the mineralogy and geochemistry of the Platinum-Group Elements (PGE), especially in ore deposits

associated with mafic/ultramafic rocks. He received his PhD from the University of Granada (Spain) in 2009, having investigated the mechanisms of concentration and remobilisation of PGE in ore deposits from ophiolite complexes in Cuba, Bulgaria and New Caledonia. His research is focused on the mineralogy and geochemistry of the PGEs, to find out how these noble metals are concentrated into economic deposits in Earth's upper mantle and how they are re-mobilised during post-magmatic events. His work as a Research Fellow at CCFS has taken several new directions. One is the application of Re-Os isotopic systematics to the Platinum-Group Minerals (PGM), using *in-situ* microanalysis by LA-ICPMS; another is based on the analysis of trace-element patterns in chromite from different styles of magmatic deposits. Combining mineralogical, petrologic, geochemical, isotopic and thermodynamic approaches, he is modelling the mechanism(s) of magmatic concentration of the Platinum Group Metals and chromium. This work is providing an improved explanation for the genesis and tectonic setting of PGE-bearing chromite deposits. Another relevant aspect of his work at CCFS is a statistical study of the size distribution of the PGM in different microstructural settings and the characterisation of their Os-isotope composition. This has led to the discovery that the PGE can be re-mobilised/re-concentrated by the hydrothermal/metasomatic fluids that commonly affect lithospheric mantle rocks. This process also affects the Os-isotope signatures of Os-rich minerals, in contrast to accepted ideas about the stability of the Re-Os isotopic system in the mantle. See *Research highlight p. 37*.

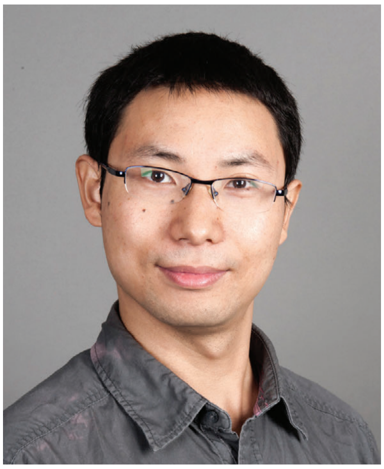
Dr Mary-Alix Kaczmarek joined CCFS in mid 2011 as a postdoctoral research fellow. She graduated with a PhD from the University of Neuchâtel (Switzerland) in 2007, with a thesis focused on upper-mantle shear zones. After her PhD, she took a postdoctoral CNRS position at Géosciences Montpellier (France), working on the microstructures and geochemistry of mantle xenoliths from southeastern Algeria. She then moved to Curtin University (Perth) in 2010, and joined the CCFS in 2011. The principal objectives of her work are to explore the relationships between deformation mechanisms and reactive fluid/melt transport. These factors have implications for the initiation of shearing and on the underlying controls this has on the way tectonic plates deform. To study these processes she applies state-of-the-art micro-analytical techniques such as EBSD and LA-ICPMS to investigate the role that fluid/melt and mineral chemistry plays in the mechanical stability of the rock. During 2012, her research has concentrated on peridotites from rifting and ocean-continent transition environments (CCFS Project 2b), and Martian meteorites (CCFS Project 7). She investigates the peridotites to constrain the interaction between deformation and fluid flow, with a special interest in the interaction between intragrain and intergrain deformation processes and chemical reactions associated with hydration of the mantle. The aim of the Martian study is to characterise the fluids and their interaction with minerals, and to obtain information on primitive mantle deformation mechanisms and processes. See *Research highlight pp. 56-57*.

Dr Marek Locmelis joined the CCFS in 2011 as part of CET's research team on Magmatic Mineral Systems, to unravel the mysteries associated with the formation of nickel-sulfide ore systems in the deep lithosphere and metal and fluid transport processes in the Earth's mantle. In 2012, Marek undertook fieldwork in the Ivrea-Verbano Zone in Italy, one of the few localities in the world where magmatic Ni-Cu-(PGE) sulfide deposits are hosted by rocks from the deep lithosphere that have been uplifted to the surface. New geochemical data demonstrate a strong relationship between mantle metasomatism and sulfide-associated mineralisation, making the Ivrea-Verbano Zone an excellent natural laboratory to investigate

metal sources and transport mechanisms in the deep Earth (see *Research highlight p. 62* and *Appendix 1*). The work on the Ivrea-Verbano Zone is integrated with a series of hydrous high-pressure and high-temperature experiments to investigate the capacity of near-solidus melts and fluids to transport metals at lithospheric mantle-asthenospheric conditions.

Marek presented his work at the International Geological Congress 2012 in Brisbane and at the American Geophysical Union's Fall meeting 2012 in San Francisco.

Dr Yongjun Lu is a Research Associate working on the CCFS Foundation Project *"4D lithospheric evolution and controls on mineral system distribution: The Western Superior-Yilgarn comparison"*. In 2012, in addition to ongoing zircon multi-isotopic analysis, Yongjun established a sound collaboration with Lakehead University and the Ontario Geological Survey to carry out a successful field season in Ontario. Yongjun also helped attract a new PhD student, Katarina Bjorkman, to join this project. To establish and maintain the leadership of CCFS in the field of 4D lithospheric mapping, Yongjun has initiated, with Professor Zengqian Hou, the zircon Hf-isotope mapping of Tibet. This is the first time this technique has been applied in a Cenozoic collisional orogen. This project has already led to exciting discoveries. Another collaborative project on *"Genesis of fertile hydrous adakitic melts in orogenic porphyry Cu system"* has been initiated and led by Yongjun in 2012 in order to address one of CCFS's themes of understanding fluids in the crust and mantle. This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes. See *Research highlight pp. 39-40.*



Dr Michael Turner joined CCFS at Macquarie in 2011 as part of a three-year Post-Doctoral Fellowship from the New Zealand Foundation of Science and Technology. In 2012 he used short-lived U-series isotopes to determine the timescales of magma degassing events. His research supplements the isotopic research by *in-situ* analysis of water in pyroxene phenocrysts. Pyroxenes crystallise over a large range of magmatic temperatures and pressures, and have the potential to record water contents of their host magmas during differentiation. The results are helping to understand the driving forces behind explosive volcanic eruptions.

Dr Xuan-Ce Wang joined CCFS in 2011 as a postdoctoral research fellow at Curtin University. His primary role in CCFS is to examine possible linkages between plate tectonics and mantle plume dynamics, to test the effects of deep water cycling on the thermal evolution of the Earth's mantle, and to identify evidence for plume-related magmatism in Australia and other continents. In 2012, he acquired high-precision Pb, Sr, Nd, and Os isotope data for the Hainan flood basalts. Synchronous basalts from the South China Sea and adjacent areas share the same Pb, Nd, Sr, and Pb isotopic compositions, implying that the generation

of these basalts probably involved a plume that originated in the lower mantle. The study, along with previously published data, confirms the coexistence of an ancient (4.5-4.4 Ga) mantle reservoir and the involvement of young (0.5-0.2 Ga) recycled materials in the source region of the late Cenozoic Hainan plume. The work also provides the first observational support for dynamic linkages between deep subduction and mantle plume generation. This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes. See *Research highlight pp. 48-49.*

The CCFS research program

The CCFS CoE builds on world-class infrastructure and has already multiplied the capabilities of the Collaborating and Partner Institutions. The research program aims to amplify existing strengths in geology, geochemistry, geophysics, experimental petrology and petrophysical/dynamic modelling, and to promote closer integration of these disparate fields.

Major Research Objectives

- **to determine, using constraints from Earth's oldest crust and mantle, lunar samples and meteorites, the role of fluids in creating a dynamic planet**
- **to understand how Earth's core-mantle system and its interaction with fluids have produced periodic cataclysms and controlled the evolution of the crust, hydrosphere and atmosphere**
- **to develop new approaches to petrophysical and dynamic modelling, integrating geophysics, geodynamics and geochemistry**
- **to develop an integrated Earth model linking tectonics, internal structure and dynamics, and the fluid-mediated transport of mass and energy from the interior to the surface**
- **to develop new approaches to interpreting geophysical imagery, for application to basic science and resource exploration**
- **to develop a new understanding of the timing and distribution of giant resource systems, based on a new level of understanding of Earth's fluid plumbing systems, processes and dynamics**
- **to undertake the strategic, frontline developments in hardware, analytical methodologies, theory and software technology that are required to fulfil the research goals**

These objectives are being addressed through the Research Projects described below.

The scope of the research, and thus of the Foundation Projects, is determined by the funding base allocated by ARC with strategic leverage planned to expand available resources.

FOUNDATION RESEARCH PROJECTS

Foundation Projects have a substantial funding component from the ARC Centre funds allocation, and many also include components from the Node University funding support. The first tranche of these Foundation Projects was chosen from formal applications by CCFS participants based on presentations and discussions at a 2-day meeting in October 2010, ratified by the Executive Committee, and accepted on report to the Advisory Board. Foundation Projects include an interdisciplinary perspective, cross-node and early-career/postgraduate researchers participation, and/or topics reflecting ARC grants relinquished consequent on the award of the CoE CCFS. These latter were, by their nature, fully aligned with Centre goals.

The range of topics covered by the Foundation Projects reflects studies within the three major Themes prioritised within the imposed funding framework, and some aspects (especially some deep-Earth experimental aspects of Theme 1) had to be postponed. Projects range across understanding Early Earth, identifying deep Earth fluids and element transport, tracking mantle evolution, geophysical imaging of deep-Earth flow, geodynamics of the Australian continent in the Proterozoic, and the 3-D architecture of the Yilgarn Craton (Australia) from new deep seismic and magnetotelluric datasets and crustal geochronology (see full list *p. 16*). Projects matured and identified new directions during 2012 as reported in *Appendix 1*.

Foundation Projects also include three whole-of-Centre projects undertaking Technology Development, one of the key goals embedded in the Centre strategy, and delivering on a key KPI.

For Foundation Project summaries, progress for 2012 and plans for 2013 see *Appendix 1*.

Independently funded basic research projects are listed in *Appendix 2*.

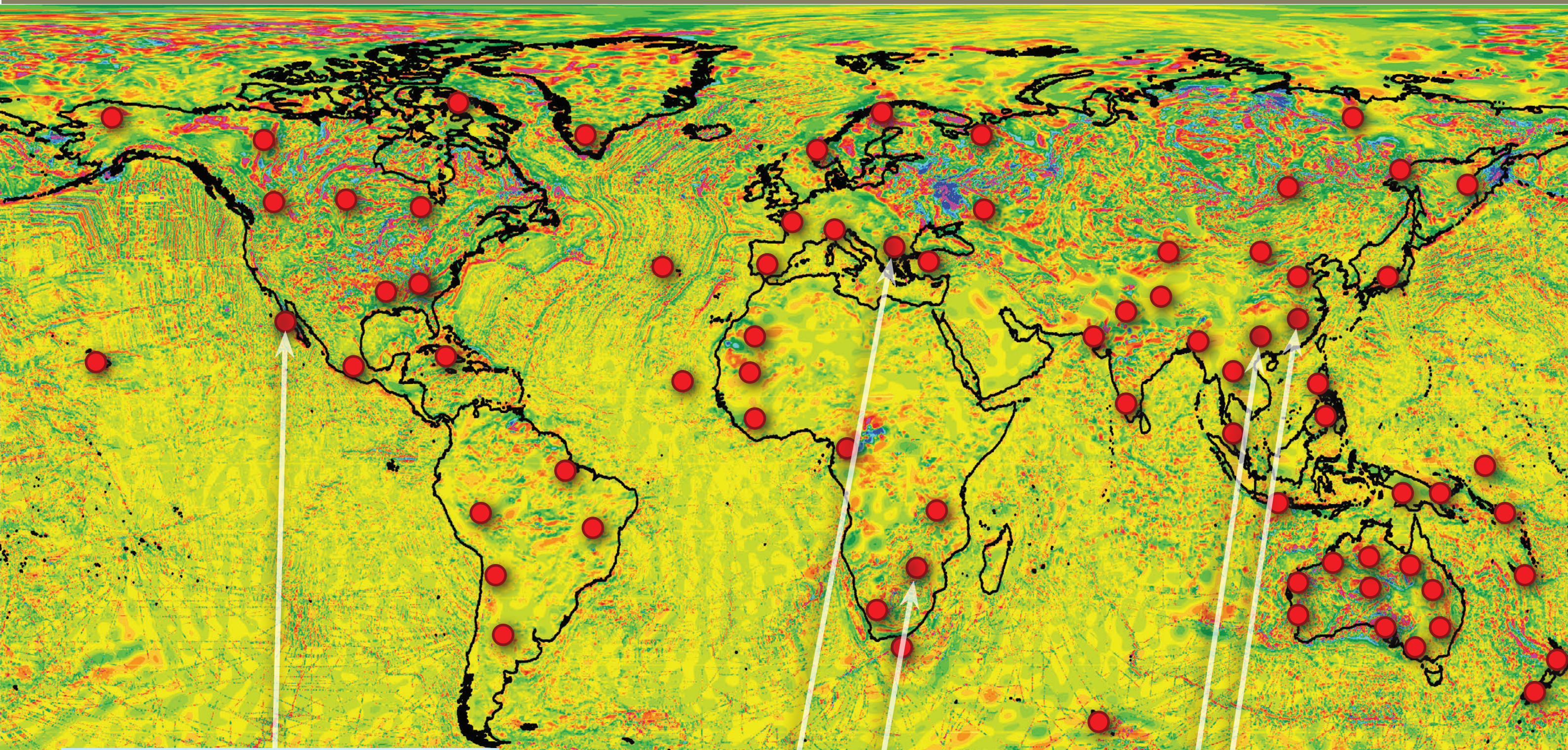
FOUNDATION RESEARCH PROJECTS

Project	Coordinator and main Centre personnel
1. The TARDIS project: Tracking ancient residues distributed in the silicate Earth	O'Reilly, Griffin, Pearson, Fiorentini, O'Neill, Afonso, Yang, Cliff, Martin, Kilburn, Belousova, González-Jiménez (ECSTAR, ECR), Satsukawa (ECSTAR, ECR), Huang (ECR), Locmelis (ECR), Xiong, Saunders, Yao and McGowan (PhDs)
2a. Metal sources and transport mechanisms in the deep lithosphere	Fiorentini, McCuaig, Barley, Rushmer, Griffin, Pearson, Evans, Reddy, Kilburn, Locmelis, Turner, O'Reilly, Davies and Owen (PhDs)
2b. Dynamics of Earth's mantle: assessing the relative roles of deformation and magmatism	Reddy, Kaczmarek (ECR)
3. Generating and stabilising the earliest continental lithosphere - Late granite blooms	Griffin, O'Reilly, O'Neill, Pearson, Van Kranendonk, Belousova, Gréau (ECR), Murphy and Gao (PhDs)
4. Two-phase flow within Earth's mantle: modelling, imaging and application to flat subduction settings	O'Neill, Afonso, Yang, Li, Gorczyk (ECR), Grose, Jiang, Ramzan, Oliveira-Bravo (from 2013), Peng, Tao, Zhu and Huang (PhDs)
5. Early evolution of the Earth system and the first life, from multiple sulfur isotopes	Barley, Fiorentini, Kilburn, Wacey, Wilde, Nemchin, Griffin, PhDs to be named
6. Detecting Earth's rhythms: Australia's Proterozoic record in a global context	Li, Pisarevsky, Wingate, Wang (ECR, ECSTAR), Niu (PhD)
7. Fluid regimes and the composition of the early Earth	Wilde, Nemchin, Grange (ECR), Barley, Kusiak, Pidgeon, Wang (PhD)
8. Diamond Genesis: Fluids in deep-Earth processes	Griffin, O'Reilly, Pearson, Cliff, Martin, Kilburn, Howell (ECR), Rubanova and Yao (PhDs)
9. 4D lithospheric evolution and controls on mineral system distribution: The Western Superior-Yilgarn comparison	McCuaig, Fiorentini, Kemp, Belousova, Cliff, Kirkland, Van Kranendonk, Lu (ECR), Bjorkman (from 2013) (PhD)
10a. 3D architecture of the western Yilgarn Craton	Gessner, Van Kranendonk, Tyler, Belousova, Yang, Afonso, O'Neill, Gorczyk, Zhang (ECR)
10b. Zircon Lu-Hf constraints on Precambrian crustal evolution in Western Australia	Wingate, Belousova, Tyler

WHOLE OF CENTRE

Cameca Ion microprobe development: maximising quality and efficiency of CCFS activities within UWA Ion Probe Facility	Kilburn, Cliff, Griffin, Fiorentini, McCuaig, Barley, Pearson, Reddy, Martin, Huang (ECR), Howell (ECR), Rubanova and Xiong (PhDs)
Frontiers in integrated laser-sampled trace-element and isotopic geoanalysis	Pearson, Cliff, Griffin, O'Reilly, Kilburn
Optimising mineral processing procedures: From rock to micro-grains	Pearson, Belousova, Daczko, wide spectrum of Centre users

WHERE IN THE WORLD IS CCFS?



Baja Californiania Sur, Mexico

Devonian Sandstones, South China

The Mpuluzi batholith, SE Africa

NE Tibet

Turkey

Communications 2012

CCFS web resources provide information on background, research and downloadable files of the Annual Report and Research highlights.

Links to the GEMOC website (http://www.gemoc.mq.edu.au/) provide past GEMOC Annual Reports, updated details on its methods, 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.

Links to the CET (Centre for Exploration Targeting) website (http://www.cet.edu.au/) provide access to wider information about CET activities beyond its involvement in CCFS and especially the wide base of end-user interaction.

Links to The Institute for Geoscience Research (TiGer) website (http://tiger.curtin.edu.au/) provide information about their facilities, participants and research activities.

Strong industry interaction in CCFS in 2012 ranged from presentations to specific industry groups in their offices to numerous formal and informal workshops at CET and GEMOC, and invited and plenary presentations at peak industry symposia, workshops and conferences nationally and internationally.

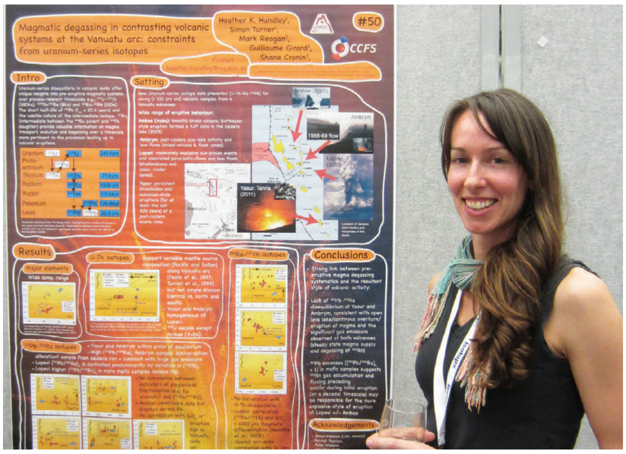
CCFS publications for 2012 are given in Appendix 4

The 133 CCFS publications that were published in 2012 are mainly in high-impact international journals as listed by the internationally recognised Thomson ISI Citation data. The publication list also includes some resulting from research prior to 2011, but from ARC grants that were relinquished because of their close alliance with Centre research, or from CET or GEMOC activity which are now part of CCFS.

PARTICIPATION IN WORKSHOPS, CONFERENCES AND INTERNATIONAL MEETINGS IN 2012

CCFS Investigators, associated staff, early-career researchers and postgraduates had a high profile at peak geophysical, metallogenic, geodynamic and geochemical conferences as convenors, invited speakers, or presenters, with 245 presentations including:

- Specialist Group in Tectonics & Structural Geology bi-annual Conference, Waratah Bay, Victoria, 29 January - 4 February 2012
- 22nd Australian Conference on Microscopy and Microanalysis (ACMM 22), - ACMM 22 /APMC 10 / ICONN 2012, Perth, Australia, 5-9 February 2012
- The 10th International Kimberlite Conference, Bangalore, India, 6-11 February 2012
- GSWA Open Day, Fremantle, 23 February 2012
- 108th Annual GSA meeting, Cordillera Section, Querétaro, Mexico, 29-31 March 2012
- Joint 5th Mineral Sciences in The Carpathians Conference (MSCC) and 3rd Central-European Mineralogical Conference (CEMC), Miskolc, Hungary, 19-21 April 2012
- European Geosciences Union General Assembly 2012, Vienna, Austria, 22-27 April 2012
- Scandem 2012 Annual Meeting of the Nordic Microscopy Society, 12-15 June 2012
- 12th International Ni-Cu-(PGE) Symposium, Guiyang, China, 16-17 June 2012
- Workshop: The Role of Metasomatism in Geological Processes, Université du Québec à Montréal, 23 June 2012
- 22nd V.M. Goldschmidt Conference, Montréal, Canada, 24-29 June 2012



Dr Heather Handley with her 'hot' Goldschmidt poster.

- XXXII Reunión Cientifica de la Sociedad Española de Mineralogía y XXII Reunión Cientifica de la Sociedad Española de Arcillas, Bilbao, Spain, 27-30 June 2012
- Geochemistry of Mineral Deposits, Gordon Conference, Protor Academy, New Hampshire, USA, 15-20 July 2012
- 34th International Geological Congress, Brisbane, 5-10 August 2012
- Meteoritical Society Annual Meeting, Cairns Australia, 12-17 August 2012
- The 13th International Conference on Thermochronology, Guilin, China, 24-28 August 2012
- The First European Mineralogical Conference (EMC2012) - Planet Earth from Core to Surface, Frankfurt, Germany, 2-6 September 2012
- AAPG International Conference and Exhibition, Fueling the Future, Singapore, 16-19 September 2012
- SEG 2012, Integrated Exploration and Ore Deposits, Lima, Peru, 23-26 September 2012

- Supercontinent Symposium 2012, Helsinki, Finland, 25-28 September 2012
- IESCA-2012 International Earth Science Colloquium on the Aegean Region, Izmir, Turkey, 1-5 October 2012
- Geochemistry and Ore Deposit Models Seminar, University of Oulu, Finland, 17-18 October 2012
- GSA Annual Meeting, Charlotte, USA, 4-7 November 2012
- 17th Australian Organic Geochemistry Conference, Biogeochemistry from Deep Time through Petroleum Resources to Modern Environments, Macquarie University, Sydney, 2-5 December 2012
- AGU's 45th Annual Fall Meeting, San Francisco, California, 3-7 December 2012
- 4th Greenland Day Workshop, Perth, Western Australia, 4 December 2012

INVITED TALKS AT MAJOR CONFERENCES 2012

22nd Australian Conference on Microscopy and Microanalysis (ACMM 22), - ACMM 22 / APMC 10 / ICONN 2012, Perth, Australia, 5-9 February 2012	Practical isotope ratio analysis using SIMS **J.B. Cliff** **Invited** Chemical and isotopic imaging at the sub-micron scale with NanoSIMS **M.R. Kilburn** **Invited** Scanning ion imaging - an underutilised yet potent tool in SIMS U-Pb zircon geochronology M. Whitehouse, C. Fedo, **M. Kusiak** and **A. Nemchin** **Invited** Unravelling early Earth evolution through microanalysis of zircon **S.A. Wilde** **Invited**
European Geosciences Union General Assembly 2012, Vienna, Austria, 22-27 April 2012	The compositional and thermal structure of the lithosphere from thermodynamically- constrained multi- observable probabilistic inversion **J.C. Afonso**, J. Fullea, **Y. Yang**, A.G. Jones, **W.L. Griffin**, J.A.D. Connolly, **S.Y. O'Reilly** and S. Lebedev **Keynote** Two types of Archean continental crust: plume and plate tectonics on early Earth **M.J. Van Kranendonk** **Eminent speaker**
Workshop: The Role of Metasomatism in Geological Processes, Montreal, Canada, 23 June 2012	Mantle Metasomatism: Characteristics, scale and distribution, and geodynamic significance **S.Y. O'Reilly** and **W.L. Griffin** **Invited**
22nd V.M. Goldschmidt Conference, Montréal, Canada, 24-29 June 2012	Development and application of LAICP-MS in the geosciences: past, present and future **N.J. Pearson**, **W.L. Griffin** and **S.Y. O'Reilly** **Keynote** What can zircon really tell us about Earth's earliest crustal evolution? M. Whitehouse and **A. Nemchin** **Keynote** Pre-Late heavy bombardment terrestrial crust: review of the zircon evidence for its nature and origin **S.A. Wilde** **Invited**
34th International Geological Congress, Brisbane, 5-10 August 2012	Zircon Hf-isotope record for the evolution of the continental crust since 4.5 Ga **E. Belousova**, **W.L. Griffin**, Y. Kostitsyn, G. Begg and **S.Y. O'Reilly** **Invited** Zircon deformation and its effect on chronometry, thermometry and fluid-rock interaction **S.M. Reddy** and N.E. Timms **Keynote** Tracking coupling and decoupling during lithosphere evolution with geochemistry and geochronology: a case history from arctic Norway **S. O'Reilly**, **W. Griffin**, N. Nicolic and **N. Pearson** **Invited** Mantle wedge olivine or subducting slab serpentinite: what is responsible for supra-subduction zone seismic anisotropy? **S.M. Reddy**, E. Gray, J. Bridges, D. Healy and **M.A. Kaczmarek** **Keynote** Destruction timing of the North China Craton J.-H. Yang, F.-Y. Wu, R. Zhu, **S.Y. O'Reilly**, **W.L. Griffin** and **S.A. Wilde** **Invited** Deep Earth recycling in the Hadean **C. O'Neill** **Keynote**

IESCA-2012 International Earth Science Colloquium on the Aegean Region, Izmir, Turkey, 1-5 October 2012	Lithospheric mapping, metallogenesis and the evolution of continents **W.L. Griffin**, **S.Y. O'Reilly**, G. Begg, **E.A. Belousova** and **N.J. Pearson** **Keynote**
Geochemistry and Ore Deposit Models Seminar, University of Oulu, Finland, 17-18 October 2012	Multiple sulfur isotopes as an indicator of sulfur source in Ni-Cu sulfide deposits E. Hanski and **M. Fiorentini** **Keynote**
Supercontinent Symposium 2012, Helsinki, Finland, 25-28 September 2012	Mesoproterozoic supercontinent - paleomagnetic synthesis and geological constraints **S.A. Pisarevsky** **Keynote**
American Geophysical Union's 45th Annual Fall Meeting, San Francisco, California, 3-7 December 2012	Incorporation of crust at the Lesser Antilles arc J.P. Davidson and **R.C. Bezard** **Invited** The opening of the South China Sea: Driven by Pacific subduction, or by India-Eurasia collision? **Z.-X. Li** **Invited**

A full list of abstract titles and authors for Conferences and Workshops attended is given in Appendix 6 and on the CCFS website.

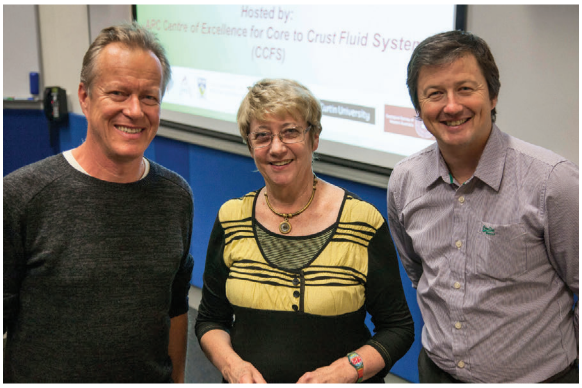
CCFS CI Dr Marco Fiorentini led the Australian organisation of 'Greenland Day' 2012 held at the University Club of Western Australia.

OTHER CONFERENCE ROLES

Goldschmidt 2012, Montreal, Canada, 24-29 June 2012	**Associate Professor Tracy Rushmer** – member, Scientific Committee and co-convened session – Theme 5 *"Evolution of the Continental Crust: Formation, Tectonics and Orogeny"* **Professor Simon Wilde** – Co-hosted session within Theme 02: Early Earth Evolution: *"From an Uninhabitable to a Habitable Planet The first billion years: assessing the geologic record"*
34th International Geological Congress, Brisbane, 5-10 August 2012	***Theme Convenors:*** **Professor T. Campbell McCuaig** – Theme 8. Mineral Exploration Geoscience **Professor Sue O'Reilly** – Theme 16. The Deep Earth **Professor Bill Griffin** – Theme 16. The Deep Earth **Professor Martin Van Kranendonk** – Theme 17. The Early Earth: Hadean and Archean Development of a Habitable Planet ***Symposia Convenors:*** **Professor T. Campbell McCuaig** – Theme 8. Mineral Exploration Geoscience. Symposium 8.2. *"The science of exploration targeting"* **Dr Craig O'Neill** – Theme 16. The Deep Earth. Symposium 16.1. *"The lithosphere-asthenosphere boundary: nature, formation and evolution from Hadean to now"* **Professor Bill Griffin** and **Associate Professor Norman Pearson** – Theme 16. The Deep Earth. Symposium 16.3. *"The crust-mantle lithosphere system"* **Dr Juan Carlos Afonso** and **Dr Yingjie Yang** – Theme 16. The Deep Earth. Symposium 16.5. *"Lithosphere structure from ambient noise and other seismology"* **Professor Martin Van Kranendonk** – Theme 17. The Early Earth: Hadean and Archean Development of a Habitable Planet. Symposium 17.2. *"Rates and mechanisms of Archean crust formation – the relative contribution of plume versus plate tectonics"* **Dr David Wacey** – Theme 17. The Early Earth: Hadean and Archean Development of a Habitable Planet. Symposium 17.3. *"The habitats and paleobiology of early life on Earth, and the rise of oxygen"* **Professor Martin Van Kranendonk** and **Dr Craig O'Neill** – Theme 17. The Early Earth: Hadean and Archean Development of a Habitable Planet. Symposium 17.4. *"Early Earth geodynamics and evolution – uncovering links between changing early Earth and biological diversification"* **Professor Zheng-Xiang Li** – Theme 18. The Proterozoic Earth. Symposium 18.3. *"Proterozoic supercontinents, processes, models, myths and possibilities"* **Adjunct Professor Robert Pidgeon** – Theme 20. Planetary Sciences. Symposium 20.3. *"Lunar research and exploration in the 21st century"* **Professor Martin Van Kranendonk** – Theme 35. Geostandards. Symposium 35.2. *"International Subcommission on Precambrian stratigraphy: a chronostratigraphic division of the Precambrian: possibilities and challenges"*
AMPC10, ICONN2012, ACCM22, Perth, Australia, 5-9 February 2012	**Steve Reddy** – Chaired *"EBSD of Synthetic and Natural Materials"* **Simon Wilde** and **Monica Kusiak** – Chaired *"Mineral Geochronology and isotopic characteristics"*
17th Australian Organic Geochemistry Conference, Macquarie, 2-4 Dec 2012	**Simon George** – Chair, member of the organising committee

2013: **Bill Griffin** is co-convenor of the special session in the 2013 Goldschmidt conference at Florence (Italy), August 25-30, 2013 under the Theme 13: *"Ores - Their Construction, Destruction and Politics"* and is co-convenor of the special session *"Coupling between Precambrian crust and subcrustal lithosphere: Combining the geochemical and geophysical evidence"* at the combined SHRIMP Centre of Beijing and the SinoProbe Program of China international meeting on Precambrian evolution of the Earth in Beijing in October 2013.

WORKSHOP ROLES

Activity	Details & Participant/s	Date
Uncover Workshops "*Searching the Deep Earth: A vision for exploration geoscience in Australia*"  	Held on behalf of the National Academy of Sciences Hosted by **CCFS and Macquarie University** Presented by **Professor T. Campbell McCuaig** *Professor Dietmar Müller (University of Sydney), Sue O'Reilly and Dr Robert Hough (CSIRO) at the UNCOVER workshop. The event was part of a nationally run series of workshops to facilitate discussion of the Exposure Draft: "Searching the Deep Earth: A vision for exploration geoscience in Australia."*	24 May 2012 18 May 2012
Leapfrog Training Workshop 	Geological modelling software training course **Hosted by UWA** *Participants in two day Leapfrog training workshop from left: Lijuan Ying, Carissa Isaac, Steven Micklethwaite, Nicolas Thebaud, Matt Hill, Jun Cowan, Geoff Batt, Erwann Lebrun, Quentin Masurel, Qingtao Zeng, David Stevenson, Margaux Le Vaillant, Denis Fougerouse, Luis Avila, Stanislav Ulrich, Jianwei Zi.*	May 2012
Plume Debate: To Plume or not to Plume... that is the Question!  *Panel members: Jean-Pierre Burg, Svetlana Tessalina, Franco Pirajno, Steve Barnes.*	Public debate / Workshop on some of the fundamental questions about the dynamics of the processes that lead to plumes, LIP's, hot spots and intra-plate volcanoes. • **Hosted by CET** • Opening statement by **Dr Weronika Gorczyk** • Leader, Processes and Mineral Systems session: **Dr Yongjun Lu** • Leader, Mechanics and Tectonics session: **Dr Weronika Gorczyk**	19 July 2012 http://www.cet.edu.au/docs/default-document-library/plume-debate-.pdf?sfvrsn=0
Agouron Institute Field School for 2012, Pilbara, NW Australia	Leader, **Professor Martin Van Kranendonk**	August 2012
International Geological Congress Fieldtrip, Pilbara, NW Australia	Leader, **Professor Martin Van Kranendonk**	August 2012
IoGAS Training Workshop	Geochemical data analysis software training course **Hosted by UWA**	August 2012

Activity	Details & Participant/s	Date
Structural Geology and Resources Conference, Kalgoorlie, Australia	**Professor Klaus Gessner** Co-presented on *"Non-linear and non-equilibrium thermodynamics without the complex mathematics"*	29 September 2012
Short Course: Migmatites, Melting and Intracrustal Differentiation	Lecturers: M. Brown, E. Sawyer, R. White, **Professor Simon Wilde**, Y. Wan: Hosted by the IPRC of China, Beijing	12-16 October 2012
4th Greenland Day Workshop, Perth, Australia (see *photo p. 20*)	Hosted by **CET & CCFS**, Co-Organised by **Professor Marco Fiorentini**	4 December 2012

ESTEEM FACTORS AND OUTREACH

Awards

Activity	Participant/s
Awarded ARC Future Fellowships (see *p. 9 -10*)	**Dr Heather Handley** and **Dr Dorrit Jacob**
Recipient of the 2012 European Association for Geochemistry Eminent Speaker Award	**Professor Martin Van Kranendonk**
Awarded the European Geosciences Union (EGU) Outstanding Young Scientist Award (Geodynamics Division). http://www.egu.eu/awards-medals/division-outstanding-young-scientists-award/2013/juan-c-afonso/	**Dr Juan Carlos Afonso**
Awarded a Copernicus Professorship for 2013 by the Research Council of Italy	**Professor Sue O'Reilly**

Outreach

Activity	Participant/s	Date
Briefing to Lynne Beazley, Chief Scientist of Western Australia	**Dr David Wacey**	
Briefing the Australian Science Ministers on Microfossils	**Dr David Wacey**	
AMIRA International's 9th Biennial Exploration Managers Conference	**Professor Cam McCuaig**	March 2012
Official launch of the Australian Seismometers in Schools Network (AuSIS), Melrose High School ACT	**Dr Craig O'Neill**	31 May 2012
CCFS posters and presence at the NSW Geological Survey 34th IGC Booth	**Dr Elena Belousova**	August 2012
Distal Footprints of ore systems and exploration in the Capricorn region of WA	**Professor Cam McCuaig**	18 October 2012
Newington College, Stanmore	**Dr Craig O'Neill** and Assoc. Professor Kelsie Dadd	October 2012

Public Lectures

Activity	Participant/s	Date
CET Seminar Series	**Professor Cam McCuaig**	23 March 2012
Australia Africa Partnerships Facility Study Tour 2012	**Professor Cam McCuaig**	3 July 2012
34th IGC: Managing uncertainty in exploration targeting	**Professor Cam McCuaig**	10 August 2012
CET Corporate Members Day	**Professor Cam McCuaig**, **Professor Marco Fiorentini**	10 December 2012

MEMBERSHIPS AND APPOINTMENTS

Professor Sue O'Reilly

Member of the International Kimberlite Conference Committee

Appointed Chair of the Earth Science National Committee for Academy of Sciences

Appointed member of National Scientific Qualification Committee, National Agency for the Evaluation of Universities and Research Institutes, Italy

Member ARC ERA Expert Committee for 2012

Co-editor, Editor of a Special Volume of *Lithos*: *"The lithosphere and beyond: a multidisciplinary spotlight"*

Member of the 2012 ERA Research Evaluation Committee

Represented Macquarie's DVC(Research) at the signing of the formal agreement with the China University of Geosciences, Wuhan (CUGW) establishing the *"International University Consortium in Earth Science"* (IUCES) (see *International links*)

Represented Macquarie University at the 60th Anniversary celebrations for the China University of Geosciences, Wuhan (*pictured above*).

Professor T. Campbell McCuaig

Chair of the Minerals Tertiary Education Council (MTEC) Mineral Geoscience Masters implementation committee

Minerals Tertiary Education Council (MTEC) Mineral Geoscience Masters / Minerals Geoscience Honours Steering committee

SEG curriculum committee

Science Advisory Committee for Discovery Theme of Minerals Down Under CSIRO Flagship

Geological Survey of Western Australia Mineral Exploration technical subcommittee

AMEC Congress Steering Committee

Professor Simon Wilde

Deputy Director of the International Precambrian Research Centre of China (IPRCC) at Beijing SHRIMP Centre and the Department of Geology, Chinese Academy of Geological Sciences

Co-editor of a special volume of the *American Journal of Science*: *"The First Billion Years: assessing the geologic record"*

Dr Juan Carlos Afonso

Division Officer of the European Geosciences Union (Geodynamics Division)

EGU Officer Geodynamics Division (Outstanding Young Scientist committee)

Co-editor of a Special Volume of *Lithos*: *"The lithosphere and beyond: a multidisciplinary spotlight"*

Professor Marco Fiorentini	Visiting Professorship for 2013 at Institut de Recherche en Astrophysique et Planétologie, Toulouse, France Visiting Professorship for 2013 at Université Joseph Fourier, St Martin d'Hères, France Member of the 'Expert Panel' of the Mineral Resource Assessment Workshop focusing on the nickel potential in Greenland, 27-29 November 2012
Professor Bill Griffin	Member of the Scientific Committee, "*International Earth Science Colloquium on the Aegean Region*", 1-5 October 2012 Invited founding core member of the of the International Precambrian Research Centre of China (IPRCC) at Beijing SHRIMP Centre and the Department of Geology, Chinese Academy of Geological Sciences Co-editor of a Special Volume of *Lithos* on "*Ore Deposits and the Role of the Lithospheric Mantle*" and Managing Editor of a Special Volume of *Lithos: "The lithosphere and beyond: a multidisciplinary spotlight"*
Associate Professor Norman Pearson	Founding member of the international organising committee of the "*Working Group on Data Acquisition, Handling and Interpretation in Laser Ablation U(-Th)-Pb Geochronology*"
Associate Professor Tracy Rushmer	NSF (National Science Foundation) panel member for Geochemistry and Petrology
Dr Bruce Schaefer	Leader, AuScope Earth Composition and Evolution Component Coordinated the National Geochemistry Program for the AuScope NCRIS capability
Professor Simon Turner	Director of the Geochemical Society
Professor Martin Van Kranendonk	Chair of the Precambrian Subcommission of the International Commission on Stratigraphy Scientific Advisory Committee Member at the University of Western Australia Core Member, International Precambrian Research Centre of China (IPRCC) Assistant Director, Australian Centre for Astrobiology
Dr Michael Wingate	Member of the Steering Committee, IAVCEI Large Igneous Provinces Commission Member, John de Laeter Centre SHRIMP Advisory Group, Curtin University

EDITORIAL APPOINTMENTS	
Acta Geologica Sinica	Griffin
Acta Geoscientia Sinica	Li
American Journal of Science	Wilde
Chemical Geology	Wilde
EGU Journal Solid Earth	Afonso
Geological Society of America Bulletin	Griffin, Li
Gondwana Research Advisory Board	Wilde
Journal of Asian Earth Sciences	Li, Wilde
Journal of Jilin University – Earth Science	Wilde
Journal of Petrology	Turner
Lithos	Griffin, O'Reilly, Rushmer
Precambrian Research	Barley, Pisarevsky, Van Kranendonk
Solid Earth	Schaefer

MEDIA

Activity	Participant/s	Date, Forum	Web address
Australia: The time traveller's guide	**Professor Simon Wilde**	25 March 2012, ABC 1	http://www.abc.net.au/tv/timetravellers
Segment: Early Earth in: "*Voyage of the continents - Oceania: the tectonic ring of fire*"	**Professor Simon Wilde**	6 June 2012, Arte France	http://www.arte.tv/fr/la-valse-des-continents/6610398.html
Keystones in evolution	**Dr David Wacey**	2 January 2012, Cosmos	http://ska.cosmosmagazine.com/features/keystones-evolution/
UWA scientists join CSIRO Minerals System Cluster	**Professor Cam McCuaig**	March 2012, Energy and Minerals Institute eNews	http://content.enewslettersonline.com/18931/58313.html
Mercury findings raise new questions	**Dr Craig O'Neill**	22 March 2012, ABC Science	http://www.abc.net.au/science/articles/2012/03/22/3460456.htm
Life, death and beyond: Chemical fossils: Marking the origins of life	**Professor Simon George** and Adriana Dutkiewicz	May 2012, Magazine article: Chemistry in Australia, Issue May	http://search.informit.com.au/documentSummary;dn=235361302167334;res=IELENG
Why is the transit of Venus so rare?	**Dr Craig O'Neill**	25 May 2012, ABC Science	http://www.abc.net.au/science/articles/2012/05/25/3510139.htm
Moon research to shed light on Earth's development	**Associate Professor Alex Nemchin**	28 May 2012, Media Release, Curtin News	http://news.curtin.edu.au/media-releases/moon-research-to-shed-light-on-earth's-development/
Microfossil and pumice origin of life	**Dr David Wacey**	June 2012, Focus	www.sciencefocus.com/issue/origin-life
AJES Awards	**Ms Cara Danis**	June 2012, The DI Groves Medal, TAG p. 15	http://www.gsa.org.au/publications/TAG%20163W.pdf
Starstuff – The transit of Venus	**Dr Craig O'Neill**	6 June 2012, Guest, ABC	http://www.abc.net.au/science/audio/2012/05/30/3514118.htm?topic=space
District to camp controls on the genesis of komatiite-hosted nickel sulfide deposits, Agnew-Wiluna Greenstone Belt, Western Australia: Insights from the multiple sulfur Isotopes	**Professor Marco Fiorentini**	August 2012, EarthEmphasis	http://environmentprogress.com/key-research-articles/district-to-camp-controls-on-the-genesis-of-komatiite-hosted-nickel-sulfide-deposits-agnew-wiluna-greenstone-belt-western-australia-insights-from-the-multiple-sulfur-isotopes/
World's oldest microfossils	**Dr David Wacey**	August 2012, La Recherche Magazine	
On the early lives of diamonds	**Ms Ekaterina Rubanova**	12 October 2012, GeoSpace	http://blogs.agu.org/geospace/2012/10/12/on-the-early-lives-of-diamonds/
Greenfields come to Perth for Greenland Day	**Professor Marco Fiorentini**	2 December 2012, Earth Explorer	http://www.earthexplorer.com/2012/Greenfields_come_to_Perth_for_Greenland_Day.asp

Dr José María González-Jiménez, Professor Sue O'Reilly, Mr Richard Morecroft, Mr Greg Walsh (MQ Communications manager) Professor Bill Griffin and Dr Craig O'Neill.

Media training

In November, Macquarie University hosted a media skills training workshop for CCFS members, which was delivered by experienced ABC television anchor and media skills trainer Richard Morecroft. The workshop offered valuable approaches to working intelligently with the media to convey key messages and avoid common pitfalls. The session was well patronised by Centre members from across the spectrum and was put to immediate good use, coinciding with the release of the ERA results (see *p. 29*).

VISITORS

CCFS 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 5*.

They have participated in:

- collaborative research
- technology exchange
- seminars
- discussions and joint publications
- collaboration in postgraduate programs

CCFS SCORED WELL IN THE DECADE OF MOST-HIGHLY-CITED PUBLICATIONS IN GEOLOGY (RELEASED 2012)

A Research Focus published in the December 2012 issue of *Geology** listed the top three most-highly-cited papers published in Geology for each year between 2000 and 2010 (data source: Web of Knowledge). The large number of CCFS authors present in this list illustrates the excellent quality of the work being carried out in the Centre.

2008

3. **Yang, J.-H.**, **Wu, F.-Y.**, **Wilde, S.A.**, **Belousova, E.** and **Griffin, W.L.** 2008. Mesozoic decratonization of the North China block. *Geology, 36, 467-470, doi:10.1130/G24518A.1*

2007

1. **Li, Z.-X.** and Li, X.-H. 2007. Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China: A flat-slab subduction model. *Geology, 35, 179-182, doi:10.1130/G23193A.1*

3. Davidson, J., **Turner, S.**, **Handley, H.**, Macpherson, C. and Dosseto, A. 2007. Amphibole "sponge" in arc crust? *Geology, 35, 787-790, doi:10.1130 /G23637A.1*

2006

1. **Chu, M.-F.**, **Chung, S.-L.**, Song, B., Liu, D., **O'Reilly, S.Y.**, **Pearson, N.J.**, Ji, J. and Wen, D.-J. 2006. Zircon U-Pb and Hf isotope constraints on the Mesozoic tectonics and crustal evolution of southern Tibet. *Geology, 34, 745-748, doi:10.1130/G22725.1*

2. **Zheng, J.P.**, **Griffin, W.L.**, **O'Reilly, S.Y.**, **Zhang, M.**, **Pearson, N.** and Pan, Y.M. 2006. Widespread Archean basement beneath the Yangtze craton. *Geology, 34, 417-420, doi:10.1130/G22282.1*

2002

2. **Li, Z.X.**, Li, X.H., Zhou, H.W. and Kinny, P.D. 2002. Grenvillian continental collision in south China: New SHRIMP U-Pb zircon results and implications for the confi guration of Rodinia. *Geology, 30, 163-166, doi:10.1130/0091-7613(2002)030<0163:GCCISC>2.0.CO;2*

2001

3. Williams, H., **Turner, S.**, Kelley, S. and Harris, N. 2001. Age and composition of dikes in Southern Tibet: New constraints on the timing of east-west extension and its relationship to postcollisional volcanism. *Geology, 29, 339–342, doi:10.1130/0091-7613(2001)029<0339:AACODI>2.0.CO;2*

* Highly cited Geology papers (2000–2010) -- What were they and who wrote them? *Geology, 40, 12, 1147-1148. http://geology.gsapubs.org/content/40/12/1147.full*

CCFS Executive Committee meeting, May 2012

Professor Simon Wilde, Dr Ian Tyler, Professor Campbell McCuaig and Professor Suzanne Y. O'Reilly.

CCFS Board meeting, December 2012

Back L-R: Dr Ian Gould, Professor Simon Wilde, Dr Jon Hronsky, Dr Ian Tyler, Professor Suzanne Y. O'Reilly, Dr Andy Barnicoat, Cate Delahunty, Professor William L. Griffin. Front: Professor Campbell McCuaig, Dr Craig O'Neill.

Professor William L. Griffin and Professor Marco Fiorentini.

Professor Suzanne Y. O'Reilly and Professor Zheng-Xiang Li.

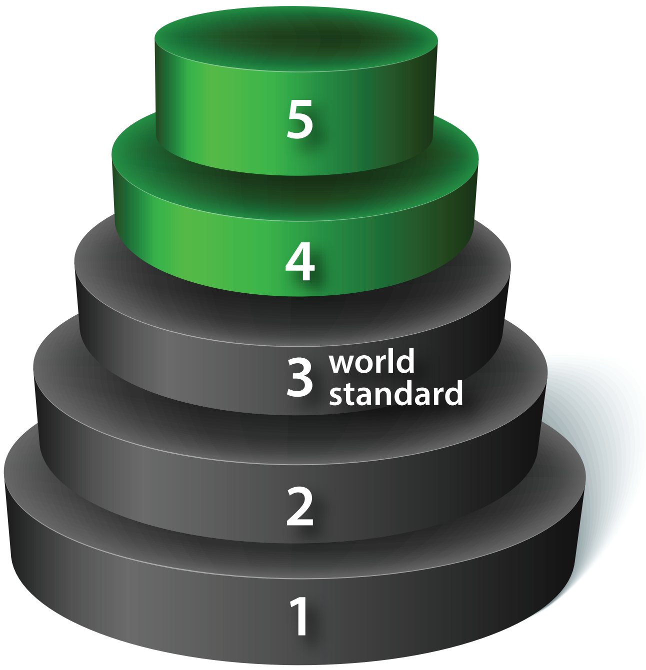
2012 ERA RESULTS

HIGH-FLYING EXCELLENCE FOR CCFS NODES IN NATIONAL QUALITY EVALUATION

The 2012 Excellence in Research for Australia (ERA) evaluation documented the world-leading position of all Australian nodes of CCFS in the relevant categories of Earth Sciences as shown in the Table. The score of 5 is the highest possible and indicates outstanding research, significantly above world standard in all assessment categories (a score of 3 indicates research at world standard). Of particular note is the Geophysics rating at Macquarie. In 2012 there were not enough publications in this area to reach the threshold for ERA assessment; the CCFS geophysicists were mainly recently appointed early-career researchers. In the 2012 ERA round, not only were there sufficient items for assessment, but Geophysics was assessed at 5. This fulfils a major goal of CCFS: to significantly raise the level of Geophysics research and training at Macquarie and nationally.

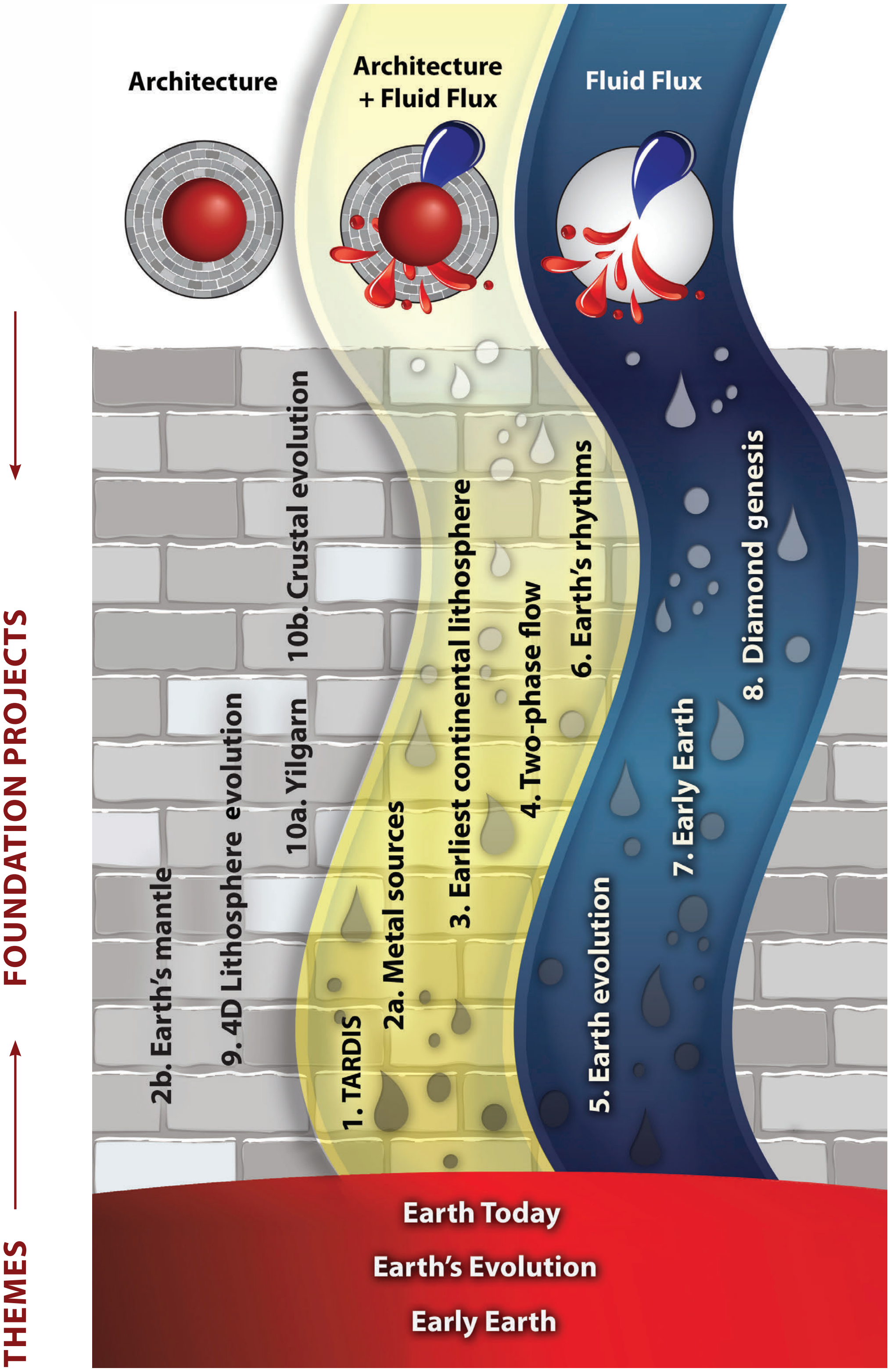
	FoR	Code	Rank
Macquarie	Earth Sciences	04	#5
	Geochemistry	0402	#5
	Geology	0403	#5
	Geophysics**	0404	#5
Curtin	Earth Sciences	04	#5
	Geochemistry	0402	#5
	Geology	0403	#5
UWA	Earth Sciences	02	#4
	Geochemistry	0402	#4
	Geology	0403	#5

*** KPI exceeded for Geophysics Development in CCFS*

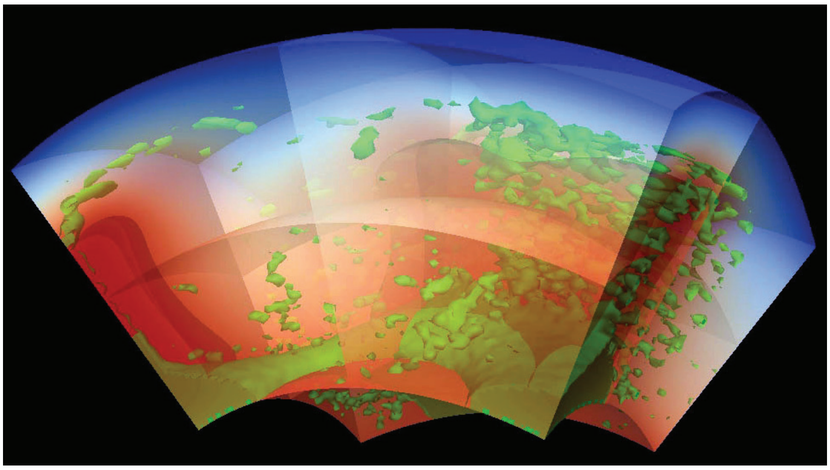


Research highlights 2012

Following the new conceptual framework outlined on page 3, these Research highlights are identified as contributing to understanding Earth Architecture (the roadmap for fluids) and/or Fluid Fluxes (the "traffic report"), with logos for easy attribution. For a full description of the Foundation Projects, see *Appendix 1*.



Deep Earth recycling in the Hadean



Could the mixing of Earth's earliest geochemical reservoirs constrain the geodynamics of the Earth during the Hadean period?

The Hadean has been referred to as a geological dark age – for the first 500 million years of Earth's history, there is a complete dearth of any geological record. The crust of this time was probably destroyed by meteorite bombardment, volcanic resurfacing, vigorous tectonic mixing or all three.

The Hadean was undoubtedly hellish – on top of the heat supplied by relentless meteorite bombardment, the mantle was efficiently heated by high rates of radioactive decay, including short-lived, and now extinct, isotopes like aluminium-26. The mantle also retained much of the substantial heat generated during accretion and the formation of the core.

Under this sort of hot mantle conditions, traditional wisdom has it that the interior viscosity of the Earth would be quite low, and mantle convection extremely vigorous. Mantle convection simulations have suggested that the mixing of early geochemical reservoirs should have been extremely efficient under these conditions, and should have been homogenised on timescales of less than 100 Myrs.

Recently, a number of lines of evidence have provided contrasting views on the Hadean. Model ages on the Nuvvuagittuq greenstone in Quebec suggest some Hadean crust has survived, and zircons from Jack Hills have been used to argue for subduction processes in the Hadean. However, the residence time for the mafic protolith for these Jack Hills zircons is ~400 Myrs – an inordinately long time for a thick mafic crust to survive on an active mantle.

The preservation of geochemical anomalies in younger Archaean rocks also suggests long survival times and inefficient mixing in the Hadean. Neodymium-142 anomalies reflect very early crustal extraction – and the identification of such anomalies in 2.666 Ga basalts from the Abitibi belt suggest these mantle anomalies survived for almost ~2 Gyr. Similarly, tungsten-182 anomalies reflect primordial partitioning events, yet are still observed in rocks as young as 2.8 Gyr from the Kostomuksha Greenstone belt in the Baltic Shield, Russia. Lastly, the present concentration of platinum-group elements in the Earth's mantle is thought to be due to a post-core meteoritic addition, called the late veneer. However, PGEs did not reach their present concentration in mafic lavas until ~2.9 Ga; prior to that they increase linearly from about 3.9 Ga onwards – suggesting they were being progressively mixed into the deep mantle and sampled during this time.

The mixing times of these independent geochemical reservoirs (~2 Gyr) are far longer than the anticipated mixing time from simple convection simulations (<~100 Myr), and so the question becomes – what is missing?

The answer may lie in the tectonic response of the Earth to its hot, early start. New work at CCFS by Craig O'Neill and colleagues suggests that for most of the Hadean the Earth may have been tectonically inactive – the low interior viscosities prevented the build-up of the stress required to fracture and mobilise plates, and the planet may have been in a "hot stagnant lid" regime. The evolution from this starting point into a tectonically episodic regime with rapid, recurring overturn events, has profound implications for Earth's mixing history and thermal evolution.

Three dimensional spherical-cap simulations (pictured), starting from a hot stagnant-lid state, suggest the mixing time in such a regime is an order of magnitude less than for either plate tectonics, or the simple convection calculations performed previously. This in itself can explain the discrepancy between observed mixing times, and those predicted by earlier models.

On top of that, the new simulations suggest that the early Earth lost its heat inefficiently. Previous thermal-evolution models for Earth invariably run into a problem called the "Archean thermal catastrophe" – where in order to match declining heat fluxes, internal temperatures would have been unreasonably high (i.e. global mantle melting) during the Archean. The new models prevent this thermal catastrophe, by demonstrating that Earth could have lost its heat inefficiently, and had lower global heat fluxes early in its history than previously assumed - meaning that internal temperatures could stay within reasonable bounds.

This project is part of CCFS Theme 1, Early Earth, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contact: Craig O'Neill

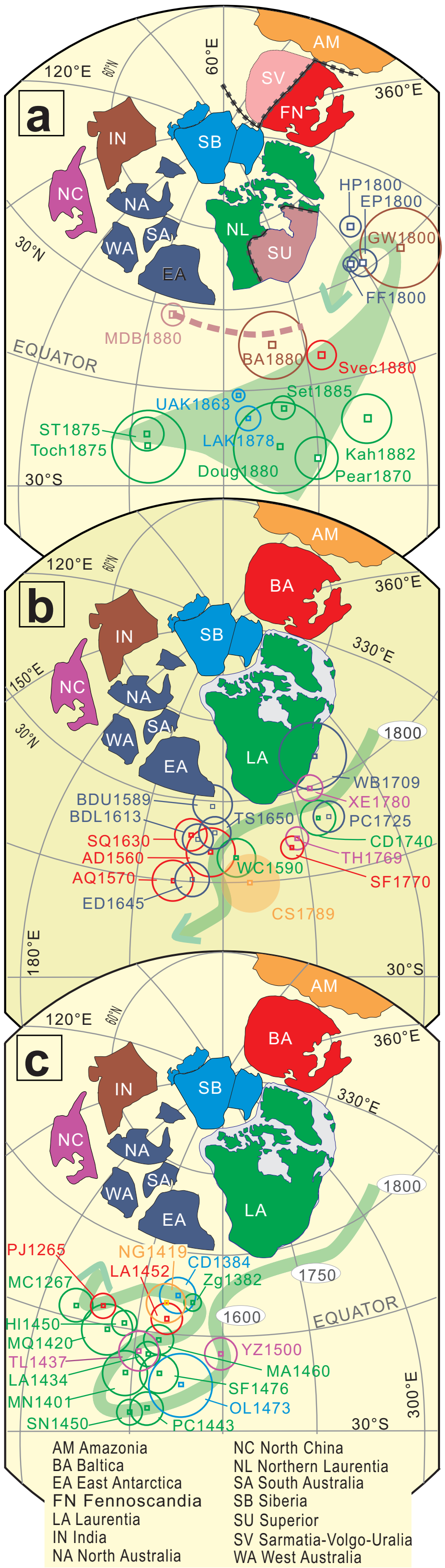
Funded by: ARC Future Fellowship; MQ infrastructure funding

Synchronous pole dancing: the state of supercontinent Nuna before Rodinia

The idea that Earth's evolution has been dominated by cycles of supercontinent assembly and breakup has been debated for decades. However, our understanding of past supercontinents has mainly been limited to the last 1000 Ma; we could be more confident about the history of the ca 320-180 Ma supercontinent Pangea than the ca 900-700 Ma supercontinent Rodinia. Our knowledge of an even older supercontinent (Nuna or Columbia), formed around 1.8 Ga, has been more tenuous, and early papers were mostly based on intercontinental geological correlations that are intrinsically non-unique. Early attempts at Nuna-related continental reconstructions were hampered by the lack of high-quality palaeomagnetic results, or merely regional, rather than global considerations.

Recently (*CCFS publication# 197*) we reported new palaeomagnetic results from North China, and by integrating recent results from Australia, India, and Amazonia and all previously reported results, we reconstructed the first near-complete reconstruction of Nuna (Fig. 1). Our work indicates that Nuna formed by ca 1750 Ma, and lasted at least until ca 1400 Ma (Fig. 1 and 2). This work was involved an ongoing international collaboration with Professor Shihong Zhang of China University of Geosciences, and Professor David Evans of Yale University.

Our reconstruction agrees with previously proposed, geologically based models, including the SAMBA connection between Baltica, Amazonia and Western Africa, the Nuna core connection between Laurentia, Baltica and Siberia, the proto-SWEAT connection between Laurentia, Mawson block and Australian blocks, and the North China-India connection. In addition, our reconstruction for the first time quantitatively merges these regional connections into a single and coherent supercontinent.



Our Nuna reconstruction, constrained by both our new results and an updated global paleomagnetic dataset, is also consistent with key geological features including the ca 1800 Ma orogenic belts leading to the assembly of Nuna (Fig. 2a) and Mesoproterozoic intraplate extensional basins and the Large Igneous Province (LIP) record that may be related to the breakup of Nuna (Fig. 2b). This breakup may have begun around 1400 Ma ago, but available paleomagnetic data are not yet complete enough to allow a more precise depiction of Nuna's fragmentation.

This research is directly related to CCFS Foundation Project 6: Detecting Earth's rhythms, and projects 2d and 9.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture.

Contacts: Zheng-Xiang Li, Shihong Zhang, and David A.D. Evans

Funded by: Chinese National Natural Science Foundation grants and 973 Program support, ARC discovery grant (DP0770228), and CCFS Foundation Project 6

Figure 1. Presently available paleomagnetic datasets enabled the reconstruction of the first palaeomagnetically constrained complete Nuna supercontinent (Zhang et al., 2012; CCFS contribution #197), all in present North American coordinates. Cratons and their poles are colour coded, and ages following pole abbreviations are in millions of years before present (Ma). (a) Palaeomagnetic poles between 1880 and 1800 Ma, showing broad convergence (light-green swath) of poles from the Slave craton of Laurentia, Siberia, Baltica, India and Australia, which suggests that these blocks might commence to join together at ca 1800 Ma. Arrow points toward the position of younger poles. (b) Poles between 1780 Ma and 1600 Ma from Australian cratons, Laurentia, Baltica and NCB, define a common apparent polar wander path (APWP) for Nuna (green curve); arrow points toward the position of younger poles. (c) Palaeomagnetic poles for 1500 -1265 Ma from North China, Siberia, Laurentia, Baltica and Amazonia against the common APWP (green curve) that is defined by all poles between 1800 Ma and 1260 Ma, indicating common motion to at least 1380 Ma. Arrow points toward the position of younger (< 1200 Ma) poles from Laurentia and Baltica. See CCFS contribution 197 for more details.

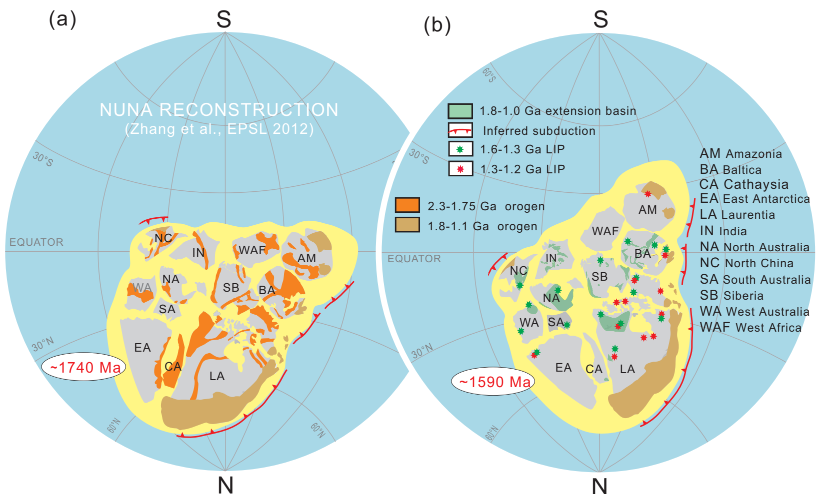
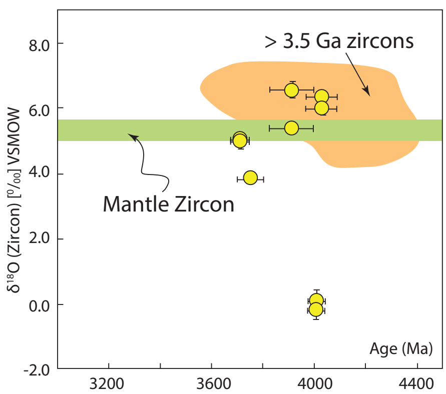


Figure 2. Configuration and palaeogeographic position of the supercontinent Nuna (a) at ca. 1740 Ma soon after its assembly, and (b) at ca. 1590 Ma, when large igneous provinces and extensional basins were extensively developed. Paleomagnetic poles from Laurentia were used to plot the paleolatitude of the supercontinent. Placing Laurentia in northern hemisphere was based on the likely westward trade-wind direction interpreted by Hoffman and Grotzinger (1993) from the 1950 -1860 Ma geological records in the Slave craton. We turned the world upside-down to make Australia and North America plotted upright, and therefore for easier viewing.
See CCFS publication #197 for more details.

More insights from Earth's oldest zircons: ~4.45 Ga crust in the North Qinling Orogenic Belt, China

Most of what we know about Earth's earliest crust comes from Jack Hills in Western Australia, where hafnium-isotope data from old detrital zircons in a younger sandstone indicate that their parent magmas were melted from still older rocks that formed about 4.4-4.5 billion years (Ga) ago. These zircons provide our only means of exploring the Hadean period, the time between the formation of the Earth and the preservation of the oldest known rocks, formed about 3.8 Ga ago. However, Hadean zircons have been found in only four other localities; the Southern Cross belt in Western Australia, the Acasta gneiss complex in northwestern Canada, and China. The Chinese examples include a single 4.1 Ga grain from the Burang area of Tibet and another ~4.1 Ga grain from the North Qinling Orogenic Belt. The latter discovery comes from rocks in a Phanerozoic collisional belt developed between the North and South China cratons. The zircon was found in Ordovician volcanic rocks of the Caotangou Group, dated at 456 ± 2 Ma. These arc volcanic rocks penetrated the basement of the North China Craton, so the zircon xenocryst could have been picked up by the magma either in its source region or during its ascent; it is the first report of Hadean crustal material in a Phanerozoic igneous rock.



For this study, over 3000 zircon grains were separated from ignimbrite collected from the same outcrop as the initial discovery, and were analysed for U-Pb age using both SHRIMP and LA-ICP-MS techniques. In total, only three grains were identified with ages ≥3.9 Ga and these were selected for U-Pb and Hf-O isotopic analysis.

The magmatic cores in these zircons range in age from 3909 ± 45 Ma to 4080 ± 9 Ma and record Hf crustal model ages up to 4.5 Ga. Importantly, the latter lie on the same Lu/Hf trajectory as the least-disturbed Jack Hills zircons, so they are only the second example of the earliest known crustal rocks on Earth. The zircon cores also show a wide range in $\delta^{18}O$, both above and below the mantle value (Fig. 1); this is strong evidence that the source rocks of the magmas had been subjected to surficial processes such as weathering. The rims of two grains record new zircon growth at 3.7 Ga and, when combined with their presence in an Ordovician volcanic rock, suggest that ancient crust was still present in the basement of the North China Craton during the Paleozoic (*CCFS publication #301*).

This project is part of CCFS Theme 1, Early Earth, and contributes to understanding Earth's Architecture.

Contact: Simon Wilde

Funded by: CCFS Foundation Project 2; The National Basic Research Program of China (973 Program; grant No. 2012CB416601), the National Natural Science Foundation of China (NSFC; grant No. 41272004) and the MOST Special Funds from the State Key Laboratory of Continental Dynamics, Xi'an, China

Figure 1. Plot of $\delta^{18}O$ versus age for the xenocrystic zircons (yellow symbols) from the North Qinling Orogenic Belt, China. In green is the band for 'mantle zircon' (Valley et al., Contrib. Mineral. Petrol., 1998); the orange area shows the field of global >3.5 Ga zircons (from Valley et al., Contrib. Mineral. Petrol., 2005; Harrison et al., Science, 2005; Trail et al., Geochem. Geophys. Geosystems, 2007; Heiss et al., Geochimica et Cosmochimica Acta, 2007).

Unmasking xenolithic eclogites: sleuthing with the key samples

Xenolithic eclogites are high-temperature and high-pressure mafic rocks, generally brought up from 150-220 km depth to Earth's surface by kimberlites. They are minor but important constituents of the subcontinental lithospheric mantle (SCLM), and information on their evolution and origin can provide unique constraints on the history of the ancient lithospheric mantle.

Extensive studies of eclogite samples from all over the world have generated two contradictory hypotheses about their origin. One regards the eclogites as deep-seated magmatic rocks, while the other regards them as components of subducted oceanic slabs. To test these hypotheses, it is essential to find out whether the samples being studied actually contain the information we are after (i.e. what is the RIGHT sample).

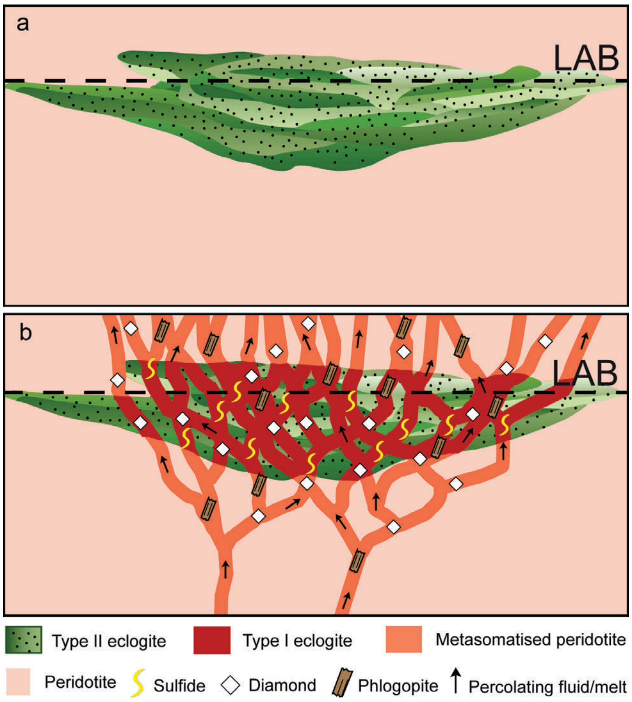


Figure 1. Cartoon of the Roberts Victor eclogite body at the base of SCLM before (a) and after (b) the metasomatism.

Previous work on the famous eclogite suite from the Roberts Victor kimberlite (South Africa) has divided the samples into Types I and II. Type I eclogites are heavily metasomatised by a sequence of melts/fluids in the carbonatitic-kimberlitic spectrum; Type II eclogites may be the protoliths of Type I (Fig. 1; *CCFS publications #3, 41*).

The progressive metasomatism inferred from studies of the whole eclogite suite has now been found within one hand specimen, RV07-17 (Fig. 2). From top to bottom, this sample becomes less equilibrated in terms of microstructure; grain boundaries that are smooth in the upper part become convolute and complex in the lower part, which also has more secondary minerals (e.g. phlogopite, sulfide) and more fluid inclusions.

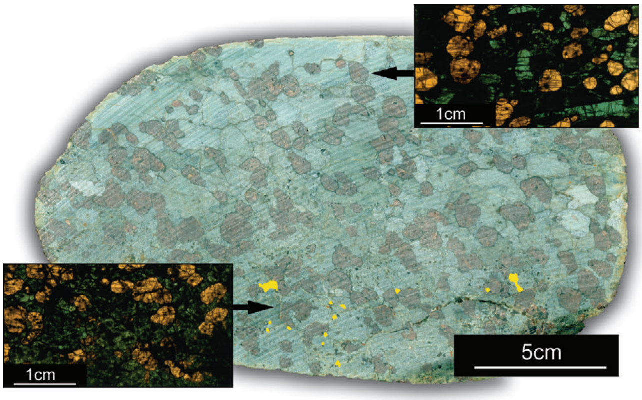


Figure 2. Hand specimen photo of RV07-17 and thin-section images of upper and lower parts of the sample.

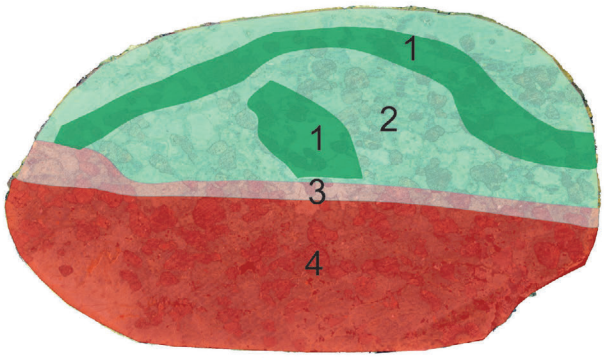
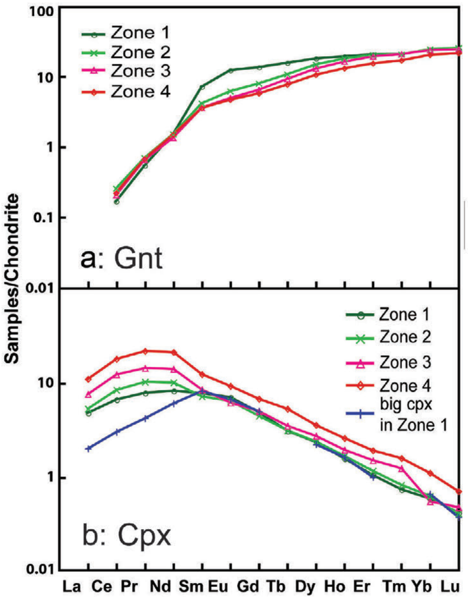


Figure 3. Drawing of RV07-17 showing four different zones.

Four zones (Zone 1, 2, 3, and 4) can be recognised using the chemical compositions of garnets (Fig. 3). From Zone 1 to Zone 4, the pyrope content of the garnets increases gradually from 0.47-0.62; cpx shows progressive enrichment in MgO (10.8-14%). The cross-cutting pattern strongly suggests that Zone 1 represents an early stage of the metasomatism, and Zone 4 the latest stage.

REE patterns of both garnet and cpx also show systematic changes (Fig. 4a-4b). The garnets of Zone 1 have flat REE patterns from Lu to Sm, but a strong depletion in the LREE. Toward Zone 4, the relative abundance of the MREE of the garnets drops significantly, giving smoother patterns. The large cpx grain in Zone 1 shows a strong depletion in the LREE, but the LREE/MREE of the cpx increases from Zone 1 to Zone 4. The Sr contents of cpx change sharply from ~230 ppm in Zone 1+2 to ~320 ppm in Zone 4, and the $^{87}Sr/^{86}Sr$ of cpx increases from ~0.7055 in Zone 1+2 to ~0.7063 in Zone 4. From Zone 1 to 4, $\delta^{18}O$ of the garnet decreases from ~8.5 ‰ to ~6.0 ‰ as the MgO content increases (Fig. 4c).



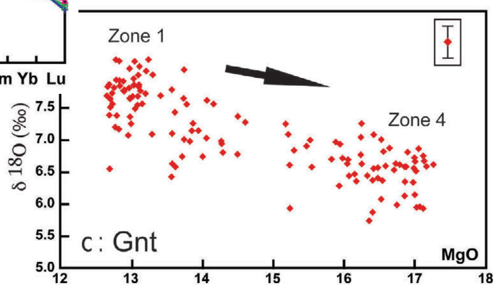


Figure 4. (a) REE patterns of average gnt composition in each of the four zones; (b) REE patterns of average cpx compositions in each of the four zones; (c) correlation between δ¹⁸O and MgO of the garnets in the zones.

These observations suggest that the eclogite was metasomatised by Mg-rich melts/fluids, which changed through time from carbonatitic in Zone 1 to more kimberlite-like in Zone 4. This is consistent with the decrease of $\delta^{18}O$ in the metasomatic agent from the early carbonatitic fluids to the late kimberlitic melt/fluid.

The metasomatism of some mantle eclogites (e.g. Type I) may be more intensive and complete than previously thought. This process can sweep away all original information on chemical compositions, making it nearly impossible to define a protolith. To know the origin of the xenolithic eclogites, and to use them as evidence for different dynamic scenarios, the least-metasomatised samples must be studied.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Fluid Fluxes.

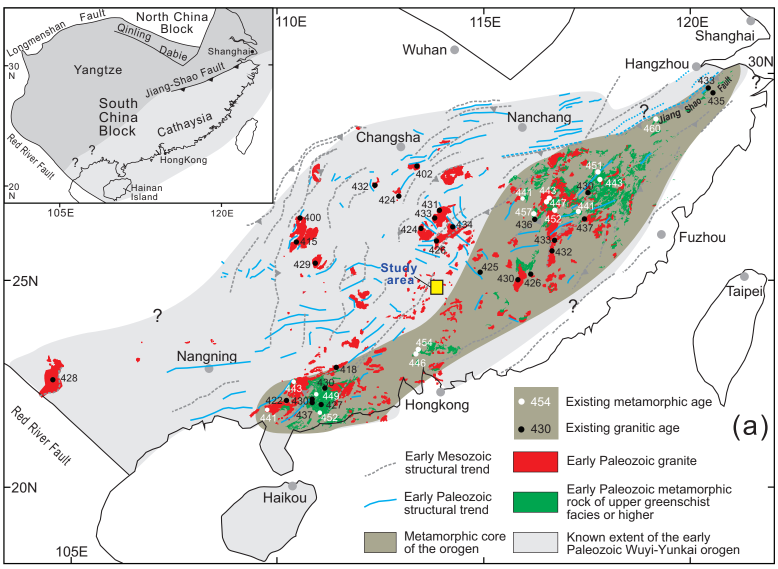
Contacts: Jin-Xiang Huang, Yoann Gréau, Bill Griffin, Sue O'Reilly

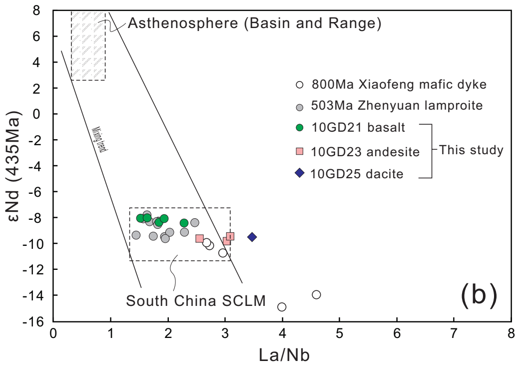
Funded by: ARC Discovery (O'Reilly and Griffin) then CCFS Foundation Project 8, MQRES, EPS Postgraduate Fund

Rare rocks – the smoking gun for lithosphere drop-off 435 million years ago

How can an orogen (mountain belt) form within a continental plate? Why do these episodes of crustal deformation end with widespread intraplate magmatism? These types of geological activity represent a "hole" in the Plate Tectonics paradigm, which emphasises activity along plate boundaries. The 2000 km-long intraplate Wuyi-Yunkai orogen, active in the early Palaeozoic South China, is well documented. It has high-grade metamorphic rocks in the orogenic core (Fig. 1a, dark grey area), and widespread, mostly late- to post-orogenic granites, in both the orogenic core and the foreland areas (light grey areas; Fig. 1a). Previous regional tectono-magmatic analyses suggested that this widespread late- to post-orogenic granitic *cont...*

Figure 1. (a) Simplified regional geological map highlighting the regional extent of the early Paleozoic Wuyi-Yunkai orogeny in South China, featuring high-grade metamorphic rocks (shown in green) in the orogenic core (shown in dark grey), and widespread late- to post-orogenic granites (shown in red) throughout the orogeny (after Li et al., GSA Bull. 2010). (b) Plot of La/Nb versus εNd(435 Ma) for the rare Chayuanshan basaltic rocks in northern Guangdong province, which point to a sub-continental lithospheric mantle (SCLM) source region.





magmatism mostly occurred during orogenic collapse when the deep crust (the "root") of the orogen delaminated. However, the lack of any syn- to late-orogenic mafic rocks made it difficult to verify this or any other possible models.

The discovery of rare Silurian post-kinematic basaltic to andesitic volcanic rocks in northern Guangdong province (*CCFS publication #193*) has made it possible to study mantle-crust interactions during the intraplate orogenic event. The Chayuanshan volcanic rocks crop out on the northwestern margin of the orogenic core (Fig. 1a, marked as "Study area"). They unconformably overlie strongly-deformed Cambro-Ordovician strata, but are in low-angle unconformable contact with overlying post-orogenic mid-Devonian strata. LA-ICP-MS and SHRIMP U-Pb dating of zircons from two andesitic samples gave consistent magmatic ages of 434 ± 6 Ma and 435 ± 6 Ma, which are younger than the 460-440 Ma peak metamorphism of the orogeny but synchronous with the widespread un-deformed, late-orogenic (440-415 Ma) granitic intrusions.

Nine basaltic samples, with the least crustal contamination, have high MgO contents (12.3-19.2 wt.%). The Nd isotope and trace-element compositions of these high-Mg basalts point to a source region of an ancient sub-continental lithospheric mantle (SCLM; Fig. 1b), which is generally depleted in basaltic-melt components in comparison with the asthenospheric mantle, resulting in high mantle Mg# values. The calculated primary basaltic melt has ~50 wt% SiO_2, ~14 wt% MgO and ~9 wt% FeOT. The estimated potential temperature for the melts is close to 1400 ºC, much higher than that of a normal sub-continental lithosphere. The effective melting pressure for the melts is 1.0-1.4 GPa. This suggests that the magma was generated from partial melting of lithospheric peridotite heated by hot upwelling asthenosphere. The related high-Mg# andesites are interpreted as the products of differentiation and assimilation, fractionation and contamination processes from the same basaltic magma source, as supported by their negative zircon εHfT values (-21.7 to -6.3) and high zircon $\delta^{18}O$ values (7.3-9.0 per mil).

Our results lend strong petrological support for the idea of an orogenic root delamination beneath the Wuyi-Yunkai orogeny. As shown in Figure 2, we interpret the Chayuanshan basaltic rocks as representing partial melts near the edge of the remaining sub-continental lithospheric mantle (SCLM). Heat from the upwelling asthenosphere as well as possible basaltic underplating, and regional decompression caused by orogenic collapse, can best explain the widespread synchronous granites along the orogen. In this model, the low- pressure and high-temperature melting of a hydrated subcontinental lithospheric mantle, as demanded by the basaltic magmas, can be satisfied by the delamination of the root, and the consequent orogenic collapse. The volcanic rocks unconformably overlie the strongly deformed Cambro-Ordovician succession, but are nearly parallel with the overlying, post-orogenic Devonian succession; this is consistent with a late-orogenic origin. The ca 435 Ma age of the volcanism post-dates the high-grade metamorphism at ca 460-440 Ma, but is synchronous with the widespread, dominantly post-kinematic felsic magmatism at ca 440-415 Ma. The underplating of mafic magmas, in combination with heat from the upwelling asthenosphere and decompression due to orogenic collapse, provides a plausible explanation for the widespread post-kinematic felsic magmatism.

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Wei-Hua Yao, Zheng-Xiang Li, Xuan-Ce Wang, Xian-Hua Li

Funded by: Chinese Academy of SciencesAS SAFEA(KZCX2-YW-Q04-06), NNSFC (40973025) and ARC (DP110104799)

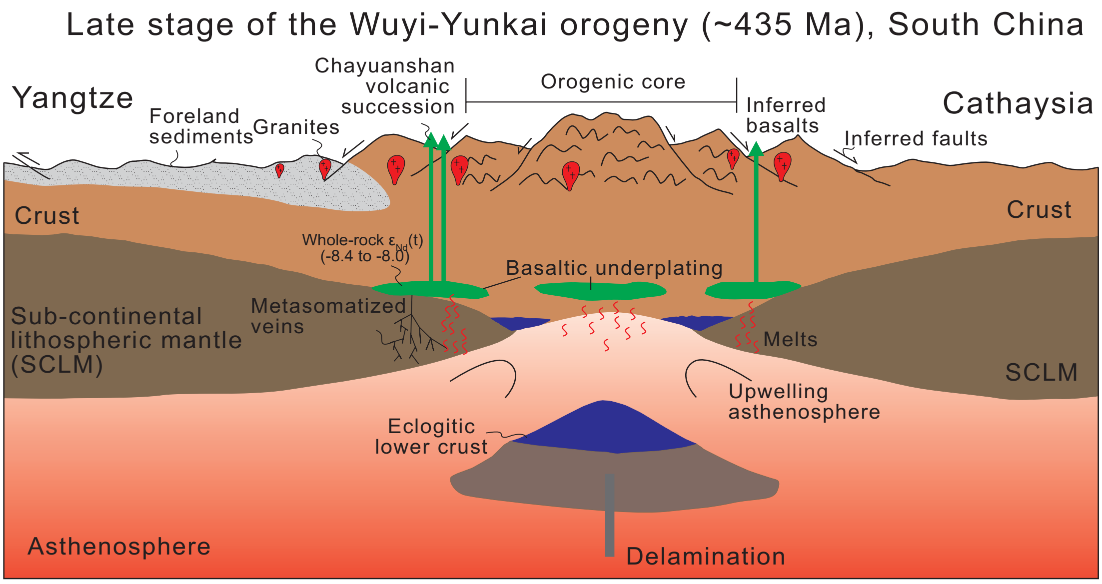


Figure 2. A cartoon diagram showing the delamination of the sub-continental lithospheric mantle (SCLM) and lower crust after crustal thickening during the intraplate Wuyi-Yunkai orogeny at ca 435 Ma.

Mobility of osmium unearthed: unexpected consequences for tracking mantle evolution

The Os-isotope compositions of platinum-group minerals (PGMs) in ophiolite chromitites are commonly regarded as resistant to fluid-related processes, and have been used to track the evolution of Earth's convecting mantle. However, we have found significant differences in $^{187}Os/^{188}Os$ between primary and secondary PGMs from metamorphosed ophiolite chromitites of the Dobromirtsi Ultramafic Massif, in the Central Rhodope Metamorphic Core Complex of southeastern Bulgaria (*CCFS publication #42*). Primary (magmatic) PGMs hosted in unaltered chromite cores have $^{187}Os/^{188}Os$ from 0.1231 to 0.1270, and $^{187}Re/^{188}Os \leq 0.002$. T_{MA} and T_{RD} model ages, calculated relative to the Enstatite Chondrite Reservoir, cluster around three main peaks: ca. 0.3, 0.4, and 0.6 Ga. Secondary PGMs, produced by alteration of magmatic PGMs, have a wider range of variation ($^{187}Os/^{188}Os = 0.1124–0.1398$, $^{187}Re/^{188}Os \leq 0.024$); these grains yield T_{MA} and T_{RD} model ages from -1.7 Ga up to 2.2 Ga. The larger range in $^{187}Os/^{188}Os$ in the secondary PGMs is interpreted as due to reactions between the primary PGMs and infiltrating metamorphic-hydrothermal fluids with a range of Os-isotope compositions. This redistribution of Os in PGMs during metamorphism has significant implications for the interpretation of both whole-rock and *in-situ* Os-isotopes.

The fact that secondary PGMs in the metamorphosed chromitites of Dobromirtsi yield $^{187}Os/^{188}Os$ within the range of depleted to enriched mantle sources suggests that much of the Os-isotopic variability previously reported for PGMs taken out of their microstructural setting (e.g. mineral concentrates or detrital grains collected from streams), and interpreted as a magmatic feature, may instead be related to secondary alteration processes. Therefore, interpretations of mantle events based on the *in-situ* analysis of PGM nuggets from placers may need to be reconsidered. On a more positive note, the Os-isotope data from the secondary Os-bearing phases in ophiolites can actually give a wider perspective on the sources and evolution of the host mantle peridotite.

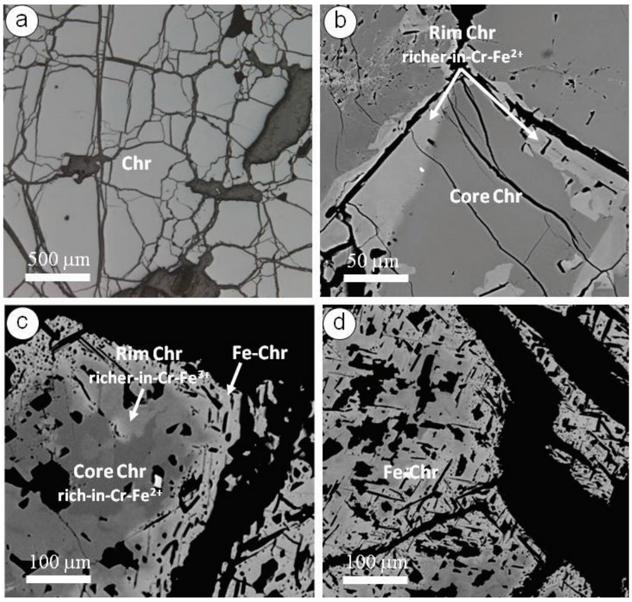
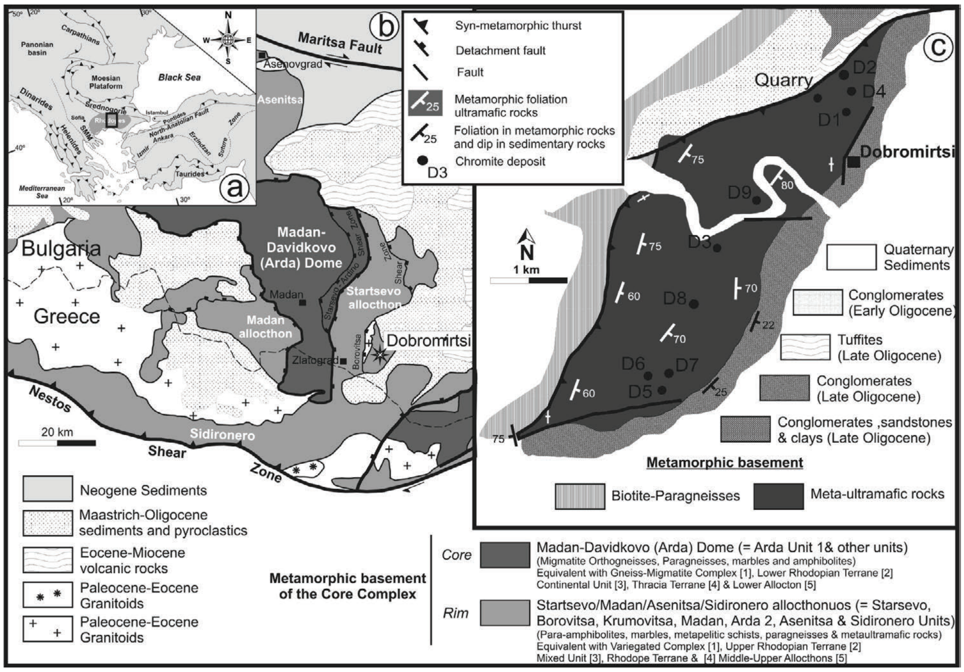


Figure 2. a. reflected-light image of massive chromitite. b. BSE image of zoned chromite; unaltered core mantled by secondary chromite enriched in Cr and Fe^{2+} and depleted in Mg and Al. c. Zoned chromite (BSE); modified core with two secondary rims: an inner rim of Cr- and Fe^{2+}-rich and Mg- and Al-depleted chromite, and an outer rim of Fe^{3+}- rich (ferrian) chromite. d. Homogenous grain (BSE) of secondary ferrian chromite.

Figure 1. Location of the Dobromirtsi ultramafic massif in the Central Rhodope Core Complex in SE Bulgaria



This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

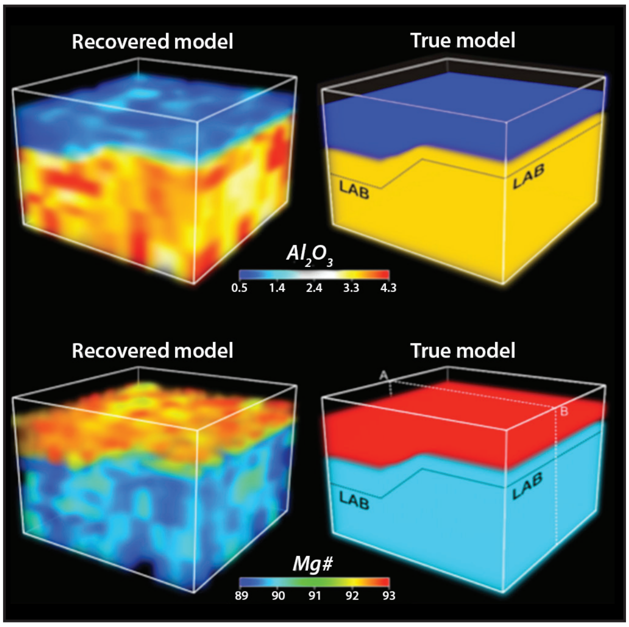
Contacts: José María, González-Jiminéz, Bill Griffin, Norman Pearson, Sue O'Reilly
Funded by: CCFS Foundation Project 1 (TARDIS-E); ARC Post-Award fund to CCFS; grants to international collaborators

Solving the biggest jigsaw puzzle in Solid-Earth Sciences

The conversion of geophysical data (e.g. seismic travel-time curves, gravity anomalies, surface heat flow, etc) into robust estimates of the true thermochemical structure of the Earth's interior is one of the most fundamental goals of the Geosciences. It is the physical state of the deep rocks that drives processes such as volcanism, seismic activity and tectonism. Detailed knowledge of the thermal and compositional structure of the upper mantle is an essential requirement for understanding the formation, deformation and destruction of continents, the physical and chemical interactions between the lithosphere and the convecting sublithospheric mantle, the long-term stability of ancient lithosphere, and the development and evolution of surface topography.

Our current knowledge of the thermal and compositional structure of the lithosphere and the sublithospheric mantle essentially derives from four independent sources.
(i) The most widely applied modelling approach uses gravity and/or surface heat flow data to obtain a model for the temperature and/or density structure of the lithosphere that fits the data to some acceptable level.
(ii) The second most common approach applied to the lithosphere and upper mantle is based on the modelling of seismic data. The aim here is to test thermal and mineralogical (or density) models that are compatible with seismic data (usually shear waves) by using either thermodynamic concepts and/or experimental data from mineral physics. Typically, these

Figure 1. Left: "True" and recovered solution from a full 3D inversion, including travel time residual tomography, using the new method/code for the compositional field. Note that although the absolute magnitudes are not well recovered, the general trend and geometries are correctly identified.



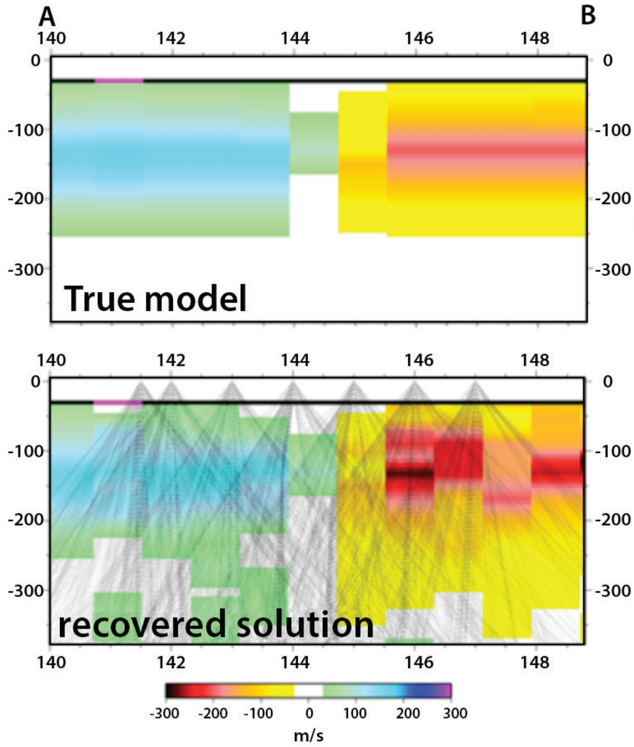


Figure 2. Top: Vertical slice from the 3D synthetic model (left) showing the Vp anomaly structure of the true model. Bottom: Recovered solution; ray traces used in the inversion are shown (modified from results presented at the AGU Fall meeting, 2012).

studies do not invert directly for composition but rather assume *a priori* "representative" compositional models.
(iii) A third source of independent information is provided by models and data derived from magnetotellurics (MT). MT is a natural-source electromagnetic method based on the relationship between the temporal variations of electric and magnetic fields at the Earth's surface and its subsurface electrical structure.
(iv) Finally, the only *direct* approach is the petrological-geochemical estimation of thermobarometric and chemical data from xenoliths (fragments of upper mantle brought up to the surface by volcanism) and exhumed mantle sections. Where specific mineral assemblages are present, xenoliths can be used to derive the compositional and paleo-thermal structure beneath specific localities.
At present, there are often significant discrepancies between the predictions from these four approaches. *The key to progress lies in integrating data from all of these sources into a single consistent model.*

We have developed the first nonlinear, 3D, multi-observable inversion method, based on a probabilistic (Bayesian) inference approach, that can simultaneously invert Rayleigh and Love (seismic waves) dispersion curves, body-wave seismic tomography, and magnetotelluric, geothermal, petrological, gravity, elevation, and geoid datasets. Assembling this giant "jigsaw puzzle" problem has required a massive collaborative effort between thermodynamicists, geophysicists and geochemists, and is the first step towards real thermochemical tomography of the Earth, which is undoubtedly the future of imaging techniques. Our preliminary results (recently published in *Journal of Geophysical Research, online Feb 2013)* indicate that we can expect to resolve temperature anomalies of $\Delta T >$ 150 °C and large anomalies of $\Delta Mg\# > 3$ (or bulk $\Delta Al_2O_3 > 1.5$) simultaneously when combining high-quality geophysical data. This resolving power is sufficient to explore some long-standing problems regarding the nature and evolution of the lithosphere (e.g. vertical stratification of cratonic mantle, compositional *vs* temperature signatures in seismic velocities, etc.) and offers new opportunities for joint studies of the structure of the upper mantle with unprecedented resolution.

This project is part of CCFS Theme 3, Earth Today, and contributes to understanding Earth's Architecture.

Contacts: Juan Carlos Afonso, Yingjie Yang
Funded by: Discovery Project DP120102372, MQ iPRS

Zircon multi-isotopic mapping: a robust roadmap to mineral discovery

Recent studies in the Yilgarn Craton of Western Australia have demonstrated that multi-isotopic maps, based on *in-situ* U-Pb and Lu-Hf analyses of zircon and whole-rock Sm-Nd data, are a powerful tool for mapping crustal growth, and for imaging lithospheric blocks and their margins.

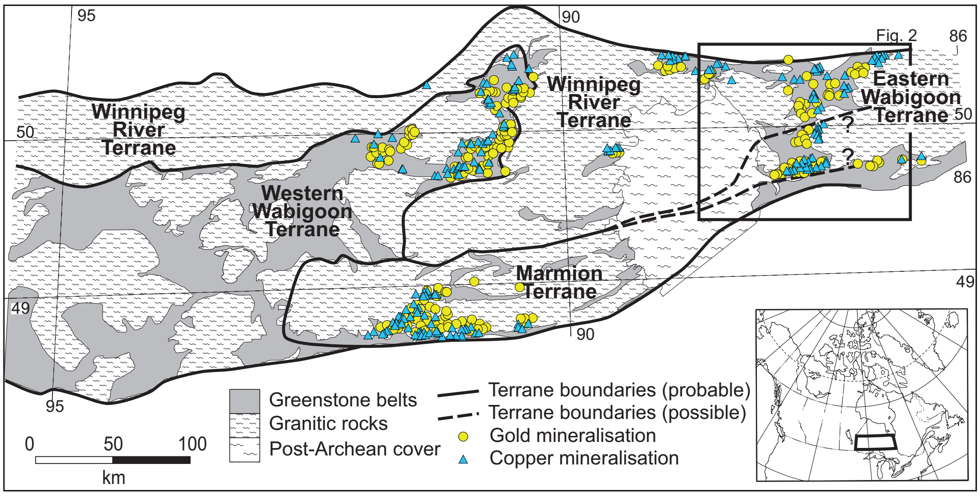


Figure 1. Simplified geological map of Wabigoon Subprovince in western Superior Craton, Canada. The inset shows the location of the study area. The subprovince has been divided into the Winnipeg River, Marmion, Western Wabigoon, and Eastern Wabigoon terranes based on whole-rock Nd-isotope data. The locations of gold and copper mineralisation are highlighted to show their relationship with terrane boundaries.

These studies pointed to a strong spatial correlation between lithospheric boundaries and the location of large concentrations of several styles of mineral deposit (e.g. Champion and Cassidy, 2007; McCuaig et al., 2010; Begg et al., 2010; Mole et al., 2012). The implication is that these isotopic boundaries mark lithosphere-scale structures that control fluid flux, and thus the location of large mineral systems through time. However, the only available case study in the Archaean is the Yilgarn of WA, and even that is only focused on the central portion of the craton. Therefore, it is critical to test this hypothesis in other parts of the world.

A comparative study has been started in the Wabigoon Subprovince in the western part of the Superior Craton of Canada. This project aims to: 1) apply multi-isotopic (U-Pb, Lu-Hf, O) analyses of zircon to map the lithospheric architecture in time and space; 2) determine if the distribution of mineral systems is controlled by this lithosphere architecture; 3) generate mappable exploration criteria for targeting various mineral systems at craton- to terrane scales.

The Wabigoon Subprovince can be subdivided into four terranes based on the whole-rock Sm-Nd isotopic data published by Tomlinson et al. (2004). Gold and copper mineralisation in the region appears to be controlled by the Winnipeg River and Western Wabigoon terrane boundaries (Fig. 1). However, the mineralisation within the Marmion and Eastern Wabigoon terranes does not follow the previously defined terrane boundaries (Fig. 1). In the Eastern Wabigoon Terrane, the assumed boundaries trend nearly E-W, whereas the gold and copper mineralisation forms a zone that trends northward. This discrepancy suggests that the terrane boundary may in fact strike northward (Fig. 2). Preliminary zircon Hf isotopic analysis shows that samples collected west of this hypothetical boundary have older Hf model ages (3.5 Ga) than those from east of the boundary (3.1 Ga), suggesting that the western area has an older basement than the eastern area (Fig. 2). This difference in zircon Hf isotopes also suggests that the boundary of the East Wabigoon Terrane trends northward, which is consistent with the spatial arrangement of gold and copper mineralisation in the region. However, more data from both sides of this possible boundary are necessary to prove the case. In the Marmion Terrane, the NE-trending mineralisation

cont...

coincides with a NE-striking structure. There is contrast in magnetic anomalies across this structure within the Marmion Terrane, which suggests that it is also a possible terrane boundary. The ongoing zircon mapping will test this hypothesis.

In summary, it appears that the spatial distribution of mineral systems (Au and Cu) in the Wabigoon Subprovince is controlled by the terrane boundaries (similar to the scenario in the Yilgarn Craton). The enhanced understanding of the interplay between lithospheric architecture potentially can help to bring about a paradigm shift in exploration strategy within the mineral industry, encouraging companies to use higher-precision multi-isotopic datasets to guide their area selection on the large scale.

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture.

Contacts: Campbell McCuaig, Yongjun Lu
Funded by: CCFS

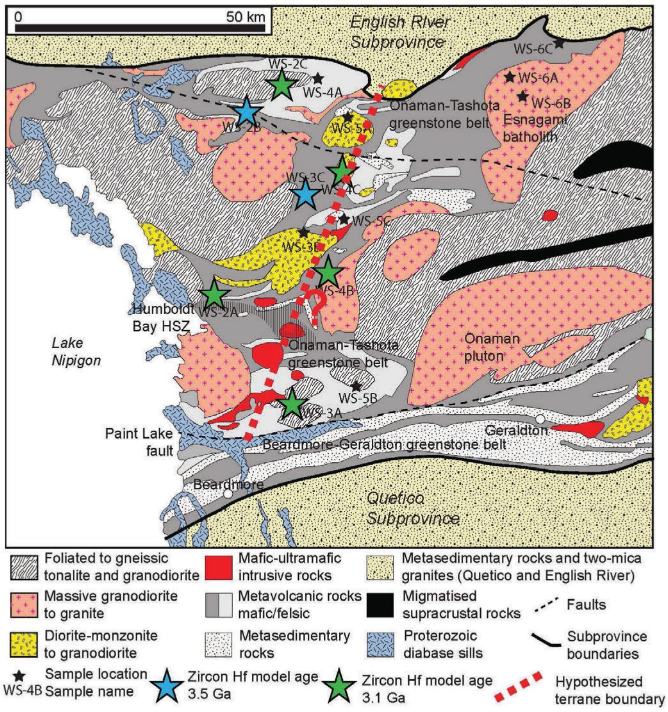


Figure 2. Geology of Eastern Wabigoon area. The preliminarily analysed zircon samples are shown by stars. The blue stars represent samples with older Hf model ages of 3.5 Ga, whereas the green stars having younger Hf model ages of 3.1 Ga. The hypothesised terrane boundary is highlighted by a red thick dashed line.

Cooking the lower crust: high-calorie ultramafic magmas in Arctic Norway

Most geologists are familiar with a wide range of mafic to felsic magmatic rocks, but the idea of ultramafic (high-Mg, low-Si) magmas is hard to assimilate, simply because laboratory experiments show that such magmas could only exist at temperatures that are not seen in the crust. Ultramafic lavas (komatiites) occurred widely in Archean time, but very rarely afterward; this has been used to argue for much higher mantle temperatures in the Archean. If ultramafic magmas do exist in the modern Earth, it would raise serious questions: how would they be generated, and how could they rise into the crust without crystallising?

The serendipity of a major continental collision, and

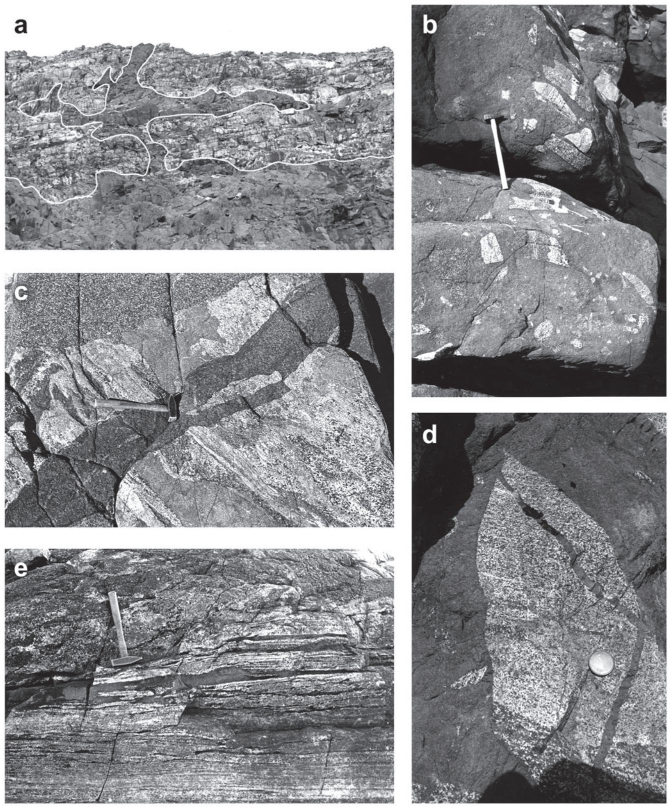


Figure 1. Intrusive relationships. (a) Overview of the roof zone of the Nordre Bumandsfjord pluton, showing the contact between the dunite (massive grey) and the layered gabbros, which are intruded by the dunite along the contact, and by dunite sills and dikes. Length of photo ca 200 meters. (b) Intrusive breccia, with angular blocks of variably remelted layered gabbros in matrix of contaminated peridotite, which is cut in turn by a more massive dunite dike on the right side of the view; hammer shaft = 60 cm. (c) Xenolith of partially remelted gabbro with dunite sill along the layering is cut by a dike of contaminated peridotite; the whole xenolith is enclosed in a strongly contaminated, plagioclase-rich peridotite; hammer shaft = 30 cm. (d) Thin dunite dikes cutting a gabbro xenolith, enclosed in dunite; coin = ca 2 cm. (e) Massive dunite penetrating as sills along the layering of a strongly foliated gabbro near the eastern contact; hammer shaft = 30 cm.

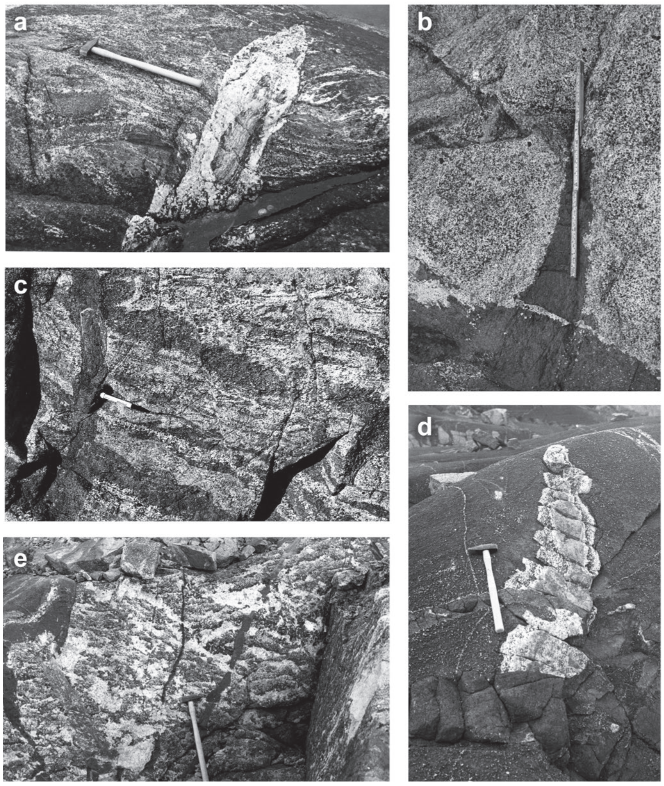


Figure 2. Anatectic phenomena. (a) Anorthositic dike, carrying xenolith of layered gabbro, crosscutting melted and strongly deformed gabbro; hammer shaft = 60 cm. (b) Bleaching at the rim of a gabbro xenolith, illustrating the removal of cpx-rich melts; note backveining of dunite by anorthositic melt issuing from rim of xenolith; ruler = 20 cm. (c) Wholesale melting of gabbroic xenolith (in peridotite visible at upper left), producing pegmatitic textures; hammer shaft =60 cm. (d) gabbro xenolith enclosed in contaminated peridotite, showing pegmatitic melting of xenolith rim; both xenolith and host peridotite are cut by dikes of less contaminated peridotite; hammer shaft = 60 cm. (e) Melting within gabbro xenolith, mimicking the pre-existing layering; gabbro is cut by dike of contaminated peridotite; pen = 15 cm.

the expansive exposures uncovered by a retreating icecap, the Caledonian nappe complex of Arctic Norway provides rare insights into the interaction between mafic-ultramafic magmas and the deep continental crust. The Kalak Nappe Complex contains >25,000 km^3 of mafic igneous rocks, mostly layered gabbros, making up the 570-560 Ma Seiland Igneous Complex. The Complex has been intruded by a series of ultramafic magmatic rocks, including the Nordre Bumandsfjord Pluton. Field relationships in this pluton (Fig. 1-3) show that extremely fluid, dry, relatively Fe-rich (Fo81) dunite magmas intruded a pile of cumulate gabbros, with extensive block stoping and intrusive brecciation. Diking on scales from mm to meters, and extensive melting and assimilation of the gabbros, attest to high temperatures, consistent with a 2 km-wide granulite-facies contact aureole.

Major- and trace-element trends show that the dunites were progressively contaminated by a clinopyroxene-rich partial melt of the gabbros, producing a range of lithologies from dunite through lherzolites to wehrlite. Experimental studies of natural samples at 0.8-1 GPa define the dunite solidus at 1650-1700 °C. In the average peridotite, contamination has dramatically lowered the solidus of the magma, producing a crystallisation interval of ca 400 °C (1600-1200 °C). This would provide large amounts of heat for melting and metamorphism, while the magmas remained fluid to relatively low T, consistent with the field relationships. Thermochemical and dynamic modelling shows that the dunitic primary magmas may represent the last melting of a rapidly ascending diapir of previously depleted subducted oceanic lithosphere. The mafic rocks of the Seiland Complex may already have been extracted from this diapir, and the late dikes of the province may reflect melting of the asthenosphere as the diapir spread out beneath the lithosphere. Ultramafic magmas, abundant in the Archean, may still be more common than usually assumed. However, they would only penetrate to the shallow crust under unusually extensional conditions, where ascent could outpace assimilation. See *CCFS publication #237.*

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Bill Griffin, Sue O'Reilly, Craig O'Neill
Funded by: TARDIS-E Foundation Project 2, CCFS

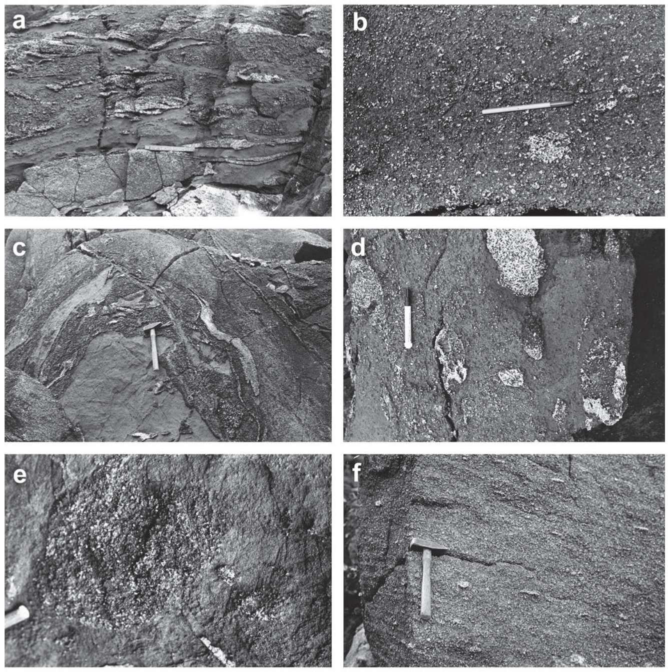


Figure 3. Contamination processes. (a) Dunite sills in heavily contaminated gabbro studded with fragments of residual anorthosite; scale ruler = 7 cm. (b) Residual clots of gabbroic plagioclase, scattered in heavily contaminated dunite; pen = 15 cm. (c) Heavily contaminated peridotite with folded schlieren of residual anorthosite, in sharp contact with relatively clean dunite, which appears to be intruded by the contaminated dunite; hammer shaft = 30 cm. (d) Ghost xenoliths, defined by residual plagioclase, enclosed in strongly foliated contaminated peridotite; pen = 15 cm. (e) Ghost xenolith of gabbro (10 cm diam.), defined by residual plagioclase, in moderately contaminated dunite. (f) Relatively homogeneous, strongly foliated and strongly contaminated peridotite, with relict knots of gabbroic plagioclase; hammer shaft = 30 cm.

Archean lower crustal rocks in southeastern Greenland: to hell and back

Figure 1. Field work in remote and rugged areas in southeastern Greenland relies on helicopter.

Ongoing work in CCFS suggests that many areas of relatively young crust are underlain by much older crust (*CCFS publications #37, 38, 75, 95, 97, 163, 190*), but the lower crust is rarely available for direct study. Much of the upper crust is commonly interpreted as originating from the partial melting of the lower crust, but there is considerable debate as to how these magmas are produced and move through the lower crust to their ultimate sites of emplacement, at shallower levels.

The Thrym Complex in southeastern Greenland appears to represent a very rare example of a section through the Archean crust, which includes *ca* 2750 Ma granulite-facies and *ca* 2700 Ma greenschist-facies rocks. It is made up of highly metamorphosed rocks representing major multiphase granitic bodies and a wide range of felsic, intermediate, mafic and ultramafic intrusions. These rocks are located in a high-alpine terrain at altitudes of around 3500 m above sea level (Fig. 1), and is one of the least studied regions of high-grade Archean gneisses and granulites in the North Atlantic Craton (if not in the world). The CET is studying this remote region, in collaboration with the Geological Survey of Denmark and Greenland (GEUS), within the framework of the Foundation Project 'Metal Sources and Transport Mechanisms in the Deep Lithosphere' in the ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS).

This study took a regional approach in understanding the petrogenesis of the *ca* 2790-2700 Ma orthogneisses using new field data, petrology, whole rock geochemistry and U/Pb zircon age data on material collected in 2011. The principal aim was to understand the evolution of the early lower crust and to better decipher the regional geological history of the area.

Earlier studies have implied that the lower crust is predominantly mafic in nature. However, in the Archean lower-crustal section of the Thrym Complex, felsic gneisses predominate over mafic and ultramafic rocks.

The chemical and isotopic data suggest that the protoliths for the *ca* 2750 Ma orthogneiss in the Thrym Complex formed at the base of a tectonically thickened arc-like crust at temperatures between 800° and 1000 °C, and depths between 35 and 50 km. The mafic granulites and ultramafic rocks were metamorphosed at high grade, leading to partial melting with garnet and rutile present, consistent with the conditions expected in deep crustal levels or an arc root. With crustal thickening during continental collision, temperatures in this already hotter-than-normal crust can be amplified by increased radioactive heat production, leading to partial melting. This high-grade metamorphism was synchronous with similar metamorphism in western Greenland, suggesting that significant crustal thickening and possible relamination took place over much of the eastern part of the North Atlantic Craton in NeoArchean time (the Skjoldungen Orogeny; Fig. 2).

Our study of the Archean Thrym Complex in southeastern Greenland highlights the importance of integrating geochemical data with field observations in the development of geological models for high-grade gneiss terranes. For further information, see *CCFS publication # 228*.

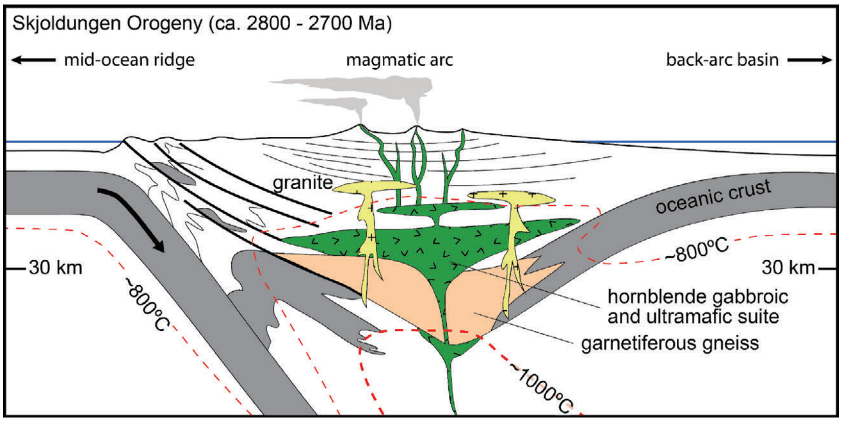


Figure 2. Model for the formation of the protoliths for gneisses in southeastern Greenland (from Bagas et al., Lithos 2013).

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture and Fluid Fluxes.

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Funded by: CCFS, Greenland BMP, GEUS, CET, UWA

Subduction switches: geochemistry as a proxy for paleogeophysics in South China

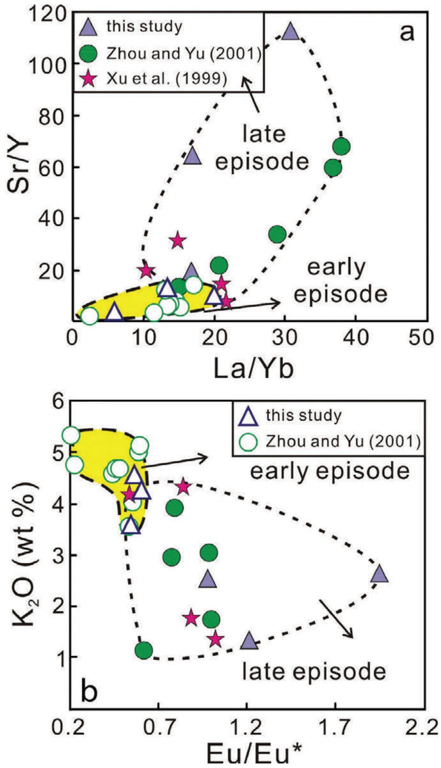


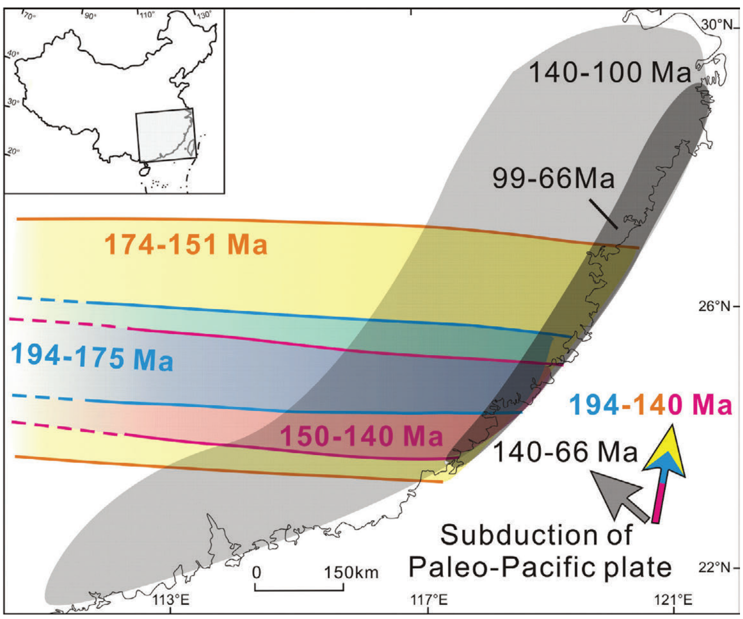
Figure 2. Simplified new distribution and genetic model for late Mesozoic igneous rocks in the South China Block. The subduction of the Paleo-Pacific plate is inferred by Engebretson et al. (1985), Maruyama and Seno (1986) and Maruyama et al. (1997).

It is generally thought that late Mesozoic granite magmatism in the South China Block (SCB) shows an oceanward-younging migration. However, our new geochronological study of granites along the Pingtan-Dongshan Metamorphic Belt in the coastal part of the SCB, is not consistent with this trend. These late Mesozoic granites (and all those previously published) can be subdivided on their zircon U-Pb ages, into an early episode (194-140 Ma) and a later episode (140-66 Ma); the granites of the two episodes also have different geochemistry.

Both age groups of granites in this area are relatively depleted in Nb, Ta and Ti, but enriched in large-ion lithophile elements (e.g. Rb, Ba), with low Rb/Ba and Rb/Sr ratios and A/CNK values. These features are typical of I-type granitoids related to subduction. However, the early granites have higher Sr and K_2O contents and higher La/Yb, Sr/Y and Eu/Eu* ratios than the later ones (Fig. 1), suggesting that the former originated from a shallower source with higher geothermal gradients, probably in a back-arc extensional setting, whereas the later ones derived from a deeper source with lower geothermal gradients; this probably was related to a compressional continental arc setting.

Integrating all recent precise zircon U-Pb ages, we find that the early episode of late Mesozoic igneous rocks (194-140 Ma) in the southeastern SCB formed in three pulses: 194-175 Ma, 174-151 Ma and 150-140 Ma. These pulses of magmatism mainly occur in the Nanling Range with EW-striking trends, probably extending eastward to the coast (Fig. 2). The granites of the later episode (140-66 Ma) mainly are found in the coastal SCB along a SW-NE trend. The early (140-100 Ma) magmatism is characterised by calc-alkaline I-type granites and probably formed in a continental-arc setting, whereas late (99-66 Ma) magmatism features alkaline A-type granites and occurred in an extensional setting.

The different distributions and tectonic settings of the late Mesozoic igneous rocks in the SCB contradict previous genetic models. Integrating our observations with previous studies on the subduction direction of Paleo-Pacific plate (Fig. 2), we propose that the early episode of late Mesozoic igneous rocks in the SCB were probably formed under extensional tectonics related to the northward subduction of the Paleo-Pacific plate in Jurassic time. In contrast, the granites of the later episode, running NE-SW along the coastal SCB, resulted from the NW-ward subduction of the Paleo-Pacific plate in Cretaceous time. This represents a major switch in the subduction direction. The oceanward-younging trend of the later episode probably was related to the rollback of the subducted plate.



This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture.

Contacts: Qian Liu, Jinhai Yu, Sue O'Reilly

Funded by: NSF of China

Figure 1. Geochemical differences between the early and late episode of late Mesozoic granites in the PDMB.

Unveiling mantle fluids using diamonds

Diamond-bearing eclogite xenoliths are common in the Udachnaya kimberlite, Siberia. Three types of garnet (Gnt) can be recognised in these eclogites, with different major-, trace-element and O-isotope compositions and related to different stages of mantle metasomatism.

The major- and trace-element compositions of garnets from 25 xenoliths show a well-defined change from positive to negative ratios of the heavy to light rare-earth elements (HREE/LREE) at a CaO content of 7.8-8.7%. This suggests either a change in fluid

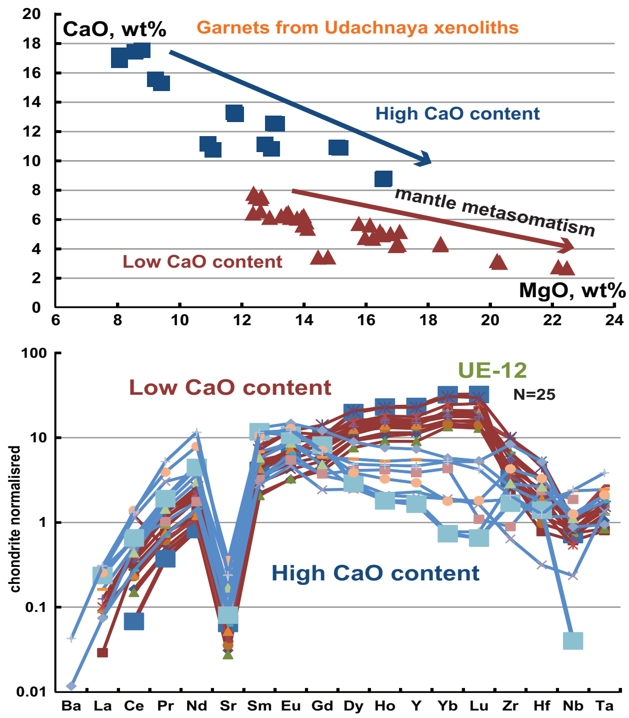


Figure 1. Major- and TE- element composition of garnets from Udachnaya xenoliths.

compositions or a change in garnet/fluid partitioning related to garnet composition. Both groups show similar trends of increasing MgO content in garnet due to mantle metasomatic processes. This is well evidenced by the difference in major-element, trace-element and oxygen isotope compositions between the original Garnet 1 and the metasomatic Garnet 2 in sample UE-12-2. Gnt1 and Gnt2 are usually found together with diamonds in metasomatic veins (Fig. 1). Garnet 2 forms Mg-rich rims on Garnet 1 (mg#=0.67-0.80 vs 0.57-0.58 for Garnet 1). The significant zoning in chemistry and its relationship to diamond with mantle-like carbon isotopes ($\delta^{13}C$ =-5.6 - -6.6‰) suggest that Garnet 2 (and the diamond?) were produced by mantle fluids/melts shortly before eruption. Garnet 2 has a wide range in oxygen isotope composition ($\delta^{18}O$ = 6.2-9.0‰), suggesting mixing of mantle fluids with the original isotopic system (Gnt1, $\delta^{18}O$ =11.1-12.0‰). This pattern of decreasing $\delta^{18}O$ with

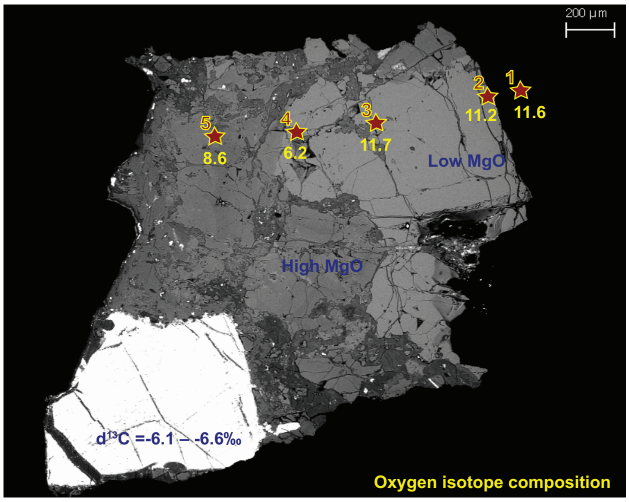


Figure 2. Oxygen isotope composition of Garnet 1 (original) and Garnet 2 (metasomatised); backscattered electron image of the sample (stars show traverse).

increasing mg# during metasomatism is similar to that identified in the Roberts Victor eclogite suite (see *Research highlight pp. 33-35*).

Garnet 3 is found in corundum-bearing eclogites and has much higher Ca (CaO=15.61-16.56 wt%) and different isotopic characteristics ($\delta^{13}C$ =-3.6 - -5.3‰; $\delta^{18}O$ =3.2-5.7‰). This suggests a different protolith, or a different metasomatic fluid from the one that produced Garnet 2. The Lu/Gd ratio increases significantly from Garnet (0.06-0.12) to Garnet 1 (4.0-4.2) to Garnet 2 (5.5-9.0). The demonstrated correlation between the oxygen composition of metasomatic garnet and high MgO contents, related to the formation of diamond with mantle-like carbon-isotope compositions, demonstrate the important role of mantle fluids. These fluids may also have been a trigger for the eruption.

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Fluid Fluxes.

Contacts: Ekaterina Rubanova, Bill Griffin, Sue O'Reilly

Funded by: CCFS Foundation Project "Diamond Genesis: Fluids in deep-earth processes, IPRS, MQ PGRF

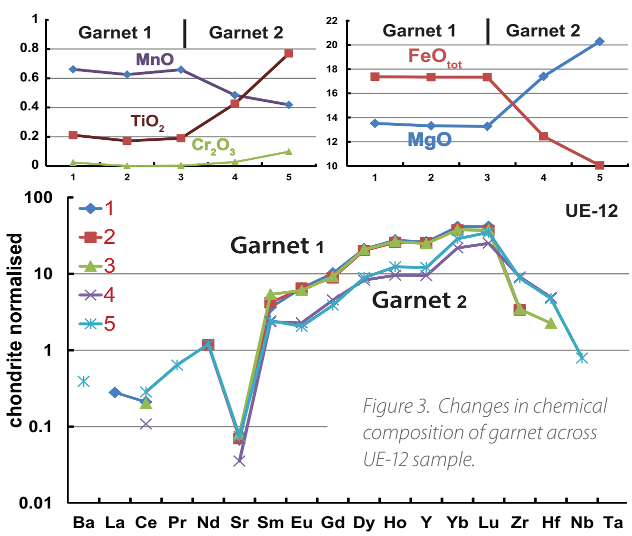


Figure 3. Changes in chemical composition of garnet across UE-12 sample.

Yilgarn dykes track details of supercontinent events: the transition from Nuna to Rodinia

It has been widely accepted that the supercontinent Nuna (also known as Columbia) formed about 1800 million years ago (Ma) (see *Research highlight pp. 32-33* for more information about Nuna). However, precisely when it broke up, and how the resulting continental blocks reassembled to form the next supercontinent (Rodinia), is less certain. Australia held key positions in both supercontinents, and high-quality paleomagnetic data for Mesoproterozoic Australia are therefore crucial for understanding this process.

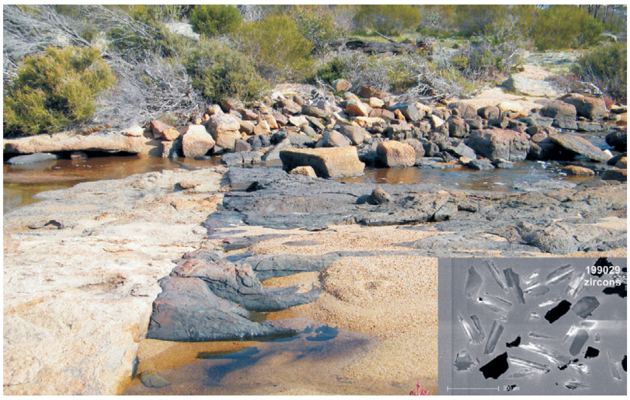


Figure 1. A northeast-trending, ca. 1.2 Ga mafic dyke (the dark outcrop) intruding granitic gneiss at the southeast margin of the Yilgarn craton. Inset shows zircon grains from the dyke. (Photographs by Michael Wingate)

The Gnowangerup-Fraser mafic dyke swarm is part of the Marnda Moorn large igneous province (LIP) and runs subparallel to the southern and southeastern margins of the Yilgarn Craton. Some dykes towards the craton margin are strongly recrystallised and others are deformed within the orogen, implying that at least some dykes were emplaced before the youngest deformation in the Albany-Fraser Orogen. Five dykes have previously yielded U-Pb ages between 1203 and 1218 Ma, and a positive baked-contact test suggests a that the magnetic remanence in the dykes is primary. The fossil record of past geomagnetic direction, which reflects the orientation and palaeolatitude of the continent at the time the rock formed, had been retrieved from a 1212 Ma Fraser dyke. To check this result and to get a true, time-averaged palaeomagnetic record, we collected samples from 19 dykes, along the Phillips and Fitzgerald Rivers, and north of Ravensthorpe. Stepwise demagnetisation provided a stable bipolar remanence from 14 dykes. A block sample from one of them, a coarse-grained dolerite was collected from the centre of a 20 m wide, vertical, northeast-trending (043°) dyke exposed in the Fitzgerald River (Fig. 1). The GSWA's SHRIMP analysis of zircons from this sample indicated high and variable U and Th contents and Th/U ratios, typical of primary zircons in a mafic intrusion, and provided a preliminary crystallisation age of 1218 ± 6 Ma. A similar dyke, further east in the Phillips River, yielded a preliminary crystallisation age of 1211 ± 42 Ma, based on SHRIMP analyses of low-uranium baddeleyite.

The mean palaeomagnetic direction from the 14 dykes gives a palaeomagnetic pole at 55.8°N, 323.9°E, A95=6.5°, almost identical to the previously reported preliminary pole position from the 1212 Ma Fraser dyke. This robust paleopole, a rare key-pole for Mesoproterozoic Australia, places the West Australian Craton in a near-polar position at 1210 Ma (Fig. 2a). Comparison with coeval Laurentian paleopoles indicates that Laurentia and Australia would have been widely separated at that time (Fig. 2a). The two continents travelled very different paths between 1200 Ma and 1000 Ma (Fig. 2), and therefore could not have been parts of any supercontinent. This implies that the supercontinent Nuna must have broken apart before 1200 Ma, and Rodinia probably did not form until after 1070 Ma. Our concurrent geochemical analyses of this dyke swarm suggest a possible mantle plume connection for its formation. However, whether this swarm and coeval LIP events in other continents can be treated as parts of a single LIP to reconstruct palaeogeography, and how such plume event(s) are linked to supercontinent cycles, require further investigations.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Architecture.

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Funded by: CCFS Foundation Project 6, Detecting Earth's rhythms: Australia's Proterozoic record in a global context

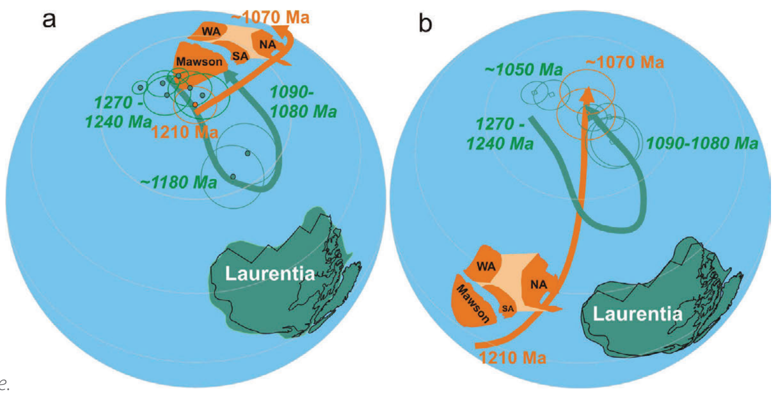

Figure 2. Palaeomagnetically permissive palaeolatitudes of Australia and Laurentia at ca 1210 ma (a) and ca 1070 Ma (b), respectively, illustrating rapid changes in both palaeolatitudes and relative positions during the transition time between supercontinents Nuna (ca. 1800-1400 Ma) and Rodinia (ca. 900-700 Ma). The ca 1200 Ma key pole for Australia is from this study. The distinctively different apparent polar wander paths for the two continents (the thick bands with arrows, with colours corresponding their respective continents) suggest that the two continents travelled different paths during that time interval; in other words, they could not have been part of a supercontinent at that time.

Stealth attacks in Earth's uppermost mantle: recognition of a new type of metasomatism and its consequences

Mantle metasomatism is a relatively recent concept, introduced in the early 1970s when detailed studies of lithospheric mantle rock fragments (xenoliths), brought to the surface in basaltic to kimberlitic magmas, became widespread. Two main types of metasomatism were defined: modal (or patent) metasomatism describes the introduction of new minerals; cryptic metasomatism describes changes in composition of pre-existing minerals without formation of new phases. A new type of metasomatism has now been documented (*CCFS publication #5*),

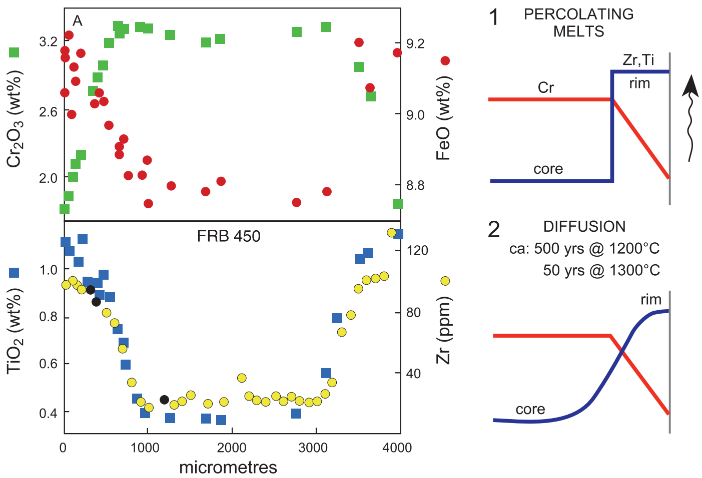

Figure 1. Zoning in a garnet from sheared lherzolite xenolith FRB450, and a model. (1) Instantaneous overgrowth of a garnet rim high in Zr and Ti, but low in Cr. (2) Diffusional modification of Zr and Ti profile. Chromium diffuses much more slowly, if at all (After Griffin et al. (1996)).

stealth metasomatism; this process involves the addition of new phases (e.g. garnet and/or clinopyroxene), but is a "deceptive" metasomatic process because it adds phases indistinguishable mineralogically from common mantle peridotite phases. The recognition of stealth metasomatism reflects the increasing awareness of the importance of refertilisation by metasomatic fluid fronts in determining the composition of mantle domains. Tectonically exposed peridotite massifs provide an opportunity to study the spatial relationships of metasomatic processes on scales of a metre to kilometres.

Mantle fluid types:

The nature of mantle fluids can be determined from the nature of fluid inclusions in mantle minerals and indirectly from changes in the chemical (especially trace-element) compositions of mantle minerals. Metasomatic fluids in off-craton regions cover a vast spectrum from silicate to carbonate magmas containing varying types and abundances of dissolved fluids and solutes.

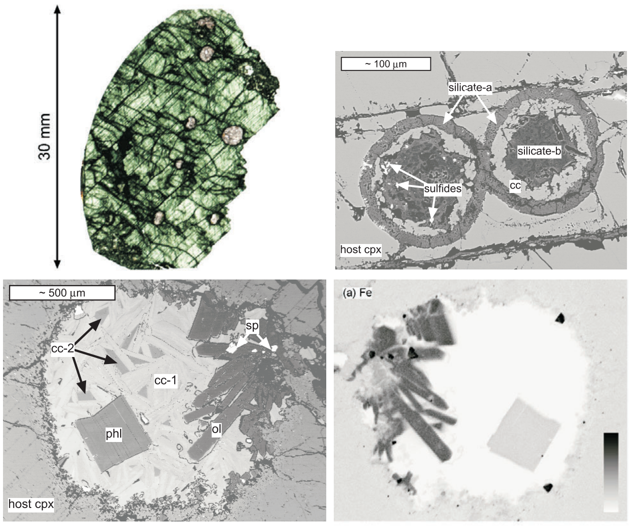

Figure 2. Inclusions of carbonatitic and silicic melts trapped in the Cr-diopside of megacrystalline lherzolite xenoliths from the A154 kimberlite, Slave Craton, Canada. Quench crystals of a Sr-rich carbonate and olivine show that these inclusions were molten at the time of kimberlite eruption, but that the melts had penetrated the pyroxene long enough before the eruption that the pyroxene was able to partially recrystallise and trap the melt inclusions. The lower two frames are mirror images at the same scale (After van Achterbergh et al. (2004)).

Fluid inclusions in diamond and deep xenoliths reveal the presence of high-density fluids with carbonatitic and hydro-silicic and/or saline-brine end-members. The data from deep cratonic xenoliths reinforce the importance of highly mobile melts spanning the kimberlite-carbonatite spectrum, which may become immiscible with changing conditions.

Effects of metasomatism on mantle geophysical properties:

A critical conceptual advance in understanding Earth's geodynamic behaviour is emerging from understanding the linkage between mantle metasomatism and the physical properties of mantle domains recorded by geophysical data. For example, metasomatic refertilisation of cratonic lithospheric mantle increases its density, lowers its seismic velocity and strongly affects its rheology. Introduction of radioactive

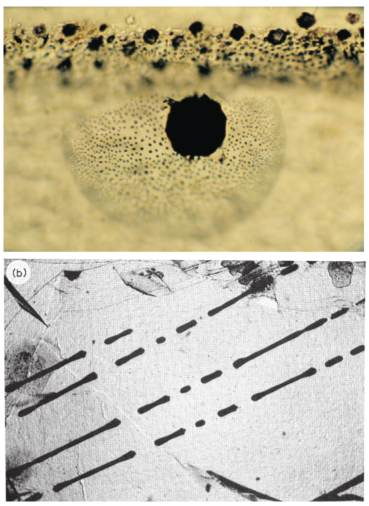

Figure 3. Photomicrographs of inclusions of sulfide melts, trapped in pyroxene from pyroxenite xenoliths from SE Australia. Left panel shows a single large inclusion that has expanded and fractured the pyroxene, sending molten sulfide and CO_2 into the crack, which has recrystallised to trap a swarm of microinclusions. Right panel shows sulfide melts that originally were trapped as elongate hollow rods filled with liquid CO_2, and then necked down to hollow spheres (After Andersen et al. (1987)).

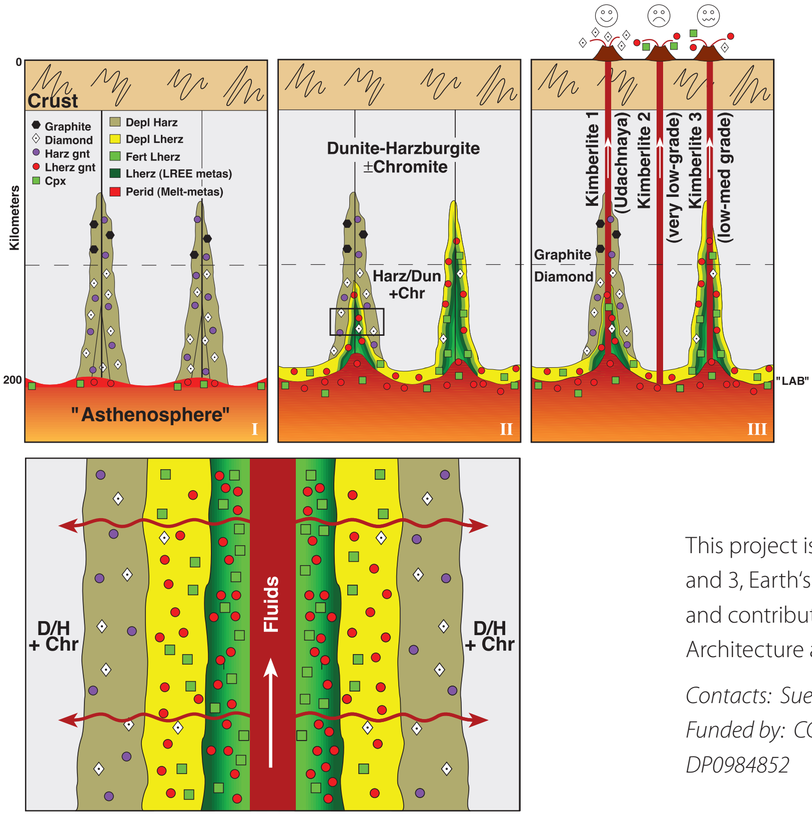

Figure 4. Cartoon illustrating a model for the early stages of cratonic metasomatism (After Malkovets et al. (2007)). (I) Primitive Archean SCLM, consisting of relatively oxidised harzburgite/dunite, is metasomatised by Si-bearing CH_4-rich fluids brought in by low-degree melts from the underlying "asthenosphere". Precipitation of diamond/graphite - harzburgitic garnet near fluid conduits. Melt-related metasomatism near the lithosphere-asthenosphere bound-ary (LAB) converts some harzburgites to lherzolite by addition of Ca, Fe, and Al. (II) Continued input of melts/fluids. Reduced harzburgite does not precipitate diamond/graphite. Melt-related metasomatism refertilises harzburgite to lherzolite at the base of the lithosphere and along conduits (weakly in left conduit, more extensively in right conduit). Relict harzburgitic diamonds in lherzolites. (III) Kimberlite eruption; high-grade pipes sample remnants of Stage-A modified mantle. Barren pipes sample least-metasomatised mantle and lack both harzburgitic garnets and diamonds. Some low-grade pipes sample highly metasomatised mantle with relict diamonds. The lower panel shows a detail of the melt conduit and the progressive metasomatism of the wall rocks, first by CH_4-rich fluids expelled from the melts, and then by the melts themselves. Dun dunite, Harz harzburgite, Lherz lherzolite, Fert (re)-fertilised, Perid peridotite, Cpx clinopyroxene, Gnt garnet, Chr chromite, LREE light rare earth elements, metas metasomatised.

elements (U, Th, K) increases heat production, and the key to understanding electromagnetic signals from mantle domains may be closely related to the distribution and type of fluids (e.g. carbonatitic, hydrous) and their residence in or between grains.

Consequences of mantle metasomatism through time:

The lithospheric mantle is a palimpsest recording the multiple fluid events that have affected each domain since it formed. Metasomatism is the mechanism that primes mantle regions for metallogenic fertility (see *Research highlight p. 60-61*) and recognition of metasomatic processes is providing a potentially global predictive framework for the location of some ore deposits (e.g. as Ni. Cr, Au, Cu, diamond) in the crust. These metasomatic events, involving different fluids and compositions, have repeatedly overprinted variably depleted original mantle wall-rocks. This produces a complex, essentially globally metasomatised lithospheric mantle, heterogeneous on scales of microns to terranes and perhaps leaving little or no "primary" mantle wall-rock. Decoding this complex record by identifying significant episodes and processes is a key to reconstructing lithosphere evolution and the nature and origin of the volatile flux from the deep Earth through time.

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

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Funded by: CCFS Foundation Projects 1 and 8, relinquished DP DP0984852

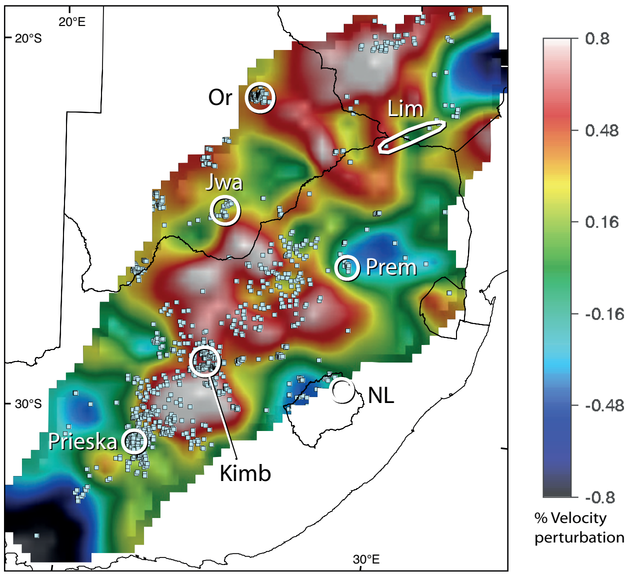

Figure 5. Detailed Vs tomography along a 1,000-km traverse at 200 km depth across the SW part of the Kalahari craton of southern Africa (Begg et al. 2009), with locations of kimberlites (Faure 2006). Circles and oval mark locations of well-studied xenolith and xenocryst suites. Lim Limpopo Belt, Prem Premier (Cullinan) Mine, NL northern Lesotho, Kimb Kimberley area, Or Orapa area, Jwa Jwaneng area, Prieska area lies across the craton margin. These suites clearly do not sample the highest-velocity (most depleted) parts of the SCLM root.

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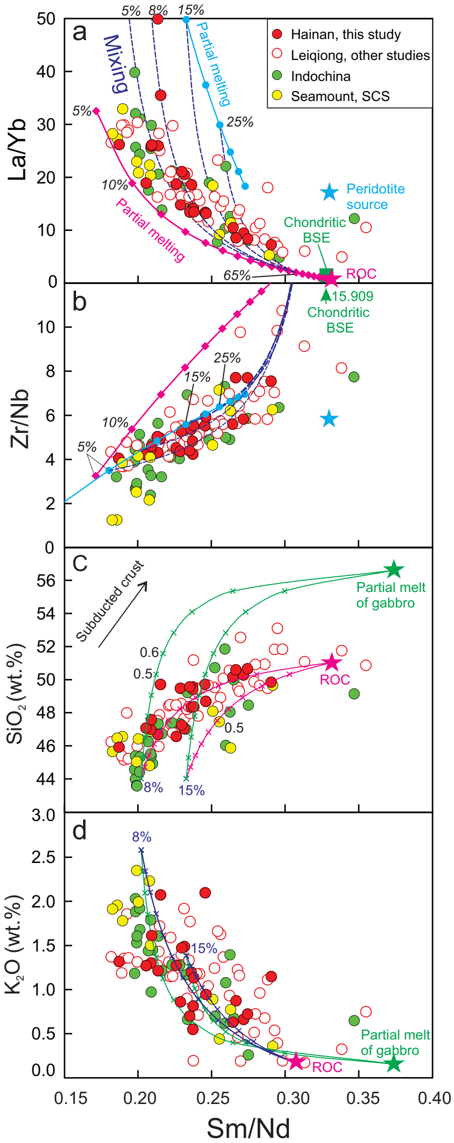
Ancient reservoirs and recycled components: Linking plumes and plate tectonics

Whether mantle plumes and plate subduction are genetically linked is a fundamental question that impinges on our understanding of how Earth works. Earth's materials are circulated between the surface and the bottom of the mantle through mantle-plume and plate-tectonic processes. The late Cenozoic basalt province in southeastern Asia is the first example that may demonstrate direct links between a young mantle plume and deep subduction. The presence of a young mantle plume rooted in the lower mantle is suggested by low-velocity seismic structures and a thinned mantle transition zone. Our pilot work, led by Dr Xuan-Ce Wang, has demonstrated that these young basalts were generated by partial melting of unusually hot mantle (*CCFS publication #24*).

Figure 2. Covariation of selected trace element ratios and major elements with Sm/Nd ratios in the LIS basalts. The chondritic bulk silicate Earth (BSE), nonmodal batch partial melting (solid lines with square or circle) and binary mixing (dark blue dashed lines) between recycled oceanic crust (ROC) and peridotitic source derived melts are shown.



The synchronous less-contaminated basalts (εNd>+3) from the Leiqiong area, on the nearby Indochina peninsula, and the South China Sea seamounts (the LIS basalts) fall close to or within the range suggested for a FOZO (focal zone) mantle component, which is commonly proposed as a major component of the lower mantle (Fig. 1). The LIS basalts show a narrow range of $^{206}Pb/^{204}Pb$, but large variations in $^{207}Pb/^{204}Pb$, so they are bracketed by the 4.5- and 4.4 Gyr-old geochrons. This suggests the presence of a 4.5-4.4 Ga-old reservoir resulting from primordial differentiation of Earth mantle. This implies the presence of rocks that have been isolated from mantle convection currents since early in Earth's history. These isotopic signatures are consistent with previous observations that argue for the existence of a plume, rising from the lower mantle in the Hainan region.

An important feature of the LIS basalts is the decoupling between isotopic and elemental signatures. The trace- and major-elements are highly correlated with trace-element

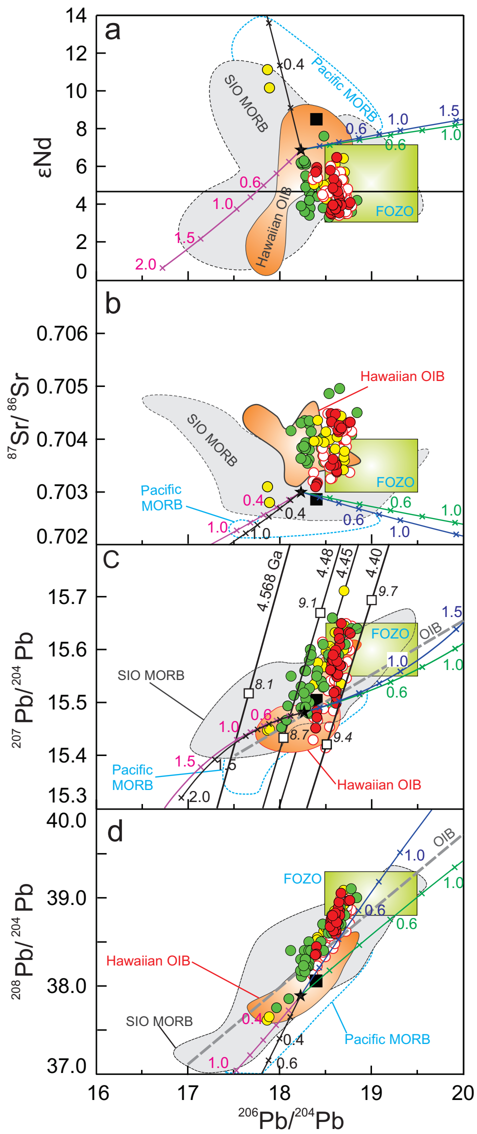
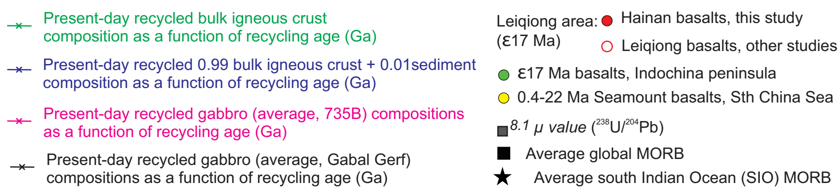


Figure 1. Sr, Nd and Pb isotopes of late-Cenozoic least-contaminated LIS basalts from the Leiqiong area, the Indochina peninsula, and the South China Sea seamounts compared with Pacific MORB, south Indian Ocean MORB, and the Hawaiian OIBs. The fields of Pacific and south Indian Ocean MORB and the isotopic evolution of recycled components are also shown (for detail, please contact: Xuan-Ce Wang).



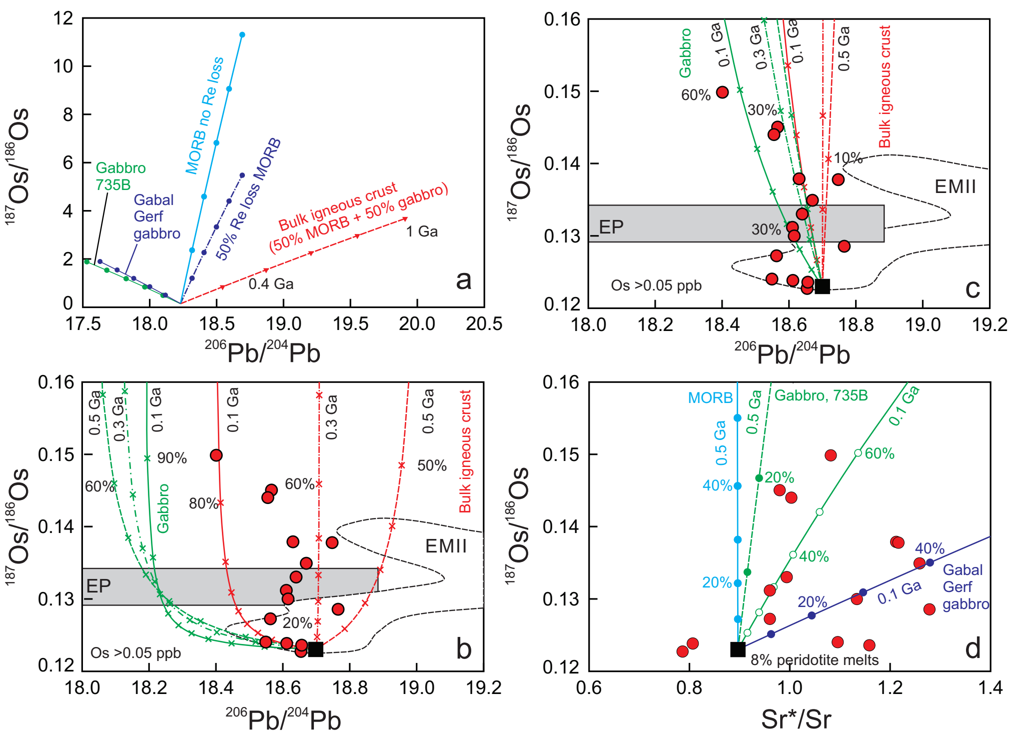


Figure 3. Comparison of the Os-Pb isotopes of the Hainan basalts with isotopic evolution of different recycled lithologies.

ratios. With crustal contamination excluded, the correlations presented in Figure 2 suggest two end-member (high- and low-silica) melts. The high-silica end-member is similar to the bulk recycled oceanic crust and experimental melts of oceanic gabbro. The low-silica end-member melt compares well with the composition of incipient partial melts of garnet peridotite. However, there are no prominent correlations between elements and isotopes identified in this study. This suggests that the source of the late Cenozoic basalts may also contain young recycled components.

These conclusions have been confirmed by modelling of the isotopic evolution of recycled components (Figs. 1 and 3). First, the recycled oceanic crust may be the dominant factor controlling Pb isotopic heterogeneities in OIBs sources. Second, extremely high $^{187}Re/^{188}Os$ ratios recently reported in oceanic crust (80-675) would lead to very radiogenic $^{187}Os/^{188}Os$ ratios ($^{187}Os/^{188}Os$ = 2-12) over 1 Ga (Fig. 3a), suggesting that such a component probably is absent in the LIS basalt source. Third, both ancient (>0.6 Ga) gabbro- and bulk oceanic crust-derived melts have distinctive Pb-Sr-Nd (Fig. 1) and Os (Fig. 3) isotopes that are significantly different from what we observed in the natural LIS basalts. Overall, our modelling results show that the maximum age for the recycled components in the source of the LIS basalts is <0.6 Ga.

These new findings, along with existing geophysical, petrological, geochemical evidence, confirm the coexistence of an ancient (4.5-4.4 Ga) mantle reservoir and young (0.2-0.5 Ga) recycled materials in the source region of the young Hainan plume. This study may provide the first observational support for dynamic linkages between deep subduction and the generation of mantle plumes (Fig. 4).

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Xuan-Ce Wang and Zheng-Xiang Li
Funded by: CCFS and NSFC

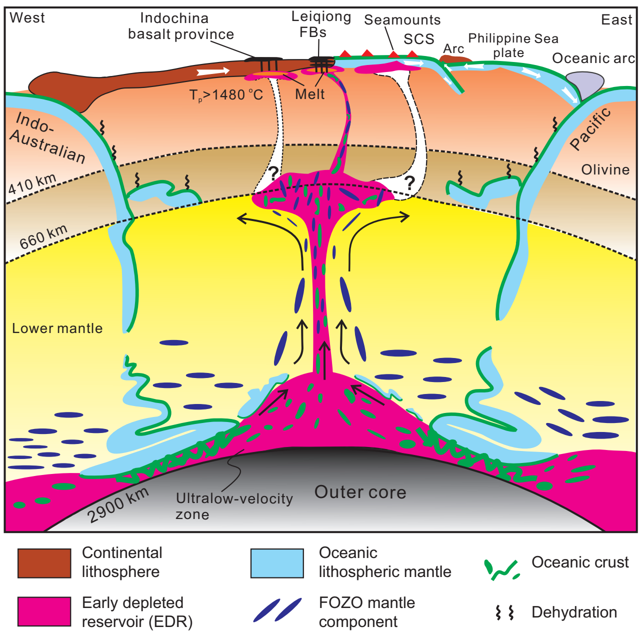
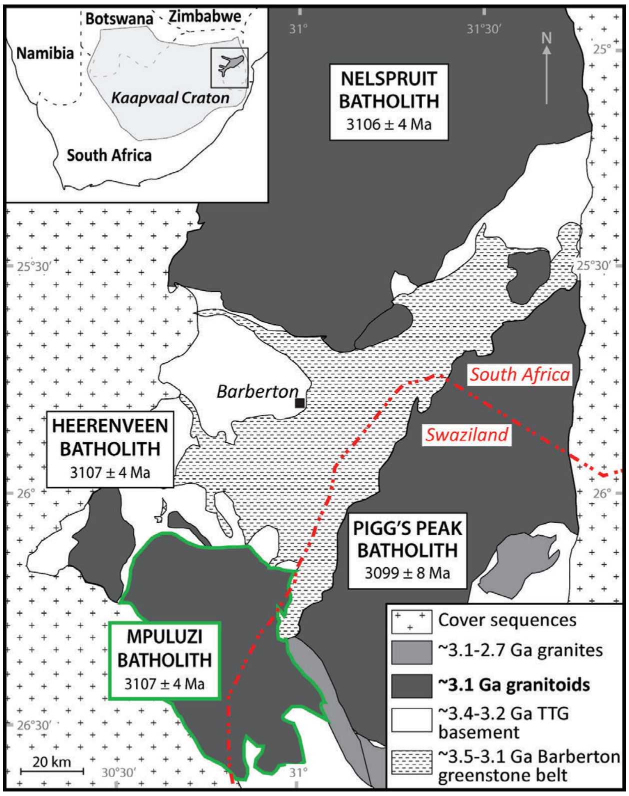


Figure 4. A cartoon illustrating the formation mechanism of the Hainan plume based on seismic imaging results and this study.

The end of the Archaean in the eastern Kaapvaal Craton: the 3.1 Ga Mpuluzi batholith

The Mpuluzi batholith forms part of the eastern Kaapvaal Craton in southeastern Africa - a piece of Archaean continental crust that has been stable for the past three billion years. The Mpuluzi outcrops over an area of approximately 2000 km^2, and dominates the landscape, forming a high plateau that rises above the African grasslands (Fig. 1). The Mpuluzi is one of several large bodies of similar age in the region, along with the Nelspruit, Piggs Peak and Heerenveen batholiths, which total approximately 10,000 km^2 (Fig. 2). These large granitoid intrusions were all emplaced at ~3.1 Ga, and are all unusual in form - they occur as 1-2 km thick sheets, rather than the deep-rooted batholiths common in Archean cratons. For half a billion years prior to their emplacement, the eastern Kaapvaal Craton was an active region, with large-scale melt emplacement events recorded at 3.51, 3.44 and 3.2 Ga. After the emplacement of the Mpuluzi and other 3.1 Ga granitoids, no major geological events were recorded in the region for another 600 Ma.



The emplacement of the Mpuluzi batholith, marking such a turning point in the history of the Kaapvaal Craton, is thus an event of significant interest in terms of crustal evolution processes. Although the older crustal remnants beneath the granite sheets - the Barberton Greenstone Belt to the northeast and the Ancient Gneiss Complex to the southeast - have been extensively studied, the Mpuluzi itself is still poorly understood, and there are few constraints on either the melt generation or emplacement chronology. This project has been designed to tackle some major questions: What was the heat source for the magmas, and what was the source material? How many pulses of magma were involved, and over what timescale? Why did emplacement occur in this unusual sheet-like form?

Dating the zircon from the Mpuluzi samples has proved to be a challenge, with many grains full of cracks and inclusions, leaving little 'clean' material to analyse. The high concentrations of the radioactive elements U and Th in the grains has meant that their 3 billion year life has been rather a hard one. Many have lost a lot of their radiogenic lead, as radiation damage progressively destroyed the crystal lattice.

The U-Pb ages obtained from Mpuluzi samples range from ~3.14 to ~3.09 Ga, with the main cluster of ages at 3.123 ± 7 Ga, emplacement may have occurred over a period as long as 50 million years. Some samples have a minor inherited population at ~3.5 Ga, which suggests that older crustal material was melted to produce the magmas. The Hf-isotope data provide further supporting evidence, with mean model ages of ~3.5 Ga, and in some samples extending back as far as ~4 Ga.

The Mpuluzi samples are currently being analysed for their Sr and Nd isotopic compositions, which will provide further constraints on the composition and age of the source material. The problems of the heat source and the unusual emplacement style will then be addressed through geodynamic modelling. Watch this space!

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Rosanna Murphy, Bill Griffin, Norman Pearson, Sue O'Reilly, Craig O'Neill

Funded by: CCFS Foundation Project, MQRES, EPS Postgraduate Fund

Metals in dirty water – the genesis of ore deposits

Field evidence shows that metal ore bodies are deposited by fluids derived from deeper in the Earth – but we do not yet understand in any detail how the metals are picked up from the deeper lithosphere and transported in the fluids. We have begun a multi-scale integrated study to address this void in our understanding. One part of the study involves a set of key experiments designed to evaluate the chemical behaviour of fluid systems at the conditions of the lithospheric mantle and the asthenosphere. The current focus is on the complex transport and concentration mechanisms of siderophile-chalcophile elements such as Ni, Cu and PGE in the deep lithosphere. Researchers from Macquarie and The University of Western Australia are collaborating on this Foundation Project, which addresses Theme 3 (Earth Today - and its Resources) of the CCFS.

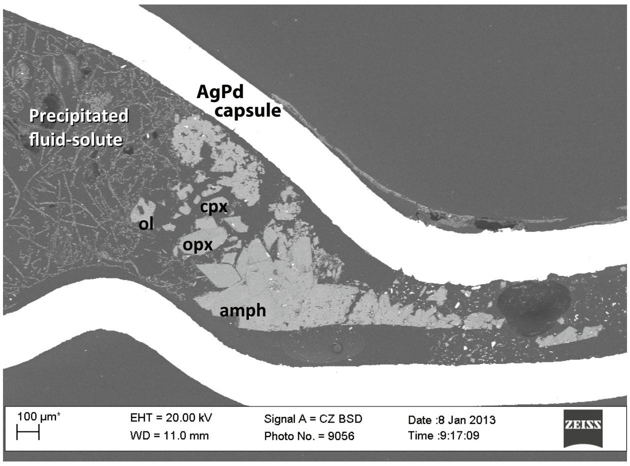


Figure 1. A longitudinal section of a capsule showing run products from a water-saturated experiment on a nepheline basanite at 950 °C and 2.0 GPa. The run products include solute precipitated from the quenched H_2O-fluid (seen as filamentous strands of fine beads) and crystals of clinopyroxene, orthopyroxene, olivine, ilmenite, mica and amphibole.

We have conducted twelve experiments at 0.5-3.0 GPa and 950-1100 °C to determine the partitioning of minor and trace elements (including chalcophile metals) between hydrous fluids, peridotite minerals and typical intraplate basanitic melts. Five experiments were also conducted under H_2O-undersaturated conditions on coexisting basanite and sulfide melts. The fluid/mineral/melt partitioning data, combined with previously obtained mineral/melt partition coefficients for the same basanite, provide information on the contrasting abilities of H_2O-fluids and silicate melts to transport metals and incompatible elements within the mantle lithosphere.
A particular feature of the experimental approach is that it avoids the use of fluid traps (including carbon spheres and fluid inclusions in solid minerals) commonly employed in

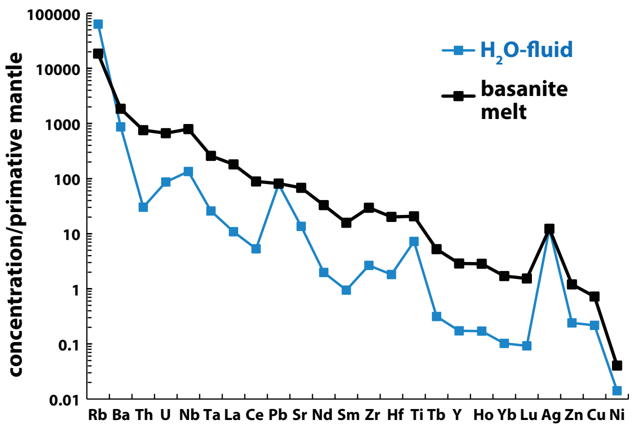


Figure 2. Mantle-normalised element concentrations in aqueous fluids and silicate melts equilibrated with a garnet lherzolite of Primitive Mantle composition. The fluid composition was calculated using partition coefficients from this study.

similar experiments. This allows the experimental run products produced to be unambiguously identified (see Fig. 1) and analysed by electron microprobe and LA-ICPMS.

The successful experiments have produced a small but unique data set for H_2O-fluids in equilibrium with mantle phases. There are very few equilibrium data on such very fluid-rich systems under these deep mantle conditions, so the data set is being carefully analysed. At 950-1100 °C and 2.0 GPa the fluids contain 15-25 wt % of dissolved solute. The solutes are enriched in SiO_2 (56-66 wt %), Al_2O_3, and alkalis (10.9-12.6 wt % $Na_2O + K_2O$) but depleted in TiO_2, FeO, MgO and CaO relative to the basanite. Overall the transport capacities of H_2O-fluids within the upper mantle are distinctly different from those of silicate melts (Fig. 2). Alkalis, Pb and Ag are relatively enriched in the aqueous fluids, whereas most chalcophile and incompatible elements are not. As we continue to analyse these unique experiments, more partitioning data will be available on the economically important elements. Currently the results suggest the silicate melts can transport sulfides much more efficiently than aqueous fluids, but fluids may be critical in transporting metals such as Ag.

This project is part of CCFS Theme 3, Earth Today, and contributes to understanding Earth's Fluid Fluxes.

Contacts: Marco Fiorentini, John Adam, Tracy Rushmer, Marek Locmelis

Funded by: CCFS Project 2a: Experimental determination of metal sources and transport mechanisms in the deep lithosphere

Decoding sulfur DNA solves how ancient ore deposits formed in Western Australia

Figure 1. Exhalative sulfides in close spatial association with the largest komatiite-hosted nickel-sulfide deposit in the world, Mount Keith, Western Australia.

Magmatic hydrothermal oceanic vents represent places where metals accumulate in the form of exhalative and sedimentary sulfides associated with submarine felsic volcanoes. These are also loci where life can flourish in the form of a wide range of complex and diversified bacteria colonies. In the Archean Earth (more than 2.5 billion years ago), coeval to the emplacement of sulfide-bearing felsic magmas, komatiites locally erupted on the floor of the ocean. These hot and highly turbulent magmas assimilated previously formed volcanogenic exhalative and sedimentary sulfides, leading to the formation of discrete sulfide melts, which concentrated chalcophile and siderophile metals such as nickel, copper and the platinum group elements from the komatiite magma.

Figure 2. Typical "komatiite country" in the Eastern Goldfields of Western Australia.

Multiple sulfur isotope data on sulfides from variably mineralised komatiite units in the Archean north Eastern Goldfields, Western Australia, provide new constraints on these assimilations and ore-forming processes. Although magmatic sulfides from komatiites display very similar $\Delta^{33}S$ signatures to volcanogenic exhalative and sedimentary sulfides, they have consistently lower $\delta^{34}S$ values relative to these sources. In other words, the sulfur-bearing compounds from the magmatic sulfides in the komatiites are on average isotopically lighter than the sulfur compounds contained in the volcanogenic exhalative and sedimentary sulfides. This lowering of the $\delta^{34}S$ signature is consistent with degassing of the komatiite-sulfide melt system. At the temperatures and oxygen fugacities relevant to komatiite magmatism, sulfur in the melt exists primarily as ^{34}S-poor sulfide species, while sulfur in the co-existing gas would be dominated by ^{34}S-rich SO_2. Continuous loss of this ^{34}S-enriched gas would lower the $\delta^{34}S$ values of coexisting sulfide melt, leading to magmatic sulfides with the isotopic compositions measured here.

Our results indicate that komatiites from the north Eastern Goldfields of Western Australia, irrespective of their initial sulfur content, degassed upon emplacement at Earth's surface. Komatiite degassing likely influenced physical and chemical parameters of the primordial oceans by the addition of heavy sulfur in the form of SO_2, thus contributing to the positive heavy S ocean signature. This then indirectly contributed to the creation of a complex chemical gradient at the interface between seawater and seafloor in the primordial Earth.

This project is part of CCFS Themes 1 and 2, Early Earth and Earth's Evolution, and contributes to understanding Earth's Fluid Fluxes.

Contacts: Carissa Isaac, Marco Fiorentini

Funded by: CCFS Foundation Project "Early evolution of the Earth system and the first life, from multiple sulfur isotopes"; ARC Linkage LP0776780; SIEF postgraduate scholarship

Slaking the Earth's thirst at mid-crust levels

Numerous studies have identified low-δ^{18}O fluids in ductile shear zones that dissect volumes of otherwise anhydrous crustal rocks. A prime example is the shear-zone network that dissects the Proterozoic granulite terranes in central Australia. The pronounced lowering of δ^{18}O values by up to 10‰ between rehydrated fault-zone rocks and their adjacent largely anhydrous equivalents precludes the involvement of internally-derived fluid sources. This is problematic because these shear zones typically post-date the high-grade regional metamorphism of their wall rocks by tens or hundreds of millions of years. As a consequence, in cases where calculated fluid compositions are below the mantle signature (δ^{18}O = 5.7 ± 0.3‰), such alteration patterns are typically interpreted as the product of deep crustal metasomatism driven by the influx of surface-derived fluids. However, models that propose the migration of a mobile fluid phase from the surface to the mid-crust are both mechanically and geochemically challenging.

We have used the Cameca 1280 ion microprobe at the University of Western Australia to analyse oxygen isotopes in garnet porphyroblasts from the mid-crustal Walter-Outalpa shear zone, southern Curnamona Province, South Australia. All the garnets have homogeneous δ^{18}O values of < 3‰. Integrated Lu-Hf geochronology and compositional mapping by electron microprobe demonstrate that the closed-system growth of these isotopically light garnets (Fig. 1) started as early as 531 Ma, prior to the peak of metamorphism and deformation during the Delamerian Orogeny (514–490 Ma). These new data have led to the proposition that the prograde burial and dehydration of altered fault panels under thick sedimentary sequences during pre-orogenic basin formation has produced the observed lowering of the δ^{18}O values. This contrasts with established fluid transport models, where surficial fluid signatures are imposed at depth by large fluxes of downward-penetrating fluids. The existence of low δ^{18}O values in deeply-exhumed shear zones may therefore indicate that the fault structures had a pre-metamorphic history of near-surface exposure, weathering, burial/metamorphism and re-exposure.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Fluid Fluxes.

Contacts: Chris Clark, John Cliff

Funded by: ARC Discovery

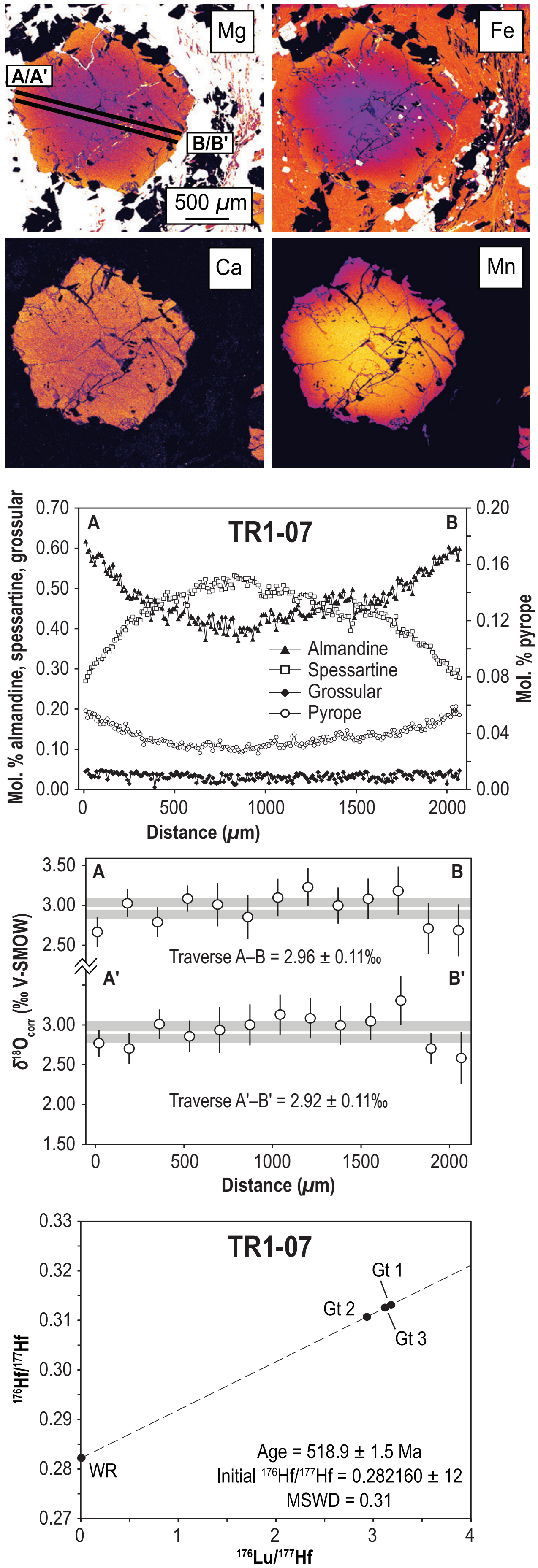


Figure 1. Major element chemical, O-isotopic and Lu-Hf geochronological dataset from a single garnet from within the Walter-Outalpa shear zone in central Australia (Raimondo et al., 2013, Geology, in press).

Unravelling the early Earth's record of biological fingerprints using sulfur isotopes

Multiple sulfur isotopes (^{32}S, ^{33}S, ^{34}S, ^{36}S) are becoming an increasingly important tool to investigate biological processes on the early Earth. They can tell us about the types of life present in Earth's earliest sedimentary environments and trace the transfer of sulfur species in fluids and gases from the interior of the Earth via the atmosphere, hydrosphere, and finally into the biosphere.

Figure 1. 3.5 billion-year-old pillow lavas from the Barberton greenstone belt, South Africa, containing microtubes with microbially-mediated sulfide inclusions.

One problem in this type of study is the spatial resolution at which multiple sulfur isotopes are currently analysed. Traditional bulk analyses can lead to artificial homogenisation of sulfur-isotope signals in a sample and conceal evidence of processes on the micron scale (the scale where microbial mediation might be observed). Our work under the CCFS Theme: The Early Earth is using *in-situ* techniques (SIMS and NanoSIMS), where the spatial context of the analyses is retained, to gain new insights into this problem.

Using the CAMECA NanoSIMS at UWA in the past year, we have been able to extract sulfur-isotope data ($\delta^{34}S$) from tiny (<15 µm) pyrite grains within microtubes in ca 3.5 billion-year-old basalts. These record $\delta^{34}S$ values as low as ca -40 ‰, indicating that sulfur processing microbes were a likely component of the early Archean sub-seafloor biosphere (*CCFS publication #230*).

We have also used the CAMECA IMS1280 (see *Technology development* section of this Report) to analyse some of Earth's oldest sedimentary sulfides from the 3.5 billion-year-old Dresser Formation of Western Australia. Here we have measured all 4 stable sulfur isotopes, and while the $\delta^{34}S$ and $\Delta^{33}S$ values appear to be similar to previous bulk analyses, the $\Delta^{36}S$ values have a much greater spread than previously reported. This could be significant for understanding the sources of sulfur on the early Earth, but more work is needed to test the robustness of SIMS $\Delta^{36}S$ data. As a result we are now collaborating with international experts such as James Farquhar (University of Maryland) to conduct further tests on these samples using both SIMS and more traditional techniques.

We are also implementing modern analogue experiments to discover the micron-scale distribution of multiple sulfur isotopes in microbially-precipitated sulfides. Here we are working in collaboration with microbiologists and isotope geochemists in Norway and USA, using cultures of different sulfur-processing microbes, in particular sulfate-reducers and sulfur-disproportionators. The isotopic compositions of the end products of these experiments will soon be analysed using SIMS and NanoSIMS. It is hoped that this will give us more accurate interpretations of Archean sulfur isotope data and help us understand the anomalous $\Delta^{36}S$ signatures seen in our data from the Dresser Formation.

This project is part of CCFS Theme1, Early Earth, and contributes to understanding Earth's Fluid Fluxes.

Contacts: David Wacey, Mark Barley

Funded by: ARC CCFS CoE

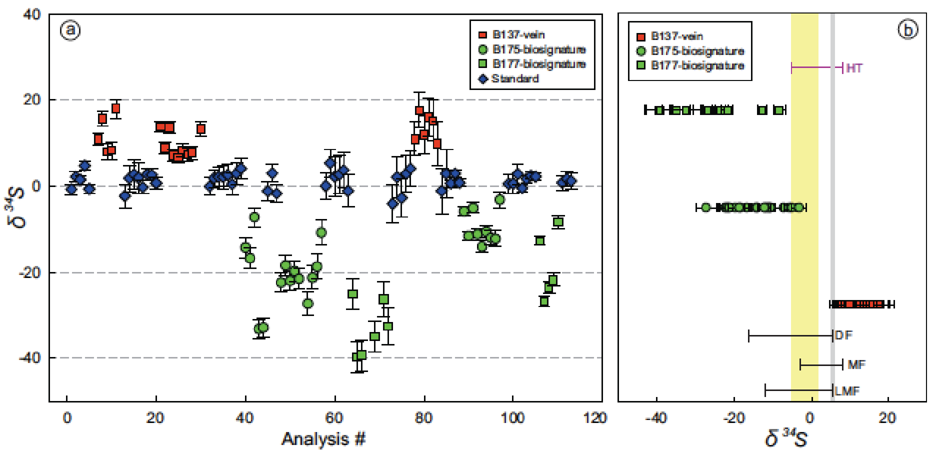


Figure 2. Nanoscale secondary ion mass spectrometry $\delta^{34}S$ sulfide data from ~3.5 Ga Hooggenoeg Formation South Africa shows vein sample (red), two candidate biotexture-bearing samples (green), and standard (blue). (a): Analyses in order performed: B137 ranges from +6.7‰ to +18‰ and is positively shifted from CMCA-S1 pyrite standard; B175 and B177 are negatively shifted from standard, with B175 ranging from -27.3‰ to -3.2‰ and B177 from -39.8‰ to -8.3‰ (error bars are 2σ). (b): Range in measured $\delta^{34}S$ values compared to other Archean sulfides. Candidate biotexture-bearing samples show largest range and most negatively shifted values yet measured, whereas vein sample is positively shifted and shows smaller range. For reference, yellow band indicates mantle sulfur, gray line indicates Archean seawater, and purple line (HT) indicates hydrothermal sulfides (from Mojzsis, 2007). For comparison, $\delta^{34}S$ range of sulfides from cherts and sediments of similar age are shown: 3.49.

How hot is the Earth, really?

The internal heat of the Earth drives plate tectonics, so the surface heat flux can give us an important constraint on the properties and behaviour of the Earth through geologic history. The surface heat flow can be reliably measured over continents, but due to hydrothermal circulation in oceanic crust, measurements in ocean basins often do not reflect deep lithospheric heat flow. As such, estimates of lithospheric heat flow over ocean basins usually are based on geodynamic models. These models usually are simple, using constant thermal properties and boundary conditions – but are they useful? We have developed new thermal models that incorporate a petrologically and thermodynamically more complete view of lithospheric cooling. These models show that several thermal complexities are important as they change the predicted surface heat flow over ocean basins significantly while remaining compatible with reliable measurements. Specifically, we have shown that the effective thermal properties of the oceanic lithosphere depend strongly on age, and that this age-dependence is primarily due to the thermal insulation effect of oceanic crust. Therefore, heat flow over young seafloor is significantly lower than conventional models predict while predictions at older ages are similar.

This revision of conventional thermotectonic theory has several major implications. For example, lower heat flux over young seafloor indicates that the advective or hydrothermal component of heat transport has been significantly overestimated. This changes the hydrogeological regime of oceanic lithosphere and impacts on geochemical mass-balance problems related to the fluid interaction of lithosphere and oceans. Also, strongly age-dependent cooling affects the seafloor subsidence rate, and in this case our models are consistent with global topographic data. This shows that persistent features of lower magnitude than roughness in the data can be identified. In addition, the modelled net seafloor heat flow, and thus global heat flow, is lower than conventional models predict. Since the low conductivity of oceanic crust is the principal reason for the low heat flow over young seafloor, this effect is expected to be more important early in Earth history when the oceanic crust was thicker than it is now. This means that seafloor heat flow in the Archean may have been significantly lower than conventional models predict, or that plate velocity would have to be much higher to compensate for low-conductivity lithosphere.

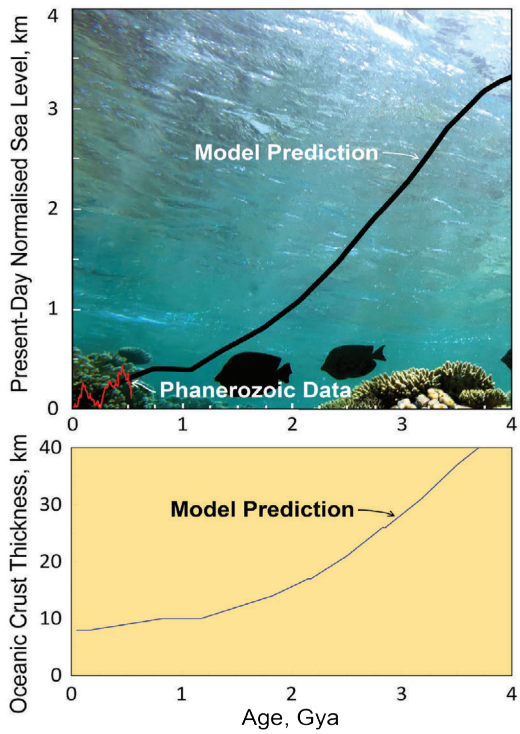


Figure 2. Predicted sea level and thickness of oceanic crust since the start of the Archean. The red line shows data for Phanerozoic sea level (Hallam, Phanerozoic sea-level changes, Columbia Univ. Press, 224p, 1992).

We also have coupled our revised thermotectonic model of oceanic lithosphere to an isostatic model of the Earth to predict eustatic sea level changes over Earth history. Remarkably, our model predicts systematic sea-level change in good agreement with the Phanerozoic record, and we calculate that sea level at the end of the Archean (2.5 Ga) was at least 2 km higher than it is now, although our estimates are highly dependent on the choice of melting model. Ongoing research in this project will refine these predictions.

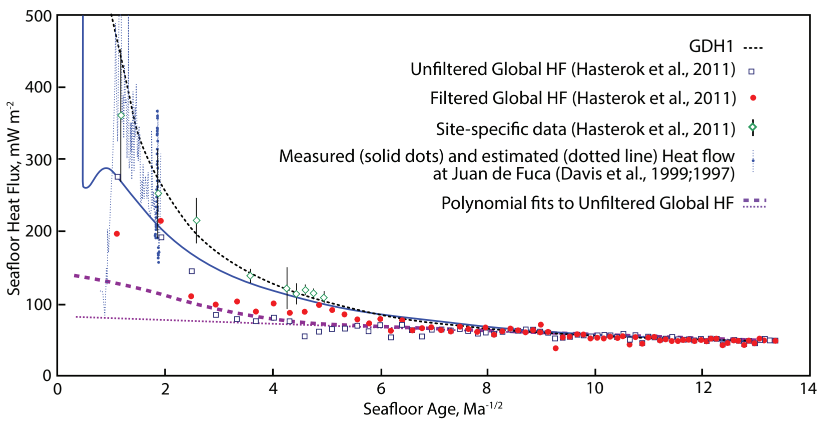


Figure 1. Predicted and measured seafloor heat flow. The thick blue line is our preferred model. The dashed red line is a conventional plate model, and the data points and dashed violet lines describe global heat flow data.

This project is part of CCFS Theme 3, Earth Today and contributes to understanding Earth's Architecture

Contacts: Chris Grose, Juan Carlos Afonso

Funded by: ARC Discovery (JCA); ARC IPRS

Squeezing the mantle: between an ocean and a continent

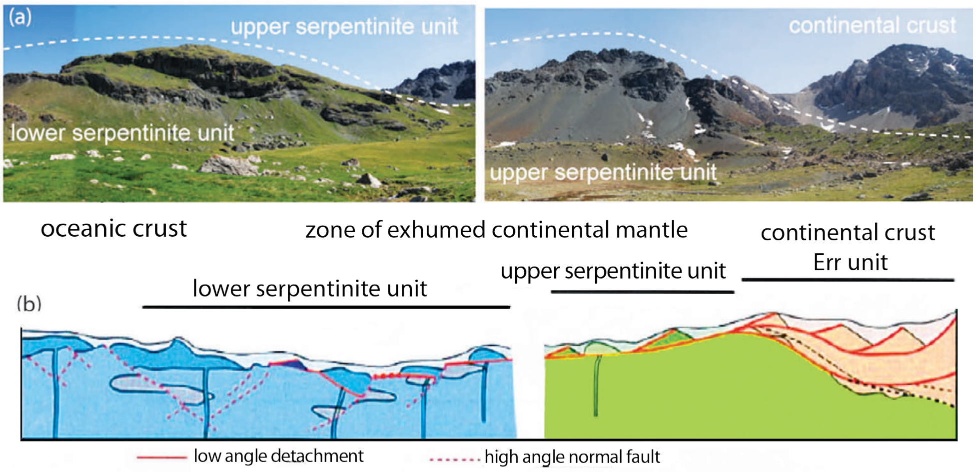
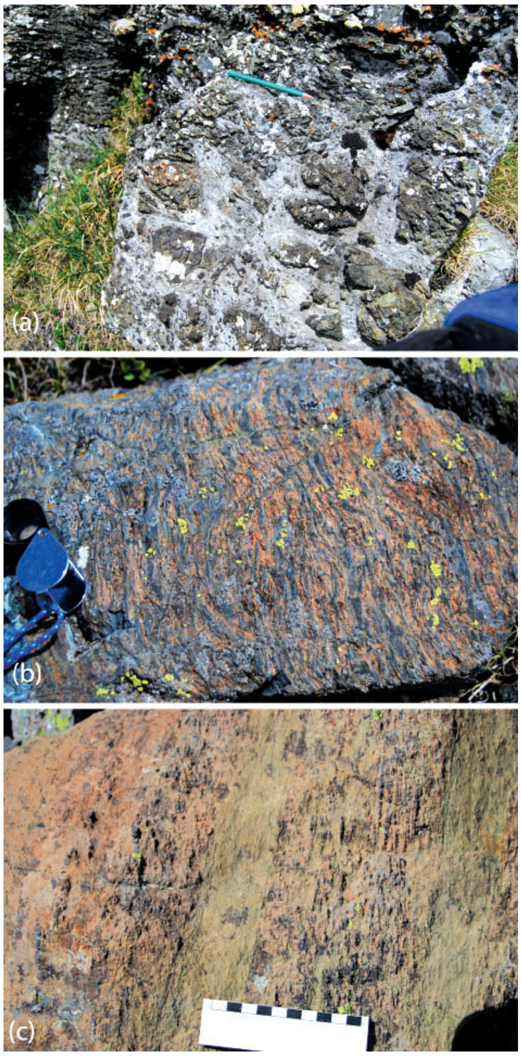


Figure 1. Palinspastic reconstruction of the Platta nappe (Desmurs et al. 2001, Geol Soc London Spec Publ). (a) Pictures showing the present observed Alpine structure. (b) Palinspastic section across the Platta-Err ocean -continent transition. It shows the position of the upper and lower serpentinite units within the former ocean-continent transition and summarises the field relationships between fault structures, continental rocks, exhumed mantle rocks and intrusive and extrusive mafic rocks (Schaltegger et al. 2002, Terra Nova).

Tectonically-driven deformation of the lithosphere leads to strain localisation through the formation of ductile shear zones, and their development is responsible for lithosphere-scale deformation that controls the nature and distribution of Earth's tectonic plates. Divergent plate boundaries, such as ocean-continent transitions, are the perfect place to study mechanisms activated during extension leading to localisation of deformation. The Platta-Totalp massifs in the Eastern Central Alps (Grison, Switzerland) are a type example of a zone of exhumed continental mantle. Mapping and structural analysis of the nappes has produced a palinspastic reconstruction of a complete stratigraphic sequence of an ocean-continent transition (Fig. 1) that can guide sampling for a study of deformation processes.

The mantle rocks in these units are spinel lherzolites and harzburgites, into which gabbros and basaltic dykes were intruded (Fig. 2a). Mantle rocks close to the continent are spinel peridotite mixed with (garnet)-pyroxenite layers while the ultramafic rocks at some distance from the continent are pyroxenite-poor peridotite that equilibrated in the plagioclase stability field (Fig. 1). Two-pyroxene and single-orthopyroxene thermobarometric data from the Platta nappe show that the equilibration temperature (at 25-45 km depth) increases from 850±50 °C near to the continent to >1000 °C further oceanwards (*Desmurs, 2001, PhD*). The change in temperature is related to the exhumation of the massif during crustal thinning. Some peridotites contain garnet pyroxenite, indicating high-pressure formation within the spinel peridotite field (>45 km depth) in the mantle sequence.



Fieldwork in the upper mantle part (Fig. 1) reveals heterogeneous distribution of deformation from lower to upper serpentinite units. The peridotite is deformed in both units, but is more deformed in the upper serpentinite unit (Fig. 2b). At a smaller scale, the deformation and the composition of the rock are heterogeneous. The peridotite shows dunitic and harzburgitic layers, and high-temperature shear zones at metre or centimetre scale (Fig. 2c and 3). Sampling across this sequence gives a spatial resolution of the deformation within an ocean-continent transition. A detailed study of the peridotite texture is being combined with the analysis of the crystallographic preferred orientation of minerals, using electron backscatter diffraction method (EBSD) to

Figure 2. (a) Ophicarbonate at the top of the mantle sequence; (b) Peridotite with foliation in the upper serpentinite unit; (c) Variation of the peridotite composition in the upper serpentinite unit.

determine the deformation mechanisms activated during extension. This study is coupled with thermometric calculations to constrain the temperature of the deformation. The study will constrain the localisation of the deformation related to decreasing temperatures and possible percolation within extensional settings such as ocean-continent boundaries.

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Mary-Alix Kaczmarek, Steve Reddy
Funded by: CCFS and Curtin University

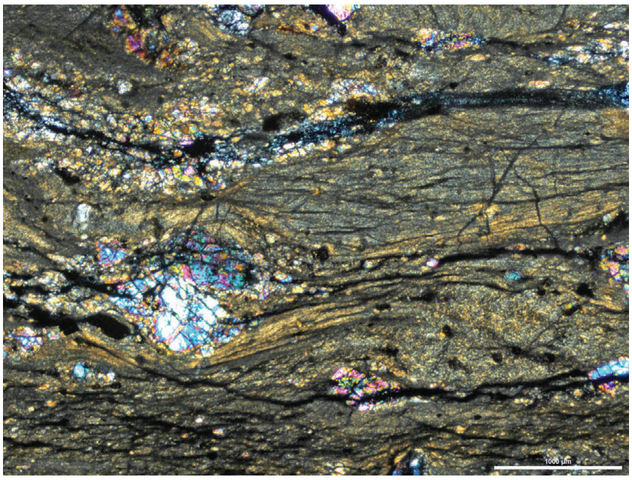


Figure 3. Crossed-nicol photomicrograph of an ultra-mylonitic peridotite.

Multistage refertilisation of an Archean peridotite massif (NE Tibet, China)

Peridotite massifs in orogenic belts and mantle xenoliths brought up by volcanic rocks both reveal the lithological and geochemical heterogeneity of the subcontinental lithospheric mantle (SCLM). Pyroxene-rich veins, secondary metasomatic phases and elemental and isotopic enrichments of Ca-, Al-rich minerals are common in orogenic peridotites. These fertile markers within the depleted host rocks suggest a complicated history of refertilisation. To sort out the sequence of multistage refertilisation in the SCLM is tricky, because of the overlapping of enrichment events and the rarity of useful dating targets. However, a study of elemental and isotopic (Sr-Nd-Hf-Os) compositions of minerals of the Shenglikou peridotite massif from the North Qaidam orogen (NE Tibet, China; Fig. 1) has revealed unusually clear details of the refertilisation history.

This ultramafic massif was scraped off from the Qilian continental-margin mantle wedge by the subducting Qaidam block during early Paleozoic assembly of the Tibetan plateau.

Refractory dunite and harzburgite formed the original lithologies, which enclose fertile garnet lherzolite zones, secondary clinopyroxene-rich lherzolite/wehrlite layers (Fig. 2) and rare garnet pyroxenite dykes. Re-Os isotopic analyses of Fe-Ni-sulfides from the peridotite give some ancient Re-depleted model ages (oldest $\approx$ 3.0 Ga), suggesting an Archean origin. Whole-rock oxide compositions show a linear mixing trend between the dunite and pyroxenite. Trace-element patterns imply the dunite-harzburgite protoliths were re-enriched by slab-derived fluids, and the lherzolite and wehrlite look like the products of reaction between the refractory peridotite and a pyroxenite melt with an arc signature.

However, mineral elemental and isotopic data argue against a single refertilisation by binary mixing. The initial Nd-Hf isotopic patterns (Fig. 3) indicate that the dunite-harzburgite protoliths, clinopyroxene-rich peridotites and pyroxenites record different isotopic evolution paths. Their Hf and Nd isotopes, compared with chondrite and depleted-mantle values, suggest that the Hf isotopes can record ancient events and are more immune to later metasomatism, but the Nd isotopes were largely shifted to less radiogenic values (Fig. 3) by subsequent enrichment events. Lu-Hf analysis of garnet and clinopyroxene from refractory garnet harzburgites away from the refertilised lithologies give an isochron age around 1.5 Ga (Fig. 4),

cont...

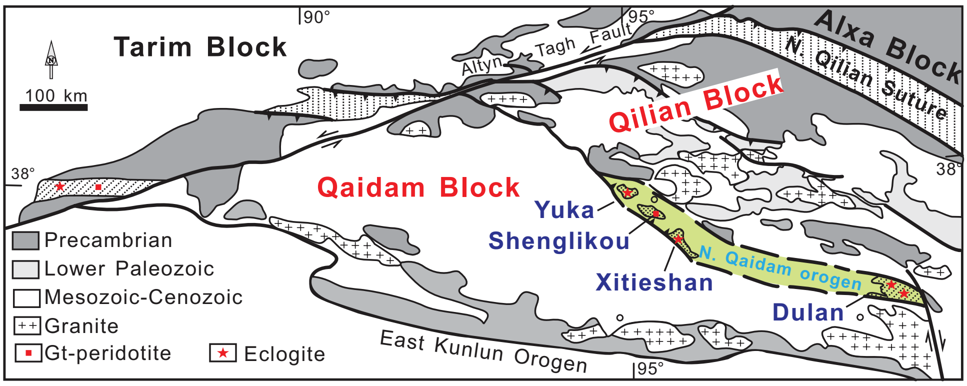


Figure 1. Tectonic units of the Northeastern Tibet area, China. The garnet peridotite massif is enclosed by ultrahigh-pressure (UHP) metamorphosed gneiss in the Shenglikou area, located at the western segment of the North Qaidam orogen. This orogen also exposes UHP rocks at the Yuka, Xitieshan and Dulan areas.

Figure 2. Clinopyroxene-rich garnet lherzolite/wehrlite (light green) inter-banded with garnet harzburgite host (dark green). The exposed pen is about 10 centimetres.

consistent with their Hf depleted-mantle model ages; this suggests an early Mesoproterozoic refertilisation of this piece of Archean mantle. Garnet- and clinopyroxene-rich rocks (secondary layers and pyroxenite dykes) show Sm-Nd and Lu-Hf isochron ages of ~1.1-0.6 Ga. This time span may imply a refertilisation event at ~1.1-0.9 Ga (Xiong et al., 2010) that formed the secondary peridotite layers; then pyroxenite melts intruded the refertilised mantle before the incorporation of this mantle fragment into the subducting slab at ~430 Ma. Radiogenic Sr ($^{87}Sr/^{86}Sr$ initial=0.71266-0.71388), unradiogenic Nd isotopic data but near-DM Hf isotopes (Fig. 3) suggest the melt came from the asthenosphere, which had been metasomatised by slab-derived material.

This work has shown that different incompatibilities and activities of isotopic pairs in rock-melt or rock-fluid systems can reveal different mantle events, and help us to clarify the sequence of multistage refertilisation in a volume of ancient SCLM.

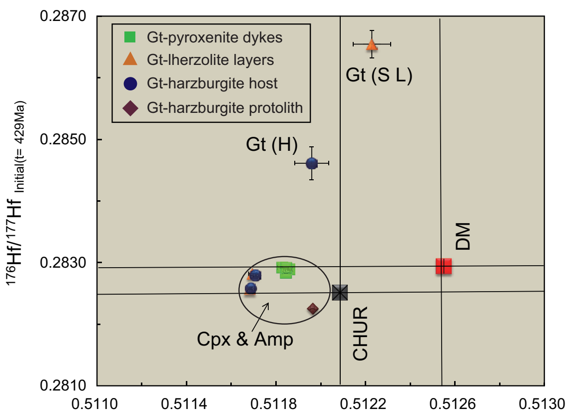


Figure 3. $^{143}Nd/^{144}Nd$ initial versus $^{176}Hf/^{177}Hf$ initial ratios of garnet, clinopyroxene and amphibole in different lithologies of the Shenglikou peridotite massif. Nd and Hf isotopic ratios are calculated back to 429 Ma, when the zircon formed in this massif by UHP metamorphism. Error bars are shown as ±1σ, and those of clinopyroxene and amphibole are smaller than the symbol size. "S L", secondary lherzolite; "H", harzburgite; "DM", depleted mantle; "CHUR", chondrite uniform reservoir; "Gt", garnet; "Cpx", clinopyroxene; "Amp", amphibole.

This project is part of CCFS Theme 2, Earth's Evolution and contributes to understanding Earth's Architecture and Fluid Fluxes.

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Funded by: ARC Discovery and Centre of Excellence (S.Y.O'R and W.L.G.), NSFC (J.P.Z.)

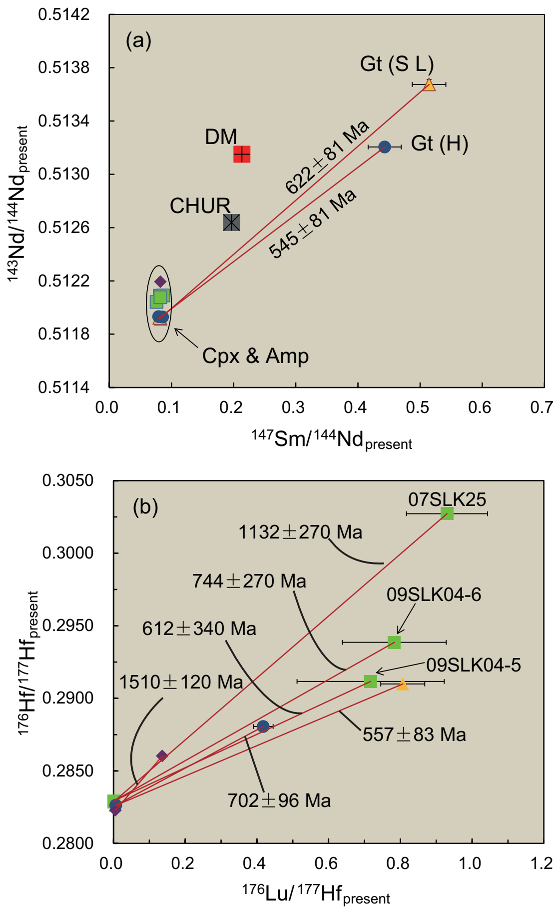


Figure 4. $^{147}Sm/^{144}Nd$ present versus $^{143}Nd/^{144}Nd$ present (a) and $^{176}Lu/^{177}Hf$ present versus $^{176}Hf/^{177}Hf$ present (b) diagrams of garnet, clinopyroxene and amphibole in different lithologies of the Shenglikou peridotite massif. Error bars are shown as ±1σ, and those of clinopyroxene and amphibole are smaller than the symbol size. Isochron ages (±2σ) are shown; the large uncertainties reflect the measurement of Lu/Hf ratios by LA-ICPMS and will be improved by further work. Abbreviations and symbols are the same as those of Figure 3.

Spurious Hadean ages in East Antarctica: the tribulations of moving Pb

Zircons from early Archean ortho- and paragneisses in the ultrahigh-temperature (UHT) metamorphic rocks of the Napier Complex of East Antarctica show very complex U-Th-Pb systematics. Published ages from the Mount Sones, Dallwitz Nunatak and Gage Ridge localities are scattered, and the oldest ages are reversely discordant (U/Pb ages older than ^{207}Pb/^{206}Pb ages). This problem attracted scientific attention several years ago, because ^{207}Pb/^{206}Pb ages are considered to be more robust than U-Pb ages in ancient rocks. Several different mechanisms were proposed to explain this phenomenon, but no satisfactory answer was forthcoming. Since uranium is strongly lattice-bound in zircon, it is unlikely to be mobilised, so the favoured explanation was "Pb gain", a mechanism opposite to Pb loss in normally-discordant data. However, the source of the "extra Pb" was not defined, and this problem has remained unresolved for more than 25 years.

We have used a novel high spatial resolution ion microprobe imaging technique to investigate the problem (*CCFS publication #276*). Selected areas of 70 µm x 70 µm of Antarctic zircons were imaged using a small (~2 µm) rastered primary beam on the Cameca IMS 1280 at the National History Museum in Stockholm. The distribution of ^{48}Ti, ^{89}Y, ^{180}Hf, ^{206}Pb, (Fig. 1), ^{232}Th and ^{238}U was imaged in the single-collector mode and ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{180}Hf in the multi-collector mode. Hafnium is evenly distributed in these zircons and served as a proxy matrix peak in both routines.

A zircon grain from a paragneiss from Mount Sones with a spot age of 3008±21 Ma (^{207}Pb/^{206}Pb age) and U content of 2561 ppm was one of those selected for investigation. The ion maps (Fig. 1b) reveal the distribution of selected elements. Cathodoluminescence (CL) images show that Yttrium, Th and U define a zonation. The Pb distribution, in contrast, shows an unusual patchiness (Fig. 1d). Although it broadly follows the U and Y zonation, there are bright patches with enhanced signals which do not correspond to any zones or to crystal imperfections (e.g. cracks). Ti also shows patchy distribution, but there is no direct correlation between patches of Pb and Ti.

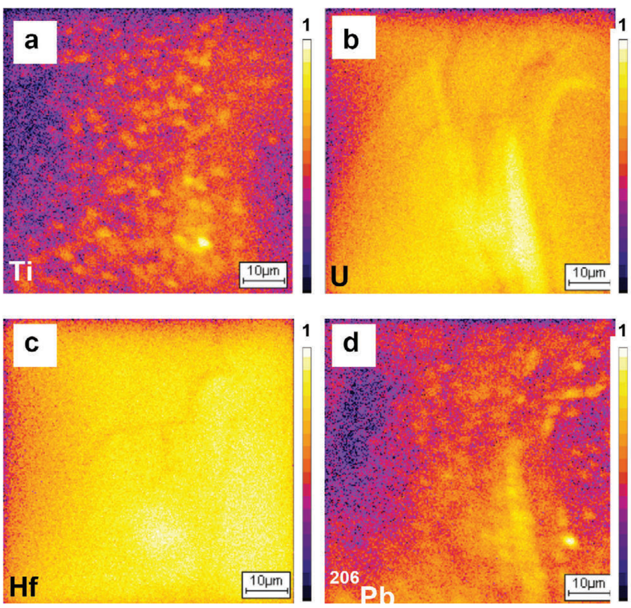


Figure 1. Scanning ion images of grain n3852-08 from Mount Sones sample 14178-2 using a single-collector routine: (a) ^{48}Ti, (b) ^{89}Y, (c) ^{180}Hf, (d) ^{206}Pb.

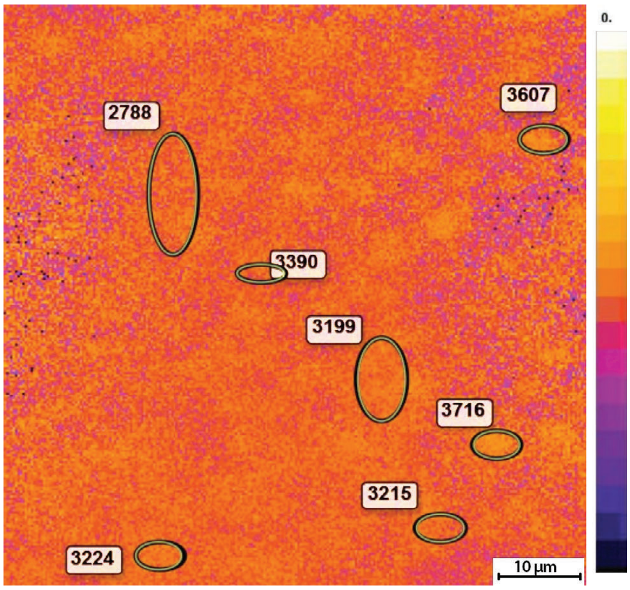


Figure 2. Multi-collector map of ^{207}Pb/^{206}Pb. Ellipses show the areas used for ^{207}Pb/^{206}Pb age calculation. Field of view is 70 µm x 70 µm.

In the multicollector mode, ^{206}Pb and ^{207}Pb isotopes exhibit similar patchiness. The ^{204}Pb image (not shown) is black, showing there is common Pb in the analysed area. Using the WinImage program, we produced maps of ^{207}Pb/^{206}Pb (Fig. 2), and these maps allow calculation of ^{207}Pb/^{206}Pb ages for spots of any size from ~2 µm^2 upward, within the frame of the picture (70 µm x 70 µm) and at any time after data collection. This is a new and unique method for obtaining age information from zircon, and new applications await.

These maps show areas of enhanced brightness where the ^{207}Pb/^{206}Pb ratio is higher and demonstrate that within these small areas (µm scale) the apparent ^{207}Pb/^{206}Pb age is older than in the rest of the crystal. Using these images, we have calculated ^{207}Pb/^{206}Pb ages ranging from 2.8 Ga up to 3.7 Ga (Fig. 2), both older and younger than the apparent SIMS age. Spuriously old ^{207}Pb/^{206}Pb ages in areas enriched in radiogenic Pb reflect a combination of supported and unsupported radiogenic Pb; Pb has indeed moved, but only within the grain, so there is no reason to invoke "extra Pb". In addition, the 'patchy' distribution of Ti has the potential to affect Ti-in-zircon thermometry, with implication for the accurate determination of zircon crystallisation temperatures.

Some of the ages measured in this zircon suite are Hadean (>4 Ga) and hence Pb redistribution of this type might have led to the rocks being classified as samples of Earth's oldest crust. *cont...*

In the present example, the mobilisation and redistribution of Pb in Antarctic zircons probably occurred at ~2.5 Ga, the time of UHT metamorphism in the Napier Complex. This well-documented event reached temperatures >1100 °C, the highest recorded in Earth's continental crust.

All images are normalised to the HfO image to minimise the effect of enhanced ion emission from the original spot analysis crater. The colour-scale bars are relative intensity (i.e. do not correspond to ppm).

This project is part of CCFS Theme 1, Early Earth and contributes to understanding Earth's Architecture.

Contacts: Monika Kusiak, Simon Wilde

Funded by: EU-FP7, Marie Curie Grant: CCFS Foundation Project 2

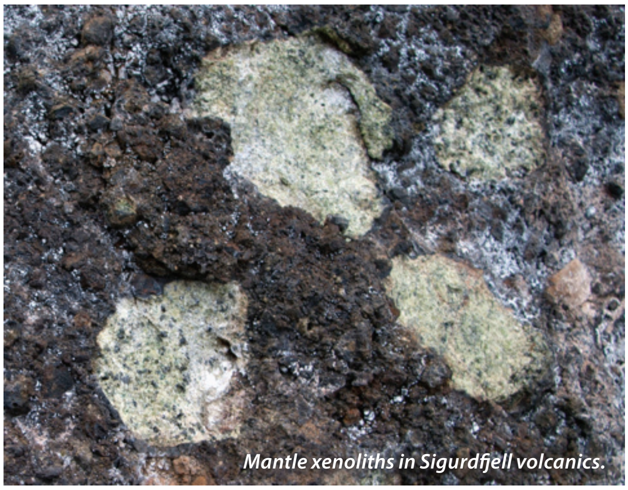
The glitter of gold 60 km beneath the Earth's surface

Glittering gold nugget!

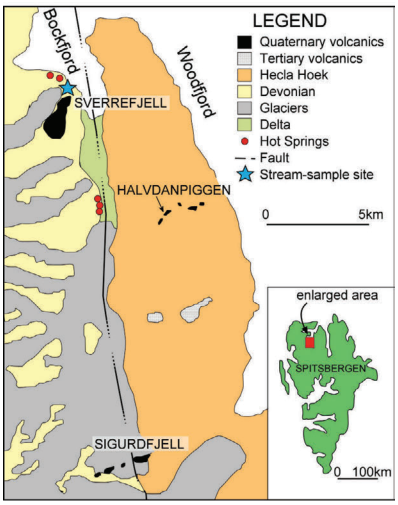
Gold is a highly siderophile element (HSE) along with the platinum group elements (PGEs: Pt, Pd, Rh, Ru, Os and Ir) and Re. HSEs are elements that strongly prefer the metallic phase in comparison to silicate phases, and therefore are important tracers for differentiation events in Earth's history during the formation of the metallic core. However, our knowledge of gold abundance and its distribution in the mantle is limited. In this study, Au has been analysed along with major- and trace-elements in sulfides in fragments of the Earth's mantle (xenoliths) brought to the Earth's surface in basaltic magmas that formed Quaternary volcanoes in the Svalbard Archipelago (between north Norway and the North Pole). Combining these data with silicate data allows us to build a model of Au behaviour during mantle processes.

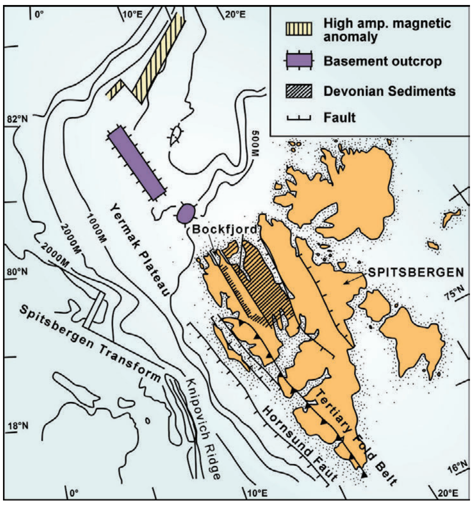
Analyses of the trace elements in clinopyroxene grains from the peridotite (olivine-rich) mantle xenoliths reveals there are three different types as seen by the contrasting patterns in Figure 1. There is an increase in the light rare-earth (LREE) elements progressing from Group I to Group II to Group III. This type of change in pattern can be due to the changing composition of fluids infiltrating the mantle rocks. These fluids change the composition of minerals in these rocks (metasomatism), and also progressively change their own composition through two-way reaction, a process similar to that in a chromatographic column. The strong enrichment in LREEs and Sr coupled is accompanied by a decrease in Ti and suggests that the metasomatic agent was a carbonatitic melt or fluid.

Sigurdfjell sample locality.



Mantle xenoliths in Sigurdfjell volcanics.





Locality maps: left shows the sample localities, right shows the broader geological context of Svalbard.

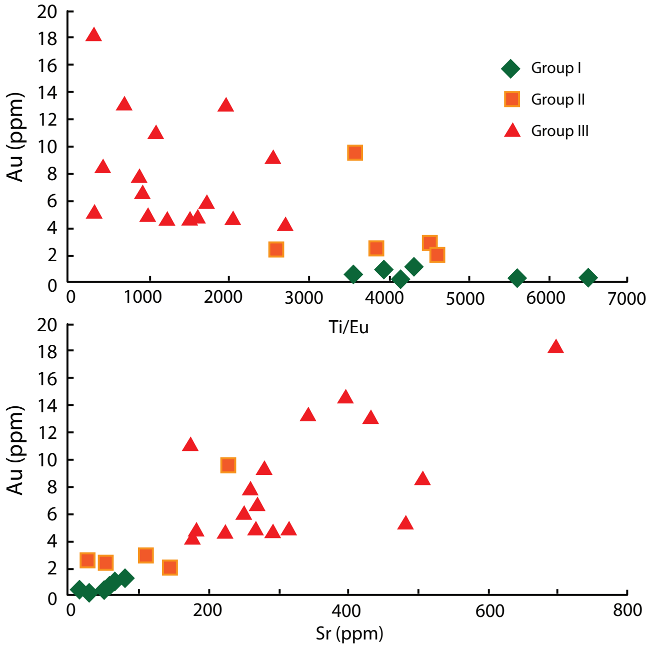


Figure 1. Svalbard metasomatism increase La/Yb and Sr, while decreasing Ti/Eu ratios – a typical signature of carbonatitic metasomatism.

Sulfide grains are the residence site for platinum group elements in mantle rocks. Three distinct patterns for PGEs have been observed in the Svalbard sulfides (Fig. 2). The PGEs can be divided into two groups: the PPGEs (Pt, Pd and Rh), which are incompatible and therefore removed during melting, and the IPGEs (Ir, Os and Ru), which are left behind with the residue during mantle melting. Type 1 sulfides are residual sulfides, with average (PPGE/IPGE)n = 0.53; Type 3 sulfides were introduced during metasomatism with average (PPGE/IPGE)n = 3.61; Type 2 sulfides fall in between with average (PPGE/IPGE)n = 0.80. The Type 2 sulfides represent a mixing between a residual sulfide and the metasomatic agent that introduced the Type 3 sulfides. The gold content across all three sulfide types is remarkably consistent, and overlaps completely between the three types of sulfides (average AuType1 = 0.41±0.25 ppm; AuType2 = 0.84±1.00 ppm; AuType3 = 0.69±0.58 ppm). This is within the range of peridotite hosted sulfides from south-eastern Australia, and south-eastern China (Fig. 3). The sulfide types are not limited to any one group, but the relative amount of each sulfide type does change, with Group III having more Type 3 sulfides, while the Groups I and II samples are dominated by Type 2 sulfides. The Group I samples are the only ones that contain any Type 1 sulfides.

The sulfide chemistry broadly reflects changes in the metasomatic history defined by the clinopyroxene. There is also an increase in the absolute abundance of sulfides with increasing metasomatism, with a corresponding decrease in the average Au content in the sulfides. This indicates the gold was scavenged locally rather than introduced from an external source. However, there is a lack of correlation between La/Yb in clinopyroxene and Au/Ir or Pd/Ir in sulfides. This is typical for other sample sets

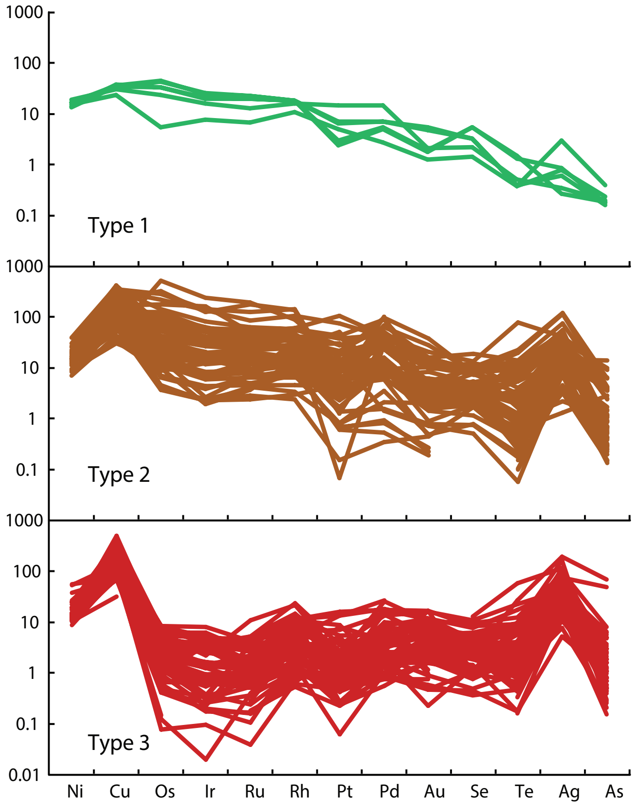


Figure 2. Trace element characteristics of sulfides in Svalbard xenoliths.

(e.g. south-eastern China, south-eastern Australia, and Kaapvaal Craton), indicating a global decoupling sulfide and silicate metasomatism (Fig. 3).

This project is part of CCFS Themes 2 and 3, Earth's Evolution and Earth Today, and contributes to understanding Earth's Fluid Fluxes.

Contacts: Ed Saunders, Norman Pearson, Sue O'Reilly, Bill Griffin
Funded by: CCFS Foundation Project 1 (TARDIS); APA, MQPGRF

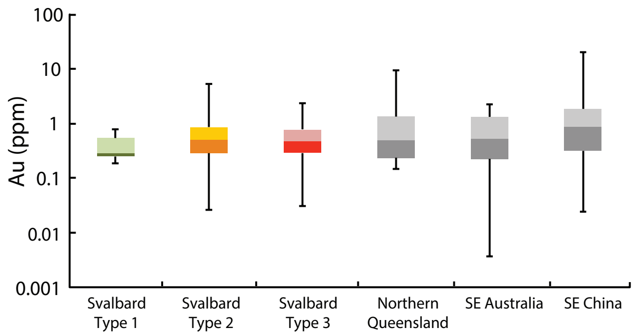


Figure 3. Gold content in Svalbard sulfides compared to other xenolith suites. Metasomatism has little effect on the average Au concentration within mantle sulfides.

Nickel sulfide deposits in the deep Earth - The future of mining?

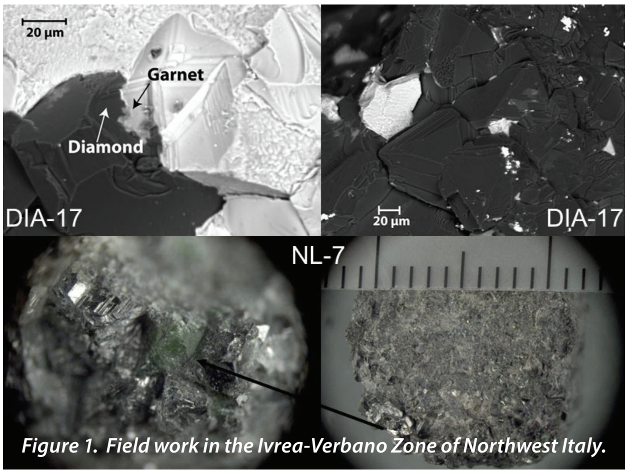


Figure 1. Field work in the Ivrea-Verbano Zone of Northwest Italy.

Many world-class magmatic nickel sulfide deposits formed close to Earth's surface and there are probably few easily accessible deposits left to be discovered. The opening of new "exploration space" is essential to guarantee a steady metal supply in the future. One promising approach involves exploration for magmatic nickel-copper sulfide deposits that are hosted in the deep lithosphere, possibly at the crust-mantle boundary. However, very little is known about their genesis because such deep-seated deposits are rarely obducted to near-surface levels. The first step in developing exploration models for metal deposits in the deep Earth is to understand how metals are transported and concentrated at sub-crustal levels: an issue addressed by the CCFS project 'Metal Sources and Transport Mechanisms in the Deep Lithosphere'.

This project includes two detailed case studies: the first is the Ivrea-Verbano Zone of Italy (Fig. 1) and the second is the Archaean Thrym Complex of southeastern Greenland: these are among the few known areas where magmatic nickel-copper sulfide deposits occur in rocks that came from the deep lithosphere. How many more are there? Nobody knows, because the current dominant ore-genesis models, are largely focused on terrains that contain rocks from the upper crust while neglecting areas with outcropping deep lithosphere.

The formation of magmatic nickel-copper sulfide deposits in rocks from the deep lithosphere appears to be directly linked to the occurrence of metasomatic fluids, which are most evident in the Ivrea-Verbano Zone as a series of peridotitic, pipe-like intrusions up to 300 metres in diameter. These pipes contain water-rich magmatic minerals, such as phlogopite and amphibole, which are closely associated with nickel, copper and iron sulfides (Fig. 2). These minerals have isotopic signatures indicative of a mantle source, so the Ivrea-Verbano Zone is an excellent natural laboratory to investigate the role of fluids in the transport and concentration of metals in the deep Earth.

Trace-element data (LA-ICPMS) for amphibole and phlogopite from several pipes in the Ivrea-Verbano Zone suggest that juvenile, carbonate-rich hydrous fluids played an important role in the genesis of the pipes. The metasomatic fluid carried nickel, iron and copper and caused the parental rock to partially melt. The resulting melts evolved into the volatile-rich, pipe-like intrusions that reached sulfide-saturation during their emplacement, forming the sulfide deposits that we see today.

The Thrym Complex of southeastern Greenland is part of the North Atlantic Craton and is made up of migmatitic orthogneiss, narrow bands of mafic granulite, ultramafic and possible meta-sedimentary rocks, and alkaline-carbonatitic intrusive rocks. The narrow bands of mafic granulite are interpreted as mafic volcanic or gabbroic rocks from the lower crust. Ni-Cu-sulfide mineralisation can be found in the mafic granulite units and is most significant next to ultramafic bodies locally found within the mafic granulite bands. Sulfide mineralisation is also hosted in shear zones associated with the later part of the 2790-2700 Ma Skjoldungen Orogeny. The mafic and ultramafic rocks that host the mineralisation all show evidence for interaction with an incompatible-element-rich fluid at some point in their evolution.

This project is part of CCFS Theme 3, Earth Today and contributes to understanding Earth's Fluid Fluxes.

Contacts: Marek Locmelis and Marco Fiorentini

Funded by: Foundation Project 2a: Experimental determination of metal sources and transport mechanisms in the deep lithosphere

Figure 2. Spectacular outcrops in Southeast Greenland.

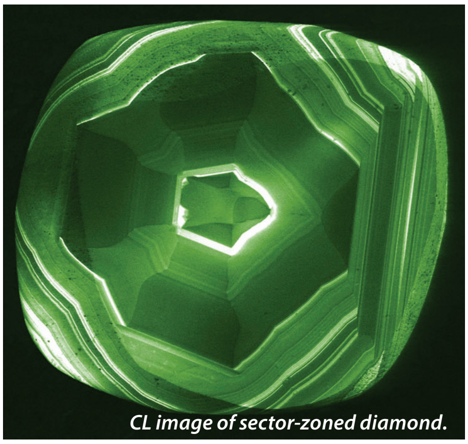
Pink diamonds spotlight deep deformation

Deformation in the mantle is the cause of brown and pink colours in diamonds: brown diamonds are worth relatively little, while pink ones can bring very high prices indeed. The colour of brown and pink diamonds commonly is confined within {111} lamellae created during deformation, and this spatial phenomenon is commonly referred to in the gem trade as graining. Despite this inherent relationship between plastic deformation and pink colour in diamonds, the exact internal crystal defect responsible for the colour absorption has not yet been identified.

Recent studies (*CCFS publication #211*) have identified the {111} deformation lamellae in natural pink and experimentally-deformed brown diamonds as micro-twins. However, we cannot assume that all brown and pink diamonds will contain micro-twins.

The Argyle diamond mine in Australia produces 90 to 95% of the world's pink diamonds. However, a recent study has shown that pink diamonds from Argyle have characteristics very different from the even rarer pink diamonds from other localities (Gaillou et al., 2010; *Diamond & Related Materials*). We have investigated these two groups of pink diamonds to better understand their differences and the processes of deformation in diamonds deep within the Earth.

Scanning electron microscope (SEM)-based electron backscatter diffraction (EBSD) is an ideal tool for investigating the deformation of diamonds and identifying the presence of micro-twins. We have used this technique available in the CCFS Geochemical Analysis Unit at Macquarie to study a set of diamonds provided by the Diamond Trading Company. Combining EBSD with cathodoluminescence (CL) imaging, another SEM-based technique, we have confirmed that pink diamonds from Argyle mine have a very unusual growth pattern, while pink diamonds from other localities have previously described growth patterns, where the {111} deformation lamellae cut across the growth stratigraphy (Fig. 1). Our work has confirmed that these {111} deformation lamellae are micro-twins, and that these features are not observed in the pink diamonds from Argyle. Work is ongoing to fully understand the mechanism by which the micro-twins form and what they tell us about the deformation environment experienced by the diamonds and their subsequent history deep within the Earth.



CL image of sector-zoned diamond.

The Argyle Diamond Mine.

This project is part of CCFS Theme 2, Earth's Evolution, and contributes to understanding Earth's Fluid Fluxes.

Contacts: Dan Howell, Bill Griffin
Funded by: CCFS Foundation Project 8

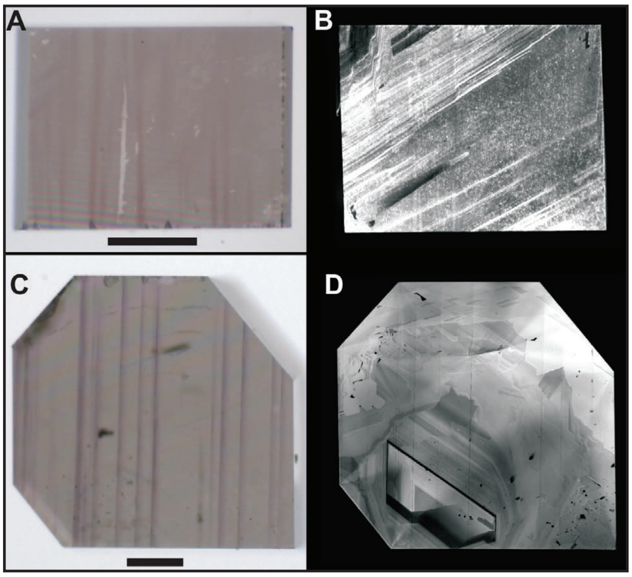


Figure 1. Images of two different pink diamonds. Images A & B are of an Argyle pink diamond, under plane light and CL respectively. The pink colour is less restricted to the {111} lamellae, and in the CL image the colour is very grained and does not correlate clearly with the {111} lamellae. Images C & D are from a pink diamond from South Africa. The plane light photo (C) shows the pink colour is very clearly retained in the {111} lamellae while the bulk of the diamond is colourless. These lamellae, shown to be micro-twins by EBSD analysis, are clearly picked out in the CL image (D), cross cutting the primary growth stratigraphy of the diamond. Scale bars represent 0.5mm.

Mechanisms of moving glaciers and ice sheets

Interpretation and prediction of past and future behaviour of polar and glacial ice is a major challenge, especially in view of changing climate. We performed unique deformation experiments to advance our knowledge of the effects of temperature changes and deformation rates on the flow properties of ice. In-depth knowledge of these properties is essential in order to develop reliable climate models incorporating the effects of polar and glacial ice mass flow and their reduction through time.

The team used a novel, world-first technique to investigate the deformation of ice. Heavy-water ice (D_2O) was used as a direct analogue for natural-water ice (H_2O). The use of heavy-water ice offers the unique opportunity to utilise neutron diffraction analysis in order to simultaneously monitor the flow properties, microstructure and orientation properties of ice. Laboratory grown polycrystalline samples were shortened up to 40% at variable temperatures and at three different constant deformation rates. Results show that ice exhibits a highly dynamic deformation behaviour. With deformation grain orientations change rapidly and distinctly. The processes that govern the flow properties of ice are changing with increasing temperature and amount of deformation. The competition of these processes is highly dynamic but predictable and this competition defines ice dynamics and needs to be incorporated in ice mass modelling.

Within this ongoing project the research team will expand the analysis to so called "dirty" ice, ice which is mixed with rock powder. The behaviour of "dirty" ice is not well understood, despite its growing importance as ice masses become more and more rock powder laden in response to climate change.

This project is relevant to CCFS theme 3, Earth Today and contributes to understanding Earth's Fluid Fluxes.

Contact: Sandra Piazolo

Funded by: ARC Future Fellowship, Bragg Institute, ANSTO Lucas Heights

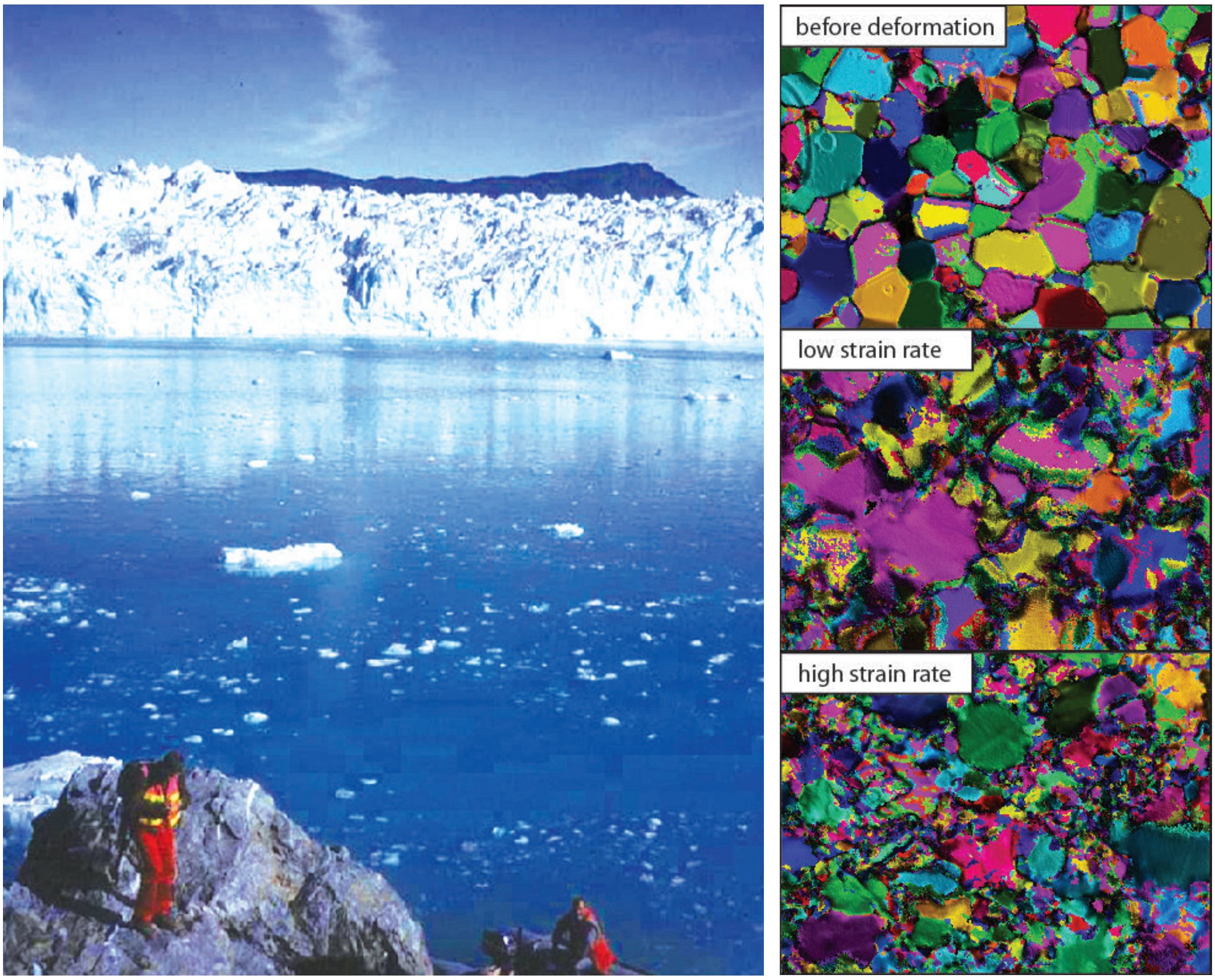


Figure 1. (left) Studying a rapidly flowing glacier which drains the Greenland ice cap, West Greenland. The rapid flow is a direct effect of elevated temperatures. Understanding the underlying principles of ice mass flow is essential for the prediction of climate change effects. (right) Experimental ice microstructures before deformation (top), after 10% deformation at low strain rates (middle) and high strain rates (bottom); optical micrographs where different colours signify different orientations, width of image is 4.8 mm.

CCFS honours students

THE FOLLOWING HONOURS PROJECTS IN CCFS WERE COMPLETED IN 2012:

MACQUARIE

Mid 2012 Finish

Madeline Kobler: Petrographic, geochemical and geochronological characterisation of Batavia Knoll dredge samples, Perth Abyssal Plain: implications for linkage with Eastern Gondwana

Roderick Lawrence: Gravity modelling of the Late-Permian Dundee Rhyodacitic Ignimbrite, New England Region, NSW

Allyson Jennings: An experimental investigation of primitive magmas from the Kermadec Arc

Katherine Farrow: Petrographic and geochronological investigation of S-Type granites from a low-pressure high-temperature regional aureole: Mt Stafford, Central Australia

Emma-Kate Chisholm: Geochemical and isotopic constraints on timing and nature of Siluro-Devonian magmatism between Wombeyan and Yerranderie

End of 2012 Finish

Ristch Camille: Constrained 3D magnetic modelling predicting the resource grade of magnetite at Hawsons, Broken Hill, New South Wales

Emma Flannery: Organic Geochemistry of the Mesoproterozoic Velkerri Formation, McArthur Basin

Samuel Matthews: Geodynamics of Venusian-type planets

James Smith: Investigating the complex interactions between deformation, fluids and the rates of reactions in northern Fiordland, New Zealand

Catherine Stuart: Aqueous liquid advection: A plausible mechanism for heating the shallow crust to form HTLP metamorphic belts?

Alexander Tickle: Magmatic/hydrothermal evolution of tin in an ore-forming environment: A case study of the Mole Granite using a combined geochemical and geophysical approach

Curtin honours student Ryan Dethian taking a closer look while attending "A Tectonic History of South China in Nine Days" – CCFS Joint Field Workshop with Chinese Partners, researchers from the Chinese Academy of Sciences, staff and students from Zhejiang University, Curtin University and Nanjing University. During the fieldtrip students held evening discussions, and final seminar presentations on what they learned during the trip.

CURTIN

Ryan Dethian: Smarter look at Fool's Gold: Microstructural analysis of sulfides from the Mickey Doolan deposit, Meekatharra Western Australia

UNIVERSITY OF WESTERN AUSTRALIA

Trent Batterham: Dolerites from the Rosie Nickel Prospect

Graeme Hardwick: Regolith geochemistry of the Katanning gold discovery

Brendan Lally: Geological mapping of an area in south-east Greenland

CCFS postgraduates

CCFS postgraduate students include those already in progress in 2011 with projects relevant to CCFS Research Themes, as well as those who commenced in 2012. Fourteen papers by CCFS postgraduates were published in high-profile international journals in 2012, including *Geology, Precambrian Research, Journal of Petrology, Lithos, Earth and Planetary Science Letters and Chemical Geology*. Presentations were also given at a number of international conferences (see *Appendix 6*).

Yuya Gao, Jin-Xiang Huang, Sue O'Reilly, Qiuling Gao at Jin-Xiang's Graduation Ceremony, April 2012.

AWARDS

Yuya Gao won the award for the student's best presentation at the Chinese National Symposium on Petrology and Geodynamics in 2012. This is the fifth time that a Macquarie PhD has won this award: previous winners are: Lijuan Wang, Jin-Xiang Huang and Yao Yu.

Rachel Bezard

Finalist, Faculty of Science Three Minute Thesis (3MT), Macquarie University

Rajat Taneja

Finalist, Faculty of Science Three Minute Thesis (3MT), Macquarie University

Cara Danis was one of two DI Groves Medal winners awarded the best paper published in AJES by a young author for her paper *"Gunnedah Basin 3D architecture and upper crustal temperatures"*, AJES, V57, 2010. The award was presented at the 2012 IGC, Brisbane in August.

Carissa Isaac and **Ekaterina Rubanova** were co-awarded best poster presentation at the CCFS Science Advisory Committee meeting, August, 2012.

COMPLETED

Dr Cara Danis (PhD): Geothermal state of the Sydney-Gunnedah-Bowen Basin system (Macquarie)

Dr Jin-Xiang Huang (PhD): Origin of eclogite and pyroxenite xenoliths in kimberlites and basalts (Macquarie)

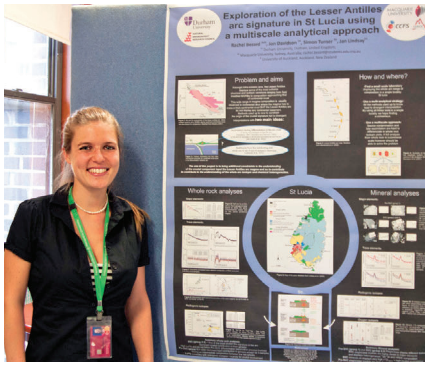
Dr Yongjun Lu (PhD): Controls on porphyry emplacement and Porphyry Au-Cu mineralisation along the Red River Fault Hunnan Province, China (UWA)

CONTINUING

MACQUARIE

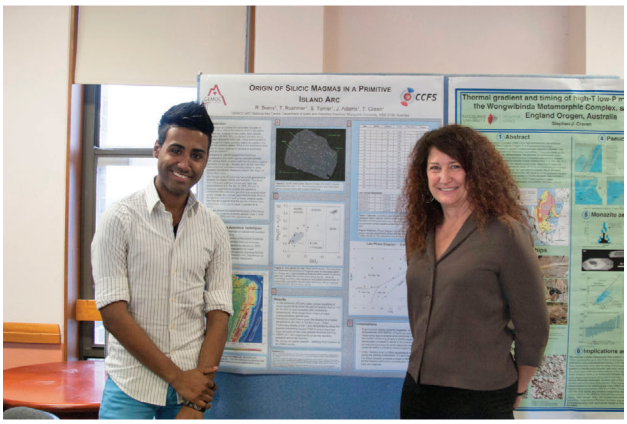
Soumaya Abassi (PhD): Mass balance of generation and escape of methane on the North West Shelf of Australia in the Tertiary; *MQRES* (commenced 2010)

Rachel Bezard (PhD): Evolution of the Qualibou volcanic complex, St Lucia, Lesser Antilles; *iMQRES COTUTELLE* (commenced 2012)



Rachel Bezarde with her poster at the EPS PhD seminars held in November 2012.

Raul Brens (PhD): Origin of silicic magmas in a primitive island arc; *iMQRES* (commenced 2011)



Raul Brens with his supervisor, Associate Professor Tracy Rushmer at the EPS PhD seminars held in November 2012.

David Child (PhD): Characterisation of Actinide particles in the environment for nuclear safeguards using mass spectrometric techniques (commenced part time 2007)

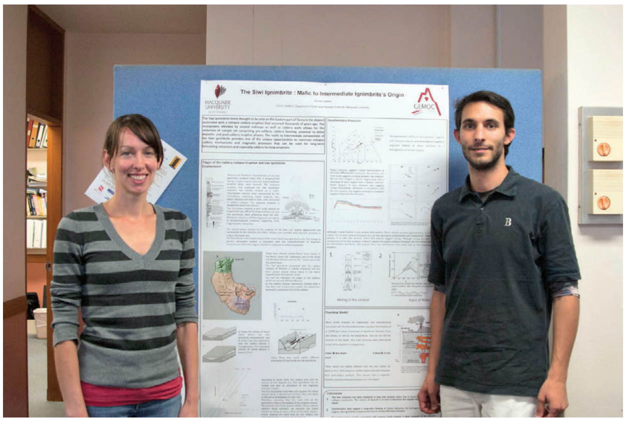
David Clark (PhD): Contributions to integrated magnetics - applications to the Earth Sciences (commenced part time 2006)

Steven Craven (PhD): The structural and metamorphic evolution of the Wongwibinda Complex, NSW, Australia (commenced part time 2006)

Daria Czaplińska (PhD): Flow characteristics of lower crustal rocks: Developing a toolbox to improve geodynamic models; *iMQRES* (commenced 2012)

Eileen Dunkley (PhD): Hf isotopic behaviour in turbidites, migmatites and granites at Mount Stafford, Central Australia; *MQRES* (commenced 2010)

Fiona Foley (PhD): Magmatic consequences of subduction initiation and its role in continental crust formation; *iMQRES* (commenced 2009)



Clement Gaildry with his supervisor, Dr Heather Handley, at the EPS PhD seminars held in November 2012.

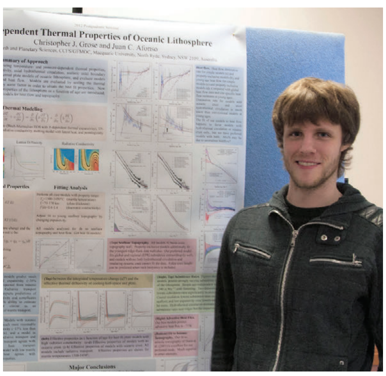
Clement Gaildry (PhD): Development of the larger Yasur Caldera system, Tanna, Vanuatu; *iMQRES* (commenced 2011)

Yuya Gao (PhD): Comparative Study of Origin and Petrogenesis of A-type Granites in Eastern China and Southeastern Australia: Evidence from Hf-O-Li Isotopes; *iMQRES* (commenced 2012)

Robyn Gardner (PhD): Understanding the flow characteristics of lower continental crust to improve the geodynamic modelling of rifting events; *MQRES* (commenced 2012)

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

Christopher Grose (PhD): Geodynamics of the oceanic lithosphere; *iMQRES* (commenced 2011) *See Research highlight p. 55.*



Chris Grose with his poster at the EPS PhD seminars held in November 2012.

Yosuke Hoshino (PhD): Demonstrating the syngeneity and interpreting the palaeobiology of hydrocarbon biomarkers in the Fortescue Group (2.7 Ga); *iMQRES* (commenced 2011)

Chengxin Jiang (PhD): Combining seismic tomography and sedimentology to understand the deep structure and evolution of the northern edge of the Tibetan Plateau; *iMQRES* (commenced 2012)

Elizabeth Keegan (PhD): ^{231}Pa-^{227}Ac studies in Earth Sciences (commenced 2011)

Kostas Kotzakoulakis (PhD): Ecological risks associated with the use of fuels in Antarctica: characterising hydrocarbon behaviour and assessing toxicity on sensitive early life stages of Antarctic marine invertebrates; *ENDVR* (commenced 2012)

Pablo Lara (PhD): Late Neoproterozoic granitoid magmatism of the Southernmost section of the Don Feliciano Belt in Uruguay: Regional geology, geochemistry, geochronology and its significance for the geotectonic evolution of the region (commenced 2011)

Nicole McGowan (PhD): Messages from the Mantle: Geochemical Investigations of Ophiolitic Chromitites; *APA* (commenced 2012)

Melissa Murphy (PhD): A novel approach for economic uranium deposit exploration and environmental studies; *APA* (commenced 2009, submitted Jan 2013)

Rosanna Murphy (PhD): Stabilising a craton: origin and emplacement of the 3.1 Ga Mpuluzi batholith (Swaziland/RSA); *MQRES* (commenced 2011) *See Research highlight p. 50.*

Matt Pankhurst (PhD): Geodynamic significance of shoshonitic magmatism within the Andean Altiplano; *MQRES* (commenced 2009, submitted Jan 2013)

Mehdi Tork Qashqai (PhD): Inversion of multiple geophysical data for composition and thermal structure of Earth's upper mantle; *iMQRES* (commenced 2012)

Ekaterina Rubanova (PhD): Fluid processes in the deep mantle: Geochemical studies of diamonds and related minerals; *iMQRES* (commenced 2010) *See Research highlight p. 44.*

Edward Saunders (PhD): Gold distribution and mobility within the mantle and its significance to mineralised provinces; *APA* (commenced 2010) *See Research highlight pp. 60-61.*

Elyse Schinella (PhD): Landform evolution on Venus; *APA* (commenced 2010)

Ramzan Shahid (PhD): The strength of oceanic plate-bounding faults; *iMQRES* (commenced 2012)

Liene Spruzeniece (PhD): The fundamental link between deformation, fluids and the rates of reactions in minerals; *iMQRES* (commenced 2012)

Cait Stuart (PhD): Flow characteristics of lower crustal rocks in the presence of melt; *MQRES* (commenced 2012)

Qing Xiong, Tibet.

Rajat Taneja (PhD): Geodynamic evolution of the NE Indian Ocean; *iMQRES* (commenced 2010)

Jennifer van Holst (PhD): Understanding microbial gasification of coal: A study of the stable isotope composition of microbial gas generation (commenced 2010)

Qing Xiong (PhD): Shenglikou and Zedang peridotite massifs, Tibet: Upper mantle processes and geodynamic significance; *China Science Council Scholarship and cotutelle with China University of Geosciences, Wuhan* (commenced 2010) Pictured above. *See Research highlight pp. 57-58.*

Yao Yu (PhD): The evolution and tectonic dynamics of the subcontinental lithospheric mantle, SE China; *China Science Council Scholarship and cotutelle with Nanjing University* (commenced 2010)

Commencing 2013:

Shad Asif, Qiang Ma, Kim Jessop, Benat Oliveira Bravo, Romain Tilhac and Irina Tretiakova

UWA

Jane Collins (PhD): The structural evolution and mineralisation history of the Flying Fox komatiite-hosted Ni-Cu-PGE sulfide deposit, Forrestania Greenstone Belt, Western Australia; *Western Areas NL, with technical support given by Newexco Pty Ltd* (commenced 2006, submitted December 2012)

Ellen Davies (PhD): The emplacement dynamics of mineralised ultramafic rocks in the Ivrea Zone in Italy (commenced 2012)

Alex Eves (MSc): Geology, mineralogy and geochemistry of the newly discovered Speewah Dome V-Ti-Fe Deposit, East Kimberley; *Niplats Australia Limited* (commenced 2012)

Denis Fougourouse (PhD): 4D geometry and genesis of the Obuasi gold deposit, Mali (commenced 2012)

Christopher Gonzalez (PhD): CO_2 devolatilisation and its influence on partial melting, subduction, and metasomatism in the mantle lithosphere (commenced 2012)

Matthew Hill (PhD): 4D Structural, Magmatic and Hydrothermal Evolution of the Au-Cu-Bi System in the Tennant Creek Mineral Field, NT, Australia; *Emmerson Resources Ltd and APA* (commenced 2010)

Carissa Isaac (PhD): 4D architecture of the Eastern Goldfields Superterrane in the Yilgarn Craton of Western Australia, in order to constrain the role of the lithospheric structure at 2.7 Ga in the localisation of nickel mineral systems; *ARC Linkage* (commenced 2009)

Margaux Le Vaillant (PhD): Characterisation of the nature, geometry and size of hydrothermal remobilisation of base metals and platinum group elements in magmatic nickel sulfide deposit systems. Implications for exploration targeting; *MERIWA, UWA SIRF scholarship, ARC linkage grant* (commenced 2011)

Erwann Lebrun (PhD): 4D geometry and genesis of the Siguiri gold deposit, Guinea (commenced 2011)

Ben Li (PhD): Evolution of fluid associated with gold mineralisation in the Paleoproterozoic Granites–Tanami Orogen; *SIRF, ARC Linkage grant* (commenced 2011)

Volodymyr Lysytsyn (PhD): Mineral prospectivity analysis and quantitative resource assessments for exploration targeting-development of effective data integration models and practical applications (commenced 2010)

Jelena Markov (PhD): 3D Geophysical Interpretation of the Archean-Paleoproterozoic Boundary, Leo-Man Shield, West Africa; *SIRF, UIS* (commenced 2011)

Quentin Masurel (PhD): Controls on the Genesis, Geometry and Location of the Sadiola-Yatela Gold Deposit, Republic of Mali (commenced 2012)

Kombada Mhopjeni (MSc): Investigating the Uranium potential in Namibia using GIS-based techniques (commenced 2011)

Aileen Mirasol-Robert (PhD): Field Characterisation of Australian Gold Systems (commenced 2012)

David Mole (PhD): Quantifying melt-lithosphere interaction in space and time: understanding nickel mineral systems in the Archaean Yilgarn craton; *UWA Scholarships for International Research Fees, ARC Linkage* (commenced 2008, submitted 2012)

John Owen (PhD): Evolution and emplacement of Ni-Cu-PGE bearing magmatic systems in the lower crust and the nature and role of magmatic vapour phases in these systems; SORF, UIS, ARC (commenced 2012)

Louis Parra (PhD): 4D evolution of felsic magmatic suites and lithospheric architecture of the Paleoproterozoic Birimian terranes, West Africa; *IPRS recipient; UWA SIRF UIS, Ad Hoc Safety-Net Top-Up Scholarship, ARC Linkage* (commenced 2011)

Christian Schindler (PhD): Petrogenesis of intrusive rocks in the Telfer region, Patterson orogen, Western Australia: implications for gold mineralisation; *UWA Scholarship for International Research Fees, Industry Funding* (commenced 2010)

David Stevenson (PhD): 4D modelling of the Tanami Inlier, Northern Territory (commenced 2012)

Zoja Vukmanović (PhD): A micromechanical and geochemical analysis of remobilisation of komatiite-hosted Ni sulfide ores; *CSIRO Flagship Scholarship; Meriwa Top-up Scholarship* (commenced 2009)

Qingtao Zeng (PhD): Regional controls on gold mineral systems in the western Qinling Belt, Gansu Province, China; *UWA Scholarship for International Research Fees China, Peking University, China Science Council* (commenced 2008, submitted 2012)

Ganyang Zhang (PhD): Sb-Au Mineralisation Mechanism and Exploration Targeting Prediction Research in Northern Himalaya Metallogenetic Belt, Tibet, China; *China Scholarship Council* (commenced 2009)

Jianwei Zi (PhD): Igneous petrogenesis and tectonic evolution of Cretaceous plutons, eastern Tibetan Plateau; *UWA Scholarship for International Research Fees China, Top-Up Scholarship for China Science Council* (commenced 2008)

Commencing 2013:

Katarina Bjorkman

CURTIN

Rengfeng Ge (PhD): Precambrian to Paleozoic tectono-thermal evolution in the Korla area, northern Tarim Craton, NW China; *Joint China Scholarship Council and Curtin University and cotutelle with Nanjing University* (commenced 2012)

Huiqing Huang (PhD): The Petrogenesis of Jurassic Granitic Rocks in Western Nanling Ranges of South China and Tectonic Implications; *Joint Curtin-CAS PhD under Curtin University Scholarship* (commenced 2009, submitted 2012)

Shan Li (PhD): Early Mesozoic Magmatism and Tectonics in the Beishan area of Inner Mongolia, China; *China Scholarship Council* (commenced 2010)

Liping Liu (PhD): Timing and kinematics of Mesozoic-Cenozoic mountain building and cratonic thinning in eastern North China: a combined structural and thermochronological study; *China Science Council and Curtin University joint Scholarship* (commenced 2010)

Yingchao Liu (PhD): Recognising Gold Mineralisation Zones using GIS-Based modelling of multiple ground and airborne datasets; *APRA* (commenced 2010)

Jiawen Niu (PhD): Neoproterozoic paleomagnetism of South China and implications for global geodynamics; *Curtin University ARC DP scholarship* (commenced part time 2008)

Chongjin Pang (PhD): Basin record of Mesozoic tectonic events in South China; *China Science Council and Curtin University joint Scholarship* (commenced 2010)

Curtin PhD students and participants, field trip to South China (L-R) Mr Qin, Weihua Yao (PhD Curtin), Prof Wuxian Li, Zheng-Xiang Li, Dr Martin Danisik, Ni Tao (PhD Curtin) and Mr Wei Gao.

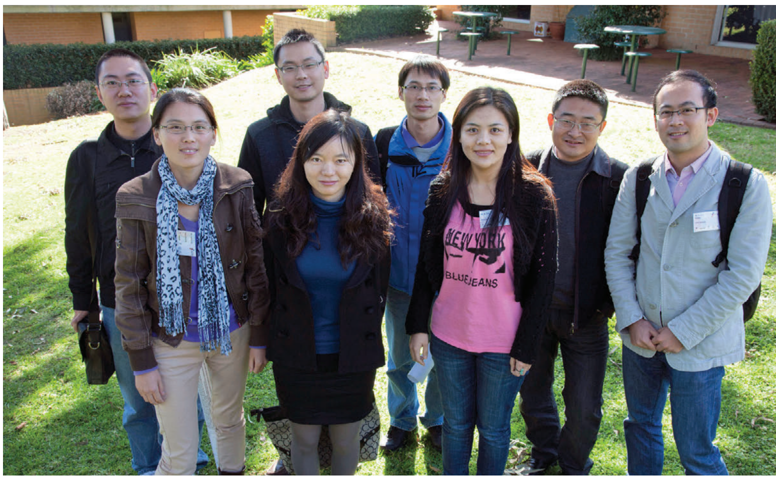
Mingdao Sun (PhD): Late Mesozoic Magmatism and its Tectonic implication for the Jiamusi Block and adjacent areas of NE China; *Joint Zhejiang and Curtin University Scholarship and cotutelle with Zhejiang University* (commenced 2011)

Ni Tao (PhD): Thermochronological record of vertical tectonic movements in Mesozoic-Cenozoic South China; *ARC DP scholarship* (commenced 2011)

Qian Wang (PhD): Distribution of the Proterozoic Sedimentary Rocks in the Jack Hills, Metasedimentary Belt, Western Australia; *China Scholarship Council* (commenced 2010)

Weihua Yao (PhD): Lower Palaeozoic basin record in Southern South China: Nature of the Cathaysia basement and evolution of the Wuyi-Yunkai Orogeny; *China Science Council and Curtin University joint Scholarship* (commenced 2010) *See Research highlight pp. 35-36.*

Kongyang Zhu (PhD): Petrogenesis and tectonic setting of Phanerozoic granitic rocks in eastern South China; *China Science Council and Curtin University joint Scholarship* (commenced 2010)



Curtin PhD students at the CCFS Science Advisory Committee meeting, August 2012, Top L-R: Kongyang Zhu, Yingchao Lu, Chongjin Pang, Dr Xuan-Ce Wang and Huiqing Huang. Bottom L-R: Lipeng Lu, Weihua Yao and Ni Tao.

A highlight of CCFS postgraduate activity in 2012

Was a series of extended exchange visits by international PhD students for collaborative studies with CCFS research groups. These included:

Qiuling Gao from China University of Geoscience, Wuhan: *"The relationship between the volcanism across the Permo-Triassic Boundary for the Xinmin section in Guizhou Province in South China, and the Permo-Triassic Mass Extinctions"*

Vanessa Colás Ginés, Departamento Ciencias de la Tierra, Universidad de Zaragoza, Spain: *"Distribution and mobility of major, minor and trace elements in metamorphosed and unmetamorphosed chromite deposits from ophiolites"*

Ria Mukherjee *(pictured below operating the MQ GAU Zeiss SEM)* from Department of Geological Sciences, Jadavpur University, Kolkata, India: *"PGE patterns and Os-isotope compositions of the base-metal sulfides and platinum-group minerals in chromitites of the Nuggihalli deposits in the western Dharwar Craton"*

Qian Liu from China University of Geoscience, Wuhan: *"Zircon geochemistry and geochronology from two episodes of late Mesozoic granitic magmatism in South China: geodynamic implications for subduction geometry"* (see *Research highlight p. 43*)

José Godinho from the Department of Geological Sciences, Stockholm University, Sweden is investigating the effect of porosity, crystal orientation and deformation microstructures on the dissolution of geological material as well as analogues for nuclear waste pellets. During his visit at MQ he developed a new numerical simulation code to simulate dissolution in two and three dimensions and deformed fluorite samples in the Griggs deformation rig.

Lavinia Tunini visited MQ from Ins. Earth Sci. Juame Almera Barcelona to work with Dr Afonso on different aspects of thermal modelling of the lithosphere (Spain)

Jiangang Han from Peking University, Beijing, PR China: *"Nature of lithosphere and sublithospheric upper mantle in northwest China"*

Mr Christophe Brouzet from the University of Lyon is a Masters student in Physics and completed an internship with Sandra Piazolo in view of a joint PhD between CNRS Grenoble (Dr Maurine Montagnat) and CCFS. He took part in the conduction and initial analysis of results of *in-situ* Neutron Diffraction Analysis of deforming ice at the Braggs Institute at ANSTO, Lucas Heights. He worked on developing new analysis routines for these novel Neutron Diffraction Experiments.

Tine Larson: *"Structural evolution of the Rover Goldfield, Northern Territory, and comparison to Scandinavian sedimentary-hosted systems"*

Lijuan Ying from the College of Earth Sciences, Chengdu University of Technology: *"Porphyry mineralisation in the North China Craton"*

Dayu Zhang from School of Resources and Environmental Engineering, Hefei University of Technology, Hefei: *"Late Paleozoic petrogenesis and mineralisation in Jueluotage area, Eastern Tianshan, Northwest China"*

Sebastian Grignola from the Facultad de Ciencias Naturales, University of Tucumán, Argentina: *"The Casposo epithermal deposit low sulfidation gold-silver hydrothermal alteration and geochronological implications in gold-silver mineralisation, volcanic rocks and dikes spatially associated granitoids, San Juan, Argentina"*

Peter Kollegger from the University of Leoben, Austria: *"A multi-technical mineralogical, petrological and geochemical approach to the origin of ore mineralisation in the mafic-ultramafic rocks of the Ivrea-Verbano zone, Piedmont, Northern Italy"*

Thomas Dittrich from the Technical University Bergakademie Freiberg, Germany: *"Genesis and exploration of cesium deposits"* in co-operation with Rockwood Lithium Inc.

Infrastructure and technology development

CCFS links three internationally recognised concentrations of analytical geochemistry infrastructure: GEMOC's Geochemical Analysis Unit (Macquarie University) and the associated Computing Cluster, the Centre for Microscopy, Characterisation and Analysis (UWA/Curtin) and the John de Laeter Centre of Mass Spectrometry. All are nodes for the NCRIS AuScope and Characterisation Capabilities, and have complementary instrumentation and laboratories. In addition, Curtin and UWA share a leading facility for paleomagnetic studies.

CCFS/GEMOC INFRASTRUCTURE, LABORATORIES AND INSTRUMENTATION

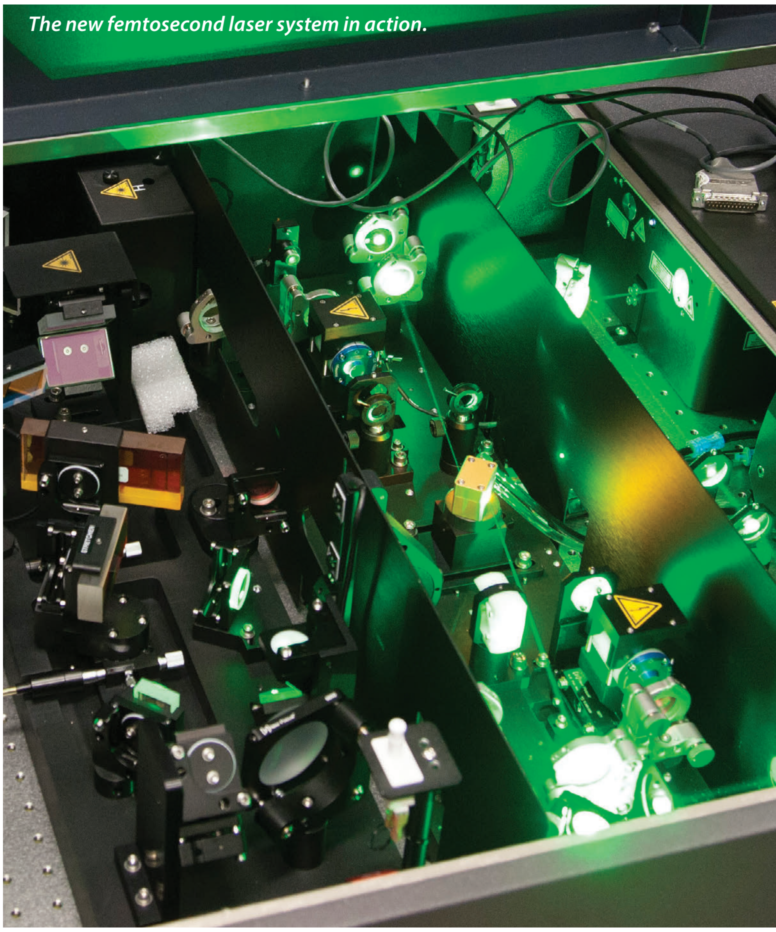
The analytical instrumentation and support facilities of the Macquarie University Geochemical Analysis Unit (GAU) represent a state-of-the-art geochemical facility.

The GAU contains:

- a Cameca SX-100 electron microprobe
- a Zeiss EVO MA15 Scanning electron microscope
- four Agilent ICPMS (industry collaboration; two 7500cs; two 7700cx)
- a Nu Plasma multi-collector ICPMS
- a Nu Plasma high resolution multi-collector ICPMS
- a Thermo Finnigan Triton TIMS
- a custom-built UV laser microprobe, usable on the Agilent ICPMS
- three New Wave laser microprobes (one 266 nm, two 213 nm, each fitted with large format sample cells) for the MC-ICPMS and ICPMS laboratories (industry collaboration)
- a Photon Machines Excite Excimer laser ablation system
- a Photon Machines Analyte198 Femto-second laser ablation system
- a PANalytical Axios 1kW XRF with rocker-furnace sample preparation equipment
- a LECO RC412 H_2O-CO_2 analyser
- an Ortec Alpha Particle counter
- a New Wave MicroMill micro-sampling apparatus
- a ThermoFisher iN10 FTIR microscope
- selFrag electrostatic rock disaggregation facility
- clean labs and sampling facilities provide infrastructure for ICPMS, XRF and isotopic analyses of small and/or low-level samples
- experimental petrology laboratories include four piston-cylinder presses (pressures to 4 GPa), hydrothermal apparatus, controlled atmosphere furnaces, Griggs apparatus and a multi-anvil apparatus for pressures to 27 GPa

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

Within CCFS, 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



The new femtosecond laser system in action.

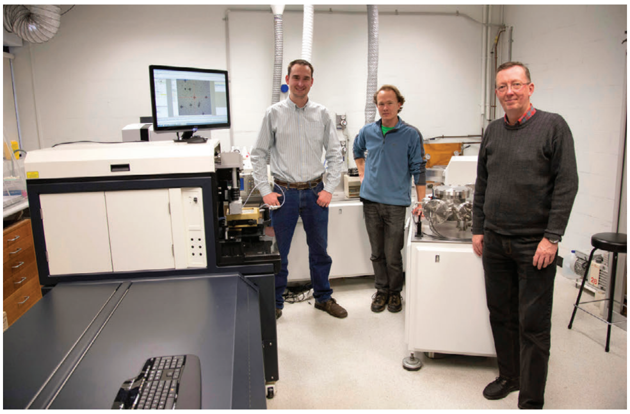
of Newcastle, Sydney, Western Sydney and Wollongong as partners. In late 2009 GEMOC was awarded an ARC LIEF grant to integrate the two existing multi-collector inductively-coupled-plasma mass spectrometers (MC-ICPMS) with 3 new instruments: a femtosecond laser-ablation microprobe (fs-LAM); a high-sensitivity magnetic-sector ICPMS; a quadrupole ICPMS. The quadrupole ICPMS was purchased and installed in 2010; a Photon Machines femtosecond laser system was installed in June 2012; and a Nu Attom ICPMS to be installed in January 2013.

PROGRESS IN 2012

1. Facility for Integrated Microanalysis

a. Electron Microscope; Electron Microprobe: The Zeiss EVO MA15 SEM carried the electron imaging workload, providing high-resolution BSE and CL images for *TerraneChron*® (http://www.gemoc.mq.edu.au/TerraneChron.html) and all other research projects, including diamonds and diamondites, and PGM in chromitites. In 2012 a new Oxford Instruments AZtec Synergy combined Energy Dispersive System and Electron Back-Scatter Diffraction detector were installed on the Zeiss SEM. This combined capability for elemental and crystal orientation mapping has enabled new research directions in the study of deformation processes in mantle and crustal rocks. The SX100 serviced the demands for quantitative mineral analyses and X-ray composition maps for all projects including analysis of chromites; analysis of base metal sulfides and platinum group minerals; minor and trace element analysis of metals. A MQSIS 2013 Faculty of Science Infrastructure Fund grant was awarded for the upgrade of the integrated Energy Dispersive Spectrometer system on the SX100.

b. Laser-ablation ICPMS microprobe (LAM): In 2012 the LAM laboratory was used by thirteen Macquarie PhD thesis projects, twelve international visitors, four Honours students, and several in-house funded research projects and industry collaborations. Projects included the analysis of trace elements in the minerals of mantle-derived rocks, in sulfide minerals and in a range of unusual matrices. U-Pb analysis of zircons was again a major activity with geochronology projects (including *TerraneChron*® applications: http://www.gemoc.mq.edu.au/TerraneChron.html) from Australia (NSW, WA, SA), New Zealand, Algeria, Colombia, Indonesia, Mongolia, Papua New Guinea, Russia, and west Africa. Method development was also undertaken for the U-Pb dating of apatite. 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.

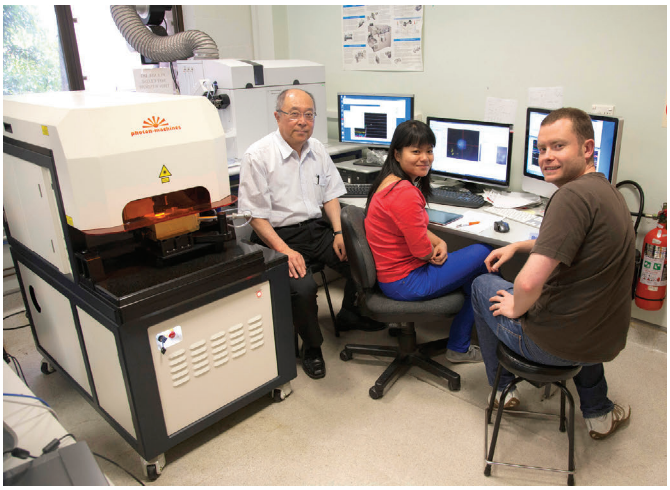


Photon engineer Ben Staal with the new Photon Machines Analyte198 Femto-second laser ablation system.

c. MC-ICPMS: The continued increase of *TerraneChron*® activities (see http://www.gemoc.mq.edu.au/TerraneChron.html) involving the measurement of Hf isotopes, coupled with the growing demand for *in-situ* analysis of other radiogenic isotope systems (e.g. Re-Os analysis in sulfide and PGM; Nd-Sm and Rb–Sr in perovskite) and stable isotope analysis, created severe competition for instrument time on the LAM MC-ICPMS.

Major applications during 2012 using in situ techniques continued to centre on the high-precision analysis of Hf in zircons to trace lithosphere evolution and 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 (NSW, WA, SA), New Zealand, Algeria, Colombia, Indonesia, Mongolia, Papua New Guinea, Russia, and west Africa. Re-Os studies were undertaken on xenoliths from eastern China, Siberia, Mongolia, Spain, USA, South Africa and northern Africa, and sulfide and platinum group minerals in chromitites from Cuba, Spain, Turkey.

d. Laboratory development: The clean-room facility established in 2004 continued to be used primarily for isotope separations for analysis on the Triton TIMS and Nu Plasma MC-ICPMS. Routine procedures have been established for Rb-Sr, Nd-Sm, Lu-Hf and Pb isotopes, as well as U-series methods (U, Th and Ra). Further developments of methods were undertaken for whole-rock Re-Os isotopes of basaltic rocks. A project was initiated to adapt conventional techniques for Rb-Sr and Nd-Sm isotope separation to the nano-scale to process small sample sizes.



Dr Masahiko Honda (ANU/RSES), and ANU honours student Hanling Yeow with Dan Howell using the Photon Excite Excimer laser ablation system.

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. Sales are handled by Access MQ and GEMOC provides customer service and technical backup. During 2012 a further 16 full licences of GLITTER were sold bringing the total number in use to 202 worldwide, in forensics and materials science, as well as earth science applications. Dr Will Powell continued in his role in GLITTER technical support and software development through 2012. The current GLITTER release is version 4.4.3 and is currently available without charge to existing customers and accompanies all new orders (http://www.glitter-gemoc.com/).

2. X-Ray Fluorescence Analysis

In November 2012 a PANalytical Axios 1 kW X-ray Fluorescence Spectrometer was installed. This instrument is a wavelength spectrometer system and replaced the Spectro XLAB2000 energy-dispersive X-ray spectrometer, which was installed in November 2000. The new instrument will be used to measure whole-rock major element compositions on fused glass discs and trace-element concentrations on pressed-powder pellets. An upgrade of the sample preparation infrastructure is planned for early 2013.

Navigating the halls with the new PANalytical Axios 1 kW X-ray Fluorescence Spectrometer, installed in November 2012.

3. Whole-rock solution analysis

An Agilent 7500cs ICPMS produces 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 ICPMS dedicated to solution analysis continued to be used for the further development of 'non-traditional' stable isotopes with the refinement of separation techniques and analytical protocols for Mg isotopes in garnet and for the separation and analysis of Li isotopes in granitic rocks.

4. Diamond preparation and analysis

The GEMOC laser-cutting system (donated by Argyle diamonds in 2008), was used during 2012 to cut thin plates of single diamond crystals as part of the on-going research into diamond genesis. The plates are used for detailed spatial analysis of trace elements, isotopic ratios and the abundance and aggregation state of nitrogen. The nitrogen measurements are made using the ThermoFisher iN10FTIR microscope, which allows the spatial mapping of whole diamond plates at high resolution with very short acquisition times.

5. selFrag – a new approach to sample preparation

GEMOC's selFrag instrument was installed in May 2010 and was the first unit in Australia. 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 higher proportion of unbroken grains of trace minerals such as zircon. Since its installation selFrag, usage has continued to grow and in 2012 it was used for a range of applications including 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. Method development also continued in 2012 on the CNT Hydroseparator for the separation of small volumes of ultrafine material (e.g. alloys in chromitites). See *p. 122-123*.

6. Computer cluster

A 64-core ARC-funded computer cluster (Enki) came online in 2010, with the capability to run massively parallel high-resolution geodynamics simulations in 3D at a global scale. Further funding in 2011 was used to expand the cluster into a 160-core machine. Updated rack storage and power supplies have been completed, and the upgraded machine is currently in full operation.

The cluster is running some of the most cutting-edge simulation software packages, including CitcomS – enabling 3D spherical mantle simulations, and Underworld – a lithosphere and mantle deformation computational framework designed for massively parallel simulations. It has supported four Honours student projects, as well as two ongoing PhD projects, and underpins at least four successful ARC Discovery projects.

Internal capacity in this kind of computing is necessary as externally available clusters (e.g. At AC3/Intersect, or at NCI) are specifically for "production" runs only – not for research and development of experimental codes. However, many of these codes have absolute minimum resolution requirements which can only be met by a large cluster. For example, CitcomS requires at least 12 nodes to run, or 96 for a fully resolved simulation, which is often necessary for the testing of new modules. This cannot be done on a desktop machine, and since testing is not allowed on the public machines, the in-house cluster is essential to the development of the next generation of simulation tools.

CMCA TECHNOLOGY DEVELOPMENT AND INSTRUMENTATION

The University of Western Australia's Centre for Microscopy, Characterisation and Analysis (CMCA) is a $40M core facility providing analytical solutions across a diverse array of scientific research. The world-class facilities and associated technical and academic expertise are the focus of micro-analytical and characterisation activities within Western Australia, while strong links and collaborations have earned the CMCA an excellent national and international reputation. The CMCA incorporates the Western Australian Centre for Microscopy, and is a node of the NCRIS Characterisation capabilities, the National Imaging Facility (NIF) and the Australian Microscopy and Microanalysis Research Facility (AMMRF). It is also associated with the NCRIS-funded Australian National Fabrication Facility (ANFF) and AuScope, which have made a substantial contribution to facilities run by CMCA.

CMCA capabilities:

- CAMECA IMS 1280 and CAMECA NanoSIMS 50 ion microprobes
- JEOL JXA 8530F electron microprobe, with Cathodoluminescence imaging (CL)
- Transmission Electron Microscopes (JEOL 3000F, 2100 and 2000FX), with EDS and energy-filtered EELS analysis capabilities
- Scanning electron microscopes (Zeiss 1555, 2 JEOL 6400, Philips XL30)
- X-ray powder diffraction (Panalytical Empyrean)
- NMR spectroscopy (2 Bruker Avance and 2 Varian spectrometers)
- Optical and confocal microscopy
- Micro-CT (to be installed 2012)
- Bioimaging, flow cytometry, cell sorting, and laser micro-dissection
- X-ray crystallography
- GC and HPLC mass spectrometry
- Biological sample cryo-preparation and ultramicrotomy

THE AMMRF FLAGSHIP ION PROBE FACILITY

The CMCA at UWA is home to two state-of-the-art ion microprobes that are integral to the goals of the CCFS. The CAMECA IMS 1280 and NanoSIMS 50 are flagship instruments of the Australian Microscopy and Microanalysis Research Facility (AMMRF). The AMMRF Flagship Ion Probe Facility offers state-of-the-art secondary ion mass spectrometry (SIMS) capabilities to the Australian and international research communities, allowing *in-situ*, high-precision isotopic and elemental analyses, secondary ion imaging, and depth profiling on a wide range of samples.

The IMS 1280 large-geometry ion probe, installed in 2009, was co-funded by the University, the State Government of Western Australia, and the Federal Government's Department of Innovation, Industry, Science and Research (DIISR) under the 'Characterisation' (AMMRF) and 'Structure and Evolution of the Australian Continent' (AuScope) capabilities of the National Collaborative Research Infrastructure Strategy (NCRIS). The CAMECA IMS 1280 is optimised for *in-situ* stable isotope analyses (e.g. S, O, C) at a spatial resolution of 10 to 30µm and a precision of ~0.1-0.4 per mil.

The NanoSIMS 50, installed in 2003, was funded through the Federal Government's NCRIS-precursor, the Major National Research Facility scheme (NANO-MNRF). The CAMECA NanoSIMS 50 is designed to provide elemental and isotopic imaging on a wide range of materials with a spatial resolution down to 50 nm – albeit, with considerably less sensitivity than the IMS1280.

Both instruments are relatively rare – there are only about 30 of each in the world – and until recently UWA was the only institution in the world to have both side by side.

The instruments are managed by the Western Australia Ion Probe Management Committee, which also manages the two SHRIMP II ion probes located at Curtin University. Access to the Ion Probe Facility is subsidised for publicly-funded researchers within Australia via a merit-based competitive application scheme, where projects are assessed by a scientific committee of international experts.

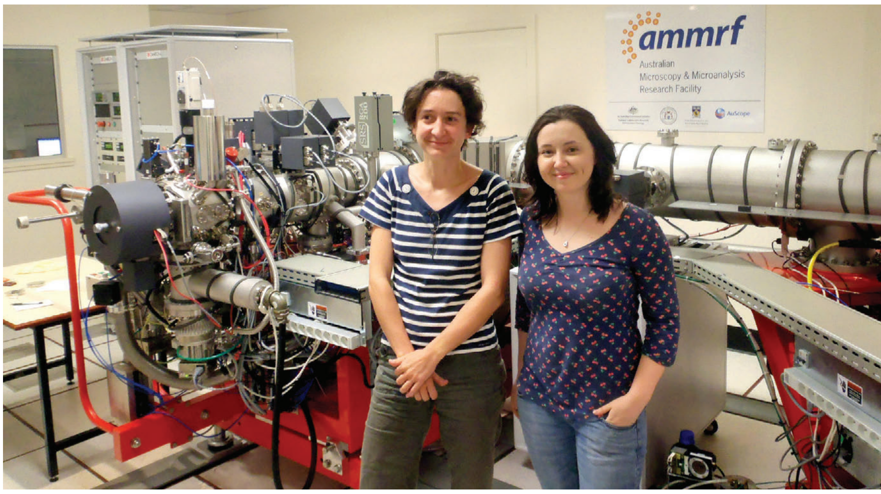
The Ion Probe Facility is a key characterisation component within the ARC Centre of Excellence for Core to Crust Fluid Systems. To ensure the highest levels of quality and throughput, the CCFS has provided funding for a Research Associate position within the Ion Probe Facility, to facilitate direct scientific and technical interaction for all CCFS users and projects.

PROGRESS IN 2012

In 2012, the Ion Probe Facility at CMCA-UWA has embraced a wealth of projects in the context of CCFS (see *CMCA Research highlight p. 75*). These have included a wide range of topics, from the characterisation of mantle metasomatism (O isotopes in zircon and garnet; E. Rubanova, E. Belousova, Q. Xiong, J. Huang), the origin of diamonds (O isotopes in garnet and C isotopes in diamond; E. Rubanova), magmatic processes and crustal growth (O isotopes in zircon; S. Li, E. Belousova, M. Sun), the origin of ore deposits (S isotopes in sulfides; M Fiorentini). Altogether, these projects account for ~30% of the available analysis time on the CAMECA IMS 1280. In addition, the NanoSIMS has also been applied to the measurement of element diffusion across mineral interfaces, trace element transportation along grain boundaries, and S isotopes (D Wacey, M Fiorentini).

Standards development:

High-precision isotope measurement with SIMS requires calibration against known standards to correct for instrumental mass fractionation between analysis sessions. This varies significantly between materials, such that each new material analysed by SIMS necessitates the development of new standards. Standards are in constant development at CMCA and currently include diamond (C isotopes), lawsonite, pyroxene,



Laure Martin and Ekaterina Rubanova with the Cameca IMS1280 ion probe.

garnet and olivine (O isotopes), tourmaline and serpentine (B isotopes), pentlandite, pyrrhotite and chalcopyrite (S and Fe isotopes).

Personnel:

Dr Laure Martin was appointed to the position of Research Associate within the CMCA to facilitate the use of the ion probes by the CCFS. With a considerable background in geological SIMS analysis, Dr Martin has already made valuable contributions to the development of standards and analytical protocols, while providing assistance in sample preparation, data acquisition, and data processing. In addition to this service role, Dr Martin also carries out her own research on the evolution of fluids in subduction zones and mineral/fluid interaction in metamorphic rocks, both key subjects within CCFS.

The Ion Probe Facility also employed Dr Rong Liu as a Senior Research Officer.

CMCA RESEARCH HIGHLIGHTS:

In 2012, a wealth of innovative CCFS research projects passed through the doors of the Ion Probe Facility at CMCA, illustrating the strong collaborative environment within the CCFS. Examples include:

4D lithospheric evolution and controls on mineral system distribution: The Western Superior-Yilgarn comparison (Yongjun Lu, Foundation project)

The O isotope analysis of zircon samples using the CAMECA IMS 1280, show that terrane boundaries appear to control the location of mineralization within the Wabigoon subprovince. The zircon Hf-O isotopes also indicate that the supracrustal recycling and juvenile crustal growth in the Wabigoon subprovince mainly developed at ca. 2.7 Ga. By contrast, the proceeding 3.1-2.9 Ga felsic magmatism mainly represents crustal reworking of deep crust without supracrustal input.

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

Carbon isotope analyses in diamond and oxygen isotope analyses in coexisting garnets have been undertaken to provide a better understanding of diamond formation processes in the mantle. The analytical results confirm that diamonds have complex mantle-residence histories and were involved in mantle metasomatic processes. These data combined with other geochemical analyses are contributing to the study of mantle fluid systems.

Textural and spatial variability in multiple sulfur isotope biosignatures (David Wacey, John Cliff, Mark Barley)

The CAMECA IMS1280 has been used to analyse some of Earth's oldest sedimentary sulfides from the 3.5 Ga Dresser Formation of Western Australia. Here we have measured all 4 stable sulfur isotopes, and while the $\delta^{34}S$ and $\Delta^{33}S$ values appear to be similar to previous bulk analyses, the $\Delta^{36}S$ values have a much greater spread than previously reported. This could be significant for understanding the sources of sulfur on the early Earth but more work is now needed to test the robustness and further develop SIMS $\Delta^{36}S$ data.

Multiple sulfur isotope measurements (James Farquhar, John Cliff)

One highlight of 2012 included the two-month visit of Professor James Farquhar (University of Maryland) as a UWA Gledden Senior Fellow, working with Dr John Cliff on the development of multiple S isotope measurements. A part of this work will be published in the Proceedings of the National Academy of Sciences (in press). Not only does the work provide fresh evidence of sulfate reduction at 2.6 Ga, but also provides evidence of two distinct sulfur pools in the Archean oceans.

Isotopic standards development (John Cliff, Laure Martin)

Due to the strong 'matrix effect' inherent in SIMS analysis, each new material requires a chemically (and isotopically) homogeneous standard of known composition with which to calibrate the instrument. In addition, new standards extend our capabilities into hitherto unexplored isotope systems. Recent standards development has included diamond (C isotopes), lawsonite, pyroxene, garnet and olivine (O isotopes), tourmaline and serpentine (B isotopes), pentlandite, pyrrhotite and chalcopyrite (Fe, Cu and S isotopes).

NanoSIMS development (Matt Kilburn, Rong Liu)

The NanoSIMS 50 was also involved in isotope development work. In February, Francois Hillion, the R&D manager from CAMECA visited the lab to work on improving the precision of isotope ratio measurements. David Wacey and Professor Martin Brasier (University of Oxford) performed $\delta^{34}S$ measurements on Ediacaran pyrite microfossils, and Dr Chen Lei (Chinese University of Geoscience – Wuhan) visited to analyse Au in sulfide minerals. High-resolution imaging was employed by Marco Fiorentini and Zoja Vuckmanovic to detect element segregation along twin-boundaries in sulfide minerals.

JOHN DE LAETER CENTRE

The John de Laeter Centre houses a suite of mass spectrometry instruments and is a collaborative research venture involving Curtin University, the University of Western Australia, CSIRO and the Geological Survey of WA. It hosts over $25M in infrastructure in key facilities supporting research in: geosciences (geochronology, thermochronology and isotope studies); environmental science and global change; isotope metrology; forensic sciences; economic geology (minerals and petroleum); marine sciences; nuclear sciences. The components are organised into nine major facilities.

The Advanced Ultra-Clean Environment (ACE) Facility: This consists of a ~400m^2 class 1000 containment space that houses four class 10 ultra-clean laboratories, a class 10 reagent preparation laboratory and a –18 °C class 10 cold clean laboratory, located at Curtin University. The extremely low ultimate particle counts are achieved with successive 'spaces within spaces' and HEPA (99.999% high efficiency particle arresting) filtration at each stage.

Inductively-Coupled Plasma Mass Spectrometry (ICPMS) Facility: This facility is located at UWA and consists of:

- TJA (VG/Fisons) PlasmaQuad 3 Quadrupole ICP-MS. The system has a high sensitivity interface to facilitate ultra-low detection limits.
- TJA (VG/Fisons) Laserlab high resolution 266 nm (Frequency quadrupled Nd-YAG) laser. The laser system is adapted with a high-resolution interface to facilitate the ablation of craters down to 10 µ in diameter.
- GBC Optimas 8000 Time of Flight ICP-MS
- Leco Renaissance Time of Flight ICP-MS
- A wide range of chromatographic and thermal dissociation interfacing is also available.

Argon Isotope Facility: This is located at Curtin and is equipped with a MAP 215-50 mass spectrometer with a low-blank automated extraction system coupled with a NewWave Nd-YAG dual IR (1064 nm) and UV (216 nm) laser, an electron multiplier detector and Niers source. Laser analysis allows for high spatial resolution up to 10 µm beam size for UV laser and 300 µm for IR laser. Larger sample sizes (>8-10 mg) are accommodated by an automated Pond-Engineering low-blank furnace. The extraction line has a Nitrogen cryocooler trap and three GP10 getters that allow gas purification. An Argus VI Mass Spectrometer and a Photon Machines Laser have been ordered for the JdL facility.

A joint ANU-John de Laeter Centre for Mass Spectrometry (JdL) Argon Facility has been established following a successful ARC bid. A total of ~$988,200 will be expended with the ARC contribution being $420,000. A management committee comprising two Facility Directors (Dr Marnie Forster, RSES, and Dr Fred Jourdan, JdL), Director JdL (Professor Brent McInnes), Mr Michael Avent (School Manager, RSES) and Professor Gordon Lister (RSES and named Project Manager and Chief Investigator on the ARC grant) has been set up and approved by all Collaborating and Partner Organisations.

A new Thermo Argus VI multi-collector noble gas mass spectrometer was installed in November 2012 with funding from a 2012 ARC LIEF grant. This new instrument is a low volume (~700 cc) instrument providing excellent sensitivity and is particularly suited to the isotopic analysis of small samples of the noble gases, and in particular, Argon. The muti-collector design gives it the ability to measure all five Ar isotopes simultaneously leading to reduced analysis time and greater productivity.

The new instrument allows the JDLC Argon isotope facility to carry out specialised work on rare extra-terrestrial sample materials, such as micrometer-size grains recovered from the Itokawa asteroid (see below) by the Japanese spacecraft Hayabusa. Dr Jourdan was awarded the grains because of the international standing of his laboratory in the study of meteorites and asteroid impacts, as well as the new Argus instrument established in the John de Later Centre for Isotope Research.

Above: Curtin University has been selected by the Japanese Space Agency to undertake Ar-Ar dating of two rare and precious grains that it recovered from the asteroid Itokawa using the Hayabusa spacecraft. The Japanese mission was the first to bring back samples from an asteroid, and the argon analysis at Curtin will determine its formation age and contribute new knowledge about the history of the solar system.

Organic Geochemistry Facility: This facility is located within Applied Chemistry at Curtin and the instruments used for biomarker, petroleum and water studies include:

- GCMS (Gas Chromatograph Mass Spectrometer)
- GC-HRMS-MS (Gas Chromatograph-High Resolution Mass Spectrometer)
- Py-GC-MS (Pyrolysis-Gas Chromatograph-Mass Spectrometer)
- LCTOFMS (Liquid Chromatograph-Time of Flight-Mass Spectrometer)
- LC-MS-MS (Liquid Chromatography-Mass Spectrometry-Mass Spectrometer)

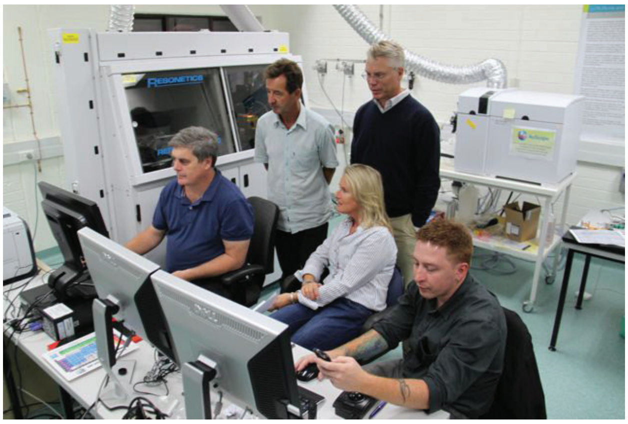
- HPSEC-DAD (High Performance Size Exclusion Chromatograph-Diode-Array Detection)
- GCIRMS (Gas Chromatograph-Isotope Ratio-Mass Spectrometer)
- TD-GC-IRMS (Thermal Desorption-Gas Chromatograph-Isotope Ratio-Mass Spectrometer)
- EA-IRMS (Elemental Analysis-Isotope Ratio-Mass Spectrometer)

Sensitive High Resolution Ion Micro Probe (SHRIMP): The facility at Curtin has two automated SHRIMP II ion microprobes capable of 24-hour operation, together with a preparation laboratory. The equipment allows *in-situ* isotopic analysis of chemically complex materials with a spatial resolution of 5-20 microns. The main application of the SHRIMP instruments at Curtin is for U-Th-Pb geochronology of mineral samples. Zircon and other U-bearing minerals, including monazite, xenotime, titanite, allanite, rutile, apatite, badelleyite, cassiterite, perovskite and uraninite are the main minerals studied, where multiple growth zones commonly require high spatial resolution analyses.

Stable Isotope Ratio Mass Spectrometry (SIRMS) Facility: The West Australian Biogeochemistry Centre (WABC) at UWA is associated with the WA John de Laeter Centre of Mass Spectrometry and provides a range of analytical and interpretive services to researchers both within UWA and in the broader scientific community. The WABC currently operates three isotopic ratio mass spectrometers (IRMS) plus a considerable range of further analytical instrumentation (GC, HPLC, CE autoanalyser) routinely used in biogeochemical studies. A fourth IRMS (especially for small-sample $\delta^{13}C$ and $\delta^{18}O$ and carbonate analysis) is now being commissioned. Our IRMS are coupled with a variety of sample preparation modules to facilitate analysis of a broad range of sample matrices. Consequently, a wide range of applications of stable isotopes is supported by this facility.

Thermal Ionisation Mass Spectrometry (TIMS) Facility: The TIMS facility at Curtin incorporates a Thermo Finnegan Triton™ and a VG 354 multicollector mass spectrometer. The Triton is equipped with a 21-sample turret and 9 faraday cups, enabling a precision of 0.001% on isotopic ratios. As well as geological applications within the broad field of isotope geochronology (Re/Os, U/ Pb, Pb/Pb, Sm/Nd, Rb/Sr) the TIMS instruments can be applied to a variety of subject areas involving isotope fingerprinting, such as mantle geodynamics, forensics and the environmental impact of human activities. The TIMS instruments are also widely used in chemical metrology for the calibration of isotopic standards, and the calculation of isotopic abundances and atomic weights.

AuScope GeoHistory and (U-Th)/He Facility: The laboratory at Curtin hosts the prototype of the *Alphachron*™ automated helium microanalysis instrument now marketed by Australian Scientific Instruments in Canberra. (U-Th)/He thermochronology involves the measurement of ^{4}He generated by the radioactive decay of U and Th in minerals. Helium is an inert gas that is quantitatively retained by minerals at low temperature, but is gradually lost from the mineral lattice by diffusion at elevated temperatures. Some minerals are more retentive to helium than others (e.g. zircon = 200 °C vs apatite = 75 °C), a unique characteristic that, when integrated with other techniques such as U-Th-Pb and Ar-Ar dating, can be used to produce complete time-temperature histories through a temperature interval from 900 °C to 20 °C. The JDLC (U-Th)/He Facility provides thermal-history analysis of metallogenic and petroleum systems by integrating several age-dating capabilities along with 4D thermal modelling. The Facility is also involved in fundamental collaborative research in the fields of orogenic tectonics, volcanology and quantitative geomorphology. The facility has grown in 2012-13 to integrate a new *Alphachron*™ machine coupled to a RESOlution Excimer laser + Agilent 7700 mass spectrometer. This "RESOchron" instrument enables the development of *in-situ* U-Pb and (U-Th)/He dating on single crystals of U-bearing minerals and immensely increases our application potential. In addition, laser ablation trace element analysis and U-Pb geochronology is now routinely undertaken in this facility, supporting industry, government and University projects.



Above: Installation of the ELA-ICP-MS instruments in the AuScope AGOS GeoHistory Facility at Curtin University. Left to right: Fred Fryer (Agilent), Brad McDonald, Noreen Evans, Brent McInnes, Mike Hamel (Resonetics).

K-Ar Geochronology Facility: The K-Ar facility utilises the following instrumentation and techniques:

- VG3600 noble gas mass spectrometer
- Heine double vacuum resistance furnace
- Clay mineral separation laboratory utilising cryogenic disaggregation of rock samples
- XRD, SEM, TEM, particle size analysis for clay characterisation
- Vacuum encapsulation station for Ar-Ar dating of ultrafine samples
- Clays – illite: Dating the timing of diagenetic and deformation events
- Fault gouge dating (illite) – earthquake and hazard assessment

selFRAG: The purchase of a new selFrag installation, similar to the one at the Macquarie node, is being negotiated with Curtin's administration. A lab is being prepared, and a technician is being sought. The instrument will be available to CCFS staff.

ARC LIEF success: An AZtec Electron Backscatter Diffraction Facility for State-of-the-Art Quantitative Microstructural Analysis

The microstructures recorded in rocks and minerals record essential information relating to growth, deformation and mass transfer processes in Earth's crust and mantle, meteorites and moon. Quantification of these relationships is critical in interpreting the small-scale geochemical variations in minerals that underpin our understanding of large-scale tectonic and impact processes and the formation of ore deposits. In 2012 CCFS and JDLC researchers, led by Steve Reddy, were involved in a successful ARC LIEF application to develop a new state-of-the-art quantitative microstructural characterisation facility at Curtin University. This equipment will complement existing high-spatial resolution microanalytical equipment within Curtin's Electron Microscopy Facility, to provide a cutting-edge platform for pure and applied research in the Geosciences for the next decade.

WESTERN AUSTRALIA PALAEOMAGNETIC AND ROCK-MAGNETIC FACILITY

The Western Australia Palaeomagnetic and Rock-magnetic Facility was established at the University of Western Australia by CCFS CI Z.X. Li in 1990, funded by a UWA start-up grant to the late Professor Chris Powell. It was subsequently upgraded through an ARC Large Instrument Grant in 1993 to purchase a then state-of-the-art 2G Enterprises AC-SQUID cryogenic magnetometer and ancillary demagnetisation and rock magnetic instruments. It was upgraded again in 2006 into a regional facility, jointly operated by Curtin University, UWA and the Geological Survey of WA through an ARC LIEF grant with a 4k DC SQUID system plus a Variable Field Translation Balance (VFTB). A MFK-1FB kappabridge was installed in 2011.

The facility is one of the three similar laboratories in Australia, with major instruments including:

- 2G cryogenic magnetometer upgraded (LE0668377) to a 4K DC SQUID system
- MMTD80 (one) and MMTD18 (two) thermodemagnetisers
- Variable Field Translation Balance (VFTB)
- MFK-1FB kappabridge
- Bartington susceptibility meter MS2 with MS2W furnace

A wide range of research topics have been investigated using the facility, including reconstructing the configuration and drifting history of continents all over the world from the Precambrian to the present, analysing regional and local structures and deformation histories, dating sedimentary rocks and thermal/chemical (e.g. mineralisation) events, orienting rock cores from drill-holes, tracing ancient latitude changes, palaeoclimates, and recent environmental pollution.

Program 1: Regional and Global Tectonic Studies

Palaeomagnetism and rock magnetism are employed to study tectonic problems ranging from global to microscopic scales. The WA research group plays a leading role in a worldwide effort to establish the configuration and evolution of supercontinents Pangaea, Gondwanaland, Rodinia, and pre-Rodinia supercontinents.

Program 2: Ore genesis studies and geophysical exploration

We carried out a major research program on the timing and genesis of the giant iron ore deposits in the Pilbara region, and obtained a systematic set of petrophysical parameters for rock units in the region that enables more reliable interpretations of geophysical survey results (gravity and magnetic).

Program 3: Magnetic signatures in sediments as markers of environmental change

Sediments in suitable environments can incorporate a large number of environmental proxies. A major strength of environmental-magnetism analyses, such as magnetic susceptibility and saturated isothermal magnetism, is that they provide a rapid and non-destructive method of obtaining information on changes in palaeoclimate and environment of sedimentation. In addition, rock magnetism can be used for monitoring and tracing industrial pollution.

Program 4: Magnetostratigraphy

We are conducting major research programs in the Canning Basin and in East Timor, both linked to petroleum resources.

Industry interaction

INDUSTRY INTERACTION AND TECHNOLOGY TRANSFER ACTIVITIES

CCFS has a strategic goal to interact closely 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 industry and to the scientific community in several ways:

- collaborative industry-supported Honours, MSc and PhD projects
- short courses relevant to industry and government-sector users, designed to communicate and transfer new technologies, techniques and knowledge in the discipline areas relevant to CCFS
- 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 on a collaborative research basis with industry and government organisations, extending our industry interface
- use of consultancies and collaborative industry projects (through the commercial arms of the national universities) which employ and disseminate the technological and conceptual 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 continues to be available from GEMOC through Access MQ (http://www.gemoc.mq.edu.au/); the software is continually upgraded.
- collaborative relationships with technology manufacturers (more detail in the section on Technology Development)

The Centre for Exploration Targeting (CET) at UWA (http://www.cet.edu.au/industry-linkage) provides CCFS with a unique interface with a broad spectrum of mineral exploration companies and many CET activities (e.g. research projects, workshops and postgraduate short courses).

SUPPORT SOURCES

CCFS industry support includes:

- direct funding of research programs
- industry subscriptions (CET)
- "in kind" funding including field support (Australia and overseas), access to proprietary databases, sample collections, digital datasets and support for GIS platforms
- logistical support for fieldwork for postgraduate projects
- collaborative research programs through ARC Linkage Projects and the University External Collaborative Grants (e.g. Macquarie's Enterprise Grant Scheme) 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 by industry personnel for interaction and research
- ongoing informal provision of advice and formal input as members of the Advisory Board

ACTIVITIES IN 2012

- *TerraneChron*® studies (see *p. 81* or http://www.gemoc.mq.edu.au/TerraneChron.html) have continued uptake by a significant segment of the global mineral exploration industry. This methodology, currently unique to CCFS/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 of regional terranes (http://www.gemoc.mq.edu.au/TerraneChron.html). The unique extensive database (over 26,000 zircon U-Pb and Hf-isotope analyses) in the Macquarie laboratory allows unparalleled contextual information in the interpretations and reports provided to industry. Three major Industry Reports were completed for collaborative industry projects related to *TerraneChron*® at CCFS/GEMOC. This involved collaboration with five industry partners.
- An ARC Linkage project commenced, aimed at understanding the lithospheric architecture and mineral systems across the Neoarchean to Paleoproterozoic time periods, specifically comparing the Yilgarn Craton, Tanami Orogen, and western African craton. This project is based at CET but involves cross-node participation in CCFS.
- The Paleomagnetic group at Curtin and UWA were funded for a collaborative project with MMG (Minerals and Metal Group) to explore the spatiotemporal and tectonic controls on the location of clastic lead-zinc concentrations.
- The ARC Linkage Project titled "Global Lithosphere Architecture Mapping" (GLAM) was extended as the "LAMP"

(Lithosphere Architecture Mapping in Phanerozoic orogens) project through a Macquarie University Enterprise Grant with Minerals Targeting International as the external industry partner.

- A sub-licencing agreement was executed with Minerals Targeting International to accommodate Dr Graham Begg's role and access to GLAM IP (in relationship to Macquarie, BHP Billiton and the GLAM project) as Director of this company. Dr Begg spent significant research time at GEMOC through 2012 as part of the close collaborative working pattern for this project.
- On-going collaboration with BHP Billiton (Dr Kathy Ehrig) and University of Tasmania (Professor Vadim Kamenetsky) looking for evidence of younger magmatic events (e.g. Grenville-age events) in the magmatic evolution of the Gawler Craton, with a particular focus on the region around the giant Olympic Dam deposit.
- GEMOC's development of a methodology for analysis of trace elements in diamond continued to open 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. This work is continuing, with a focus on understanding the growth and chemical history of individual diamonds and diamond populations. It was supported in 2012 by CCFS Foundation Project 8 and MQ Research Associate funding for Dr Dan Howell.
- The GEMOC technique for dating the intrusion of kimberlites and lamproites using LAM-ICPMS U-Pb analysis of groundmass perovskite continued. This rapid, low-cost application has proven very attractive to the diamond exploration industry, and has led to several small collaborative projects; it was also applied in a 2012 ARC Linkage project sponsored by De Beers.
- The application of U-series isotopes to groundwater studies for both exploration and investigation of palaeoclimate continued in 2012. Collaboration with Heathgate Resources at the Beverley Uranium mine in South Australia is investigating these processes using a well-constrained aquifer system in both a mining and exploration context.
- Geodynamic modelling capabilities have now been extended to industry-related projects. An ongoing collaboration between GEMOC and Granite Power Ltd has led to important data exchange, and to a paper (*CCFS publication #165*) on the thermal and gravity structure of the Sydney Basin.
- A continuing collaborative relationship with New South Wales Geological Survey is applying *TerraneChron*® to investigations of the provenance of targeted sequences in the Paleozoic sedimentary terranes of eastern Australia, and the development of the Macquarie Arc.
- A collaborative research project continued in 2012 with the Geological Survey of Western Australia as a formal CCFS Foundation Project, 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.
- CET held their annual "Corporate Members Day", at The University Club of Western Australia on 10 December 2012, to showcase its research to its Corporate Members. The day provided members with the opportunity to discuss the innovative work of the CET, including its involvement in CCFS, and also gave the CCFS ECR and postgraduate students a chance to interact with industry (http://www.cet.edu.au/industry-linkage). A new feature of the day was the introduction of posters and poster presentations by CET staff and students showcasing the width and breadth of research. CET also launched a new Theme: "*Training and Knowledge Transfer*" as well as the exciting new plans for CET in 2013 and beyond.

- Industry visitors spent varying periods at Macquarie, Curtin and UWA (CET) in 2012 to discuss our research and technology development (see visitor list, *Appendix 5*). This face-to-face interaction has proved highly effective both for CCFS researchers and industry colleagues.
- DIATREEM (an AccessMQ Project) continued to provide LAM-ICPMS analyses of garnets and chromites to the diamond-exploration industry on a collaborative basis.
- CCFS publications, preprints and non-proprietary reports are available on request for industry libraries.
- CCFS participants were prominent in delivering keynote and invited talks and workshop modules at national and international industry peak conferences in 2012. See *Appendix 6* for abstract titles and *Appendix 4* for recent publications.

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


TerraneChron®
A new tool for regional exploration for minerals and petroleum
GEMOC
CCFS
✓ Based on zircon analyses
✓ Efficient and cost-effective
✓ Identifies regional tectonic events
✓ Dates magmatic episodes
✓ Fingerprints crust reworking and mantle input (fertility)
Contact: Elena Belousova, Bill Griffin or Suzanne O'Reilly
ARC CoE CCFS & GEMOC National Key Centre
Department of Earth and Planetary Sciences
Macquarie University, NSW 2109, Australia
MACQUARIE UNIVERSITY
www.gemoc.mq.edu.au/ www.ccfs.mq.edu.au/
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 sampling (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 (eg 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

CURRENT AND 2012 INDUSTRY-FUNDED COLLABORATIVE RESEARCH PROJECTS

These are brief descriptions of 2012 and current CCFS projects that have direct cash support from industry, with either formal ARC, internal University or State Government support 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 databases (with varied confidentiality considerations). Such projects are administered by the commercial arms of the relevant universities (e.g. Access MQ Limited, at Macquarie).

CCFS industry collaborative projects are designed to develop the strategic and applied aspects of the basic research programs, and are many are 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. Basic research strands translated to strategic applications include the use of geochemical data on crustal and mantle rocks and integration with tectonic analyses and large-scale datasets (including geophysical data) to understand the relationship between lithosphere domains and large-scale mineralisation. The use of 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 *p. 81*) 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 Paleomagnetic group at Curtin and UWA are exploring the spatiotemporal and tectonic controls on the location of clastic lead-zinc concentrations, based on their basic research focus of reconstructing continental configurations.

CCFS PROJECTS FUNDED BY INDUSTRY (INCLUDING ARC LINKAGE)

Lithospheric Architecture Mapping in Phanerozoic Orogens	***Supported by MQ Funds*** ***Industry Collaborator: Minerals Targeting International (PI G. Begg)*** ***CIs: Griffin, O'Reilly, Pearson, Belousova, Natapov*** ***Summary:*** The GEMOC Key Centre has developed the conceptual and technological tools required to map the architecture and evolution of the upper lithosphere (0-250 km depth) of cratons (the ancient nuclei of continents). Through two industry-funded programs we have mapped most of the world's cratons, making up ca 70% of Earth's surface. The remaining 30% consists of younger mobile belts, which hold many major ore deposits, but are much more complex and difficult to map. This pilot project is developing the additional tools required to map the mobile belts.
A novel approach to economic uranium deposit exploration and environmental studies	***Supported by ARC Linkage Project*** ***Industry Collaborator: Heathgate Resources*** ***CIs: Turner, Schaefer, McConachy*** ***Summary:*** The project proposes the use of a novel approach to prospecting 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.

Composition, structure and evolution of the lithospheric mantle beneath southern Africa: improving area selection criteria for diamond exploration	***Supported by ARC Linkage Project*** ***Industry Collaborator: De Beers*** ***CIs: Griffin, O'Reilly, Pearson*** ***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 ~250 km 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.
Four-dimensional lithospheric evolution and controls on mineral system distribution in Neoarchean to Paleoproterozoic terranes	***Supported by ARC Linkage Project*** ***Industry Collaborator: WA Department of Mines and Petroleum*** ***CIs: McCuaig, Barley, Fiorentini, Kemp, Belousova, Jessell, Hein, Begg, Tunjic, Bagas, Said*** ***Summary:*** This project will obtain a better understanding of the evolution, architecture and preservation of continents and their links to mineral deposits between 2.7 and 1.8 billion years ago (a period in Earth history that is endowed with mineral deposits and reflects a very important transition in the evolution of our planet and its biosphere-hydrosphere-atmosphere). By producing and integrating new high quality geophysical and geochemical data and making a major contribution to training students and researchers, the project aims to develop a superior model to help understand Earth's evolution and target areas of high prospectivity for important mineral deposits. The results will be applicable to exploration in Australia and world-wide.
Tectonic evolution and lode gold mineralisation in the Southern Cross district, Yilgarn Craton (Western Australia): a study of the Meso- to NeoArchean missing link	***Supported by ARC Linkage Project*** ***Industry Collaborators: Geological Survey of Western Australia*** ***CIs: Barley, McCuaig, Gessner, Miller, Thebaud, Tohver, Doublier, Romano, Wyche, Partner Organisations*** ***Summary:*** The aim of this project is to unravel the tectonic evolution of gold mineralisation in the Neoarchean 3.0 Ga to 2.6 Ga Youanmi Terrane as a base for a base for an improved metallogenic model for targeting orogenic gold deposits. The objectives of the study are to: 1) define the tectonic and metamorphic evolution of the Southern Cross granite-greenstone belt using a scale-integrated multidisciplinary approach. 2) Constrain the structural control on gold mineralisation events, their alteration style and timing of emplacement and integrate these into a coherent regional geodynamic event history. 3) Develop a 4D geodynamic model of the Southern Cross district and Youanmi Terrane. 4) Integrate the newly defined Southern Cross structural and mineralisation scheme into the broader context of the evolution of the Youanmi Terrane and Yilgarn Craton.
4D evolution of the Agnew gold field, Yilgarn Craton	***Supported by industry*** ***Industry Collaborator: Gold Fields Australia Pty Ltd*** ***CIs: Thebaud, McCuaig, Miller*** ***Summary:*** This project aims to assess the controls and significance of the variations in the gold systems in the Agnew region of Western Australia. The project is doing 4D reconstruction of the gold deposits by integrating the structural, metamorphic and alteration histories of the various deposits with new geochronology on key phases of the alteration history, structurally constrained intrusive rocks and host rock types. The aim is to use this knowledge in a mineral systems context to aid exploration targeting.

Multiscale dynamics of ore body formation

Supported by ARC Linkage Project
Industry Collaborators: Geocrust Pty Ltd, Geological Survey of Western Australia, Golden Phoenix International Pty Ltd, Mineral Mapping Pty Ltd, Primary Industries and Resources South Australia (PIRSA), Silver Swan Group Ltd, Swiss Federal Institute of Technology Zurich, Vearncombe & Associates Pty Ltd, Western Mining Services (Australia) Pty Ltd
CIs: Gessner, McCuaig, Hobbs, Cawood, Gorczyk, Connolly, Gerya, O'Neill, Lester
Summary: We develop a model for hydrothermal mineralising systems where processes are coupled from the scale of the Earth's lithosphere down to the scale of an ore body. The goal is to define measurable parameters that control the size of such systems and that can be used as mineral exploration criteria. We explore proposals that special lithospheric structural architectures associated with old craton margins are sites for influx of CO_2 into the lithosphere so that eventually these architectures control metal sources. At the mineralising site diagnostic features result from strong interaction between deformation, fluid flow, thermal transport and chemical reactions. This system is analysed using the principles of non-equilibrium thermodynamics.

Hydrothermal remobilisation of base metals and platinum group elements in magmatic nickel deposits

Supported by ARC Linkage Project
Industry Collaborator: Minerals and Energy Research Institute of Western Australia
CIs: Fiorentini, Brugger, Barnes, Perring
Summary: Magmatic nickel sulfide deposits are highly valuable but extremely challenging exploration targets, characteristically lacking the distinctive geochemical halos that allow small targets to be identified from sparse drilling. Consequently, undiscovered deposits are highly likely to exist at depth, even in well explored terranes. The remobilisation of metals during post-deposition hydrothermal alteration has the potential to result in large halos, whose recognition could revolutionise exploration for magmatic nickel deposits. In this ARC Linkage project, new field observations are currently being combined with innovative experiments aimed at answering critical questions about the mobility of these metals in H_2O-CO_2-H_2S-Cl fluids in order to develop new exploration models.

International links in CCFS

BACKGROUND

CCFS' International links provide leverage of intellectual and financial resources on a global scale, and an international network for postgraduate experience. International Partners provide the core of such collaborations. Other international activity includes funded projects and substantial collaborative programs with major exchange-visit programs in France, Norway, Germany, United Kingdom, New Zealand, Canada, USA, Taiwan, Italy, Spain, South Africa, South America, China, Brazil, Mexico, Japan, Thailand and Russia. The listing below is not exhaustive, but demonstrates the global network with targeted leaders in fields relevant to CCFS.

FUNDED COLLABORATIVE ACTIVITIES AND PROJECTS COMMENCED OR ONGOING IN 2012 INCLUDE:

Macquarie

- Sue O'Reilly, on behalf of Macquarie University, signed a formal agreement in November 2012, with the China University of Geosciences, (CUG) Wuhan establishing the "International University Consortium in Earth Science" (IUCES). The consortium was organised by the president of the CUG Wuhan, Professor Yanxin Wang, and consists of eleven universities from seven countries, all renowned in earth science research. Among the IUCES partners are the Lawrence Berkeley National Lab and Stanford University, the Université Pierre et Marie Curie (Paris), Karlsruhe Institute of Technology, the University of Queensland, Waterloo University (Canada), the University of Hong Kong, Moscow State University and the Russia National Mineral Resources University (Mining). *Signing pictured below.*

  The Consortium promotes research collaboration and exchange as well as undergraduate training exchange and joint postgraduate programs.

- The above IUCES agreement followed the formal MOU signed in 2011 with the China University of Geosciences (CUG), Wuhan, to promote collaborative research and exchange of postgraduate students. Professors Sue O'Reilly and Bill Griffin in their role as as Guest Professors at CUG (Wuhan) participated in a postgraduate seminar workshop in November 2012. The first cotutelle student (Mr Qing Xiong) continued at GEMOC/CCFS in October 2011, and Dr Huayun Tang was awarded a 12-month fellowship by the China Scholarship Council for research at Macquarie. During 2013 ongoing research continued in collaboration with Professor Jianping Zheng and his group, and with seismologist Professor Yinhe Luo (e.g. *see CCFS publication #18)*. Areas of geochemical research include the evolution of the lithosphere beneath several parts of China, crustal/mantle evolution in the North China Block, the Yangtze Block and southeastern China, the UHP metamorphism of Dabie-Sulu peridotites and ultramafic rocks and ophiolites in Tibet. Geophysical research includes shallow and deep seismology in western and southeastern China and Tibet.

- Professors Sue O'Reilly and Bill Griffin were formal guests at the 60th Anniversary of the founding of the China University of Geosciences, Wuhan. Professor O'Reilly gave the formal speech representing both Macquarie University and IUCES (the International University Consortium in Earth Sciences)

Fireworks and fanfare as over 10,000 people celebrate the 60^{th} Anniversary of the founding of the China University of Geosciences, Wuhan. Below: Professors Bill Griffin and Sue O'Reilly after Sue delivered a speech on behalf of both Macquarie University and the IUCES.

to an audience of over 10,000. The ceremony ended with fireworks and the release of hundreds of doves.

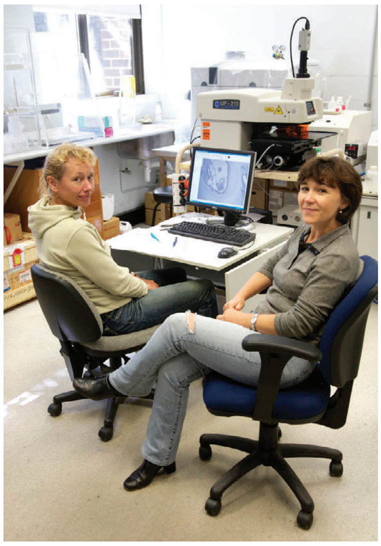
- Following the signing of a formal MOU in 2011 with the Institute of Geology and Geophysics (China Academy of Science, Beijing), collaboration expanded in 2012 with exchange of personnel, and the continuing cotutelle PhD project of Ms Yuya Gao, with joint access to the complementary analytical equipment at each institution. Dr Jin-Xiang Huang (TARDIS-E Project) has been undertaking development of standards for the O-isotope analysis of high-Cr garnets on the Cameca Ion probes (CMCA, UWA) with colleagues at IGG. Collaboration on technology development remains a focus, capitalising on complementary strengths of each institution.
- A formal MOU with the University of Science and Technology, Hefei, to promote collaborative research and postgraduate joint projects was signed following a visit from 10 researchers led by Professor Yongfei Zheng.
- Professor Bill Griffin flew to New Caledonia at the invitation of SLN Doniabo, the French company that mines the ophiolitic laterites of the island to extract Ni. The purpose of the visit was to advise the company and the BRGM on the poitential to expand the metallurgical processes to produce Scandium. A project proposal involving a collaboration with French synchrotron researchers has been submitted to the company and is under evaluation.
- Trace elements and fluids in diamonds and relevance to mantle fluids and processes; continued in collaboration with Professor Oded Navon (Hebrew University, Israel), Professor Thomas Stachel (Edmonton, Canada) and Dr Jeff Harris (University of Glasgow, UK). This was originally funded by an ARC Discovery Project, which was relinquished, with the funding now provided from a CCFS allocation. This includes the PhD project of Ms Ekaterina Rubanova. Dr Zdislav Spetsius (Mirny, Siberia) visited CCFS/GEMOC in January-February 2012 as an external advisor to this PhD, and for analytical work connected with the links between eclogites, metasomatism and diamonds.
- 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 Minerals Targeting International, BHP Billiton and Professor Steve Grand (University of Texas at Austin).
- Collaboration continued with Professor Massimo Coltorti and Dr Costanza Bonadiman from the University of Ferrara, starting a new project on the nature of the mantle beneath Sardinia.
- 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 Institute for Tibetan Plateau Research, Beijing.

Researchers from the University of Science and Technology (USTC), Hefei with Professor Bill Griffin. Behind, Professor Yongfei Zheng (USTC).

- The nature of the lithosphere in Mongolia, Vietnam and Russia, with Dr Kuo-Lung Wang (Institute of Earth Sciences, Academia Sinica, Taiwan).
- Development of methodology for lithium-isotope signatures in ultramafic and mafic rocks continued with Dr Mei-Fei Chu (National University of Taiwan).

Dr Hao-Yang Lee and Dr Te-Hsien Lin from National Taiwan University, with Dr Mei-Fei Chu, Professor Sue O'Reilly and Yuya Gao.

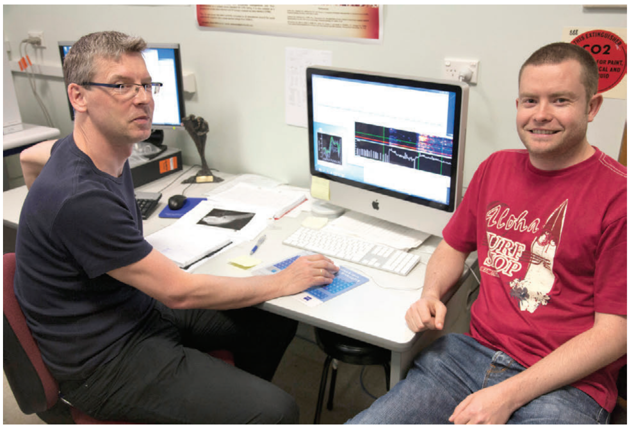
- Collaboration with colleagues at the University of Jean Monnet, St Etienne, including Professor Jean-Yves Cottin, Dr Bertrand Moine and Dr Marie-Christine Gerbe continued. A formal agreement between the two universities includes PhD exchange, academic exchange and research collaboration relevant to the nature of the lithosphere in the Kerguelen Archipelago, Crozet Islands and the Hoggar region of Algeria.
- A cotutelle agreement was signed with Toulouse University, and Mr Romain Tilhac commences a joint PhD at Macquarie University in early 2013, with a project titled "*Peridotite massifs from the north-western Iberia: Origin and mechanisms for pyroxenite abundance in a supra-subduction context*".
- Collaboration with colleagues at the University of Montpellier continued with projects on the mantle budget of platinum group elements, microstructures of meteorites and mantle rocks, and ophiolites. A collaboration funded by the DIISR Grant "Probing the composition of the early Solar System and planetary evolution processes" was completed as planned, but expanded to include collaboration with Professor David Mainprice on a project related to the microstructure of eclogite xenoliths.
- 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). Cotutelle PhD student Yao Yu from Nanjing undertook research at CCFS/GEMOC and Nanjing University, to carry out further FTIR studies of water in mantle-derived xenoliths.



- A new collaborative research project was initiated with the University of Witwatersrand, South Africa *(Dr Marina Yudovskaya, pictured right with Elena Belousova)*. The aims of this study are (1) to place further constraints on osmium-isotope signatures of the mantle sources for Os-rich alloy grains from the Bushveld Complex and (2) to look at the crustal evolution of the Complex using the U-Pb and Lu-Hf isotope systematics of zircons from ultramafic rocks as well as from felsic rocks in the roof of the Bushveld Complex (felsite, granophyre and young granitic veins).
- Ongoing collaboration with Alfred Kröner (University of Mainz, Germany) is focused on the continental growth history of the Central Asian Orogenic Belt (CAOB). The main outcome of this study is that that the production of mantle-derived or juvenile continental crust during the accretionary history of the CAOB has been grossly overestimated. Two papers have been accepted for publications in Gondwana Research and the results were also presented during the Workshop on "Geodynamic Evolution of the Central Asian Orogenic Belt" in St. Petersburg, Russia, May 25-27, 2012.

- Continuing collaboration with Professors Carlos Villaseca *(pictured right)* from the Complutense University of Madrid, Spain to provide further insights into the age, nature and composition of the lower continental crust in central Spain. The initial outcomes of this collaborative project are presented by Villaseca et al. (2012) in *Lithos* reporting "*Recycled metaigneous crustal sources for S- and I-type Variscan granitoids from the Spanish Central System batholith: Constraints from Hf isotope zircon composition*".

- Collaborative project continued with Dr Irina Nedosekova, Institute of Geology and Geochemistry, Urals Division of the Russian Academy of Sciences to investigate the genesis and evolution of the of the Ilmeny-Vishnevogorsky carbonatites of the Ural Mountains, Russia. The new integrated results on trace-element compositions and Rb-Sr, Sm-Nd, U-Pb, Lu-Hf isotope data were presented during the 34th International Geological Congress in Brisbane, August 5-10, 2012 and published in *Mineralogy and Petrology* in 2013.
- Professor Frank Brenker *(pictured below (left) with Dan Howell)* from the Institute of Geosciences, Goethe University (Frankfurt) visited CCFS in March to work with Dr Dan Howell on a set of unusual diamonds that carry



mineral inclusions from depths of 300 - 660 km below the surface. The diamonds were cut in parallel-sided plates and polished, using the diamond preparation facility. Cathodoluminescence imaging, infrared mapping and laser-ablation analyses were used to investigate the growth, deformation and impurity contents of these diamonds. Once Frank returned to Frankfurt, he began a novel ion beam-based analysis on the same plates. Early indications are that the results are going to be very interesting.
- 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 paleorift-related ultramafic-mafic intrusions of the Noril'sk area (northern Siberia, Russia), including economic and subeconomic PGE (platinum-group element)-Cu-Ni sulfide deposits; now published in *Lithos* and *Russian Geology and Geophysics*; (2) analysis of Os-(Ir-Ru) alloy grains in 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 the Witwatersrand grains) represent the oldest known terrestrial platinum-group minerals.
- Studies on the geochemical signatures of Mesozoic granites as indicators of geodynamic processes in southeastern China were undertaken with Professor Jinhai Yu (collaborative project with Nanjing University) and included a research visit by PhD student, Ms Qian Liu (*Research highlight p. 43*).
- Studies continued with Dr Rendeng Shi (Institute of Tibetan Plateau Research, China Academy of Sciences, Beijing) on the age and origin of platinum group alloy phases in podiform chromitites in ophiolites from Tibet *(CCFS publications #190, 239)*.

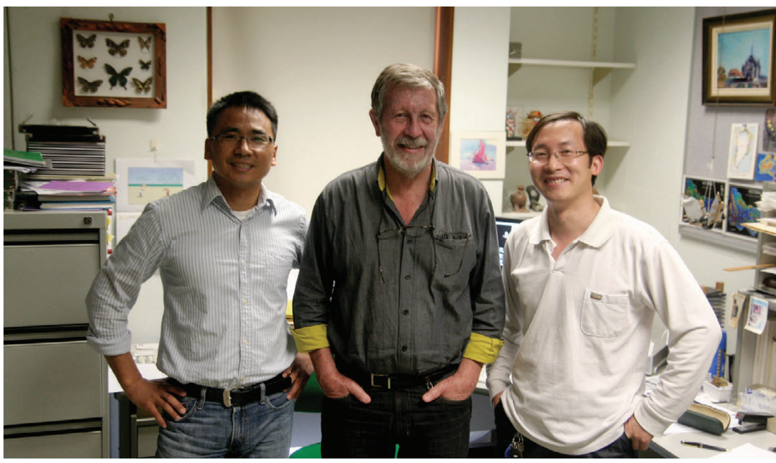
Professor Jianping Zheng (Right) with Professor Sue O'Reilly and Bill Griffin as they listen to presentations by PhD students at China University of Geosciences in Wuhan.

- *TerraneChron*® analysis of Proterozoic terrains in Africa, North America and Europe, with several mineral-exploration companies.
- GEMOC continued relationships with the newly established International Precambrian Research Centre of China (IPRCC); Bill Griffin is on the Board and involved in organising the 2013 meeting in Beijing in October.
- Formal visits to Chinese institutions strengthened or initiated collaborative research projects and agreements: China Academy of Sciences, Geology and Geochemical Institute and Tibet Institute, CAS Beijing; China University of Geosciences (Beijing, Wuhan). A new 5-year research project with Nanjing University was funded.

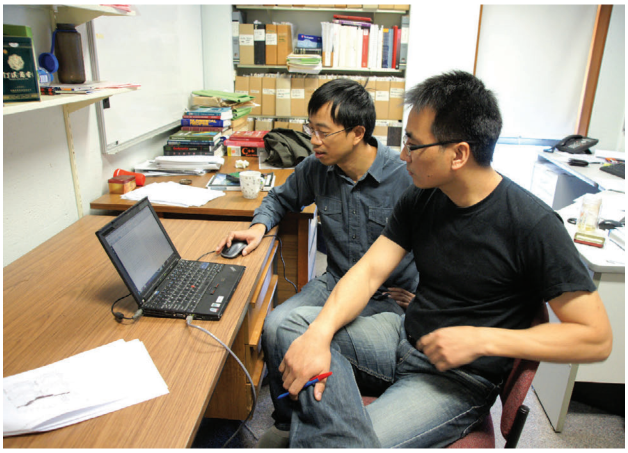
Workshop at the Institute for Tibetan Plateau Research, China Academy of Sciences, Beijing, with leader Dr Rendeng Shi on right.

- Collaboration continued with Dr Monica Escayola (Geological Survey of Canada) on the Os-isotope compositions of sulfides and alloys from ultramafic complexes in the Yukon.
- Collaboration continued with Professor Fernando Gervilla (University of Granada), Dr Carlos J. Garrido (University of Granada, Spain), Dr Isabel Fanlo (University of Zaragoza, Spain), Dr Joaquin A. Proenza (University of Barcelona) and Dr Antoni Camprubí (National University of Mexico) on the origins of chromitite deposits in ophiolites, including Os-isotope analysis of platinum group minerals.
- Collaboration continued with Dr Vlad Malkovets (Novosibisrk, currently Okayama University, Misasa, Japan) on the origins and modification of the lithospheric mantle beneath cratonic areas, using the compositions (including Os-isotope compositions) of sulfide phases included in mantle-derived minerals.
- Collaboration continued with Professor Csaba Szabo, investigating sulfide phases in xenoliths from around the Pannonian Basin.
- Dr Juan Carlos Afonso continued collaborating with Professors Ivone Jimenez-Munt, M. Fernandez, J. Verges and D. Garcia-Castellanos from Institute of Earth Sciences 'Jaume Almera', CSIC, Barcelona, Spain on a project "*Characterisation of the lithospheric mantle beneath the Alpine orogenic belt from numerical modelling: a comparison between Atlas, Tibet, and Zagros*" funded by the National Research Council of Spain.
- Dr J.C. Afonso collaborated with Professor Alan Jones and Dr J. Fullea from the Dublin Inst. for Advanced Studies (Ireland) on the characterisation of the lithospheric mantle beneath Ireland, funded by IRETHERM (Science Foundation Ireland).
- Dr J.C. Afonso collaborated with Professors Dave Eaton (Univ. of Calgary, Canada) and Jeroen Tromp (Princeton University, USA) on the synthetic computation of receiver functions and waveforms using a combination of the two software platforms SPECFEM3D and LITMOD3D. The project is funded by the Canadian Research Council.
- Dr J.C. Afonso collaborated with Dr Max Tirone (Bochum University, Germany) and Professors Jibamitra Ganguly (University of Arizona, USA) and Paul Asimov (Caltech, USA) on the set up of thermodynamic benchmarks for internally consistent thermodynamic databases for mantle minerals.
- Dr J.C. Afonso collaborated with Professors James Connolly (ETH Zurich), Alan Jones (DIAS), W.L. Griffin, S.Y. O'Reilly, and Dr Y. Yang on the development of 3D multiobservable probabilistic inversion methods for the thermochemical structure of the lithosphere and sublithospheric upper mantle. This project is funded by ARC DP project 120102372.
- Dr J.C. Afonso collaborated with Professor David Pedreira on the characterisation of the lithospheric mantle across the Pyrenees. The project is funded by the Spanish Research Council.
- Professor Alan Jones visited MQ in October to collaborate with Dr Afonso on the integration of MT inversion methods into LitMod software.
- Professor Manel Fernandez (CSIC, Barcelona) visited MQ to work with Dr Afonso on the application of LitMod2D to study the lithospheric structure of several mountain chains in Europe and Asia.
- PhD candidate Lavinia Tunini (Spain) visited MQ to work with Dr Afonso on different aspects of thermal modelling of the lithosphere.
- Dr Craig O'Neill continued collaborations with Adrian Lenardic (Rice University) and Shijie Zhong (University of Colorado, Boulder) as part of the Flat Subduction Geodynamics CCFS project (Two-phase flow within Earth's mantle: modelling, imaging and application to flat subduction settings).

- Professor Yinhe Luo *(pictured above right with Yingjie)* from China University of Geosciences at Wuhan visited CCFS/GEMOC from July 23 to September 29, 2012 working with Dr Yingjie Yang on a project "*Imaging crustal anisotropy of the Dabie Orogenic Belt using ambient noise tomography*".
- Dr Yong Zheng *(pictured below)* from Institute of Geodesy and Geophysics of China Academy of Sciences, visited CCFS from October 11 to November 26 to work with Dr Yingjie Yang on a project "*Using two-plane wave tomography method to map the upper mantle structure of Tian Shan*".



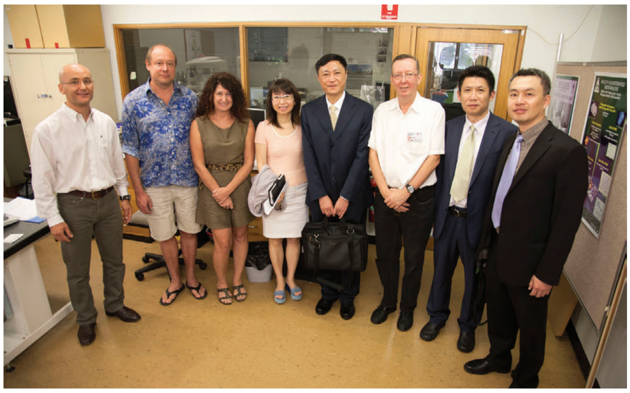
- Professor Jieyuan Ning and his postgraduate student Jiangang Han from Beijing University visited CCFS/GEMOC in March to work with Dr Yingjie Yang on *"Ambient noise tomography in northeast China"*.
- Dr Longquan Zhou *(pictured below left)* from China Earthquake administration visited CCFS from 14 -23 August for training on the ambient noise tomography method.



- 2012 saw the initiation of a collaborative program based around the ophiolites scattered across Turkey. The Turkish program is led by Professor Cahit Helvaci of Dokuz Eylül Üniversitesi in İzmir, Turkey, and recently appointed Associate Professor Mehmet Akbulat. Bill Griffin, Sue O'Reilly, José M. González-Jiménez and new PhD student Nicole McGowan Attended the IESCA conference in Izmir, and then joined Mehmet for a week's field work in the ophiolites surrounding Antalya in southern Turkey. The observations and samples collected will become part of Nicole's PhD project, while Jose will concentrate on Platinum Group Minerals in the chromitites. It is expected that Mehmet Akbulat will visit CCFS-Macquarie for an extended period in 2013.

Sue O'Reilly and Professor Cahit Helvachi in front of a famous mylonite zone in Turkey.

- In February 2012, Macquarie hosted a Vice President delegation from Jilin University, one of the universities key Chinese partners. A tour through the GEMOC/CCFS research laboratories was conducted to showcase Macquarie's research excellence. The visit was aimed at exploring future opportunities in joint PhD supervision, teaching and research collaboration



Delegate visit by representatives from Jilin University, February, 2012 (L-R) Karl Lukezic, Professor Simon Turner, Associate Professor Tracy Rushmer, Professor Jian Yang, Professor Zhenwu Wu (Vice President Jilin University), Associate Professor Norman Pearson, Professor Lian Hu (Dean of College of Computer Science, Jilin University), and Tiejun Bu (Deputy Director, Division of International Relations, Jilin University).

University of Western Australia

- Professor Cam McCuaig was invited by Professor Zeng-qian Hou, Director of the Institute of Geology, Chinese Academy of Geological Sciences (CAGS), to participate in the international project of IGCP/SIDA 600 "Metallogenesis of collisional orogens in the East Tethyside domain". This project (2011-2014) is jointly funded by UNESCO and the Swedish International Development Cooperation Agency (SIDA) and lead by Professor Hou. The Centre for Exploration Targeting (CET), UWA was invited to be a partner institute and Professor Marco Fiorentini, Dr Robert Loucks and Dr Yongjun Lu from CET are actively collaborating with CAGS under this IGCP framework. This collaboration between CET and CAGS involves multi-isotopic mapping in Tibet, experimental and field studies of adakites and associated porphyry Cu systems in Tibet, Pakistan and Iran.
- Researchers at UWA have an ongoing collaboration with Professor Robert Kerrich from University of Saskatchewan, Canada, which ranges from studying potassic intrusions in SW China and porphyry magmatism in the Philippines, to greenstone belts in the Yilgarn Craton and western Africa.
- Professor Cam McCuaig continued collaboration with Dr David Leach from the U.S. Geological Survey (USGS), leading to a paper "Banded Iron Formation to Iron Ore: Implications for the Evolution of Earth Environments".
- A new collaborative project between Dr David Wacey and Martin Brasier (Oxford University, UK) commenced, investigating the geology and biodiversity of the 1900 Ma Gunflint Formation of Canada, in particular sulfur-based metabolisms.

- Dr David Wacey commenced a collaborative project with Nicola McLoughlin, Harald Furnes, Ingunn Thorseth from University of Bergen, Norway, investigating the emergence of life on Earth 3+ billion years ago funded by the Bergen Research Foundation and the University of Bergen.
- Professor Mark Barley continued his collaborations with international leaders in multiple sulfur isotope geochemistry (James Farquar, Boz Wing, Shuhei Ono, Doug Rumble, Sue Golding, Jay Kaufman etc.) to determine how the range of methods fits together.
- Dr Matt Kilburn continued a collaboration begun in 2009 with Bernard Wood and Jon Wade (University of Oxford, UK), to investigate the isotopic fractionation of elements between metal and silicate melts at high pressures and temperatures.
- Within the framework of CCFS Foundation Project 2a, Professor Marco Fiorentini has an ongoing collaboration with scientists from the Geological Survey of Denmark and Greenland (Prof Jochen Kolb). In July-August 2012, students and researchers from the CET Magmatic Mineral System Theme carried out field work in south east Greenland. In November 2012, Marco Fiorentini was invited to be part of a small and selected panel of experts at the Greenland Nickel Workshop in Copenhagen to assess the prospectivity of nickel-sulfide magmatic systems in Greenland. Furthermore, in December 2012 Marco Fiorentini organised the hugely successful Greenland Day in Perth, a forum to outline the exploration potential of Greenland for a wide range of commodities.
- Within the framework of CCFS Foundation Project 2a and his Future Fellowship, Professor Marco Fiorentini has an ongoing collaboration with scientists from the University of Leoben (Austria). In particular, Marco Fiorentini and Marek Locmelis are currently working with Giorgio Garuti, Federica Zaccarini and Oskar Thalhammer to constrain the geochemical and isotopic architecture of nickel-sulfide mineralisation in the Ivrea-Verbano Zone of Italy.

Curtin University

- Dr Xuan-Ce Wang is collaborating with Dr Jie Li (Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China) on the petrogenesis of the Leiqiong flood basalts, with the aim of understanding the links between mantle plumes and subduction.
- Dr Sergei Pisarevsky is Paleomagnetic Coordinator on the International project "Reconstruction of supercontinents back to 2.7 Ga using the Large Igneous Province (LIP) record", in collaboration with Dr Richard Ernst (Carleton University, Canada) and Dr Wouter Bleeker (Geol. Surv. of Canada). He also is Team Leader in the IGCP-SIDA Project 599 "*The Changing Early Earth*", in collaboration with Dr Jaana Halla (University of Helsinki, Finland).
- Professor Zheng-Xiang Li has an ongoing collaborative project with a large group of researchers from around the world, including Dr D.A.D. Evans (Yale University), Dr S. Zhang (China University of Geosciences, Beijing) and the Nordic Paleomagnetic Working Group, aiming to establish the configuration and evolution of a pre-Rodinia supercontinent Nuna (Columbia) that probably existed between 1.8-1.4 Ga.
- Professor Zheng-Xiang Li's work on the Phanerozoic magmatism and tectonics of South China is part of an ongoing collaborative project with Dr X.H. Li (Chinese Academy of Sciences (CAS), Beijing), Dr W.X. Li (CAS, Guangzhou), Professor X. Xu (Nanjing University), and Professor S.L. Chung and Dr Q.H. Lo (National Taiwan University).
- Li has an ARC-CAS jointly-funded project on Mesozoic vertical tectonic movements in South China and subduction dynamics involves collaboration with Dr Y.G. Xu and Dr W.X. Li (CAS, Guangzhou), and Dr M. Danisik (Univ. of Waikato, NZ). A project on the tectonic evolution of Tibet and NW China is a collaboration with Dr Q. Wang (CAS, Guangzhou) and Dr C.L. Zhang (China Geological Survey, Nanjing). A newly funded NSF-China project to work on the development and evolution of the Red River Fault System involves a collaboration with Professor X.D. Jiang (China Ocean University).
- Professor Simon Wilde continues to work with Professors Jian-Bo Zhou and Xing-Zhou Zhang of Jilin University on the evolution of the NE China segment of the Central Asian Orogenic Belt. Collaboration with Professor Xiao-Long Huang from the Guangzhou Institute of Geochemistry has led to the characterisation of the TTG gneisses in the Taihua complex at the extreme south of the North China Craton. Professor Xiao-Long Huang spent 12 months at Curtin working with Simon, supported by the Chinese Science Council and the Chinese Academy of Sciences.
- Simon's ongoing collaboration with Dr Guochun Zhao of the University of Hong Kong has led to the recognition of two high-grade metamorphic events in rocks of the Huaian complex near the junction between two Proterozoic mobile belts: the Khondalite Belt and the Trans-North China Orogen. Collaborative work on the Central Indian Tectonic Zone with Professor Santanu Bhowmik of the Indian Institute of Technology at Kharagpur has focused on the application of U-Pb and Lu-Hf isotopic work on zircon and dating of monazite in high-grade metamorphic rocks.
- Simon's long-standing collaboration with Professors Fuyuan Wu and Jinhui Yang at the Institute of Geology and Geophysics at the Chinese Academy of Sciences (CAS) in Beijing has led to compilation of an extensive geochronological data base for the Chinese part of the Central Asian Orogenic Belt and continued investigation of the isotopic signature of magma mixing in the North China Craton. Ongoing collaboration with Profs Dunyi Liu and Yusheng Wan and their students at the Institute of Geology at the Chinese Academy of Geological Sciences (CAGS) in Beijing has recently focused on examining events that

straddle the Archean/Proterozoic boundary in the Western Block of the North China Craton. Collaboration with Dr Yuruo Shi of CAGS has concentrated on Precambrian rocks close to Beijing.

- Simon is also collaborating with Alfred Kröner from the University of Mainz on several projects, including the eclogites of the Escambray in Cuba, the Precambrian rocks along the Namibia-Angola border, and several studies in China in the Central Tectonic Zone and Western Block of the North China Craton
- A Tectonic History of South China in Nine Days – CCFS Joint Field Workshop with Chinese Partners - A biannual field workshop on tectonic history of South China was jointly conducted by CCFS CI Professor Zheng-Xiang Li of Curtin University, Professor Hanlin Chen and Dr Fengqi Zhang of Zhejiang University, and Professor Xian-Hua Li of the Chinese Academy of Sciences. It featured a one-day indoor lecture by Zheng-Xiang Li on the tectonic history of South China, followed by a 8-day field excursion from eastern Zhejiang Province to central Jiangxi Province *(pictured below)*.

GSWA

- Dr Klaus Gessner maintains international research collaboration links with a number of international researchers. Within the ARC Linkage Project "Multiscale Dynamics of orebody formation" he continues collaboration with Professor Jamie Connolly and Professor Taras Gerya (ETH, Zurich, Switzerland) on simulating the dynamics of lithosphere-scale fluid and melt transport.
- As part of the International Synchrotron Access Program-funded project on *"3D imaging and structural analysis of fault rocks from recent and ancient earthquakes*."
  Klaus has collaborated with Dr Virginia Toy (Otago University, Dunedin), and Dr Xianghui Xiao at the Advanced Photon Source's 2-BM-B beamline (Argonne National Laboratories, USA).
- Dr Klaus Gessner has collaborated with Prof Uwe Ring at Stockholm University and Dr Stuart Thomson at the University of Arizona (Tucson) on the tectonic evolution of Turkey.

UNSW

- Martin Van Kranendonk is tracing the geochemical origin and evolution of granitoid rocks in the Ancient Gneiss Complex of Swaziland, with the help of Professor Alfred Kroner (University of Mainz), Dr Elis Hoffman (University of Bonn) and Professor Carsten Munker (University of Cologne). He is collaborating with Dr Steven Shirey (Geophysical Lab., Washington, D.C.) on the onset of subduction on Earth at ca 3.0 Ga, and working with Professor John Valley, Professor Clark Johnson, and Dr K. Williford (University of Wisconsin) on collaborative projects including: *in-situ* investigation of kerogen of microfossils from the 2.3 Ga Turee Creek Group; Fe-isotope investigation of 2.75 Ga BIF from the Murchison Domain of the Yilgarn Craton; U-Th-Pb dating of jaspilite from the ca 3.5 Ga Marble Bar Chert Member of the Duffer Formation, Pilbara Craton; oxygen isotope studies of cherts from the Pilbara Craton.

Professor Zheng-Zhiang Li with participants on the CCFS joint field excursion to South China.

CCFS funding

Financial accounting for allocated funds is carried out at each node. MQ is responsible for the final reporting to ARC through the DVC Research, and is audited through the Macquarie University process.

STRATEGY FOR CCFS FUNDING LEVERAGE

ARC anticipates that Centres of Excellence will develop a profile of basic and strategic research outcomes that provides an attractor for leveraging resources. Active strategies within CCFS include:

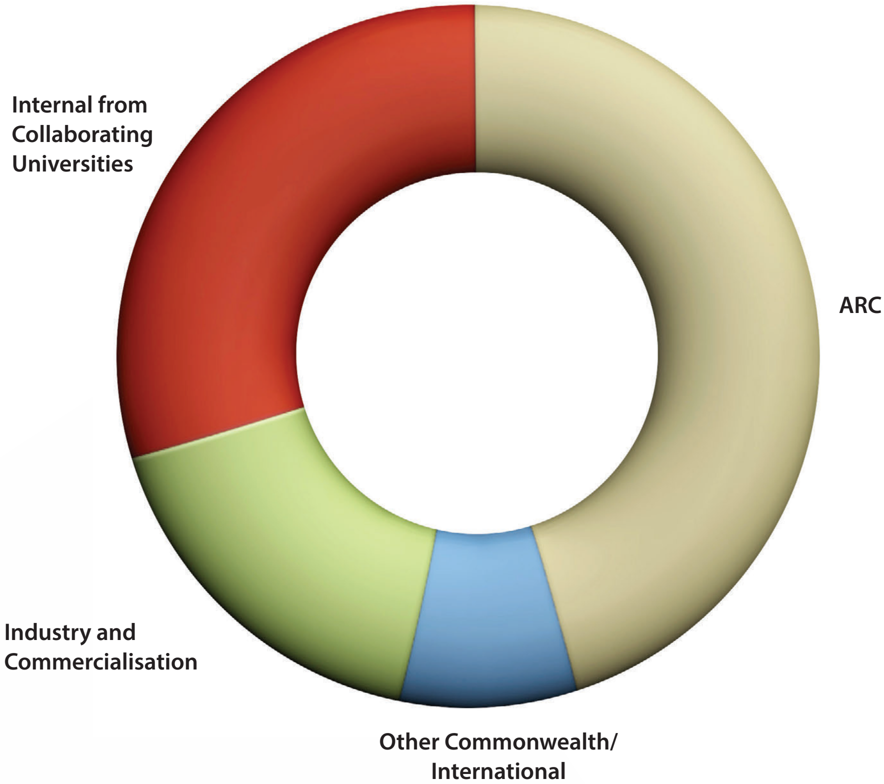
- Collaborative project building with industry partners
- Technology development to deliver new and improved methodologies and tools for enhanced research collaboration and for the exploration industry
- Diversification of the funding portfolio to include other Government schemes, industry and participation in international research programs
- Applications to relevant ARC funding schemes for projects not funded from the ARC CCFS allocation, but aligned with CCFS goals
- Applications to funding schemes for matching funds for new infrastructure purchases and partner co-investment
- Providing input into future NCRIS (especially AuScope) policies, using CCFS research concentration and leading directions to inform national priorities

This is an unaudited summary of 2012 income. A full, audited statement of detailed expenditure and income is prepared by Macquarie University. No in-kind support is included here.

CCFS INCOME 2012

	$K
ARC	
CoE CCFS	2,004
Discovery (including Fellowships), Linkage (Project and International)	2,511
LIEF	409
Other Commonwealth	
NCRIS	55
DIISR	50
GSWA	256
MERIWA, CSIRO, AINSE, NeCTAR	466
Industry and Commercialisation	
Collaborative research projects and commercial contracts (e.g. GLITTER) via Access MQ	234
Industry contributions to ARC Linkage and internal collaborative research projects	1,608
Internal from Collaborating Universities	
Internal Capital Equipment	232
Research Fellowships	116
Matching to other commonwealth/state	50
Matching to ARC schemes	1,758
Research grants	126
Postgraduate awards (MQ)	918
Postgraduate research grants	3
Infrastructure (RIBG)	33
Interest	37
Other	30
TOTAL	**$10,896**

INCOME SOURCES 2012



National Benefit

- Scientific innovation relevant to National Priority Areas

  Research Priority 1: An Environmentally Sustainable Australia

  Goal 1: Water – a Critical Resource

  Goal 2: Transforming existing industries

  Goal 6: Developing Deep Earth Resources

  Research Priority 3: Frontier Technologies for Building and Transforming Australian Industries

  Goal 1: Breakthrough Sciences

  Goal 2: Frontier Technologies

- Implementation of significant parts of the UNCOVER initiative set out in: "*Searching the deep earth: a vision for exploration geoscience in Australia*" published by the Australian Academy of Science (2012; http://www.science.org.au/policy/uncover.html/). CCFS addresses initiatives (ii) – (iii): investigating Australia's lithospheric architecture, 4D geodynamic and metallogenic evolution, and distal footprints of ore deposits.
- 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)

Sue O'Reilly and Bill Griffin with colleagues from the China University of Geosciences, Wuhan after the main ceremony celebrating the University's 60th Anniversary.

Appendix 1: Foundation Project summaries, progress in 2012 and plans for 2013

1. THE TARDIS PROJECT: TRACKING ANCIENT RESIDUES DISTRIBUTED IN THE SILICATE EARTH

Themes 2 and 3, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

Aims: Platinum Group Minerals in chromite-rich rocks from ophiolites and komatiites can provide a faithful and robust record of the osmium-isotope composition of Earth's convecting mantle through time; this record contains vital information on Earth's origins and the overall evolution of its core-mantle system. In this project an international team of leading mantle researchers will use a unique combination of geochemical and isotopic techniques to decode this information and provide new insights into deep-Earth processes. Specific objectives are:

- To define the initial composition and long-term evolution of Earth's convecting mantle, using the isotopic systematics of platinum-group minerals and sulfides from ophiolites and komatiites
- To understand the origins of ophiolitic chromitites and the processes that concentrate the platinum group elements in these and other samples of the convective mantle to help unravel Earth's geochemical evolution
- To understand the Os-isotope heterogeneity observed in samples from the convective mantle, and how this heterogeneity may reflect major events in Earth's evolution
- To evaluate the evidence for the preservation of large volumes of ancient continental mantle within the ocean basins

PROGRESS DURING 2012

1. Significant advances in understanding Ultra-High-Pressure (UHP) systems – our deepest crust/mantle sequences:

- Zircon data from gneisses and their enclosed peridotites in western Norway (now a classic UHP terrain) demonstrated that the gneisses were derived from the depleted mantle ca 1700 Ma ago, and show no sign of older components in their sources; the peridotites, in contrast, proved to be Archean. This confirmed that the peridotites represent pieces of the subcontinental mantle beneath Greenland, picked up by the crustal slab when it was subducted to more than 200 km depth in the Caledonian continental collision. (Beyer et al, *CCFS publication #38)*
- Combined regional geology and isotopic data in the Qaidam area of North China were used to develop a model of an eclogitic "sinker" as the driving force that pulled down the continental slab, before breaking off to allow the slab to rebound to the surface. (Qiong et al. *CCFS publication #136;* see *Research highlight pp. 57-58)*
- In 2013 this model will be extended to understand deep continental subduction at major collision zones, and to initiate a major program of research on the UHP peridotites ("ophiolites"?) along the large suture zones across Tibet.

2. Chromitites and the genesis of ophiolites:

We made major breakthroughs in understanding the origins of Platinum Group Minerals (PGM) and the generation of chromitites in ophiolites.

- The demonstration of Os-isotope heterogeneity at the single-grain scale in PGM assemblages implies that chromitites form by the mixing of many individual batches of melt, derived from small isotopically distinct volumes in the convecting mantle. This discovery immediately rules out several of the previous models for chromitite generation. *(CCFS publications #13, 42, 65, 71, 176, 178; see Research highlight p. 37)*

Chromite in dunite outcrop from Turkey fieldtrip.

- Os isotopes of PGMs also demonstrate that many ophiolites represent ancient continental lithosphere, rather than oceanic or convecting mantle. Whole-rock Os-isotope data on the Luobusa peridotites/chromitites in Tibet, which contain evidence of subduction to depths over 400 km, show that this mantle fragment is at least 3.4 Ga old. *(CCFS publications #190, 239)*
- A synthesis of Os-isotope data from mantle-derived xenoliths, peridotite massifs and ophiolites from central Spain demonstrated that the Mediterranean is underlain by a collection of ancient mantle fragments, with ages back into the Archean, while the surrounding areas of Europe, North Africa and the near East are underlain by SCLM that is not older than 1.8 Ga. An article (González-Jiménez et al.) will appear in Geology in 2013. (González-Jiménez et al., *CCFS publication #234)*

3. Deep-crustal magmatic processes:

- Studies of ultramafic rocks exposed in Caledonian nappes in N. Norway demonstrated the existence of ultra-high-T (1600-1700 °C) dunite magmas, which caused extensive melting and assimilation of the deep-crustal rocks they intruded. This may be a relatively common phenomenon in the deep crust, and can explain many aspects of the chemistry of other ultramafic magmas such as komatiites. Dynamic modelling showed that such magmas could be derived from rapidly ascending diapirs of previously depleted/subducted mantle. *(CCFS publication #237;* see *Research highlight pp. 40-41)*
- Detailed work on the 3.1 Ga Mpuluzi and related granites, a gigantic sill complex in Swaziland, provided new insights into the generation of the great Archean granite "blooms". We confirmed that the entire volume of the bloom was derived from only slightly older crust (ca 3.5 Ga) and was emplaced over about 50 million years (see *Research highlight p. 50).* This magmatism stabilised the craton for the next billion years; modelling in 2013 will explore melting models and their effects on rheology. (Also links with part of Foundation Project 3 and the PhD project of Rosanna Murphy)

4. Mantle eclogites: our deepest cratonic samples:

- A multidimensional study showed that eclogites from kimberlite pipes record a wide range of metasomatic processes: 95% of the samples have suffered total makeovers of their major-element, trace-element and isotopic (Sr, Nd, Hf, O, C) compositions, including the deposition of diamonds. *(CCFS publications #15, 41)*
- Previous models for the origins of mantle eclogites, involving subduction of crustal materials, are based on faulty premises about their geochemistry, and are thus invalid. However, our studies have demonstrated that the eclogites can tell us a great deal about magmatic and fluid-related processes in the deepest parts of the cratonic mantle. *(CCFS publications #15, 41;* see *Research highlight pp. 34-35)*

Short overviews:

- A study of the residence and mobility of gold in the mantle showed that sulfides are the main host for gold (see *Research highlight pp. 60-61)*
- A study of the microstructure of mantle-derived samples has been commenced, integrating water content, composition and modelling with geophysical data to better understand lithospheric structure (see *Dr Takako Satsukawa, p. 11)*

The projects of PhD students Qing Xiong, Ed Saunders and Nicole McGowan were an integral part of this research.

José María González-Jiménez, Mehmet Akbulat (Dokuz Eylül Üniversitesi in İzmir), and Nicole McGowan, hunting down ophiolites in Turkey.

This project was closely involved in 2012 with the CCFS Technology Development projects including ion-microprobe method development (see the CMCA Report), and the refinement of Mg-isotopic analysis in the GAU at Macquarie.

OUTPUTS

Publications:

CCFS publications (**2012**) #**13**, **15**, **31**, **38**, **42**, 65, 71, **136**, **176**, **178**, **190**, 234, **239**.
See *Research highlight pp. 40-41.*

Abstracts:

30 international conference presentations

AIMS AND WORK PLAN FOR 2013

The main aims of the project remain unchanged for 2013, but we have added a focus on the UHP "ophiolites". We will collaborate with Professors Yang and Robinson, and Dr Shi, on further detailed studies of the field relations, mineralogy and geochemistry of the UHP peridotites in Tibet. Bill Griffin and Jin-Xiang Huang will join Rendeng Shi for field work in Tibet in May, to get a first-hand look at these significant rocks. Further field work will be done in Turkey, and more extensive collections of ophiolite material will be provided by collaborators. The work on these will follow the template developed in 2011 and 2012. The chromite database will be expanded significantly, to test the synthesis achieved in 2012; this work will be prepared for publication and presentation in international fora.

Qing Xiong will continue studies of the Tibetan ophiolites, and Nicole McGowan will continue on her project on the ophiolites of Tibet, Spain and Turkey. Jin-Xiang Huang will carry out detailed studies on a new set of Type II eclogites provided by Prof D. Mainprice (Montpellier), and will work with Nicole on the development of techniques for the analysis of Mg-Fe isotopes in mantle rocks. She also will complete the development of standards for the SIMS analysis of O isotopes in mantle-derived Cr-bearing garnets, and use this to investigate metasomatic effects in deep-seated garnet peridotites.

2A. METAL SOURCES AND TRANSPORT MECHANISMS IN THE DEEP LITHOSPHERE

Theme 3, Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

This project is designed to (1) provide new knowledge of the character and behaviour of Earth fluids, such as silicate and sulfide melts, brines, vapours, hydrocarbons, supercritical fluids, in mantle rocks at the P-T conditions of the lower lithosphere and asthenosphere and (2) unravel the complex transport and concentration mechanisms of siderophile-chalcophile elements such as Ni, Cu and PGE in the deep lithosphere.

Context and rationale:

Despite the significance attributed to mantle-derived fluids as key elements in the transport and concentration of metals within the crust, we lack a robust understanding of the processes through which the mantle evolves and interacts with fluids at sub-crustal depths, in the lithospheric mantle and asthenosphere.

The rationale of this multi-scale integrated study is to address this void in our understanding through (1) designing a set of key experiments to evaluate the chemical behaviour of fluid systems at lithospheric mantle-asthenospheric conditions, and (2) parameterising and testing these experiments through the measurement of rock samples collected from two key areas: (a) the Ivrea-Verbano Zone in northern Italy and (b) the granulite facies terrains of South Eastern Greenland.

As well as representing direct exposure of continental lithospheric mantle rocks, these zones host unusual nickel sulfide deposits that offer rare insight into how metallogenic fluids behave at such depths. Most known world-class nickel sulfide deposits were emplaced far from their primary mantle metal sources, at the surface or in the uppermost levels of the lithosphere. The nickel sulfide systems of the Ivrea-Verbano Zone and in the granulite terrains of Eastern Greenland, however,

Figure 1. The impervious location of the Gula Nickel Mine, Ivrea-Verbano Zone, Italy.

were formed in the mid-to-lower crust and upper lithospheric mantle. Evaluation of these areas thus offers critical insight into the deeper behaviour of mantle-sourced metallogenic fluids that is not currently incorporated into deposit evolution and exploration models.

As a corollary to these two key research streams, the proposed study will also investigate the optimisation and integration of analytical techniques to constrain the behaviour of fluids and melts at relevant P-T conditions. This approach will provide improved insight into the meaning and significance of the geochemical signature of deep mineral systems, with a specific focus on the Nickel Mineral System. Consequently, the experimental results from the proposed study will generate new parameters that can be integrated in the predictive modelling of metal reservoirs, contributing to improved exploration models and opening up new exploration search space for nickel sulfide systems in the deeper portions of the lithosphere.

Figure 2. Marek Locmelis emerges from the wet entrance to the Valmaggia Nickel Mine, Ivrea-Verbano Zone, Italy.

PROGRESS DURING 2012

Study on the Ivrea-Verbano Zone:

In 2012, two field seasons have been completed in May and September-October. The first sampling trip was in collaboration with researchers from Leoben University (Austria). The second trip mapped all available outcrops and identified areas of specific interest where more detailed structural work could be completed in 2013. It is crucial to emphasise that Prof Steve Reddy from Curtin University came along to the Ivrea-Verbano Zone on the second field trip. His visit was crucial to the understanding of the structural and geodynamic setting of the area. His presence in the field is part of the ongoing collaboration between researchers involved in Foundation Projects 2a and 2b. In addition, Olivier Vanderhaege (Prof at Universite de Nancy, France), Celia Guergouz (Masters Student, Universite de Nancy, France) and Nicholas Thebaud (CET, UWA) joined us in the field. Their input was crucial to understanding the geotectonic evolution of the IVZ: further work is planned with them in 2013.

Figure 3. Ellen Davies and Marek Locmelis in the Valmaggia Nickel Mine, Ivrea-Verbano Zone, Italy.

Electron microbe work on silicate and oxide phases from a wide range of locations was undertaken at Leoben. Laser ablation ICP-MS data of amphibole and phlogopite from several pipes in the Ivrea-Verbano Zone were generated in the GEMOC Geochemical Analytical Unit at Macquarie University. Preliminary data suggest that juvenile, carbonate-rich mantle water played an important role in the genesis of the pipes. It is argued that the mantle-derived metasomatic fluid not only carried metals such as nickel, iron and copper, but also increased the water activity, causing the parental rock to undergo partial melting. The melts then evolved into the volatile-rich, pipe-like intrusions that reached sulfide-saturation during their emplacement, thus forming the sulfide deposits that we see today.

Study of the Thrym Complex of Southeastern Greenland:

During 2012, fieldwork was carried out from the 26th of July to the 4th of September. During the fieldwork field relationships were documented in detail and 87 samples were collected. Of those samples the whole-rock geochemistry was determined for 66 samples. A database was constructed containing the data pertaining to the samples collected in both 2011 and 2012. Analysis of the geochemical data was carried out and a manuscript entitled "*The Archaean Thrym Complex of southeastern Greenland: Sulfide mineralisation in the lower crust.*" was drafted and will be submitted in early 2013.

Experimental study of the metal transport capacity of aqueous fluids in the mantle lithosphere:

In 2012, twelve high pressure and temperature experiments (at 0.5-3.0 GPa and 950-1100 °C) have been conducted to determine the partitioning of minor and trace elements (including chalcophile metals) between hydrous fluids, peridotite minerals and typical intraplate basanitic melts. Five experiments were also conducted under H_2O-undersaturated conditions on coexisting basanite and sulfide melts. The fluid/mineral/melt partitioning data, combined with previously obtained mineral/melt partition coefficients for the same basanite, provide information on the contrasting abilities of H_2O-fluids and silicate melts to transport metals and incompatible elements within the mantle lithosphere.

The successful experiments have resulted in a small but unique data set for H_2O-fluids in equilibrium with mantle phases. At 950-1100 °C and 2.0 GPa the fluids contain 15-25 wt. % of dissolved solute. The solutes are enriched in SiO_2 (56-66 wt. %), Al_2O_3, and alkalis (10.9-12.6 wt. % $Na_2O + K_2O$) but depleted in TiO_2, FeO, MgO and CaO relative to the basanite. Overall the transport capacities of H_2O-fluids within the upper mantle are distinctly different from those of silicate melts (Fig. 2). Alkalis, Pb and Ag are relatively enriched in the aqueous fluids, whereas most chalcophile and incompatible elements are not.

OUTPUTS

Publications:

CCFS publication #277

Abstracts:

M. Locmelis, J. Adam, F. Zaccarini, M.L. Fiorentini, T.A. Rushmer, G. Garuti, S. Turner, P. Kollegger and E. Davies, 2012. Metal transport between the upper mantle and the lower crust. American Geophysical Union's 45th Annual Fall Meeting, San Francisco, California, 3–7 December 2012.

M.L. Fiorentini, L. Bagas, J. Owen, B. Lally, B. M. Stensgaard, J. Kolb, N. Thebaud, 2012. A joint CET-GEUS-BMP research project: Nickel mineral systems in Archaean ultramafic rocks in South-East Greenland. Greenland Day, Perth, Western Australia, 4 December 2012.

M.L. Fiorentini, B. M. Stensgaard, J. Kolb, L. Bagas, 2012. The potential for nickel mineralisation in entire Greenland. Greenland Day, Perth, Western Australia, 4 December 2012.

AIMS AND WORK PLAN FOR 2013

Ivrea-Verbano Zone Studies:

In 2013, two more extended field seasons are planned in August and September 2013. The focus will be on the sites that were identified during the sampling campaigns in 2012. In terms of analytical work, mineral chemistry of all phases of interest will be completed. Modelling of the composition of the source region and primary melts that evolved to form nickel-sulfide mineralisation will be undertaken. More importantly, the study will integrate the data from the natural samples collected in the Ivrea-Verbano Zone with a series of hydrous high-pressure and high-temperature experiments to investigate the capacity of near-solidus melts and fluids to transport metals at lithospheric mantle-asthenospheric conditions.

Study of the Thrym Complex of Southeastern Greenland:

In 2013, selected samples of the felsic orthogneisses will be used for geochronological U/Pb zircon analysis in the SHRIMP. Representative samples of the ultramafic rocks will be characterised in petrography and detailed mineral chemistry in preparation for detailed metamorphic studies to be carried out in collaboration with Alfons Berger at University of Bern, Switzerland. A manuscript for the geochronology of the felsic orthogneisses and the stratigraphy of the Sehesteds Fjord section will be prepared. Stable isotope studies will be carried out on selected samples, both O and H for amphiboles and multiple sulfur isotopes.

Experimental study of the metal transport capacity of aqueous fluids in the mantle lithosphere:

The experiments experienced an unexpectedly high failure rate, partially due to equipment failure but also to the unfamiliar nature of some of the materials and experimental designs employed. However the lessons from the unsuccessful experiments in 2012 have helped in the design of future experiments and equipment acquisitions which should avoid these problems. A particular feature of the experimental approach adopted is that it avoids the use of fluid traps (including carbon spheres and fluid inclusions in solid minerals), such as are commonly employed in similar experiments. This allows the experimental run products to be unambiguously identified and analysed.

In 2012, particular difficulties were experienced with experiments on sulfide-enriched compositions (owing to the tendency of sulfur to attack the capsule materials). In 2013, this problem will be overcome by the use of gold capsules. The use of gold capsules will also allow the fluid-saturated experiments to be extended to include sulfide- and halide-enriched compositions. The effects of variations in fO_2 will also be examined.

2B. DYNAMICS OF EARTH'S MANTLE: ASSESSING THE RELATIVES ROLES OF DEFORMATION AND MAGMATISM

Theme 3, Earth's Evolution, contributing to understanding Earth's Architecture.

Understanding the evolution of continental and oceanic mantle in extensional environments is key to understanding plate tectonics. How and why divergence initiates in extensional zones, and how continental rifts evolve to oceanic accretion centres are poorly constrained processes, but fundamental to our understanding of the processes structuring the lithosphere. This project explores the upper mantle in rifting and ocean-continent transition environments. We will study several localities, such as the East-African Rift (Marsabit, Kenya) and Platta massif (Alps) to find how the deformation has been initiated, localised and evolved in such geological settings, and what are the structural and geochemical relationships with fluids. We will characterise the microstructures and the deformation mechanisms recorded by mantle minerals, such as olivine and pyroxenes, with EBSD technique. We will determine the evolution of the deformation related to the extensional settings.

PROGRESS DURING 2012

The study of the East-African Rift (Marsabit, Kenya) mantle xenoliths is now finalised with the submission of a paper to Tectonophysics. The microstructural study of high-strain mantle peridotite xenoliths from the East African rift in Kenya (Marsabit volcanic field) has been conducted to investigate lithospheric mantle deformation related to continental extension. The xenoliths are spinel peridotite xenoliths displaying a range of textures from porphyroclastic to ultramylonitic. Bulk rock fabric analysis of almost all samples indicates a dominant (001)[100] (E-type) slip system, with only one porphyroclastic sample showing the more classical (010)[100] (A-type) fabric. A weak E-type fabric is also present within the fine-grained matrix of the mylonitic and ultramylonitic peridotites. Weakening is probably the effect of dynamic recrystallisation, diffusion creep and grain boundary slip. Detailed inspection of the microtexture of individual olivine grains within the xenoliths indicates the operation of multiple slip systems A-, E-, to C-type even in a single sample. The individual olivine grains show that with increasing strain the dominant slip direction changes from [100] to [001].

This study confirms the activity of the E-type slip system in a rifting environment and provides the first evidence of [001] slip in such environments. The variability of the slip systems shows the heterogeneity of the deformation mechanisms, and probable heterogeneity of strain partitioning in the Marsabit mantle. The presence of highly deformed peridotite testifies to zones of intense deformation and strain localisation in the shallow lithospheric mantle, most likely associated with the decrease of pressure and temperature. In the Marsabit peridotite, the decompression and cooling from high-pressure/high-temperature to lower-pressure and temperature could be the major factor influencing the localisation of deformation and the change in the dominant slip direction in olivine. Our new results highlight that mantle recording exhumation in rift margin is deformed under an E-type regime and becomes more C-type when deformation is localised. The activation of these two slip systems in peridotite might be an indicator of the early stages of deformation in extensional rift margin setting.

A fieldwork season was done in late-June/early-July by Mary-Alix Kaczmarek and Steve Reddy in the Eastern Alps, Switzerland (Fig.1). The Platta and Totalp massifs have been visited because they represent a type example of a zone of exhumed continental mantle, and they offer a complete sequence of an ocean-continent transition (more details in *Research highlight p. 56-57*). Fieldwork in the upper mantle reveals a heterogeneous distribution of deformation within the peridotite sequence. The peridotite is more deformed in the upper part of the mantle sequence, and contains metre to centimetre high-temperature shear zones. The sampling done across the mantle sequence will permit a detailed study of the peridotite texture relative to its position in the sequence. A series of thin sections have been received in late 2012 and will be the base for 2013 work.

Figure 1. Mary-Alix Kaczmarek making structural measurements in the field.

OUTPUTS

Publications:

Kaczmarek, M.-A. and Reddy, S. Mantle deformation during rifting: Constraints from quantitative microstructural analysis of olivine from the East African Rift (Marsabit – Kenya). *Tectonophysics*. (Submitted)

Abstracts:

Kaczmarek, M.-A., 2012. The understanding of mantle shearing with EBSD. ACMM 22 /APMC 10 / ICONN 2012, Perth, 5-9 February.

Kaczmarek, M.-A and Reddy, S., 2012. Mantle deformation during rifting in East Africa (Marsabit - Kenya). IGC, Brisbane, 5-10 August.

AIMS AND WORK PLAN FOR 2013

In 2013, laboratory work on previously (2012) collected material in the Alps will be implemented. The first step is to undertake a detailed petrographical study of the samples to characterise the microstructures and parageneses in relation to their position in the mantle sequence. Then, selected samples will be mapped using EBSD (Electron Backscatter Diffraction) to characterise the preferred crystallographic orientation of minerals (CPO). The CPO will give an indication of the mechanisms that were activated during the exhumation of the mantle, to better understand the processes leading to localisation of deformation in ocean-continent transitions. In parallel, the chemical composition of the minerals measured using electron and ion microprobes will determine the chemical variability within the mantle sequence to study the percolation of fluid/melt during exhumation, and the relationship between chemistry, fluids and deformation.

The chemical composition of the minerals will be used to estimate temperatures, and to constrain the conditions that activate deformation mechanisms.

3. GENERATING AND STABILISING THE EARLIEST CONTINENTAL LITHOSPHERE - LARGE GRANITE BLOOMS

Theme 2, Earth's Evolution, contributing to understanding Earth's Architecture and Fluid Fluxes.

The project aims to understand the genesis of the earliest continental lithosphere, including the processes of fluid/melt extraction that stabilise, and thus preserve, Archean cratonic lithosphere. This will involve isotopic studies of zircons from ancient terrains and deep-crustal xenoliths worldwide, to further constrain the nature of the oldest preserved crust, and a continued search for the oldest mantle samples beneath cratonic areas. Targeted studies involving (1) a regional characterisation of the 3.1 Ga Mpuluzi batholith (Swaziland/RSA) and (2) a similar characterisation of the end-Archean granites of the North China Craton, will provide a basis for static and dynamic modelling of the rheology of the crust before, during and after melt extraction.

This project has close linkages with the research of Future Fellow Dr Elena Belousova. This will involve regional surveys (*TerraneChron®* approach) of zircons (U-Pb, Hf isotopes, O isotopes) from old continental areas, in an attempt to pick up the signatures of the oldest crust. The project also will study zircons from deep-crustal and mantle xenoliths in basaltic and kimberlitic rocks, to look deeper into the lithosphere. This work will be integrated with Os-isotope analysis of sulfides in the mantle xenoliths (see *TARDIS-E project*) to define the origins of the subcontinental lithospheric mantle beneath the old areas where ancient crust is identified, and constrain the role of the SCLM in stabilising ancient crust.

Two targeted areas will be investigated to look at some of the processes of crustal stabilisation. The Barberton Greenstone Belt and Ancient Gneiss Complex in Swaziland and adjacent RSA represent some of best-preserved and most-studied Early- to Mid-Archean (3.6 to 3.2 Ga) crustal remnants. There are several models for their formation, ranging from oceanic to continental settings; all may need revision in light of Sm-Nd data and unpublished zircon-Hf data (A. Kroener, pers. comm.) that indicate the participation of older crust (model ages ≥3.8 Ga). However, it is clear that the tectonic and magmatic processes that produced the greenstones, associated TTG magmatism, sedimentation and (locally high-grade) metamorphism ended abruptly at ca 3.1 Ga, with the emplacement of regionally extensive granitic magmas (Mpuluzi granodiorite, Nelspruit potassic granite, Boesmanskop syenite, Salisbury Kop granodiorite). These form thick sheets extending over at least 10,000 km^2. This intrusive episode marks the final cratonisation of the crust in this area; little happened thereafter until ca 2.5 Ga. The sheer volume of these magmas raises several fundamental questions relevant to the generation and stabilisation of ancient crust in general.

(1) What sort of materials were melted to produce the magmas?

(2) Where did the heat come from?

(3) What controlled the formation of regionally extensive sheets, rather than deep-rooted batholiths?

(4) How many different pulses of magma were involved, and over what time span?

Collaborators include Professor Alfred Kroener (Mainz and Beijing), a world-recognised expert on Precambrian geology and, in particular, that of southern Africa. This incorporates the PhD project of Ms Rosanna Murphy, who began in 2011 with Professor Alfred Kroener as an external supervisor.

The second area to be investigated will be the southern part of the North China Craton, where a similar "granite bloom" at the end of the Archean appears to have been the defining event that stabilised the crust, although studies of deep-crustal xenoliths have already shown that felsic-intermediate crust was already in place by 3.4 Ga.

PROGRESS DURING 2012

Dr Belousova started her Future Fellowship project in 2012 and has already produced results contributing to our knowledge of the structure of the Archean crust in the Volgo-Uralia region of the of the East European Craton. She has also begun work on samples from unique drill-core material (depths over 10,000 km) of both Archean and Paleoproterozoic rocks from Volga-Uralia and Baltic Shield (Kola super-deep drillhole).

PhD student Yuya Gao (cotutelle with CAS, Beijing, a CCFS Partner) began a thesis analysing Li isotopes in A-type granites, following from the success of Dr Xian-Hua Li in establishing this technique during 2011. These granites are typically the latest components in "granite blooms" and this work will be directly relevant, as an analogue, to the aims of the project. A paper dealing with the zircon systematics of the samples was submitted for publication in 2012.

PhD student Rosanna Murphy presented her preliminary work at an international conference in Johannesburg in January 2012; this was followed by a field trip that allowed her to carry out further sampling, and to link up with a French group who have overlapping interests in the area. The samples she returned have been processed, including whole-rock isotopic studies on selected samples. The zircons have been analysed for U-Pb ages, Hf-isotope composition, and trace elements; a selection has also been analysed for O isotopes at CMCA. The results support the work on the earlier sample sets; they have confirmed the narrow spread of intrusion ages around 3.1 Ga, and a scattering of older inherited zircons, stretching back to 3.5-3.6 Ga. This is consistent with the Hf isotopes, which give model ages in the same range. There is, thus far, little evidence of a Hadean crust in the area. See *Research highlight p. 50*.

Visiting PhD student Qian Liu (from China University of Geosciences, Wuhan) employed zircon geochemistry and geochronology from Mesozoic granites representing two timeslices in southeastern China, to demonstrate the power of zircon geochemistry as a remote sensor for paleogeodynamics (see *Research highlight p. 43)*

A synthesis of lithosphere evolution incorporating zircon geochemistry and geochronology from this project was presented as an invited lecture "The world turns over" at the 34th IGC and has been submitted for publication

OUTPUTS

Publications:

CCFS publications #12, 97

AIMS AND WORK PLAN FOR 2013

The aims of the project will remain unchanged. Dr Belousova and Ms Gao will continue their analytical work in 2013. Dr Belousova will carry out more analytical work on samples collected from Russia and Spain.

Analytical work for the African Craton part will be finalised, and a paper prepared on the geochemical outcomes; these data will provide the constraints for a program of thermal/compositional/dynamic modelling (with Dr Craig O'Neill) to explore the processes that produced these huge volumes of magma in such a short time. One possibility to be tested is the *in-situ* heat generated by a K-U-Th-rich deep crust blanketed by a refractory upper crust; another is a deep-seated source such as a mantle overturn.

Dr Elena Belousova sampling the rivers and streams of Yakutia.

4. TWO-PHASE FLOW WITHIN EARTH'S MANTLE: MODELLING, IMAGING AND APPLICATION TO FLAT SUBDUCTION SETTINGS

Theme 3, Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

The overarching goal of this project is the development and application of an in-house state-of-the-art computational tools to simulate and image complex geochemical-geodynamic processes involving two-phase reactive flow in multi-component deformable media. These tools, in combination with advanced seismic imaging techniques, will be applied to the problem of fluid transport from shallow-dipping to flat subduction settings, in both the western USA and South China in the past.

PROGRESS DURING 2012

People:

A full-time technical staff member was employed in early 2012 (Farshad Salajegheh) to assist with development and application of the numerical tools.

The postdoctoral position was advertised, and candidates shortlisted. A formal offer was finally made to Siqi Zhang, who will be arriving on the 20th of February 2013 to begin work on the project.

Dr Zheng visited Yingjie Yang for about one month late in 2012 to work on seismic imaging of upper mantle structure. He has mastered the tomographic method applied for upper mantle imaging during the last trip.

We have also had 4 PhD students begin in 2012, working on issues related to the project:

Chris Grose: The nature and thermo-chemical evolution of the oceanic lithosphere

Beñat Oliveira Bravo: Two-phase multi-component reactive transport in the Earth's lithosphere and mantle

Chengxin Jiang: Imaging the crustal structure of Northern Tibet and surrounding regions by Ambient Noise Tomography

Shahid Ramzan: The strength of oceanic plate-bounding faults.

OUTPUTS

Publications:

Early work utilising the multicomponent mantle flow framework available in CitcomS have been submitted, e.g:

O'Neill, C. Debaille, V., Griffin, WL., (submitted, AJS), Deep Earth Recycling in the Hadean and constraints on surface tectonics.

Also work on the utilisation of Underworld for subduction modelling and melting calculations was submitted:

O'Neill, C., Lenardic, A., Coltice, N., Moresi, L. (submitted), Divergent tectonic evolution of Venus and Earth from ^{40}Ar constraints, in: Comparative Climatology of Terrestrial Planets, Arizona Press Space Science Series.

Development of the tomographic imaging was published in: CCFS publications #35, 217

Work on the probabilistic inversion for lithosphere/mantle structure is appearing in: #217, 218

Conference Presentations:

Some selected presentations of special relevance to the project's science themes:

Yang, Y. and Jiang, C., 2012. Applications of long period surface wave dispersion measurements from ambient noise in regional surface wave tomography, , S53C-2516 American Geophysical Union's 45th Annual Fall Meeting, San Francisco, California, 3-7 December.

Grose, C.J. and Afonso, J.C., 2012. Petrology of oceanic lithosphere from thermodynamic models: implications for geophysical observations and geodynamics. AGU Fall meeting, San Francisco, T43F-2755.

Afonso, J.C., Fullea, J., Yang, Y., Rawlinson, N., Jones, A.G., Connolly, J.A.D., 2012. Towards multi-observable thermochemical tomography of the lithosphere and sublithospheric upper mantle. AGU Fall meeting, San Francisco, V51D-03.

O'Neill, C., Afonso, J.C., 2012. The role of serpentinisation in fault stress and long-term deformation in the Java-Sumatra subduction system, Specialist Group in Tectonics and Structural Geology (SGTST/GSA) Bi-annual Conference, Waratah Bay, 29 January - 3 February 2012.

O'Neill, C., 2012. Deep Earth recycling in the Hadean (Invited Keynote talk), 34th IGC, Brisbane, August 2012.

O'Neill, C., 2012. Plate tectonics: A phase a planet goes through? 34th IGC, Brisbane, August 2012.

Debaille, V., O'Neill, C., Brandon, AD., Haenecour, P., Yin, Q.-Z., Mattielli, N., Treiman, AH., 2012. How to preserve a chemically heterogeneous martian mantle? A plate tectonics point of view. MetSoc 2012, Cairns, August 2012.

Leverage:

A NecTar (nectar.org.au) grant was successful which leverages off the Underworld development component portion of this project (project funded through Monash – Macquarie subcontracting off this arrangement - $364K NecTar funding, $372 co-investment, including in-kind contribution. Net cash flow to Macquarie of $60K per year for the duration of the project).

A description of the project follows:

Geology from Geodynamics — a geophysics workflow for Underworld

This new research tool is designed specifically for use by Australian geologists and geophysicists. It will enable the geology, geophysics and geodynamics research community to link into industry-standard 3D modelling to access geophysical data for improved accuracy when using 3D modelling technology. This new tool will help link workflows from both commercial and research-developed geophysics modelling software.

AIMS AND WORKPLAN FOR 2013

The aims in 2013 are to begin development on the implementation of mantle rheology formulations and MCMP flow in Aspect, a new, cutting edge FEM formulation for simulating mantle flow, based on the deal.II FEM library. The code is a collaborative effort, partly orchestrated by the CiG consortium. Siqi Zhang is familiar with the architecture of the software and will be heavily involved in bringing it up to usability for CCFS problems.

Application work will continue on CitcomS and Underworld (the latter supported by NecTar funding), and additional papers on upcoming results will be submitted this year.

Afonso and Oliveira will work on novel multi-scale algorithms for two-phase multi-component reactive flow in the Earth's mantle.

Seismology will continue its existing research collaboration stream with Wuhan, factoring in a long visit for Zhang and some of his group in 2013. With the development of the imaging and maturation of the modelling components, we will also draw in Li's (Curtin) expertise in the local area geodynamics of South China in developing an integrative approach to exploring the problem.

5. EARLY EVOLUTION OF THE EARTH SYSTEM AND THE FIRST LIFE FROM MULTIPLE SULFUR ISOTOPES

Theme 1, Early Earth, contributing to understanding Earth's Fluid Fluxes.

Aims:

1. To define the nature of the first life in the early Archean and links between the early evolution of life and the rise of atmospheric oxygen in the Neoarchean.

2. To understand the evolution of the Earth's oceanic and atmospheric composition during the Archean and Paleoproterozoic.

3. To evaluate the links between the evolution of the sulfur cycle and the formation of important Archean submarine ore deposits.

Context and rationale:

Mass-independent fractionation (MIF) of multiple sulfur isotopes ($\partial^{34}S$, $\Delta^{33}S$ and $\Delta^{36}S$) in rocks older than 2.45 Ga provides the best evidence for changes in early Earth's atmosphere and ocean due to the evolution of the sulfur cycle. Recent work indicates that variations in the MIF record have important implications for understanding changing environmental conditions in the evolving Archean Earth system. Prior to 3.1 Ga the record is characterised by significant MIF, with reduced variation between 3.1 and 2.8 Ga and increased variation from 2.75 to 2.5 Ga, followed by reduction as the Great Oxidation Event occurred between 2.45 and 2.32 Ga. We have the capability to analyse samples that may resolve how these changes were linked to tectonic events (e.g. a fluctuating sulfur cycle linked to increased subaerial volcanic gas as continents grew) and the evolution of life. Multiple sulfur isotopes are important to investigation of biological processes on the early Earth. They provide the potential to elucidate the types of life present in Earth's earliest sedimentary environments, and to trace the transfer of sulfur in fluids and gases from the interior of the Earth, via the atmosphere and hydrosphere into the biosphere.

Although compilations of sulfur isotope data from Archean sedimentary rocks indicate the sulfur content of oceans was very low, Archean greenstone successions contain some of the world's largest submarine metal sulfide deposits, and these commonly have non-zero $\partial^{33}S$ values. A better understanding of the role of different sulfur sources in Archean mineral systems will provide important insights into the evolution of the early sulfur cycle and keys for exploration. Also analysis of multiple sulfur isotopes in sulfide inclusions in mantle derived diamonds and eclogites from kimberlites has the potential to tell us how Archean sulfur was recycled to depth in the crust and mantle and sulfide inclusions in Hadean zircons and meteorites have potential for understanding very early Earth fluids.

One problem that has held back research in the biological field is the spatial resolution at which multiple sulfur isotopes can be analysed. Bulk analyses can lead to artificial homogenisation of sulfur isotope signals in a sample, and a lack of understanding of processes on the micron scale, where microbial mediation may be observed. For example, recent Nano SIMS sulfur isotope studies have revealed large variations in $\partial^{34}S$ in both modern and ancient microenvironments. These small-scale heterogeneities in sulfur isotope composition cannot be detected by bulk techniques, and emphasise the growing need to study sulfur isotopes on a spatial scale relevant to microbial processes. Hence, as an extension to studying multiple sulfur isotopes in Archean sediments and mineral deposits we will also investigate the biogeochemistry of sulfur using samples from key times in Earth history (e.g. early Archean to investigate Earth's earliest life; late Archean to investigate the interplay between sulfur metabolisms and the rise of atmospheric oxygen), and will incorporate new technology available at the CMCA. An increased understanding of the biological S-cycle is not only important for studies of life in the Archean, but also for elucidating the composition of the early atmosphere, the mechanisms for cycling of these elements between the lithosphere, biosphere and atmosphere, and the cycling of other elements essential for life.

Methods/methodologies:

The major aims of the project require analysis of multiple sulfur isotopes from relevant samples, some that we already have and others to be collected soon.

The most appropriate method for bulk multiple sulfur isotope analyses is use of the EA-CF-IRMS at the University of Queensland (key analyses in the 2009 DP) this will be used to see which sedimentary and mineral deposit samples require more detailed spatial analyses. The CAMECA IMS 1280 ion microprobe is capable of measuring $\partial^{34}S$ and $\Delta^{33}S$ with precisions of better than 0.2‰ and from samples as small as ca 15 mm. For $\Delta^{36}S$ it can achieve precisions of better than 0.3‰ from samples as small as ca 40 mm. The CAMECA Nano SIMS 50 extends this capability to samples as small as 2-3 microns for $\partial^{34}S$. This will allow us for the first time to analyse $\partial^{34}S$, $\Delta^{33}S$ and $\Delta^{36}S$ from individual sulfides and sulfates at the correct scale to identify individual microbial processes.

Innovation:

This is the first time all three analytical methodologies for multiple sulfur isotopes have been available in Australia and will provide the chance of very important high-impact results and one of the best global databases.

PROGRESS DURING 2012

The research plans for this project are to obtain appropriate samples and undertake the necessary analyses; we will target key areas and important mineral deposits in the Murchison and West Pilbara. We have been able to get appropriate sample sets from Mesoarchean (3.3 to 2.8 Ga) greenstone belts and volcanic hydrothermal massive-sulfide deposits and komatiite-hosted Ni-sulfide deposits. Australia is the only place with a wide variety of samples of this key age, which has been a gap in the existing global database. We have gotten excellent first results from the 2.9 Ga Lake Johnston Belt and the Murchison area, showing key evidence for variations in the sulfur cycle through this period of time. This contrasts with previous data, which have suggested rather minor oxygen-fugacity variations before the great oxidation event. These data show that the strongest variations in the Mesoarchean S-MIF record are linked to the only preserved evidence for major volcanic events, suggesting that subaerial volcanism produced the key volcanic gases. The largest 2.95 Ga Mesoarchean deep-submarine volcanic massive-sulfide deposit, Golden Grove, is evidence for major sulfur recycling after plate tectonics started. These are important results and we will submit them to key journals in the next few months. The CIs have given talks at conferences and PhD students have had talks and posters. PhD student Carissa Isaac (started 2010) whose initial analytical work was partly supported by the Discovery Grant (VMS and sedimentary S isotopes in the North Eastern Yilgarn), has gotten a larger and more appropriate batch of samples for ongoing research in this project; she gave presentations and posters at conferences in 2012, and will publish papers and complete her thesis in 2013.

There are three PhD students working on this project, giving us the potential for some important milestones in the hope of providing a better understanding of the variations of the sulfur cycle and its links to tectonics, life and mineral deposits in the early Earth between 3.5 and 2.4 Ga.

Using the different methods described above has given us the first clear data on how the methods fit together for this important work. We have been collaborating with international leaders in multiple sulfur isotope geochemistry (James Farquhar, Boz Wing, Shuhei Ono, Doug Rumble, Sue Golding, Jay Kaufman etc.) in 2011, 2012 and 2013.

David Wacey's CCFS Research Fellowship commenced in 2012. As part of CMCA, his expertise lies in early life and related biogeochemistry and astrobiology (illustrated by his publications and conference presentations), he has collected a quality set of samples and has a high level of experience using Nano SIMS and IMS 1280. David has a paper in review and one more to be submitted soon and is expecting his key international collaborations to continue in 2013.

OUTPUTS

Publications:

CCFS publications# 182, 183

Abstracts:

Barley, M.E., 2012. Links between tectonics and life, 4.0 to 2.3 Ga and the rise of oxygen. Abstract, Goldschmidt Conference 2012.

Barley, M.E., Golding, S.D., Fiorentini, M.L., 2012. The first multiple sulfur isotope evidence for a 2.9 Ga Mesoarchean sulfate reservoir linked to a major volcanic event. Abstract, 34^{th} IGC 2012.

Issac, C., Fiorentini, M., Wing, B., Golding S., and Barley, M., 2012. Distribution of sulfur reservoirs through the Archean in the North Eastern Goldfields, Yilgarn Craton, Western Australia and their significance for nickel sulfide formation in komatiites. Abstract, 34th IGC 2012.

McLoughlin, N., Grosch, E.G., Kilburn, M.R. and Wacey, D., 2012. Evaluating the earliest traces of Archean sub-seafloor life by NanoSIMS. Abstract, AGU Fall Meeting, San Francisco, USA.

Noffke, N.N., Christian, D., Wacey, D. and Hazen, R., 2012. A microbial ecosystem in an ancient sabkha of the 3.49 Ga Pilbara, Western Australia, and comparison with Mesoarchean, Neoproterozoic and Phanerozoic examples. Abstract, GSA Annual Meeting, Charlotte, USA, 4-7th November.

Wacey, D., McLoughlin, N., Saunders, M. and Brasier, M., 2012. Electron Microscopy of Early Cellular Life. Abstract, Scandem 2012 Annual Meeting of the Nordic Microscopy Society, 12-15 June 2012.

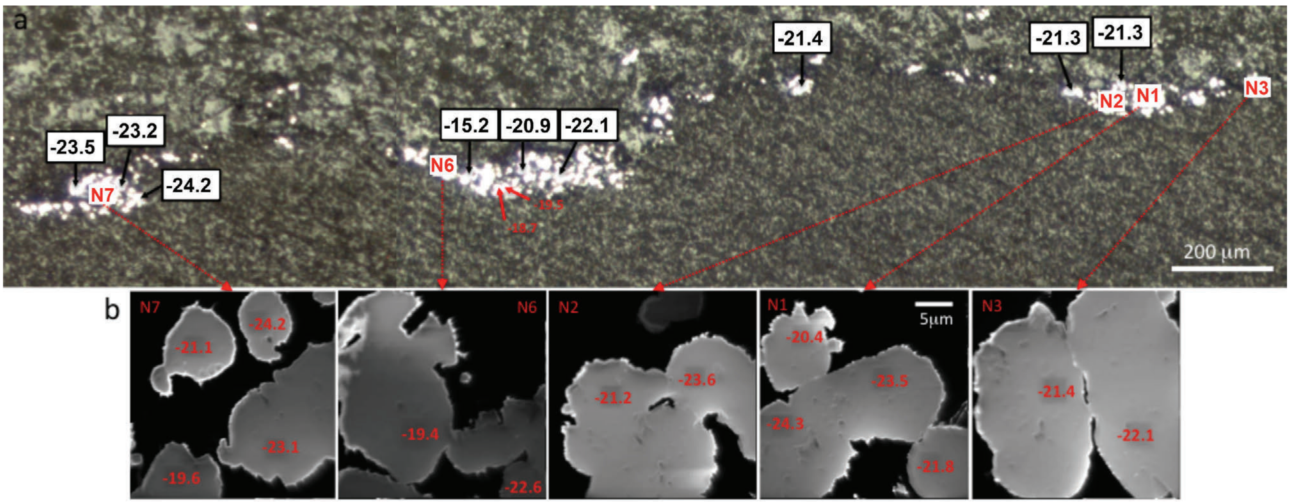
AIMS AND WORK PLAN FOR 2013

With David Wacey's increasing involvement in this project in 2013, we are planning to link the variation of SMIF in different-sized sulfide minerals in areas where there has been controversy over when the first evidence for early microbes appears.

1. Obtaining bulk values of Δ^{36} and Δ^{33} on the Dresser sulfides to back up the SIMS work from last year (James Farquhar). We will use another session on the 1280 to see if the values we got last year are repeatable. Because some data suggest there was evidence for early life, we hope to provide the first unambiguous S-isotope evidence.
2. Analysing the products of lab experiments where sulfate-reducing bacteria have been used to precipitate sulfides, to see if a biological signal can be seen in $\Delta^{36}S$ and/or $\Delta^{33}S$ on the micro-scale. Micro-scale analyses will be done on the SIMS at UWA; bulk analyses will probably be done with James Farquhar in Maryland.
3. A different Gunflint data set, looking at possible hydrothermal pyritisation of microfossils - compare and contrast these data with those from biological pyritisation that we obtained last year.
4. Analysis of pyrite from Ediacara sediments containing macrofossils from Newfoundland to test our hypothesis that the Ediacara biota may have been thiotrophic. We are planning to get more sulfur data in 2013 - these are 1200 Ma pyrite microfossils from the Stoer Group in NW Scotland. The aim is to investigate the sulfur cycle in Proterozoic lakes. These are all focused on the Precambrian sulfur cycle and its links to early life and are relevant to the CCFS objectives and the major aims of this project.

We are continuing our collaborations with international leaders in multiple sulfur isotope geochemistry (James Farquhar, Boz Wing, Shuhei Ono, Doug Rumble, Sue Golding, Jay Kaufman) from 2011 and 2012. We plan to convene a 2 - 3 day MIF Work Shop in Australia (Sydney) in 2013 with these collaborators.

Prof James Farquhar, a pioneer of MIF, had a Sabbatical at UWA to see how his bulk analyses compared to the CAMECA NanoSIMS analyses. We hope that with his help, new bulk analyses will be completed.



Technique development for Sulfur Isotopes: Validating NanoSIMS $\delta^{34}S$ analysis. This is a sample from the Ediacara of Newfoundland showing that NanoSIMS can be used to measure $\delta^{34}S$ of biological pyrites. NanoSIMS data is tested against 1280 data from nearby (or sometimes the same grains). Results are nearly identical. Black = Cameca IMS 1280 data, Red = NanoSIMS data.

6. DETECTING EARTH'S RHYTHMS: AUSTRALIA'S PROTEROZOIC RECORD IN A GLOBAL CONTEXT

Theme 2, Earth's Evolution, contributing to understanding Earth's Architecture and Fluid Fluxes.

The main goals of this project are (1) to test a groundbreaking hypothesis that the birth and death of a supercontinent on Earth's surface is intimately linked to the spatial and temporal location of superplumes, and that cyclic supercontinent-superplume events and associated fluid events dominate Earth's evolution; (2) pushing our knowledge of the Earth's palaeogeographic and geodynamic history back to the Archaean.

Context and rationale:

How plate tectonics on the Earth's outer shell interacts with its mantle, and what drives plate tectonics, remain a challenge to the 21st century geoscience community.

Does plate tectonics drive mantle convection, or vice versa? What determines the formation, positions and lifespan of hot mantle plumes and superplumes deep in the mantle, and how do plumes/superplumes interact with plate dynamics? Are mantle plumes and superplumes fixed relative to the Earth's rotation axis? Are the formation and breakup of supercontinents in Earth's history accidental events, or more regular events determined by some internal mechanisms?

While working on the evolution of Rodinia, Z.-X. Li and co-workers noticed that the assembly of Rodinia was followed by a >100 million years (Ma) of worldwide plume activity that is at least temporally linked to the breakup of the supercontinent. The sequence of events resembles that during Pangaean time both in its lateral extent and its duration, including a time lag of tens of millions of years between the final assembly of the supercontinent and the onset of plume breakout. More intriguingly, Neoproterozoic palaeomagnetic data suggest that Rodinia and the mantle plumes beneath it may have rotated rapidly between ca 0.81 and 0.75 Ga, confirming that mantle plumes and supercontinents are probably coupled. Did such coupling occur during Earth's earlier history?

In this project we will further test this hypothesis by analysing global palaeogeography back to the Neoarchaean era. Primary data gathering in the first three years will focus on numerous Paleo- to Mesoproterozoic Australian igneous complexes with studies of palaeomagnetism and geochemistry. We will compare the Australian records with those of the entire world through international collaborations.

PROGRESS DURING 2012

The project made significant progress in both primary data gathering and scientific interpretation and synthesis. The combined palaeomagnetic, geochronological and geochemical analyses of mafic dykes in the Ravensthorpe region of the southeastern Yilgarn craton are nearly completed. Radiometric dating of one of the dykes confirmed the dominant presence of the ca 1.2 Ga Gnowangerup–Fraser mafic dyke swarm in the region. However, palaeomagnetic analyses also revealed the likely existence of ca 755 Ma mafic dykes, probably a southern extension of the Mundine Well dyke swarm in the northwestern Yilgarn craton. Both generations of dykes represent typical anhydrous and tholeiitic intraplate magmas with the possible involvement of recycled components in their source region. This finding is consistent with a mantle plume-origin for both events.

The palaeomagnetic results from the 1.2 Ga dykes, combined with previously reported preliminary results from the interior of the Yilgarn Craton, now make the Fraser dyke pole a rare key Precambrian pole. A revised apparent polar wonder path, when compared with that of Laurentia, suggests that (1) the late-Paleoproterozoic to Mesoproterozoic supercontinent Nuna/Columbia probably broke up before 1.2 Ga, and (2) Rodinia was not formed until after 1050 Ma. The geochemical, palaeomagnetic and geochronological data are all being written

Figure 1. Narimbunna sills in the Peedawarra area.

Figure 2. Contact between mafic dyke (left-hand side of the photo) and sediments of the late Paleoproterozoic - Mesoproterozoic Edmund Group (right-hand side of the photo). Photograph by Sergei Pisarevsky.

up for publication, and a more detailed presentation of the scientific findings can be found under *Research highlights* in the 2012 CCFS Annual Report.

We carried out a pilot sampling trip to the Bangemall Basin in Western Australia. Our main targets are the 1500-1450 Ma Narimbunna mafic sills and probably some ca 1070 Ma dykes in the Peedawarra, Tangadee and Capricorn areas (Fig.1). We collected oriented block samples for the palaeomagnetic analyses and potential geochemical and petrological analyses.

As an extension of this project, we are conducting a number of international collaborative research projects on rocks outside of Australia. One is on ca 1250 Ma mafic dyke samples from the Vestfold Hills, East Antarctica though collaboration with Russia's Antarctic research team (samples currently being prepared). Together with colleagues from the Indian Institute of Technology Bombay, we completed a combined palaeomagnetic, geochronological and geochemical study of ca 1460 Ma Lakhna Dykes in the Bastar Craton of India. The new palaeopole helps to constrain India's position in Nuna (Pisarevsky et al., *Lithos*, in press; *CCFS contribution #195*). We have also collaborated with Russian colleagues from the Institute of Earth's Crust in Irkutsk on Siberian rocks. New palaeopole and geochemical characteristics of 760 Ma mafic dykes led to a new model of Siberia in Rodinia (Pisarevsky et al., submitted to Precambrian Res.). Palaeomagnetic analyses of two other collections of Meso- to Neoproterozoic mafic dykes from Siberia have been completed, and relevant manuscripts are currently being prepared. Palaeomagnetic and geochronological study of previously undated St Simeon dykes in Quebec of northern Laurentia will be presented in the EGU 2013 General Assembly and published soon after with Canadian colleagues. Palaeomagnetic and geochronological study of 2.4 Ga dykes east of Kalgoorlie, WA revealed a new palaeopole which is similar, but not identical to the pole from the 10 Ma older Widgiemooltha dykes, providing new insights into Paleoproterozoic palaeogeography and magmatism in Western Australia. The two latter studies were done in collaboration with the international LIPs project team (www.supercontinent.org). Another collaborative publication with that team on the Mesoproterozoic mafic magmatism in Angola has been recently accepted for Precambrian Research (*CCFS publication #221*).

A major scientific breakthrough of this project during the year is the publication of the first palaeomagnetically constrained reconstruction of the Nuna supercontinent through an ongoing international collaboration with researchers from China University of Geosciences and Yale University (see report under *Research highlight p. 45*).

OUTPUTS

Publications:

CCFS publications directed linked to the project: #39, 179, 186, 195, 197, 221, 224, 250, 269, 270

CCFS Publications contributing to general CCFS goals: #16, 23, 24, 31, 34, 115, 143, 148, 156, 159, 166, 173, 193, 208, 212, 219, 223, 281, 303

Abstracts:

10 directly linked to this project, plus 10 related presentations.

Li, Z.X., 2012. Coupled supercontinent-superplume cycles and the geodynamic driving force: an overview. The 34th International Geological Congress, 5-10 August 2012, Brisbane, Australia.

Li, Z.X., Evans, D.A.D., Halverson, G.P., 2012. Global Cryogenian and Ediacaran paleogeography: A new kinematic and lithostratigraphic model. Supercontinent Symposium 2012, 25-28 September 2012, Helsinki, Finland.

Li, Z.X., The opening of the South China Sea: Driven by Pacific subduction, or by India-Eurasia collision? American Geophysical Union's 45th Annual Fall Meeting, San Francisco, California, 3–7 December 2012. **Keynote**

Li, Z.X., Pang. C., Batt, G., Li, W.X., Xu, Y., 2012. Large-scale and rapid vertical continental movements due to the eclogisation of a flat-subducted oceanic plateau in Mesozoic south China. The 34th International Geological Congress, 5-10 August 2012, Brisbane, Australia.

Pisarevsky S.A., 2012. Mesoproterozoic supercontinent - paleomagnetic synthesis and geological constraints. In: Mertanen, S., Pesonen, L. J. and Sangchan, P. (eds.), 2012. Supercontinent Symposium 2012 – Programme and Abstracts. Geological Survey of Finland, Espoo, Finland, 117-118. **Keynote**

Lubnina N.V., Pisarevsky S.A., Söderlund U., Nilsson M., Sokolov S.J., Khramov A.N., Iosifidi A.G., Ernst R., Romanovskaya M.A., Pisakin B.N., 2012. New palaeomagnetic and geochronological data from the Ropruchey sill (Karelia, Russia): implications for late Palaeoproterozoic palaeogeography. In: Mertanen, S., Pesonen, L. J. and Sangchan, P. (eds.), 2012. Supercontinent Symposium 2012 – Programme and Abstracts. Geological Survey of Finland, Espoo, Finland, 81-82.

Gladkochub D., Nicoll G., Zhang S., Stanevich A., Pisarevskiy S., Mazukabzov A., Donskaya T., 2012. LA-ICP-MS U-Pb dating of detrital zircons from sediments of the southern part of the Siberian craton: constraints for Precambrian supercontinents. In: Mertanen, S., Pesonen, L. J. and Sangchan, P. (eds.), 2012. Supercontinent Symposium 2012 – Programme and Abstracts. Geological Survey of Finland, Espoo, Finland, 49-50.

Pisarevsky, S.A., Li, Z.X., 2012. India in Nuna — possibilities and problems. 34th IGC, Brisbane, Australia, abstract 1881. **Invited**

Mochales, T., Rosenbaum, G., Speranza, F., Pisarevsky, S.A., 2012. Unravelling New England Orogen by anisotropy of magnetic susceptibility studies. 34th IGC, Brisbane, Australia, abstract 2717.

Hansma, J., Tohver, E., Yan, M., Trijnastic, K., Playton, T., Pisarevsky, S.A., Kirschvink, J.L., Hillbun, K., Ward, P.D., Haines, P.W., Hocking, R., 2012. Late Devonian carbonate magnetostratigraphy from the south Oscar Range, Lennard Shelf, Western Australia. 34th IGC, Brisbane, Australia, abstract 2767.

Pisarevsky, S.A., Li, Z. X., Wingate, M. T. D., Tohver, E., 2012. Paleomagnetism of the 1210 Ma Gnowangerup-Fraser dyke swarm, Western Australia. Geophysical Research Abstracts, 14, EGU2012-4049, 2012 EGU General Assembly 2012.

Huang, H.Q., Li, X.H., Li, Z.X., and Li, W.X., 2012. Formation of Jurassic high-K granitoids in the Nanling Range of southern China by reworking of supracrustal rocks by mantle-derived magmas. The 34th International Geological Congress, 5-10 August 2012, Brisbane, Australia.

Yao, W.H., Li, Z.X., Li, W.X., Wang, X.C., Li, X.H., Yang. J.H., 2012. Post-kinematic lithospheric delamination of the Wuyi-Yunkai orogen in South China: Evidence from ca. 435 Ma high-Mg basalts. The 34th International Geological Congress, 5-10 August 2012, Brisbane, Australia.

Sun, M.D., Chen, H.L., Wilde, S.A., 2012. Detrital Zircon Record of Cretaceous Sedimentary Basins on the Jiamusi Block and Sikhote-Alin Accretionary Complex, NE China. The 34th International Geological Congress, 5-10 August 2012, Brisbane, Australia.

Pang, C., Li, Z.X., Krapez., B., Xu, Y., 2012. Sedimentary facies analysis of a latest Triassic to early Jurassic shallow marine delta in northern Guangdong Province, South China: consequence of eclogisation and foundering of a flat-slab? The 34th International Geological Congress, 5-10 August 2012, Brisbane, Australia.

Wang, X.C., Li, Z.X., Li, Q.L., Li, X.H., 2012. A mantle hydrated by stagnated Pacific slab that produced intraplate continental flood basalts in northeastern China. The 34th International Geological Congress, 5-10 August 2012, Brisbane, Australia.

Liu, Y., Li, Z.X., Laukamp, C., West, G., Gardoll, S., 2012. Quantified Spatial Relationships between Gold Mineralisation and Key Ore Genesis Controlling Factors, and Predictive Mineralisation Mapping, St Ives Goldfield, Western Australia. The 34th International Geological Congress, 5-10 August 2012, Brisbane, Australia.

Liu, L., Li, Z.X., Danišík, M., Li, S., Evans, N.J., Liu, X., 2012. Post-UHP exhumation history of the Sulu Orogenic Belt, eastern China: evidence from integrated thermochronology. The 13th International Conference on Thermochronology, 24-28 August 2012, Guilin, China, 58-59.

Tao, N., Li, Z.X., Danišík, M., Evans, N.J., Xu, Y.G., Pang, C.J., Li, W.X. and Liu, D.H., 2012. Thermochronological record of central and southern South China since the Mesozoic. The 13th International Conference on Thermochronology, 24-28 August 2012, Guilin, China, 88-89.

Pisarevsky, S.A., Li, Z. X., Wingate, M. T. D., Tohver, E., 2012 Paleomagnetism of the 1210 Ma Gnowangerup-Fraser dyke swarm, Western Australia. EGU General Assembly 2012, 22-27 April 2012, Vienna, Austria.

AIMS AND WORK PLAN FOR 2013

Our main tasks in 2013 are the following:

(1) Publish the geochronological, geochemical and palaeomagnetic results from the Ravensthorpe dykes;

(2) Complete the analyses of pilot samples from the Bangemall Basin, conduct a comprehensive sampling trip to this remote region if the results are promising, and start to process the samples;

(3) Plan for and probably conduct a sampling trip to the Kimberley region with Paleoproterozoic rock targets, and start to process the samples;

(4) Continue our international collaborations on a number of targets (Antarctica, India, China, Russia, Sweden);

(5) Publish a new, comprehensive palaeomagnetic examination of Nuna's evolution through a collaboration with the Nordic Paleomagnetic Working Group;

(6) Publish a revised Neoproterozoic global palaeogeography and map of sedimentary facies distributions (glacial deposits in particular) through collaborations with researchers from Yale and McGill universities.

7. FLUID REGIMES AND THE COMPOSITION OF THE EARLY EARTH

Theme 1, Early Earth, contributing to understanding Earth's Architecture and Fluid Fluxes.

The aims of this Project are twofold:

Part 1: Characterising the earliest crust on Earth: The objective is to characterise the nature and origin of the earliest crust on Earth and to identify new localities where ancient crust may still be preserved. This will be achieved by working on newly-discovered samples of ancient zircon and acquiring full geochemical and isotopic data from these to compare with the huge inventory already obtained from Jack Hills and Mt Narryer. In addition, utilising data already acquired from the 4.4-3.5 Ga detrital zircon suite at Jack Hills, we will be comparing these with comparable new data that will be obtained from the earliest known rocks on Earth; preserved in Antarctica, Canada, China, Greenland, India, and Western Australia. We will attempt to identify any changes that may have taken place from the formation of the earliest zircons (4.4 Ga) to the time when crust was widely preserved, contributing to our knowledge as to why so few Hadean rocks apparently survived on Earth.

Part 2: Characterisation of minerals and related fluids phases in extraterrestrial samples: In this study, conditions on the early Earth will be compared with those in the early solar system. This will include work on the Martian meteorites in order to characterise any fluid present and obtain information on primitive mantle deformation mechanisms and processes. This will be done by combining geochemical and microstructural techniques including SEM imaging, electron and ion microprobes, EBSD and Raman.

Background:

The Earth grew from solar and planetary debris, and heat generated during this process would have resulted in the expulsion of volatile elements into space. Earth's current inventory of water and other volatiles was most likely added by a "late bombardment" of cometary material. However, the lack of water on the Moon, and our discovery that Earth may have had surface water 4.2-4.4 billion years ago, raise important issues with respect to the source and role of water during Earth's early evolution.

Studies of lunar samples, meteorites, and Earth's oldest rocks and minerals enable us to link the geochemical evolution and deformation histories of proto-planetary bodies. We aim to use a variety of techniques, including synchrotron-based spectroscopy and high-precision stable-isotope analysis of oxidation/reduction-sensitive elements such as Cr, Fe, O, C and S in minerals from Earth, the Moon and meteorites, to assess planetary oxidation states and provide new clues as to how the planets formed. Some of these elements had short-lived isotopes (e.g. ^{53}Mn - ^{53}Cr, half-life 3.5 Ma) and can be used to investigate how oxidation states changed during the accretion and very early evolution of Earth.

Mars is the only planetary body in the Solar System where surface conditions similar to those observed on the Earth can be studied directly, using samples of Martian meteorites, and our attention will be focused here. This fits in well with the current activity of the Mars Curiosity rover and the exciting discoveries already made during this mission. Mars provides a unique opportunity to test models of atmospheric, hydrospheric and biospheric evolution, as well as climate variations possibly similar to those on Earth. We will use information from Martian meteorites to derive new constraints on the initial state of Earth's atmosphere and hydrosphere. Carbonates preserved in several of these meteorites might contain information about the Martian surface, since such minerals are associated with sedimentary processes on Earth.

Further analysis of the oldest zircons on Earth will provide constraints on the nature, evolution and weathering of Earth's earliest crustal remnants. We have identified several outstanding questions:

1) what is the significance of the inclusion suite in ancient zircons which, where amenable to dating, are always younger than their host?
2) were the earliest zircons derived through melting of a solidified magma ocean or do they require extensive continental crust and oceans?
3) when was the onset of plate tectonics on Earth that led to transfer of material back into the mantle? These and other related questions provide the inspiration for this project.

PROGRESS DURING 2012

Part 1: Zircon grains from ultra-high temperature rocks of the Napier Complex were ion imaged by SIMS using a single collector for Ti, Y, Hf, Pb, Th and U and a multicollector for the Pb isotopes. Patchy distribution of Pb was identified that is unrelated to zoning or crystal imperfections and it was shown that this can affect the ^{207}Pb/^{206}Pb age. Spurious Hadean ages could be generated from areas up to 5µm in diameter and this was attributed to the presence at such sites of both supported and unsupported Pb (i.e. Pb 'gain' resulting in reverse discordance on standard concordia diagrams). This redistribution of Pb is attributed to the 2.5 Ga high-grade metamorphic event affecting the Napier Complex, although the precise reason is currently unknown. Experiments on Ti show a similar patchiness, and this has important implications for Ti-in-zircon thermometry.

Work was completed on the re-investigation of >3.9 Ga zircon in the North Qinling Orogenic Belt in Central China (Gondwana Research, in press). Although only three grains are known from this area, they show a range in ages from 3909 ± 45 Ma to 4080 ± 9 Ma and record Hf crustal model ages up to 4.5 Ga. The old

Hf ages are similar to the oldest components recorded from Jack Hills and establish this as only the second known example of the earliest generation of continental crust on Earth. The rims of two grains record zircon growth at 3.7 Ga, and their presence in an Ordovician volcanic rock indicates that ancient continental crust was present in the basement of the North China Craton during the Paleozoic.

Further work in the Dharwar Craton of India substantiates that TTG components as old as 3.3 Ga are present in the eastern part, although the major events occurred in the Neoarchean with magmatism at ~2.55 and ~2.15 Ga. Hafnium data on zircon and whole-rock Nd data have been collected on a suite of samples from the Eastern Dharwar Craton and the results are currently being evaluated.

Work commenced on the isotopic systematics of zircons from the oldest rocks in Canada and Greenland, but few results are available at present.

Part 2: We are working on five thin sections from three Martian meteorites (Zagami, Nakhla and ALH84001) from the Smithsonian Institute, the Johnson Space Centre Curation Office and the WA Museum.

Analysis of preferred crystallographic orientation (CPO) of minerals has been undertaken at Curtin University and the University of Lausanne (Switzerland) using EBSD. Complete maps of both the Zagami and Nakhla samples, and detailed maps of single clinopyroxene grains, were obtained with EBSD. CPOs of clinopyroxene show several point concentrations of (001) axes in Nakhla and several orientations of subgrain boundaries suggest the activation of several glide systems. The classical slip system observed within the grains is (100)[001], with a possible activation of the (010)[100] slip system in Zagami sample. There is no variation in the slip system from the augite cores to the pigeonite rims of clinopyroxene, suggesting either no variation of deformation during the evolution of the geochemical system, or a late deformation event. Nakhla has been only mildly shocked with an estimated peak pressure of about 20 GPa, suggesting that the observed deformation should pre-date the shock event. Zagami exhibits more shock-related microtextures (e.g. formation of melt pockets, plagioclase converted to maskelynite). Consequently, the various systems observed could be related to both magmatic deformation and a shock event.

Carbonate phases present in Antarctic sample ALH84001 are identified as Fe-Mg-Mn-Ca carbonates; they are globular and grow within small vesicles. They are strongly zoned with Mn- and Ca-rich cores, passing outward toward more Fe- and Mg-rich rims. Carbon and oxygen isotopes of the different carbonate phases located in sub-sample 83 have been analysed with an ion microprobe in July 2012.

Apatite found in the Zagami sample from the WA museum has been imaged by optical and electron microscope. The internal microstructure of several apatite grains has also been tested with EBSD and show they complex microstructures related to ductile deformation.

AIMS AND WORK PLAN FOR 2013

Part 1: Further work on the Antarctic samples will be focused on the nature and origin of the 'patchy' Pb and an investigation of the reasons for the uneven distribution of Ti. Studies will continue on Jack Hills and include the distribution of both Archean and Proterozoic sedimentary rocks and the timing of metamorphism based on a study of matrix monazite and xenotime. Work will continue on zircons extracted from the oldest rocks in Canada and Greenland, and fieldwork will be undertaken to obtain additional samples from key localities in Labrador. A re-investigation of the oldest rocks in the North China Craton will commence in association with the Chinese Academy of Geological Sciences.

Part 2: Carbonates in sub-sample 83 of ALH84001 have been analysed for stable isotopes. Given their highly zoned nature and the sensitivity of the ion probe to "matrix" effects, several new carbonate standards have had to be used during analyses. These new carbonate standards for ion microprobe are in the process of being fully characterised by conventional isotope analyses. As soon as they are available, more data on Martian carbonates will be collected and processed.

Apatite grains in the Zagami sample are ready to be dated using the ion microprobe (SHRIMP II) at Curtin University. Their microstructure will be further studied and eventually linked with their geochemistry to identify potential correlation between both sets of data.

A second sub-sample of ALH84001 (314) has been polished and prepared for EBSD measurement. This sample will be fully investigated during 2013, aiming at identifying more carbonate phases and presence of fluids.

8. DIAMOND GENESIS: CRACKING THE CODE FOR DEEP-EARTH PROCESSES

Theme 2, Earth's Evolution, contributing to understanding Earth's Fluid Fluxes.

The aims of the project are:

- To combine LAM-ICPMS analysis of diamonds, developed at Macquarie, with other types of *in-situ* data to define the nature and evolution of diamond-forming fluids
- To constrain the causes of isotopic variability of carbon, oxygen and nitrogen in diamond-forming fluids; are these primary signatures, or do they reflect isotopic fractionation during diamond growth?
- To understand the links between diamond formation and the redox state of the lithospheric and asthenospheric mantle
- To develop a new exploration/evaluation methodology for application to kimberlites, by defining the trace-element signatures of mantle minerals that have been exposed to diamond-bearing fluids
- To better characterise different types of mantle fluids and their interactions with mantle rocks

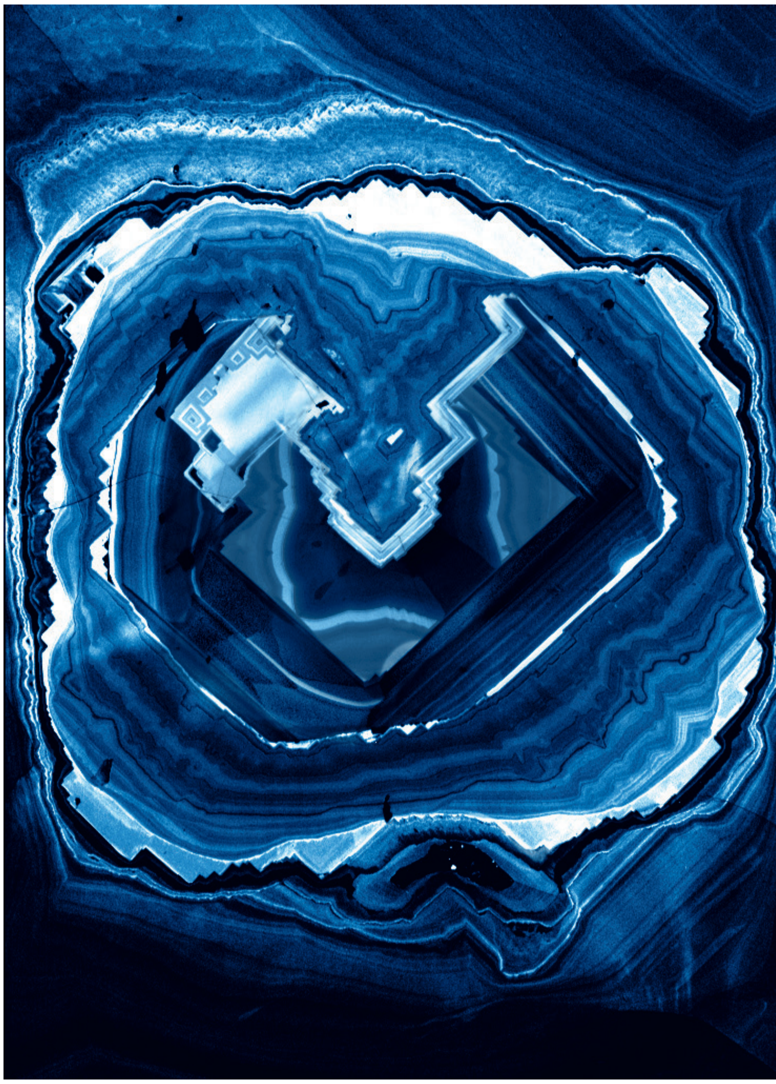
This project engages Postdoctoral Researchers Daniel Howell and Takako Satsukawa, and PhD student Ekaterina Rubanova.

PROGRESS DURING 2012

The aims of the project were expanded with progress during 2012, to characterise other types of fluids in the lithospheric mantle. An FTIR-based study of the distribution of water in different types of lithospheric mantle, using xenoliths from basalts and kimberlites, was carried out by PhD student Yao Yu (cotutelle with Nanjing University). Following the study involving spinel peridotites from the North China Craton in 2011 *CCFS publication #2*, samples of a range of previously-studied xenoliths from the kimberlites of the Kaapvaal Craton were prepared.

D. Howell, working together with Craig O'Neill, completed the development of the DiaMap software package, which allows the construction of maps derived from the reduction of the huge volumes of FTIR data collected by our state-of-the-art FTIR spectrometer. A full description of the program was published (*CCFS publication #168*) and the software went online on the CCFS website as freeware. Dr Howell continued with a detailed study of a large parcel of diamonds from the Diavik kimberlites (Lac de Gras, Canada), many of which show several stages of growth, of varying habit. The ongoing project aimed at improving the detection limits for the LAM-ICPMS analysis of diamonds using the excimer laser and a special cell design paid several dividends in 2012. One of these was the demonstration of the sectorial partitioning of Ni (and Co) in mixed-habit diamonds (*CCFS publication #178*), which required a detailed evaluation of detection limits. Another was the analysis of low-level trace elements in the mysterious UHP diamonds in the Tibetan ophiolites (see *Foundation Project 1*) carried out with collaborator J-S Yang from CAGS, Beijing.

The relationships between diamonds and silicates in suites of diamondiferous eclogites and polycrystalline diamond-silicate intergrowths formed part of the PhD project of E. Rubanova. C-isotope analyses of diamonds in diamondites and eclogites xenoliths, and O-isotope analyses of the coexisting silicates were undertaken with the CMCA at UWA, involving ongoing refinement of methodology (*Research highlights p. 44* and *p. 75).* The results of EBSD studies of diamondites were published in *CCFS publication #210*. (See *Research highlights 2011*), and presented at the 10th International Kimberlite Conference in India (February 2012).



False colour cathodoluminescence (CL) image of the core of a diamond cube from the Democratic Republic of Congo. While many natural diamond cubes are assumed to be of fibrous growth, detailed study has shown many contain cores of different diamond growth. Sometimes these cores are much older than the fibrous overgrowth. The cause of the blue CL are nitrogen defects within the diamond lattice. Image is approximately 1mm across.

This is one of the samples being worked on in collaboration with Dr Masahiko Honda (ANU RSES).

Dr Sandra Piazolo started her Future Fellowship in 2012, and has established an EBSD capability at Macquarie-CCFS in 2012; this will facilitate further studies of diamonds and their host rocks. Dan Howell has already used this to examine the origins of pink colour in diamond (see *Research highlights*). This work, coupled with the studies on sector-zoned diamonds, is shedding light on the process of nitrogen distribution and aggregation in diamonds and may have important implications for commonly used protocols for estimating diamond age from nitrogen aggregation characteristics.

We continued our collaborations with Russian and Israeli colleagues on the nature of diamond-related fluids, which is not only directly relevant to questions of diamond growth, but also is a unique pathway to characterising deep mantle fluids.

OUTPUTS

Publications:

CCFS publications #2, 11, 52, 135, 178, 180, 210, 212, 236

Abstracts:

10 international conference presentation for the diamond project

AIMS AND WORK PLAN FOR 2013

The aims of the project, as expanded in 2011 and 2012, will be followed and further expanded in 2013.

The new excimer-based LA-ICPMS system will be developed to carry out ultra-trace analyses of diamonds showing multiple stages of growth and/or mixed-habit growth, to quantify the trace-element characteristics of the fluids from which such diamonds grow. This can then be cross-compared with our extensive database of fluid compositions in fibrous diamonds. The new techniques also will be used to re-evaluate our older data on gem-quality diamonds, where many analyses were near the detection limits available at the time. C-isotope analyses will be done on the same diamonds, to correlate trace-element patterns with isotopic characteristics, and C-isotope studies on zoned and centre-cross diamonds will be completed.

Trace-element and isotopic analyses on UHP diamonds from Tibet, the Polar Urals and other localities (to be provided by Prof J-S. Yang, CAGS, Beijing), will be undertaken, forming an unanticipated a link to Foundation Project 1 and leading to a new strand investigating the redox state of different mantle regions.

The PhD project of E. Rubanova will be completed, fulfilling the planned program of chemical, isotopic and microstructural analysis of the relevant diamonds, diamondites and diamondiferous xenoliths for thesis submission and publication.

9. 4D LITHOSPHERIC EVOLUTION AND CONTROLS ON MINERAL SYSTEM DISTRIBUTION: THE WESTERN SUPERIOR-YILGARN COMPARISON

Theme 2, Earth's Evolution, contributing to understanding Earth's Architecture.

Aims of Project: The project will provide a very well-constrained case study in an Archaean craton outside of the Yilgarn to (1) apply multi-isotopic (U-Pb, Lu-Hf, O) analyses of zircon to map lithospheric architecture in space and time, (2) determine if the distribution of mineral systems (VMS, Fe, NiS, Au) shows strong control by this architecture, as it appears to in the Eastern Goldfields Superterrane of the Yilgarn Craton, and (3) generate mappable exploration criteria for targeting exploration for various Archaean mineral systems at the craton to terrane scale.

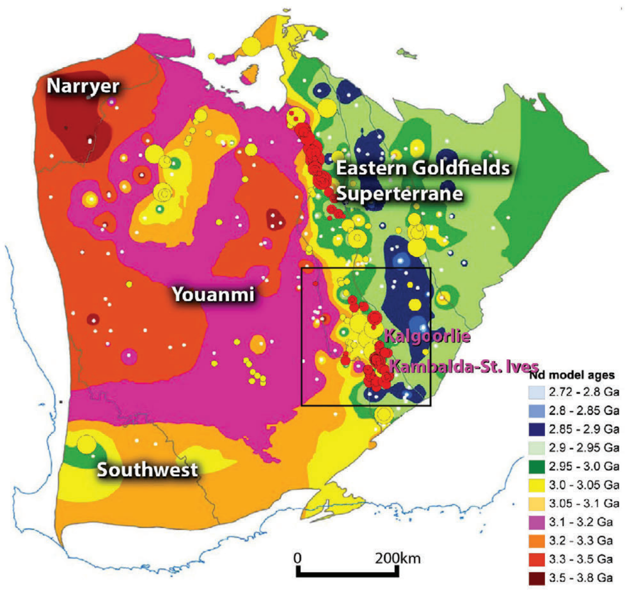


Figure 1. Nd model ages with Au (yellow) and Ni (red) deposits in Yilgarn Craton (After Cassidy and Champion, 2007).

Context and rationale: Recent studies (Champion and Cassidy, 2007; McCuaig et al., 2010; Mole et al., 2010; Begg et al., 2010) have demonstrated in the Yilgarn Craton of Western Australia that multi-isotopic maps (*in-situ* zircon U-Pb and Lu-Hf analyses combined with whole-rock Sm-Nd data) are a powerful tool to map crustal growth and image lithospheric blocks of different age (putative paleocraton margins). Moreover, these studies have pointed to a strong spatial correlation between these lithospheric block edges and the location of large concentrations of multiple styles of mineral deposits. The interpretation is that these isotopic boundaries mark lithosphere-scale structures that control the flux of mass and energy, and thus the location of large mineral systems through time.

The western Superior Province of Canada is the perfect place to undertake a comparative study to complement the Yilgarn example. The western Superior is host to major gold (Red

Lake Camp, Musselwhite mine, Hemlo), VMS (Kidd Creek) and diamond (Victor Mine) deposits as well as the recent discoveries of the world-class chromite and nickel deposits in the Ring of Fire. Yet, the western Superior Province has important contrasts to the Yilgarn in that it is relatively VMS-rich, and NiS-poor. Moreover, the Western Superior is an exceptionally well constrained Archaean craton, with well-defined stratigraphy, an abundance of high precision geochronology to constrain its evolution, and abundant high quality geophysical data including crustal seismic and potential field datasets. Current thinking is that the southwestern Superior Province comprises largely juvenile lithosphere at ca. 2.75-2.65 Ga, growing by combinations of arc-plume interactions and accretion of terranes. This contrasts the Yilgarn Craton, comprising largely evolved lithosphere at that time, and tectonic models that range from intracratonic rifting through to assembly of accretionary terranes. Systematic delineation of lithospheric blocks of different character would radically change the views on assembly of these ancient cratons.

Methodologies: This project will investigate the U-Pb, Lu-Hf and O isotope characteristics of zircons from key units in the Wabigoon subprovince of the western Superior Province, in order to obtain a better understanding of the evolution, architecture and preservation of this complex 3.0-2.7 Ga Archaean terrane and the mineral deposits that formed within it.

PROGRESS DURING 2012

In 2012, we obtained 48 zircon separates from Don Davis and Kirsty Tomlinson. SHRIMP U-Pb dating and Cameca IMS O-isotope analysis have been conducted on 30 samples. LA-MC-ICPMS Lu-Hf analysis has been done on 12 samples; the remaining analysis is continuing.

Yongjun Lu collected another 114 samples during a field trip in August-September, 2012. Mineral separation and whole-rock geochemical analysis of these primary samples are ongoing.

We have secured a UWA scholarship for Katarina Bjorkman, who will join this project in February 2013 as a full-time PhD at CET to study the Marmion Terrane in detail.

As part of this project, a collaboration with Pete Hollings at Lakehead University has been established under a NSERC Discovery Grant that will let us extend this work northward to Uchi/North Caribou boundary.

Branded under CCFS, the collaboration of zircon Hf mapping in Tibet with Zengqian Hou at CAGS has led to exciting discoveries, which will radically transform the division of the Lhasa Terrane. Manuscripts are in preparation.

OUTPUTS

Publications:

CCFS publications #23, 162, 167, 170, 185, 206, 222, 253, 255, 257, 258, 259, 260, 273

AIMS AND WORK PLAN FOR 2013

One of the major aims in 2013 is to obtain the SHRIMP U-Pb ages, oxygen- and hafnium-isotope compositions of zircons from ca 100 samples.

A field trip is scheduled in mid-2013 for additional sampling and the detailed study of Marmion Terrane as Katarina Bjorkman's PhD project.

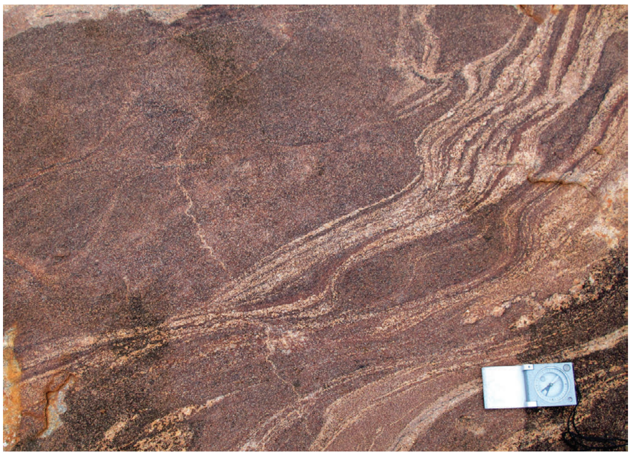
Data collection for E. Wabigoon will be finalised for writing a manuscript.

Figure 2. Sampling by helicopter around Thunder Bay, Canada. Yongjun Lu is accompanied by OGS colleagues Robert Cundari (left) and Mark Puumala (right).

10A. 3D ARCHITECTURE OF THE WESTERN YILGARN CRATON

Theme 2 and 3, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture.

This project is a major initiative by the Geological Survey of Western Australia (GSWA) to integrate the results of 1:100,000 scale regional mapping, geochronology and geochemistry with newly acquired high-quality geophysical data, including gravity and aeromagnetic data, and deep seismic and magnetotelluric surveys.



High-temperature deformation in the Lakeside granite complex, Murchison domain, Yilgarn craton.

Aims:

The aims of the project are to integrate the data into a 4-dimensional, integrated model of crustal evolution for the western Yilgarn Craton, and to derive a better understanding of the mineralisation processes for this region, how the crust links to underlying lithospheric mantle, and what relationships this piece of lithosphere has with the more highly endowed, eastern part of the craton (Eastern Goldfields Superterrane (EGS)).

Context and rationale:

The Yilgarn Craton of Western Australia is a large and highly complex piece of Archean crust with a long history extending from 4.4–2.6 Ga. It is locally well endowed with a variety of mineral deposits, particularly gold and nickel in the EGS. Previous work has identified a number of lithostratigraphic terranes interpreted to have had distinct crustal histories prior to tectonic amalgamation at ca 2.65 Ga. However, recent work by the GSWA in the northwestern part of the craton has identified a long-lived, autochthonous history of crustal development there, including episodes of volcanism, granitic magmatism, shearing and gold mineralisation that are similar in composition and temporal development to those further east, in what has been interpreted as the accreted, younger part of the craton (EGS). This, together with a number of other features of the surface geology, suggests there are significant problems with current models of crustal development through arc-accretion tectonics.

This project incorporates 2-D and 3-D imaging, modelling and analysis of newly acquired deep seismic, magnetotelluric, gravity, and aeromagnetic data along three linked transects totalling 700 km in length across the northwestern part of the Archean Yilgarn Craton, Australia. These geophysical data will be synthesised in conjunction with new geological data to develop an integrated lithospheric model of the Narryer and Youanmi terranes, and their relation to the Eastern Goldfields Superterrane. Additional studies will include integrated analysis of Lu-Hf in zircons from dated surface samples in order to better understand the roles of juvenile mantle additions to the crust and crustal recycling, and when these different, but possibly linked, factors occurred. The project involves close collaboration between staff of the Geological Survey of WA and researchers at Macquarie and UWA.

The proposed research project will apply well-established, existing research technologies to the previously poorly studied, and underexplored, northwestern part of the Yilgarn Craton: it is the first study of this kind to cover over more than half of the craton. The project is further innovative in developing an integrated research framework from mantle through to crust, involving a team of researchers with different expertise at a variety of scales.

High-temperature deformation in the Yalgoo granite dome, Murchison domain, Yilgarn craton.

PROGRESS DURING 2012

Work on the Yilgarn craton in 2012 has focused on the interpretation of the Youanmi seismic reflection survey (http://www.dmp.wa.gov.au/11799.aspx) – a collaboration between the Geological Survey of Western Australia (GSWA) and Geoscience Australia. Activities included field work along the seismic traverses with the aim of relating geological observations to structures imaged in the reflection data.

The GSWA-funded Research Associate position within CCFS has been filled in 2012. Dr Huaiyu Yuan, currently at the University of

Typical Yilgarn landscape near Golden Grove, Murchison domain, Yilgarn Craton.

California's Berkeley Seismological Laboratory, will join CCFS in 2013. Employed through Macquarie University, Dr Yuan will be based at the Centre for Exploration Targeting at the University of Western Australia in Perth, where he will work on imaging the structure of the Australian lithospheric mantle.

AIMS AND WORK PLAN FOR 2013

A one-day workshop led by the Geological Survey of Western Australia and Geoscience Australia on 27 February will present the results of the new seismic reflection and magnetotelluric data collected along the Youanmi and Southern Carnarvon seismic traverses across the northern Yilgarn Craton in Western Australia. A series of abstracts covering the preliminary interpretation of the seismic reflection data as well as magnetotelluric data, forward models and inversions of potential field data will become available on the GSWA website on the day of the workshop*. Using the preliminary results from the interpretation of the seismic reflection survey and other geophysical datasets and models, Dr Ruth Murdie and Dr Klaus Gessner will develop a 3D structural model of Earth's crust in the northern Yilgarn.

** Youanmi and Southern Carnarvon seismic and magnetotelluric (MT) workshop 2013: extended abstracts, compiled by S Wyche, T.J. Ivanic and I. Zibra: Geological Survey of Western Australia, Record 2013/6.*

10B. ZIRCON LU–HF CONSTRAINTS ON PRECAMBRIAN CRUSTAL EVOLUTION IN WESTERN AUSTRALIA

Theme 2, Earth's Evolution, contributing to understanding Earth's Architecture.

Modern geochronology has led to substantial advances in understanding the Precambrian geological evolution of Western Australia. However, in many cases it is unclear how rocks or terranes of similar age might be related. This project will obtain and integrate zircon Lu–Hf isotope data with other geological, geochemical and geophysical information to understand the evolution of the continental crust in specific areas of Western Australia.

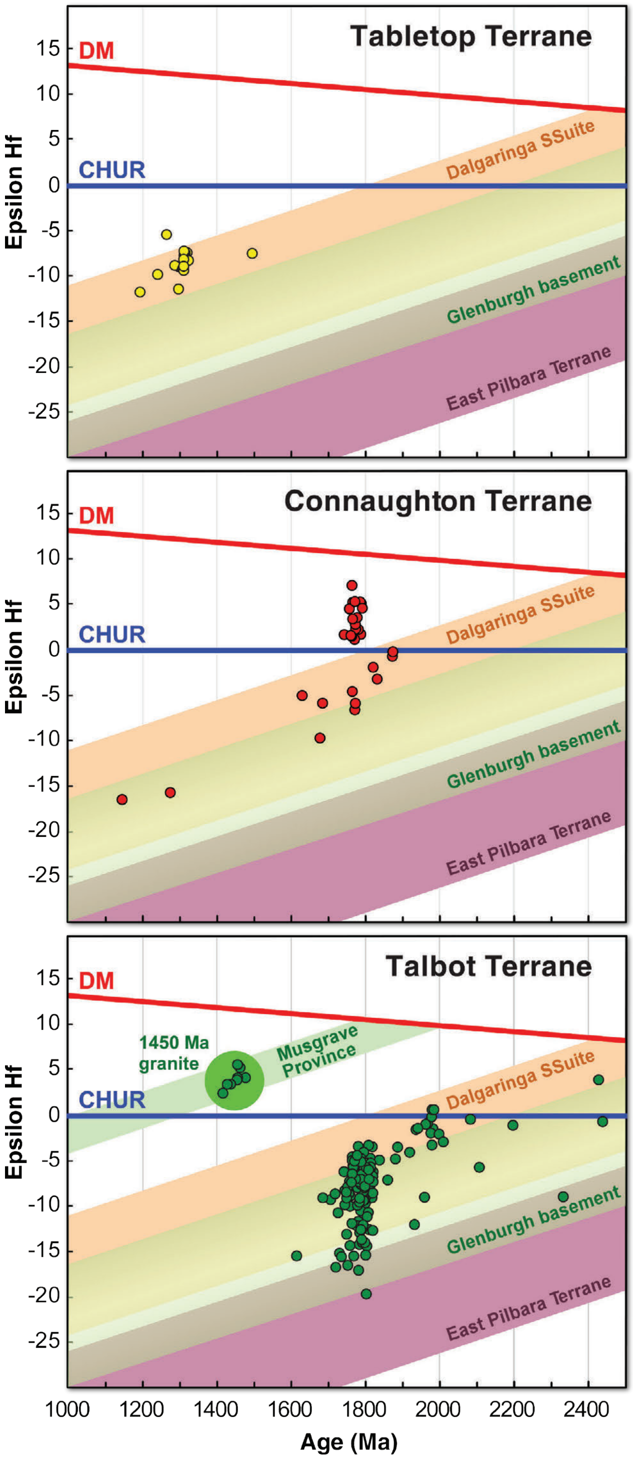
Zircon Lu–Hf analyses provide insights into the relative contributions of juvenile sources and recycled crust to the continental crust through time, and 'Event Signature' curves permit the evolution of different crustal domains to be visually compared. Integrating these constraints with other isotopic and geochemical information, geological mapping, and recently acquired geophysical datasets will advance our understanding of geodynamics and test hypotheses of tectonic evolution. Efforts will be aimed at addressing specific geological questions in key areas, particularly along the new geophysical transects, as well as in under-explored regions (e.g. The Albany–Fraser and Capricorn Orogens) where the new information will improve the targeting of mineral exploration.

Measurement of hafnium isotopes in zircon crystals allows determination of the Hf isotope ratio at the time of zircon crystallisation. The ability to generate large amounts of data for zircons of a range of ages (within single crystals, single samples, and by compiling data from several samples) means that time-space variations in crustal evolution can be readily evaluated. The project will include analysis of detrital zircons in sedimentary rocks as well as zircons with multiple growth stages in both igneous and metamorphic rocks. In collaboration with GEMOC, isotopic analyses will be performed by laser-ablation ICPMS on zircons selected from the GSWA archive of >1000 samples dated using SHRIMP. This is the first time in Western Australia that Lu–Hf isotope data obtained on this scale can be integrated with geological and geochemical data and newly acquired gravity, aeromagnetic, seismic and magnetotelluric datasets.

PROGRESS DURING 2012

Zircons for Lu–Hf analysis were selected from the Pilbara and Yilgarn Cratons, the Rudall and Musgrave Provinces, the Albany–Fraser Orogen, and the Kimberley and Amadeus Basins. About 1300 analyses, from about 100 samples, were obtained in 2012. The results were integrated with existing isotope data, published in refereed journal articles and GSWA Records and Reports, and made available via GSWA's web site.

New zircon Lu–Hf data from the Rudall Province indicate that its three constituent terranes (Connaughton, Tabletop, and Talbot) had similar source compositions, and that the isotopic compositions and ages of inherited zircons in Rudall Province rocks are similar to those of the Capricorn Orogen and other proximal regions of the West Australian Craton. This means that it is unnecessary to invoke a North Australian Craton (e.g. Arunta Orogen) origin for the terranes of the Rudall Province. Furthermore, 1.9 Ga Hf model ages and mantle-like oxygen isotopes in a 1450 Ma granite from the Rudall Province indicate crust formation at that time and suggest the existence of a ca 1.9 Ga underplate, similar to that recently inferred for the Musgrave Province.



Initial $^{176}Hf/^{177}Hf$ evolution diagram for Rudall Province samples compared to potential source regions. Most Arunta Orogen data are dissimilar to those for the Rudall Province, Capricorn Orogen, and East Pilbara Terrane.

New Lu–Hf results, together with existing isotope data, define model-age peaks in the central and eastern Yilgarn Craton at ca 4200, 3500, 3100, 2800, and 2700 Ma. The 3100, 2800, and 2700 Ma peaks likely correspond to crust formation events. The earliest peak is not recorded in the Eastern Goldfields Superterrane, indicating that crust formation in this region postdated the earliest development of the Yilgarn Craton. The Eastern Goldfields Superterrane and Southern Cross Domain appear to have been subjected to major heating at ca 3100 and 2800 Ma, accompanying the generation of juvenile crust in the east and reworking of older crust in the west. However, the events at ca 3100 and 2800 Ma are recorded by both granite suites and greenstone successions across the craton, whereas the ca 2700 Ma event is most evident in the Eastern Goldfields Superterrane.

OUTPUTS

Publications:

CCFS publications #61, 68, 78, 185, 209, 256, 264, 265, 266, 267, 274

AIMS AND WORK PLAN FOR 2013

The project will continue to generate Lu–Hf isotope data, and integrate them with geological and geochemical data as well as geophysical datasets. The research will be focused in 'greenfields' areas where little information presently exists. Based on results obtained, it is likely that new samples will be collected during the normal course of GSWA fieldwork to address specific geological problems.

Foundation Centre Technology Development projects (Whole-of-Centre projects)

1. CAMECA ION MICROPROBE DEVELOPMENT: MAXIMISING THE QUALITY AND EFFICIENCY OF CCFS ACTIVITIES WITHIN THE UWA ION PROBE FACILITY

The Centre for Microscopy, Characterisation and Analysis at UWA is home to two state-of-the-art Secondary Ion Mass Spectrometers: the CAMECA IMS 1280 large-radius ion microprobe, for the high-precision analysis of stable isotopes in minerals, and the CAMECA NanoSIMS 50 for imaging mass spectrometry at the sub-micron scale. In addition to the analytical capabilities located at the other nodes, the CCFS is poised to become a world-leader in *in-situ* stable isotope analysis, and it is therefore essential that the data and interpretations be of the highest quality.

This project provides a dedicated Research Associate for the development of CCFS activities utilising the CAMECA Ion Microprobes at UWA, thereby increasing the capacity of the facility, enabling a higher degree of interaction and participation on projects, and allowing greater synergy with other CCFS node facilities. The Research Associate will play an integral role in experimental design, planning, sample preparation, and the acquisition, processing and interpretation of data. The complex nature of the Ion Microprobes demands a high-degree of technical ability, while an understanding of the aims of the individual projects requires a deep understanding of geological and geochemical processes. This position is fundamental to the generation of high-quality, in situ, elemental and isotopic data for a diverse range of projects and, as such, represents a significant investment into the overall success of the CCFS.

PROGRESS DURING 2012

Dr Laure Martin was appointed to the position of Research Associate within the CMCA to facilitate the use of the ion probes by the CCFS. With a considerable background in geological SIMS analysis, Dr Martin has already made valuable contributions to the development of standards and analytical protocols, while providing assistance in sample preparation, data acquisition, and data processing. Next to this service role, Dr Martin also carries out her research on the evolution of fluids in subduction zones and mineral/fluid interaction in metamorphic rocks.

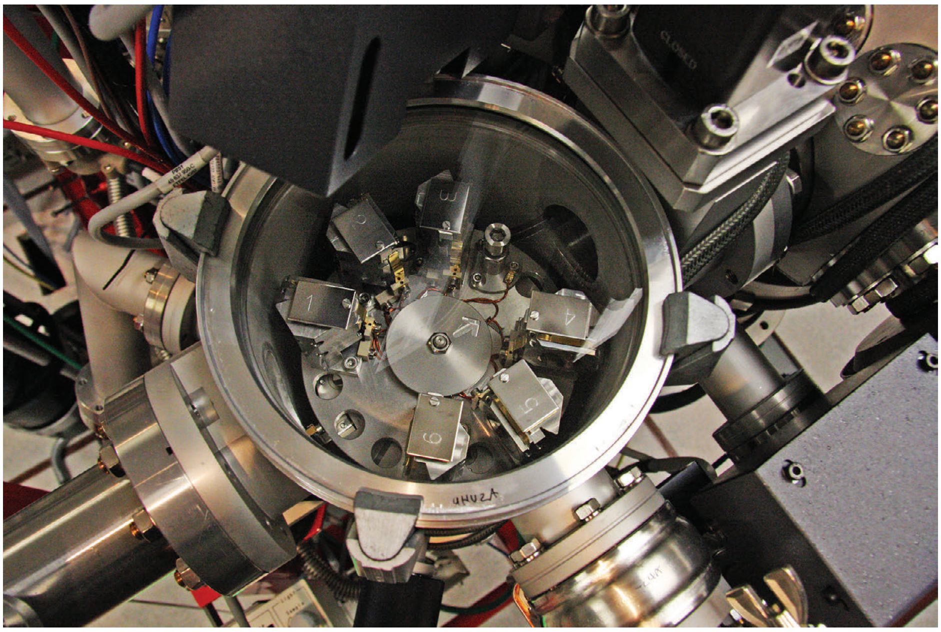
The Ion Probe Facility also employed Dr Rong Liu as a Senior Research Officer.

The ion probe facility has been highly active during the past year, with CCFS projects accounting for more than 30% of the available analysis time. See *Technology Development*.

Professor James Farquhar of the University of Maryland spent six weeks in the Ion Probe Facility as a UWA Gledden Visiting Senior Fellow Professor Farquhar carried out S isotope research using the Cameca IMS 1280. *(pictured below)*

AIMS AND WORK PLAN FOR 2013

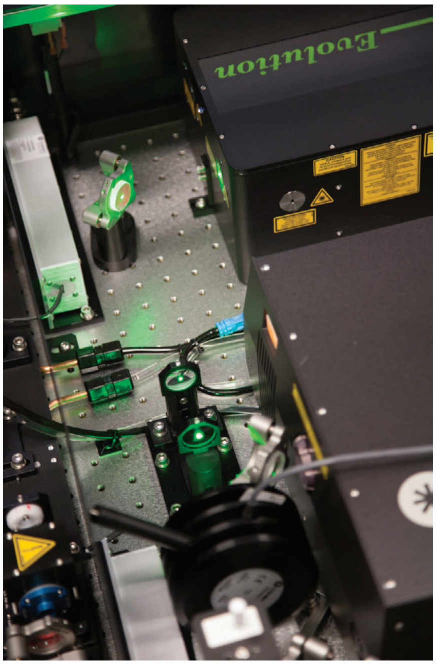
Ion Probe Facility will continue in the development of standards, protocols, and the training of new staff where appropriate.

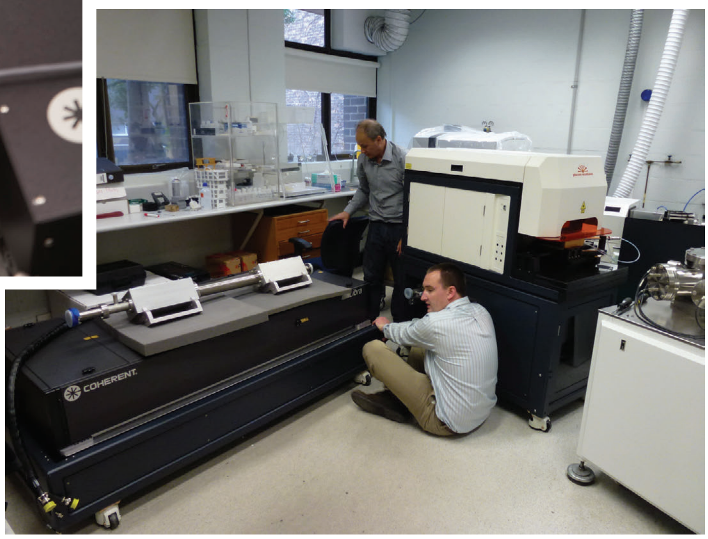


2. FRONTIERS IN INTEGRATED LASER-SAMPLED TRACE-ELEMENT AND ISOTOPIC GEOANALYSIS

The project aims to enhance the world-class facility for *in-situ* isotopic and elemental analysis at GEMOC, in order to maintain Australia's LAM-ICPMS capabilities at international standards, and to advance beyond it in some aspects. The advances will be based on femtosecond-laser sampling and the coupling of instruments for simultaneous analysis.

Research in CCFS depends critically on world-class geochemical and high-pressure experimental infrastructure. The on-going improvement and refinement of the geochemical methodologies and techniques is driven by the CCFS research program and the acquisition of new instrumentation. In 2010 GEMOC was awarded a $1.5M LIEF grant, to purchase a femto-second laser sampling system, a new quadrupole (Q-)ICP-MS and a single collector sector-field (SF-)ICP-MS. The stated aim of the LIEF proposal was to investigate ways of linking these instruments in different combinations with laser sampling, to achieve simultaneous analysis of two isotopic systems or trace-element data and isotopic data. Examples drawn from the LIEF bid illustrate the potential range of combinations, and their usefulness. Combinations of instruments can be achieved by splitting the ablation gas into two lines downstream from the ablation chamber, and using different instruments to analyse the two gas fractions.





Installation of the Photon Machines fs198 laser system in June 2012.

This will allow a range of innovative analytical approaches, including:

1. U-Pb dating of zircon and other U-bearing minerals + Hf-isotope analysis
2. Os-isotopes of sulfide grains + trace elements (Q-ICP-MS) or S-isotopes (SF-ICP-MS)
3. Sr-isotopes (MC-ICP-MS) + Pb isotopes (SF-ICP-MS) in feldspars
4. "Non-conventional" stable isotopes (e.g. Li, Si, Mg, Ca, Fe, Ga, Cu, Zn, Mo, Se, Tl and other still unexplored systems; MC-ICP-MS) + trace elements (Q-ICP-MS)

With this enhanced capability, the plan is to expand the stable-isotope program, including:

- Mg, Fe, Si and Li isotopes in olivine from mantle-derived rocks as tracers of mantle processes: melting, metasomatism and the recycling of crustal material
- Mg, Ca and Si isotopes in chondrules, Ca-Al inclusions and other silicate phases in meteorites, as tracers of cosmogenic processes and their timescales
- Mg and Li isotopes in speleothems and microfossils to constrain past climate change
- Si isotopes in quartz from crustal rocks to study hydrothermal processes, and in SiC from kimberlites, to understand the fractionation of Si and C in mantle processes
- Cu, Fe, Zn, Mo, Se, S isotopes in ore systems, including sea-floor "black smoker" chimneys, to investigate biological and other low-T fractionation processes

In each case the collection of trace-element and isotopic data from the same analytical spot will provide better constraints on each data than if they were collected from different spots.

The development of new methodologies and applications in this project will provide more analytical options for CCFS researchers and create new research opportunities across all CCFS themes. This facility and the innovation that it represents will help maintain the high profile that Australian geoscience has enjoyed internationally, making it easier to attract high-quality researchers, postgraduate students and industry-related research funding.

PROGRESS DURING 2012

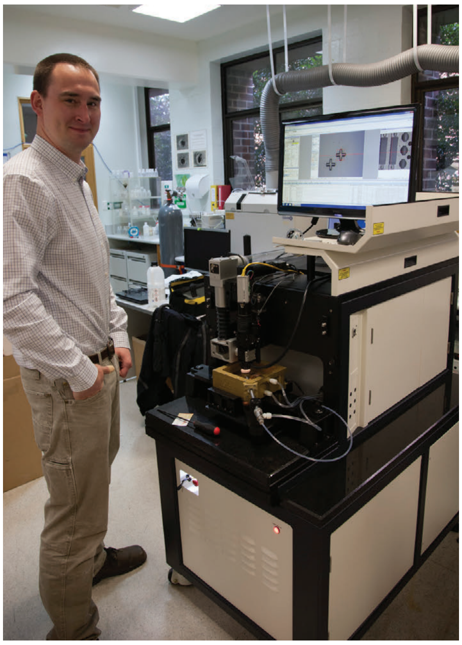
Planned innovations in the Geochemical Analysis Unit (GAU) at Macquarie University in the first term of the Centre of Excellence Core to Crust Fluid Systems, are based on new instruments that have been purchased with funding provided by an ARC LIEF grant. This equipment is needed to proceed with the development of the 'split-system' techniques in which two mass spectrometers (a MC-ICP-MS and an ICPMS) will be connected to a common laser source for novel simultaneous measurement of geochemical parameters. The current status of this new instrumentation is as follows:

Q-ICP-MS: An Agilent 7700cx Q-ICP-MS was installed in 2010, joining the existing stable of Q-ICPMS (3) and MC-ICPMS (2) instruments.

Femtosecond Laser Microprobe: An order was placed for a Photon Machines fs198 laser system in August 2011 and the instrument was installed in June 2012. The laser system has not been fully commissioned due to recurring damage to optics in the beam delivery system. A redesigned beam delivery system will be installed in January 2013.

SF-ICP-MS: Following the order of the femtosecond laser, an order was placed for the Nu Attom high resolution SF-ICP-MS. The features of this instrument include continuously variable high-resolution capabilities, fast electrostatic scanning/jumping and a fully laminated, high-scan-speed magnet. Fast data acquisition is critical in the measurement of the transient signals produced by laser ablation and the performance and operation of the magnet in fast scanning mode during evaluation of the Nu Attom proved to be critical for the types of applications for which it is to be used. The Nu Attom was delivered in December 2012 and will be installed in January 2013.

In addition to the femto-second laser, a Photon Machines Excite 193nm excimer laser system was installed in June 2012. Since this time the Excite has been used with the Agilent 7700 for all *in-situ* U-Pb and trace-element analytical work.



Photon engineer Ben Staal installing the new Photon Excite Excimer laser ablation system.

The advancement of geochemical methodologies and techniques in the Geochemical Analysis Unit at Macquarie University continues to be a significant factor in the establishment of new research initiatives. While the issues with the femto-second laser system were being addressed by the manufacturer and with the delays in the delivery of the Nu Attom, a number of development projects were undertaken in support of CCFS-funded research programs. Specific developments in 2012 include:

- revision of GLITTER data reduction software and *in-situ* methodologies for trace-element analysis and U-Pb isotope measurements
- refinement of Li isotope methodologies for ultramafic rocks and adaptation to other applications (A-type granites, corals)
- on-going development of the procedures for the measurement of Mg isotope composition of garnet (development of potential microbeam standards for laser ablation MC-ICP-MS or SIMS)
- development of *in-situ* methods for the analysis of Re-Os isotopes in Pt-rich alloys and sulfides
- development of U-Pb geochronology of apatite
- refinement of *in-situ* Sr and Nd isotope ratio measurement of apatite
- determination of error budgets for isotope ratio measurements using Monte Carlo techniques
- development of whole-rock trace element analysis of fused glasses by laser ablation ICPMS
- development of new sample preparation methods for geochemical and isotope analysis in the GAU

AIMS AND WORK PLAN FOR 2013

- Commissioning of femtosecond laser system (January 2013)
- Installation and commissioning of Nu Attom high resolution SF-ICP-MS (January 2013).
- The appointment of a Research Associate (Post-doctoral position) with existing expertise in laser sampling and ICP-MS analysis to undertake method development of the femtosecond laser system.
- Establish and undertake the first phase of an experimental program to investigate fundamental properties of femtosecond ablation processes in geological materials, focusing on laser-induced isotopic fractionation.
- Transfer of *in-situ* methodologies for trace-element analysis and U-Pb isotope measurements from the Q-ICP-MS to the Nu Attom.
- Development of split-stream laser ablation analysis using Q-ICP-MS (U-Pb isotopes) and MC-ICP-MS (Hf isotopes)
- Refinement of Li isotope methodologies and expansion to other applications.
- On-going development of the procedures for the measurement of Mg isotope composition of garnet.

3. OPTIMISING MINERAL PROCESSING PROCEDURES: FROM ROCK TO MICRO-GRAINS

Liberation and recovery of accessory mineral components of any type of rock, are critical stages in sample preparation for many types of geochemical and geochronological analysis. This project involves the development of new separation methods using state-of-the-art instruments to fragment rocks into their constituent components. Implementation of the new techniques will improve yields of high-purity mineral separates and provide the essential materials for analysis in the CCFS research and industry collaborative projects.

Aims: Liberation and recovery of accessory mineral components of any type of rock, for geochemical and geochronological analysis.

The aims of many CCFS projects require the separation of accessory minerals from a range of different rock types. There are several major issues with these processes: breakage of grains, potential laboratory contamination, and the concentration and separation of extremely fine-grained phases. These problems can now be reduced if not eliminated by using new technology and newly developed procedures: (1) electrostatic pulse disaggregation (EPD); (2) the use of disposable sieves; (3) hydroseparation procedures for ultrafine material.

The first selFrag instrument in Australia was installed in GEMOC in May 2010. SelFrag uses EPD to break rock samples into their component phases and produces better liberation of mineral phases, especially accessory minerals, than conventional crushing procedures. Because disaggregation proceeds along grain boundaries, it greatly increases the proportion of unbroken grains. Disaggregation takes place inside a large Teflon-lined container, which is easily cleaned to prevent cross-contamination.

Examples:

- Zircon separation: Increasing the yield of zircon crystals for geochronology. The liberated zircon crystals are virtually unbroken and the surfaces are very clean. In contrast to mechanically crushed samples, no remnants of other minerals such as biotite have been found on the zircon surfaces.
- Separation of Platinum Group Minerals from chromite ores. Conventional mechanical crushing of compact chromite samples produces multi-mineral grains and excessive amounts of dust. The recovery of PGMs is very difficult. Selective fragmentation using selFrag, on the other hand, produces only small amounts of fines and no dust. Breakage occurs preferentially along grain boundaries and inclusions, thus liberating the platinum minerals.
- Separation of minor components from complex rocks, e.g. kimberlites and diamondites

PROGRESS DURING 2012

Since its installation selFrag has been used for a range of applications including zircon separation, the analysis of grain size and shape of phenocrysts in volcanic rocks, and the liberation of trace minerals from a range of mantle-derived and crustal rocks (e.g. alloys in mantle peridotites, platinum group minerals in chromitites). selFrag has increased the yield of zircon crystals and the liberated crystals are virtually unbroken and the surfaces are very clean. This has enabled the dating of rocks with low zircon abundances and expanded the application of the U-Pb technique to mantle geochronology.

In 2012 selFrag was used to process more than 190 samples for 45 different research projects, including CCFS research projects (TARDIS; PhD projects; Honours), TerraneChron and users from other institutions (e.g. ANU, Wollongong, NSW Geological Survey). Users are trained in the operation of selFrag and mineral separation procedures, and the training program is an important aspect of the facility's operations and achievements. The defragmentation of each new rock type requires the development and refinement of experimental procedures depending on grain size, mineralogy and the amount of sample. A handbook of the most successful experimental conditions is being compiled. This is a valuable resource for users of all levels of experience and has contributed to the efficient functioning of the facility.

selFrag is the centrepiece of the facility for mineral separation at GEMOC, but for most samples it is the first stage in the separation process. In this project the following separation methods using material produced by selFrag have been developed and are being refined:

- sample sieving using disposable plastic/nylon sieves to prevent (cross-) contamination of samples
- heavy liquid mineral separation using aqueous solutions of the nontoxic chemical sodium polytungstate (SPT) for heavy-mineral separation.
- magnetic/paramagnetic separation using Frantz® Magnetic Barrier Laboratory Separator for separation of dry materials according to magnetic susceptibility, exploiting either paramagnetic or diamagnetic properties => output fractions: magnetic, paramagnetic and non-magnetic.
- micropanning equipment is available for further concentration of phases with densities slightly different from their matrix – best suited to grains >200 microns.

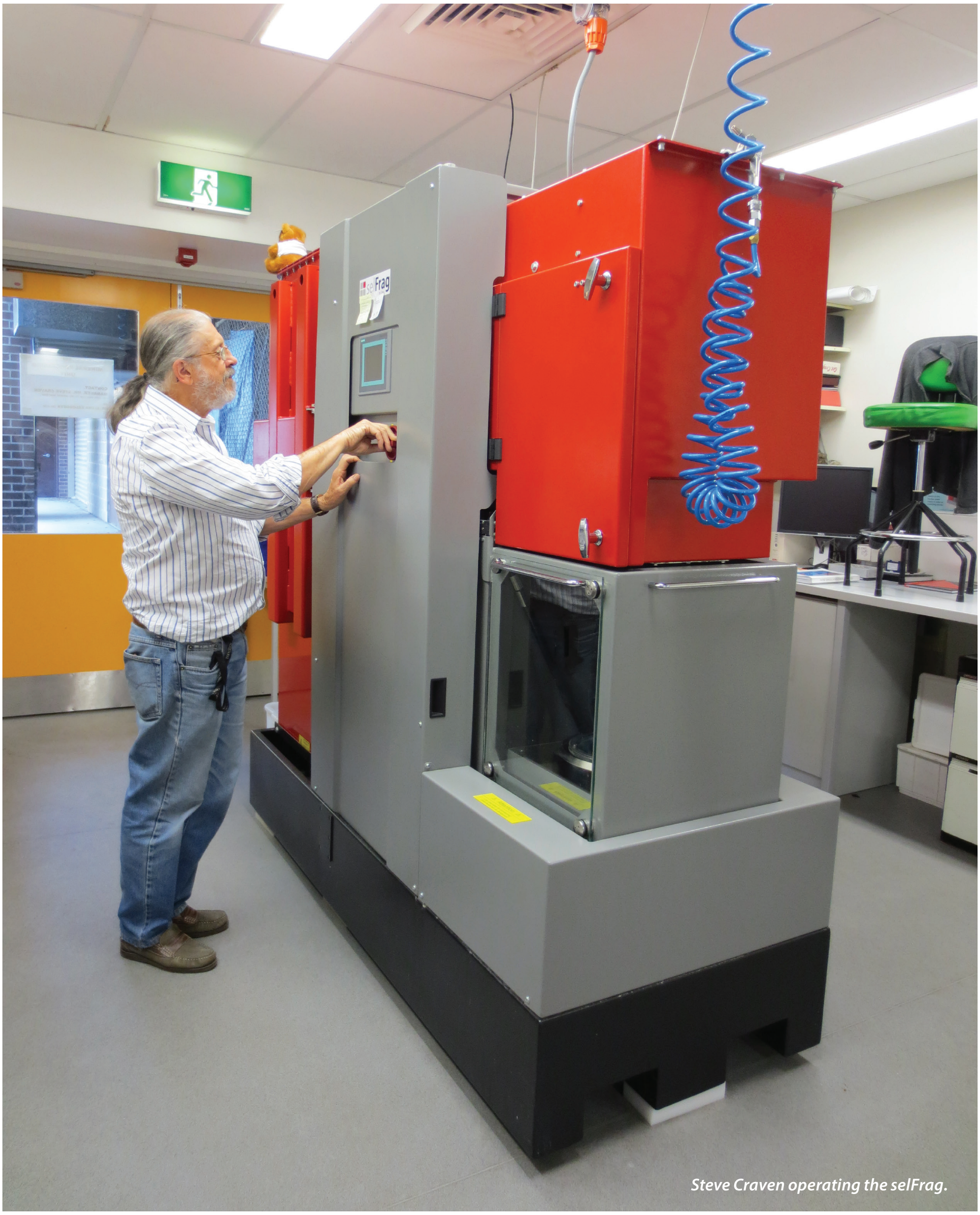
A hydroseparator (CNT-HS-11, manufactured by CNT Corporation, Canada) was purchased in 2011 and installed in 2012. This device processes samples of extremely fine-grained (down to a few microns) water-insoluble particles/grains to produce "heavy-mineral concentrates" from material of similar physical properties. Methods are being developed to process the ultra-fine material from selFrag to concentrate rare accessory phases such as alloys in mantle peridotites and platinum group minerals in chromitites.

AIMS AND WORK PLAN FOR 2013

The principal objectives for 2013 are to service the CCFS research programs requiring the production of high-purity mineral separates and to continue the transfer of the new mineral separation technologies by training researchers from other national and international universities.

Planned development and refinement of procedures and protocols for selFrag include:

- Expansion to new rock types as required
- Use of small volume cell to extract mineral inclusions
- Use of 'sandwich-sieve' to improve yield of ultra-fine materials from selFrag
- Adaptation of the hydro-separator to the separation of sub-10 µm zircon grains



Steve Craven operating the selFrag.

ECSTAR projects

The following projects are supported by ARC Post-Award funds allocated mid 2011 for early-career researchers. These are ARC ECSTAR Fellowships (Early Career Startup Awards for Research). The two appointees in 2011 were Dr José María González-Jiménez and Xuan-Ce Wang and a third, Takako Satsukawa, was appointed in 2012.

ECSTAR PROJECT 1. PLATINUM-GROUP MINERALS: MONITORS OF DEEP EARTH PROCESSES

José María González-Jiménez: Supported by ARC CCFS ECSTAR (commenced 2011)

Themes 2 and 3, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

This project interfaces with Foundation Project 1, The TARDIS-E Project: "*Tracking Ancient Residual Domains in the Silicate-Earth*". The Re-Os isotopic system in Platinum-Group Minerals (PGM) from Earth's mantle potentially provides the most robust record of long-term interactions between distinct regions of Earth's interior. However, the reliability of this approach needs further testing, because the chemistry of many PGM hosted in mantle-derived rocks has been modified by hydrothermal alteration or metamorphism during or before excavation of the mantle rocks from deep Earth to surface. The fact that PGM of different suites of mantle rocks exhibit variable scales of heterogeneity in Os isotopes suggests that post-magmatic alteration could also disturb the Re-Os compositions of these minerals. This project uses a combination of classical mineralogical methods and novel micro-analytical techniques for isotopic measurements to test the robustness of the Re-Os system in PGM from mantle-derived rocks affected by variable degrees of hydrothermal alteration and metamorphism, and thus to constrain the interpretation and applications of Os-isotope data.

José María González-Jiménez enlightening the eager crowd about the origins of SE Australian chromitites.

PROGRESS DURING 2012

The sampling strategy for 2012 has been fully accomplished, and new samples of chromitites were collected *in-situ* by Dr González-Jiménez from ophiolites exposed in the Coolac Serpentinite Belt in southern Australia (low-temperature ocean-floor serpentinisation), the Vizcaino Peninsula in northern Mexico (mid-grade metamorphism) and the Dobromirtsi, Jakovitsa, Avren and Golyamo Kamenyane Ultramafic Massifs in southern Bulgaria (mid-to-high grade metamorphism). The preliminary petrographic study of the chromitites has revealed for the first time the presence of grains of laurite in the chromitites of the Coolac Serpentinite Belt. New PGM species that include members of the solid solutions of laurite (RuS_2)-erlichmanite (OsS_2) and irarsite(IrAS)-hollingworthite (RhAsS) were identified in the chromitites of the Vizcaino Peninsula. Previous studies had neglected to record the presence of these types of PGM. Abundant PGM grains were also identified and analysed for Re-Os isotopes in the chromitites of Dobromirtsi. These were treated and interpreted in a paper submitted to a special volume of Gondwana Research on *"Ophiolitic Peridotites, Ultrahigh Pressure Minerals and Podiform Chromitites: Their Origin and Evolution"*.

This project has also made progress in understanding the link between the mechanism of alteration of chromite and how the PGMs are altered. The analysis of the chromitites of the Golyamo Kamenyane Massif (Bulgaria) revealed that alteration of chromite takes place mainly during retrograde rather than prograde metamorphism, as previously proposed by many researchers (*CCFS publication #176*). The identification of different patterns of alteration of the chromite during metamorphism was used as a benchmark for the analysis of the mobility of trace and minor-elements in an aim to understand the types of fluids involved in the alteration process. This part of the work was carried out in collaboration with visiting PhD students Vanessa Colas (University of Zaragoza, Spain) and Ria Mukjerhee (Jadavpur University, Kolkata, India). Their preliminary results have shown that the minor elements may be significantly mobilised during metamorphism, providing a new tool for identifying metamorphic alteration in chromitites that, at least in terms of major elements, appear not to be altered.

Finally, the application of the selFrag electrostatic rock disaggregation technique to whole-rock chromitite samples has allowed the identification of accessory zircons that allowed better constraints on the reliability of the Re-Os model ages of the PGMs. The preliminary results on the Dobromirtsi chromitites show that Re-Os model ages of primary PGM and Lu-Hf model ages obtained in the zircons match well, indicating the reliability of primary PGM for understanding magmatic events in the mantle.

AIMS AND WORK PLAN FOR 2013

The strategic plan for 2013 aims to expand the set of PGM analysable for *in-situ* Re-Os isotopes by sampling PGM-bearing rocks from ultramafic bodies with well-established P-T conditions of post-magmatic alteration. This involves sampling of chromitites from ophiolites of southern Chile metamorphosed in amphibolite-facies. It also is planned to continue expanding the set of PGM potentially useful for Re-Os isotopes and zircons by obtaining concentrates from whole-rock samples using the combination of selFrag electrostatic rock disaggregation plus hydroseparation, both facilities being currently developed at the Geochemical Analysis Unit at CCFS/GEMOC. The new development of hydroseparation at CCFS/GEMOC is being carried out in collaboration with two Spanish labs from the University of Barcelona and Granada, which already have experience in the use of this technique. This is being carried out in close collaboration with CCFS/GEMOC and overseas collaborators. The project aims for 2013 also mesh with current research projects of undergraduate and postgraduate students under the supervision of the project leader. These include students from Earth Sciences departments of international Universities: National University of Mexico (UNAM, Mexico), Universities of Zaragoza and Barcelona (Spain) and the Geological Institute of the Bulgarian Academy of Science (BAS, Bulgaria). Communication of results is planned to be mainly through high-profile international scientific journals and presentations in high-profile international geoscience conferences.

José María González-Jiménez and Elena Belousova collecting chromitite samples in the Coolac Serpentinite Belt in southern Australia (beware of gabro monsters).

ECSTAR PROJECT 2. ESTABLISHING THE LINKS BETWEEN PLATE TECTONICS AND MANTLE PLUME DYNAMICS: MESSAGE FROM THE LATE CENOZOIC LEIQIONG BASALTS IN SE ASIA

Xuan-Ce Wang: Supported by ARC CCFS ECSTAR funding and NSFC (National Science Foundation of China) Project grant (commenced 2011)

Theme 2, Earth's Evolution, contributing to understanding Earth's Architecture and Fluid Fluxes.

Whether mantle plumes and plate subduction are genetically linked is a fundamental question that impinges on our understanding of how Earth works. Late Cenozoic basalts in Southeastern Asia are globally unique in relation to this question because they occur above a seismically-detected thermal plume adjacent to major deeply-subducted slabs that also have been imaged seismically. The main goal of this project is to examine the petrogenesis of late Cenozoic continental flood basalts (CFBs) that are located directly above the plume-like mantle seismic structure, and spatially close to major subduction zones in southeastern Asia. We will take a multidisciplinary approach, determining the chemical composition of the primary melts of the basalts, characterising the chemical compositions of their mantle source, and examining the temporal-spatial variations in the geochemical characteristics of the Leiqiong CFB. We will also test the geological and thermochronological evidence for lithosphere uplift. The results will be used to test major predictions of plume models as well as other end-member geodynamic models for such unique CFBs. This study will advance our understanding of (1) the thermochemical state of the deep Earth where a lower-mantle-rooted plume-like seismic structure exists unusually close to subducted slabs; (2) relationships between geophysical and geological manifestations of mantle plume activities at mantle downwellings; (3) the nature and origin of enriched mantle source regions; and (4) the behaviour of mantle plumes at plate boundaries and inter-relationships between mantle plume dynamics and plate tectonic processes. Knowledge obtained in this project will help to address one of the most fundamental questions in geodynamics: how the two major processes of whole-mantle convection, i.e. deep subduction that drives mantle downwelling, and mantle plumes that drive mantle upwelling, relate to and interact with each other.

PROGRESS DURING 2012

During 2012, we acquired high-precision Pb, Sr, Nd, and Os isotope data for the Hainan flood basalts and compiled all published geochemical and isotopic data on the late Cenozoic basalts from the South China Sea and adjacent area. The most important finding for this year is that the source of the late Cenozoic basalts in this region contained both an ancient (4.5-4.4 Ga) mantle volume and a young (0.2-0.5 Ga) recycled component. Our work shows that less-contaminated and synchronous basaltic samples from the Hainan-Leizhou peninsula, the Indochina peninsula and South China Sea seamounts share the same isotopic and geochemical characteristics. They have FOZO-like Sr, Nd, and Pb isotopic compositions (the dominant lower mantle component) and plot within the field of typical plume-induced basalts (e.g. Hawaiian lavas). These basalts have primitive Pb-isotopic compositions that lie on, or very close to, 4.5- to 4.4-Ga-old geochrons on a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram, suggesting a mantle source developed early in the Earth's history (4.5–4.4 Ga). These new findings, along with existing geophysical, petrological, and geochemical evidence, confirm the existence of a lower mantle-rooted plume (the Hainan plume) fuelled by an ancient reservoir at the CMB. Furthermore, the geochemical modelling of the isotopic evolution of recycled components has several important implications. First, the recycled oceanic crust may be the dominant factor controlling Pb isotopic heterogeneities in OIB sources. Second, extremely high $^{187}Re/^{188}Os$ ratios recently reported in oceanic crust (80-675) would lead to very radiogenic Os isotopes ($^{187}Os/^{188}Os$ = 2-12) over 1 Ga, suggesting that such a component cannot be present in pristine form in the LIS basalt source. Third, both ancient (ca 0.6 Ga) gabbro- and bulk oceanic crust-derived melts have distinctive Pb-Sr-Nd and Os isotopes that are significantly different from what we have observed in the natural LIS basalts. Overall, our modelling results show that the maximum age for the recycled components in the source of the LIS basalts is 0.5-0.2 Ga. This implies a mantle circulation at an average rate of about 1-3 cm/yr, which is similar to that of previous estimates for the Hawaiian mantle plume. The coexistence of an ancient mantle reservoir and young recycled materials in the young Hainan plume is consistent with the geophysical observation that this young plume is adjacent to deep subducted slab-like seismic structures just above the Core-Mantle Boundary. We speculate that the continued deep subduction and the presence of a dense segregated basaltic layer may have triggered the plumes to rise from the thermal-chemical pile. This study may therefore provide the first observational support for dynamic linkages between deep subduction and mantle plume generation.

AIMS AND WORK PLAN FOR 2013

In 2013, the core task is to conduct the chemical and isotopic analyses and to synthesise the all acquired geochemical, isotopic, and petrological data to examine the interplay between plume and lithosphere. The specific aims in 2013 are the following:

(1) To conduct chemical and isotopic analysis and $^{39}Ar/^{40}Ar$ dating on the drill-core samples of the Hainan basalts in order to examine temporal-spatial chemical variations.

(2) To conduct Re-Os isotopic and PGE chemical analysis on the mantle xenoliths hosted by the Hainan alkalic basalts that will help us to determine the age of the subcontinental lithospheric mantle beneath Hainan Island. This will enable us to quantify the contribution of sub-continental lithospheric mantle to the Hainan basalts.

(3) Through combining outcomes as stated in Aims 1 and 2 and existing data, we will examine the interplay between mantle plume and lithosphere.

(4) To synthesise all the geochemical, isotopic, petrological, geophysical, and geological data to unravel the possible effects of the Hainan plume on the opening and evolution of the South China Sea.

(5) To evaluate the effect of alteration on the whole-rock chemical isotopic compositions and to examine the relationship between chemical variation and depth in drill core samples. The results from the Hawaiian OIBs will help us to decipher the commonalities and differences between the Hainan and Hawaiian plumes.

OUTPUTS

Publications:

2012 CCFS publications # 16, 24, 156, 159, 193, 195, 270

Conference abstracts:

X.-C. Wang, Z.-X. Li, Q.-L. Li and X.-H. Li, A mantle hydrated by stagnated Pacific slab that produced intraplate continental flood basalts in northeastern China. Abstract, 34th International Geological Congress, Brisbane, 5-10 August 2012.

Xuan-Ce Wang in the field.

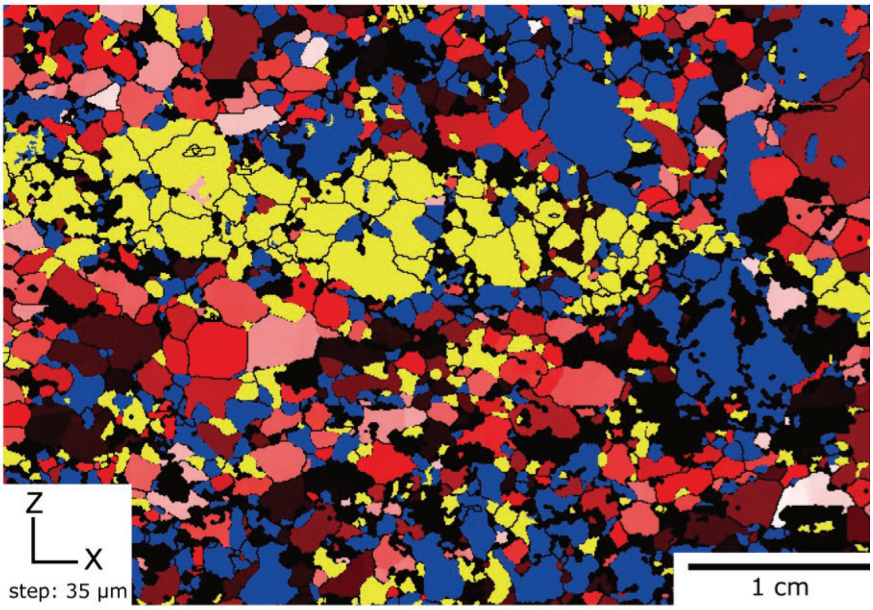
ECSTAR PROJECT 3. MAPPING THE DEFORMATION OF SUBCONTINENTAL LITHOSPHERE: THE EVOLUTION OF MICROSTRUCTURE AND FLUID-MELT-ROCK INTERACTION IN THE UPPERMOST MANTLE

Takako Satsukawa: Supported by ARC CCFS ECSTAR funding (commenced 2012)

Themes 2 and 3, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

This project interfaces with Foundation Project 1, The TARDIS-E Project: "*Tracking Ancient Residual Domains In the Silicate-Earth*".

The deep Earth water cycle is strongly coupled to plate tectonics, and the evolution of the uppermost mantle is commonly controlled by partial melting and/or refertilisation processes. The amount of water carried into the deep mantle by descending oceanic crust is relatively small, but even trace amounts of water affect physical and chemical properties such as melting temperature, rheology, deformation mechanism, electrical conductivity, etc.



EBSD map of a peridotite xenolith from Ichinomegata (NE Japan).

Cratons are domains of thick lithosphere with cold geotherms, which have remained stable for long geologic periods since their formation. The processes that result in the stability or destruction of the cratonic mantle roots are poorly understood, and are a major open question in geodynamics. In this project, we mainly focus on the rheology of the uppermost mantle and the history of the roots of ancient continents to provide new constraints on the rheological properties of the lithospheric mantle. The development of a systematic approach combining microstructural analysis, the mapping of Crystallographic Preferred Orientations (CPO), water contents, numerical modelling of the seismic properties of individual samples, and geochemical analyses of xenoliths from different lithospheric levels and different degrees of melt-rock interaction. Previous work by GEMOC has focused on geochemical analysis; we will develop a new methodology for mapping 'hidden' microstructures by combining these approaches.

This approach will provide new tools for the investigation of rock deformation, the rheological state of the mantle and the styles of mantle dynamics. As this project has just started, we are now characterising the microstructural evolution of mantle-derived rocks from the cratonic lithosphere by exploring the CPO mapping of a statistically representative sample set, which previously was well characterised geochemically.

AIMS AND WORK PLAN FOR 2013

1. To estimate water contents of peridotite xenoliths from Kaapvaal craton for the better understanding of water distribution beneath the craton, as existing water-content studies in this region have used limited numbers of samples.
2. To develop a robust model for the deformation history of the roots of ancient continents (subcontinental lithospheric mantle) by using the constraints derived from microstructural characteristics. These sample sets are from the North China Craton (NCC) and the Kaapvaal craton, and are well- characterised geochemically and petrologically.
3. To calculate CPO-derived seismic properties which will provide a unique basis for comparison with the detailed seismological data available in these areas.

Appendix 2: Independently funded basic research projects

Independently funded research projects within CCFS contribute to the long-term, large-scale strategic goals and play an important role in determining the shorter-term research plans. Research goals for each year are thus linked to the aims of funded projects. Summaries of the current independently funded CCFS-related projects are given below. For Industry funded Projects see *Industry Interaction p. 82.*

Multiple vertical tectonic movements in a continental interior: consequences of flat-subduction and foundering of an oceanic plateau?	**Z.X. Li**, M. Danisik, Y. Xu: *Supported by ARC Discovery (commenced 2011)* ***Summary:*** This project will investigate how the subduction of particularly thick oceanic crust impacts on the landscape, climate, structure and composition of the adjacent continent. It will help in understanding the history and distribution of mineral and hydrocarbon resources of similar provinces in Australia.
What lies beneath: Unveiling the fine-scale 3D compositional and thermal structure of the subcontinental lithosphere and upper mantle	**J.C. Afonso**, **Y. Yang**, N. Rawlinson, A.G. Jones, J.A.D. Connolly, S. Lebedev: *Supported by ARC Discovery (commenced 2012)* ***Summary:*** Characterising the compositional and thermal structure of the lithosphere and upper mantle is one of the most important goals of Geoscience. Yet, a method capable of providing robust estimates of these two fields in 3D has still not been achieved. This limitation is the focus of this project, which will develop the first full 3D method that integrates multiple geophysical and petrological datasets. We will apply our methodology to image the fine-scale thermochemical structure of the lithosphere beneath Australia, South Africa, and western USA. This project will not only help us understand the evolution of continental lithosphere but its outcomes will be translatable into predictive exploration methods for Australia's Deep Earth Resources.
The application of very short-lived Uranium-series isotopes to constraining Earth system processes	**S. Turner**, T. Dosseto, M. 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.
The effective strength of oceanic plate bounding faults	**C. O'Neill**, **J.-C. Afonso**: *Supported by ARC Discovery and MQ (commenced 2011)* ***Summary:*** The strength of the ocean faults surrounding the Australian plate controls the long-term fault motions, stress partitioning across the plate boundary and, ultimately, the seismicity of such fault systems. Numerous lines of evidence suggest such faults are far weaker than previous models predict, possibly due to the alteration of crustal and lithospheric rocks into hydrous phases. This is a critical gap in our understanding of such fault systems, and this project will ultimately constrain the weakening mechanisms acting on such faults, and produce a geodynamic-scale model for their effective strength. This project addresses the anomalously weak behaviour of the seismically active faults on the boundary of the Australian plate, in three key geodynamic areas. This will constrain the mechanisms which weaken such faults, and produce a model for their effective strength and evolution over geological timescales.
Investigating the fundamental link between deformation, fluids and the rates of reactions in minerals	**S. Piazolo**, **N.R. Daczko**, A. Putnis, M.W. Jessell: *Supported by ARC Discovery (commenced 2012)* ***Summary:*** In Earth's crust and mantle, minerals are constantly undergoing chemical changes while simultaneously being deformed. In this project we use a novel combination of techniques in order to advance our understanding of how deformation influences these chemical changes.

Investigation of the early history of the Moon: implications for the understanding of evolution of Earth and Solar System	**A. Nemchin**, **M.L. Grange**: *Supported by ARC Discovery (commenced 2012)* ***Summary:*** The goal of the project is to characterise the chemistry and timing of processes that shaped the specific evolutionary path followed by the Moon during the early history of the Solar System. This is not only vital for evaluation of lunar history, but is also essential for a better understanding of early evolution of the Earth, where the record of the first 500 m.y. of history has been erased by the continuous activity of the planet. The project will test existing models of lunar evolution describing initial global differentiation, early plutonic magmatism, impact history and volcanic activity, shedding new light on the processes driving these major events on the Moon and determining the ability of these models to describe the early history of the Earth.
Down under down under: using multi-scale seismic tomography to image beneath Australia's Great Artesian Basin	**Y. Yang**, N. Rawlinson: *Supported by ARC Discovery (commenced 2011)* ***Summary:*** Seismic arrays will be deployed in the Great Artesian Basin to image the crust and mantle using distant earthquake and ambient noise sources. This will answer fundamental questions about the tectonic evolution of eastern Australia and elucidate the structure of a region containing significant deep Earth resources.
Origin of silicic magmas in a primitive island arc: the first integrated experimental and short-lived-isotope study of the Tongan Kermadec system	**T. Rushmer**, **S. Turner**: *Supported by ARC Discovery (commenced 2011)* ***Summary:*** Silicic magmas are the building blocks of the continental crust and constitute the most hazardous of volcanic eruptions. Silica-rich magmas are found in the Tonga-Kermadec arc, which extends for several thousand km north of New Zealand. Application of a novel combination of experiments and short-lived isotopes to selected magma samples from the primitive Tonga arc will explain the origin of these magmas. The combined technique will also allow us to estimate water content, rates of melting and magma migration at depth, which are critical factors for understanding volcanic hazards. This approach can then be expanded to other parental magma types here and to other arc systems. The Tongan arc forms a large portion of the Australian plate boundary and is one of the most chemically primitive systems known. Oddly, it produces volumes of more evolved, dangerous silicic magmas. The results of this project will establish the source of these magmas and rates of migration, which are fundamental for understanding volcanic hazards.
Oxygenating the Earth: using innovative techniques to resolve the timing of the origin of oxygen-producing photosynthesis in cyanobacteria	M.R. Walter, B.A. Neilan, **S.C. George**, R.E. Summons, J.W. Schopf: *Supported by ARC Discovery (commenced 2011)* ***Summary:*** The early Earth was a hostile place with little oxygen in the atmosphere. Then cyanobacteria ('blue green algae') invented oxygen releasing photosynthesis. That profound event affected many fundamental processes, from the course of evolution to the formation of ore deposits. However, estimates of when these bacteria originated are disputed with uncertainties of hundreds of millions of years. We will resolve those uncertainties. We have developed new analytical techniques that we will apply to well preserved 2.7-2.8 billion year old rocks in Western Australia. We will couple that approach to the use of the latest genetic techniques to reveal the origins of living cyanobacteria.
Supercells and the supercontinent cycle	W.J. Collins, J.B. Murphy, **E. Belousova**, M. Hand: *Supported by ARC Discovery (commenced 2012)* ***Summary:*** Phanerozoic plate motions can be explained by westerly and northerly migration of continental blocks toward Laurentia during protracted (~500 Ma) northerly mantle flow, confined within a hemispheric supercell. The other supercell on Earth encompasses the oceanic Pacific realm, characterised by E-W mantle flow diverging from the East Pacific Rise. We aim to determine if similar supercells and mantle flow patterns existed during the Proterozoic, by characterising contrasting orogenic systems within different supercells through tectonostratigraphic review, isotopic fingerprinting using Lu-Hf isotopes in zircon, and by paleomagnetic analysis. This is a new holistic approach to solving Precambrian geodynamics and continental reconstructions.

Dating Down Under: Resolving Earth's crust - mantle relationships	**E. Belousova**: *Supported by ARC Future Fellowship and MQ (commenced 2012)* ***Summary:*** How the continental crust has grown is a first-order problem in understanding the nature of the surface on which we live. Was most of the crust formed early in Earth's history or did it grow episodically? Was its growth related to underlying mantle processes? The project will use in-situ isotopic and trace-element microanalysis of the mineral zircon (a geological "time capsule"), extracted from rocks and sediments worldwide, to answer these fundamental questions. It will develop a new model for the timing of crustal formation and the tectonic and genetic links between Earth's crust and mantle. The results will be relevant to the localisation of a wide range of mineral resources.
The timescales of Earth-system processes: extending the frontiers of uranium-series research	**H. Handley**: *Supported by ARC Future Fellowship and MQ (commenced 2012* ***Summary:*** This project will advance our understanding of the timescales of Earth processes using short-lived (22 to 380,000 years) isotopes. The results will provide better constraints on the timescales of magmatic processes and frequency of large-scale eruptions for volcanic hazard mitigation and also soil production rates for landscape erosion studies.
A new approach to quantitative interpretation of paleoclimate archives	**D. Jacob**: *Supported by ARC Future Fellowship and MQ (commencing 2013)* ***Summary:*** Skeletons of marine organisms can be used to reconstruct past climates and make predictions for the future. The precondition is the knowledge of how climatic and environmental information is incorporated into the biominerals. This project will use cutting-edge nano-analytical methods to further our understanding of how organisms build their skeletons.
Strength and resistance along oceanic megathrust faults: implications for subduction initiation	**C. O'Neill**: *Supported by ARC Future Fellowship and MQ (commenced 2010)* ***Summary:*** Plate tectonics is enabled by the sinking of dense oceanic lithosphere at ocean trenches - a process known as subduction, but how this process initiates is poorly understood. The development of an incipient subduction zone involves a major evolution of the plate boundary, into an oceanic megathrust fault system, capable of generating devastating earthquakes. An example is the Hjorta Trench, at the Australian-Pacific plate boundary south of Macquarie Island. This project will explore the evolution of this plate-boundary fault system during subduction initiation. Recent advances in our understanding of physical processes along plate-bounding faults will be incorporated into regional geodynamic simulations of this evolving fault system.
Flow characteristics of lower crustal rocks: developing a toolbox to improve geodynamic models	**S. Piazolo**: *Supported by ARC Future Fellowship and MQ (commenced 2012)* ***Summary:*** This project will investigate in detail how rocks flow in the lowest part of the Earth's crust. The results will be used to improve sophisticated computer simulations of large-scale geological processes, allowing a better understanding of earthquakes, the formation of volcanic areas and location of energy resources.
From Core to Ore: emplacement dynamics of deep-seated nickel sulphide systems	**M. Fiorentini**: *Supported by ARC Future Fellowship (commenced 2012)* ***Summary:*** Unlike most mineral resources, which are generally concentrated in a wide range of crustal reservoirs, nickel and platinum are concentrated either in the core or in the mantle of our planet. In punctuated events throughout Earth history, large cataclysmic magmatic events have had the capacity to transport and concentrate these metals from their deep source to upper crustal levels. This project aims to unravel the complex emplacement mechanism of these magmas and constrain the role that volatiles such as water and carbon dioxide played in the emplacement and metal endowment of these systems.
A world-class rock magnetic facility to support Australian palaeomagnetic and environmental research	A.P. Roberts, D.C. Heslop, B.J. Pillans, P. De Deckker, G.S. Lister, **Z.-X. Li**, G. Rosenbaum, P.M. Vasconcelos, J.C. Aitchison, **S.A. Pisarevsky**, E. Tohver, P.W. Schmidt, M.O. McWilliams: *Supported by ARC LIEF (commenced 2012)* ***Summary:*** Magnetic properties of rocks and environmental particles provide information about a vast range of geological and environmental processes. We propose to develop a facility that will enable detection and interpretation of these magnetic signals to aid understanding of climate change, mineral exploration, and the geological development of Australia.

The first Australian high pressure Synchrotron facility for geoscience research	**T. Rushmer**, H.S. O'Neill, A.R. Cruden, **S.P. Turner**: *Supported by ARC LIEF (commenced 2012)* ***Summary:*** In high-pressure mineral physics and chemistry, mineral properties, stress-strain relationships and processes like partial melting are applied to geophysical research about the deep Earth. This project will provide a large volume, high pressure capability at the Australian Synchrotron which will allow these mineral properties to be measured under conditions which simulate the deep earth.
How does the continental crust get so hot?	**C. Clark**: *Supported by ARC DECRA (commenced 2012)* ***Summary:*** This project is aimed at constraining the tectonic drivers of high geothermal gradient crustal regimes. The key outcomes of this project are better constraints on the tectonic drivers of high geothermal gradient metamorphism and the development of quantitative tools to assess the evolution of heat within areas of mountain building.
Hydrothermal footprints of magmatic nickel sulfide deposits	**M. Fiorentini**, S. Barnes, Miller: *Supported by MERIWA, WA State Government (commenced 2011)* ***Summary:*** (MERIWA M413) This study focuses on the mineralogical and lithogeochemical footprints around syngenetic magmatic nickel-sulfide deposits, which arise from the interaction of these deposits with later hydrothermal fluids. Hydrothermal footprints are in common use in gold and Cu-Zn exploration, but have so far received little attention from nickel explorers, mainly because the nature and the scale of the alteration halo are largely unconstrained. This study addresses this window of opportunity: The new knowledge acquired from this study will aid exploration for nickel-sulfide systems at multiple scales, and will be applied in the interpretation of isolated "orphan" drill holes under cover in greenfields terranes, as well as in more data-rich mine-scale environments.
AuScope Australian Geophysical Observing System - Geophysical Education Observatory	**C. O'Neill**: *Supported by DIISR EIF and Macquarie University (commenced 2011)* ***Summary:*** AuScope Australian Geophysical Observing System is designed to augment existing NCRIS AuScope infrastructure with new capability that focuses particularly on emerging geophysical energy issues. It will build the integrated infrastructure that facilitates maximum scientific return from the massive geo-engineering projects that are now being considered – such a deep geothermal drilling – in effect building the platform for treating these as mega geophysical science experiments. AuScope AGOS infrastructure will enable collection of new baseline data including surface geospatial and subsurface imaging and monitoring data, thereby providing for better long-term management of crustal services, particularly in our energy-rich sedimentary basins. The Geophysical Education Observatory – comprising the development of digital real-time connection to existing teaching laboratories, will use the national observatory to provide a unique opportunity for integrating scientific research and education by engaging students, teachers, and the public in a national experiment that is going on in their own backyard.
Archean subduction in the Kaapvaal Craton	**M.J. Van Kranendonk**: *Supported by UNSW SPF01 (commenced 2012)* ***Summary:*** This project will investigate claims of a fossil Archean subduction zone (ca. 3.2 Ga) within the Kaapvaal Craton of Southern Africa. Previous work has suggested the presence of such a structure based on interpreted metamorphic conditions preserved in amphibolites, but no convincing map of the area has been presented in which to place this claim in context. This project will map the area and determine the nature of the metamorphism within a regional structural and lithological framework.
The Archean-Proterozoic boundary in Western Australia	**M.J. Van Kranendonk**: *Supported by UNSW SPF01 (commenced 2012)* ***Summary:*** This project is aimed at investigating the changes wrought across the Archean-Proterozoic boundary in Western Australia, marking the transition from juvenile, reducing, early Earth to more modern, oxidised, adolescent Earth. Details of stratigraphy, stable isotope geochemistry, and paleontology will be examined and integrated into global events.
Residual stress investigations of polycrystalline natural diamond aggregates	Venter, **S. Piazolo**, Luzin: *Suported by Braggs Institute, ANSTO (commencing 2013)* ***Summary:*** Our research interest is in the non-destructive investigation of the residual stresses locked into carbonado polycrystalline diamond samples in their raw as-discovered form.

Australian Drilling Program: Biomarkers, oxygen and geobiology	**S. George**, Dutkiewicz, Webb: *Supported by Agouron Institute Research Grant (commenced 2010)* ***Summary:*** The project aims... • To resolve whether Archean hydrocarbon biomarker molecules are indigenous or not, • To obtain geobiological and redox-indicator samples in environmental and temporal context, • From drill-cores of strata that are too weathered at the surface for reliable preservation of hydrocarbon biomarkers and other redox-sensitive biosignatures and environmental indicators, • From rocks dating from before the ecological dominance of animals, • With particular emphasis on time intervals and rock types relevant to the rise of oxygen, • To complement and extend the environmental and stratigraphic range of samples obtained from the Agouron South African drilling program.
New horizons in geochemical isotopic analysis with a new-generation multicollector plasma mass spectrometer: towards unravelling the deep earth system	**W.L. Griffin**, **N.J. Pearson**, **S.Y. O'Reilly**, **E.A. Belousova**, Collins, Aitchison, **C. Clarke**, **M. Fiorentini**, **Z.-X. Li**, **N. Daczko**: *Supported by ARC LIEF (commencing 2013)* ***Summary:*** A new-generation plasma mass spectrometer will let us develop novel applications in geochemistry to better understand Earth processes. This will enhance Australian Geosciences' high international profile, and help attract high-quality researchers to attack problems relevant to the Deep Earth Resources National Priority and mineral exploration.
An AZtec electron backscatter diffraction facility for state-of-the-art quantitative microstructural analysis	**S. M. Reddy**, N.J. McNaughton, N.E. Timms, R.M. Hough, A. van Riessen, P.A. Bland, J.S. Cleverley, **M. Fiorentini**, B.J. Griffin, A. Kemp, **M.R. Kilburn**: *Supported by ARC LIEF (commencing 2013)* ***Summary:*** Establishing a state-of-the-art quantitative microstructural analysis facility will provide critical infrastructure to complement existing high-spatial resolution microanalytical techniques and facilitate pure and applied research in the geoscience over the next decade.

Appendix 3: Participants list

Chief Investigators

Professor Suzanne Y. O'Reilly (Centre Director)	Professor Zheng-Xiang Li (Curtin)
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Professor Mark Barley (UWA)	Professor Simon Turner (Macquarie)
Professor William L. Griffin (Macquarie)	Professor Martin Van Kranendonk (University of NSW, from 2012)

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Dr Heather Handley (Macquarie)	Dr Sergei Pisarevsky (Curtin, UWA)
Dr Daniel Howell (Macquarie)	Dr Michael Turner (Macquarie)
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- Northwest University Xi'an (PR China)
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- Professor Martin Brasier (Oxford University, UK)
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- Professor Harald Furnes (University of Bergen, Norway)
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- Professor Suzanne Golding (The University of Queensland, Australia)
- Dr Peter Hollings (Lakehead University, Thunder Bay, Canada)
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- Professor Jochen Kolb (Geological Survey of Denmark and Greenland)
- Dr David Leach (U.S. Geological Survey (USGS), USA)
- Dr Nicola McLoughlin (University of Bergen, Norway)
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- Dr Boswell Wing (McGill University, Canada)
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Appendix 4: 2012 Publications

A FULL LIST OF CCFS PUBLICATIONS IS UPDATED AT: http://www.ccfs.mq.edu.au/

4. Wang, K.L., **O'Reilly, S.Y.**, Kovach, V., **Griffin, W.L.**, **Pearson, N.J.**, Yarmolyuk, V., Kuzmin, M.I., Chieh, C. and Shellnutt, J.G. 2012. Microcontinents among the accretionary complexes of the Central Asia Orogenic Belt (CAOB): *in situ* Re-Os evidence. *Journal of Asian Earth Sciences, 62, 37-50.*

5. **O'Reilly, S.Y.** and **Griffin, W.L.** 2012. Mantle Metasomatism. In: *Metasomatism and the Chemical Transformation of Rock: The Role of Fluids in Terrestrial and Extraterrestrial Processes. (eds) D. Harlov and H. Austrheim Lecture Notes in Earth System Sciences. Springer-Verlag, Berlin, 471-533.*

6. **Howell, D.**, Wood, I.G., Nestola, F., Nimis, P. and Nasdala, L. 2012. Inclusions under remnant pressure in diamond: A multi-technique approach. *European Journal of Mineralogy, 24, 563-573.*

7. **Danis, C.**, **O'Neill, C.** and Lackie, M. 2012. Building 3D geological knowledge through regional scale gravity modelling for the Bowen Basin. *Exploration Geophysics, 43, 8-25.*

10. **O'Neill, C.J.** 2012. Tectonothermal evolution of solid bodies: terrestrial planets, exoplanets, and moons. *Australian Journal of Earth Sciences, 59, 189-198.*

11. **Howell, D.** 2012. Strain-induced birefringence in natural diamond: a review. *European Journal of Mineralogy, 24, 4, 575-585.*

12. Andersson, U.B., Begg, G., **Griffin, W.L.** and Hàgdah, K. 2012. Ancient and juvenile components in the continental crust and mantle: Hf isotopes in zircon from Svecofennian magmatic rocks and rapakivi granites in Sweden. *Lithosphere, 3, 6, 409-419.*

13. **González-Jiménez, J.M.**, Gervilla, F., **Griffin, W.L.**, Proenza, J.A., Augé, T., **O'Reilly, S.Y.** and **Pearson, N.J.** 2012. Os-isotope variability within sulfides from podiform chromitites. *Chemical Geology, 291, 224-235.*

14. Kahoui, M., Kaminsky, F.V., **Griffin, W.L.**, **Belousova, E.**, Mahdjoub, Y. and Chabane, M. 2012. Detrital pyrope garnets from the El Kseibat area, Algeria: A glimpse into the lithospheric mantle beneath the north-eastern edge of the West African Craton. *Journal of African Earth Sciences, 63, 1-11.*

15. **Huang, J.-H.**, **Griffin, W.L.**, **Gréau, Y.** and **O'Reilly, S.Y.** 2012. Seeking the primary compositions of mantle xenoliths: isotopic and elemental consequences of sequential leaching treatments on an eclogite suite. *Chemical Geology, 328, 137-148.*

16. Meng, L., **Li, Z.-X.**, Chen, H., Li, X.-H. and **Wang, X.-C.** 2012. Geochronological and geochemical results from Mesozoic basalts in southern South China Block support the flat-slab subduction model. *Lithos, 132-133, 127-140.*

17. **Afonso, J.C.** and Schutt, D. 2012. The effects of polybaric partial melting on the density and seismic velocities of mantle restites. *Lithos, 134-135, 289-303.*

18. Luo, Y., Xu, Y. and **Yang, Y.** 2012. Crustal structure beneath the Dabie orogenic belt from ambient noise tomography. *Earth and Planetary Science Letters, 313-314, 12-22.*

19. **Adam, J.**, **Rushmer, T.**, O'Neil, J. and Francis, D. 2012. Hadean greenstones from the Nuvvuagittuq fold belt and the origin of the Earth's early continental crust. *Geology, 40, 4, 363-366.*

20. Zheng, Y., Shen, W., Zhou, L., **Yang, Y.**, Xie, Z. and Ritzwoller, M.H. 2012. Crust and uppermost mantle beneath the North China Craton, northeastern China, and the Sea of Japan from ambient noise tomography. *Journal of Geophysical Research, B12312, 1-25.*

21. Barnes, S., **Van Kranendonk, M.J.** and Sontag, I. 2012. Geochemistry and tectonic setting of basalts from the Eastern Goldfields Superterrane. *Australian Journal of Earth Sciences, 59, 707-735.*

23. Lu, Y.-J., Kerrich, R., Cawood, P.A., **McCuaig, C.**, Hart, C.J.R., **Li, Z.-X.**, Hou, Z.-Q. and **Bagas, L.** 2012. Zircon SHRIMP U-Pb geochronology of potassic felsic intrusions in western Yunnan, SW China: Constraints on the relationship of magmatism to the Jinsha suture. *Gondwana Research, 22, 2, 737-747.*

24. **Wang, X.-C.**, **Li, Z.-X.**, Li, X.-H., Li, J., Liu, Y., Long, W.-G., Zhou, J.-B. and Wang, F. 2012. Temperature, Pressure, and Composition of the Mantle Source Region of Late Cenozoic Basalts in Hainan Island, SE Asia: a Consequence of a Young Thermal Mantle Plume close to Subduction Zones? *Journal of Petrology, 53, 177-233.*

26. Caulfield, J., **Turner, S.**, Arculus, R., Dale, C., Pearce, J. and Macpherson, C. 2012. Mantle flow, slab-surface temperatures and melting dynamics in the north Tonga arc - Lau Basin. *Journal of Geophysical Research, 117, B11209.*

28. Adams, C.J., Mortimer, N., Campbell, H.J. and **Griffin, W.L.** 2012. Detrital zircon geochronology and sandstone provenance of basement Waipapa Terrane (Triassic-Cretaceous) and Cretaceous cover rocks (Northland Allochthon and Houhora Complex) in northern North Island, New Zealand. *New Zealand Journal of Geology and Geophysics, 150, 1, 89-109.*

29. Caulfield, J.T., **Turner, S.P.**, Smith, I.E.M., Cooper, L.B. and Jenner, G.A. 2012. Magma evolution in the primitive, intra-oceanic Tonga arc; petrogenesis of basaltic andesites at Tofua volcano. *Journal of Petrology, 53, 6, 1197-1230.*

30. Villaseca, C., Orejana, D. and **Belousova, E.A.** 2012. Recycled metaigneous crustal sources for S- and I-type Variscan granitoids from the Spanish Central System batholith: constraints from Hf isotope zircon composition. *Lithos, 153, 84-93*.

31. **Li, Z.-X.**, Li, X.-H., Chung, S.-L., Lo, C.-H., Xu, X. and Li, W.-X. 2012. Magmatic switch-on and switch-off along the South China continental margin since the Permian: Transition from an Andean-type to a Western Pacific-type plate boundary. *Tectonophysics, 532-535, 271-290*.

33. **Grose, C.** 2012. Properties of oceanic lithosphere: Revised plate cooling model predictions. *Earth and Planetary Science Letters, 333-334, 250-264*.

34. Tang, G.J., Wyman, D.A., Wang, Q., Li, J., **Li, Z.X.**, Zhao, Z.H. and Sun, W.D. 2012. Asthenosphere-lithosphere interaction triggered by a slab window during ridge subduction: Trace element and Sr-Nd-Hf-Os isotopic evidence from Late Carboniferous tholeiites in the western Junggar area (NW China). *Earth and Planetary Science Letters, 329-330, 84-96*.

35. Zhou, L., Xie, J., Shen, W., Zheng, Y., **Yang, Y.**, Shi, H. and Ritzwoller, M.H. 2012. The structure of the crust and uppermost mantle beneath South China from ambient noise and earthquake tomography. *Geophysical Journal International, 189, 1565-1583*.

37. **Griffin, W.L.**, Nikolic, N., **O'Reilly S.Y.** and **Pearson, N.J.** 2012. Coupling, decoupling and metasomatism: Evolution of crust-mantle relationships beneath NW Spitsbergen. *Lithos, 149, 115-135*.

38. Beyer, E.E., Brueckner, H.K., **Griffin, W.L.** and **O'Reilly, S.Y.** 2012. Laurentian provenance of Archean mantle fragments in Proterozoic Baltic crust of the Norwegian Caledonides. *Journal of Petrology, 53, 1357-1383*.

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Appendix 5: CCFS visitors & GAU users

CCFS VISITORS 2012
(Excluding participants in conferences and workshops)

Macquarie

VISITOR	ORGANISATION	COUNTRY
Mr Jamie Barbula	Photon Machines Inc, Redmond, WA	USA
Dr Graham Begg	Minerals Targeting International Pty Ltd, West Perth, WA	Australia
Dr Frank E. Brenker	Geoscience Institute/Mineralogy, Goethe University, Frankfurt	Germany
Mr Christophe Brouzet	Department of Physics, University of Lyon	France
Mr Tiejun Bu	Deputy Director, Division of International Relations, Jilin University, Jilin	PR China
Ms Montgarri Castillo	Department of Crystallography, Mineralogy and Ore Deposits, Universitat de Barcelona	Spain
Mr Mark Chandler	Nu Instruments, Wrexham	UK
Mr Renxu Chen	University of Science and Technology of China (USTC), Hefei	PR China
Mr Yixiang Chen	School of Earth and Space Sciences, University of Science and Technology of China (USTC), Hefei	PR China
Dr Mei Fei Chu	National Taiwan University, Taipei	Taiwan
Ms Vanessa Colas	University of Zargoza, Zargoza	Spain
Dr Manel Fernandez	Universitat de Barcelona, Barcelona	Spain
Ms Quiling Gao	China University of Geosciences, Wuhan	PR China
Mr Jose Godinho	Department of Geological Sciences, Stockholm University	Sweden
Mr Xiaofeng Gu	University of Science and Technology of China (USTC), Hefei	PR China
Dr Jiangang Han	School of Earth and Space Sciences, Peking University, Beijing	PR China
Dr Zhenyu He	Institute of Geology, Chinese Academy of Geological Sciences (CAGS), Beijing	PR China
Dr Graham Heinson	University of Adelaide, SA	Australia
Professor Liang Hu	Dean of College of Computer Science, Jilin University, Jilin	PR China
Professor Alan Jones	Dublin Institute for Advanced Studies, Dublin	Ireland
Professor Brian Kennett	ANU, Canberra, ACT	Australia
Dr Hao-Yang Lee	National Taiwan University, Taipei	Taiwan
Mr Wancai Li	University of Science and Technology of China (USTC), Hefei	PR China
Professor Xian-Hua Li	Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing	PR China
Dr Te-Hsien Lin	National Taiwan University, Taipei	Taiwan
Ms Qian Liu	Nanjing University, Nanjing	PR China
Mr Yican Liu	University of Science and Technology of China (USTC), Hefei	PR China
Professor Yinhe Luo	China University of Geosciences, Wuhan	PR China
Dr Tim McCoy	Geologist - Curator-in-Charge, Meteorite Collection, Department of Mineral Sciences	USA
Ms Ria Mukherjee	Earth Sciences, Jadavpur University	India
Dr Irina Nedosekova	Urals Division of Russian Academy of Science (UDRAS), Ekaterinburg	Russia
Professor Jieyuan Ning	School of Earth and Space Sciences, Peking University, Beijing	PR China
Dr Yingming Sheng	University of Science and Technology of China (USTC), Hefei	PR China
Dr Zdislav Spetsius	Geology of Diamond Deposits, NIGP Alrosa Co Ltd	Russia
Dr Huayun Tang	Faculty of Earth Sciences, China University of Geosciences, Wuhan	PR China
Dr Stephan Thiel	University of Adelaide, SA	Australia

	VISITOR	ORGANISATION	COUNTRY
Macquarie	Ms Lavinia Tunini	Institute of Earth Sciences Jaume Almera	Spain
Macquarie	Dr Carlos Viillaseca	Department Petrología y Geochuímica, Universidad Complutense Madrid	Spain
Macquarie	Professor Rucheng Wang	Dean of the School of Earth Sciences and Engineering, Nanjing University	PR China
Macquarie	Mr Andong Wang	University of Science and Technology of China (USTC), Hefei	PR China
Macquarie	Dr Kuo-Lung Wang	Academia Sinica Institute of Earth Sciences, Nankang, Taipei	Taiwan
Macquarie	Dr Yanbin Wang	GSECARS high pressure synchrotron laboratory, The University of Chicago, Chicago	USA
Macquarie	Professor Zhenwu Wu	Vice President, Jilin University, Jilin	PR China
Macquarie	Dr Xiongxia Xia	University of Science and Technology of China (USTC), Hefei	PR China
Macquarie	Dr Jun Xie	University of Science and Technology of China (USTC), Hefei	PR China
Macquarie	Dr Jin-Hui Yang	Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing	PR China
Macquarie	Dr Chunmai Yu	China University of Geosciences, Wuhan	PR China
Macquarie	Dr Marina Yudovskaya	University of Witwatersrand, Johannesburg	South Africa
Macquarie	Dr Yong Zheng	Geodesy and Geophysics, Chinese Academy of Sciences, Beijing	PR China
Macquarie	Professor Yongfei Zheng	School of Earth and Space Sciences, University of Science and Technology of China (USTC), Hefei	PR China
Macquarie	Dr Longquan Zhou	China Earthquake Network Center, China Earthquake Administration, Beijing	PR China
Macquarie	Mr Ligang Zhou	University of Science and Technology of China (USTC), Hefei	PR China
Macquarie	Dr Lenka Baratoux	Institut de recherche pour le développement, Marseille	France
University of Western Australia	Mr Steve Barnes	CSIRO, Kensington, NSW	Australia
University of Western Australia	Dr Graham Begg	Minerals Targeting International, West Perth, WA	Australia
University of Western Australia	Professor Jean-Pierre Burg	ETH/University of Zurich, Institute of Geology, Zürich	Switzerland
University of Western Australia	Mr Stefano Caruso	University of Milano, Milan	Italy
University of Western Australia	Professor Peter Cawood	University of St Andrews, Centre of Earth Resources, St Andrews	UK
University of Western Australia	Dr Deon de Bruin	Intertek Genalysis, Gosnells	Australia
University of Western Australia	Mr Thomas Dittrich	Technical University Bergakademie Freiberg, Freiberg	Germany
University of Western Australia	Professor James Farquhar	University of Maryland, Department of Geology, Maryland	USA
University of Western Australia	Mr Sebastian Grignola	University of Tucumán, Tucumán	Argentina
University of Western Australia	Professor David Groves	The University of Western Australia, Faculty of Science, Crawley, WA	Australia
University of Western Australia	Dr Douglas Haynes	Douglas Haynes Discovery Pty Ltd, Maleny	Australia
University of Western Australia	Dr Bruce Hobbs	CSIRO, Kensington, NSW	Australia
University of Western Australia	Dr Julie Hollis	Geological Survey of Western Australia, East Perth, WA	Australia
University of Western Australia	Dr Jon Hronsky	Western Mining Sevices, West Perth, WA	Australia
University of Western Australia	Dr Mark Jessell	Université Paul Sabatier de Toulouse, Earth and Planetary Sciences, Toulouse	France
University of Western Australia	Dr Allan Jones	School of Cosmic Physics, Dublin	Ireland
University of Western Australia	Mr Jochen Kolb	Geological Survey of Denmark and Greenland (GEUS), Copenhagen	Denmark
University of Western Australia	Mr Peter Kollegger	University of Leoben, Leoben	Austria
University of Western Australia	Dr Tine Larson	University of Tromso, Department of Geology, Tromsø	Norway
University of Western Australia	Dr Robert Loucks	The University of Western Australia, Faculty of Science, Crawley, WA	Australia
University of Western Australia	Mr Bo Møller	Geological Survey of Denmark and Greenland (GEUS), Copenhagen	Denmark
University of Western Australia	Dr Franco Pirajno	The University of Western Australia, Faculty of Science, Crawley, WA	Australia
University of Western Australia	Dr Andrew Rate	University of Western Australia, Faculty of Science, Crawley, WA	Australia
University of Western Australia	Professor Thomas Seifert	Technical University Bergakademie Freiberg, Freiberg	Germany

	VISITOR	ORGANISATION	COUNTRY
University of Western Australia	Dr Hugh Smithies	Geological Survey of Western Australia, East Perth, WA	Australia
	Mr Henrik Stendal	Geological Survey of Denmark and Greenland (GEUS), Copenhagen	Denmark
	Dr Sasha Stepanov	Australian National University, Research School of Earth Sciences, Acton, ACT	Australia
	Dr Svetlana Tessalina	Curtin University, Department of Applied Geology, Bentley, WA	Australia
	Dr Nick Timms	Curtin University, Curtin Applied Geology, Perth, WA	Australia
	Dr Ian Tyler	Geological Survey of Western Australia, Perth, WA	Australia
	Dr Florian Wellmann	CSIRO, Floreat	Australia
	Professor Dan Wood	University of Queensland, WH Bryan Mining and Geology Research Centre, St Lucia	Australia
	Dr Roberto Xavier	Dept. Geology and Natural Resources, Universidade Estadual de Campinas, São Paulo	Brazil
	Dr Lijuan Ying	Chinese Academy of Geological Science, Institute of Mineral Resources, Beijing	PR China
	Dr Dayu Zhang	School of Resources & Environment Engineering, Hefei University of Technology, Hefei	PR China
Curtin	Professor Xiaolong Huang	Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou	PR China
	Mr Shan Li	Institute of Geology, Chinese Academy of Geological Sciences (CAGS), Beijing	PR China
	Professor Stefano Mazzoli	Università di Napoli Federico II, Dipartimento Scienze della Terra, Naples	Italy
	Dr Touping Peng	Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou	PR China
	Professor Shihong Zhang	China University of Geosciences, Beijing	PR China
	Professor Weiguang Zhu	Institute of Geochemistry, Chinese Academy of Sciences, Guiyang	PR China

EXTERNAL USERS OF THE GEOCHEMICAL ANALYSIS UNIT FACILITIES IN 2012

(Note: this does not include contract work)

Macquarie	Dr Chris Adams	Institute of Geological & Nuclear Science, Lower Hutt	New Zealand
	Dr Frank E. Brenker	Geoscience Institute/Mineralogy, Goethe University, Frankfurt	Germany
	Dr Mei Fei Chu	National Taiwan University, Taipei	Taiwan
	Professor Geoff Clarke	University of Sydney, NSW	Australia
	Ms Vanessa Colas	University of Zargoza	Spain
	Asst Res Prof James Davis	CET, University of Western Australia, Crawley, WA	Australia
	Ms Quiling Gao	China University of Geosciences, Wuhan	PR China
	Mr Muatasam Hassan	University of Wollongong, NSW	Australia
	Ms Carissa Issac	CET, University of Western Australia, Crawley, WA	Australia
	Dr Hao-Yang Lee	Nankang, Taipei	Taiwan
	Ms Qian Liu	Nanjing University, Nanjing	PR China
	Ms Ria Mukherjee	Earth Sciences, Jadavpur University	India
	Dr Irina Nedosekova	Urals Division of Russian Academy of Science (UDRAS), Ekaterinburg	Russia
	Ass Prof Allan Nutman	University of Wollongong, NSW	Australia
	Mr Luis Parra	CET, University of Western Australia, Crawley, WA	Australia
	Mr Asi Sarmad	University of Wollongong, NSW	Australia
	Mr Keith Scott	Visiting Fellow RSES ANU, and Honorary Fellow CSIRO, ACT	Australia
	Dr Zdislav Spetsius	Geology of Diamond Deposits, NIGP Alrosa Co Ltd	Russia
	Dr Huayun Tang	Earth Sciences, China University of Geoscience, Wuhan	PR China
	Dr Carlos Viillaseca	Department Petrología y Geochuímica, Universidad Complutense Madrid, Madrid	Spain
	Dr Kuo-Lung Wang	Academia Sinica, Nankang, Taipei	Taiwan
	Dr Chunmei Yu	China University of Geosciences, Wuhan, Hubei	PR China
	Dr Marina Yudovskaya	University of Witwatersrand, Johannesburg	South Africa

Appendix 6: 2012 Abstract titles

A FULL LIST OF CCFS ABSTRACTS FOR CONFERENCE PRESENTATIONS IS AVAILABLE AT: http://www.ccfs.mq.edu.au/

Specialist Group in Tectonics and Structural Geology bi-annual conference, Waratah Bay, Victoria, 29 January - 4 February 2012

The relationship between microstructure, metasomatism and hydrogen incorporation in deformed mantle olivine
E. Gray, **S. Reddy**, K.E. Evans, N.E. Timms and B. McInnes

The role of serpentinisation in fault stress and long-term deformation in the Java-Sumatra subduction system
C. O'Neill and **J.C. Afonso**

Serpentinite deformation in subducting plates and implications for seismic anisotropy in supra subduction zone environments: Cause and effects of deformation in the lithosphere
S. Reddy, J. Bridges, **M.-A. Kaczmarek**, **C. Clark** and D. Healy

Deformation of the lithosphere by impact events: what we can learn from zircon microstructure
N. Timms, **S. Reddy**, D. Healy, **A. Nemchin**, **M. Grange**, **R. Pidgeon** and R. Hart

22nd Australian Conference on Microscopy and Microanalysis (ACMM 22), - ACMM 22 / APMC 10 / ICONN 2012, Perth, Australia, 5-9 February 2012

Practical isotope ratio analysis using SIMS
J.B. Cliff Invited

The understanding of mantle shearing with EBSD
M.-A. Kaczmarek

Chemical and isotopic imaging at the sub-micron scale with NanoSIMS
M.R. Kilburn Invited

Assessment of electron backscatter diffraction as a radiation damage probe
N.E. Timms, **M.L. Grange**, **A.A. Nemchin**, T. Geisler-Wierwille, **S.M. Reddy**, **R.T. Pidgeon** and R. Hart

Scanning ion imaging - an underutilised yet potent tool in SIMS U-Pb zircon geochronology
M. Whitehouse, C. Fedo, **M. Kusiak** and **A. Nemchin** Invited

Unravelling Early Earth Evolution through Microanalysis of Zircon
S. Wilde Invited

The 10th International Kimberlite Conference, Bangalore, India, 6-11 February

Petrological inferences for the role of exsolution in upper mantle: evidence from the Yakutian Kimberlite xenoliths
T.A. Alifirova, L.N. Pokhilenko, V.G. Malkovets and **W.L. Griffin**

Petrology, bulk-rock geochemistry, indicator mineral composition, and zircon U-PB geochronology of the end-Cretaceous diamondiferous Mainpur Orangeites, Bastar Craton, central India
N.V. Chalapathi Rao, B. Lehmann, **E. Belousova**, D. Frei and D. Mainkar

Petrogenesis of composite xenoliths from alkaline basalts (west Sangilen, Russia)
A.A. Gibsher, V.G. Malkovets, **W.L. Griffin** and **S.Y. O'Reilly**

Pyrope garnet from the El Kseibat area, Algeria and lithosphere beneath the north-eastern part of the West African Craton
M. Kahoui, Y. Mahdjoub, M. Chabane, **E. Belousova**, **W.L. Griffin** and F.V. Kaminsky

Late metasomatic addition of garnet to the SCLM: Os-isotope evidence
V.G. Malkovets, **W.L. Griffin**, **N.J. Pearson**, D.I. Rezvukhin, **S.Y. O'Reilly**, N.P. Pokhilenko, V.K. Garanin, Z.V. Spetsius and K.D. Litasov

Lithosphere mantle structure beneath the Nakyn Kimberlite Field, Yakutia
V.G. Malkovets, **W.L. Griffin**, N.P. Pokhilenko, **S.Y. O'Reilly**, A.I. Dak, A.V. Tolstov, I.V. Serov, I.S. Bazhan and D.V. Kuzmin

Tables vs. benches: Trace elements in fibrous diamonds
O. Navon, **W.L. Griffin** and Y. Weiss

Mineral inclusions in pyropes from some kimberlite pipes of Yakutia
D.I. Rezvukhin, V.G. Malkovets, A.A. Gibsher, D.V. Kuzmin, **W.L. Griffin**, N.P. Pokhilenko and **S.Y. O'Reilly**

Heterogeneous mantle beneath Lunda area in Angola
S.E. Robles-Cruz, S. Galía, **M. Escayola** and J.C. Melgarejoa

Geochemistry and microstructure of diamondites
E.V. Rubanova, **W.L. Griffin**, **S. Piazolo**, **S.Y. O'Reilly**, T. Stachel, R. Stern and A.C. Birnie

The 10th International Kimberlite Conference, Bangalore, India, 6-11 February *cont...*	High-Mg carbonatitic HDFS, kimberlites and the SCLM Y. Weiss, **W.L. Griffin**, D.R. Bell and O. Navon Fluid microinclusions in monocrystalline diamonds Y. Weiss, I. Kiflawi, **W.L. Griffin** and O. Navon
GSWA Open Day, Fremantle, 23 Feb 2012	A multi-isotopic approach to the crustal evolution of the west Musgrave Province **C.L. Kirkland**, R.H. Smithies, A. Woodhouse, **M.T.D. Wingate**, M.H. Howard, **J. Cliff** and **E.A. Belousova**
108th Annual GSA meeting, Cordillera Section, Querétaro, Mexico, 29-31 March 2012	Metallogenic and tectonomagmatic evolution of Mexico during the Mesozoic: a review and new insights A. Camprubí, M. Martini, **J.M. González-Jiménez**, E. González-Partida, J.A. Proenza, E. Centeno-García, E. Fitz-Díaz, M. Valencia-Moreno, A. Izaguirre and A. Iriondo A Mesozoic back-arc in the Guerrero Composite Terrane (Mexico): evidence from trace elements and Re-Os isotopes in podiform chromitites from Loma Baya **J.M. González-Jiménez**, A. Camprubí, **W.L. Griffin**, E. Centeno-García, **S.Y. O'Reilly**, M. Martini, J.A. Proenza and **N.J. Pearson**
Joint 5th MSCC & 3rd CEMC 2012, Miskolc, Hungary, 19–21 April 2012	Distribution of platinum-group elements in upper mantle xenoliths from the Carpathian-Pannonian region L. Aradi, K. Hattori, **W. Griffin**, **S. O'Reilly**, A. Szabó and Cs. Szabó New U–Pb dating and Hf-isotope composition of the Gornjane Granitoids (South Carpathians, east Serbia) N. Vaskovi, **E. Belousova**, **S.Y. O'Reilly**, **W.L. Griffin**, D. Srekovi-Batoanin, G. Christofides and A. Coroneos
European Geosciences Union General Assembly 2012, Vienna, Austria, 22-27 April 2012	The compositional and thermal structure of the lithosphere from thermodynamically-constrained multi-observable probabilistic inversion **J.C. Afonso**, J. Fullea, **Y. Yang**, A.G. Jones, **W.L. Griffin**, J.A.D. Connolly, **S.Y. O'Reilly** and S. Lebedev **Keynote** Petro-geochemical constraints for origin of pyroxenites xenoliths associated with mantle peridotites from Adrar N'ajjer caenozoic volcanics (NE Ahaggar, Algerian Sahara) F. Ait-Hamou, R. Laloui, M. Gregoire, **W.L. Griffin**, **S.Y. O'Reilly**, G. Ceuleneer and H. Afafiz Li isotopic constraints from the Erro-Tobbio serpentinites on Alpine subduction processes M.-F. Chu, M. Scambelluri, **W.L. Griffin**, **S.Y. O'Reilly** and **N.J. Pearson** A 1-Ga history of melting in the western Mediterranean Subcontinetal Lithospheric Mantle recorded in chromitites from the Ojén Ultramafic Massif (SW Spain) **J.M. González-Jiménez**, C. Marchesi, **W.L. Griffin**, R. Gutiérrez-Narbona, J.-P. Lorand, **S.Y. O'Reilly**, C.J. Garrido, F. Gervilla and **N.J. Pearson** $^{40}Ar/^{39}Ar$ dating of unusual minerals (tourmaline, K-richterite, yimengite, wadeite and priderite) and applicability to the geological record F. Jourdan, E. Thern, **S.A. Wilde** and L. Frewer Carbon flux from plants to soil microbes is highly sensitive to nitrogen addition and biochar amendment C. Kaiser, Z.M. Solaiman, **M.R. Kilburn**, P.L. Clode, L. Fuchslueger, M. Koranda and D.V. Murphy Provenance and evolution of the western Mediterranean lithospheric mantle beneath the eastern Betics (S. Spain): insights from *in-situ* analyses of Os isotopes and platinum-group elements in sulphides from the Tallante mantle xenoliths Z. Konc, C. Marchesi, C.J. Garrido, **J.M. González-Jiménez**, **W.L. Griffin**, O. Alard, K. Hidas, **S.Y. O'Reilly** and **N. Pearson** The Seismic Structure of the Mantle Wedge under Cascade Volcanoes, Northwestern U.S.A. A. Levander, K. Liu, R. Porritt, R. Allen and **Y. Yang** Zircon and baddeleyite from the economic ultramafic-mafic Noril'sk-1 intrusion (Russia): Hf-isotope constraints on source composition K.N. Malitch, **E.A. Belousova**, I.Y. Badanina and **W.L. Griffin** Paleomagnetism of the 1210 Ma Gnowangerup-Fraser dyke swarm, Western Australia **S.A. Pisarevsky**, **Z. X. Li**, **M.T.D. Wingate** and E. Tohver New geochronological ages (U-Pb/Lu-Hf) from high-pressure rocks of the Escambray terrane and Santa Clara serpentinite mélange, central Cuba. Regional correlations and geodynamic implications Y. Rojas-Agramonte, A. García-Casco, A. Kröner, D. Herwartz, A. Ibis Despaigne and **S. Wilde** Two types of Archean continental crust: plume and plate tectonics on early Earth **M.J. Van Kranendonk** **Eminent speaker**

European Geosciences Union General Assembly 2012, Vienna, Austria, 22-27 April 2012 *cont...*	The stepwise growth of tectonic plates across Earth's evolving supercontinent cycle **M.J. Van Kranendonk** and **C.L. Kirkland**
Scandem 2012 Annual Meeting of the Nordic Microscopy Soc., Bergen, Norway, 12-15 June 2012	Electron Microscopy of Early Cellular Life **D. Wacey**, N. McLoughlin, M. Saunders and M. Brasier
12th International Ni-Cu-(PGE) Symposium, Guiyang, China, 16-17 June 2012	Use and Calibration of portable X-Ray fluorescence analyzers: case studies from komatiite-hosted nickel-sulfide deposits of the Yilgarn Craton, Western Australia **M. Le Vaillant**, **M.L. Fiorentini**, L. Fisher, S.J. Barnes and S. Caruso Microstructural control on trace element distribution in komatiite hosted Ni sulphide deposits, Yilgarn Craton (Western Australia) **Z. Vukmanović**, S.J. Barnes, **S.M. Reddy** and **M.L. Fiorentini**
Workshop: The Role of Metasomatism in Geological Processes, Montreal, Canada, 23 June 2012	Mantle Metasomatism: Characteristics, scale and distribution, and geodynamic significance **S.Y. O'Reilly** and **W.L. Griffin** **Invited**
22nd Annual V.M. Goldschmidt Conference, Montréal, Canada, June 24-29 2012	Links between tectonics and life, 4.0 to 2.3 Ga and the rise of oxygen **M.E. Barley** The early formation of the continental crust: constraints from zircon Hf-isotope data **E.A. Belousova**, **W.L. Griffin**, Y.A. Kostitsyn, **N.J. Pearson**, G. Begg and **S.Y. O'Reilly** How does the continental crust get really hot? **C. Clark**, I.C.W. Fitzsimons and D. Healy Igneous and metamorphic garnet-clinopyroxene assemblages in eclogite and granulite, Breaksea Orthogneiss, New Zealand: major and rare earth element characteristics G.L. Clarke, **N.R. Daczko** and D. Miescher O isotopes in the Azores: mantle melting versus AFC **F.S. Genske**, C. Beier, S. Krumm, K.M. Haase and **S.P. Turner** Apollo 15 zircons reveal age of young impact **M.L. Grange**, **A.A. Nemchin**, **R.T. Pidgeon** and C. Meyer The end of the Hadean: The world turns over **W.L. Griffin**, V. Malkovets, **E.A. Belousova**, **S.Y. O'Reilly** and **N.J. Pearson** LA-ICP-MS analysis on spinel from chromitites of different tectonic settings: their contrasted minor- and trace-elements compositions **J.M. González-Jiménez**, **W.L. Griffin**, **M. Locmelis**, **S.Y. O'Reilly** and **N.J. Pearson** Magmatic degassing in contrasting volcanic systems of the Vanuatu arc: constraints from uranium-series isotopes **H. Handley**, **S. Turner**, M. Reagan, G. Girard and S. Cronin PGE abundances in upper mantle xenoliths from the Carpathian-Pannonian Region K. Hattori, C. Szabo, **W. Griffin**, **S. O'Reilly** and L. Elod Aradi High-resolution chemostratigraphy of the 2.46 Ga Joffre banded iron formation, Western Australia: implications for the hydrosphere-atmosphere-lithosphere in the early Palaeoproterozoic R. Haugaard, E. Pecoits, S.V. Lalonde, N. Aubet, **M.J. Van Kranendonk** and K.O. Konhauser Trace element partitioning in mixed-habit diamonds **D. Howell**, **W.L. Griffin**, **W. Powell**, **P. Wieland**, **N. Pearson** and **S.Y. O'Reilly** A Tertiary record of Australian plate motion from ages of diamondiferous alkalic intrusions B. McInnes, N. Evans, F. Jourdan, B. McDonald, J. Gorter, C. Mayers and **S. Wilde** Microstructures in lunar zircon: key to interpretation of U-Pb ages **A.A. Nemchin**, **M.L. Grange**, N.E. Timms and **R.T. Pidgeon**

22nd Annual V.M. Goldschmidt Conference, Montréal, Canada, June 24-29 2012 *cont...*	Development and application of LA-ICP-MS in the geosciences: past, present and future **N.J. Pearson**, **W.L. Griffin** and **S.Y. O'Reilly** **Keynote** The geochemical features of the garnets from peridotites of Udachnaya pipe (Yakutia) L. Pokhilenko, V. Malkovets, A. Agashev and **W. Griffin** Origin of silicic magmas in the primitive, intra-oceanic Tongan arc **T. Rushmer**, **S. Turner**, **J. Caulfield**, **M. Turner**, S. Cronin and I.E. Smith Recycling of ancient SCLM constraints on the genesis of the Tethys ophiolitic podiform chromitites in Tibet R. Shi, **W.L. Griffin**, **S.Y. O'Reilly**, Q.S. Huang, X.R. Zhang and L. Ding Mantle flow, slab-surface temperatures and melting dynamics in the north Tonga arc–Lau Basin **S. Turner**, **J. Caulfield**, R. Arculus, C. Dale, N. Keller, J. Pearce and C. Macpherson Implications of unsupported radiogenic Pb in ancient zircon M. Whitehouse, **M. Kusiak** and **A. Nemchin** What can zircon really tell us about Earth's earliest crustal evolution? M. Whitehouse and **A. Nemchin** **Keynote** Pre-Late Heavy Bombardment terrestrial crust: review of the zircon evidence for its nature and origin **S.A. Wilde** **Invited** Sr isotopic composition of pore water of shelf cores from IODP Expedition 317: Canterbury Basin, New Zealand. T. Yoshimura, H. Kawahata, M. Tanimizu, **S.C. George**, J.S. Lipp and G.E. Claypool
XXXII Reunión SEM, Bilbao, Spain, 27-30 June 2012	Factors controlling chromite alteration: Example from Kosturino, SE Bulgaria V. Colás, F. Gervilla, I. Fanlo, T. Kerestedjian, I. Sergeeva, **J.M. González-Jiménez** and E. Arranz Back-arc origin for chromitites of the Dobromirtsi Ultramafic Massif **J.M. González-Jiménez**, V. Colás, I. Sergeeva, **W.L. Griffin**, **S.Y. O'Reilly**, F. Gervilla, T. Kerestedjian, I. Fanlo, **M. Locmelis**, **N. Pearson** and **E. Belousova**
Geochemistry of Mineral Deposits, Gordon Conference, New Hampshire, USA, 15-20 July 2012	Preliminary Craton wide geochronology and geochemistry of the Leo Man shield, West Africa **L.A. Parra**, **D.R. Mole**, N. Said, **T.C. McCuaig** and **M.L. Fiorentini** Lithosphere architecture and the role of the Subcontinental Lithospheric Mantle in mineral deposits **N. Pearson**
34th International Geological Congress, Brisbane, 5-10 August 2012	Crustal structure of a latest Mesoproterozoic intracontinental rift— the Ngaangatyarra Rift (Giles Event), central Australia A.R.A. Aitken, R.H. Smithies, M.C. Dentith, A. Joly, H.M. Howard, S. Evans, **T.C. McCuaig** and I.M. Tyler The Australian Seismometers in Schools project: educating students in earth shaking science N. Balfour, M. Sambridge and **C. O'Neill** The first multiple sulphur isotope evidence for a 2.9 Ga Mesoarchean sulphate reservoir linked to a major volcanic event **M. Barley**, S. Golding and **M. Fiorentini** The lithosphere, geodynamics and Archean mineral systems G.C. Begg, **W.L. Griffin**, **S.Y. O'Reilly** and **L. Natapov** Zircon Hf-isotope record for the evolution of the Continental crust since 4.5 Ga **E. Belousova**, **W.L. Griffin**, Y. Kostitsyn, G. Begg and **S.Y. O'Reilly** **Invited** Tectonic mode switches at the Australian Mesoproterozoic Boundary — tectonic events at the same scale lengths as modern tectonic systems P. Betts, R. Armit, J. Stewart and **B. Schaefer** UHT metamorphism in Peninsular India: a consequence of anomalous enrichment in heat producing elements? **C. Clark**, F. Korhonen, R. Taylor, M. Hand and A. Collins Igneous and metamorphic garnet-clinopyroxene assemblages in eclogite and granulite, Breaksea Orthogneiss, New Zealand: major and rare earth element characteristics G. Clarke, **N. Daczko** and D. Miescher

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LA-ICP-MS analysis on chromite: a guide for the geodynamic setting of formation of ultramafic massifs in the Bulgarian Rhodopes
V. Colás, **J.M. González-Jiménez**, **W.L. Griffin**, **M. Locmelis**, F. Gervilla, **S.Y. O'Reilly**, **N.J. Pearson**, I. Fanlo, T.N. Kerestedjian and I. Sergeeva

Earth's changing thermal regime between 3 and 2.5 Ga: a primary control of planetary evolution?
K. Condie and **C. O'Neill**

Integrating geophysics with mapping — defining a new volcano-sedimentary belt, Mali, West Africa
J. Davis, J. Miller, **T.C. McCuaig**, **L. Parra**, N. Said, J. Tunjic and E. Baltis

Full-waveform synthetic seismograms for evaluating seismic proxies for the lithosphere-asthenosphere boundary
D. Eaton, C. Hogan, **J.C. Afonso** and J. Tromp

Dating the geological history of the northwestern North American Plate: Re-Os isotopic analyses of sulfides from western Yukon ultramafic complexes
M.P. Escayola, **J.M. González-Jiménez**, **W.L. Griffin**, J. Proenza, N. Pearce, D. Murphy, C. van Staal and **S.Y. O'Reilly**

Banded iron formation to iron ore: implications for the evolution of Earth environments
K.A. Evans, **T.C. McCuaig**, D. Leach, T. Angerer and S.G. Hagemann

A record of life in changing Neoarchean environments of the Fortescue Group, Pilbara region, Western Australia
D. Flannery, Y. Hoshino, M. Walter, **M. Van Kranendonk** and **S. George**

Low-^{18}O Suzhou A-type granite revisited: Uranium influences *in-situ* zircon Oxygen-isotope Analyses
Y.-Y. Gao, X.-H. Li and **S.Y. O'Reilly**

Biomarkers in offshore Canterbury Basin sediments, New Zealand: organic matter input and thermal maturity
S.C. George, E. Teague, J.S. Lipp, T. Yoshimura and G.E. Claypool

Os isotopes in mantle-derived minerals: what can they really tell us?
J.M. González-Jiménez, **W.L. Griffin**, **S.Y. O'Reilly**, **N.J. Pearson**, F. Gervilla and C. Marchesi

Topographic response to development of Rayleigh-Taylor instability at the base of the mantle lithosphere
W. Gorczyk, B. Hobbs, **K. Gessner**, A. Ord, T. Gerya and R. Korsch

Intra-plate melt intrusion as a consequence of Rayleigh-Taylor instability
W. Gorczyk, K. Vogt, T. Gerya and B. Hobbs

New REE data from Apollo 14 and 17 zircons
M. Grange, **A. Nemchin** and M. Whitehouse

The end of the Hadean: a global revolution
W.L. Griffin, V. Malkovets, **E.A. Belousova**, **S.Y. O'Reilly** and **N.J. Pearson**

Late Devonian carbonate magnetostratigraphy from the south Oscar Range, Lennard Shelf, Western Australia
J. Hansma, E. Tohver, M. Yan, K. Trijnastic, T. Playton, **S.A. Pisarevsky**, J.L Kirschvink, K. Hillbun, D.P. Ward, P.W. Haines and R. Hocking

Investigating the syngeneity and paleobiology of hydrocarbon biomarkers in the Fortescue Group at 2.7–2.8 Ga
Y. Hoshino, D. Flannery, M. Walter and **S. George**

Trace element partitioning in mixed-habit diamonds
D. Howell, **W. Griffin**, **W. Powell**, **P. Wieland**, **N. Pearson** and **S. O'Reilly**

Multi-stage origin of Roberts Victor eclogites: progressive metasomatism
J.-X. Huang, **W.L. Griffin**, **Y. Gréau**, **S.Y. O'Reilly** and **N.J. Pearson**

Formation of Jurassic high-K granitoids in the Nanling Range of southern China by reworking of supracrustal rocks by mantle-derived magmas
H.-Q. Huang, X.-H. Li, **Z.-X. Li** and W.-X. Li

Placement of the Guadalupian-Lopingian (Capitanian-Wuchiapingian) boundary in the Permian of eastern Australia
M.H. Huyskens, J. Crowley, R.S. Nicoll and **I. Metcalfe**

Multiple sulphur isotopes record degassing in komatiite hosted nickel systems during Emplacement
C. Isaac, B. Wing and **M. Fiorentini**

Distribution of sulfur reservoirs through the Archean in the North Eastern Goldfields, Yilgarn Craton, Western Australia and their significance for nickel sulfide formation in komatiites
C. Isaac, **M. Fiorentini**, B. Wing, S. Golding and **M. Barley**

Late Archean crustal accretion patterns and continental growth in the Eastern Dharwar Craton: constraints from SHRIMP U-Pb zircon ages and whole rock geochemistry
M. Jayananda, **M.A. Kusiak**, K. Sekhamo, **S.A. Wilde** and R.V. Gireesh

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An experimental investigation of primitive magmas from the Kermadec Arc
A. Jennings, **T. Rushmer**, **J. Adam** and **S. Turner**

High-resolution lithosphere structure beneath the North China Craton from teleseismic Rayleigh wave tomography
M. Jiang, Y. Ai, L. Chen and **Y. Yang**

4D integrative-approach for target generation in the west Musgrave Province
A. Joly, A. Aitken, M. Dentith, A. Porwal, H. Smithies, S. Evans, I. Tyler and **C. McCuaig**

Emplacement of ophiolite in Papua New Guinea: new field data
L. Jonda, **M.A. Kaczmarek**, H. Davies and F. Boudier

Two collisions, two sutures: punctuated pre-1950 Ma assembly of the West Australian Craton during the Ophthalmian and Glenburgh Orogenies
S.P. Johnson, S. Sheppard, A.M. Thorne, B. Rasmussen, **M.T.D. Wingate**, **C.L. Kirkland**, J.R. Muhling, I.R. Fletcher and **E. Belousova**

Synchronicity between the Kalkarindji large igneous province and the Early-Middle Cambrian Extinction
F. Jourdan, K. Hodges, B. Sell, U. Schaltegger, **M. Wingate**, L. Evins, U. Söderlund, P. Haines and D. Phillips

The Marum Ophiolite Complex (Papua New Guinea): the origin of depleted peridotite
M.-A. Kaczmarek, L. Jonda, H. Davies and F. Boudier

Mantle deformation during rifting in East Africa (Marsabit – Kenya)
M.-A. Kaczmarek and **S.M. Reddy**

Late Permian-Early Triassic palynology of the Bowen and Sydney basins: more CA-IDTIMS isotopic ages
T.E. Kelly, D. Mantle, C.B. Foster, R.S. Nicoll, **I. Metcalfe**, J. Crowley and R. Mundil

Long-lived ultrahigh temperature (UHT) metamorphism in the Eastern Ghats orogenic belt (India): constraints from zircon and monazite geochronology
F.J. Korhonen, **C. Clark**, M. Brown and S. Bhattacharya

Provenance and formation model of Ti-Zr placers of Murray basin (southeastern Australia) from SHRIMP data on dating recrystallization crystals
A. Kremenetskiy and **E. Belousova**

Ion imaging of Pb isotopes illuminates complexity of zircon geochronology
M.A. Kusiak, M.J. Whitehouse, **S.A. Wilde** and **A.A. Nemchin**

Late Neoproterozoic granitoid magmatism in the southernmost section of the Dom Feliciano Belt, Uruguay
P. Lara, P. Oyhantcabal and K. Dadd

Crustal and upper mantle velocity structure in the northeastern Tibetan Plateau
H. Li, **Y. Yang**, Z. Huang, M. Gong, X. Li, Y. Shen, D. Shi, E. Sandvol and A. Li

Geochronology, petrogenesis and tectonic implications of Triassic granitoids from Beishan, NW China
S. Li, T. Wang, **S.A. Wilde**, Y. Tong and D. Hang

Coupled supercontinent-superplume cycles and the geodynamic driving force: an overview
Z.-X. Li

Large-scale and rapid vertical continental movements due to the eclogisation of a flat-subducted oceanic plateau in Mesozoic south China
Z.-X. Li, C. Pang, G.E. Batt, W.-X. Li and Y. Xu

Quantifying spatial relationships between gold mineralisation and relevant control factors, St Ives Goldfield, Western Australia
Y. Liu, **Z.-X. Li**, G. West, C. Laukamp and S. Gardoll

Laser ablation ICP-MS analysis of ruthenium in chromite — a new tool in the exploration for komatiite-hosted nickel-sulphide deposits
M. Locmelis, **M.L. Fiorentini**, S.J. Barnes and **N.J. Pearson**

Geochemical, Sr-Nd-Pb, and zircon Hf-O isotopes of Cenozoic K-adakitic and shoshonitic granitoid rocks in Western Yunnan, SW China: Petrogenesis and tectonic implications
Y.J. Lu, **T.C. McCuaig**, R. Kerrich and Z.Q. Hou

Managing uncertainty in exploration targeting
T.C. McCuaig, A. Porwal, A. Joly and A. Ford

Cratonic source codes: a new tool in Archean plate reconstructions?
N. McNaughton, D. Srinivasa Sarma, M. Ram Mohan, I. Fletcher, C. Gregory, B. Krapez, B. Rasmussen and **S. Wilde**

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Occurrence of inherited supra-subduction zone mantle in the oceanic lithosphere as inferred from mantle xenoliths from Dragon Seamount (southern Tore-Madeira Rise)
R. Merle, **M.A. Kaczmarek**, E. Tronche and J. Girardeau

Unravelling New England Orogen by anisotropy of magnetic susceptibility studies
T. Mochales, G. Rosenbaum, F. Speranza and **S. Pisarevsky**

Nickel mineral systems within an evolving Archean craton
D.R. Mole, **M.L. Fiorentini**, N. Thebaud, **T.C. McCuaig**, K.F. Cassidy, **C.L. Kirkland**, S. Romano, M. Doublier, **E.A. Belousova** and S.J. Barnes

Wordian (Middle Permian) U-Pb CA-IDTIMS isotopic ages from the Lightjack Formation, Canning Basin, Western Australia
A.J. Mory, J. Crowley, R.S. Nicoll, **I. Metcalfe**, D. Mantle, R. Mundil and J. Backhouse

Il'meno-Vishnevogorsky Alkaline Complex (IVAC) from Urals, Russia: age, sources and origin
I. Nedosekova, **E. Belousova** and B. Belyatsky

U-Pb systematics of glass beads from lunar soils
A. Nemchin, **M. Grange**, M. Whitehouse and M. Norman

Using high precision CA-IDTIMS zircon age determinations to interpret correlation and depositional rates in Permian coal sediments of the Sydney, Gunnedah and Bowen basins
R.S. Nicoll, **I. Metcalfe**, J. Crowley, M. Ives and J.R. Laurie

A 4.2 billion year old impact basin on the Moon
M. Norman and **A. Nemchin**

Deep Earth recycling in the Hadean
C. O'Neill **Keynote**

Plate tectonics: a phase a planet goes through?
C. O'Neill

Tracking coupling and decoupling during lithosphere evolution with geochemistry and geochronology: a case history from arctic Norway
S. O'Reilly, **W. Griffin**, N. Nikolic and **N. Pearson** **Invited**

Sedimentary facies analysis of a latest Triassic to early Jurassic shallow marine deltaic succession in northern Guangdong Province, south China: consequence of eclogisation and foundering of a flat-slab?
C. Pang, **Z.-X. Li** and Y. Xu

Advances in *in-situ* Re-Os isotope ratio measurements by LA-MC-ICP-MS
N. Pearson, **W. Griffin** and **S. O'Reilly**

Comparative early history of the Moon and the Earth: zircon geochronological evidence
R. Pidgeon, **A. Nemchin**, **M. Grange** and C. Meyer

India in Nuna – possibilities and problems
S. Pisarevsky and **Z.-X. Li**

Calibration of a Sydney Gunnedah Basin thermal model and insights into the Bowen Basin
S. Quenette, L. Moresi, C. Danis and **C. O'Neill**

Do externally-derived fluids influence the large-scale reactivation of continental interiors?
T. Raimondo, **C. Clark**, M. Hand, **J. Cliff** and R. Anczkiewicz

Zircon deformation and its effect on chronometry, thermometry and fluid-rock interaction
S.M. Reddy and N.E. Timms **Keynote**

Mantle wedge olivine or subducting slab serpentinite: what is responsible for supra-subduction zone seismic anisotropy?
S.M. Reddy, E. Gray, J. Bridges, D. Healy and **M.A. Kaczmarek** **Keynote**

Geochemistry of diamondiferous eclogites from Udachnaya Pipe, Siberia
E.V. Rubanova, **W.L. Griffin**, Z.V. Spetsius, **S.Y. O'Reilly**, **N.J. Pearson**, R. Stern, T. Stachel and **J. Cliff**

Geochemistry and microstructure of diamondites
E.V. Rubanova, **W.L. Griffin**, **S. Piazolo**, **S.Y. O'Reilly**, **N.J. Pearson**, R. Stern, T. Stachel and **J. Cliff**

When a bolide hits a world class Pb/Zn deposit: new insights into the Lawn Hill impact structure
J.A. Salisbury, A.G. Tomkins and **B.F. Schaefer**

U-Pb ages and Hf-isotope systematics of detrital zircons from the Gadag Greenstone Belt: implications for the Archaean crustal growth processes in the western Dharwar Craton, India
D.S. Sarma, N. McNaughton, **E. Belousova**, M. Ram Mohan and I. Fletcher

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Gold mobility in the mantle: constraints from sulfides in variably metasomatised peridotites
J.E. Saunders, **N.J. Pearson**, **S.Y. O'Reilly** and **W.L. Griffin**

Constraining deformational processes on Venus from rheology and lithospheric structure
E. Schinella, **C. O'Neill** and **J.C. Afonso**

Detrital zircon record of Cretaceous sedimentary basins on the Jiamusi Block and Sikhote-Alin accretionary complex, NE China
M.-D. Sun, H.-L. Chen, **S.A. Wilde**, **Z.-X. Li**, F.-Q. Zhang and M.-N. A **Invited**

SHRIMP U-Pb zircon geochronological, geochemical and Sr-Nd isotopic study of a mid-Cretaceous bimodal composite dyke complex in the Jiamusi Block, NE China, and its geodynamic implication
M.-D. Sun, H.-L. Chen, F.-Q. Zhang, **S.A. Wilde**, C.-W. Dong and S.-F. Yang

Constraining paleo-latitudes of rocks from Christmas Island
R. Taneja, **C. O'Neill**, P. Schmidt and **T. Rushmer**

Timing of ultra-high temperature (UHT) metamorphism from zircon, monazite and garnet in Kerala, southern India
R. Taylor, **C. Clark**, S.L. Harley and I.C.W. Fitzsimons

Origin of depleted mantle xenoliths from South Africa
S. Tessalina, **W. Griffin** and **S. O'Reilly**

Deformation of the lithosphere by impact events: what we can learn from zircon microstructure
N.E. Timms, **S.M. Reddy**, D. Healy, **A.A. Nemchin**, **M.L. Grange**, **R.T. Pidgeon** and R. Hart

Deep structures of the Alpine-Himalaya collision in the Zagros Mountains and Tibetan Plateau: a combined geophysical and petrological study
L. Tunini, I. Jiménez-Munt, M. Fernàndez, J. Vergés and **J.C. Afonso**

Coal degradation in anaerobic sediments associated with acid mine drainage
J. van Holst, D.J. Midgley, L. Stalker, M. Gillings and **S.C. George**

Earth's evolving supercontinent cycle: a planetary driver of environmental change
M.J. Van Kranendonk and **C.L. Kirkland**

3 Ga onset of the supercontinent cycle and modern-style subduction and hydrological weathering
M.J. Van Kranendonk, S.B. Shirey, S.H. Richardson, **C.L. Kirkland**, R. Hugh Smithies and **J. Cliff**

A 2.3 Ga sulfuretum at the GOE: microfossil and organic geochemistry evidence from the Turee Creek Group, WA
M.J. Van Kranendonk, J.W. Schopf, K. Grice, M. Walter, A. Pages, A.B. Kudryavtsev, V.A. Gallardo, C. Espinoza, I. Melendez and A. Lepland

Appraisal of prospects for buried commercial placers of Ti-Zr placer provinces in Australia and Russia on the basis of reconstruction of the system: bedrock – intermediate collector – Ti-Zr sands
L.I. Veremeeva, **E.A. Belousova**, N.A. Gromalova and I.M. Kulikova

Metamorphic microstructures in komatiite hosted-Ni sulphides from the Yilgarn Craton, Western Australia
Z. Vukmanović, S.J. Barnes, **S.M. Reddy**, **M.L. Fiorentini** and B. Godel

A long-lived UHT Grenvillian belt in central Australia
A.K. Walsh, D.E. Kelsey, M. Hand, R. Hugh Smithies, **C.L. Kirkland** and **C. Clark**

Early crustal evolution in the western Yangtze block: evidence from U-Pb and Lu-Hf isotopes on detrital zircons from sedimentary rocks
L. Wang, J. Yu, **W.L. Griffin** and **S.Y. O'Reilly**

Detailed geochronological traverse along the Jack Hills Metasedimentary Belt, Western Australia
Q. Wang and **S.A. Wilde**

A mantle hydrated by stagnated Pacific slab that produced intraplate continental flood basalts in northeastern China
X.-C. Wang, **Z.-X. Li**, Q.-L. Li and X.-H. Li

CET exploration simulator: a training tool for mineral exploration decision making
J.C. Wong, E.-J. Holden, P. Kovesi and **T.C. McCuaig**

Protoliths and ~440-Ma ultrahigh-pressure metamorphism of eclogite and gneiss in the north Qaidam orogen, NE Tibet: implications for deep subduction of the Qaidam Basin
Q. Xiong, J. Zheng, **S.Y. O'Reilly** and **W.L. Griffin**

Destruction timing of the North China Craton
J.-H. Yang, F.-Y. Wu, R. Zhu, **S.Y. O'Reilly**, **W.L. Griffin** and **S.A. Wilde** **Invited**

34th International Geological Congress, Brisbane, 5-10 August 2012 *cont...*	The structure of the crust and uppermost mantle in China from ambient noise tomography **Y. Yang**, Y. Zheng, L. Zhou, W. Shen, J. Xie and M.H. Ritzwoller Post-kinematic lithospheric delamination of the Wuyi-Yunkai orogen in south China: evidence from ca. 435 Ma high-Mg basalts W.-H. Yao, **Z.-X. Li**, W.-X. Li, X.-C. Wang, X.-H. Li and J.-H. Yang Long-time linking of Cathaysia Block, south China with East Gondwanaland from Paleoproterozoic to early Paleozoic J.-H. Yu, **S.Y. O'Reilly**, L. Wang, **W.L. Griffin** and Q. Liu Pangea assembly and breakup control long-wavelength mantle structure evolution N. Zhang, S. Zhong, W. Leng and **Z.-X. Li** Pre-Rodinia supercontinent Nuna shaping up: a global synthesis with new paleomagnetic results from north China S. Zhang, **Z.-X. Li**, D.A.D. Evans, H. Wi, H. Li and J. Dong Zircon U-Pb study of the Heilongjiang complex in the NE China: evidence and tectonic implications X.-Z. Zhang, L.-L. Zhao, J.-B. Zhou and **S.A. Wilde** Zircon U-Pb and Lu-Hf isotope study of the Neoproterozoic Haizhou Group in the Sulu Orogen: provenance and tectonic implications J.-B. Zhou, X.-Z. Zhang, **S.A. Wilde** and H. Chen
Meteoritical Society Annual meeting, Cairns Australia, 12-17 August 2012	Microstructural analysis of troilite in IAB iron meteorites G.K. Benedix, **M.-A. Kaczmarek** and **S. Reddy** How to preserve a chemically heterogeneous martian mantle? A plate tectonics point of view V. Debaille, **C. O'Neill**, A.D. Brandon, P. Haenecour, Q.-Z. Yin, N. Mattielli and A.H. Treiman Preferred mineral orientations in martian shergottites: magmatism or shock? **M.-A. Kaczmarek**, **M. Grange**, **S. Reddy** and **A. Nemchin** Comparison of zircon U-Pb ages of Apollo 14 breccias R.E. Merle, **M.L. Grange**, **A.A. Nemchin**, M.J. Whitehouse and **R.T. Pidgeon** Prolonged early bombardment of the inner solar system from ages of lunar samples M.D. Norman and **A.A. Nemchin** The development of lunar zircon/apatite U-Pb geochronology at Curtin University **R.T. Pidgeon**, **A.A. Nemchin** and **M.L. Grange** Br isotope signatures in Ordinary Chondrites **B.F. Schaefer** Unravelling the impact history of the Moon using deformed zircon N.E. Timms, **S.M. Reddy**, **M.L. Grange**, **A.A. Nemchin**, **R.T. Pidgeon** and D. Healy Impact-driven disequilibrium melting and melt migration: implications for rapid planetesimal core formation A.G. Tomkins, R.F. Weinberg, **B.F. Schaefer** and A. Langendam
The 13th International Conference on Thermochronology, Guilin, China, 24-28 August 2012	Post-UHP exhumation history of the Sulu Orogenic Belt, eastern China: evidence from integrated thermochronology L. Liu, **Z.X. Li**, M. Danišík, S. Li, N.J. Evans and X. Liu Thermochronological record of central and southern South China since the Mesozoic N. Tao, **Z.X. Li**, M. Danišík, N.J. Evans, Y.G. Xu, C.J. Pang, W.X. Li and D.H. Liu
The First European Mineralogical Conference (EMC2012) - Planet Earth from Core to Surface, Frankfurt, Germany, 2-6 September 2012	Clues for unravelling metamorphic alteration on Kosturino (SE Bulgaria) chromitites F. Gervilla, V. Colás, I. Fanlo, T. Kerestedjian, I. Sergeeva, **J.M. González-Jiménez** and E. Arranz Tracking the evolution of the convecting mantle in ophiolites: the case of the Dobromirtsi Ultramafic Massif, Central Rhodope, Bulgaria **J.M. González-Jiménez**, **W.L. Griffin**, **E. Belousova**, **M. Locmelis**, F. Gervilla, **S.Y. O'Reilly**, T.N. Kerestedjian, I. Sergeeva, **N.J. Pearson**, V. Colás and I. Fanlo

AAPG International Conference and Exhibition, Fueling the Future, Singapore, 16-19 September 2012	Source rock mapping using fluid inclusion geochemistry in the offshore Perth Basin H. Volk, R. Kempton, S. Gong, M. Ahmed, **S.C. George**, C.J. Boreham and E. Grosjean
SEG 2012, Integrated Exploration and Ore Deposits, Lima, Peru 23-26 September 2012	Nickel mineral systems within an evolving Archean Craton **D.R. Mole**, **M. Fiorentini**, N. Thebaud, **C. McCuaig**, K.F. Cassidy, **C.L. Kirkland**, S.S. Romano, M.P. Doublier, **E.A. Belousova** and S.J. Barnes
Supercontinent Symposium 2012, Helsinki, Finland, 25-28 September 2012	LA-ICP-MS U-Pb dating of detrital zircons from sediments of the southern part of the Siberian craton: constraints for Precambrian supercontinents D. Gladkochub, G. Nicoll, S. Zhang, A. Stanevich, **S. Pisarevsky**, A. Mazukabzov and T. Donskaya New palaeomagnetic and geochronological data from the Ropruchey sill (Karelia, Russia): implications for late Palaeoproterozoic palaeogeography N.V. Lubnina, **S.A. Pisarevsky**, U. Söderlund, M. Nilsson, S.J. Sokolov, A.N. Khramov, A.G. Iosifidi, R. Ernst, M.A. Romanovskaya and B.N. Pisakin Mesoproterozoic supercontinent - paleomagnetic synthesis and geological constraints. **S.A. Pisarevsky** **Keynote**
ESCA-2012 International Earth Science Colloquium on the Aegean Region, Izmir, Turkey, 1-5 October 2012	Dating the geological history of the northwestern North American plate: Re-Os isotopic analyses of sulfides from western Yukon ultramafic complexes **M.P. Escayola**, **J.M. González-Jiménez**, **W. Griffin**, J. Proenza, N. Pearce, D. Murphy, C. van Stall and **S.Y. O'Reilly** Lithospheric mapping, metallogenesis and the evolution of continents **W.L. Griffin**, **S.Y. O'Reilly**, G. Begg, **E.A. Belousova** and **N.J. Pearson** **Keynote** The use of trace elements and Os isotopes in chromite deposits to understand the origin and evolution of old upper mantle fragments within young ophiolites **J.M. González-Jiménez**, **W.L. Griffin**, **S.Y. O'Reilly** and **N.J. Pearson** Ancient mantle domains stranded in ocean lithosphere add complexity to understanding Tethyan ophiolites **S.Y. O'Reilly**, **W.L. Griffin** and **N.J. Pearson**
Geochemistry and Ore Deposit Models Seminar, University of Oulu, Finland, 17-18 October 2012	Multiple sulfur isotopes as an indicator of sulfur source in Ni-Cu sulfide deposits E. Hanski and **M. Fiorentini** **Keynote**
GSA Annual Meeting, Charlotte, USA, 4-7 November 2012	Phase equilibria modeling integrated with geochronology in highly residual UHT granulites from the Eastern Ghats Province, India **M. Brown**, F.J. Korhonen and **C. Clark** A microbial ecosystem in an ancient sabkha of the 3.49 ga Pilbara, Western Australia, and comparison with Mesoarchean, Neoproterozoic and Phanerozoic examples N. Noffke, D. Christian, **D. Wacey** and R.M. Hazen
17th Australian Organic Geochemistry Conference, Macquarie University, Sydney, 2-5 December 2012	The organic geochemistry of the Mesoproterozoic Velkerri Formation and investigations into syngenicity and indigeneity of hydrocarbons using slice experiments E.N. Flannery and **S.C. George** An exciting future for biomarker geochemistry in very old rocks: single oil inclusion analysis by TOF-SIMS **S.C. George**, S. Siljeström, H. Volk, A. Dutkiewicz, J. Lausmaa, P. Sjövall and T. Hode Flash pyrolysis GCMS analysis of fluid inclusions P.F. Greenwood., Z. Zhirong, K. Liu, K. Grice, **S.C. George**, L. Fisher and R. Hough

17th Australian Organic Geochemistry Conference, Macquarie University, Sydney, 2-5 December 2012 *cont...*	Investigating the Syngeneity and the Palaeobiology of Hydrocarbon Biomarkers in the Fortescue Group at 2.7-2.8 Ga Y. Hoshino, D. Flannery, M.R. Walter and **S.C. George** Application of a linear transfer model for the estimation of the hydrocarbon concentration in the seawater of Antarctica following a fuel spill K. Kotzakoulakis and **S.C. George** Sr isotopic composition of pore water of shelf cores from IODP Expedition 317: Canterbury Basin, New Zealand T. Yoshimura, H. Kawahata, M. Tanimizu, **S.C. George,** J.S. Lipp and G.E. Claypool
American Geophysical Union's 45th Annual Fall Meeting, San Francisco, California, 3-7 December 2012	Liquidus and sub-liquidus phase equilibria for an Archaean tonalite: matching experimental data to models of TTG genesis **J. Adam**, **T.A. Rushmer** and J. O'Neil Towards multi-observable thermochemical tomography of the lithosphere and sublithospheric upper mantle **J.C. Afonso**, J. Fullea, **Y. Yang**, N. Rawlinson, A.G. Jones and J.A. Connolly The first year of the Australian Seismometers in Schools Network: Inspiring Students to follow careers in science by participating in a national science experience N. Balfour, M. Sambridge and **C. O'Neill** Exploration of the Lesser Antilles arc signature in St Lucia using a multiscale analytical approach **R.C. Bezard**, J.P. Davidson, **S. Turner** and J.M. Lindsay Using experimental petrology to constrain genesis of wet, silicic magmas in the Tonga-Kermadec island arc **R. Brens**, **T.A. Rushmer**, **S. Turner** and **J. Adam** A new high-pressure research facility at the Australian Synchrotron **S. Clark**, **T.A. Rushmer**, C. Glover, **S. Turner**, R. Garrett and Y. Wang Incorporation of crust at the Lesser Antilles arc J.P. Davidson and **R.C. Bezard** **invited** Dome and Keel dynamics in the hot Archean lithosphere: a numerical approach G. Duclaux, N. Thebaud, **K. Gessner** and M. Doublier Lawsonite Veins in Eclogite and Bluschist as Recorders of Subduction Fluids K.F. Fornash, L. Gauthiez-Putallaz, D.L. Whitney and **L. Martin** Intra-cratonic melting as a result of delamination of mantle lithosphere - insight from numerical modelling **W. Gorczyk**, K. Vogt, T. Gerya and B.E. Hobbs Petrology of Oceanic Lithosphere from Thermodynamic Models: Implications for Geophysical Observations and Geodynamics C.J. Grose and **J.C. Afonso** Along-arc geochemical and isotopic variations in Javanese volcanic rocks: 'crustal' versus 'source' contamination at the Sunda arc, Indonesia **H. Handley**, J. Blichert-Toft, **S. Turner** and C.G. Macpherson The opening of the South China Sea: Driven by Pacific subduction, or by India-Eurasia collision? **Z.-X. Li** **Invited** No crustal material flow through the northeast corner of the Tibetan Plateau into the Ordos basin H. Li, **Y. Yang**, Z. Huang, M. Gong, X. Li, Y. Shen, D. Shi, E.A. Sandvol and A. Li Metal transport between the upper mantle and the lower crust **M. Locmelis**, **J. Adam**, F. Zaccarini, **M.L. Fiorentini**, **T. Rushmer**, G. Garuti, **S. Turner**, P. Kollegger and **E. Davies** Crustal radial anisotropy in the Dabie orogenic belt from ambient noise tomography Y. Luo, Y. Xu and **Y. Yang** Evaluating the earliest traces of Archean sub-seafloor life by NanoSIMS N. McLaughlin, E.G. Grosch, **M. Kilburn** and **D. Wacey** Two styles of lithosphere stabilisation as recorded by post orogenic A-type magmas from each side of the Tasman Line, Australia **M.J. Pankhurst**, **B.F. Schaefer** and **S. Turner** Crustal anisotropy in Eastern Tibet M.H. Ritzwoller, J. Xie, W. Shen, P.H. Molnar, **Y. Yang**, L. Zhou and Y. Zheng

American Geophysical Union's 45th Annual Fall Meeting, San Francisco, California, 3-7 December 2012 *cont...*	Core formation in Planetesimals: Textural analyses from 3D synchrotron imaging and complex systems modeling **T.A. Rushmer**, A. Tordesillas, D.M. Walker, D.Y. Parkinson and **S.M. Clark** The uppermost mantle evolution during back-arc spreading: Microstructural and petrological characteristics of Ichinomegata peridotite xenoliths in the back-arc region of Japan Islands **T. Satsukawa**, K. Michibayashi, G. Marguerite and S. Demouchy Origin of seamount volcanism in northeast Indian Ocean with emphasis on Christmas Island **R. Taneja**, **C. O'Neil**, **T.A. Rushmer**; F. Jourdan, J. Blichert-Toft, **S. Turner** and M.A. Lackie Recycling of water within the mantle: New insights from pyroxene water data **M.B. Turner**, **S. Turner**, T.R. Ireland, **J. Adam**, G.M. Yogodzinsk, D.L. Blatter and M.R. Perfit Extremely young metasomatism of the continental lithospheric mantle **S. Turner** and **M.B. Turner** Imaging crustal anisotropy in eastern Tibet and South China using ambient noise and earthquake data J. Xie, W. Shen, M.H. Ritzwoller, **Y. Yang**, L. Zhou and Y. Zheng Applications of long period surface wave dispersion measurements from ambient noise in regional surface wave tomography **Y. Yang** The crustal and upper mantle structure of the Tien Shan Orogen and surroundings from ambient noise and earthquake tomography Y. Zheng, **Y. Yang**, W. Shen, M.H. Ritzwoller and X. Xiong
4th Greenland Day Workshop, Perth, Western Australia, 4 December 2012	Proterozoic deposits in Australia and Greenland **L. Bagas**, J. Kolb, **M. Fiorentini**, B.M. Stensgaard and **J. Owen** The potential for nickel mineralization in entire Greenland **M. Fiorentini**, B.M. Stensgaard, J. Kolb and **L. Bagas** A joint CET-GEUS-BMP research project: Nickel mineral systems in Archaean ultramafic rocks in South-East Greenland **M. Fiorentini**, **L. Bagas**, **J. Owen**, B. Lally, B.M. Steensgaard, J. Kolb and N. Thebaud Comparison between endowed terranes in Greenland and Australia J. Kolb, **L. Bagas**, **M. Fiorentini** and B.M. Steensgaard Introduction to 4 billion years of geological history of Greenland and data J. Kolb, **L. Bagas**, B.M. Stensgaard and **S. Piazolo**

Appendix 7: Research funding

GRANTS AND OTHER INCOME FOR 2012

Investigators	2012 Funding Source	Project Title	Amount
O'Reilly	ARC Centre of Excellence	Core to Crust Fluid Systems	$2,004,179
Wilde	ARC CoE (Curtin contribution)	Core to Crust Fluid Systems	$250,000
GSWA	ARC CoE (GSWA)	Core to Crust Fluid Systems	$150,000
O'Reilly	ARC CoE (MQ contribution)	Core to Crust Fluid Systems	$400,000
O'Reilly	ARC CoE (MQ EPS contribution)	Core to Crust Fluid Systems	$100,000
McCuaig	ARC CoE (UWA contribution)	Core to Crust Fluid Systems	$320,000
O'Reilly	Interest	Core to Crust Fluid Systems	$37,149
Afonso, Yang, Rawlinson, Jones, Connolly, Lebedev	ARC Discovery Project	What lies beneath: Unveiling the fine-scale 3D compositional and thermal structure of the subcontinental lithosphere and upper mantle	$95,000
Li, Danisik, Xu	ARC Discovery Project	Multiple vertical tectonic movements in a continental interior: consequences of flat-subduction and foundering of an oceanic plateau?	$70,000
Nemchin, Grange	ARC Discovery Project	Investigation of the early history of the Moon	$70,000
O'Neill, Afonso	ARC Discovery Project	The effective strength of oceanic plate bounding faults	$65,000
Piazolo, Daczko, Putnis, Jessell	ARC Discovery Project	Investigating the fundamental link between deformation, fluids and the rates of reactions in minerals	$90,000
Rawlinson, Yang	ARC Discovery Project	Down under down under: using multi-scale seismic tomography to image beneath Australia's Great Artesian Basin	$40,159
Rushmer, Turner	ARC Discovery Project	Origin of silicic magmas in a primitive island arc: the first integrated experimental and short-lived isotope study of the Tongan-Kermadec system	$80,000
Turner, Dosseto, Reagan	ARC Discovery Project	The application of short-lived Uranium-series isotopes to constraining Earth system Processes	$103,000
Walter, Neilan, George, Summons, Schopf	ARC Discovery Project	Oxygenating the Earth: using innovative techniques to resolve the timing of the origin of oxygen-producing photosynthesis in cyanobacteria	$30,000
Collins, Belousova, Murphy, Hand	ARC Discovery Project	Supercells and the supercontinent cycle	$18,500
Jacob	ARC Future Fellowship	A new approach to quantitative interpretation of paleoclimate archives	$102,846
Belousova	ARC Future Fellowship	Dating Down Under: Resolving Earth's crust-mantle relationships	$177,797
Fiorentini	ARC Future Fellowship	From Core to Ore: emplacement dynamics of deep-seated nickel sulphide systems	$169,532
Handley	ARC Future Fellowship	The timescales of Earth-system processes: extending the frontiers of uranium-series research	$77,788
O'Neill	ARC Future Fellowship	Strength and resistance along oceanic megathrust faults: implications for subduction initiation	$153,938
Piazolo	ARC Future Fellowship	Flow characteristics of lower crustal rocks: developing a toolbox to improve geodynamic models	$204,247
Roberts, Heslop, Pillans, De Deckker, Lister, Li, Rosenbaum, Vasconcelos, Aitchison, Pisarevsky, Tohver, Schmidt, McWilliams	ARC LIEF	A world-class rock magnetic facility to support Australian palaeomagnetic and environmental research	$254,078

Investigators	2012 Funding Source	Project Title	Amount
Rushmer, O'Neill, Cruden, Turner	ARC LIEF	The first Australian high pressure Synchrotron facility for geoscience research	$155,000
Rushmer, O'Neill, Cruden, Turner	ARC LIEF External contribution	The first Australian high pressure Synchrotron facility for geoscience research	$20,000
Rushmer, O'Neill, Cruden, Turner	ARC LIEF MQ contribution	The first Australian high pressure Synchrotron facility for geoscience research	$50,000
Arculus, De Deckker, Exon, Barley, Brocks, Clennell, Cooper, Dodson, Drysdale, Fergusson, Hergt, Howard, Kershaw, McCuaig, Muller, Poiner, O'Reilly, Webster, Yeats, Vasconcelos, Stilwel	ARC LIEF MQ contribution	Australian Membership of the Integrated Ocean Drilling Program	$40,000
Barley, Thebaud	ARC Linkage Project	Tectonic evolution and lode gold mineralisation in the Southern Cross district, Yilgarn Craton (Western Australia): a study of the meso- to Neoarchaean missing link	$81,532
Fiorentini, Brugger, Perring, Liu, Barne	ARC Linkage Project	Hydrothermal remobilisation of base metals and platinum group elements in magmatic nickel deposits	$63,278
Gessner, McCuaig, Hobbs, Cawood, Gorczyk, Connolly, Gerya, O'Neill, Lester	ARC Linkage Project	Multiscale dynamics of ore body formation	$180,000
McCuaig, Hobbs, Cawood, Liu, Ord, Gorczyk, Lester, Connolly, Gerya, Gessner	ARC Linkage Project (industry cont.)	Multiscale dynamics of ore body formation	$338,812
McCuaig, Barley, Fiorentini, Kemp, Miller, Belousova, Jessell, Hein, Begg, Tunjic, Angerer, Said, Bagas	ARC Linkage Project	Four dimensional lithospheric evolution and controls on mineral system distribution in Neoarchean to Paleoproterozoic terranes	$520,000
McCuaig, Barley, Fiorentini, Kemp, Miller, Belousova, Jessell, Hein, Begg, Tunjic, Angerer, Said, Bagas	ARC Linkage Project (industry cont.)	Four dimensional lithospheric evolution and controls on mineral system distribution in Neoarchean to Paleoproterozoic terranes	$1,080,208
Turner, Schaefer, McConachy	ARC Linkage Project	A novel approach for economic uranium deposit exploration and environmental studies	$118,500
Turner, Schaefer, McConachy	ARC Linkage Project Heathgate Resources	A novel approach for economic uranium deposit exploration and environmental studies	$45,000
George, Christensen, King, McIntyre, McRae, Snape, Stark	Australian Antarctic Division	Rates of depletion of lubricant and fuel contaminants from Antarctic regions during natural attenuation and remediation procedures	$15,000
González-Jiménez	Contrib to Post-award	Core to Crust Fluid Systems	$33,000
Wang	Contrib to Post-award	Core to Crust Fluid Systems	$30,000
McCuaig, Greenwood, McCulloch	CSIRO Flagship Collaboration Fund	Mineral Systems Flagship Cluster	$264,497
Clark	Curtin University Research Fellowship	The thermal evolution of continental crust	$116,647
O'Reilly, DEPS	Department of Earth and Planetary Sciences	GAU Maintenance Contribution	$30,000
O'Neill, O'Reilly	Department of Innovation, Industry, Science and Research (DIISR) EIF	AuScope Australian Geophysical Observing System - Geophysical Education Observatory	$50,000
George	DVC (Research) Discretionary Fund	Organic Geochemistry Conference	$6,145
Griffin, O'Reilly, Pearson, Belousova	DVC (Research) Discretionary Fund	Lithospheric Architecture Mapping in Phanerozoic Orogens	$20,000

Investigators	2012 Funding Source	Project Title	Amount
Dentith, McCuaig, Miller, Beresford, Gallardo, Holden, George, Hagemann, Porwal, Joly	Geological Survey of Western Australia	GSWA-CET Targeting Products	$255,613
Fiorentini, Barnes, Miller	MERIWA M413	Hydrothermal footprints of magmatic nickel sulphide deposits	$128,000
Vaillant	MERIWA Scholarship	Characterisation of the nature, geometry and size of hydrothermal remobilisation of base metals and platinum group elements in magmatic nickel sulphide deposit systems	$5,000
Belousova	MQ Academic Non-Discretionary Fund	Start-up funds for Future Fellowship FT110100685	$130,000
Handley	MQ Academic Non-Discretionary Fund	Start-up funds for Future Fellowship FT120100440	$85,314
Piazolo	MQ Academic Non-Discretionary Fund	Start-up funds for Future Fellowship FT110100070	$150,000
O'Reilly	MQSIS Infrast	Xray fluorescence Spectrometer	$162,389
O'Reilly	NCRIS AuScope	A4.45; Macquarie University Project - Earth Composition and Evolution	$55,000
O'Reilly	NCRIS MQ Contribution	AuScope (www.auscope.org.au)	$50,000
Reddy	Office of Research and Development, Curtin University	Mary-Alix	$50,000
Thebaud, McCuaig, Miller	Industry Grant	4D evolution of the Agnew gold field, Yilgarn Craton	$68,000
Rubanova	PGRF	Fluid processes in the deep mantle: Geochemical studies of diamonds and related minerals	$2,750
George, Turner, Rushmer, Schaefer, Brock	MQ RIBG	Precision saw for finely cutting and slicing geological samples	$32,562
O'Neill	Sub-contract: NeCTAR project 'Geology from Geodynamics' Monash University	Geology from Geodynamics	$65,917
Van Kranendonk	UNSW SPF	Archean subduction in the Kaapvaal Craton	$20,000
Van Kranendonk	UNSW SPF	The Archean-Proterozoic boundary in Western Australia	$30,000
George, Dutkiewicz, Webb	Agouron Institute Research Grant for 2010–2013	Australian Drilling Program: Biomarkers, Oxygen and Geobiology	$76,000
Piazolo	AINSE Award	In-situ deformation of ice II: Temperature, strain rate and finite strain effects (ID 2178)	$2,934
Kane, Smith, Carman, Jagadish, Fu	MQRES	MQ	$200,000
Murphy, Murphy, Saunders, Schinella	APA	MQ	$175,114
Foley, Genske, Gaildry, Rubanova, Taneja	iMQRES	MQ	$543,134
Macquarie University	GLITTER software	Core to Crust Fluid Systems	$49,689
Macquarie University	Access MQ	Core to Crust Fluid Systems	$184,266

GRANTS AND OTHER INCOME FOR 2013

Investigators	2013 Funding Source	Project Title	Amount
O'Reilly	ARC Centre of Excellence	Core to Crust Fluid Systems	$1,800,000
Wilde	ARC CoE (Curtin contribution)	Core to Crust Fluid Systems	$250,000
GSWA	ARC CoE (GSWA)	Core to Crust Fluid Systems	$150,000
O'Reilly	ARC CoE (MQ contribution)	Core to Crust Fluid Systems	$400,000

Investigators	2013 Funding Source	Project Title	Amount
O'Reilly	ARC CoE (MQ EPS contribution)	Core to Crust Fluid Systems	$100,000
McCuaig	ARC CoE (UWA contribution)	Core to Crust Fluid Systems	$320,000
Afonso, Yang, Rawlinson, Jones, Connolly, Lebedev	ARC Discovery Project	What lies beneath: Unveiling the fine-scale 3D compositional and thermal structure of the subcontinental lithosphere and upper mantle,	$95,000
Li, Danisik, Xu	ARC Discovery Project	Multiple vertical tectonic movements in a continental interior: consequences of flat-subduction and foundering of an oceanic plateau?	$70,000
Nemchin, Grange	ARC Discovery Project	Investigation of the early history of the Moon	$70,000
O'Neill, Afonso	ARC Discovery Project	The effective strength of oceanic plate bounding faults	$65,000
Piazolo, Daczko, Putnis, Jessell	ARC Discovery Project	Investigating the fundamental link between deformation, fluids and the rates of reactions in minerals	$70,000
Rawlinson, Yang	ARC Discovery Project	Down under down under: using multi-scale seismic tomography to image beneath Australia's Great Artesian Basin	$38,120
Rushmer, Turner	ARC Discovery Project	Origin of silicic magmas in a primitive island arc: the first integrated experimental and short-lived isotope study of the Tongan-Kermadec system	$80,000
Turner, Dosseto, Reagan	ARC Discovery Project	The application of short-lived Uranium-series isotopes to constraining Earth system Processes	$103,000
Walter, Neilan, George, Summons, Schopf	ARC Discovery Project	Oxygenating the Earth: using innovative techniques to resolve the timing of the origin of oxygen-producing photosynthesis in cyanobacteria	$30,000
Collins, Belousova, Murphy, Hand	ARC Discovery Project	Supercells and the supercontinent cycle	$18,500
Jacob	ARC Future Fellowship	A new approach to quantitative interpretation of paleoclimate archives	$205,387
Belousova	ARC Future Fellowship	Dating down under: resolving earth's crust - mantle relationships	$177,797
Fiorentini	ARC Future Fellowship	From Core to Ore: emplacement dynamics of deep-seated nickel sulphide systems	$167,732
Handley	ARC Future Fellowship	The timescales of Earth-system processes: extending the frontiers of uranium-series research	$157,858
O'Neill	ARC Future Fellowship	Strength and resistance along oceanic megathrust faults: implications for subduction initiation	$141,938
Piazolo	ARC Future Fellowship	Flow characteristics of lower crustal rocks: developing a toolbox to improve geodynamic models	$204,655
Clark	ARC DECRA	How does the continental crust get so hot?	$125,000
Griffin, Pearson, O'Reilly, Belousova	ARC LEIF	New horizons in geochemical isotopic analysis with a new-generation multicollector plasma mass spectrometer: towards unravelling the deep earth system	$390,000
Griffin, Pearson, O'Reilly, Belousova	ARC LEIF (MQ contribution)	New horizons in geochemical isotopic analysis with a new-generation multicollector plasma mass spectrometer: towards unravelling the deep earth system	$500,000
Fiorentini, Brugger, Perring, Liu, Barnes	ARC Linkage Project	Hydrothermal remobilisation of base metals and platinum group elements in magmatic nickel deposits	$62,770
Turner, Schaefer, McConachy	ARC Linkage Project	A novel approach for economic uranium deposit exploration and environmental studies	$65,000

Investigators	2013 Funding Source	Project Title	Amount
Reddy, McNaughton, Timms, Hough, van Riessen, Bland, Cleverley, Fiorentini, Griffin, Kemp, Kilburn	ARC LIEF	An AZtec electron backscatter diffraction facility for state-of-the-art quantitative microstructural analysis	$190,000
Gessner, McCuaig, Hobbs, Cawood, Gorczyk, Connolly, Gerya, O'Neill, Lester	ARC Linkage Project	Multiscale dynamics of ore body formation	$95,000
McCuaig, Barley, Fiorentini, Kemp, Miller, Belousova, Jessell, Hein, Begg, Tunjic, Angerer, Said, Bagas	ARC Linkage Project	Four dimensional lithospheric evolution and controls on mineral system distribution in Neoarchean to Paleoproterozoic terranes	$560,000
McCuaig, Barley, Fiorentini, Kemp, Miller, Belousova, Jessell, Hein, Begg, Tunjic, Angerer, Said, Bagas	ARC Linkage Project (industry cont.)	Four dimensional lithospheric evolution and controls on mineral system distribution in Neoarchean to Paleoproterozoic terranes	$458,893
Venter, Piazolo, Luzin	Braggs Institute, ANSTO	Residual stress investigations of polycrystalline natural diamond aggregates	$30,000
González-Jiménez	Contrib to Post-award	Core to Crust Fluid Systems	$33,000
Wang	Contrib to Post-award	Core to Crust Fluid Systems	$30,000
Satsukawa	Contrib to Post-award	Core to Crust Fluid Systems	$33,000
McCuaig, Greenwood, McCulloch	CSIRO Flagship Collaboration Fund	Mineral Systems Flagship Cluster	$268,532
Clark	Curtin University Research Fellowship	The thermal evolution of continental crust	$114,761
O'Reilly, DEPS	Department of Earth and Planetary Sciences	GAU Maintenance Contribution	$30,000
O'Neill, O'Reilly	Department of Innovation, Industry, Science and Research (DIISR) EIF	AuScope Australian Geophysical Observing System - Geophysical Education Observatory	$50,000
Dentith, McCuaig, Miller, Beresford, Gallardo, Holden, George, Hagemann, Porwal, Joly	Geological Survey of Western Australia	GSWA-CET Targeting Products	$267,060
Fiorentini, Barnes, Miller	MERIWA M413	Hydrothermal footprints of magmatic nickel sulphide deposits	$130,000
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (Minerals Targeting International Pty Ltd)	Lithospheric architecture mapping in Phanerozoic orogens	$60,000
O'Reilly	MQSIS Research Infrastructure Special Reserve Fund	Energy dispersive x-ray system for Cemeca SX100 Electron Microprobe	$157,219
Afonso	MQ RIBG	Cluster computing for 21st-century Geophysical simulations	$90,587
Pearson	MQ RIBG	Front-line microscope imaging for Geosciences	$91,522
Gore, Taylor, Fryirs, Pearson, Belousova, Handley, Sheedy, Shoat	MQ RIBG	A hand-held portable XRF analyser	$59,146

Appendix 8: Standard performance indicators

% Values maximised at 100%, numeric values maximised at double target

Area	Sub-area	Code	Indicator	Actual	Target
RESEARCH	Number & quality of publications	R1	Research outputs	140	20
		R2(a)	Journals with Impact Factor >2.5	66%	70%
		R2(b)	Journals with impact Factor >3	62%	50%
		R2(c)	Journals with specific target audiences	32%	20%
		R2(d)	Book chapters / international conference proceedings	4%	10%
		R3(a)	Number of presentations / talks / papers / lectures given at major international meetings	245	20
		R3(b)	Number of invited or keynotes given at major international meetings	22	6
		R4	No. & nature of commentaries about the Centre's achievements In general/specialist publications.	11	4
		R5	Citation data for publications	To be set	
	Research training and professional education	R6	Number of attended professional training courses for staff and postgraduate students	68	10
		R7	Number of Centre attendees at all professional training courses	256	20
		R8	No. of new postgrads working on core Centre res. & supervised by CoE staff (PhD, MRes & Cwork)	20	6
		R9	Number of new postdoctoral researchers recruited to the Centre working on core Centre research	4	4
		R10	No. new Honours students working on core Centre research and supervised by Centre staff	15	6
		R11(a)	No. of postgrad. completions working on core Centre research and supervised by Centre staff	3	6
		R11(b)	Postgrad completion times: students working on core CoE research and supervised by Centre staff	3.5	3.5
		R12	No. of Early Career Researchers (within 5 years of completing PhD) working on core Centre research	12	6
		R13	Number of students mentored	91	18
		R14	Number of mentoring programs	3	3
	Build int. national & regional links/networks	R15	Number of international visitors and visiting fellows	72	20
		R16	Number of national and international workshops held / organised by Centre	4	3
		R17	Number of visits to overseas laboratories and facilities	18	15
		R18	Examples of relevant interdisciplinary research supported by the Centre	93%	50%

RESEARCH	Build end-user links	R19	Number of government, industry & business community briefings	Actual	6
				Target	4
		R20	Number and nature of public awareness programs	Actual	8
				Target	5
		R21	Currency of information on the Centre's website	Actual	12
				Target	4
		R22	Number of website hits	Actual	5,076
				Target	3,000
		R23	Number of public talks given by centre staff	Actual	8
				Target	4
ORG SUPPORT	Generate cash & in-kind contributions from partners & other sources & build collab. & infrastructure support	O1	Annual cash contributions from collaborating organisations	Actual	1,790,000
				Target	1,790,000
		O2	Annual in-kind contributions from collaborating organisations	Actual	12,436,116
				Target	12,418,100
		O3	Annual cash contributions from partner organisations	Actual	150,000
				Target	150,000
		O4	Annual in-kind contributions from partner organisations	Actual	1,920,995
				Target	1,229,300
		O5	Other research income secured by Centre staff	Actual	615,813
				Target	140,000
		O6	Number of new organisations collaborating with, or involved in, the Centre	Actual	8
				Target	5
		O7	Level and quality of infrastructure provided to the Centre	Actual	To be set
				Target	
GOVERNANCE	Intersect the right set of expertise to guide the Centre	G1	Breadth, balance and experience of the members of the Advisory Committee	Actual	Qualitative
				Target	
		G2	Frequency, attendance and value added by Advisory Committee meetings	Actual	Qualitative
				Target	
		G3	Vision and usefulness of the Centre strategic plan	Actual	Qualitative
				Target	
		G4	Adequacy of the Centre's performance measure targets	Actual	Qualitative
				Target	
		G5	Effectiveness of the Centre in bringing researchers together to form an interactive and effective research team	Actual	Qualitative
				Target	
		G6	Capacity building of the Centre through scale and outcomes	Actual	Qualitative
				Target	
BENEFIT	Contribute to the national research agenda; expand the national capability in Earth Sci.	N1	Contributions to National Research Priorities and National Innovation Priorities	Actual	4
				Target	4
		N2	Measures of expansion of Australia's capability in the priority	Actual	N/A
				Target	

CCFS KPI	Outcomes	C1	*Linkage of geochemical / petrologic / geological data with geophysical datasets / modelling* *2012 - Progress relevant research projects*	*Actual*	*Complete*	
				Target	*Complete*	
		C2	*Technology & method development related to NCRIS infrastructure* *2012 - 1st results submitted for publication / conference presentation*	*Actual*	*Complete*	
				Target	*Complete*	
	Training	C3	*Establishment of formal postgraduate units & training within host and collaborating university frameworks*	*Actual*	*2013*	
				Target		
	End-user	C4	*Establishment of linkages and collaborative projects with end-users relevant to external core business of the Centre* *2012 - submission of applications to relevant funding schemes and or funding by end-user*	*Actual*	*Complete*	
				Target	*Complete*	

Appendix 9: CCFS postgraduate opportunities

POSTGRADUATE OPPORTUNITIES

CCFS has a flourishing postgraduate research environment with postgraduate students from many countries (currently 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 at all universities.
- **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. CCFS/GEMOC). These include cotutelle programs with international universities (http://www.international.mq.edu.au/research/cotutelles).
- **International Postgraduate Research Scholarships (E-IPRS Endeavour Scholarships):** available to overseas students to cover tuition fees with a closing date in late August annually (http://www.innovation.gov.au/InternationalEducation/EndeavourAwards/Pages/default.aspx).

Macquarie University also provides research funding through a competitive internal scheme; CCFS and externally funded projects provide further resources to support postgraduate research projects; and some CCFS support is available for approved postgraduate research support.

Postgraduate projects are tailored to your expertise and interests within the framework of CCFS research goals. CCFS carries out interdisciplinary research across the boundaries of petrology, geochemistry, tectonics, metallogenesis, geodynamics and geophysics to explore the nature and evolution of the Earth and global geodynamics. Current funded projects are based in Australia, Antarctica, Canada, China, Taiwan, Italy, France, Spain, Siberia, Norway, North America, South America, Africa, Kerguelen Islands, Greenland and other locations globally (see the map on *p. 17* of this Report).

CCFS postgraduate programs have opportunities through access to our outstanding analytical facilities (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 (but are not limited to):

- 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

Initial enquiries can be sent to: ccfs.admin@mq.edu.au; or to any CCFS staff.

Contact details

- **CCFS information is accessible at:**

  http://www.ccfs.mq.edu.au/

- **Contact CCFS via email at:**

  ccfs.admin@mq.edu.au

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Glossary

AINSE	Australian Institute of Nuclear Science and Engineering
AMIRA	Australian Mineral Industry Research Association
AMMRF	Australian Microscopy and Microanalysis Research Facility
ANU	Australian National University
APA (I)	Australian Postgraduate Award (Industry)
ARC	Australian Research Council
BMP	Bureau of Minerals and Petroleum
BSE	Backscattered Electrons
CAS	Chinese Academy of Sciences
CAGS	Chinese Academy of Geological Sciences
CCFS	Core to Crust Fluid Systems
CET	Centre for Exploration Targeting
CMCA	Centre for Microscopy, Characterisation and Analysis (UWA)
CNRS	French National Research Foundation
CoE	Centre of Excellence
COO	Chief Operating Officer
CSIRO	Commonwealth Scientific Industrial Research Organisation
CU	Curtin University
DECRA	Discovery Early Career Researcher Award
DEST	Department of Education, Science and Training (from 2002)
DIATREEM	Consulting company within Access MQ Limited
DIISR	Department of Innovation, Industry, Science and Research
DP	Discovery Project
EBSD	Electron Backscatter Diffraction
ECR	Early Career Researcher
ECSTAR	Early Career Start-up Awards for Research
(D)EPS	(Department of) Earth and Planetary Sciences
EMP	Electron Microprobe
GA	Geoscience Australia (formerly AGSO)
GAU	Geochemical Analysis Unit (DEPS, Macquarie University)
GEMOC	Geochemical Evolution of Metallogeny of Continents
GEUS	Geological Survey of Denmark and Greenland
GIS	Geographic Information System
GLAM	Global Lithospheric Architecture Mapping
GLITTER	GEMOC Laser ICPMS Total Trace Element Reduction software
GSWA	Geological Survey of Western Australia
ERA	Excellence in Research for Australia
FIM	Facility for Integrated Microanalysis
FTIR	Fourier Transfer Infrared Spectroscopy
ICPMS	Inductively Coupled Plasma Mass Spectrometer
IPRS	International Postgraduate Research Scholarship
LAM-ICPMS	Laser Ablation Microprobe - ICPMS
LIEF	Linkage Infrastructure, Equipment and Facilities
MC-ICPMS	Multi-Collector - ICPMS
MERIWA	The Minerals and Energy Research Institute of Western Australia
MQRDG	Macquarie University Research Development Grant
(i)MQRES	(International) Macquarie University Research Excellence Scholarships
NCRIS	National Collaborative Research Infrastructure Scheme
NeCTAR	National eResearch Collaboration Tools and Resources
PGE	Platinum Group Element
PIRSA	Primary Industries and Resources, South Australia
RIBG	Research Infrastructure Block Grant
RSES	Research School of Earth Sciences at ANU
SAC	Science Advisory Committee
SEM	Scanning Electron Microscope
SIRF	Scholarship for International Research Fees
TIGeR	The Institute for Geoscience Research
UWA	University of Western Australia

Australian Government
Australian Research Council

MACQUARIE University

Curtin University

The University of Western Australia
Achieving International Excellence

Geological Survey Western Australia

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2012
Annual Report
ISSN:2205-9709