CCFS
Annual Report

2013

Delivering the fundamental science needed to sustain Australia's resource base

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

- CCFS information is accessible on WWW at:

  http://www.ccfs.mq.edu.au/

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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: CCFS's vision - Delivering the fundamental science needed to sustain Australia's resources base. Image by Sally-Ann Hodgekiss.

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Australian Government
Australian Research Council

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Director's preface

This report summarises the activities of the Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS) in 2013 (commenced mid 2011). 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 were five formal international nodes in 2013 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 included active projects with 134 international institutions, with 186 international collaborators as co-authors on research articles in 2013. These international collaborations leverage the resources in CCFS and provide access to a wide variety of complementary expertise, logistics, instrumental capabilities and funding.

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 some activities of the Institute for Geoscience Research (TiGeR: http://tiger.curtin.edu.au/) of Curtin University are also aligned with CCFS.

A highlight of 2013 was the joint Research Meeting held as part of the visit of the Science Advisory Council (SAC) in June 2013, just 2 years after CCFS commenced. The SAC presented a comprehensive report praising the Centre structure and activities and providing some very constructive suggestions. Some extracts illustrate the views of the 2013 SAC:

"At the time of the SAC meeting, the reputation of CCFS as a world-class research centre was solidly established…."

"CCFS brings together several areas of expertise that are world-class, and the combination makes it world leading. These include the core of GEMOC which is now part of the CCFS expertise in mantle fluid sources and transport in time and space, expertise related to Earth's early environments, analytical expertise and facilities…. expertise and numerical geodynamic modelling and geophysical imagery, and finally, connections to economic geology and industry."

"An important consensus of the SAC was the recognition of significant high-quality contributions by participating early-career CCFS members, postdocs and graduate students, and also an overall enthusiastic attitude about larger questions studied by the CCFS."

2013 has been a year of review, realignment and renewal. Two more leading national stakeholders have joined the active and engaged external Advisory Board, and seven new Chief investigators will have been appointed from early 2014, bringing new and enhanced core research expertise, visibility and resources. CCFS' new Vision statement ("*Delivering the fundamental science needed to sustain Australia's resource base*") was extensively workshopped with the Advisory Board, and reflects our conceptual framework of delivering world-leading research in directions informed by stakeholder collaboration and national benefit. All the Foundation Projects have undergone scrutiny and will be realigned from mid 2014, informed by our two Science Advisory Council meetings and reports, and by intensive CCFS-wide workshopping. A scheme of 2-year Pilot Projects was introduced in late 2013 on an internally competitive basis, to identify and support new directions which, if successful, can become self-supporting with external funding or become new strands within Foundation Projects.

The success of gaining external leverage was continued. New grants included the seventh ARC Future Fellowship awarded to a CCFS participant (Dr Yingjie Yang) and the large SIEF grant with CSIRO and industry partners, addressing the recognition of distal footprints of economic deposits and evidencing the strong mineral exploration connection.

The postgraduate cohort keeps burgeoning with 80 PhD students undertaking research aligned with CCFS. The success of strategies to encourage and mentor early- and mid-career researchers is evidenced in the "*Participants*" Section.

There has been huge scientific and intellectual growth and building energy in CCFS, highlighted by the exciting project renewals and initiatives for the next phase of CCFS. This emphasises the strength of our Centre of Excellence heading into 2014 and the mid-term review. The extensive Research Highlight section reflects this steeply upward trajectory in outcomes matched by a high level of outputs.

2014 promises to be another exciting year for CCFS as the new and re-aligned projects start and we use our increased knowledge and new tools to further explore Earth's inner space and workings since its formation over 4.5 billion years ago. This is ultimately the pathway to help secure Australia's future mineral security, ensuring economic health for our society.

Professor S.Y. O'Reilly

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

Vision

Delivering the fundamental science needed to sustain Australia's resource base

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, the 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, as well as 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 only in its developmental stages. 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.

Sue O'Reilly with representatives of the 2013 Science Advisory Committee, Rob van der Voo, James Farquhar, Michel Gregoire and Giorgio Ranalli.

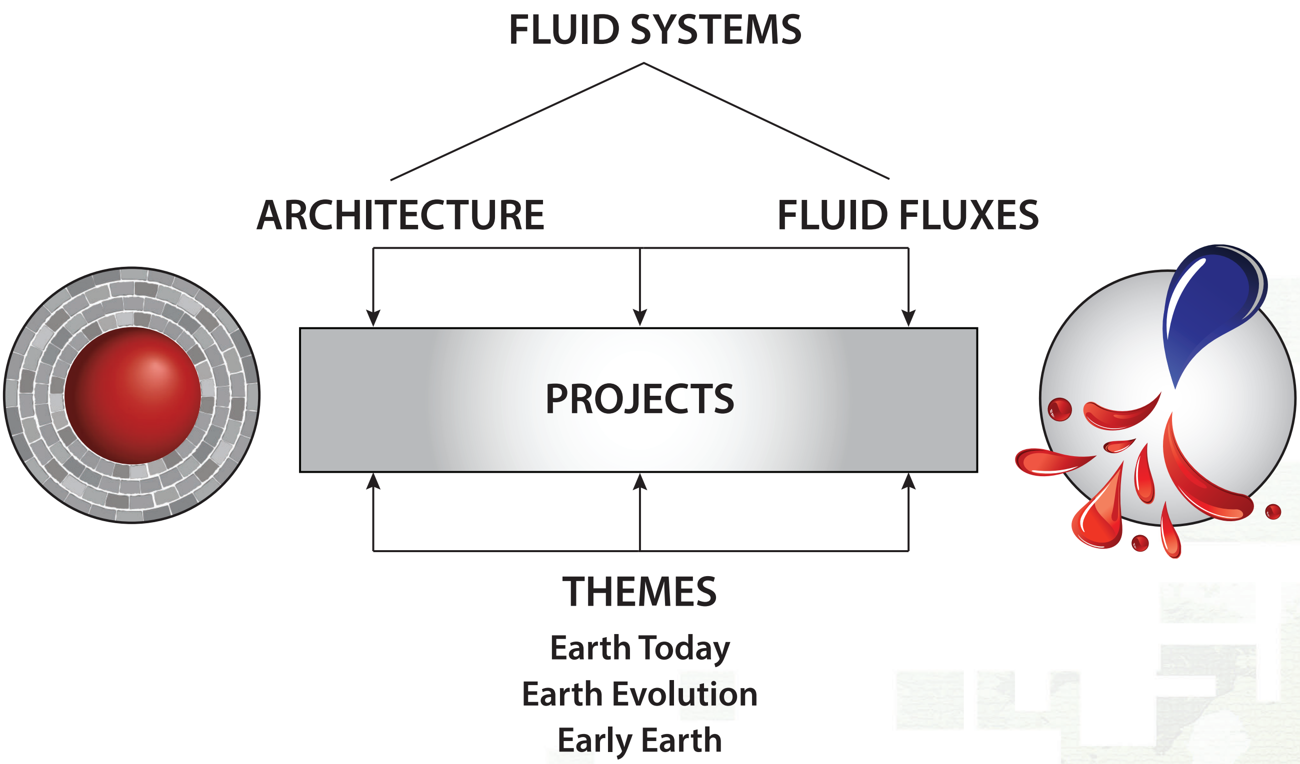
The research activity of the CoE is built around three linked interdisciplinary and cross-institutional Themes, each with several Programs. We have structured these to promote synergy and the interchange of ideas and information between the Programs, across the Themes, and especially across the three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

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:



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. These codes will be used to identify the processes that have controlled the fluid cycle through Earth's history.

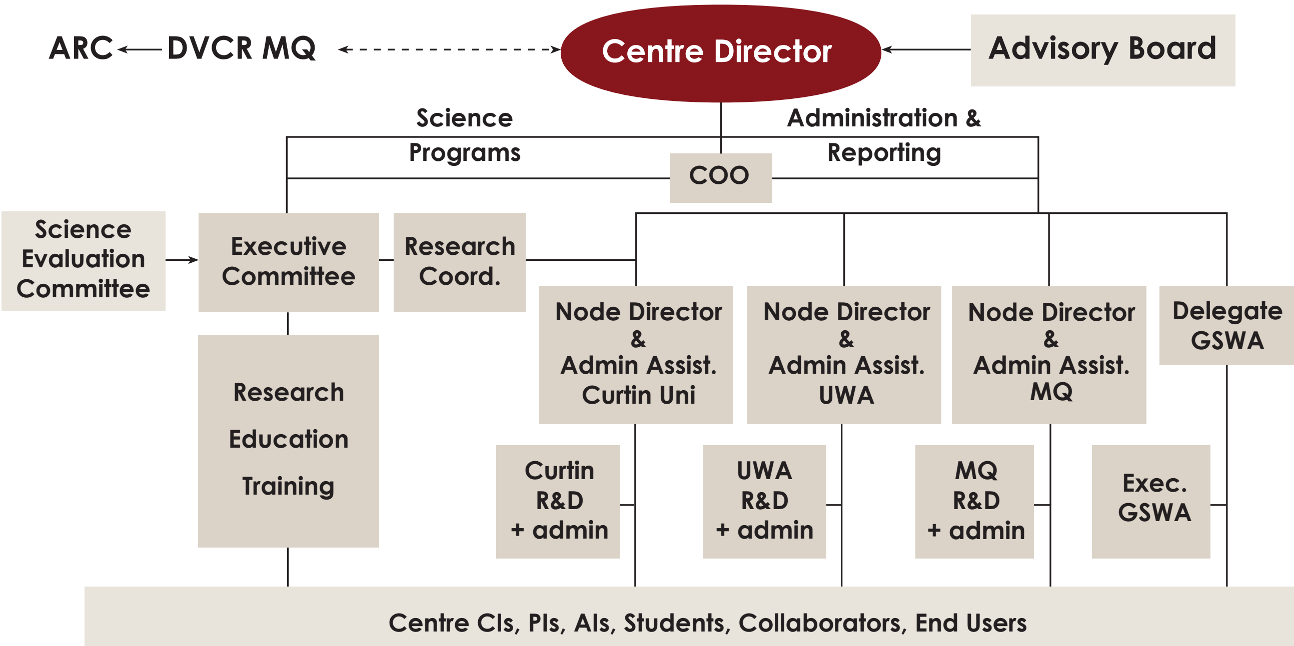
Measurement of the physical properties of potential deep Earth materials at extreme conditions will feed into petrophysical modelling of seismic data in terms of composition, temperature and anisotropy. Measurements of metal complexing at realistic conditions that mimic real ore-system fluids/melts will 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 June, 2013.

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), University of Newcastle, 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 4*).



Governance & management

Centre Director, Professor Suzanne O'Reilly is supported by a Chief Operating Officer and a Business 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. A new Executive position of Centre Research Coordinator was introduced in 2013, taken on by recent MQ appointment Professor Stephen Foley.

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. Two new Advisory Board members (Drs Phil McFadden and Roric Smith) were appointed in 2013, both widening and deepening the outstanding expertise. The six external members of the Advisory Board are very engaged and supportive of CCFS (95% attendance at meetings) and extensively workshopped the new vision statement to reflect the national benefit deriving from the fundamental research in 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

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

(Ex Officio)

Professor Stephen Foley - Research Coordinator
Department of Earth and Planetary Sciences
Macquarie University

Dr Ian Tyler - GSWA
Assistant Director Geoscience Mapping
Geological Survey of Western Australia

Cate Delahunty - COO
Department of Earth and Planetary Sciences
Macquarie University

Advisory Board

Dr Ian Gould
Chancellor
University of South Australia

Dr Andy Barnicoat
Chief of Minerals & Natural Hazards
Geoscience Australia

Dr Paul Heithersay
Deputy Chief Executive, Resources & Energy
DMITRE

Dr Jon Hronsky
Principal
Western Mining Services

Dr Phil McFadden
Chief Scientist of Geoscience Australia
National Geoscience advocate and lobbyist;
driver of the UNCOVER initiative

Dr Roric Smith
VP Discovery / Chief Geologist
Evolution Mining

plus the Executive Committee

Science Advisory Committee

Professor James Farquhar
Earth Systems Science Interdisciplinary Center
Department of Geology
University of Maryland, USA

Professor Michel Gregoire
Directeur de Recherche,
CNRS, Observatoire Midi-Pyrénées
Head of the Laboratory Géosciences,
Environnement, Toulouse, France

Professor Giorgio Ranalli
Department of Earth Sciences
Carleton University, Ottawa, Canada

Professor Rob van der Voo
Geological Sciences
University of Michigan, USA

INTERNATIONAL SCIENCE ADVISORY COMMITTEE MEETING 2013

A combined meeting of all CCFS national Collaborating Institutions and the Geological Survey of Western Australia (Partner Institution) was held at Macquarie University on 11-14 June 2013, just 2 years after the Centre officially commenced. 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, James Farquhar, Michel Gregoire, Giorgio Ranalli and Rob van der Voo, 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:

CCFS PhD student Elyse Schinella delivering her presentation to participants at the SAC meeting; "Constraining Venus' Mantle Dynamics".

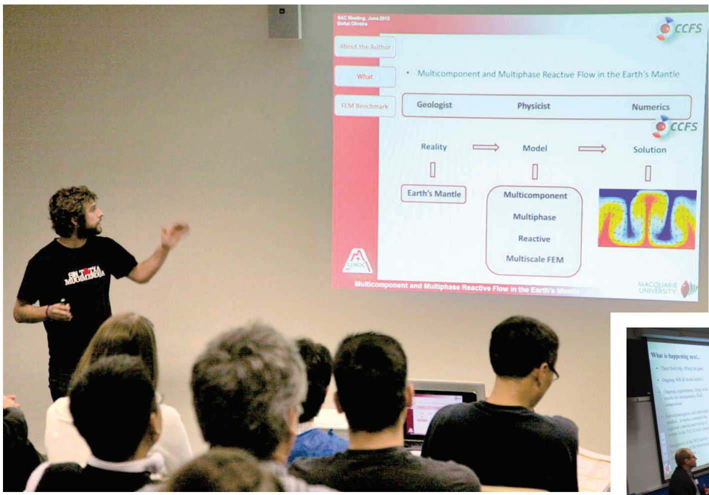
"At the time of the SAC meeting, the reputation of CCFS as a world-class research centre was solidly established, as testified by the very impressive list of publications and conference participations…."

"An important consensus of the SAC was the recognition of significant high-quality contributions by participating early-career CCFS members, postdocs and graduate students, and also an overall enthusiastic attitude about larger questions studied by the CCFS."

"the SAC recognised the strong integration of research groups and approaches in many of the projects…. This type of interdisciplinary research is not usually accomplished as well by centres that the SAC is aware of other than CCFS."

"The quality appears…. outstanding. In addition to areas where CCFS is already recognised as a world centre of excellence, other emerging areas were evident…. SAC was particularly impressed by the concentrated effort in geophysical and geodynamic modelling, and by the number and quality of cooperations involving projects in China."

Some of the CCFS early career researchers who participated in the SAC meeting; (L-R) Xuan-Ce Wang, Monica Kusiak, Marion Grange, Bin Shan, Chris Clark, Huaiyu Yuan, Yoann Gréau, Takako Satsukawa, Dan Howell, Marek Locmelis, José María González-Jiménez and Siqi Zhang.



PhD student Beñat Oliveira Bravo delivering his presentation; Multicomponent and multiphase reactive flow in the Earth's mantle.

"In addition, SAC thinks that the integration of fundamental research, strategic research – including cooperation with the mineral resources industry – and technology development represents a fundamental aspect of CCFS' mission and development. This is reflected by the "Whole of Centre" projects."

"With respect to geophysics/geodynamics, two things stand out: the extremely rapid development of this field within CCFS, and the determined attempt to develop a numerical modelling platform for integrated use in combination with geochemical, geological and petrological data."

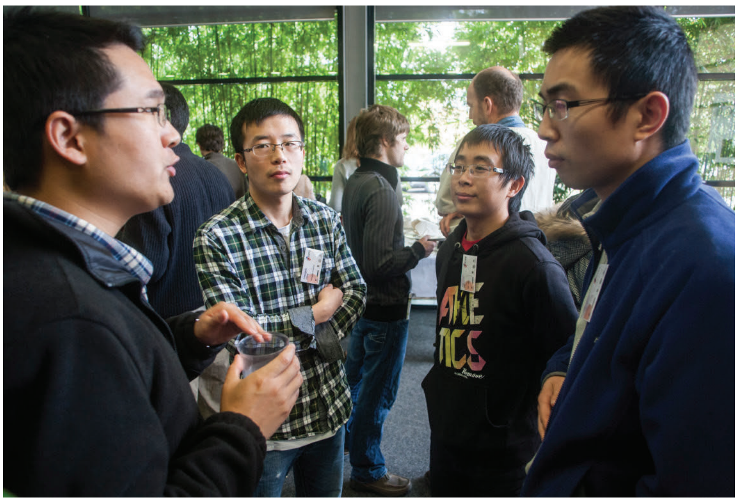
Marek Locmelis enlightening the SAC about his research on the chemistry of fluids and melts in natural systems.

Cam McCuaig workshopping new CCFS directions.

"CCFS brings together several areas of expertise that are world-class, and the combination makes it world leading. These include the core of GEMOC which is now part of the CCFS expertise in mantle fluid sources and transport in time and space, expertise related to Earth's early environments, analytical expertise and facilities (also noted above), expertise and numerical geodynamic modelling and geophysical imagery, and finally, connections to economic geology and industry."

Laure Martin, Irina Tretiakova and Elena Belousova.

"The group at Macquarie University contributes world-class microanalytical ICP-MS capabilities. The groups at UWA and Curtin University contribute world-class microanalytical secondary ion mass spectrometry capabilities which in many cases are world leading .... integration of these techniques with numerical modelling, geophysics, petrography and ore deposit research promises ***transformational*** *insights into fluid systems. The CCFS provides a direct way to integrate these techniques into some of the most important questions facing earth science today."*



Qing Xiong, Chengjin Jiang, Jun Xie and Bin Shan.

Participants

Significant changes were made to the Chief and Associate Investigator (CI and AI) inventory based on new staff with new relevant expertise, and also on performance over the past 3 years. Four CIs have been added formally at the time of this Report, and three more CI additions are in progress, reflecting the CCFS achievements of three original CCFS Early-Career Researchers. Two CIs were changed to AIs reflecting one retirement and CCFS activity over the period. The current CI list reflects well the expertise and commitment spread needed to further the overarching vision and research goals of CCFS.

Organisations

Administering Organisation

Macquarie University (MQ)

Collaborating Organisations

Curtin University (CU)

University of Western Australia (UWA)

Partners

Australian Partner

Geological Survey of Western Australia

International Partners

CNRS and Université de 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 - MQ

Professor Simon Wilde, Node Leader - CU

Professor T. Campbell McCuaig, Node Leader - UWA

Professor Mark Barley - UWA

Associate Professor Simon Clark - MQ (from 2014)

Professor Stephen Foley, Research Coordinator - MQ

Professor William Griffin - MQ

Professor Matt Kilburn - UWA (from 2014)

Professor Zheng-Xiang Li - CU

Associate Professor Alexander Nemchin - CU

Associate Professor Norman Pearson - MQ

Professor Simon Turner - MQ

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 (vale *p.18*)

Professor Catherine McCammon - Bayreuth

Associate Investigators

Dr Juan Carlos Afonso - MQ

Dr Olivier Alard - Universite de Montpellier, France

Dr Leon Bagas - CET, UWA

Dr Elena Belousova - MQ

Dr Christopher Clark - CU

Assistant Professor John Cliff - CMCA UWA

Associate Professor Nathan Daczko - MQ

Associate Professor Marco Fiorentini - UWA

Professor Simon George - MQ

Dr Richard Glen - NSW Geological Survey

Dr Masahiko Honda - Australian National University

Associate Professor Dorrit Jacob - MQ

Dr Mary-Alix Kaczmarek - CU

Dr Chris Kirkland - Geological Survey of Western Australia

Professor Jochen Kolb - Geological Survey of Denmark and Greenland

Professor Louis-Noel Moresi - University of Melbourne

Dr Craig O'Neill - MQ

Associate Professor Sandra Piazolo - MQ

Professor Steven Reddy - CU

Associate Professor Tracy Rushmer - MQ

Dr Bruce Schaefer - MQ

Professor Paul Smith - MQ

Dr Michael Wingate - Geological Survey of Western Australia

Dr Yingjie Yang - MQ

Professor Shijie Zhong - University of Colorado, Boulder, USA

ECSTARS	
	Dr José María González-Jiménez - MQ
	Dr Yongjun Lu - UWA
	Dr Takako Satsukawa - MQ
	Dr Xuan-Ce Wang - CU

Early Career Researchers	
	Dr Leon Bagas - UWA
	Dr Yoann Gréau - MQ
	Dr Daniel Howell - MQ
	Dr Jin-Xiang Huang - MQ
	Dr Marek Locmelis - UWA
	Dr David Mole - CU
	Dr Edward Saunders - MQ
	Dr Zoja Vukmanovic - CU
	Dr Siqi Zhang - MQ
	plus the ECSTARS (above)

A full list of CCFS participants is given in *Appendix 4* and at http://www.ccfs.mq.edu.au/

NEW STAFF

Professor Stephen Foley joined the CCFS in April 2013 after spending 9 years as Professor in Mainz, Germany, where he also led the Earth System Science Research Centre Geocycles since its inception in 2005.

He studied internationally – BSc in England, MSc in Canada and PhD in Tasmania – before taking up a post-doc position at the Max Planck Institute for Chemistry and staying in Germany for the next 26 years.

His main research interests are in igneous petrology, particularly the composition and geodynamic effects of small melt fractions in the mantle, and in geodynamic processes on the early Earth. He began his career with a petrological and geochemical study of an alkaline dyke complex in Labrador, before branching into experimental petrology, studying the then newly discovered

diamond-bearing lamproites during his PhD. Since then, he has broadened his interests, continuing experimental work on trace element partitioning using a combination of high-pressure experiments, ion microprobe analyses of trace elements, and single-crystal structure refinements of tiny experimental crystals.

Field based studies around the world have included intrusive complexes in Siberia, alkaline igneous rocks in Labrador and Uganda, Archean basement rocks in Finland and Uganda, and volcanic rocks in Spain. Through the interdisciplinary Geocycles Research Centre, he has also become involved in Anthropocene studies and the composition of atmospheric aerosols.

In the CCFS, he has taken up the role of Research Coordinator, and will inject his petrological knowledge into several Foundation Projects, particularly those looking at enrichment processes in the mantle lithosphere and its stabilisation. He will also work on expanding the experimental capabilities of the CCFS, enabling study of the lithosphere and deep mantle. See *Research Highlight p. 77.*

Associate Professor Dorrit Jacob moved into the geosciences after being stimulated by lectures on cosmochemical themes from international celebrities whilst she was working as a chemical laboratory assistant at the Max Planck-Institute for Chemistry. She then studied mineralogy and geology at the University of Mainz, followed by a PhD at the University of Göttingen in 1995 for work on the geochemistry and radiogenic isotopes of mantle eclogites. She moved to Mainz in 2004 after a few years in Greifswald, and here she extended her research fields to biomineralisation, steadily building up her own research group in this field from 2006 onwards. This led to national recognition by the award of a Heisenberg Chair in Biomineralisation in 2012. However, Dorrit chose to leave this full professorship after just five months to take up an ARC Future Fellowship at the CCFS as an Associate Professor at Macquarie University in April 2013.

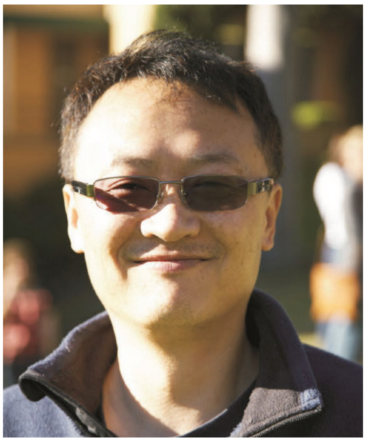
In her research, she continues to combine the unlikely duo of biomineralisation and diamond research with her expertise in micro-geochemistry and nano-methods such as Laser-Raman spectroscopy and FIB-TEM.

In her Future Fellowship project, she is studying the structure, chemistry and mineralogy of the skeletons of marine organisms in order to characterise their growth environments. This includes understanding the effects of physiological processes on the composition of biominerals to be characterised, unlocking the door to a real understanding of paleoclimate 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. The robust links that biomineralisation studies will provide between environmental conditions and biomineral nanostructure will enable new tools for the analysis of paleoclimate and past environmental change. See *Research Highlight p. 66*.

Associate Professor Simon Clark took up his jointly funded position, (ANSTO and Macquarie), in the Department of Earth and Planetary Sciences at Macquarie University at the beginning of September 2012. Prior to that he led the high-pressure program at the Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, USA and held an adjunct Associate Professorship in the Department of Earth and Planetary Science, University of California, Berkeley.

In 2013 he became an Associate Investigator in CCFS and will become a Chief Investigator in 2014. Simon's research uses X-rays and neutron scattering and imaging, coupled with high-pressure and high-temperature devices, to recreate Earth processes in the laboratory. His current research interests are centred on understanding the role of melts and volatiles in Earth structure and dynamics. This directly links to the major themes of CCFS. The facilities for non-ambient studies that he is developing in the laboratory at Macquarie University, at the Australian neutron source, OPAL, and at the Australian Synchrotron will enable a new range of experiments, complementary to current CCFS capability, to be carried out. His interests and expertise will add a new dimension to the topology of the CCFS research landscape enabling more complete descriptions of melt and fluid systems in the Earth. In addition Simon's half time appointment with the Australian Nuclear Science and Technology Organisation, managers of the Australian neutron and synchrotron sources, is facilitating the expansion of CCFS science into the major Australian central research facilities.

Dr Huaiyu Yuan (aka H.Y.) joined CCFS in April 2013, and is based at CET (UWA), employed at Macquarie and interacts closely with GSWA. Huaiyu's research focuses on craton evolution using conventional earthquake seismology imaging techniques, including body/surface wave tomography, receiver functions, and shear wave splitting. During his PhD at the University of Wyoming, USA, Huaiyu constructed crustal and upper mantle seismic images of the Wyoming craton, and inferred information regarding craton formation and its interaction with subsequent tectonic activity such as rifting, subduction and most recently the Yellowstone hotspot system. After graduation in 2007 Huaiyu moved to the University of California, Berkeley as a post-doc and was then promoted as an assistant researcher at the Berkeley Seismological Laboratory. There he enhanced his seismic toolbox with surface wave full waveform tomography, and discovered wholesale upper mantle anisotropy stratification in the North American craton, a prominent feature that was proposed to mark episodes of tectonic history in the craton formation and evolution.



Huaiyu's current projects include exploring the anisotropy layering in other cratons globally. He is interested in the structure of oceanic lithosphere, particularly the Pacific. He is also working on projects related to crustal and upper mantle seismic structural imaging of the Western Australia craton and the craton margins, in collaboration with other researchers across CCFS and from the Geological Survey of Western Australia. Currently Huaiyu is working on a temporary broadband seismic deployment in the Capricorn region, which starts in March 2014 and will last for the coming 3 years. The results from the new deployment will help us understand how the different parts of the Western Australian continent fit together. Huaiyu is also collaborating with Professor Liang Zhao at the Institute of Geology and Geophysics, Chinese Academy of Sciences in his newly funded Chinese NSF proposal from 2014 to 2018, to study the lithosphere structure and tectonic evolution in the south China craton. See *Research Highlight p. 51-52*.

Other new staff *(featured in our ECR section)...*

Dr Leon Bagas - University of Western Australia, see *p. 13*.
Dr David Mole - Curtin University, see *p. 13*.
Dr Zoja Vukmanovic - Curtin University, see *p. 14*.
Dr Siqi Zhang - Macquarie University, see *p. 14*.

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 ARC Future Fellow rounds emphasises this role of our Centre in recruiting high-flyers at early to mid-career levels. Six Future Fellows *(above, from left to right)*, Dr Heather Handley, Associate Professor Marco Fiorentini, Associate Professor Dorrit Jacob, Associate Professor Sandra Piazolo, Dr Elena Belousova and Dr Craig O'Neill, have projects relevant to CCFS goals and are profiled in the *Participants* section of our previous reports (http://www.ccfs.mq.edu.au/AnnualReport/Index.html). One new Fellowship was awarded in 2013 to Dr Yingjie Yang.

Dr Yingjie Yang is an observational seismologist. He took his Bachelor of Sciences from the University of Science and

Technology of China in 2000. His PhD studies were done at Brown University majoring in Geophysics/Seismology during 2000-2005. Afterwards, he held research associate and senior research associate positions at University of Colorado at Boulder. In 2010, he moved to Macquarie University as a lecturer and in 2014, he will take up an ARC Future Fellowship. His primary research interests lie in understanding the structure, dynamics and deformation of the Earth's lithosphere and upper mantle by studying seismic velocity, anisotropy, and attenuation using seismological techniques. His specific research topics include: ambient noise surface-wave tomography by extracting seismic Green functions from cross-correlating sequences of ambient or background seismic noise; teleseismic surface-wave tomography using earthquake data to constrain the seismic structure of lithosphere; joint inversion of multiple seismic data sets to improve the imaging of thermal and chemical status of the lithosphere and upper mantle.

In his future fellowship project, he will work on developing a novel seismological approach to map the small-scale dynamics of the upper mantle. The concept of small-scale convection currents about 100-400 km below the Earth's surface has been proposed to explain the origins of intraplate volcanoes and mountains. However, direct evidence for the physical reality of small-scale convection cells is generally weak. This project will develop a novel seismological approach combining both random noise and earthquake data that can image such small-scale upper mantle convection. This project will help to fill the gap left in the Plate Tectonic paradigm by its inability to explain intraplate geological activity (volcanoes, earthquakes, mountains), which would be a significant step towards unifying conceptual models about how the Earth works.

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 three and one third 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.

The following profiles present 2013 ECRs (including the appointed ECSTARs in CCFS) and summarise their expertise and research areas.

New

Dr Leon Bagas has studied Archean and Paleoproterozoic terranes in many parts of the world. The majority of this work has been with Geological Surveys. He joined the Centre For Exploration Targeting (CET) at The University of Western Australia (UWA) in 2010, where he is leading studies of the tectonic evolution and economic geology of the North Australian Craton, Man Craton of Liberia (with the Liberian Geological Survey), North China Craton (with the Chinese Institute of Mineral Resources) and the Thrym Complex of southeastern Greenland (with the Geological Survey of Denmark and Greenland). These studies address the problem of deciphering the genesis of mineralisation through the lithosphere utilising detailed outcrop mapping, structural geology, geochemistry, isotope geochemistry, and geochronology. Leon has been collaborating with CCFS since 2011 through supervision of Honours and PhD students in Greenland.

His research focus has been in the Archean to Paleoproterozoic crust, which is very well endowed with a wide range of mineral deposits. The general lack of exposure of lower crustal rocks has led researchers and explorers alike to consider that the upper crust is the most common environment for mineral deposits and the lower crust is not prospective. However, many deposits are located near lithospheric-scale discontinuities through which metal species are carried from the mantle. In this context, the lower crust represents a key gateway between the mantle and the upper crust. Yet, very little is known about the lower crust, its architecture, and its metal endowment (predominantly due to the lack of exposure). The discovery of mineralisation in granulite-facies rocks of southeastern Greenland has cast some doubt on the idea that the lower crust is only a conduit for mineralisation that is eventually deposited in the upper crust, and this is a major focus for Leon's current research.

Dr David Mole completed his PhD at the Centre for Exploration Targeting at the University of Western Australia (2012), investigating the effects of lithospheric evolution on the localisation of major komatiite flow-fields, and associated Ni-Cu-PGE mineralisation. He also has a Master's degree in Geology from University College London (UCL) in the UK.

David joined Curtin as an industry-sponsored Research Associate investigating the multi-scale 4D evolution of the Proterozoic Ntaka Hill Ultramafic Complex in the Mozambique Belt of south-east Tanzania. The project uses a variety of geochemical and isotopic techniques to understand the tectono-stratigraphic evolution of the Ultramafic Complex and high grade (granulite-amphibolite facies) metamorphic host rocks. The genesis, localisation and internal architecture of the intrusion are also investigated using 3D modelling and geochemical methods, in order to understand the orthomagmatic Ni-Cu mineralisation associated with the mafic-ultramafic sequence. The project is sponsored by IMX Resources and affiliated with the Centre for Exploration Targeting, UWA.

David's expertise primarily lies in using isotope geochemistry (particularly Sm-Nd and Lu-Hf isotopes) and U-Pb geochronology to understand the 4D evolution of crustal terranes. He is also interested in the application of this 4D lithospheric understanding to the evolution of multiple geological systems within a given terrane, such as structural regimes, volcanism, sedimentary facies and mineral systems. In addition to crustal-evolution work, David is particularly interested in the evolution of the primordial Earth (Hadean-Archean) and how different Earth systems such as the surface (atmosphere, oceans, crust) and internal (core-mantle) environments were affected by major temporal changes in geodynamics and crustal evolution. He is also interested in how the secular evolution of these reservoirs and processes affected the establishment of the current Earth and the development of life. Through his Master's and PhD projects, David also acquired an avid interest in fundamental igneous processes, including the physical emplacement of magmas, their geochemistry and volcanology, as well as the internal architecture of igneous systems and its influence on orthomagmatic mineralisation. See *Research Highlight p. 66*.

Dr Zoja Vukmanovic joined Curtin University after completing her PhD at the University of Western Australia studying the microstructure of magmatic sulfides from the Bushveld complex, South Africa and komatiite hosted Ni deposits from Western Australia. Before this, she received her Master's degree from the Free University, Amsterdam, Netherlands.

As a research associate, she will investigate the nature and exhumation of the La Balma Monte Capio intrusion in Italy's Ivrea-Verbano Zone from a geochemical and microstructural perspective, in order to constrain the interaction between deformation and fluid flow. She will study the relationship between intragrain and intergrain deformation processes and chemical reactions associated with hydration of the mantle. The outcomes will improve our understanding of the role of metasomatic fluids at lithospheric conditions on Ni-Cu-(PGE) sulfide mineralisation.

Zoja's research interests are focused on ultramafic and mafic systems and associated ore minerals. Her expertise lies in high-precision in-situ mineral chemistry (EMPA and LA-ICP-MS) and rock microstructures (EBSD). She also uses 3D imaging (X-ray computed tomography) in order to better understand problems such as trace element remobilisation, metal endowment and post-crystallisation deformation. Apart from mantle geology, Zoja is interested in layered intrusions and the role of post-emplacement events on the crystallisation of the magmatic column. See *Research Highlight p. 42-43*.

Dr Siqi Zhang completed his undergraduate study at Peking University, Beijing, and graduated with a PhD from the University of the Chinese Academy of Science (July 2011). He then took up a postdoctoral fellowship at University of Chinese Academy of Science from 2011 to 2013. His research focuses on using high performance computation with high resolution models

to solve different geodynamic problems. One of his studies on lithosphere mantle coupling under Tibetan region using numerical simulation suggests that mantle flow is playing an active role during the collision of the Eurasia and Indian plates. He also makes contributions to numerical computation method development on parallel computing. He and his colleagues developed a novel method to calculate the co-seismic deformation, reducing the complexity of model construction and improving the accuracy of far field results.

He joined CCFS as a postdoctoral research associate in April 2013. Since then his research has been focused on using high resolution mantle flow models to study the evolution of Earth and other terrestrial planets. He built a mantle-core coupling model to study the early evolution of Mars. He is also exploring the construction of an Earth mantle-flow model taking into account the plate motion in the past few million years to recover the mantle structure and to track its evolution over that time. See *Research Highlight p. 63-64*.

Continuing

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-MC-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 Highlights p. 46-47, 55, 70-71, 80.*

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 2013 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 2013, TerraneChron® imaged and analysed 3463 grains of zircons for a total of 23 different projects from different regions of 4 continents.

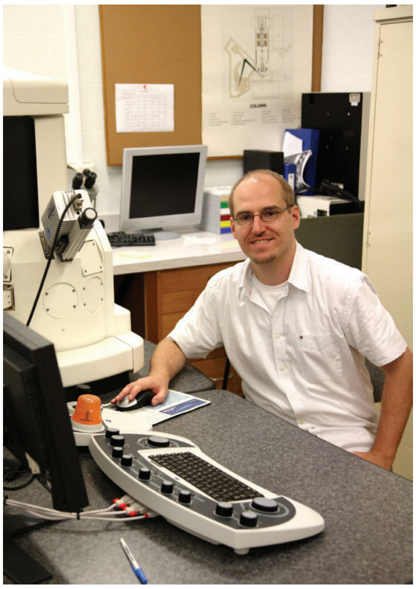
Dr Dan Howell is a postdoctoral research associate in CCFS working on the growth, structure and origins of diamonds, a unique recorder of mantle fluid activity. By studying fluid and mineral inclusions trapped within them, this robust capsule mineral can provide direct samples from the depths of the Earth. Publications in 2013 showed how laser ablation ICPMS analysis (developed at MQ) of trace elements in clean, gem-quality diamonds has revised our understanding of how transition metals (like nickel and cobalt) can be present during natural

diamond growth *(CCFS publication #332)*. He is also investigating the similarity of pink diamonds from Argyle (Australia) to those found in Santa Elena (Venezuela), as well as reporting a new finding in southern Africa. His research is also contributing to the TARDIS project by documenting the characteristics of diamonds found in Tibetan ophiolites, and understanding their formation conditions in this new environment for diamond occurrences. See *Research Highlight p. 50-51.*

Dr Jin-Xiang Huang completed her undergraduate study at China University of Geosciences, Beijing as one of the top students in her class. She received her PhD from Macquarie University, in 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 produce precise

geochemical data, and in integrating a wide range of information into a coherent 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 completing her PhD, she joined CCFS as a post-doctoral research associate, to work on the oxygen and magnesium 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 2013, she was developing the chemical method to purify Mg for isotopic analysis by MC-ICPMS. The Mg isotopic heterogeneity of garnet from the xenolithic eclogites will provide further information on eclogite origins and isotopic fractionation processes in the mantle.



Dr Marek Locmelis is a Research Assistant Professor in the CET working on the CCFS foundation project *"Metal sources and transport mechanisms in the deep lithosphere"*. In 2013, Marek continued his research on the processes that lead to mass transfer of fluids and metals between the mantle and the crust. His work integrates (i) 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, with (ii) the analysis of rock samples collected from the Ivrea-Verbano Zone (IVZ) in northwest Italy. This exhumed section of the critical crust-mantle interface shows tantalising relationships between ultramafic fluid-rich rocks and metal-rich sulfide mineralisation, making the Ivrea-Verbano Zone an excellent natural laboratory to test and parameterise the high P/T experiments.

Dr Yongjun Lu is a Research Associate funded by an ARC ECSTAR Fellowship in CCFS. He is undertaking the CCFS Foundation Project *"4D lithospheric evolution and controls on mineral system distribution: The Western Superior-Yilgarn comparison"*. In 2013, Yongjun started supervising PhD student Katarina Bjorkman, who is studying the 4D crust-mantle evolution of the 3.0 Ga Marmion Terrane (Canada) as part of the Foundation Project. He also supervised honours student Lei Shi in 2013 with a thesis on a porphyry Cu deposit in the North China

Craton. In addition to ongoing collaboration with the China Academy of Geological Sciences on the investigation of Tibetan porphyry systems, Yongjun also established collaboration with Iran to study the mineral systems in the Urumieh-Dokhtar magmatic arc, highlighted by arrival of Professor Hooshang Haroni at CET in 2013. Yongjun has been instrumental in the design and submission of a new $1.3M AMIRA proposal in late 2013, aiming to enhance predictive capability for magmatic-hydrothermal copper and gold exploration targeting. He is Deputy Theme Leader of the Magmatic Mineral Systems theme at CET and member in the Geoconferences Main Committee and the Strategic Planning and Implementation subcommittee of Geoconferences. He also serves as reviewer for international journals such as Economic Geology, Lithos, Gondwana Research, Mineralium Deposita, and Ore Geology Reviews. See *Research Highlight p. 59-60, 64-65*.

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.

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.

In 2013, she characterised the microstructure of mantle-derived rocks from the Japan arc to investigate the uppermost mantle evolution during the initial stage of back-arc spreading. She presented her work at the Goldschmidt conference 2013 in Florence and the 19th International conference on Deformation Mechanisms, Rheology and Tectonics in Leuven.

This project is part of CCFS Themes 2 and 3, Earth Evolution, and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes. See *Research Highlight p. 55.*

Edward Saunders completed his BSc (Hons) with a major in geology at the University of Western Australia in 2006. After graduation, he worked as an exploration geologist for a junior mining company in the Pilbara region for three years before commencing a PhD with GEMOC/ CCFS in 2010. His PhD investigated the nature, abundance and mobility of gold in the upper mantle. This research focused on in situ analysis of sulfide grains in upper mantle peridotites, and found that gold was very heterogeneously dispersed as a result of its mobility in fluids. These results are important for understanding sulfide metasomatism in the upper mantle, and the role that process plays in ore systems and ore formation processes. This has important implications for understanding the fluid flux within the lithospheric mantle. Ed completed his thesis in 2013, and he presented some of the results at the Goldschmidt Conference in August.

In 2014, Ed commenced employment at Macquarie University as a lecturer and is an early career researcher in CCFS. He is teaching and convening a number of undergraduate- and masters-level courses while continuing his research with CCFS into the mobility of chalcophile elements in the upper mantle. See *Research Highlight p. 53.*

Dr Xuan-Ce Wang joined CCFS in 2011 as a postdoctoral research fellow at Curtin University. His primary role in CCFS is to examine 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 2013, Dr Wang and his collaborators defined the

Gnowangerup–Fraser Dyke Suite, a major part of the 1.21 Ga Marnda Moorn large igneous province (LIP) of the Yilgarn Craton (*CCFS publication #371*). They also identified an ancient mantle reservoir, formed at ca 4.5-4.4 Ga, in both the 60 Ma old Baffin Bay lavas (*CCFS publication #354*) and late Cenozoic basalts in the Hainan-Leizhou peninsula, the Indochina peninsula and South China Sea seamount (*CCFS publication #336*). This ancient mantle reservoir is chemically heterogeneous, containing at least two (depleted and enriched) end-member components (*CCFS publication #354*), and shows that the chemical effects of early differentiation can persist in mantle reservoirs to the present day. These studies have provided a potential breakthrough that links generation, preservation, and sampling of early reservoirs into a self-consistent Earth system. These projects are part of CCFS Theme 2, Earth Evolution, and contribute to understanding Earth's Architecture and Fluid Fluxes. Wang and Associate Professor Jie Li of Guangzhou Institute of Geochemistry, (CAS) also demonstrated an improved procedure for determination of platinum-group elements and Os isotopes by isotope dilution using inductively coupled plasma-mass spectrometry and N-TIMS (*CCFS publication #338*) and a novel preconcentration method for determination of Mo isotopic composition of geological samples by MC-ICPMS (*CCFS publication #369*). See *Research Highlight p. 57.*

VALE - CCFS PARTNER INVESTIGATOR, PROFESSOR ROB KERRICH (1948-2013)

The economic geology community suffered a tremendous loss with the passing of one of the giants of our profession, Professor Rob Kerrich on April 17th, 2013, after a long battle with cancer.

Born on December 15, 1948, in the UK, Rob received his BSc from the University of Birmingham in 1971, and a PhD from Imperial College, London, in 1975. He held a NATO postdoctoral fellow at the University of Western Ontario from 1975–1977, before joining the faculty in 1977. In 1987 Rob moved to the University of Saskatchewan as the recipient of the George J. McLeod Chair in the Department of Geological Sciences, a position he held until his passing. Rob was an inaugural Partner Investigator in CCFS, an Adjunct Professor at the University of Western Australia, and a strong contributor to CCFS research programs.

Among Rob's many accolades were his award of a Steacie Fellowship in 1987, the GAC's William Harvey Gross Medal in 1988, the CIM Distinguished Lecturer in 1989, the MAC Past President's Medal in 1989, election as Fellow of the Royal Society of Canada in 1992, the Willett G. Miller Medal of the Royal Society of Canada in 1999, election as a Member of the European Academy of Sciences in 2001, the GAC Mineral Deposits Division's Duncan Derry award in 2003, the Saskatchewan Centenary Medal in 2006, a Career Achievement Award from the Volcanology and Igneous Petrology Division of GAC, SEG's Penrose Medal in 2011, and GAC's Logan Medal in 2012.

Rob mentoring students in the field.

Rob's Impact on our profession has been enormous. Publishing over 300 papers, many of them benchmarks still heavily cited well over a decade after their publication (with >6000 citations), Rob was one of the most impressive innovators in geoscience. From an economic geology perspective, he continually demonstrated his holistic approach to mineralising systems, reaching far outside the field to bring advances from multiple science disciplines and apply them to the understanding of mineral deposits. Some of his contributions include: the chemistry and physics of shear zone development and dynamics of fluid flow through them; seminal work with Bill Fyfe on Yellowknife gold deposits that inspired all subsequent research on orogenic gold deposits; pioneering the development of the metamorphic model for orogenic gold deposits; pioneering the use of high-precision ICP-MS analyses of trace elements to constrain Archean geodynamics; the use of stable isotopes as tracers of fluid sources in mineral deposits; looking at lithosphere-scale controls on mineral deposits before it became popular, and placing mineral deposits through time in the context of the Earth's evolving hydrosphere-biosphere-atmosphere-lithosphere system. He remained as prolific at the end of his career as he was at the beginning.

Moreover, Rob was a tremendous mentor, strongly influencing the careers of many of today's top researchers and industry geoscientists. Many who came under his direct tutelage remark that they could not have imagined a more supportive and intellectually challenging supervisor. Rob relished this mentoring role throughout his career, and many people would share these reflections on his impact on their professional lives. In many ways Rob's legacy lies even more in the scientists he helped to shape than in the world class science he undertook.

The CCFS research program

The CCFS CoE builds on world-class infrastructure and world-leading research expertise and track record, and has already multiplied the capabilities of the Collaborating and Partner Institutions. The research program aims to enhance existing strengths in geology, geochemistry, geophysics, experimental petrology and petrophysical/dynamic modelling, and to integrate knowledge and datasets from 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 are funded from the ARC Centre funds allocation, and many also include components from the Universities' funding support. The first tranche of 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 are designed to be interdisciplinary, cross-node and to foster early-career/postgraduate researchers participation. Several Foundation Projects reflect the focus of ARC grants relinquished consequent on the award of the CoE CCFS. These latter were, by their nature, fully aligned with, and core to, Centre goals.

The range of topics covered by the Foundation Projects reflects 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 *Foundation Research Projects list p. 20*). Projects matured and new directions were identified during 2013 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 and progress for 2013 see *Appendix 1.*

For the workplan for 2014 see *Appendix 2.*

Independently funded basic research projects are listed in *Appendix 3.*

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 (ECR), Turner, O'Reilly, Davies and PhDs
2b. Dynamics of Earth's mantle: assessing the relative roles of deformation and magmatism	Reddy, Kaczmarek
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, Schinella, Grose, Jiang, Ramzan, Oliveira-Bravo, 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
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, Barley, Kusiak, Kaczmarek, 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, ECSTAR), Bjorkman (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, Gao and Xiong (PhDs)
Frontiers in integrated laser-sampled trace-element and isotopic geoanalysis	Pearson, Cliff, Griffin, O'Reilly, Kilburn, Huang (ECR), Gréau (ECR), Murphy (PhD)
Optimising mineral processing procedures: From rock to micro-grains	Pearson, Belousova, Daczko, wide spectrum of Centre users

WHERE IN THE WORLD IS CCFS?

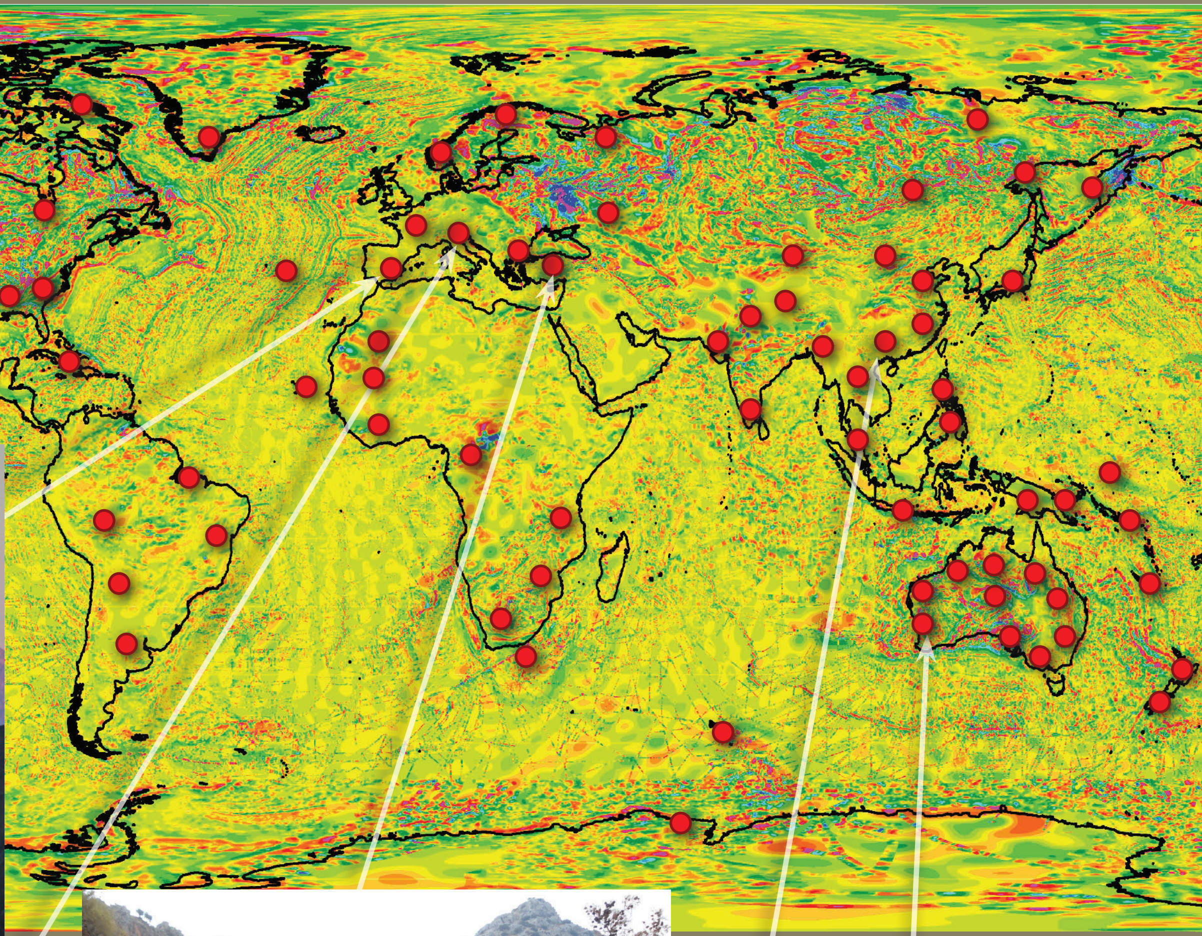


photo Nicholas Thébaud.

Full moon setting over the Ivrea Zone, Italy.

Antalya, Turkey.

View from a granite bloom, Western Australia.

Northern Spain.

Southeastern Tibet.

Communications 2013

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 2013 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.

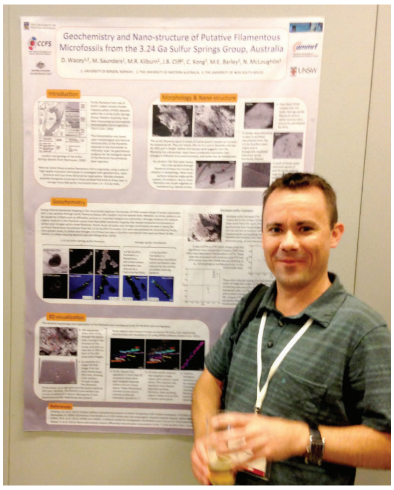
CCFS publications for 2013 are given in Appendix 5

The 139 CCFS publications that were published in 2013 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 activities which are now part of CCFS.

PARTICIPATION IN WORKSHOPS, CONFERENCES AND INTERNATIONAL MEETINGS IN 2013

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 186 presentations including:

- Granulites & Granulites 2013, Hyderabad, India, 16-20 January 2013
- 37th Annual Condensed Matter and Materials Meeting, Wagga Wagga, NSW, Australia, 5-8 February 2013
- 44th Lunar and Planetary Science Conference, Texas, 18-22 March 2013
- EGU General Assembly, Vienna, Austria, 7-12 April 2013
- International Workshop in Advanced EBSD Techniques, Wollongong, 3 May 2013
- 5th International Conference on Recrystallisation and Grain Growth, Sydney, 5-10 May 2013
- Rodinia 2013: Supercontinent Cycles and Geodynamics Symposium, Moscow State University, Moscow, Russia, 20-24 May 2013
- FUTORES Noel White Symposium, Townsville, Queensland, 2-5 June 2013
- YOM Seismic and MT Workshop, GSWA, June 2013
- MPE2013 Workshop - Recycling Rocks: Understanding Sustainability in a Dynamic Earth, Melbourne, Australia, 5-16 July, 2013
- GSA Biennial Conference of the Specialist Group in Geochemistry, Mineralogy and Petrology, Mission Beach, Queensland, 14-19 July 2013
- 76th Annual Meeting of the Meteoritical Society, Edmonton, Canada, 29 July - 2 August 2013
- 12th SGA Biennial Meeting, Uppsala, Sweden, 12-15 August 2013
- Goldschmidt 2013 Conference, Florence, Italy, 25-30 August 2013
- Building Strong Continents, Metamorphic Studies Group, University of Portsmouth, UK, 2-4 September 2013



David Wacey, Goldschmidt 2013.

- The Electron Microscopy and Analysis Group Conference, York, UK, 3-6 September 2013
- 19th International Conference on Deformation Mechanisms, Rheology and Tectonics, Leuven, Belgium, 16-18 September 2013
- 13th Australian Space Science Conference, Sydney, 30 September - 2 October 2013
- International Meeting on Precambrian Evolution and Deep Exploration of the Continental Lithosphere, Beijing, PR China, 6-9 October 2013
- The GSA 125th Anniversary Annual Meeting and Expo, Denver, Colorado, USA, 27-30 October 2013

- ICE Microstructure, Rheology and Physical Properties, University of Otago, Dunedin, New Zealand, 29-30 October 2013
- IGCP581 4th Annual Meeting, Hanoi, Vietnam, 10-15 November 2013
- Swiss Geosciences Meeting, Lausanne, Switzerland, 15-16 November 2013
- AGU Fall Meeting, San Francisco, USA, 9-13 December 2013

INVITED TALKS AT MAJOR CONFERENCES 2013

Granulites & Granulites 2013, Hyderabad, India, 16-20 January 2013	Generating TTGs in Nuvvuagittuq Fold Belt: Implications for the origin of the Earth's early continental crust **T. Rushmer** **Keynote** Implications of Late Archean magmatism and almost coeval high-grade metamorphism in the North China Craton at the Archean/Proterozoic boundary **S.A. Wilde** **Keynote**
37th Annual Condensed Matter and Materials Meeting, Wagga Wagga, NSW, Australia, 5-8 February 2013	Polyamorphism: Fact or Fiction? **S. Clark** **Invited**
European Geosciences Union General Assembly, Vienna, Austria, 7-12 April 2013	What lies beneath: Unveiling the fine-scale 3D compositional and thermal structure of the lithosphere and upper mantle **J.C. Afonso** **Keynote**
International Workshop in Advanced EBSD Techniques, Wollongong, 3 May 2013	EBSD and Numerical Modelling: Current Status, Challenges and Opportunities **S. Piazolo** **Invited**
Rodinia 2013: Supercontinent Cycles and Geodynamics Symposium, Moscow State University, Moscow, Russia, 20-24 May 2013	Proterozoic Baltica: major stages of block reorganization and supercontinent reconstruction S.V. Bogdanova, N.V. Lubnina and **S.A. Pisarevsky** **Keynote** Australia's 40° twist during Rodinia breakup and a revised Neoproterozoic global palaeogeography **Z.X. Li** and D.A.D. Evans **Keynote** Pre-Rodinian supercontinents: how "super" were they? **S.A. Pisarevsky** **Keynote**
MPE2013 Workshop Recycling Rocks: Understanding Sustainability in a Dynamic Earth, Melbourne, Australia, 5-16 July, 2013	In-situ studies of granular materials under deformation **S. Clark**, **T. Rushmer**, B. Colas, R.L.L. Jones and D.Y. Parkinson **Invited** Coupling global systems in geodynamic earth models **C. O'Neill** **Invited**
12th SGA Biennial Meeting, Uppsala, Sweden, 12-15 August 2013	The orogenic gold mineral system **T.C. McCuaig** and **J.M.A. Hronsky** **Keynote**
Goldschmidt 2013 Conference, Florence, Italy, 25-30 August 2013	Multi-observable thermochemical tomography: A new framework in integrated studies of the lithosphere **J.C. Afonso**, J. Fullea, J. Connolly, N. Rawlinson, **Y. Yang** and A.G. Jones **Invited** Ore deposits and lithosphere evolution in the early Earth G.C. Begg, **W.L. Griffin**, **S.Y. O'Reilly**, and **J.M.A. Hronsky** **Keynote** Archean lithospheric mantle: The fount of all ores? **S.Y. O'Reilly**, **W.L. Griffin**, G.C. Begg, **N.J. Pearson** and **J.M.A. Hronsky** **Invited**

Goldschmidt 2013 Conference, Florence, Italy, 25-30 August 2013 cont...

The hole story about laser ablation ICP-MS
N.J. Pearson, **W.J. Powell**, K.J. Grant, J.L. Payne, **R.C. Murphy**, **E. Belousova**, **W.L. Griffin** and **S.Y. O'Reilly** **Invited**

19th International Conference on Deformation Mechanisms, Rheology and Tectonics, Leuven, Belgium, 16-18 September 2013

Microstructural evolution of polycrystalline ice using *in situ* deformation experiments and FAME
M. Peternell, C.J.L. Wilson, M. Dierckx, D.M. Hammes and **S. Piazolo** **Keynote**

Rheology of dirty ice: first results and future perspectives
S. Piazolo, C.J.L. Wilson, V. Luzin, C. Brouzet and M. Peternell **Invited**

6th International Symposium on Hydrocarbon Accumulation Mechanisms and Petroleum Resources Evaluation, Beijing, PR China, 26-28 September 2013

Re-Os dating of the Shengli River marine oil shale, North Tibet: A development method for direct dating crude oil
X.-C. Wang and J. Li **Invited**

13th Australian Space Science Conference, Sydney, 30 September - 2 October 2013

The tectonics of exoplanets
C. O'Neill **Keynote**

Dr Sandra Piazolo.

International Meeting on Precambrian Evolution and Deep Exploration of the Continental Lithosphere, Beijing, PR China, 6-9 October 2013

The world turns over: Hadean – Archean crust-mantle evolution
W.L. Griffin, **E. Belousova**, V. Malkovets, Z. Spetsius, **S.Y. O'Reilly**, **N.J. Pearson**, and others **Keynote**

A saga of crust-mantle relationships and evolution since Archean times: Geophysical and geochemical evidence tracked in mantle xenoliths from Arctic Norway and Cape Verde (Atlantic Ocean)
S.Y. O'Reilly, **W.L. Griffin**, **N.J. Pearson** and G. Begg **Keynote**

Thirty years of progress in Precambrian paleomagnetism and continental reconstructions
S. Pisarevskiy **Invited**

The GSA 125th Anniversary Annual Meeting and Expo, Denver, Colorado, USA, 27-30 October 2013

Is plate tectonics a phase in the evolution of Earth-like planets?
C. O'Neill **Invited**

ICE Microstructure, Rheology and Physical Properties, University of Otago, Dunedin, NZ, 29-30 October 2013

Numerical simulation of ice processes
S. Piazolo **Invited**

Rheology of dirty ice: First results and future perspectives
S. Piazolo, C.J.L. Wilson, V. Luzin, C. Brouzet and M. Peternell **Invited**
(See Photo above)

AGU Fall Meeting, San Francisco, USA, 9-13 December 2013

Majorite garnet and lithosphere evolution: Kaapvaal Craton
W.L. Griffin, S. Tessalina and **S.Y. O'Reilly** **Invited**

Geochemical evolution of cratonic lithospheric mantle: A 3.6 Ga story of persistence and transformation
S.Y. O'Reilly, **W.L Griffin** and **N.J Pearson** **Invited**

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

OTHER CONFERENCE ROLES

Granulites & Granulites 2013, Hyderabad, India, 16-20 January 2013	***Chief Convenor:*** **Professor Ian Fitzsimons** - THERMOCALC Workshop at IIT-Kharagpur, 8-10 January, Pre-conference fieldtrip to the Eastern Ghats, 11-16 January, Conference in Hyderabad, 16-20 January, Post-conference fieldtrip to the Kerala Khondalite Belt, 21-26 January
EGU General Assembly, Vienna, Austria, 7-12 April 2013	***Session Co-Convenor:*** **Dr Juan Carlos Afonso** - SM4.7: Non-seismic imaging of the continents
Zhejiang Climate Workshop, Zhejiang China, 14-16 April 2013	***Organiser:*** **Associate Professor Kelsie Dadd**
International Workshop in Advanced EBSD techniques, Wollongong, 3 May 2013	***Organising Committee:*** **Associate Professor Sandra Piazolo**
5th International Conference on Recrystallisation and Grain Growth, Sydney, 5-10 May 2013	***Organising Committee:*** **Associate Professor Sandra Piazolo** ***Session Chair:*** **Associate Professor Sandra Piazolo** - B6: Experimental development and characterization
Rodinia 2013: Supercontinent Cycles and Geodynamics Symposium, Moscow, Russia, 20-24 May 2013	***Organising Committee:*** **Professor Zheng-Xiang Li** **Dr Sergei Pisarevsky**
MPE2013 Workshop Recycling Rocks: Understanding Sustainability in a Dynamic Earth, Melbourne, Australia, 5-16 July, 2013	***Organising Committee:*** **Associate Professor Tracy Rushmer**
Goldschmidt 2013 Conference, Florence, Italy, 25-30 August 2013	***Session Co-Convenors:*** **Professor Catherine McCammon** - 22: The Cutting Edge in Mineralogy and Mineral Physics **Associate Professor Tracy Rushmer, Dr David Wacey** - 03: Early Earth ***Theme Co-Convenors:*** **Professor Martin Van Kranendonk** - Session 03 Early Earth, Theme: 03b: Geodynamics and Crust Formation in the Archean – Palaeoproterozoic **Dr David Wacey, Professor Matt Kilburn** - Session 03 Early Earth, Theme 03c: Peering into the Cradle of Life **Dr Dan Howell** - Session 05 Mantle Geochemisry, Theme 05c: Investigating the Origin and Modification of Cratonic Mantle over Time: The Role of Diamonds and Xenoliths **Associate Professor Tracy Rushmer** - Session 06 Continental Crust, Theme 06a: Understanding the Lower Continental Crust: Where are We Now? **Professor Mike Brown** - Session 06 Continental Crust, Theme 06g: Quantification of Metamorphic Processes and the Thermo-Tectonic Evolution of Orogens **Professor Bill Griffin** - Session 13 Ores: Their Construction, Destruction and Politics, Theme 13f: Crust-Mantle Evolution and Changing Patterns of Ore Deposits in the Early Earth

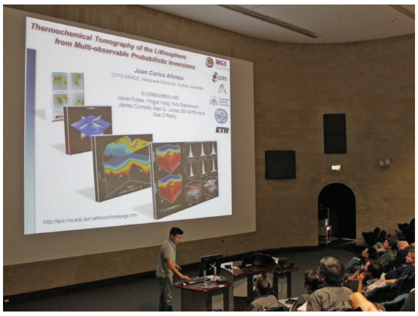
19th International Conference on Deformation Mechanisms, Rheology and Tectonics, Leuven, Belgium, 16-18 September 2013	***Session Chair:*** **Associate Professor Sandra Piazolo** - Session 7: Fluids in a Deforming Environment
GEOFLUIDS: Lubricants of the dynamic earth, Joint meeting of the MG, German Mineralogical Society, GV, German Geological Union and SEDIMENT, Tübingen, Germany, 16-19 September 2013	***Co-Chairperson:*** **Professor Catherine McCammon** ***Co-Convernor:*** **Professor Catherine McCammon** - 2. MP5: Physics and Chemistry of Carbon-Bearing Phases in the Earth's Interior **Professor Catherine McCammon** - Theme 5: Cosmochemistry and Magmatic Processes, Session 2: Earth Mantle, Solids Liquids and Gasses (Part A) and Session 3: Earth Mantle, Solids Liquids and Gasses (Part B)
Combined SHRIMP Centre of Beijing and the SinoProbe Program of China International Meeting on Precambrian Evolution and Deep Exploration of the Continental Lithosphere, Beijing, 7-9 October 2013	***Session Co-Convenors:*** **Professor Bill Griffin** - Coupling Between Precambrian Crust and Subcrustal Lithosphere: Combining the Geochemical and Geophysical Evidence **Dr Sergei Pisarevsky** - Precambrian Supercontinents: Facts–Fiction–Fantasy **Professor Simon Wilde** - Session: The Hadean Earth: Evidence From the Crustal Record and Isotopes
AGU Fall Meeting, San Francisco, USA, 9-13 December 2013	***Session Co-Convenors:*** **Dr Juan Carlos Afonso** - MR24B: Constraints and Uncertainties on the Composition, Structure, and Dynamics of the Earth's Lithosphere, Upper Mantle, and Transition Zone From Multidisciplinary Studies I **Dr Juan Carlos Afonso** - MR43: Constraints and Uncertainties on the Composition, Structure, and Dynamics of the Earth's Lithosphere, Upper Mantle, and Transition Zone From Multidisciplinary Studies III Posters **Dr Craig O'Neill** - DI23A: Probing the Earth's Interior I Posters



Participants at the Oxygen Fugacity Workshop organised by CCFS at Macquarie University with guest lecturers Catherine McCammon (Bayreuth University) and Hugh O'Neill (ANU).

SELECTED WORKSHOP ROLES

Activity	Details & Participant/s	Date
CET Seminar Series	**Professor Cam McCuaig**	2013
CCFS/EPS Seminar Series	**Dr Richard Flood**	2013

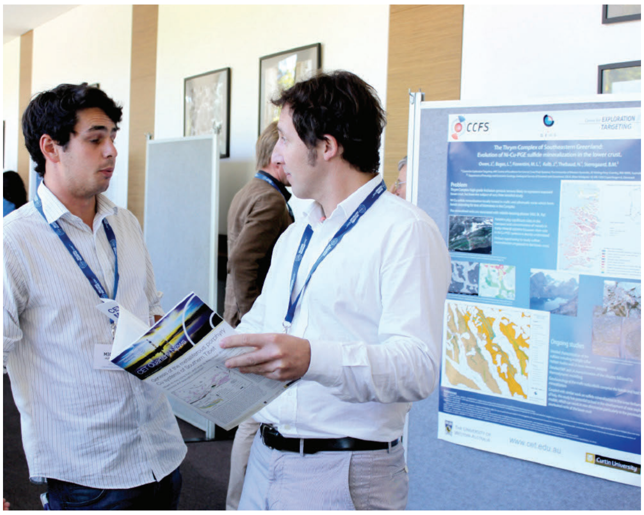


A three day CCFS Workshop on Lithosphere Dynamics was hosted by the University of Western Australia and attended by over 100 participants.

Activity	Details & Participant/s	Date
Short Course on Laser Ablation ICP-MS - for visiting researchers from the Gemological Institute of Thailand	**Associate Professor Norman Pearson**	13-17 May 2013
Oxygen Fugacity Workshop *(see photos p. 26)*	Organised by CCFS, with guest lecturers **Professor Catherine McCammon** (Bayreuth) and Professor Hugh O'Neill (ANU)	27-28 May 2013
CCFS Project definition workshop - More than 20 scientists from within CCFS and collaborating institutions contributed to discuss the direction of collaborative research on the lithospheric evolution and the related significant mineralisation of the Yilgarn craton and its margins, specifically on geochemistry and geochronology, geodynamics and modelling, and lithosphere imaging.	**Dr Klaus Gessner**, hosted by GSWA Perth	4 July 2013
Applying phase equilibria modelling to rocks - University of Florence, Italy (associated with the Goldschmidt2013 conference) Workshop on methodological aspects of applying phase equilibria modelling to rocks; aimed at metamorphic geologists who have experience of using phase equilibria calculation software.	Organised by **Professor Michael Brown**, attended by 37 participants	24-25 August 2013
CET-CCFS Fieldtrip to the Ivrea Zone: Touching the contact between the lithospheric mantle and the lower continental crust - Taking advantage of a heavy CCFS/CET staff presence in Europe this August during the brief window of time between the SGA Meeting in Uppsala (Sweden) and the Goldschmidt Conference in Florence (Italy), CCFS/CET participants Marek Locmelis, Marco Fiorentini with the help of Nicholas Thébaud organised a 5-day field trip in the Italian Alps. Ten enthusiastic geologists were guided among the outcrops of the Ivrea Zone – a rare slice of lower continental crust and subcontinental lithospheric mantle exhumed during the Alpine Orogeny.	Organised by **Dr Marek Locmelis**, **Associate Professor Marco Fiorentini** and Nicholas Thébaud	18-25 August 2013

SELECTED WORKSHOP ROLES *cont...*

Activity	Details & Participant/s	Date
Short courses in Geochemistry and Mantle processes at the University of Ferrara and Modena	 Conducted by **Professors Sue O'Reilly** and **Bill Griffin** *(pictured above)*	September 2013
CCFS Workshop on Lithosphere Dynamics - 3 day workshop The University of Western Australia	**Dr Weronika Gorczyk,** attended by over 100 participants	4-6 November 2013
Postgraduate Seminar Day	**Department of EPS Students and staff at Macquarie**	13 November 2013
A Tectonic History of South China in Nine Days (see *International Links p. 119)*	Conducted by **Professor Zheng-Xiang Li**, together with Professor Hanlin Chen and Dr Fengqi Zhang of Zhejiang University	7-15 December 2013
CET Corporate Members Day (see *Industry Interaction p. 105)*	Organised by **Professors Cam McCuaig** and **Marco Fiorentini**	9 December 2013
Fifth Greenland Day in Perth - CET-CCFS, the Geological Survey of Denmark and Greenland (GEUS) and the Greenland Ministry of Industry and Mineral Resources (MIM), organised the fifth annual Greenland Day. A great success, the day showcased the outcomes of the numerous CET-CCFS-GEUS research projects in Greenland. The event was also an opportunity to learn about ongoing mineral exploration in Greenland and the wealth of geological datasets that are available. The day provided an excellent opportunity for resource companies and investors to understand more about exploration and mining opportunities in Greenland.	Organised by **Associate Professor Marco Fiorentini**, **Dr Leon Bagas**, Cindi Dunjey, attended by more than sixty company delegates, students and researchers	10 December 2013



CCFS CI Dr Marco Fiorentini (right) led the Australian organisation of 'Greenland Day' 2013.

ESTEEM FACTORS AND OUTREACH

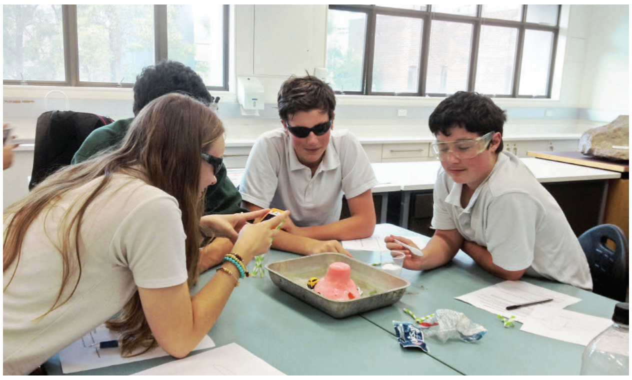
Awards

Activity	Participant/s
Presented with 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 Visiting Professorship, Universite Paul Sabatier, Toulouse, France	**Associate Professor Marco Fiorentini**
Awarded Visiting Professorship, Universite de Grenoble, Grenoble, France	**Associate Professor Marco Fiorentini**
Awarded UWA Gledden Fellowship to invite Professor Boswell Wing to CET in 2014	**Associate Professor Marco Fiorentini**
Awarded 2013 Clarke Medal of the Royal Society of NSW *"for meritorious contributions to Geology, Mineralogy and Natural History of Australasia"*, one of the most prestigious awards in Australian science (to be presented 2014)	**Professor Bill Griffin**
Awarded the Gibb Maitland Medal (the highest award of the WA branch of the GSA) *"for substantial contributions to geoscience in Western Australia"* by the Western Australian Division of the Geological Society of Australia.	**Professor Cam McCuaig**
Awarded Visiting Professorship, University De Lorraine, Nancy, France	**Professor Cam McCuaig**
Awarded a Copernicus Visiting Professorship for 2013 at the University of Ferrara, Italy	**Professor Sue O'Reilly**
Awarded ARC Future Fellowship (see *Participants, p. 12*)	**Dr Yingjie Yang**

Katy Evans presenting Cam McCuaig the Gibb Maitland Medal (right: CCFS Advisory Board member, Dr Jon Hronsky).

Outreach

Activity	Participant/s	Date
Lecture on the Faculty of Science - Information Day	**Associate Professor Kelsie Dadd**	3 January 3013
Public lecture - GSWA open day *"Crustal evolution of the Rundall Province"*	**Dr Chris Kirkland**	22 February 2013
Interviewed for article *"Hard Core"* for the Discovery Channel Magazine	**Professor Sue O'Reilly**	February 2013
Organised O-Week stall for Women in Science and Engineering	**Associate Professor Kelsie Dadd**	25 February - 1 March 2013
Talk on Earth Science at Hurstville Library	**Associate Professor Kelsie Dadd**	7 March 2013
Interviewed at the Sydney Studios of the ABC by Roland Pease for a program in the *"Discovery"* series broadcast on the Overseas Service of the ABC in July 2013.	**Professor Simon Wilde**	13 July 2013
Talk on plate tectonics to Newington College Year 12 class	**Associate Professor Kelsie Dadd**	9 August 2013
Organised and chaired first Women in Science and Engineering lunch	**Associate Professor Kelsie Dadd**	19 August 2013
Visit to Timor-Leste to discuss Professional and Community Engagement (PACE) and staff training	**Associate Professor Kelsie Dadd**	9-13 September 2013
Lecture for *"Uni in a Day"*	**Associate Professor Kelsie Dadd**	27 September 2013
NewGenGold Conference, Perth - Gold exploration event	**Professor Cam McCuaig, Dr Yongjun Lu**	26-27 November 2013

Activity *(Outreach cont...)*	Participant/s	Date
Over 100 public geochronology reports / government briefings	**Dr Chris Kirkland**	2013
Interview for a article "*Hard Core*" for Discovery Channel Magazine	**Professor Sue O'Reilly**	February, 2013
 Students from Windsor High School's Gifted and Talented (GAT) group enjoyed a 'hands on' Geoscience lecture during their visit to Macquarie	**Dr Heather Handley, Associate Professor Kelsie Dadd**	25 November 2013
Contributions to textbooks ranging from University level - *'Biology: Concepts and Applications'* and *'Encyclopedia of Scientific Dating Methods'* - down to high school level - *'Core Science Stage 5 for the Australian Curriculum'* and the Howard Hughes Medical Institute EarthViewer Application – *'Famous Fossils of the World'*	**Dr David Wacey**	2013

2013 APPOINTMENTS AND POSITIONS

Professor Sue O'Reilly	Appointed Chair Australian Academy of Sciences National Committee for Earth Sciences Appointed member, Executive Committee, UNCOVER (http://www.science.org.au/policy/uncover.html) Appointed member ARC ERA Reference Working Group 2013 Chief Guest Editor of Special Volume: The lithosphere and beyond: a multidisciplinary spotlight. *Lithos Special Issue 189, 15 February 2014* (with **Professor Bill Griffin** and **Dr Juan Carlos Alfonso**)
Dr Juan Carlos Afonso	Co-editor of Special Volume: The lithosphere and beyond: a multidisciplinary spotlight. *Lithos Special Issue 189, 15 February 2014* (with **Professor Sue O'Reilly** and **Professor Bill Griffin**)
Associate Professor Marco Fiorentini	Visiting Professor, Universite Paul Sabatier, Toulouse, and Universite de Grenoble, Grenoble France Co-editor of Special Volume: Using Research to Benefit Mineral Exploration: Examples of Recent Research Conducted at the Centre of Exploration Targeting (CET), UWA. *Australian Journal of Earth Sciences 61, 1, 2013* (with Hagemann, W.K. and Witt, M.)
Professor Ian Fitzsimons	Fellow of the Geological Society, London Fellow of the Mineralogical Society
Professor Bill Griffin	Invited core founding member of the of the International Precambrian Research Centre of China (IPRCC) at Beijing SHRIMP Centre and the Department of Geology, CAGS Co-editor of Special Volume: Ore Deposits and the Role of the Lithospheric Mantle. *Lithos Special Issue 164-167, April 2013* (with Mondal, S.K. and Maier, W.-G.) Co-editor of Special Volume: *American Journal of Science Special Issue in Honour of Bor-Ming Jahn. In press.* (with Chung S.L., Shellnutt, J.G. and Wang, K-L) to be published 2014 Co-editor of Special Volume: The lithosphere and beyond: a multidisciplinary spotlight. *Lithos Special Issue 189, 15 February 2014* (with **Professor Sue O'Reilly** and **Dr Juan Carlos Alfonso**)
Professor Matt Kilburn	Visiting Professor, Harvard University and Brigham & Women's Hospital, Boston
Dr Yongjun Lu	Appointed Member, Planning and Implementation subcommittee of Geoconferences

Professor Catherine McCammon	President, Volcanology, Geochemistry and Petrology section of the American Geophysical Union Chair, "*Earth's Deep Interior*" subcommittee of the Commission of the Physics of Minerals, IMA IAVCEI representative, Inter-association Commission for Physics and Chemistry of Earth Materials, IUGG
Dr Craig O'Neill	Appointed to the AGC organising committee for AGC 2014
Professor Cam McCuaig	SEG Councillor and member of the SEG curriculum committee Member, Science Advisory Committee for Discovery Theme "*Minerals Down Under*" CSIRO Flagship Member of the Geological Survey of Western Australia Mineral Exploration technical subcommittee
Associate Professor Norman Pearson	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
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
Professor Simon Wilde	Member of the International Association for Gondwana Research Advisory Committee 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
Dr Michael Wingate	Member of the Steering Committee, IAVCEI Large Igneous Provinces Commission

EDITORIAL APPOINTMENTS	
Acta Geologica Sinica	**Griffin, Li**
Acta Geoscientia Sinica	**Li**
American Journal of Science	**Wilde**
Chemical Geology	**Wilde**
Economic Geology	**Lu**
EGU Journal Solid Earth	**Afonso, Schaefer**
Geological Society of America Bulletin	**Griffin, Li**
GeoResJ	**Jacob**
Gondwana Research	**Wilde**
Journal of Asian Earth Sciences	**Li, Wilde**
Journal of the Geological Society, London	**Fitzsimons**
Journal of Jilin University – Earth Science	**Wilde**
Journal of Metamorphic Geology	**Brown**
Journal of Petrology	**Turner**
Lithos	**C. Clark, Foley, Griffin**
Mineralogy and Petrology	**Fiorentini**
Ore Geology Reviews	**Bagas**
Physics and Chemistry of Minerals	**McCammon**
Precambrian Research	**Barley, Pisarevsky, Van Kranendonk**

Bill Griffin, Costanza Bonadiman and Sue O'Reilly cycling through the streets of Ferrara, Italy. Sue O'Reilly was awarded a Copernicus Visiting Professorship for 2013 at the University of Ferrara.

MEDIA

Activity	Participant/s	Date, Forum	Web address
Contribution on Earth's earliest cellular life in "*Wonders of Life*" by Professors Brian Cox & Andrew Cohen	**Dr David Wacey**	Jan 2013, BBC TV	Book accompanied a major BBC TV series
Planetary science: Caught in the act	**Dr Craig O'Neill**	30 January 2013, Nature News	http://www.nature.com/news/planetary-science-caught-in-the-act-1.12324?nc=1359858974694
Hoodoos may be seismic gurus	**Dr Juan Carlos Afonso**	5 February 2013, ABC News in Science	http://www.abc.net.au/science/articles/2013/02/05/3682324.htm
Other Earths could be *'in our backyard'*	**Dr Craig O'Neill**	7 February 2013, ABC News in Science	http://www.abc.net.au/science/articles/2013/02/07/3685458.htm
Asteroid to narrowly miss Earth next week	**Dr Craig O'Neill**	8 February 2013, ABC News in Science	http://www.abc.net.au/news/2013-02-08/asteroid-to-narrowly-miss-earth/4507970
Record asteroid to fly close to Earth	**Dr Craig O'Neill**	8 February 2013, ABC News in Science	http://www.abc.net.au/science/articles/2013/02/08/3686287.htm
Saturn's rings rain on its atmosphere	**Dr Craig O'Neill**	11 April 2013, ABC News in Science	http://www.abc.net.au/science/articles/2013/04/11/3734009.htm
Iron ore deposits could be easier to find	**Professor Bill Griffin**	16 October 2013, The Advertiser	www.adelaidenow.com.au/news/breaking-news/iron-ore-deposits-could-be-easier-to-find/story-fni6ul2m-1226739325302?
Keep a lid on it: The controversy over Earth's oldest rocks	**Dr Craig O'Neill**	11 November 2013, The conversation	https://theconversation.com/keep-a-lid-on-it-the-controversy-over-earths-oldest-rocks-19825

FEATURED CCFS PAPERS

Publication	Media Activity
Wacey, D., McLoughlin, N., **Kilburn, M.R.**, Saunders, M., **Cliff, J.B.**, Kong, C., **Barley, M.E.** and Brasier, M.D. 2013. Nanoscale analysis of pyritised microfossils reveals differential heterotrophic consumption in the ~1.9-Ga Gunflint chert. *Proceedings of the National Academy of Sciences United States of America, 110, 8020-8024.*	5 news articles
Van Kranendonk, M.J. and **Kirkland, C.L.** 2013. Orogenic climax of Earth: The 1.2-1.0 Ga Grenvillian Superevent. *Geology, 41, 735-738.*	2 news articles
Liu, Y.C., **Li, Z.X.**, Laukamp, C., West, G. and Gardoll, S. 2013. Quantified spatial relationships between gold mineralisation and key ore genesis controlling factors, and predictive mineralisation mapping, St Ives Goldfield, Western Australia. *Ore Geology Reviews, 54, 157-166.*	3 news articles
Griffin, W.L., Begg, G.C. and **O'Reilly, S.Y.** 2013. Continental-root control on the genesis of magmatic ore deposits. *Nature Geoscience, 6, 905-910.*	2 news articles
Noffke, N., Christian, D., **Wacey, D.** and Hazen, R.M. 2013. Microbially induced sedimentary structures recording an ancient ecosystem in the ca. 3.48 billion-year-old Dresser Formation, Pilbara, Western Australia. *Astrobiology, 13, 1103-1124.*	31 news articles, 4 Radio, 4 TV
Humayun, M., **Nemchin, A.**, Zanda, B., Hewins, R.H., **Grange, M.**, Kennedy, A., Lorand, J.-P., Göpel, C., Fieni, C., Pont, S. and Deldicque, D. 2013. Origin and age of the earliest Martian crust from meteorite NWA 7533. *Nature, 503, 513-516.*	36 news articles
Yaxley, G.M., Kamenetsky, V.S., Nichols, G.T., Maas, R., **Belousova, E.**, Rosenthal, A. and Norman, M. 2013. Diamonds in Antarctica? Discovery of Antarctic kimberlites extends vast Gondwanan Cretaceous kimberlite province. *Nature Communications, 1-7.*	42 news articles

For full details and links to the relevant articles see http://ccfs.mq.edu.au/AnnualReport/13Report/Comms.html

JOURNAL METRICS HIGHLIGHT CCFS PARTICIPANTS

CCFS SCORED WELL IN THE DECADE OF MOST-HIGHLY-CITED PUBLICATIONS IN GEOLOGY

The top three most-highly-cited papers published in Geology (5yr impact factor: 4.660) for each year between 2000 and 2010 (data source: Web of Knowledge) included 8 papers authored by 14 CCFS related researchers.

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*

2007: #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*

2006: #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*

2003: #1. **Chung, S.L.**, Liu, D.Y., Ji, J.Q., **Chu, M.F.**, Lee, H.Y., Wen, D.J., Lo, C.H., Lee, T.Y., Qian, Q., and Zhang, Q., 2003, Adakites from continental collision zones: Melting of thickened lower crust beneath southern Tibet: *Geology, 31, 1021-1024, doi:10.1130/G19796.1*

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*

Publication	Metrics
Condie, K.C., **Belousova, E.A.**, **Griffin, W.L.** and Sircombe, K.N. 2009. Granitoid events in space and time: Constraints from igneous and detrital zircon age spectra. *Gondwana Research, 15, 228-242.*	*Gondwana Research* (5 Yr Impact factor 6.171) - 3rd Most Cited article published since 2009 (173 citations)
Belousova, E.A., Kostitsyn, Y.A., **Griffin, W.L.**, Begg, G.C., **O'Reilly, S.Y.** and **Pearson, N.J.** 2010. The growth of the continental crust: Constraints from zircon Hf-isotope data. *Lithos, 119, 3-4, 457-466.* doi:10.1016/j.lithos.2010.07.024	*Lithos* (5 yr impact factor 4.246) - 4th Most Cited article published since 2009 (81 citations)
Yaxley, G.M., Kamenetsky, V.S., Nichols, G.T., Maas, R., **Belousova, E.**, Rosenthal, A. and Norman, M. 2013. Diamonds in Antarctica? Discovery of Antarctic kimberlites extends vast Gondwanan Cretaceous kimberlite province. *Nature Communications, 1-7.*	*Nature Communications Altametric* scores - 134th of the 221,677 tracked articles of a similar age in all journals: score 386 (ranked #4 of 2,475 in this journal)

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.

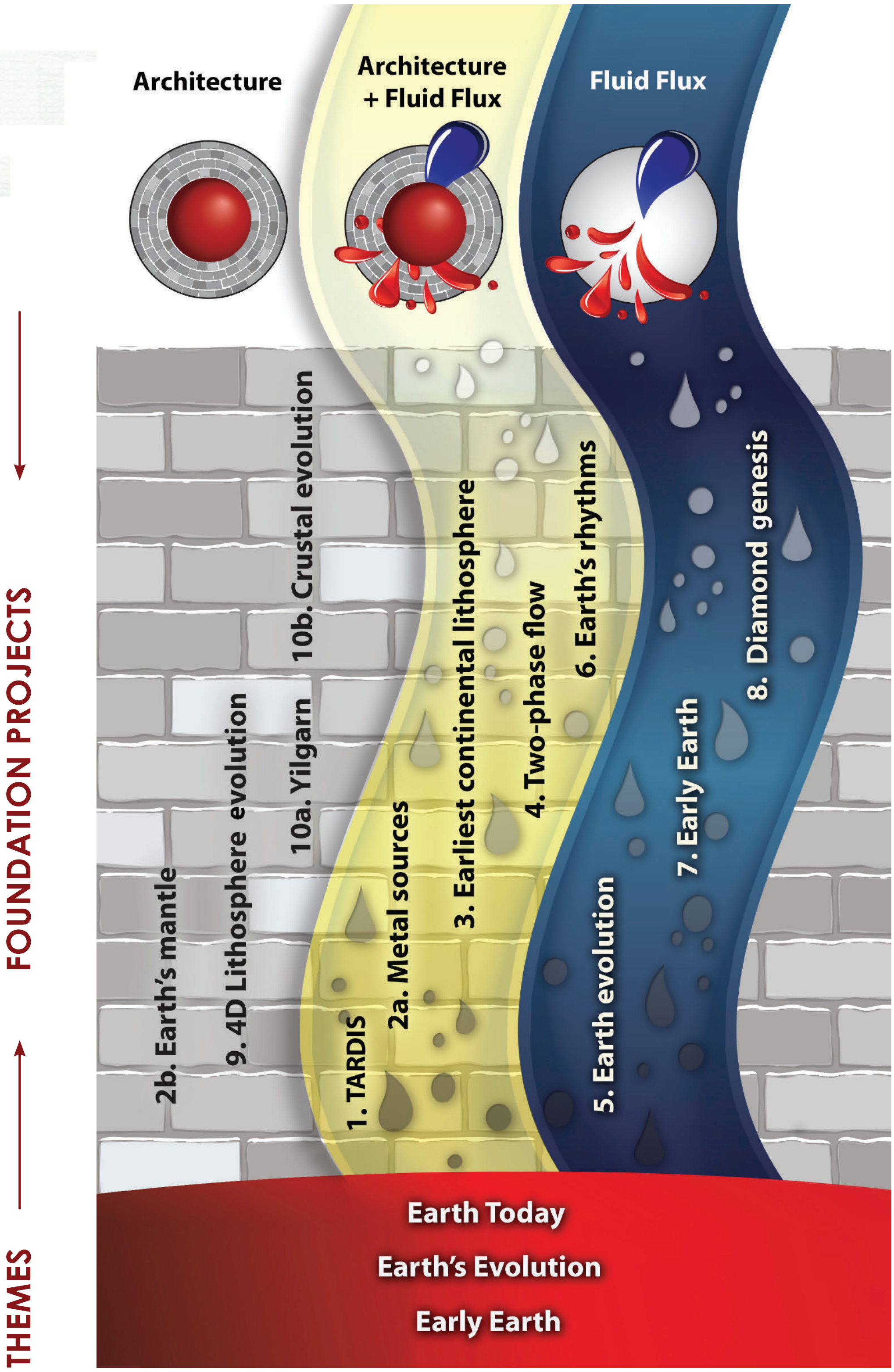
All Australian and international visitors are listed in *Appendix 7.*

They have participated in:

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

Research highlights 2013

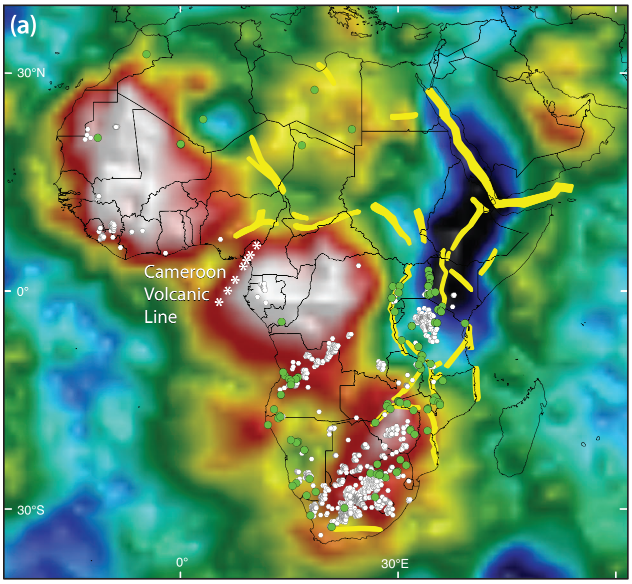
Following the new conceptual framework outlined on page 3, these Research Highlights are identified as contributing to understanding Earth Architecture (the '*roadmap*' for fluids) and/or Fluid Fluxes (the '*traffic report*'), with logos for easy attribution. For a full description of the foundation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

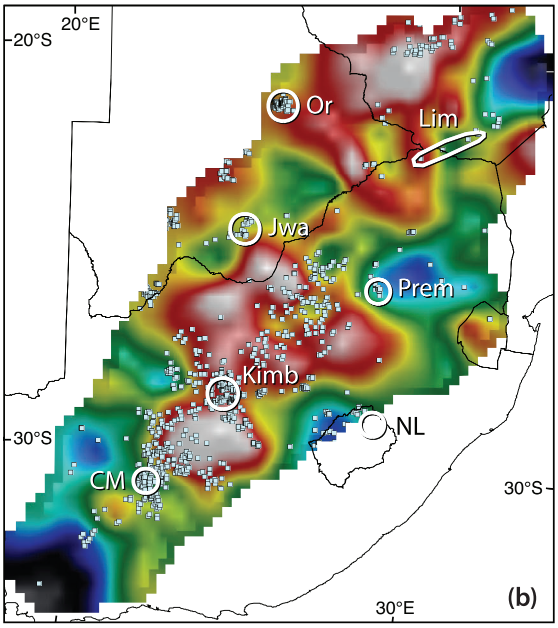


The GLAMour of mineral exploration

Giant magma-related ore systems are prime targets for modern mineral exploration – but how do they form? The Global Lithospheric Architecture Mapping (GLAM) project undertaken with industry collaboration has delivered an integrated model for more efficient global targeting of some key magma-related ore deposits. The magmas responsible for several types of ore deposit must pass through the stagnant subcontinental lithospheric mantle (SCLM) on their way to the surface - so how much control does the SCLM exert on the formation and localisation of the ores? GLAM has demonstrated that the 3D architecture of the SCLM influences the emplacement and fertility of such magmas. The GLAM outcomes to date are summarised in an invited article in Nature Geoscience (*CCFS Publication #207*), where we present evidence that the structure and evolution of the SCLM is directly relevant to the genesis and localisation of several types of major ore deposits, including diamond, Ni-Cu-(PGE), PGE and (Cu-)Au deposits.

Primary diamond deposits occur in dikes and pipes of kimberlites or lamproites, generated by low-volume melting; they pick up diamonds from the deep SCLM (>150 km) during their eruption. Blocks of cratonic SCLM can now be robustly identified in seismic tomography (e.g. *CCFS Publication #334* and references therein) and magnetotelluric (MT) surveys as volumes with high seismic velocity and high electrical resistivity. On the large scale (Fig. 1a), kimberlites are concentrated near the edges of cratonic blocks. High-resolution tomography (Fig. 1b) shows an even more obvious picture; most kimberlites cluster around high-velocity domains in the deep SCLM. These patterns reflect the geochemical requirements for diamond formation, and the structural requirements for magma emplacement. Diamond formation requires the metasomatic introduction of carbon into the depleted SCLM, typically accompanied by Ca, Al, K, Na and Fe, and such refertilised zones have lower seismic velocities.





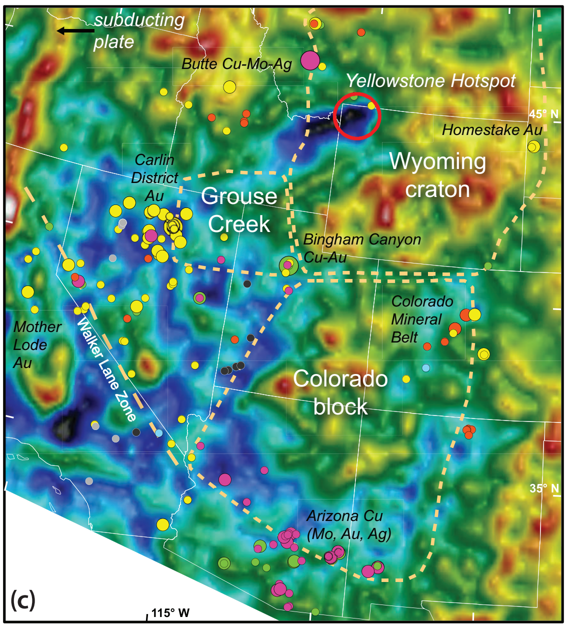


Figure 1. (Full references and sources given in Griffin et al., 2013, Nature Geoscience: CCFS Publication #207) Vs tomography (100-150 km) of the lithospheric mantle. Red to white colours indicate high Vs; blue colours low Vs.

(a) Africa, showing distribution of low-volume magmatic rocks along the boundaries of high-velocity blocks. Young rift basins shown in yellow.

(b) Detailed seismic tomography over part of the Kaapvaal craton, showing kimberlites around the margins of high-velocity volumes. Major kimberlite provinces: Kimb, Kimberley district; NL, Northern Lesotho; Prem, Premier; Jwa, Jwaneng district; Or, Orapa district; Lim, Limpopo Belt, including kimberlites such as Venetia.

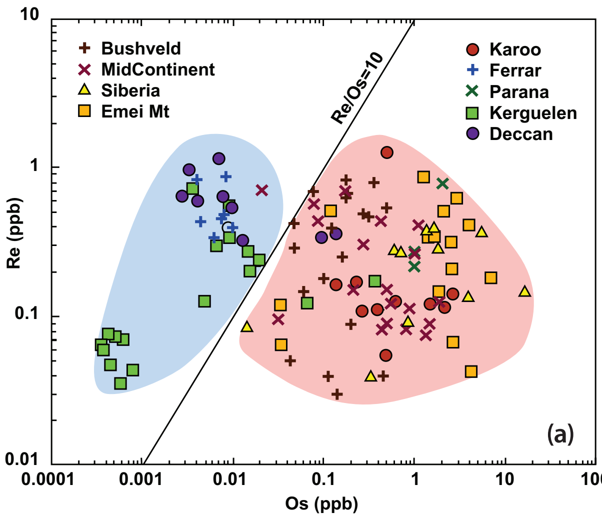
(c) Vp tomography (90 km depth, of western USA, showing major (magmatic-) hydrothermal ore deposits by size (largest, supergiant; medium, giants; smallest, majors) and dominant metals (yellow, Au; green, Cu-Au; orange, Mo; light blue, REE; light grey, W(-Sn); dark grey, Fe). Significant lithospheric blocks, defined at sub-crustal depths from multi-disciplinary data, are outlined. Note deposits concentrate along prominent lithospheric structures, particularly in lower-velocity regions or on the flanks of highs, where lower velocities reflect refertilisation of the SCLM and/or higher temperature.

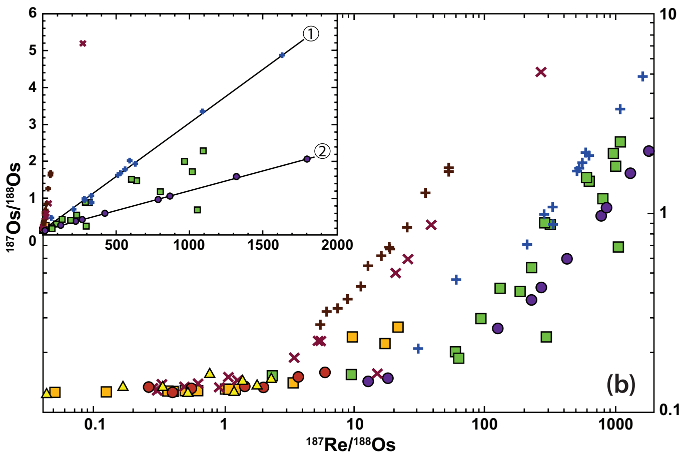
The weak zones on the margins of cratonic blocks, and in fractures within these blocks, provided channels for the C-bearing fluids, and later controlled the emplacement of the kimberlites.

Major Ni-Cu-(PGE) sulfide deposits are genetically linked to Large Igneous Provinces and komatiites, and the accumulation of metal-rich immiscible sulfide melts in mafic or ultramafic magmas (some likely scavenged from sulfides in lithospheric mantle e.g. *Zhang et al., E Sci Rev* 2008). The required high-T, low-P melting occurs only in areas of relatively thin lithosphere, and melts access the crust via major faults. This combination of factors is typical of tectonically active craton margins, where most large Ni-Cu-(PGE) deposits are found.

Ultramafic (High-MgO; generally komatiitic to picritic lavas and intrusions) magmas erupt at the surface where plume melting was focused by a transition from thick to thinner SCLM. High-MgO deposits are commonly found in pericratonic basins, which contain the S-rich sediments essential to S-saturation.

Low-MgO mafic (generally gabbro/norite intrusions) systems are also associated with trans-lithospheric faults at cratonic margins, but not with pericratonic basins. They are intrusion-hosted, and occur where magma ascent was hindered by thick crust or a compressive tectonic environment, and melt fractionation and chemical interaction with the lithosphere are enhanced.





The structural role of the SCLM in focusing magma intrusion is clear, but its compositional role is less obvious. The orthodox view is that the SCLM contributes essentially nothing to magmas, and that most mantle magmas are equally endowed in Ni, Cu and PGEs, so the genesis of an ore deposit simply reflects local factors. However, melt modelling does not explain the high PGE levels in some magmas (e.g. Bushveld Complex), or the provinciality of PGE enrichment in both Ni-Cu-PGE and PGE reef deposits. Interestingly, Large Igneous Provinces and komatiites intruded into areas without (ancient) SCLM roots are not known to contain significant deposits.

'Fertile' (mineralised, continental) flood basalts show a distinctive high-Os signature (Fig. 2a) and our isotopic studies show that these LIPs have interacted with ancient metasomatised SCLM, with high Rb/Sr and low Sm/Nd and Re/Os. Several major LIPs yield Re-Os *'isochrons'* reflecting their eruption ages, with initial $^{187}Os/^{188}Os$ below that of the asthenospheric mantle, implying derivation of the Os from older SCLM (Fig. 2b). The SCLM thus may be a critical component in the genesis of Bushveld-type PGE- bearing intrusions.

There is strong evidence that SCLM metasomatised by hydrous melts/fluids above subducting slabs is essential in producing gold-rich (magmatic-) hydrothermal deposits, including Cu-Au porphyries. In seismic images these (and other magma-related) deposits coincide with medium- and lower- velocity SCLM (Fig. 1c). This suggests a model embracing three common features: a mantle source region carrying (Cu-) Au, trans-lithospheric faults, and a tectonic±thermal trigger.

Both the asthenosphere (ca 1ppb Au) and non-refertilised lithospheric mantle are depleted in Au relative to refertilised upper mantle, such as the Lanzo and Ronda peridotite massifs. CCFS research has shown that arc-related mantle near the giant Lihir gold deposit (Melanesia) is metasomatically enriched in Cu and Au, and SCLM xenoliths in China carry up to 14 ppb Au (up to 5 ppm Au in sulfide minerals; see *Research Highlight p. 53*). Mantle gold enrichment can be related to trapping of low-degree melts; gold behaves as an incompatible element during melting. Even such metasomatised SCLM is relatively durable, and may store (Cu-)Au until a later melting event is triggered.

On balance, the evidence supports an important role for the SCLM in the genesis of some types of major ore deposits (Fig. 3). Lithospheric architecture controls the localisation of some types of ore deposits, and some types of magmas have picked up ore-forming components (e.g. diamonds,

Figure 2. Re-Os data for LIPs and other magmas
(a) Re and Os contents of mafic rocks from provinces with known Ni-Cu(-PGE) sulfide deposits (red field) and provinces lacking known deposits (blue field). (After Zhang et al, E. Sci Rev 2008) (b) $^{187}Re/^{188}Os$ vs $^{187}Os/^{188}Os$ in flood-basalt suites. Main figure, log-log scale; inset in linear scale. The 'isochrons' in the inset correspond to (1) Ferrar dolerites; 65.6±0.3 Ma, intercept 0.12843 (γOs = 1.5±0.3), (2) Deccan Traps; 177±2 Ma, intercept 0.125±0.033 (γOs = -0.6±0.26).
Data: CCFS Publication #334, reference [30].

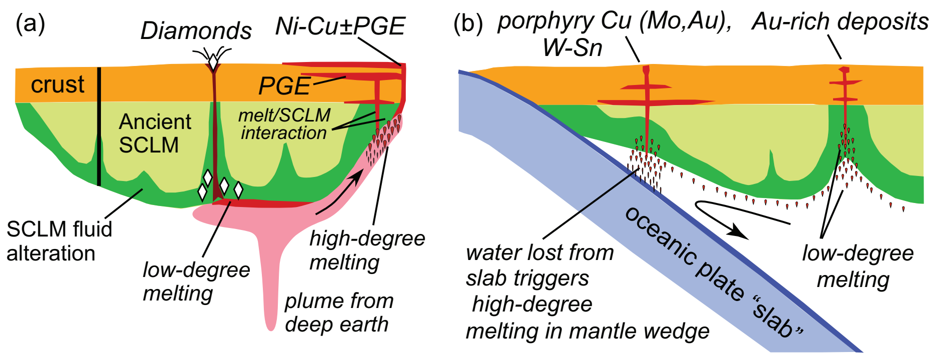


Figure 3. Interactions between magmas and the SCLM.

(a) Plume triggers kimberlite formation and flows to area of thinner SCLM where melting is focused. Variable interaction of melts with crust and SCLM influences Ni-Cu and PGE deposit genesis.

(b) Generalised convergent-margin setting. Au-poor magmatic-related deposits form from dominantly asthenospheric or crustal melts (e.g. Cu-rich or W-Sn porphyry, respectively). Low-degree melting of asthenosphere, particularly in retro-arc settings, can produce Au-rich metasomatic refertilisation of the SCLM. Subsequent melting (which may be much later) contributes Au to magmatic systems, forming deposits of porphyry Cu-Au, Epithermal Au, Iron Oxide Cu-Au, Intrusive-Related Orogenic Au, and possibly also Carlin-type Au and classic orogenic Au.

gold, PGEs) during their passage through the mantle lithosphere. A lithosphere-scale whole-system approach encompassing asthenospheric to crustal processes, with special attention to the structure, composition (fertility) and evolution of the SCLM, can produce better models for deposit genesis, and help build effective exploration models.

This project is part of all CCFS Themes 1, 2 and 3, Early Earth, Earth Evolution and Earth Today, and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Bill Griffin, Graham Begg, Sue O'Reilly

Funded by: CCFS

Youanmi seismic survey a milestone on the quest to unravel the Yilgarn's past

The Neoarchean Yilgarn Craton and the Proterozoic orogens around its margins are one of Earth's greatest mineral treasure troves, including iron, gold, copper and nickel deposits. Although the Yilgarn Craton is one of the best studied Archean cratons, its enormous size and limited outcrop make it hard to understand what controls the distribution of these vast resources and which geodynamic processes were involved the tectonic assembly of this part of the Australian continent.

In 2013, significant steps have been taken to address these outstanding questions, including the release of deep seismic reflection and MT surveys over the Youanmi, South Carnarvon, and Yilgarn Craton–Officer Basin–Musgrave Provinces, the holding of a CCFS project definition meeting, targeted field work in several locations in the Yilgarn Craton, and the planning and partial deployment of passive seismic arrays.

Three individual seismic lines (YU1, YU2 and YU3) and complementary magnetotelluric data were acquired across the northern Yilgarn Craton in 2010. Acquisition, processing and interpretation were managed by Geoscience Australia. The lines cross the northern part of the Yilgarn Craton from the Narryer Terrane in the northwest, across major bounding and internal structures of the Youanmi Terrane and into the Kalgoorlie Terrane of the Eastern Goldfields Superterrane. The north-western end of YU1 is east of the southern end of line CP3 from the 2010 Capricorn seismic survey. The two surveys are linked by the Southern Carnarvon (SC) Basin seismic survey, acquired by Geoscience Australia in 2011. The eastern end of YU2 crosses major structures on the western side of the Eastern Goldfields Superterrane that were also imaged by

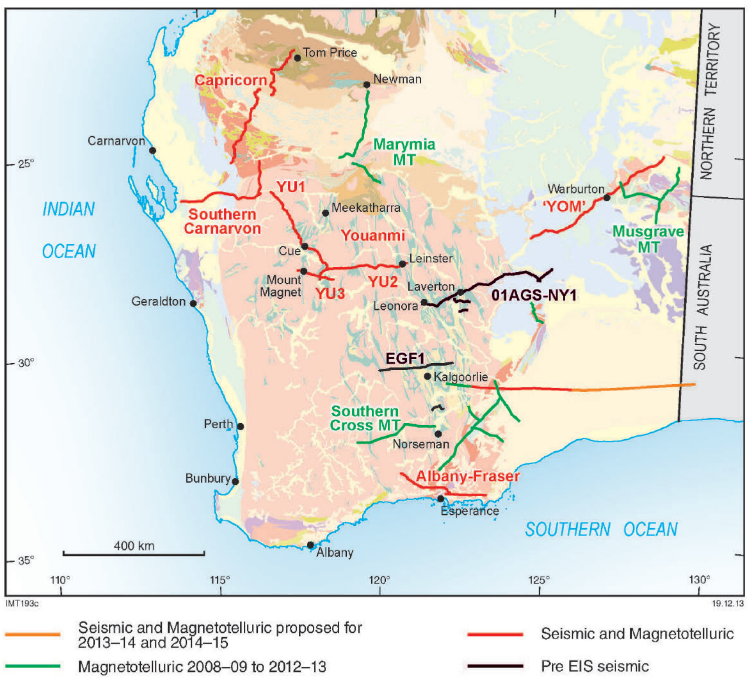


Figure 1. Location of seismic and magnetotelluric surveys funded through the Western Australian Government's Exploration Incentive Scheme (EIS).

Figure 2. Outcrop of Meeberrie gneiss in the Narryer Terrane.

the 2001 Geoscience Australia seismic line (01AGS-NY1), about 120 km to the southeast. The YU, SC and YOM surveys add to the existing network of deep-crustal seismic surveys, and have closed a data gap in the crustal structure of Western Australia, providing a c. 1800 km traverse across almost the entire southern half of Western Australia, from near the west coast to within about 80 km of the border with the Northern Territory.

Nd-isotope data suggest that the Youanmi Terrane has behaved as a coherent crustal block since at least 3000–2900 Ma ago. The Youanmi Terrane is bounded by crustal-scale fault zones that dip away from the nucleus, towards the west and northwest on the northwestern side, and towards the east on the eastern side. The accretion of the Eastern Goldfields Superterrane, which may be either an exotic terrane or an extended margin of the Youanmi Terrane, marked the amalgamation of the composite Yilgarn Craton by about 2655 Ma ago. The Narryer Terrane is generally interpreted to have accreted onto the Youanmi Terrane in the northwest, but further work may be required to better define the nature of the Narryer Terrane–Youanmi Terrane boundary.

In the CCFS Project-definition meeting held on 4 July 2013 at GSWA in Perth more than 20 scientists from within CCFS and collaborating institutions contributed to discussions on the direction of collaborative research on the lithospheric evolution and the related significant mineralisation of the Yilgarn Craton and its margins, specifically on geochemistry and geochronology, geodynamics and modelling, and lithosphere imaging.

It was agreed that to improve the geochemical and geochronological map of the Yilgarn Craton, U-Pb, Hf, and Nd isotope studies should be continued in the NE Yilgarn Craton, and extended to the SW Yilgarn Craton. To determine the relative roles of juvenile mantle and continental lithosphere in mafic/ultramafic rocks it was recommended to collect Os and Nd isotope data to develop a mantle-signature database that will supplement ongoing and future crustal isotopic mapping.

As a priority of geodynamics and modelling it was suggested that previously published geodynamic concepts that have been put forward for the Yilgarn Craton should be tested, starting with relatively well-described events such as aspects of the 2800–2600 Ma tectonic evolution in the eastern Yilgarn Craton.

A craton-scale 3D seismic passive-source deployment was proposed to improve lithospheric imaging. Passive-source techniques such as ambient- noise imaging and receiver-function CCP stacking have intermediate resolution in the crust compared with active-source studies, but unprecedented resolution in the cratonic lithosphere.

The success of the CCFS planning meeting is already evident, as some of the proposed ideas have influenced research proposals, while others have provided direction, focus and context to newly granted projects such as an ARC linkage project granted to the Australian National University and GSWA in 2013. This will fund a three-year passive-array deployment across the south-eastern margin of the Yilgarn. The 2014 deployment of a passive array within the Distal Footprint Science Investment and Education Fund project follows a similar approach for the Capricorn Orogen on the Yilgarn Craton's northern margin.

This project is part of CCFS Themes 1, 2 and 3, Early Earth, Earth Evolution and Earth Today, and contributes to understanding Earth's Architecture.

Contacts: Klaus Gessner (GSWA), Ruth Murdie (GSWA), Huaiyu Yuan (Macquarie)

Funded by: CCFS Foundation Project 10a, Western Australian Government's Royalties for Regions Exploration Incentive Scheme (EIS), Australian Research Council, SIEF

Publication: Youanmi and Southern Carnarvon seismic and magnetotelluric (MT) workshop, February 2013 (preliminary edition) on DigitalPaper: *http://geodocs.dmp.wa.gov.au/search.jsp?cabinetId=1101&Combined=N12BF*

Global komatiite sulfur dioxide degassing and the irreversible change of the late Archean atmosphere

This study has identified sulfur dioxide degassing from komatiite volcanoes as a single process that explains two major heretofore unrelated conundrums about the Archean earth system: (1) why are komatiite-hosted nickel deposits so well endowed? and; (2) why did the mass-independent record of S isotopes suddenly blossom 200 million years before the Great Oxidation Event? Although in hindsight sulfur dioxide degassing is an obvious process to call on, it has never before been proposed. This is because of disciplinary biases. First, the community studying komatiite-hosted nickel deposits focuses on how metals get into such systems, not how sulfur leaves. Second, the community studying mass-independent S isotopes focuses on sedimentary rocks, where signals are assumed to be larger, rather than igneous ones, where signals are assumed to be negligible. It took a strongly interdisciplinary approach to overcome these biases.

Komatiites are the hottest lavas that ever flowed on Earth. Most komatiite lavas erupted at temperatures of 1400-1600 °C as large submarine lava fields, rising from depths of >100 km in the Archean mantle. Upon emplacement, channelised lava flows and subvolcanic intrusions were sulfide-undersaturated and thermo-mechanically eroded their substrates. Through this process, komatiites incorporated sulfur (S) from volcanogenic exhalative sulfide lenses as well as sulfide-rich sediments that occurred close to volcanic vents, inducing the formation of an immiscible sulfide liquid. Elements such as nickel (Ni), copper (Cu) and the platinum group elements (PGEs) originally present in the komatiite magma strongly concentrated into the immiscible sulfide liquid, due to their high affinity for sulfidic and metallic phases. The progressive accumulation of immiscible sulfide liquid at the bottom of lava channels enabled prolonged partitioning of metals into the sulfide liquid from fresh parcels of komatiite magma, forming sulfide metal concentrations of potentially economic interest. However, this model does not explain the extreme variability in metal contents observed among and within different mineralised komatiites.

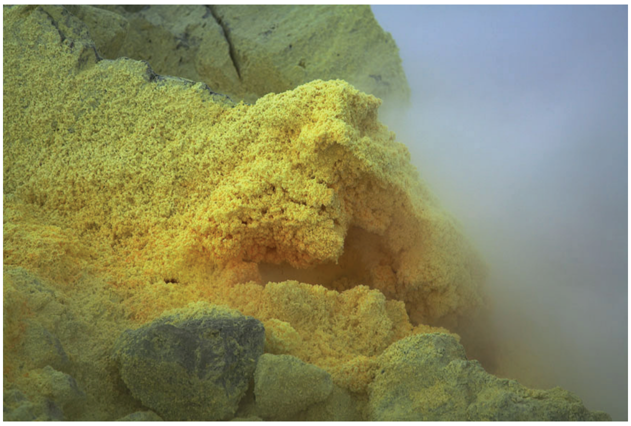
In this study we used sulfur isotope measurements on sulfides from komatiites and local volcanogenic and sedimentary country rocks to show that sulfur degassing was a critical component of the volcanic process. Data from variably mineralised komatiite units in the north Eastern Goldfields, Western Australia, indicate pervasive (>90%) sulfur loss from sulfide-saturated komatiite lavas, dominantly in the form of SO_2 gas. Rapid sulfur degassing associated with such voluminous and cataclysmic eruptions was most likely a contributing factor for economic mineralisation.

In fact, the total mass of Ni-bearing silicate melt that equilibrates with a sulfide liquid is thought to control the tenor of the resulting nickel-sulfide mineralisation. The high Ni tenors of mineralised komatiites seem to verify this proposal, since geological evidence indicates that large amounts of komatiite magmas interacted with relatively small sulfide reservoirs, leading to estimated silicate-sulfide mass ratios (R factors) of ~100-200. However, ~10- to 100-fold enrichments of Ni, Cu, and PGEs in the sulfide liquid are also a natural consequence of the sulfur loss process identified here. We suggest therefore that variable amounts of sulfur degassing may act in concert with elevated R factors to produce the wide range of nickel tenors observed across different komatiite-hosted nickel deposits.

The observed dramatic bloom in the sulfur mass-independent fractionation (S-MIF) record from sedimentary sulfides at ~2.7 billion years ago appears to reflect enhanced input of volcanic SO_2 to the atmosphere. However, the currently proposed volcanic sources of this SO_2 do not begin to dominate the global record until ~200 million years later. Our study identifies a new volcanic pulse of sulfur dioxide that fundamentally restructured the Earth's sulfur cycle in the late Archean and provides a solid geologically based hypothesis for the bloom in S-MIF at 2.7 Ga that contrasts with model-based suggestions of changing CH_4/O_2 ratios at this time. In fact, although komatiite volcanism occurred throughout much of the Archean eon, associated SO_2 degassing was probably maximised during the unique peak in komatiite-hosted nickel-sulfide mineralisation at ~2.7 billion years ago. Given the magnitude and brevity of degassing events associated with komatiite volcanism, we suggest that much of the SO_2 must have escaped direct sequestration in the marine environment, and, as recorded in the S-MIF archive, fundamentally altered the chemistry of the late Archean atmosphere.

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

Contact: Marco Fiorentini
Funded by: CCFS Foundation Project 5



A degassing sulfur cone.

The Earth's thrumming uncovers the northward trek of the Tibetan Plateau

Tibet is a natural Earth laboratory where we can study the dynamics of continental deformation. The growth and maintenance of the enormously thick crust and high topography of this plateau are best explained by the channel flow model, which postulates the existence of a weak layer in the crust beneath the Plateau. Driven by the topographic loading, this weak layer flows to the surrounding areas of the Plateau where the crust is thinner. Geophysical features, including low velocity zones (LVZs) and highly conductive layers in southeastern Tibet, support this model. However, the distribution of LVZs in northern Tibet, which could be used to test the channel flow model, is unknown.

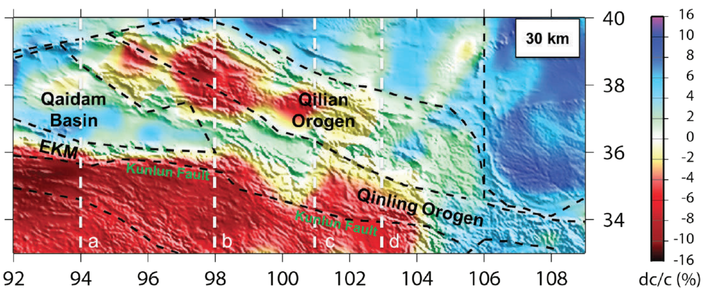


Figure 1. Vsv perturbation map at a depth of 30 km. The dashed lines indicate the four cross sections in Figure 2. EKM: East Kunlun Mountains.

By using ambient noise tomography and probabilistic inversion methods, we have constructed a 3D Vsv model of the north Tibetan crust with a resolution of ~50 km. Our 3D model (Fig. 1, 2) reveals strong LVZs at the middle crust between 20 and 40 km across northern Tibet. The LVZs show significant west-east variations along the Kunlun Fault compared to previous ambient noise tomography. In the western part (Fig. 2 left), LVZs are confined to the regions of the Kunlun Fault and the eastern Kunlun Mountains but are not observed beneath the Qaidam Basin. In the eastern part, beyond the eastern boundary of the Qaidam Basin (Fig. 2 right), LVZs extend and penetrate at least 100 km northward into the east Kunlun and Qinling Orogens. The strong contrast in the distribution of LVZs between the western and eastern parts of the study region mainly results from the distinct tectonic units neighboring northern Tibet. In the west, the strong crust of the Qaidam Basin blocks the penetration of LVZs but the predicted weaker crust in the Qinling Mountains allows the flow of LVZs.

Combined with the observations of strong radial anisotropy in the areas with strong LVZs, the existence of highly conductive layers and the high heat flow in northern Tibet, our Vsv model indicates that crustal channel flow may be occurring in northern Tibet and be responsible for the northward and outward expansion of the Tibetan Plateau. In addition to indicating that crustal flows do exist in northeastern Tibet, the distribution of LVZs from our research also defines the extent of the crustal flow, which is penetrating ~ 100 km beyond the Kunlun fault into the West Qinling Orogen.

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

Contacts: Chengxin Jiang, Yingjie Yang

Funded by: ARC Discovery Project DP120103673, iMQRES Scholarship

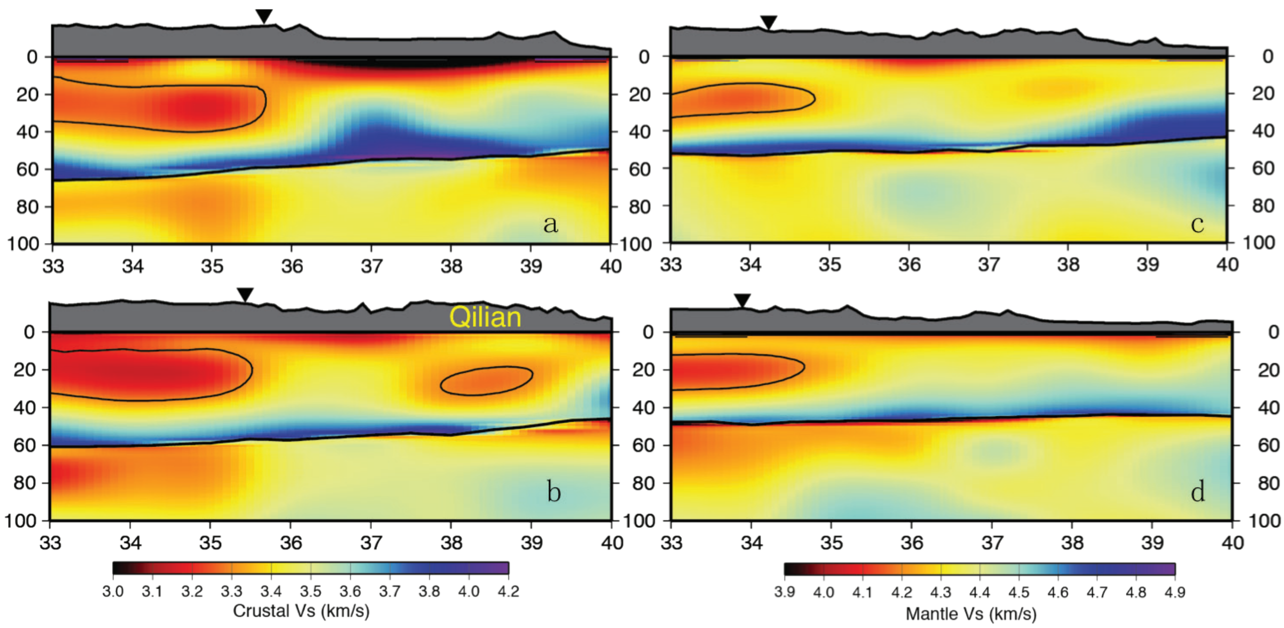


Figure 2. Four cross sections show the distribution of LVZs in north Tibet. All sections are plotted with absolute Vs values.

Microbial feasting on the early Earth

Tiny 1,900 million-year-old fossils from rocks around Lake Superior in Canada give the first ever snapshot of organisms eating each other and suggest what the ancient Earth would have smelled like.

Figure 1. Close up of ~1900 million year old Gunflint chert. The fossils are found in the black zones. Field of view is about 1 m.

While it was once thought that the earliest forms of life were based on photosynthesis from sunlight, much recent work on molecular evolution has shown that the most primitive life forms probably made do without light. Instead of carbon dioxide, such forms are thought to have broken down previously-formed organic matter, in the manner of feeding called '*heterotrophy*'.

It has been more difficult, however, to find ancient fossil evidence for this heterotrophic mode of feeding. Our new research (*CCFS publication #321*) provides both physical and chemical clues to primitive heterotrophy in the ~1900 million year old Gunflint chert (Fig. 1), from the northern shore of Lake Superior.

We examined microscopic fossils (3-15 µm in diameter) from the Gunflint chert with a battery of high-spatial-resolution techniques including nano-scale secondary ion mass spectrometry (NanoSIMS), transmission electron microscopy (TEM) and focused-ion-beam milling combined with scanning electron microscopy (FIB-SEM). We found that one species of microfossil – a tubular form thought to be the outer sheath of a cyanobacterium called Gunflintia – was more perforated after death than other kinds, consistent with them having been eaten by other bacteria. Indeed, in some places, many of the tiny fossils had been partially or entirely replaced with pyrite (FeS_2) resulting from the activities of heterotrophic sulfate-reducing bacteria. We also found that these Gunflintia microfossils carried clusters of even smaller (~1 µm diameter) spherical and rod-shaped bacteria that were seemingly in the process of consuming their hosts (Fig. 2).

Comparable processes of heterotrophic consumption can still be seen going on today. Indeed they can often be detected by the whiffs they give off – because they give rise to the rotten-egg smell of hydrogen sulfide. Recent geochemical analyses have shown that such sulfur-based activities of bacteria probably can be traced back to 3500 million years or so (as we reported in *Nature Geoscience* in 2011). While the Gunflint fossils are only about half as old, they confirm that such bacteria were indeed flourishing by 1900 million years ago. This work also shows that they were also highly particular about what they chose to eat, appearing to prefer to snack on Gunflintia as a '*tasty morsel*' in preference to another bacterium (Huroniospora).

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

Contacts: David Wacey, Mark Barley
Funded by: CCFS Foundation Project 5

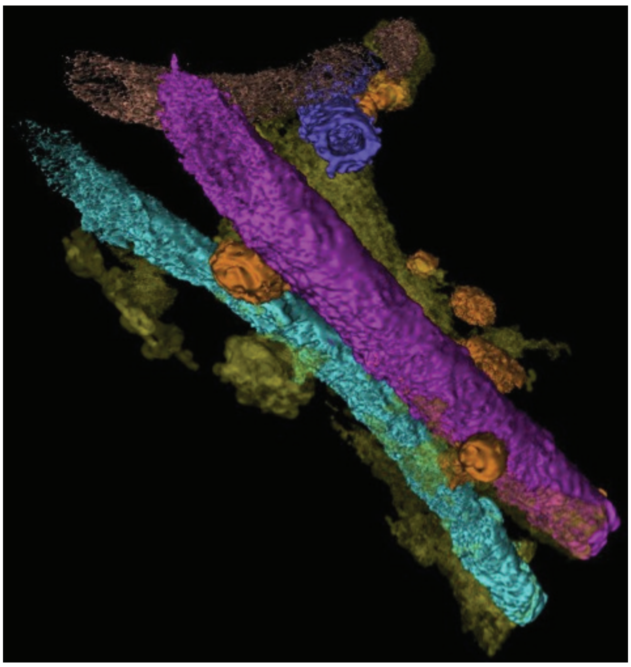
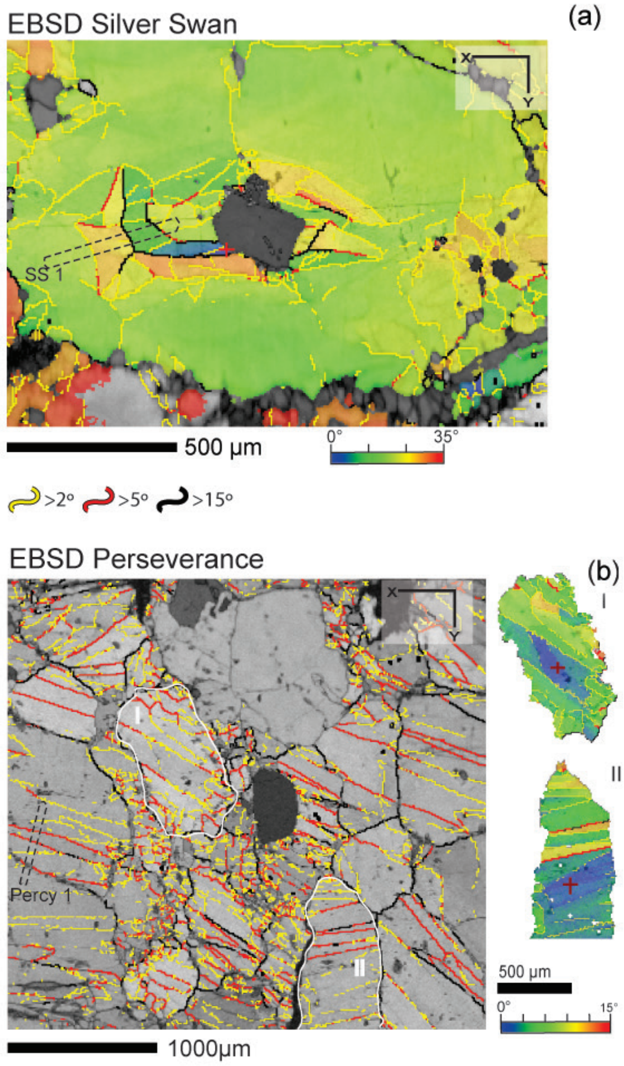


Figure 2. 3D reconstruction of tubular Gunflintia fossils being consumed by heterotrophic bacteria (orange spheres and rod-shapes that are about 1 µm in diameter).

Size matters for ion mobility in deformed Ni-sulfides

Most of the komatiite-hosted sulfide deposits in the Yilgarn craton have experienced some metamorphism and deformation. The signature of such events is well documented for the silicate phases, but what happens in the sulfides is often overlooked. This study focused on the Ni sulfides from three komatiite-hosted deposits: Silver Swan (Black Swan Ni-deposit, Kalgoorlie terrane), Perseverance (Agnew-Wiluna greenstone belt) and Flying Fox (Forrestania greenstone belt). These deposits experienced different degrees of metamorphism and deformation. The Silver Swan ore body recorded the least deformation and reached its peak metamorphic conditions at greenschist facies (*Hill et al. Min. Dep. 2004*) while Flying Fox, the most deformed, reached its peak metamorphic conditions in upper amphibolite facies (*Porter & McKay Econ. Geol, 1981*). This study *(CCFS Publication #373)* characterised the microstructures of three main sulfide phases; pyrrhotite (Fe_7S_8), pentlandite ($(Fe, Ni)_9S_8$) and pyrite (FeS_2). Electron backscatter diffraction analysis (ESBD) showed that pyrrhotite is commonly the most deformed phase. In the Silver Swan sample, pyrrhotite develops strain shadows around stronger pyrite, whereas in the Perseverance sample, pyrrhotite shows systematic parallel low-angle boundaries (Fig. 1a, b). In the Flying Fox sample, pyrrhotite contains deformation twins and strain localisation-induced low-angle boundaries (Fig. 2a). Unlike pyrrhotite, microstructures in pyrite and pentlandite are far more uniform. In all three samples, pyrite shows only minor lattice deformation whereas pentlandite locally develops a few low-angle boundaries.

Understanding the sulfide crystal lattice response to deformation leads to another question – are there compositional effects? We used two types of high-precision *in situ* analytical techniques to determine the trace-element concentrations:



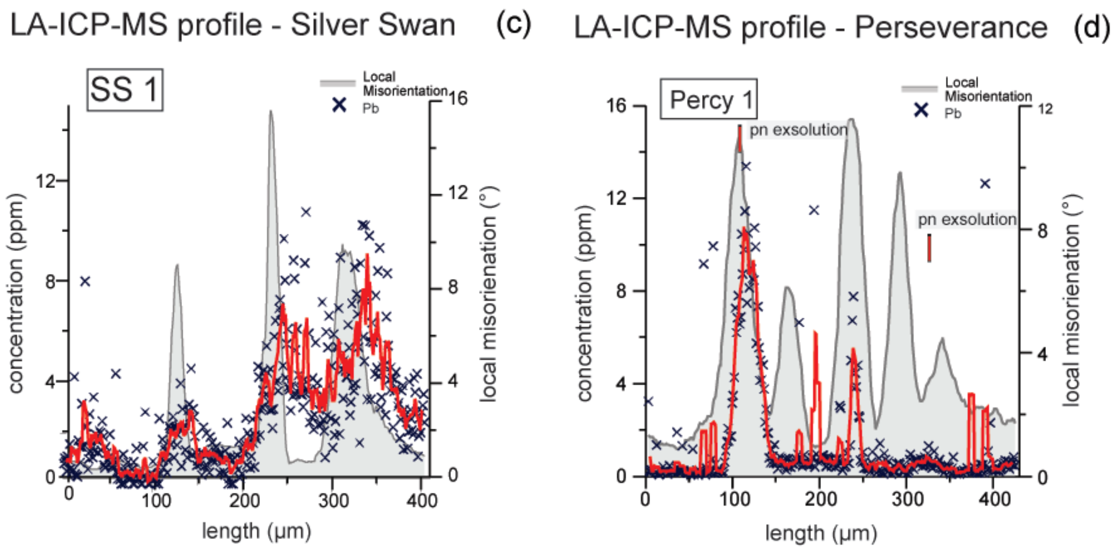


Figure 1. a) Electron backscatter diffraction (EBSD) data of Silver Swan massive sulfide. Band contrast–cumulative misorientation map for the pyrrhotite grain. Black dotted line SS1 shows the position of the ablated area from c). b) EBSD data of Perseverance massive sulfide. Band contrast– grain boundary map for the pyrrhotite grains. Black dotted line Percy 1 shows the position of the element profile from d). EBSD data shown for grains I and II indicate cumulative misorientation from the reference point (red cross). c) Laser ablation ICP-MS Pb profile along line SS1 from Silver Swan pyrrhotite. d) Laser ablation ICP-MS Pb profile along line Percy 1 from Perseverance pyrrhotite. Grey area on both c) and d) corresponds to the maximum local misorientation along the respective profile. Lead is plotted against the length in both c) and d).

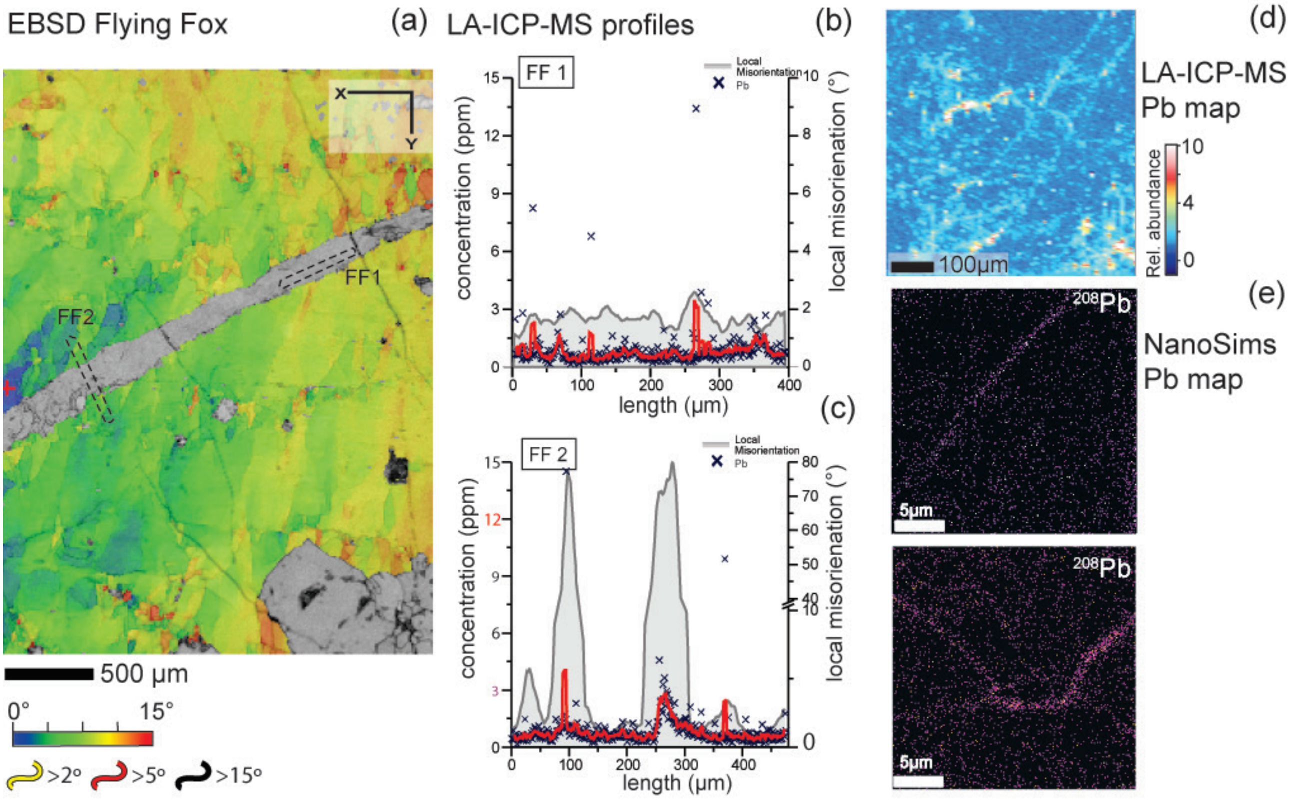


Figure 2. a) Electron backscatter diffraction (EBSD) data for Flying Fox massive sulfide show cumulative misorientation of the pyrrhotite. Black dotted lines show location of the laser profile from b) and c). b) Laser ablation ICP-MS profiles along line FF1 (b) and FF2 (c). Grey area on both b) and c) corresponds to the maximum local misorientation along the respective profile. d) Laser ablation ICP-MS element map for Pb, expressed in relative ppm abundance. e) NanoSims element maps for Pb. For location of the mapped area see CCFS Publication #373.

laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and Nano-scale secondary ion mass spectrometry (NanoSims). Both trace-element profiles and element maps were acquired using LA-ICP-MS (Fig. 1c, d and 2b-e). The results showed that particular trace-elements with large ionic radii (e.g. Pb) are more concentrated along high and low-angle boundaries as well as along twin boundaries (Fig.1c, d and 2b-e). Unlike Pb, the platinum group elements do not show such variations.

Element mapping with NanoSims has advantages relative to the LA-ICP-MS in terms of scale. Using NanoSims, we mapped an area of 25x25 µm around a twin boundary and detected increased values of Pb (Fig. 2e). It is important to note that these variations are not related to the presence of another phase, but only to the presence of particular dislocation arrays.

Two possible scenarios could explain the correlation between trace-elements and microstructures: 1) late hydrothermal fluid interaction with the sulfide phases and 2) intra-grain diffusion. In the first case, late hydrothermal fluids would play a role in introducing the elements (i.e. Pb) through fluid percolation and mineral–fluid reaction along preferential diffusion pathways such as low angle, grain and deformational twin boundaries. However, the hydrothermal fluid would need to be very similar in chemistry for three deposits hundreds of kilometres apart, so intra-grain diffusion seems the more likely mechanism. Intra-grain diffusion can occur during deformation and post-deformation. During deformation, dislocation cores move to form dislocation arrays. While they are moving, they may encounter large ions (i.e. Pb) and carry them along until they form a particular microstructure. In the case of post-deformation diffusion, intra-granular fluid (already present in the system) acts as a carrier and moves these large ions along high-diffusivity pathways (high and low-angle boundaries, and twin boundaries). At the moment we cannot distinguish between the two intra-grain processes.

Variation in trace elements is observed even in the samples from terrains that experienced metamorphic peak temperatures of no more than 350°C. This implies that the large ions still diffuse at relatively low temperatures. This revelation of strong within-grain trace-element variations, in particular for Pb, has huge implications in Pb geochronology. For more details on this work see *CCFS publication #373*.

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

Contacts: Zoja Vukmanovic, Steve Reddy, Marco Fiorentini

Funded by: (in part) CCFS Foundation Project 2

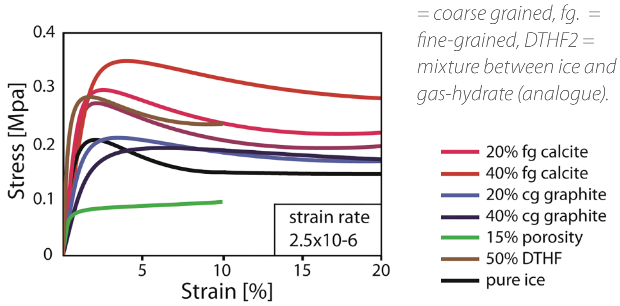
'*Dirty*' ice deformation – a peep-show for revealing properties of flowing rocks

Knowledge of the flow characteristics at the microscopic scale (rheological behaviour) of rock masses in the Earths' crust is essential to the quantitative understanding of plate tectonic processes at the global scale, such as plate movements, mountain building and the break-up of continents. The prediction of rock flow, based on in-depth understanding of the deformation mechanisms in such materials is fundamental to the accuracy of rheological models. Current geodynamic models commonly make the fundamental assumption that the rheology even of polyphase rocks can be approximated by that of a single, monomineralic rock type. However, experiments and field observations show that flow laws from monomineralic materials do not represent the true rheological behaviour of polymineralic rocks. Thus, constraining the rheology of anisotropic and multiphase materials making up the Earth is still a major challenge. Ice mixtures (ice containing another phase) represent such a material, and thus are very good analogues for understanding behaviours of multiphase rocks on Earth.

In nature, a significant percentage of ice is not pure H_2O but contains abundant air bubbles, porous hydrate crystals and second phases such as clays and fine grained rock *'powder'* i.e. *'contaminated/dirty'* ice. In both instances, these impurities may potentially represent the rheologically softest or hardest material. In nature, such *'dirty'* layers may govern movement on the large scale.

This project aims to advance our understanding of anisotropic polycrystalline material with more than one phase by using *'dirty'* ice for deformation experiments conducted at the Australian Nuclear Science and Technology Organisation (ANSTO). It represents a continuation of the pure-ice deformation work performed previously (*Piazolo et al. G3, 2013, CCFS/GEMOC publication number 342/901*).

Figure 2. Stress-strain curve for ice with different second phases, (bottom); cg. = coarse grained, fg. = fine-grained, DTHF2 = mixture between ice and gas-hydrate (analogue).



Our international research team chose to use heavy-water ice as D_2O provides a unique opportunity to use neutron diffraction analysis to simultaneously monitor the flow properties, microstructure and orientation properties of ice. Laboratory-grown polycrystalline *'dirty'* ice samples were shortened up to 20%. The results show that the rheology of ice is highly dependent on the nature of the second phases present, their shape, their relative volume and their grain size. A high proportion of second phases may stop ice from recrystallising and little to no crystallographic preferred orientation is produced. The material behaves like a Newtonian fluid with a linear relationship between stress and strain rate. This is markedly different to pure or near-pure ice, which typically shows an exponential relationship. Air bubbles as well as fluid brine significantly soften the material.

Based on these results, constitutive flow laws are being developed for mixed materials, which will be directly applicable to large-scale modelling of multiphase Earth materials.

This project contributes to the CCFS Goal *"to reach a new level of understanding of Earth's internal dynamics and fluid cycles, and how these have evolved …"* as well as CCFS Theme 3, Earth Today, and contributes to understanding Earth's Architecture.

Contacts: Sandra Piazolo, Daria Czaplinska

Funded by: Bragg Institute, ANSTO, Lucas Heights, ARC DP120102060, FT1101100070

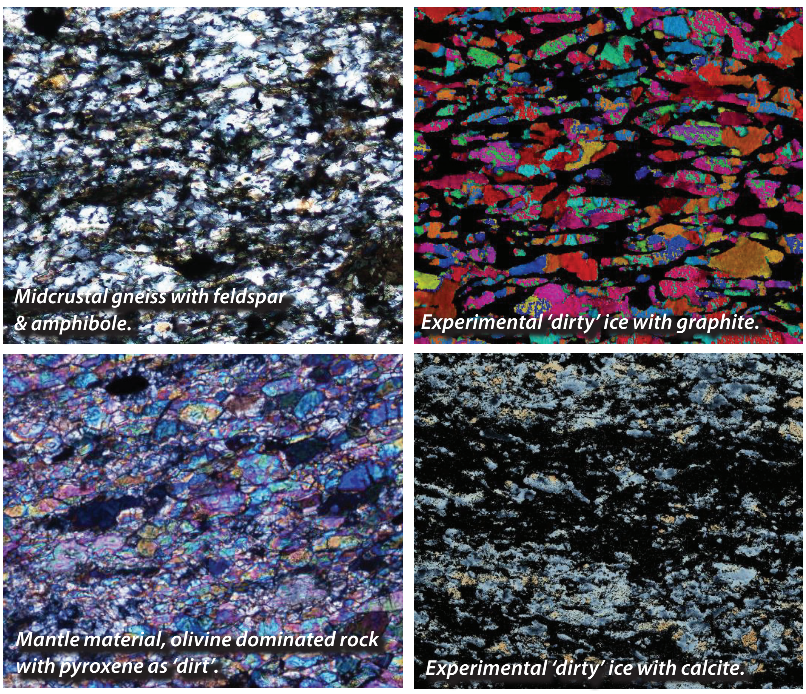


Figure 1. top left; optical photomicrographs of a typical mid-crustal rock - gneiss dominated by feldspar with amphibole as 'dirt'. Plane light, (courtesy of R. Gardner); top right; experimentally deformed D_2O ice with graphite after 10% deformation, cross polars; lower left; typical mantle material - deformed peridotite with pyroxene, cross polars, (courtesy of R. Gardner): lower right; experimentally deformed ice with calcite after deformation 10%, plane light. Field of view is 1 cm.

Mantle oddities: sulfate-dominated fluids in the Earth's mantle

Sulfur is the eleventh most abundant element in the silicate Earth, with an estimated primitive-mantle concentration of 250 ppm. It is a moderately incompatible volatile element that plays a pivotal role in transporting and concentrating chalcophile (= sulfur-loving) metals. In this regard, sulfide melts are enriched in metallic elements and sulfide and bisulfide anions complex with metallic cations dissolved in C–O–H–S fluids. However, the distribution and speciation of sulfur in the mantle remain poorly understood. CCFS Foundation Project 2 has addressed this issue by investigating S-bearing minerals in a global suite of mantle rocks. This has important implications for the formation of melts enriched in S and metals, which are ultimately involved in generating magmatic ore deposits.

Photograph of an off-cut of xenolith sample XM1/498. The off-cut was cut across a layer dominated by K-richterite with minor phlogopite (phl). The layer is pervasively cross-cut by creamy-coloured sulfate-rich veins (from Giuliani et al., 2013).

In the sub-continental lithospheric mantle (SCLM), sulfur is mainly stored in sulfide minerals in the reduced form S^{2-}. Mantle sulfides may have been deposited by immiscible sulfide melts that separated from silicate and/or carbonate melts at mantle depth, from S-bearing C–O–H fluids, and from sulfidation reactions between S-bearing fluids and silicate minerals. It has also been proposed that some sulfide minerals could be residual after the partial melting events that stabilised the lithospheric roots of continents.

In addition to sulfides, sulfur in the SCLM may also occur in the oxidised form SO_4^{2-}, in minerals such as apatite and amphibole, albeit in trace amounts. In addition, anhydrite ($CaSO_4$) has been reported as inclusions in diamond, barite ($BaSO_4$) in Cr-diopside from a peridotite xenolith, and alkali-rich sulfates in carbonate-rich inclusions hosted by ilmenite in a mantle polymict breccia. These occurrences attest to the presence of sulfate minerals in the mantle, even at depths within the diamond stability field (> 150 km). *'Daughter'* crystals of gypsum and barite have been reported in fluid inclusions hosted by mantle olivine, pyroxene and amphibole; this suggests that sulfate (SO_3) may be a more common component of some mantle fluids than previously recognised. The occurrence of sulfate compounds in mantle fluids is further supported by mass spectrometric analyses of crushed mantle xenoliths from southeast Australia, which showed the release of SO_2 during crushing. Finally, sulfates have been identified in metasomatised rocks from the mantle wedges above subduction zones, which are permeated by sulfate-rich oxidising melts.

Sulfates can crystallise from a range of chemically different fluids and are common constituents of carbonatitic rocks. Anhydrite has been shown to crystallise from silicate magmas of intermediate to acid composition. Strontium-rich barite and less commonly alkali-sulfate minerals occur in the groundmass of kimberlites. Celestine ($SrSO_4$) and aphthitalite [$(K, Na)_3Na(SO_4)_2$] have been found in melt inclusions hosted by kimberlitic olivine. Barite is a minor constituent of vein assemblages in mantle MARID (mica-amphibole-rutile-ilmenite-diopside) rocks and may have crystallised from kimberlite-related fluids.

There is also evidence for the occurrence of sulfate-bearing fluids in crustal rocks and documentation of sulfate melts from experimental simulations. However, despite increasing evidence for the occurrence of sulfate melts in crustal rocks, such fluids have never been documented in mantle rocks. Now, the occurrence of Ba-bearing celestine veins that also host abundant clinopyroxene and minor sphene, apatite, pectolite, phlogopite, barite and carbonates, in a mantle MARID xenolith sampled by the Bultfontein kimberlite (Kimberley, South Africa) has been documented (*CCFS publication #333*). On the basis of textures, mineral inclusions and mineral chemistry, and data for Sr and S isotopes in celestine and the other minerals in sulfate veins and the host MARID minerals, we suggest that the sulfate-rich veins were produced in the mantle from interaction between a sulfate-rich fluid and the MARID host rock. These celestine-bearing veins provide the first evidence for the occurrence of sulfate-dominated fluids in the Earth's mantle.

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

Contact: Marco Fiorentini

Funded by: CCFS Foundation Project 2a

The riddle of the origins of zircon in ophiolitic rocks: a case history from the Coolac Serpentinite Belt, southeastern Australia

An increasing number of studies are reporting U-Pb ages for zircons recovered from rocks of the mantle sections of the ophiolitic complexes and host peridotites. Were these zircons crystallised in the mantle from percolating metasomatic fluids or are they xenocrystic relics of crustal material recycled during subduction? What they mean in the framework of ophiolite and exhumed mantle rock genesis and evolution is controversial. The deciphering of this complexity requires integrated datasets that are not confined to zircon U-Pb data alone. Equally importantly, these data are integrated within a comprehensive geological framework. Our study of zircons from the Coolac Serpentinite Belt in southeastern Australia sends a cautionary message to the researchers who use ophiolitic zircon to unravel the past geodynamics of Earth's lithosphere and mantle.

The Coolac Serpentinite Belt (CSB) is part of the Tumut ophiolitic complex in the Lachlan Fold Belt, southeastern Australia (Fig. 1). The 63 km belt contains a high proportion of massive

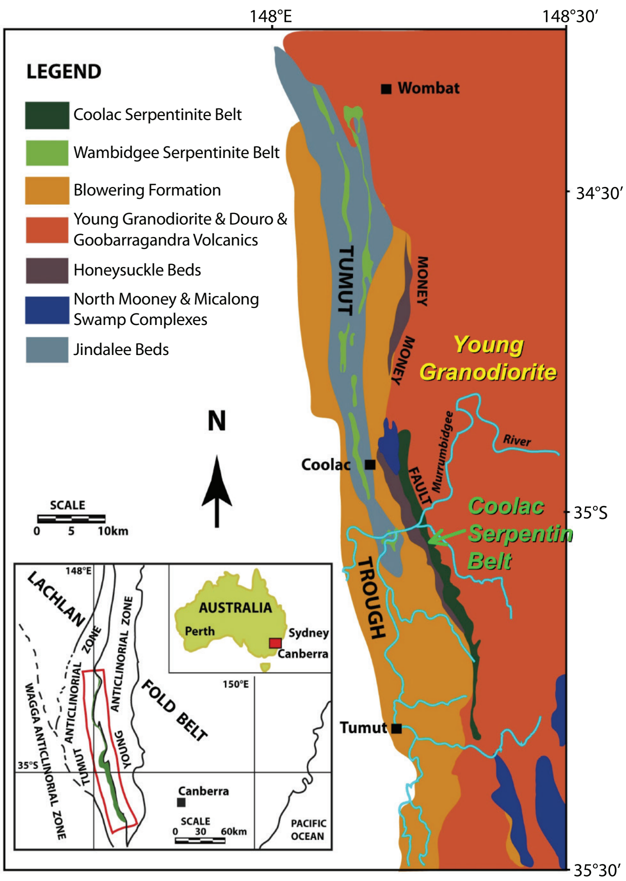


Figure 1. Map shows the location of the Tumut region within the Lachlan Fold Belt: the Coolac Serpentinite Belt (dark green) separates the Tumut and Young zones (after Graham et al., Geology, 24, 1996).

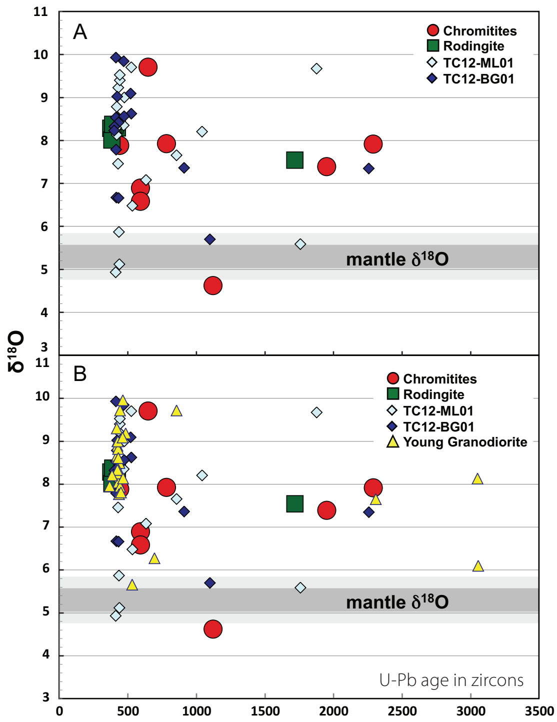


Figure 2. Plots of δ18O versus U-Pb age in zircons from the Coolac Serpentinite Belt, including detrital 'TC' TerraneChron® (A) and comparison of those with zircon from the Young Granodiorite (B). The mantle values of 5.3‰ (Valley, 2003) are shown with 1σ and 2σ deviations as dark and light bands accordingly.

(unfoliated) ultramafic rocks that have undergone lower greenschist-facies metamorphism (e.g. Graham et al., Geology, 24, 1996). New U-Pb, Hf- and O-isotope, and trace-element data have been obtained for zircons from the rocks of the belt. These include zircons separated from two (high-Al and high-Cr) massive chromitites and rodingites in the Coolac Belt, and from detrital zircon grains recovered from gullies draining from outcrops consisting of mainly weakly serpentinised massive porphyroclastic harzburgite. The Belt is either faulted against, or intruded by, the S-type Young Granodiorite. Zircons from the Young granodiorite collected at the contact with the serpentinite belt were also studied to refine the tectonic relation and timing of the granitic magmatism.

The U-Pb age of the zircons from this serpentinite belt display a wide range, from Silurian to Paleo-Proterozoic, with the main age population clustering around 430 Ma (Fig. 2A). This main peak coincides, within analytical error, with the age obtained for plagiogranites from the Belt and with the age of the Young Granodiorite intrusion (427.6 ± 3.2 Ma). Moreover, the ages for the inherited zircon populations in the granodiorite correlate well with the older zircon populations from the Coolac ultramafic rocks (Fig. 2B).

Most of the Coolac zircons have negative εHf and heavy (>6) $\delta^{18}O$ indicative of a crustal origin. Combined with U-Pb age information, this implies that the zircons in the peridotites are xenocrystic (Fig. 2). One possibility is that zircons derived from subducted sediments were incorporated into the ophiolitic rocks as in the Luobusa (Tibet) ophiolite (*Yamamoto et al., Island Arc, 22, 2013*). However, the similarity of the Coolac ophiolite-derived zircons with those from the Young Granodiorite may indicate that they were introduced into the Coolac peridotitic complex during the time of voluminous granitic magmatism that occurred in the region at ca 430 Ma ago. In the latter case, zircons carry no information on the origin of the Tumut ophiolitic rocks and only suggest that Coolac rocks had preceded granitic magmatism of the Lachlan Fold Belt.

Thus, our observations highlight that the collection of integrated information on zircons is critical for the adequate interpretation of the timing of the ultramafic rock formation, emplacement and subsequent tectonic implications in the context of regional geology. In cases of xenocrystic zircons, a clear understanding of their origin and relationships with the host ophiolitic rock would improve the probability of geological meaningful interpretation about the generation of ophiolites, and the subsequent dynamics of mantle-crustal interaction.

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

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Funded by: ARC Future Fellowship, Macquarie University contribution to ARC FF and CCFS TARDIS

Metals flow in mantle streams

The capacity of aqueous fluids to selectively extract metals and incompatible elements from the Earth's mantle and thereby enrich its crust and lithosphere has long been inferred, but has been a challenging problem to investigate experimentally. By adopting an inverse approach, we have avoided many previously encountered difficulties and obtained detailed experimental data on the capacity of aqueous mantle fluids to transport a broad range of incompatible elements and metals. Rather than directly equilibrating water with mantle peridotite, we used a previously studied basanite as a proxy for a H_2O-saturated solidus melt (of peridotite) and determined the compositions of H_2O-rich fluids in equilibrium with the basanitic melt. The experimental conditions were 950-1200 °C and 1.0 to 4.0 GPa. In this way we were able to use mineral/melt partitioning data for the basanite to infer fluid/mineral partitioning for peridotite minerals. Our results were confirmed by one experiment in which we directly equilibrated an H_2O-fluid with a mica-amphibole-lherzolite assemblage.

At the lowest pressure and temperatures investigated (1.0 GPa, 950-1100 °C) H_2O-fluids have a limited capacity to transport most

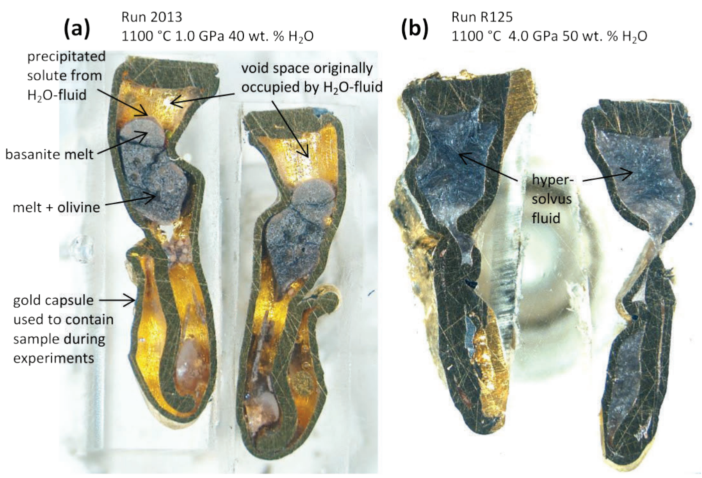

Figure 1. Longitudinal sections of sample capsules after experiments.

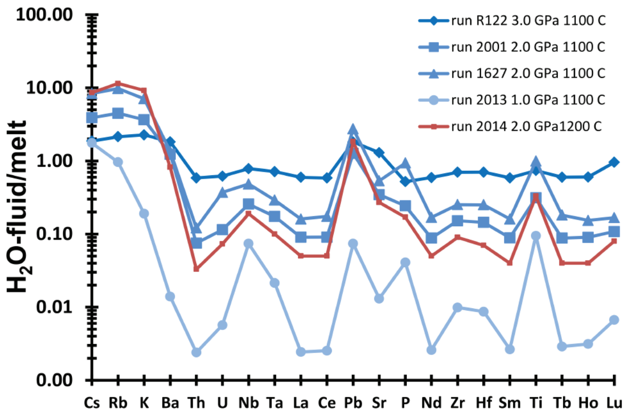

Figure 2. Partitioning of incompatible elements between H_2O-fluids and silicate melts.

incompatible elements and metals (Figs. 1a, 2). But as pressure and temperature increase, the solubility of silicates and metals in H_2O-fluids increases dramatically. By 4.0 GPa there is complete miscibility between the H_2O-rich fluid and silicate melt (Fig. 1b). Relative to coexisting melts, the H_2O-rich fluids are enriched in silica, alkalis, Ba and Pb, and depleted in FeO, MgO, CaO and rare earth elements. Surprisingly they are not especially depleted in high-field-strength elements (Nb, Ta, Zr, Hf and Ti). These features are consistent with currently accepted ideas about the role of both H_2O-rich fluids and rutile in the development of arc magmas. They are also consistent with a role for H_2O-rich fluids in the development of incompatible-element enrichments in some samples of the deep mantle lithosphere as well as the lamproite magmas that bring such samples to the surface.

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

Contacts: John Adam, Tracy Rushmer, Marek Locmelis, Marco Fiorentini
Funded by: ARC CCFS

Supercontinent breakup clues in Yilgarn mafic dykes

The 1.21 Ga Marnda Moorn large igneous province (LIP) in the Yilgarn Craton (Fig. 1) recorded the final breakup of the Nuna (Columbia) supercontinent (see *Research Highlight in CCFS 2012 Annual Report*). However, its petrogenesis has been poorly understood owing to the lack of geochemical data. Now,

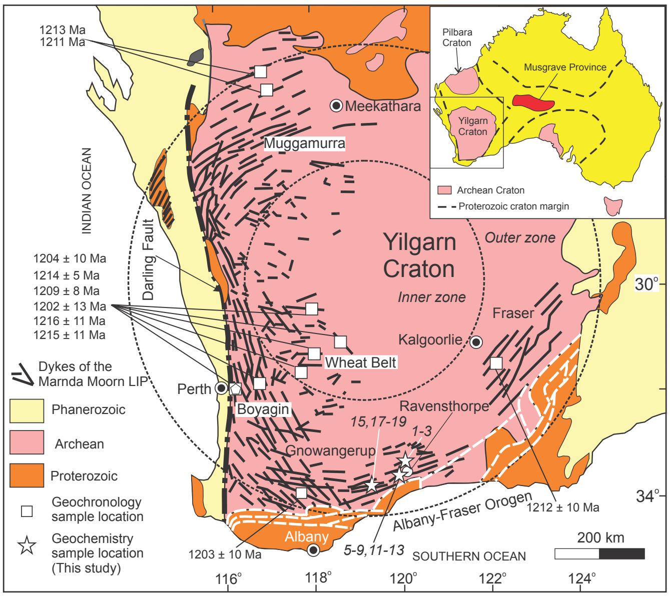

Figure 1. Simplified geology of the Marnda Moorn large igneous province. Thick black lines indicate general dyke trends. The inset map shows the location of the Musgrave Province, where ultrahigh-temperature events occurred at c. 1.21 Ga.

geochemical analyses of the Gnowangerup-Fraser Dyke Suite, a major part of the Marnda Moorn LIP, have begun to fill this gap (*CCFS publication #371*). The dykes are predominately tholeiitic and OIB-like dolerite (Type-1, high Ti), but there is one arc-like and more felsic dyke (Type-2, low-Ti) (Fig. 2). Type 1 samples have incompatible-trace-element compositions similar to those of tholeiitic Hawaiian plume-induced OIB and typical asthenospheric mantle-derived Nd isotopes with εNd(t) varying from +3.7 to +7.5, produced mainly within the spinel stability field (shallower than 75 km). Their source region most probably contains recycled oceanic crust. Samples from the Type 2 dyke have extremely unradiogenic Nd with εNd(t) of about -12, strong depletion of Nb-Ta-Zr-Hf-Ti, chondritic Nb/Ta ratios of 18–20, oversaturated silica, and strong deficiencies in CaO, FeOt, TiO_2, and Ni. This implies that the dyke was produced by partial melting of enriched sub-continental lithospheric mantle. The coexistence of OIB- and arc-like end-members but mainly Hawaiian OIB-like tholeiitic mafic dykes is interpreted to reflect large-scale asthenosphere upwelling in a very short time.

The geochemical and emplacement characteristics are attributed to relief of the lithosphere–asthenosphere boundary across the Yilgarn craton and a complex interplay between the plume, a heated lithosphere, normal asthenosphere, and recycled components. A two-stage melting model can explain the geochemical composition and emplacement of the Marnda Moorn LIP. This involves a mantle plume impinging on the base of the continental lithosphere beneath the Yilgarn craton at about 1.21 Ga. During the first stage, the root of the Yilgarn Craton would have deflected plume materials away from its centre in lateral flows, to pond beneath the cratonic margin. Heat from the underlying plume would enhance partial melting of enriched components of the SCLM to generate Type 2 dykes. At this stage, the recycled oceanic crust (pyroxenite and/or eclogite) would be extensively partially melted, further enhancing lateral flow of the plume materials and leading to significant erosion and destruction of the SCLM. The main phase of the Marnda Moorn LIP (OIB-type tholeiitic mafic rocks) was produced during the second stage by partial melting of ponded plume materials and newly formed pyroxenites, within the spinel stability field. Our plume-lithosphere interaction model is consistent with the occurrence of synchronous ultrahigh-temperature events in the Musgrave Province of central Australia and the large volume of mafic magma in the Marnda Moorn LIP.

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

Contacts: Xuan-Ce Wang, Zheng-Xiang Li, Sergei Pisarevsky, Michael Wingate

Funded by: CCFS, CCFS ARC ECSTAR fund

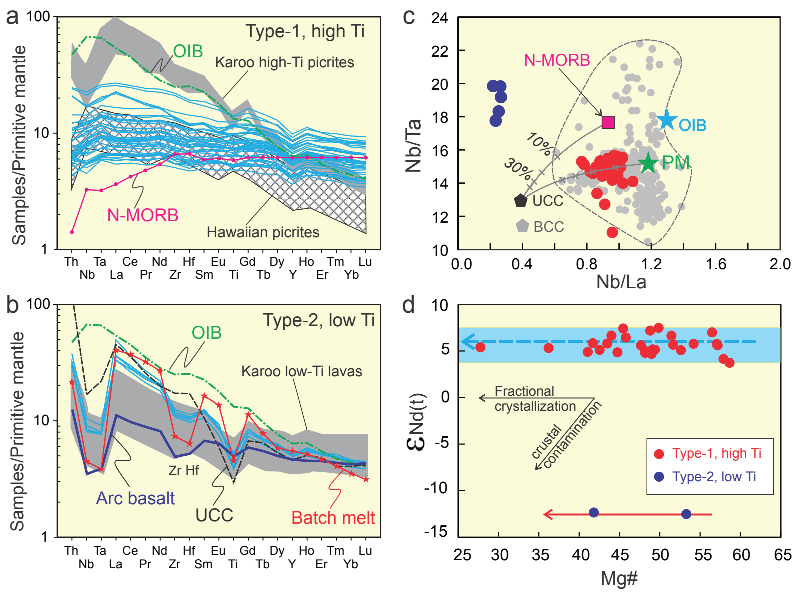

Figure 2. Primitive mantle-normalised incompatible trace-element distribution patterns (a and b) and plots of (c) Nb/Ta versus Nb/La and (d) Nd isotopes against Mg# for the samples of the Gnowangerup–Fraser Dyke Suite from the Marnda Moorn large igneous province.

Zircon: a prime witness to the Moon's early history

The first five hundred million years of Earth's history have seen most of the events that shaped it to its present form, such as differentiation into the core, mantle and crust and the formation of the atmosphere and hydrosphere. Unfortunately the later tectonic and hydrologic modifications of our planet have erased most records of these early events. The very early history of Earth is now only preserved in tiny zircon grains that survived the ca four billion years following their formation. However, due to their rarity and size they can provide only a glimpse of the early conditions on our planet. In contrast, the Moon was only geologically active for only about 1.3 billion years after its formation; the most recent basalt is about 3.2 billion years old. Therefore lunar rocks can reveal the early history of both Moon and Earth.

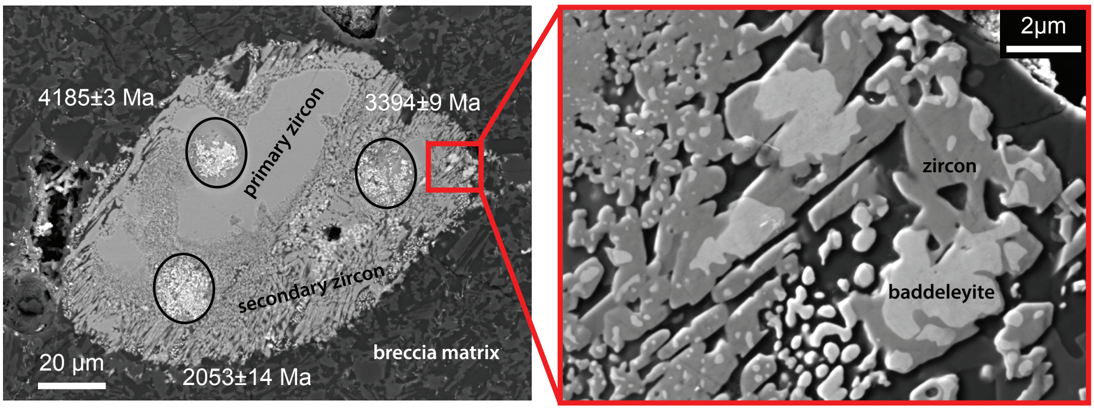

Figure 1. Left, is a back-scattered image of zircon from Apollo 15 breccia – circles indicate location of U-Pb analyses, with corresponding ages (Ma = million years). Right, a magnified view showing the relationships between zircon and baddeleyite in the zircon rim.

As on Earth, lunar zircon can be used for Uranium-Lead (U-Pb) dating, to give a timeline of early events in the differentiation of the Moon. In addition, zircon is chemically and physically robust: it can also survive meteoritic impacts and hence provide useful insight into the bombardment history of the early solar system. Our research focuses on deciphering both magmatic and impact features within tiny zircon grains to understand how these features affect their crystallography and chemistry and whether they can be used to date specific magmatic and impact events.

Since its formation, the Moon has been bombarded by countless meteorites, so that the lunar surface consists of a thick regolith covering the magmatic basement. Lunar zircons are found in impact breccias: mixtures of different rock and mineral fragments (clasts) welded together by impact-generated melts. Some zircon grains fortunately are found within their original magmatic rocks, which occur as minute clasts (up to a few centimetres) in the breccia. Lunar zircons can be classified into groups based on (i) their textural relationships with surrounding minerals in the host breccias, (ii) their internal microstructures as identified by small scale imaging and (iii) their U-Pb isotope systems as analysed in-situ by ion microprobe. Primary zircon has a magmatic origin and is unzoned or has sector and/or oscillatory zoning as identified in cathodoluminescence images. Its U-Pb age is concordant and consistent across its polished surface. Secondary zircon formed during an impact and usually shows internal structures overprinting primary features. Recrystallised or amorphous domains often yield internally consistent and close to concordant U-Pb ages that can be interpreted as dating impact events. Crystal-plastic deformation, planar deformation features and fractures, however, provide channels for Pb diffusion and result in partial resetting of the U-Pb isotopic systems.

A particular zircon with a complex structure was identified in one impact breccia sampled during the Apollo 15 mission. It has primary features preserved in its inner part while its outer rim has been transformed under high pressure and temperature during an impact. The inner part of the grain is crystalline and undeformed. The outer rim of the zircon is made of small zircon and baddeleyite (zirconium oxide) grains, formed by the breakdown of zircon [zirconium silicate] to baddeleyite and silica at pressures above 60 GPa and temperatures close to 1700°C, during impact. The age obtained for the primary inner core of the grain, although discordant, is in agreement with the age of other primary zircon grains from the same sample, at 4.33 billion years. This represents the age at which the zircon crystallised from a magma. The two other ages obtained on the outer rim of the grain are much younger and consistent with an impact that occurred 1.94 billion years ago. This zircon grain demonstrates that very small-scale microscopic imaging and precise in situ ion-probe dating can provide a wealth of information on the overall history of the Moon, and hence the Earth (see *CCFS Publications #374, 423*).

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

Contacts: Alexander Nemchin, Marion Grange

Funded by: CCFS, ARC Discovery Project #120102457 (Nemchin-Grange)

Detecting diamond distillation of nitrogen – frontiers of quantifying nitrogen mantle behaviour

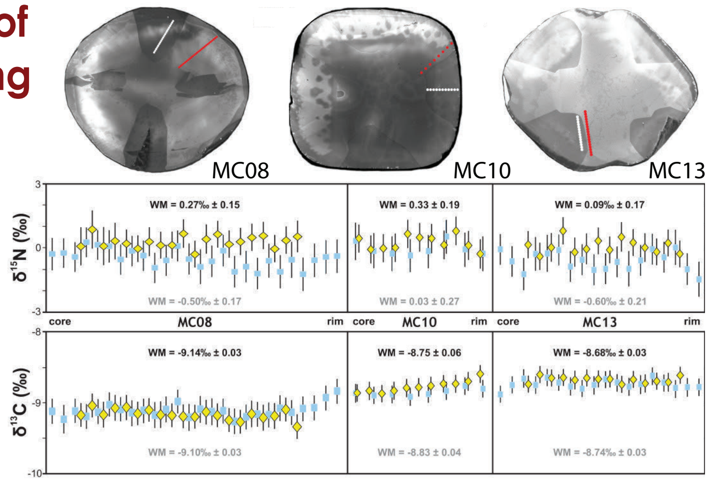

Figure 2. CL images of the three samples analysed by SIMS, showing where the data were collected. Red and white dots show analyses in the cuboid and octahedral sectors respectively. Each transect was repeated but slightly offset to obtain both C and N isotopic analyses. The data from both transects (Yellow diamonds = octahedral data, Blue squares cuboid data) are shown on the same graph, along with the weighted mean value (WM), to allow for easy sector comparison.

Nitrogen is the most common impurity in diamonds, and the properties of nitrogen in the diamond lattice are an important part of standard diamond classification. Traditionally, the isotopic characteristics of this nitrogen have been analysed by bulk combustion methods. When modern *in situ* methods (secondary ion mass spectrometry, or SIMS) were first applied to carbon-isotope analysis of diamonds, it became obvious that bulk analysis is of limited value as it provides an averaged value, hiding the real variations in C-isotope composition that can be present in a single diamond. This is unfortunate, because these variations carry very interesting stories about the origins and growth histories of diamonds; we could expect similar revelations from *in situ* analysis of N isotopes in diamonds. However, until recently SIMS analysis of nitrogen isotopes in diamond has faced large uncertainties due to issues with the methodology and the need for isotopically homogeneous reference material.

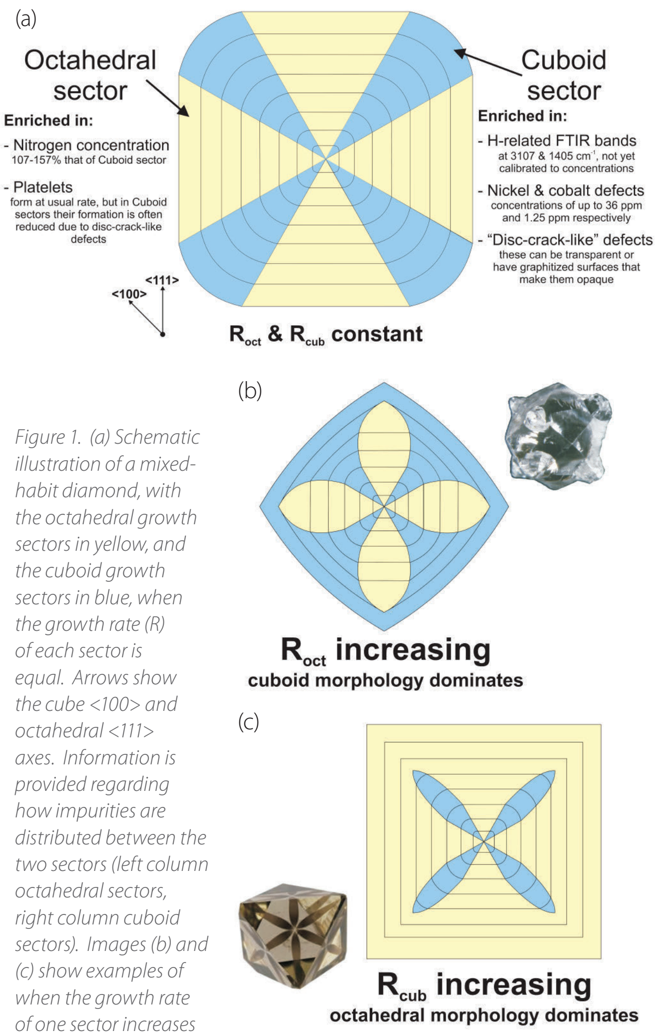

Figure 1. (a) Schematic illustration of a mixed-habit diamond, with the octahedral growth sectors in yellow, and the cuboid growth sectors in blue, when the growth rate (R) of each sector is equal. Arrows show the cube <100> and octahedral <111> axes. Information is provided regarding how impurities are distributed between the two sectors (left column octahedral sectors, right column cuboid sectors). Images (b) and (c) show examples of when the growth rate of one sector increases relative to the other. Inset are images of natural examples of these (courtesy of Tappert et.al. 2011 and G.M. Pearson).

There have been two principal goals of this research (part of Foundation Project 8) that has the overarching goal of understanding the nature of deep Earth fluids. The first was the development of a suitable standard reference material for carbon and nitrogen isotopic analysis of diamond via SIMS in collaboration with Dr Richard Stern and Professor Thomas Stachel of the Canadian Centre for Isotopic Microanalysis (CCIM) at the University of Alberta. The CCIM is leading SIMS analysis of diamonds, and this expertise and knowledge is being used to establish such methodologies at the CCFS SIMS (CMCA) facility in UWA (see *Technology Development* section). The second goal of this work is to investigate the relationship between the nitrogen isotope systematics and the crystal growth mechanisms of diamond. In particular, we want to look at the relationship of these two and what roles they play in the growth of mixed-habit diamonds. This type of diamond has been the focus of some of the diamond research being carried out at CCFS (*CCFS publications #178, 180, 332*). They are unique crystals that exhibit periods of growth in which two competing growth mechanisms were occurring at the same time. These two growth mechanisms produce the characteristic smooth, flat octahedral growth, and the hummocky, rough cuboid growth (Fig. 1).

SIMS analysis of three previously-studied mixed-habit diamonds at the CCIM has shown that on the millimetre scale, the samples are homogeneous in terms of their carbon and nitrogen isotopes (Fig. 2). They therefore represent ideal standard reference materials for this type of analysis. The methodology that has been developed produces data with 2σ uncertainties of ~ ± 0.7 ‰ for $\delta^{15}N$ measurements. This is much better than the uncertainties of ± 8 ‰ that have been reported for $\delta^{15}N$ data from SIMS by other researchers in the past. Interestingly for the investigation of mixed-habit growth, all three samples show slightly elevated $\delta^{15}N$ values in the octahedral sectors compared to the cuboid ones (although this is only above uncertainty in two of the samples). This small fractionation is in stark contrast to that seen in synthetic diamonds, where the cube sectors have are $\delta^{15}N$ values that are 30 ‰ higher than the octahedral sectors. This work is showing an understanding of the growth mechanisms involved as well as the underlying crystallography is essential to interpreting and drawing conclusions from such commonly used data. Understanding isotopic distribution and possible fractionation is a first step in understanding the origin and significance of nitrogen in the mantle, especially the relative contributions from recycled and primordial sources.

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

Contacts: Dan Howell, John Cliff, Bill Griffin

Funded by: CCFS Foundation Project 8

Stretching, pushing or something else: A memory fragment in a continent lithosphere recalls its tectonic history

A link between the deformation of the upper mantle rocks and the directional dependence (anisotropy) of seismic wave speed is one of the mainstays of the modern structural seismology toolkit. It provides a means to '*see*' processes at depth that are suggested by observations of plate motion, by differences in absolute wave speed inferred from tomography, and by scenarios of past tectonic evolution. However, interpretations of seismic anisotropy beneath continents are challenging, because the peridotites that make up both the lithospheric mantle and the asthenosphere beneath it are likely to become anisotropic under strain. The early debates over where the anisotropy resides, and whether it reflects present or past deformation (Fig. 1), have been largely settled by the recognition that both volumes of olivine-rich rock will likely have systematic texture imparted onto them by past tectonic events and/or current plate motion, or both.

We have developed high-quality constraints on the vertical and lateral variation in anisotropy at three locations in eastern North America (NA), which we could then compare with structure predicted for this region by the large-scale NA surface wave model of Yuan and Romanowicz (*Nature, 466, 2010*). We use a combination of two complementary techniques, an anisotropy-aware receiver functions (RF) analysis and an inversion for multiple layers of anisotropy on the basis of directionally variable shear-wave. Compared with the regional surface-wave model, these two methods are capable of resolving anisotropy structure at the station scale. The combination of these two techniques is complementary because P-S mode conversion is primarily sensitive to vertical gradients in properties while birefringence in SKS phases is an integral measure of anisotropic properties along their near-vertical paths (Fig. 2).

Our findings are summarised in Figure 3, focusing on anisotropic symmetry axes predicted by SKS and RF observations at three stations, and fast axis directions predicted for the lithosphere and the asthenosphere in the surface wave continent-scale model. On the basis of the close agreement we see in the orientations of fast directions at different depths, we define two distinct anisotropic layers in the upper mantle: an upper lithospheric layer with a fast direction ~120° SE (Fig. 3a) and an asthenospheric layer with a fast direction ~50° NE (Fig. 3b). This is especially pronounced in the strength of anisotropy predicted

WHERE DOES SEISMIC ANISOTROPY RESIDE?

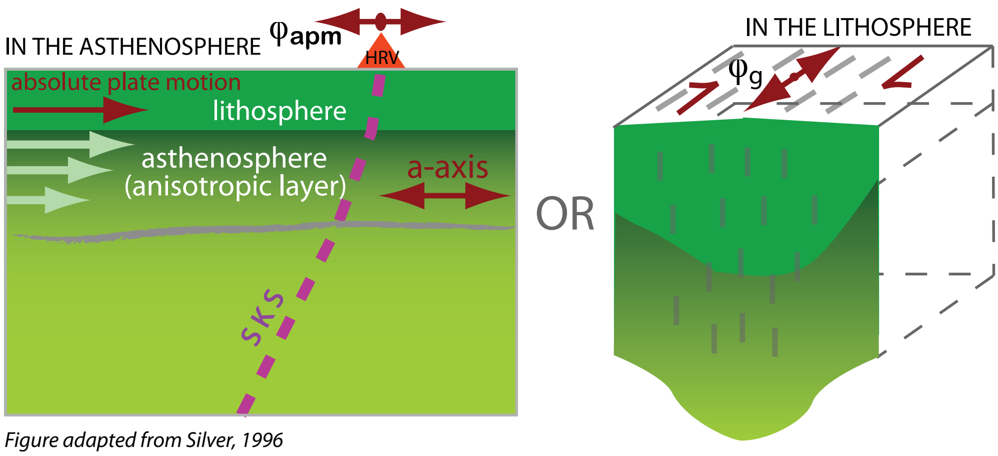

Figure adapted from Silver, 1996

Figure 1. Vertical variation of anisotropy in the shallow upper mantle. If anisotropic properties are restricted to a single layer (either frozen into the lithosphere or formed in the asthenosphere by current mantle flow), we can use observed polarisation of split shear waves as a representation of the past deformation (in the lithosphere) or current deformation (in the asthenosphere). φapm and φg: apparent fast axis directions inferred from SKS.

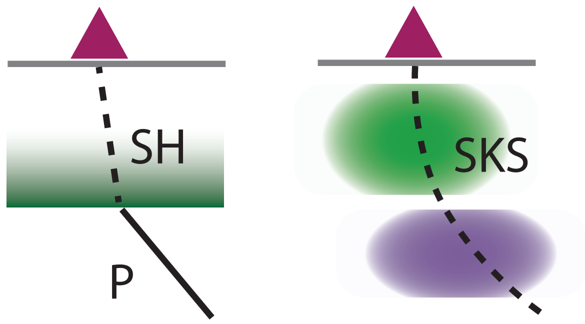

Figure 2. Depth sensitivity illustrated for receiver function analysis (left) and SKS modeling (right). Dashed lines indicated the shear wave (P-SH and SKS) paths. Preferred anisotropy depth distribution (shaded) is inferred from this study.

in the lithospheric part of the *YR2010* model, which becomes progressively smaller inward from the coast. Nevertheless, the differences between these two layers are significantly stronger than the internal variation within each.

The close alignment of fast directions in the asthenosphere with the absolute plate motion (APM) vectors was anticipated. In eastern NA our observation favours the APM directions. Their apparent directional mis-match with the predictions of the YR2010 model or the APM direction is attributed to relatively small-scale lateral variation in upper mantle velocity (Fig. 3c). On the other hand, the inferred fast axis direction in the lithosphere is at a high angle to the strike of major tectonic units in the Appalachians, and is nearly identical over a broad region. This suggests that a regional deformation event affected a large area of the present-day northern Appalachians.

Several possible tectonic episodes in North America's history could have imparted the NW-SE oriented fabric to its mantle lithosphere. Deformation related to the assembly of the Appalachians from a set of terranes is not a plausible candidate. Numerous studies note near-parallel directions of tectonic units in compressive ('*pushing*') orogens and the fast direction of anisotropy, and have argued for orogen-parallel flow. Similarly, it is difficult to relate the broadly distributed sub-horizontal deformation to the rifting ('*stretching*') of the Atlantic, which was highly focused in the area presently offshore.

A scenario ('*something else*') that may explain the observed lithospheric anisotropy would involve the loss, on a regional scale, of the lower part of the lithosphere. This episode has to occur after the assembly of the Appalachians, to impact all the terranes involved. We considered a possibility of viscous instability that would lead to the development of '*stretch marks*' in the depth range where the lithosphere detaches. Given the broad areal extent of the lithospheric fabric, we believe that a '*delamination*' sensu stricto may be more probable.

The technique designed (*Yuan and Levin, JGR submitted*) serves as a toolkit that can be easily applied to Western Australia, which will pin-point the anisotropic lithospheric structure beneath local stations, complementary to a large-scale 3D tomographic inversion that is currently under development.

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

Contact: Huaiyu Yuan
Funded by: CCFS foundation project 10a, 3D Architecture of the western Yilgarn Craton

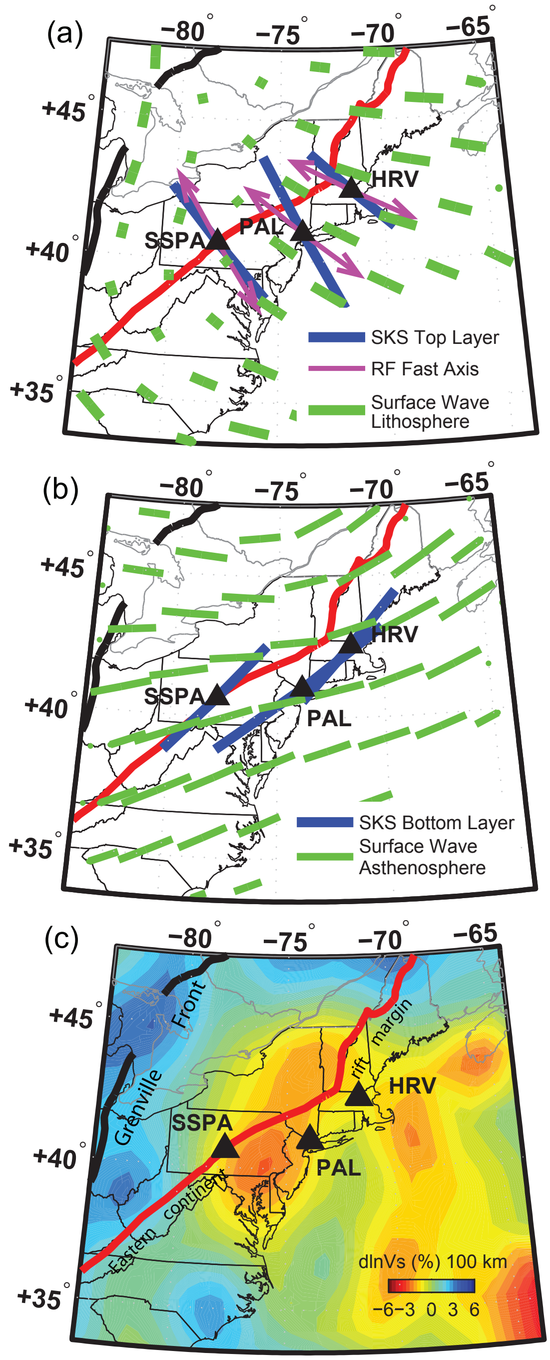

Figure 3. Map view showing the two-layer modeling results for the top layer (a) and bottom layer (b). The lithosphere anisotropy direction inferred from transverse receiver functions is also plotted as arrows in (a). Green sticks in (a) and (b) are equivalent two-layer (lithosphere and asthenosphere) model predicted from the 3D azimuthal anisotropy model of YR2010 model, maximum 1 s in the bottom layer). (c) Vs variation from Yuan et al. EPSL 2013 (http://dx.doi.org/10.1016/j.epsl.2013.11.057).

Mantle's golden secrets sparkle

The upper mantle (convecting and lithospheric) plays an important role in the formation of major metallic ore deposits (e.g. Ni, Cr, diamonds; *CCFS publication #207*). However, the role of the mantle in the genesis of gold deposits is poorly defined and still widely debated. This is primarily because the ultra-low concentrations of gold in mantle rocks are very difficult to analyse.

The state-of-the-art instrumentation at CCFS has allowed us to tackle this problem from a new perspective. We have analysed the sulfide minerals, which naturally concentrate gold, in several suites of mantle peridotite (olivine-rich) xenoliths. These data can then be combined with the well-characterised alteration history of the samples to develop a model for how gold concentrations are modified during mantle processes. We also have compiled a large database of whole-rock gold analyses in mantle samples from the literature to compare with our analyses.

Our data indicate that gold concentration in the upper mantle is very heterogeneous. This is confirmed by a meta-analysis of the literature data. This heterogeneity is present on fractal scales. Using our techniques, we can observe it between grains hosted in a single sample, but it also occurs between samples from a single suite, and between localities globally.

The variation in gold contents shows a strong relationship with the degree of metasomatism the sample has experienced, as defined by rare earth element (REE) characteristics (Fig. 1). This relationship holds true using both our *in situ* analyses and in the compiled whole-rock dataset. The samples that show the *least* interaction with metasomatic agents (i.e. the samples with the lowest La/Yb ratios) have the *greatest* heterogeneity in the Au content, both among their individual sulfide grains and between xenoliths. Conversely, the samples that show strong interaction with metasomatic agents (i.e. samples with high La/Yb ratios) have relatively homogeneous gold contents among their individual sulfide grains as well as between samples. These strongly modified samples also typically have the lowest gold concentrations.

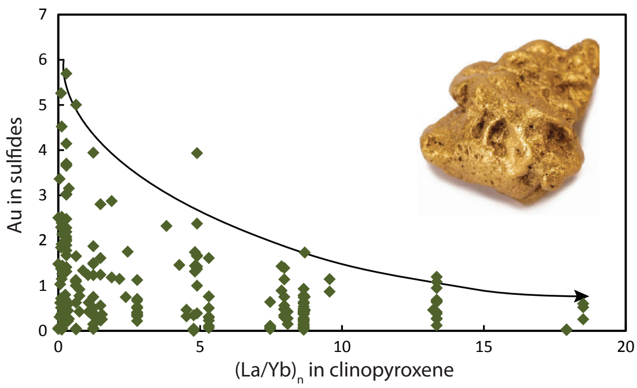

Figure 1. Au content in sulfides versus $(La/Yb)_n$ in coexisting clinopyroxene. Higher La/Yb ratios in clinopyroxene is indicative of a greater fluid flux. The samples that have experienced the greatest interaction with fluids have the lowest and the most homogenous gold contents.

This homogenisation and reduction of gold concentrations during metasomatism indicates that the samples that have experienced a high fluid flux have fully re-equilibrated with the metasomatic agent. During this process, gold has partitioned into the fluid phase and been partially removed from the system, resulting in overall lower gold concentrations. On the other hand, small fluid fluxes may introduce new sulfides into the samples but leave the previous generation of sulfides unmodified. As a result these '*unmetasomatised*' samples contain both residual and metasomatic sulfides.

These results have several major implications. Firstly, it indicates that gold is likely to be removed rather than added during major metasomatic modifications of the upper mantle. Contrary to what has previously been suggested, it is unlikely that there are regions of '*gold-rich*' metasomatised upper mantle.

Secondly, the heterogeneity of the sulfide phase in the otherwise '*unmetasomatised*' samples has implications for Os-isotope studies. Many previous studies have used whole-rock analytical techniques to determine the age of depletion of mantle samples. To exclude the effects of metasomatism, these studies often look at the REE characteristics of the samples and pick those that are '*unmetasomatised*'. This study shows that these are the samples that are likely to have the greatest mixture of sulfide generations, and thus whole-rock techniques will not give a reliable age of depletion.

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

Contacts: Ed Saunders, Norman Pearson, Sue O'Reilly, Bill Griffin

Funded by: ARC CoE CCFS Foundation Project 1 (TARDIS); APA, MQPGRF

How 'super' was Nuna?

There has been a growing interest in the proposed pre-Rodinian supercontinent, variously called Nuna, Columbia, or Hudsonland. One of the main geological arguments used for this hypothesis is the presence of 2.1–1.7 Ga orogens in most continents around the world, which might have resulted from the assembly of this supercontinent. However, most reconstructions are highly speculative, mainly due to the lack of adequate high-quality paleomagnetic data to provide independent constraints. Our latest synthesis of paleomagnetic and geological data suggests that most of the 2.1-1.7 Ga orogens may have been related to the initial stage of a longer assembly process, during which some major building blocks of Nuna were formed. Those included: (i) West Nuna (Laurentia/Greenland, Baltica, Cathaysia, Rockall and possibly India); (ii) East Nuna (North, West and South Australia, Mawson Craton of Antarctica and North China) and (iii) Siberia and Congo-São Francisco cratons. According to our model, these three blocks amalgamated into a single supercontinent (Nuna) between 1.65 and 1.58 Ga. There were also some other continents, such as Amazonia/West Africa and Kalahari, which may or may not have been parts of the Mesoproterozoic supercontinent. Nuna may have broken apart at ca 1.45–1.38 Ma by the separation between Australia/East Antarctica and Laurentia. However, West Nuna, Siberia and possibly Congo/São Francisco were rigidly connected until after 1.27 Ga. The exact timing of their breakup is still uncertain.

Using a multi-disciplinary approach, we produced the first continuous global palaeogeographic animation for the half-billion years between 1.77 and 1.27 Ga (*CCFS publication #309*). Although our model may not be a unique solution, it is paleomagnetically permissible and is supported by a range of geological data. For example, reconstructions at 1.58 and 1.5 Ga (Fig. 1) demonstrate that the proposed position of the Mesoproterozoic mantle plume in South and West Australian cratons is in accord with a suggested hot spot track *(Betts et al., Terra Nova 2007)*. The connection between Siberia and Congo/São Francisco is supported by the recently discovered matching 1.505 and 1.38 Ga dyke swarms in these continents *(CCFS publication #221)*. The suggested time of the collision between East and West Nuna reflects the coeval orogenic events in western Laurentia and Northern Australia. Their separation may be related to the formation of the Belt-Purcell Basin in North America. The positions of parts of Australia and North China have been established in previous publications *(CCFS publications #117, 197)*. Connection between India and Baltica is also supported geologically *(CCFS publications #195, 309)*. The relative positions of Laurentia, Baltica and India suggest a long-lived Mesoproterozoic active oceanic margin along their common ocean-facing edge (Fig. 1). Geological evidence for such a margin is found in all three continents (e.g. *CCFS publications #195, 309*).

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

Contacts: Sergei Pisarevsky, Zheng-Xiang Li

Funded by: CCFS Foundation Project 6

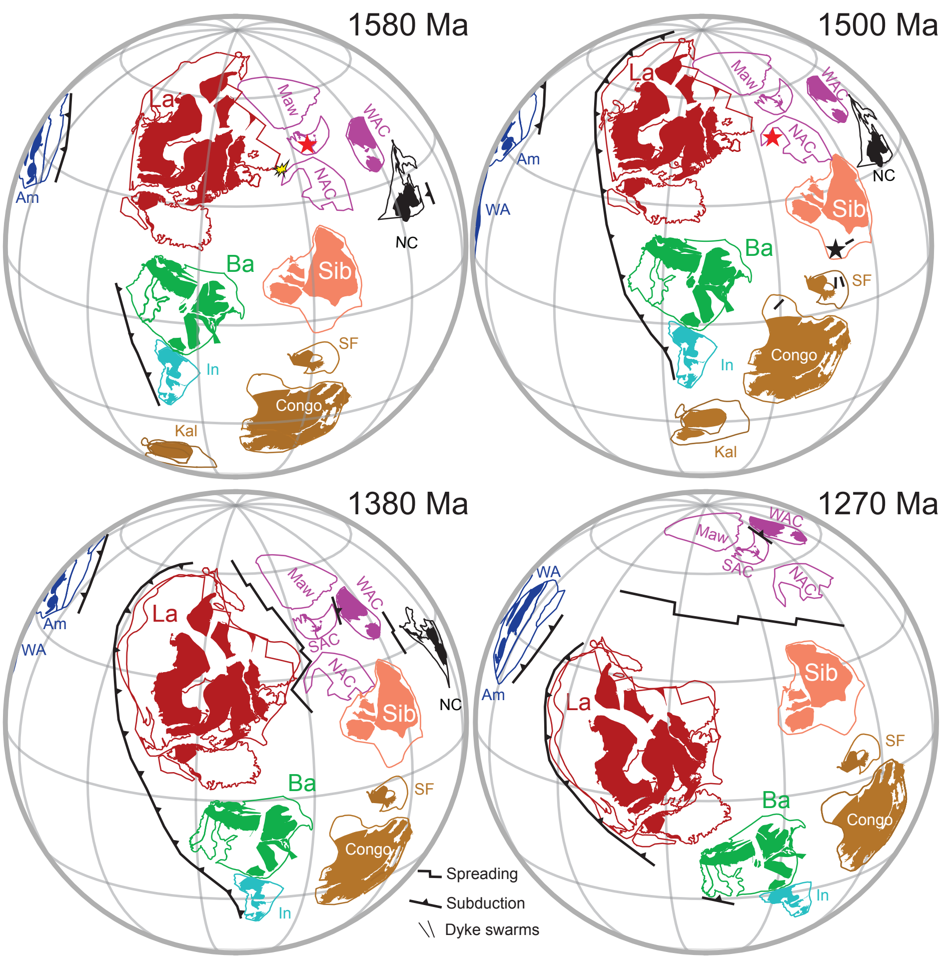

Figure 1. Mesoproterozoic global paleogeographic reconstructions. West Nuna: La = Laurentia, Ba = Baltica, In = India. East Nuna: NAC = North Australian craton, WAC = West Australian Craton, SAC = South Australian Craton, Maw = Mawson Craton, NC = North China. Si = Siberia, SF = São Francisco, Kal = Kalahari, Am = Amazonia, WA = West Africa. Filled areas represent Archean crust. Stars represent heads of mantle plumes.

Fluid-induced deformation during metamorphism

The deep-Earth water cycle is strongly coupled to the dynamics of Earth's interior. The amount of water carried into the deep mantle by descending oceanic crust is relatively small, but even a trace amount of water affects physical and chemical properties such as melting temperature, rheology, deformation mechanisms and electrical conductivity. Ophiolitic chromitites are commonly regarded as resistant to fluid-related processes, and have been used to track the evolution of Earth's mantle convection.

Chromitites occur in the Golyamo Kamenyane serpentinite, which is a part of a dismembered metaophiolite located in the Avren synform in the upper high-grade unit of the metamorphic basement of the Eastern Rhodopes crystalline massif in SE Bulgaria. These chromitites have been subjected to high-P metamorphism, but preserve evidence of fluid-rock interaction during metamorphism. The retrograde P-T exhumation path of the Golyamo Kamenyane chromitites allowed almost complete transformation of primary chromite into several types of secondary chromites, during amphibolite-facies deformation and fluid infiltration.

Detailed geochemical studies based on major element components (*Gervilla et al., 2012*) have classified the chromitites into four textural groups: partly altered chromite, porous chromite, non-porous chromite, and zoned chromite. According to their chemical modelling, chromitites reacted with two kinds of fluids during retrograde metamorphism: (1) Si-rich fluids with very low fO_2 that produced chlorite and partly altered and porous chromite, and (2) oxidising fluids that produced Fe^{3+}-rich chromite and formed non-porous and zoned chromite grains.

To investigate the chromite deformation and identify the slip systems, crystallographic orientation measurements were obtained by using the SEM-EBSD (Electron Back-Scattered Diffraction), in the CCFS Geochemical Analysis Unit at Macquarie. EBSD reveals significant crystal-plastic deformation, such as inter-crystalline deformation defined by low-angle boundaries (Fig. 1b, d). The homogeneous distribution of subgrain boundaries in zoned chromite indicates that chromite deformed after the chemical zoning had been established (Fig. 1b). Fluid percolation also produced recrystallisation of fine grains (Fig. 1d). The fine-grained aggregates of chromite probably formed by both dynamic recrystallisation and nucleation that were enhanced by reaction with oxidising fluids. However, there is no evidence of significant deformation in the partly altered chromite (Fig. 1a). Overall, fluid-rock interaction enhances deformation of chromites, which produces recrystallisation due to both dynamic recrystallisation and nucleation.

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

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Funded by: CCFS Foundation Project 1 (TARDIS)

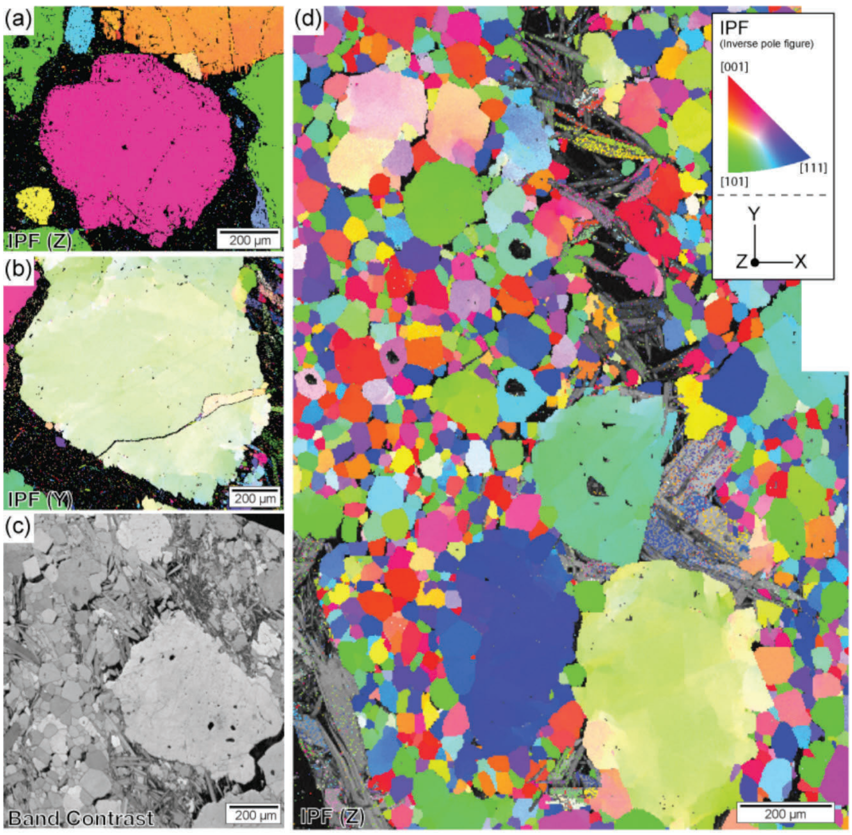

Figure 1. Crystallographic orientation maps of chromites from Golyamo Kamenyane. Rainbow scale in the maps indicated the Inverse pole figure (IPF) colour. (a) IPF map of partly altered chromite. (b) IPF map of zoned chromite. The presence of subgrain boundaries indicate crystal-plastic deformation. (c) Band contrast map of non-porous and zoned chromite. Euhedral chlorite grains fill in the chromites. (d) IPF map of non-porous chromite. Dynamic recrystallisation in coarse chromites by the development of subgrains in a matrix of recrystallised chromite.

New insights into Earth's early differentiation

To understand how Earth's mantle has evolved over time, we need to know the chemical composition and differentiation of the primordial silicate Earth. Planetary analogs (Mars and the Moon) suggest that Earth experienced large-scale melting soon after accretion, vigorous convection in the early mantle due to higher heat production from radioactive decay, core formation, and large impacts followed by crustal recycling. All this activity is generally thought to have efficiently mixed and homogenised the mantle, obliterating all signs of Earth's youthful exuberance. This implies that Earth started as a well-mixed homogeneous body that evolved progressively over geological time to form several chemically distinct domains. The isotopic and chemical heterogeneities observed in modern mantle-derived rocks thus are generally believed to reflect later production and recycling of oceanic and continental crust through geological time.

All that changed with the discovery of chemical and isotopic heterogeneities, which must have been generated ca 4.53–4.45 Ga ago, in high-magnesium lavas from Baffin Bay, which are only ca 60 Ma old (*CCFS publication #354*). Refractory lithophile elemental and isotopic evidence from less-evolved whole rock samples and olivine-hosted melt inclusions suggests a chemically heterogeneous source for the Baffin Bay lavas that contains enriched and depleted end-member components (Fig. 1a and b). Because the two end-members both have primitive Pb isotope compositions that plot within the geochrons of 4.53 to 4.40 Ga and coupled primitive He isotopes (Fig. 1c and d), the chemical heterogeneities likely formed in Earth's infancy. This implies that chemical effects of early differentiation can persist in mantle reservoirs to the present day. Figure 2a illustrates how global differentiation of the early silicate Earth from 4.55 to 4.40 Ga may have produced depleted and enriched types of dense melts in an undegassed deep Earth. The global differentiation of the bulk silicate Earth would have occurred in two independent layers at >1,800 km and ≤1,800 km depths. The density contrast would produce an enriched denser liquid phase at the core-mantle boundary. In contrast, within the upper layer (≤1,800 km) the residual liquid would rise buoyantly as crystallisation proceeded until a small fraction (≤1%) of melt ultimately formed a protocrust at the Earth's surface, resulting in depletion of 60% of the silicate Earth. The depleted dense melt may have been generated by high degree partial melting of peridotite at about 300-410 km depth, shortly after magma ocean crystallisation. These two types of dense melts would result in materials constituting the present-day thermo-chemical piles hosted within the two large low-shear-wave-velocity provinces above the core-mantle boundary, that have been protected from complete entrainment by subsequent mantle convection currents. We argue that, although such dense melts likely exhibit some *'primordial'* geochemical signatures, they are not representative of the bulk silicate Earth. Such an early-formed dense chemical layer would continue to be sampled by mantle plumes (Fig. 2b). Our work links formation, preservation, and sampling of early chemical heterogeneities into a self-consistent

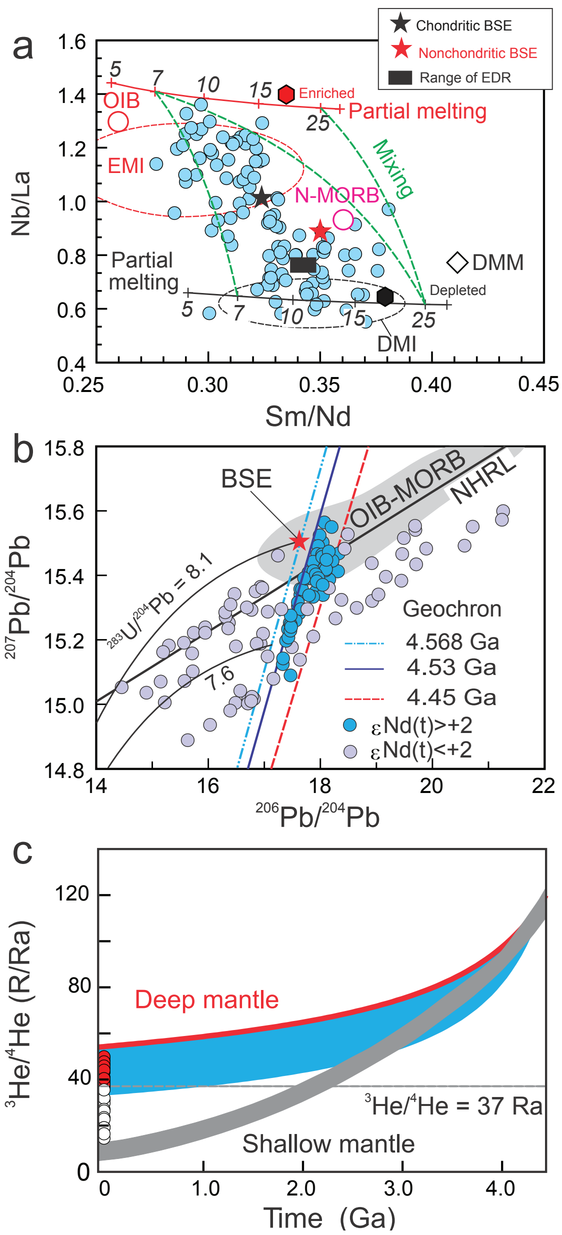

Figure 1. (a): EMI and DMI are the enriched and depleted types of melt inclusions from high ^{3}He/^{4}He BIWG picrites, compared to average normal-MORB (N-MORB), ocean island basalt (OIB), depleted MORB mantle (DMM). Lines indicate non-modal batch melting (solid lines with cross), binary mixing (green dashed lines); numbers in italics mark partial melt fractions (%). (b) Lead isotopes of Baffin Bay high-magnesium lavas. Black curves indicate evolution from the initial Pb-isotope composition of Canyon Diablo. Also shown are 4.568 Ga, 4.53 Ga, and 4.45 Ga geochrons. (c) Evolution of ^{3}He/^{4}He for the early formed dense chemical layer (blue) is based on the method of Class and Goldstein (2005) for an initial ^{3}He/^{4}He =120 RA, [^{3}He] ranging from 2.0 × 10^{11} to 0.8 × 10^{10} atomsg-1and U = 0.038 to 0.0028 ppm; Th = 0.0735 to 0.010 ppm. Evolution of deep mantle (red) and shallow mantle (grey) are from Lee et al (2010). The ^{3}He/^{4}He lower than 37 RA (open circles) were likely affected by post-eruption reduction of ^{3}He/^{4}He by ^{4}He accumulation.

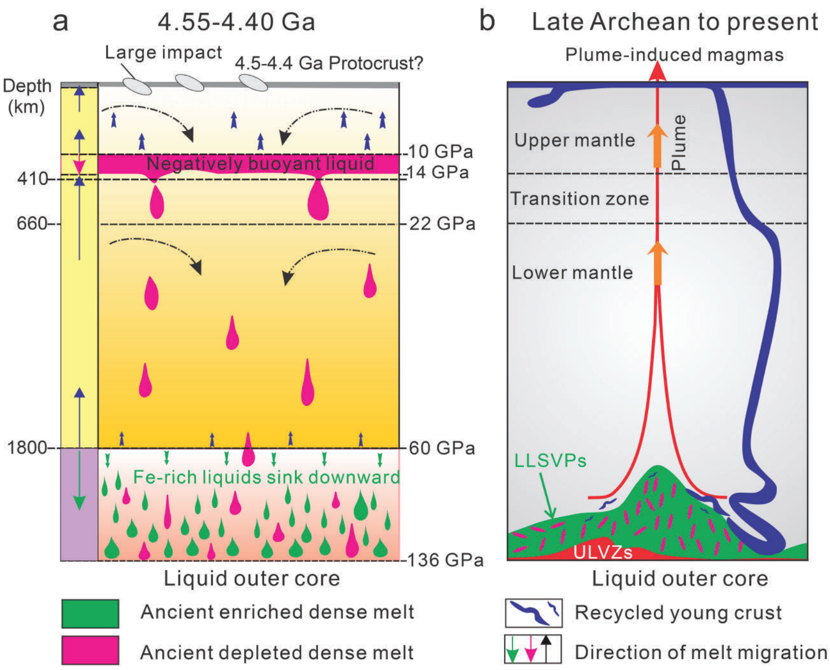

Figure 2. (a) Freezing of a magma ocean produced enriched dense melts below 1,800 km depth that accumulated at the CMB, and 60% depletion of the BSE occurred at above 1,800 km depths due to positive buoyancy of the residual melt. Shortly after magma ocean crystallisation, hot and deep melting of the upper mantle could have generated depleted dense melts at 410–300 km depth. The two types of dense liquids sunk and accumulated at the CMB to form a dense chemical layer. (b) In Late Archean and later times, melting was restricted to shallow depths. The dense chemical layer is likely hosted by large low-shear-wave velocity provinces (LLSVPs) and ultralow-velocity zones (ULVZs) and appears to have persisted for much of Earth's history.

geodynamic system and thus provides a strong case for mantle chemical heterogeneity being formed by a major differentiation event shortly after planet accretion rather than through the subsequent geodynamic evolution.

How such a dense chemical layer can be sampled and brought to the surface is another important question. Geological evidence related to supercontinent reconstructions shows that both the location and formation of superplumes were dominantly controlled by the first-order geometry of global subduction zones. Recent studies proposed that sinking subducted slabs not only can push the dense chemical layer upward, but at the same time also push the thermal boundary layer to form thermal-chemical domes, enhancing or triggering thermal instability (Fig. 2b). Our recent studies (*CCFS publication #336*) show that the late-Cenozoic less contaminated and synchronous basaltic samples from the Hainan-Leizhou peninsula, the Indochina peninsula and South China Sea seamount 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 that developed early in the Earth's history (4.5-4 Ga). These basalts occur above a seismically detected thermal plume adjacent to deep subducted slabs. Thus, they provide a strong case that the avalanches of subducted slabs to the CMB may have pushed up a thermal-chemical pile to form a thermal plume (Fig. 3; *CCFS publication #336*). The physical properties of mantle plumes also dictate that materials from the dense chemical layer near the CMB should only be a minor component of mantle plumes and thus can only be identified in the earliest phase of high temperature melts (picrites and komatiites). This implies that the ancient mantle reservoir could only be a dominant source component in the early stage of a plume magmatic event, which would then be diluted by recycled oceanic crust components as the plume magmatism continues.

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

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Funded by: CCFS ARC ECSTAR funds

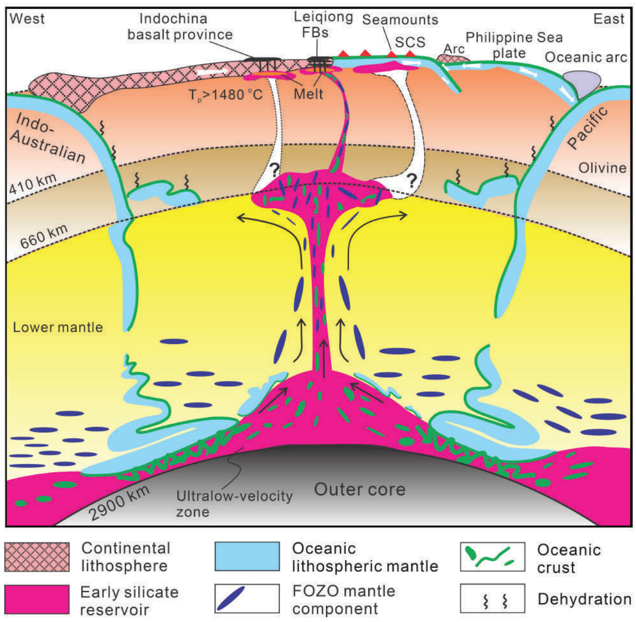

Figure 3. Formation of the Hainan plume. Broad low-velocity anomalies beneath the lithosphere and the transition zone are prominent, but the interpreted secondary plumes beneath the Indochina peninsula volcanic province and seamounts in the South China Sea (SCS) have not yet been reported by seismic tomography. Volcanism in the Indochina peninsula and the South China Sea may have been caused by thermal plumes or small-scale thermal upwellings from the edge of the broad anomaly. Early silicate reservoirs are recognised in plume-induced basaltic rocks.

Zircon and baddeleyite fingerprint platinum, nickel and copper mineralisation processes at Noril'sk (Russia)

The ultramafic–mafic Noril'sk-1 intrusion in Polar Siberia (Russia; Fig. 1) hosts one of the world's major platinum group-element (PGE)-Cu/Ni sulfide deposits. Despite years of study there is still ongoing debate about the origin of the Noril'sk-type intrusions, especially about the sources of the silicate magmas and ore metals for individual lithological units. However, it is generally accepted that the mantle-derived ultramafic–mafic magmas and PGE–Ni/Cu deposits of the Noril'sk-Talnakh region in Russia are closely linked, implying that juvenile mantle-derived materials are intrinsic to their petrogenesis. It is also commonly assumed that the '*Noril'sk-type*' intrusions are genetically linked to the 250 Ma Siberian flood-basalt volcanism.

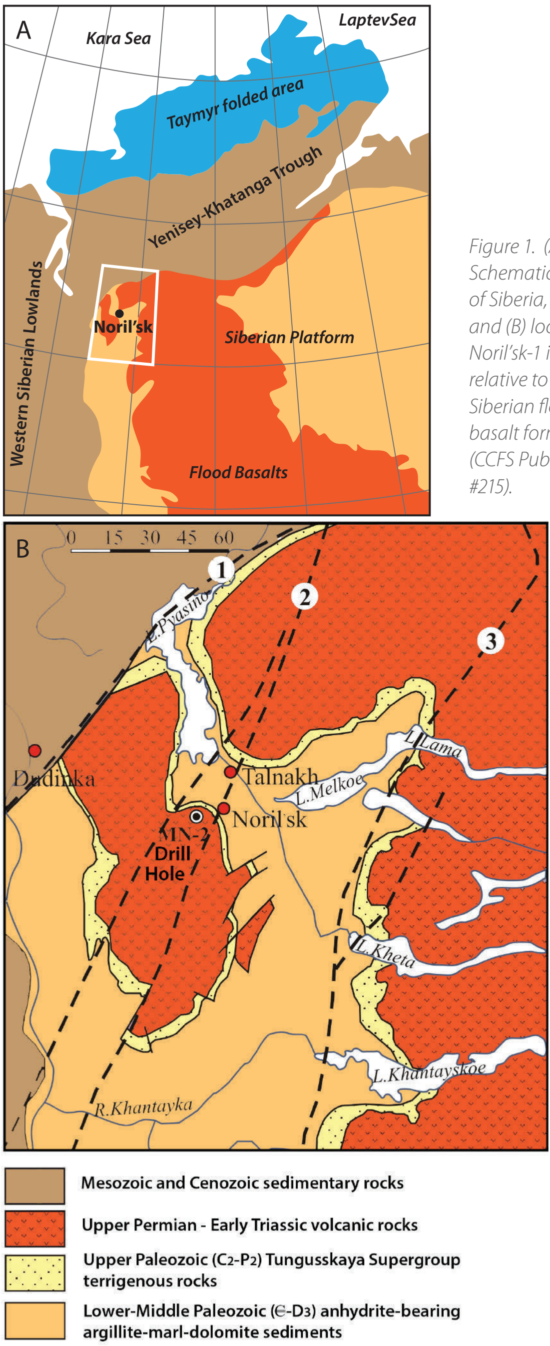

Figure 1. (A) Schematic map of Siberia, Russia and (B) location of Noril'sk-1 intrusion relative to the Siberian flood-basalt formation (CCFS Publication #215).

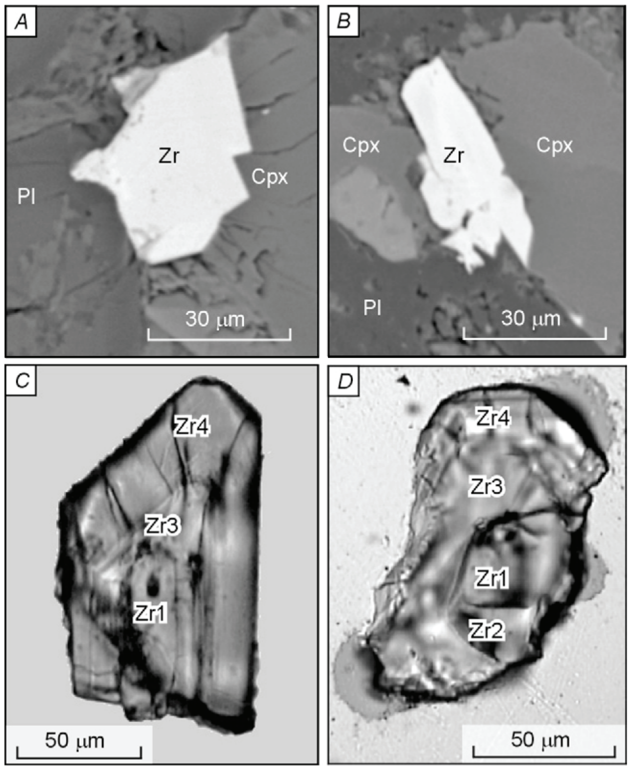

Figure 2. Examples of zircon in situ *in thin sections (A, B; in back-scattered electrons) and mineral separates (C, D; in transmitted light) from rocks of the Noril'sk-1 intrusion (GEMOC Publication #720). A, B, Assemblages of zircon and rock-forming minerals from olivine gabbro and taxitic pyroxene leucogabbro. Zr, zircon; Cpx, clinopyroxene; Pl, plagioclase. C, D, Inner structure of polyphase grains, composed of 'cores' (Zr1 and Zr2) and 'rims' (Zr3 and Zr4).*

Nd-Sr-Os-Pb isotopic studies of the main units of the economic Noril'sk-type intrusions and their ores have contributed to a better understanding of the origin of Noril'sk-type intrusive hosts and associated ores. The Os- and Pb-isotope compositions of the PGE–Cu/Ni sulfide ores preserve mantle-like values, and it has been suggested recently that staged chambers played an important role in the evolution of the Noril'sk-type deposits. Whole-rock Nd-isotope data represent the homogenised end product of these processes; they provide cumulative information and do not tell much about magma sources during the evolution of the ultramafic-mafic magmas. The wide variation of Hf-isotope values in zircon in rocks with homogeneous whole-rock Nd-isotope data has been documented previously (see *GEMOC Publications #251, #491*), demonstrating that the zircon data provide superior constraints for end-member mixing components. This emphasises the usefulness of *in situ* analytical techniques, where the Hf-isotope composition of the zircon records the evolution of the magma chamber, with

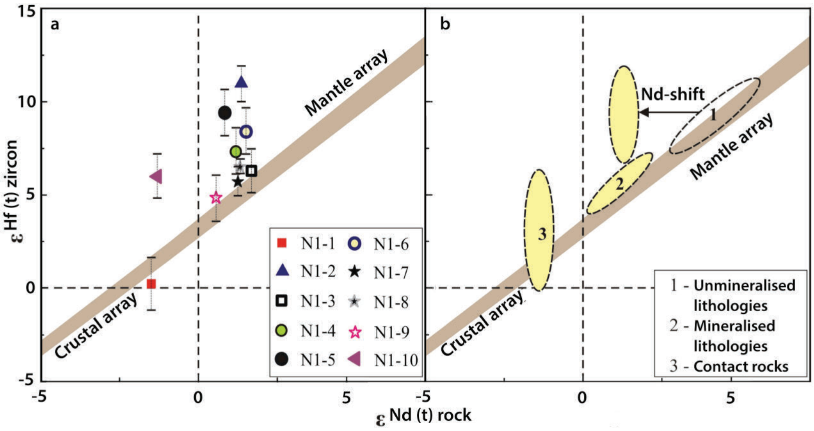

Figure 3. Plot of zircon εHf(T) versus whole-rock εNd(T), identifying three distinct clusters for the Noril'sk-1 intrusion. Mantle and crustal arrays according to Vervoort et al. (Geochim. Cosmochim Acta, 63, 1999).

input of magmas from different sources, and/or progressive contamination by country rocks.

However, there are few such data on zircon from the Noril'sk-type intrusions. To fill this gap we have explored the isotope systematics of Hf in zircon (Fig. 2) and baddeleyite from variously mineralised rocks of the economic Noril'sk-1 intrusion (*CCFS Publication #215*). *In-situ* Hf-isotope data of zircon and baddeleyite, combined with whole-rock Nd-isotope results, identify three distinct clusters of Hf-Nd isotope values (Fig. 3) typical of different lithological units (e.g. unmineralised gabbroic rocks, mineralised ultramafic and taxitic-textured rocks with disseminated PGE-Cu-Ni sulfide ores, and gabbro-diorite). These groupings suggest the interaction of three distinct magma sources during the protracted evolution of the Noril'sk-1 intrusion: (1) a juvenile source equivalent to the Depleted Mantle, (2) a subcontinental lithospheric mantle source and (3) a minor crustal component. It appears that the Hf-isotope composition of zircon and the Nd-isotope compositions of unmineralised lithologies were decoupled. These data also suggest that a prolonged period for concentration of the ore components in staged chambers during this interaction is a key factor for the formation of economic deposits, and that the zircons can fingerprint this process as a guide to exploration.

The zircon and baddeleyite from Noril'sk-1 show isotopic and geochemical features that are not usually expected for mafic and ultramafic rocks. Models for the origin of the Siberian flood basalts and their relationships to the Norilsk-type intrusions should be further investigated in light of new Hf-Nd isotopic constraints, which indicate a complex geological history for the economic ultramafic-mafic intrusions of the Noril'sk region.

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

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Funded by: ARC Future Fellowship, Macquarie University contribution to ARC FT, CCFS Foundation Project 1 (TARDIS)

Giant porphyry copper deposits on the roof of the world flow from deep wet crust

The Gangdese porphyry copper belt in Tibet, the roof of the world, is the richest porphyry copper system known to have developed in a continental collision zone. Five porphyry copper – molybdenum (Cu-Mo) deposits are currently being mined in this province, accounting for an estimated 18 million tons (Mt) of contained copper-10.5 Mt of this in the giant Jiama deposit alone (Fig. 1). Seven additional prospects are under active exploration in the region, and it is clear that the potential of the belt has not been fully unlocked.

These porphyry Cu deposits developed in the Miocene, significantly post-dating the collision of India with Asia, so the most common model of porphyry copper genesis in association with oceanic subduction cannot be applied here. One of the most striking features of the metalliferous deposits is their close association with adakite-like intrusions, felsic igneous rocks with high Sr and Eu contents, and high Sr/Y ratios. These intrusions are widely attributed to dehydration melting (in the absence of free water) of garnet-amphibolite and/or eclogite facies rocks in the thickened crust below Tibet. However, the associated mineralised porphyries contain more than 9% water by weight, and cannot be derived through any simple evolution of melts originating from anhydrous high-grade metamorphic parent rocks. This presents a dilemma in explaining the development of this important endowed province.

To resolve this dilemma, we are looking at the wider regional context of these porphyries to produce an internally consistent model that can account for their key characteristics, and give a key to developing strategies for further exploration of the Gangdese belt.

In addition to the water problem, dehydration melting of amphibolites and/or eclogites does not produce melts with the chemical characteristics that match the inferred ore-forming magmas. Such melting would consume the hornblende in the source rocks before plagioclase began to melt, and would not

Figure 1. The giant Jiama porphyry Cu deposit in Tibet. Photo taken from the elevation of 5000 m.

produce the adakite-like melts with high Sr and Eu contents and high Sr/Y. However, a high H_2O content in the starting material (and the resultant partial melt) stabilises hornblende to higher temperature and lowers the melting point of plagioclase. If significant amounts of water were added to the mafic lower crust, the chemical problems thus would be solved -- but how can large volumes of water be fluxed up into the lower crust in the Miocene, long after the cessation of oceanic subduction beneath this region?

We suggest that the coeval ultrapotassic lava flows of South Tibet provide the missing link in this puzzle. These mafic rocks are notably water-rich. Furthermore, the solubility of water in such ultrapotassic melts increases with increasing pressure, and therefore as the melts ascend, they release free water into the surrounding wall-rocks. Although they are rare at the surface, significantly larger volumes of ultrapotassic rocks are believed to occur at depth beneath the Tibetan lower crust, and underplating and crystallisation of these mantle-derived rocks may have provided the fluid required to catalyse the development of the fertile Tibetan porphyries in the Miocene.

This conceptual model is illustrated in Figure 2. We suggest that metasomatism of the lithospheric mantle and Jurassic underplating of arc melts below Tibet were essential to pre-condition the region for the subsequent development of the mineralised porphyries. In the Miocene, lithospheric thinning – probably due to convective removal of lithosphere during Himalayan orogenesis – caused melting of the water-rich metasomatised mantle domain, producing hydrous ultrapotassic-potassic melts. In the extensional conditions that prevailed across the western portion of the southern Lhasa subterrane, these mantle-derived magmas were able to ascend into the upper crust – and locally erupt. In the more compressive contemporary regime to the east of this subterrane however, the ultrapotassic-potassic magmas ponded in the lower crust. Release of water from the crystallising magmas then triggered melting of the overlying Jurassic arc material to produce the hydrous and adakite-like intrusions and associated porphyry Cu deposits.

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

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Funded by: CCFS foundation project 2a, 9, ARC CCFS ECSTAR funds

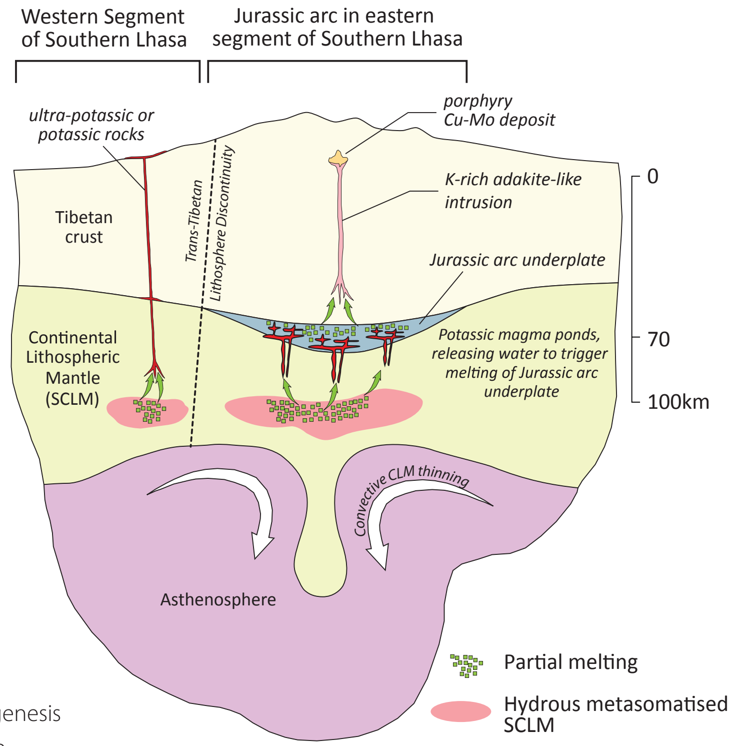
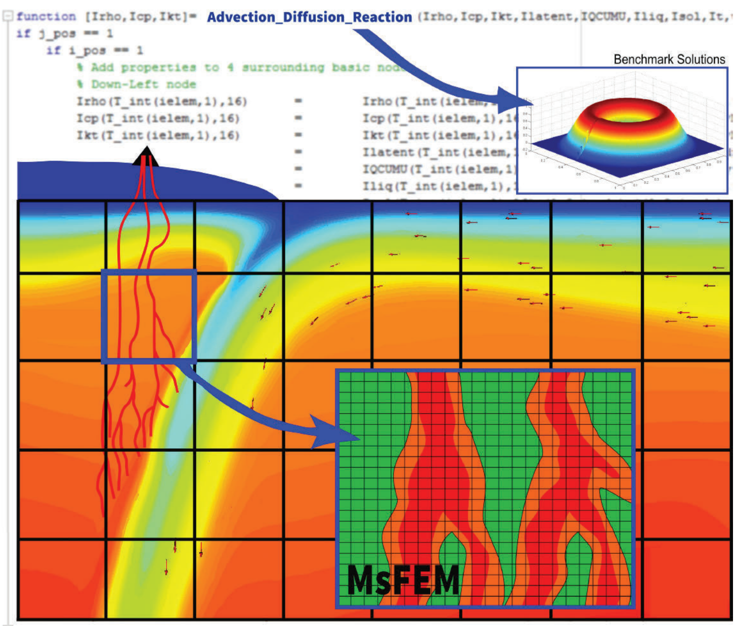


Figure 2. A conceptual model for the genesis of the hydrous fertile Tibetan porphyries, as outlined in the text.

Modelling multi-phase reactive flow in the mantle: a bottom-up approach

The physico-chemical processes that govern the evolution of continental lithosphere and its interaction with the sublithospheric upper mantle occur over very different spatial and temporal scales. The details of the interactions between these different scales and the resulting integrated macroscopic effects on the evolution of plates are still poorly understood. In order to understand these multi-scale (geological) processes, we need to be able to accurately simulate/model all the processes involved in natural multi-phase multi-component reactive systems. Unfortunately, although several groups are making progress towards this end, most modelling platforms available to the geodynamic community do not really deal with all these problems in an internally-consistent manner. It also can be difficult to scale them to a wide range of problems (e.g. from melting in cm-scale veins to mantle convection).



To bypass these limitations we take advantage of a novel numerical framework known as the Multi-scale Finite Element Method (MsFEM). The main idea is to capture the small-scale details of a problem and transfer them to the macro-scale through consistent and robust coupling of the micro- and macro-problems (back and forth). In particular, the MsFEM replaces the basis functions used in the traditional FEM, with a new set of micro-problem-dependent functions. This development provides a new numerical platform directly applicable to modelling geological phenomena such as the generation, migration and emplacement of magmas, chemical entrainment, transport of geochemical species, deposition mechanisms of sulfide liquids, the formation of ore bodies in hydrothermal systems, etc. Importantly, these '*small-scale*' processes are consistently coupled, in our numerical framework, to the large-scale driving tectonic processes, and that coupling allows us study the complex interactions between these different scales. So far, the MsFEM has been successfully applied and tested in fields such as composite materials, petroleum reservoirs and groundwater transport, but not yet in the large-scale analysis of the lithosphere-asthenosphere system.

Multi-phase reactive flow is governed by a multitude of balance and constitutive equations that need to be solved accurately with numerical methods. Ones of particular importance are the so-called '*advection-diffusion-reaction*' and the '*momentum*' equations, governing heat transfer and momentum transfer, respectively. Stability and accuracy analyses for these equations are well known and have been the subject of thousands of papers in the numerical community. Although there are many ways to solve these equations, not all of them are appropriate to a multi-scale approach. Moreover, the robustness, accuracy, and efficiency of many of these algorithms are still debatable when they are applied to geodynamic processes at different scales. This is due partly to poorly documented tests and benchmarks and partly to the geodynamics community's lack of any broad interest in multi-phase multi-component reactive flow .

As part of a larger CCFS Foundation Project 4, we are currently developing/testing a number of individual algorithms particularly designed to work under a multi-scale formalism for geodynamic problems. In particular, we have developed a new Lagrangian-Eulerian algorithm for advection-diffusion-reaction, which is proving to have remarkable accuracy, scalability, and generality. This finite-element algorithm combines the best features of fixed-mesh and marker-in-cell methods into a single conservative scheme that can accurately model processes in which there are large advective and reactive components together with isothermal and non-isothermal phase changes. We have also tested and improved existing multiscale algorithms that may be applicable to specific sub-problems. In parallel, we have implemented an efficient and fully compressible Lagrangian-Eulerian iterative solver (based on the "*Uzawa scheme*") for the momentum (and mass) equation and fast thermodynamic solvers for the computation of phase equilibria/component distributions. The internally-consistent combination of these three main components into a single thermo-chemical-mechanical algorithm will allow us to simulate a large variety of fluid-assisted geodynamic processes.

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

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Funded by: CCFS Foundation Project 4

Straining to transform from continent to ocean

The Grisons, in the Eastern Alps (Switzerland) have preserved an ocean-continent transition; numerous studies during the last decade provide an excellent structural framework. This area represents a section across a zone of exhumed continental mantle. Sub-continental spinel peridotite is exposed close to the continent (Totalp area) while the mantle further from the continent was infiltrated by melt and equilibrated in the plagioclase stability field (Platta area) (Fig. 1). The sequence includes highly deformed peridotites (ultramylonites) that allow us to study the evolution of deformation within an ocean-continent transition. A detailed study of the peridotite textures and geochemistry was combined with the analysis of the crystallographic orientation of minerals using the electron backscatter diffraction method (EBSD).

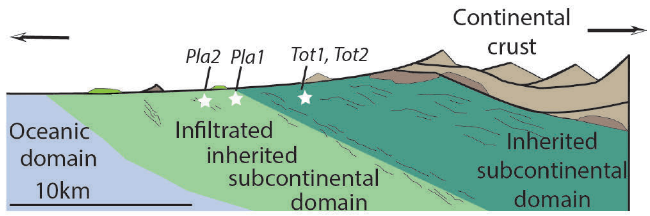


Figure 1. Schematic representation of an ocean-continent transition (after Peron-Pinvidic & Manatschal, 2009, Int.J.Earth.Sci, Muntener et al. 2010, J.Pet).

We sampled the Platta-Totalp massifs made of spinel lherzolites and harzburgites, intruded by gabbros and basaltic dykes, and partially covered by ophicarbonates. In Totalp, blocks of ultramylonites within a cataclastically deformed domain related to mantle exhumation, and ultramylonites parallel to the foliation of amphibole-bearing peridotites, were sampled.

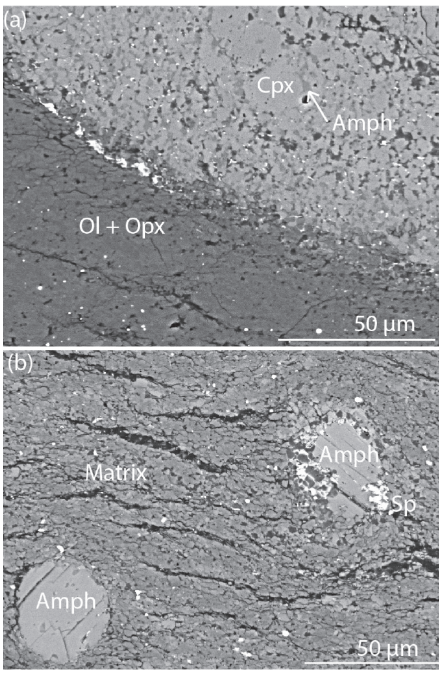


Figure 2. (a) Ultramylonite made by unmixed layers. Layers are clinopyroxene replaced by interstitial amphibole or olivine and orthopyroxene; (b) Ultramylonite contains round porphyroclasts of amphibole within a matrix of olivine, opx, cpx, amphibole and spinel.

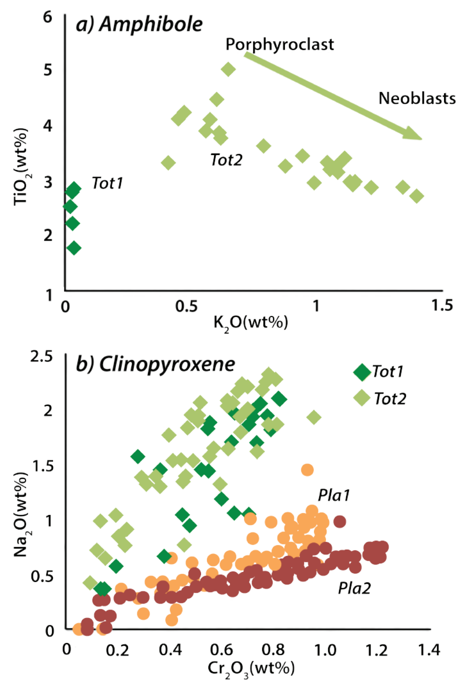


Figure 3. Chemical composition of amphibole (TiO_2 vs. K_2O wt%) and clinopyroxene (Cr_2O_3 vs. Na_2O wt%) from Totalp and Platta.

The ultramylonite blocks are formed by unmixed layers of olivine (ol) + orthopyroxene (opx) and clinopyroxene (cpx) + amphibole (Fig. 2a). Opx and ol grains are elongated, whereas the amphibole is interstitial and replaces the clinopyroxene. The ultramylonites have a fine-grained matrix (grain size 2-10 µm) composed of ol, opx, cpx, spinel and amphibole with rounded amphibole porphyroclasts (Fig. 2b). Pargasitic amphibole occurs in the former whereas kaersutitic amphibole characterises the latter. The kaersutite was related to pre-deformation metasomatism with K_2O enrichment from porphyroclasts to neoblasts during localisation of deformation (Fig. 3). The pargasite formed later than the kaersutite and was probably related to the exhumation of the mantle. The crystallographic preferred orientations of the kaersutite within the host peridotite are inherited from the porphyroclastic amphibole with a reorientation of <001> axes, to become parallel to the foliation. In the ultramylonitic matrix, the amphibole grains have elongated shapes and their <001> axes are parallel to the foliation, suggesting either a strong grain rotation or a dynamic recrystallisation.

The clinopyroxene composition has been analysed for Totalp and Platta samples. There is no distinct difference among the Totalp samples, but samples from Platta have lower Na_2O, suggesting melt percolation and crystallisation of plagioclase. Some Platta samples show slightly lower Na_2O suggesting less melt infiltration, and has a more continental affinity (Figs. 1 and 3). In porphyroclastic clinopyroxene from the host peridotite in Totalp, the activated slip is (010)[100], which is uncommon and marginal in peridotites because of using a large burger vector (Fig. 4a). In clinopyroxene porphyroclasts <100> axes are parallel to the foliation whereas the recrystallised grains show a reorientation with <001> axes more parallel to the foliation (Fig. 4b, c). Olivine porphyroclasts within the host peridotite show the activation of two slip systems within a single grain: (001)[100] and (100)[001]. In the fine-grained ultramylonitic matrix the dominant activated slip system is (001)[100] E-type.

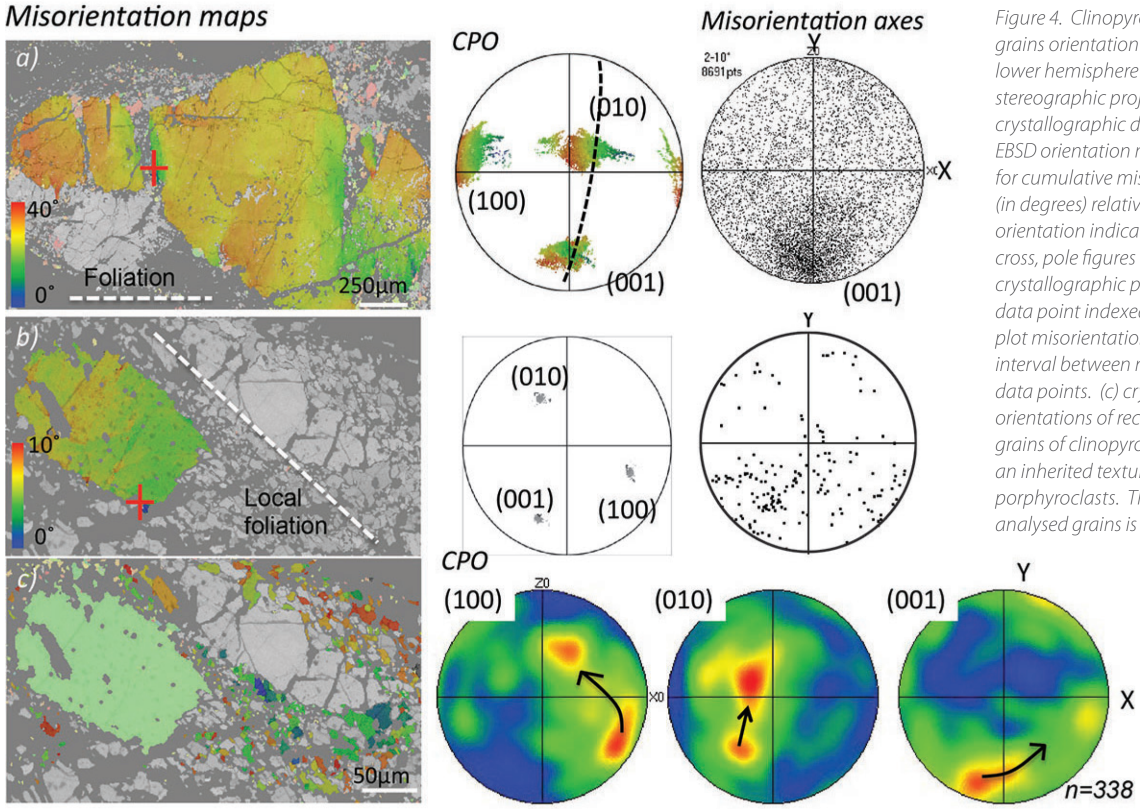


Figure 4. Clinopyroxene individual grains orientation maps and lower hemisphere equal area stereographic projections of crystallographic data. (a-b) EBSD orientation map colored for cumulative misorientation (in degrees) relative to reference orientation indicated by a red cross, pole figures of major crystallographic planes for every data point indexed on map, and plot misorientation axes for (2–10°) interval between neighbouring data points. (c) crystal preferred orientations of recrystallised grains of clinopyroxene showing an inherited texture from the porphyroclasts. The number of analysed grains is n=339.

The results obtained in 2013 show that the transition from subcontinental to infiltrated subcontinental mantle towards the ocean involved a compositional evolution and a change in deformation mechanisms. The presence of amphiboles testifies to fluid percolation before deformation, and tracks chemical evolution of the fluid during localisation of deformation. The amphibole and clinopyroxene crystal preferred orientations in the host peridotite are partially inherited from the primary texture, and overprinted by several mechanisms such as grain rotation, dynamic crystallisation and/or grain boundary sliding when the strain increases.

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

Contacts: Mary-Alix Kaczmarek, Steve Reddy
Funded by: CCFS, Curtin University (Perth), The Swiss National Foundation (SNF), The University of Lausanne

Mantle dynamics model constrained by plate history

The temporal evolution of the Earth's internal structure is very important to geoscience research, however this time-integrated evolution cannot be observed directly by available techniques. Mantle convection simulations are thus important tools to investigate this problem.

Subducting slabs descending deep into the mantle will carry, and subsequently release, water: this can promote partial melting in mantle rocks, resulting in volcanoes overlying deep, dewatering subducting slabs. Such volcanic activity can concentrate incompatible elements from Earth's interior at the surface, so models that can predict subduction dewatering pathways are of significant value to the mineral-exploration industry. However, plate boundaries have moved a lot in the past, obscuring the history of magmatism. We are developing dynamic models that can reconstruct the P-T-t path of minerals in subduction zones, and also the water content of subducting lithologies. Adopting mineral physics studies on the mantle solidus and partial melting, we will be able to calculate melting percentages and eruption rates to track the history of subduction zone volcanic activity through time, and provide quantitative and temporal maps of the generation and migration over the past few million years on a global scale.

In our approach, we use the open-source code ASPECT; this is a highly-parallelised and modularised code that uses the adaptive mesh refinement technique to achieve much better resolution than conventional approaches, at reasonable computational costs. It also supports temperature, pressure and composition - dependent simulation parameters, allowing us to adopt more realistic mineral physics models. Plate tectonics is the dominant control on the mantle flow pattern, and plate reconstructions from geophysical and geological data provide crucial constraints on surface motions in the past few hundred million years. In our mantle convection models, we use plate history as a time-dependent surface boundary condition.

Using this approach, our model successfully recovers the position of major subducting slabs and mantle upwellings, in accordance with present day seismological observations. Building such a model requires large amounts of computational power, and current models are running on a cluster with a few hundred CPUs, which may not be have the capacity to achieve the required resolution. A new resource allocation from Intersect, has delivered more computing power that will allow refinements of the current resolution over the next year.

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

Contacts: Siqi Zhang, Craig O'Neill

Funded by:
CCFS Foundation Project 4

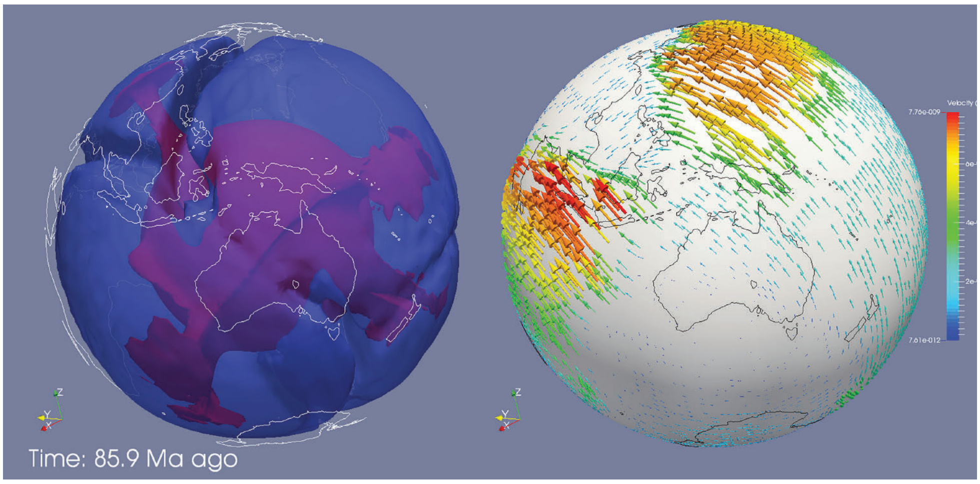


Figure 1. Snapshot at 85.9 Ma ago shows subducting slabs and plumes reconstructed by the mantle convection simulation constrained by plate history. In the left-hand figure, the transparent surfaces show contours of temperature; the present day coast-lines are shown in white. In the right-hand figure, the arrows show the surface motion constrained by plate reconstruction, and present-day coastlines are shown in black.

Zircon signposts for Gold

Multi-isotopic maps are a powerful tool for imaging lithospheric blocks of different age, and have been used in the Yilgarn Craton of Western Australia. Such maps combine *in situ* zircon U-Pb and Lu-Hf isotopic analyses with whole-rock Sm-Nd data. As the ancient lithospheric boundaries sometimes cannot be seen in modern seismic images, the isotopic mapping serves as a form of '*paleogeophysics*' for imaging paleocraton margins through time.

There is a strong spatial correlation between lithospheric boundaries and the concentration of a variety of mineral deposit types; these isotopic boundaries mark lithosphere-scale structures that control magma and fluid flux, and thus the location of large mineral systems through time. However, the only available case study in the Archean is the Yilgarn of WA, and even that is only focused on the centre of the craton. Therefore, we have tested this hypothesis in the Wabigoon Subprovince in the western part of the Superior Craton of Canada.

The Wabigoon Subprovince previously has been subdivided into four terranes based on whole-rock Sm-Nd isotopic data (Fig. 1a; *Tomlinson et al. Prec. Res., 2004)*. Gold mineralisation is pervasive within the Wabigoon Subprovince, with numerous gold occurrences and prospects (Fig. 1a). The most economic gold mineralisation, i.e. gold mines represented by red stars, clusters mainly in the Eastern Wabigoon and Marmion gold camps (rectangles 1 and 2, respectively in Fig. 1a). However, no relationship between these important gold camps and the terrane boundaries is obvious in Figure 1a. For example, the terrane boundary in Eastern Wabigoon was assumed to trend E-W, whereas the gold mineralisation trends N-S. The Marmion gold camp trends NE, but is far away from the terrane boundary (Fig. 1a).

Figure 1b shows new mapping of Hf-isotope compositions in zircon, undertaken in this study. The warm colours represent relatively juvenile blocks with higher Epsilon (Hf) values, whereas the cold colours represent relatively ancient blocks with lower Epsilon (Hf) values. The boundaries of these isotopic domains are interpreted as lithospheric boundaries between different terranes. The revised terrane boundary in Figure 1b is mainly from *Stott, OGS, 2011*. It can be seen that the new zircon isotopic mapping results fit well with the revised terrane boundaries (Fig. 1b). In particular, the boundary between the Winnipeg River and Eastern Wabigoon Terranes now trends NE, consistent with the gold trend (rectangle 1 in Fig. 1b).

This coincidence supports the hypothesis that the terrane boundaries exert important controls on the location of significant gold mineralisation. A significant observation is that there are no gold mines within the ancient Winnipeg River Terrane, but instead the gold mines cluster within the Eastern Wabigoon Terrane, which is a juvenile block. This spatial relationship of gold with more juvenile rocks is similar to that observed in the Yilgarn Craton of Western Australia.

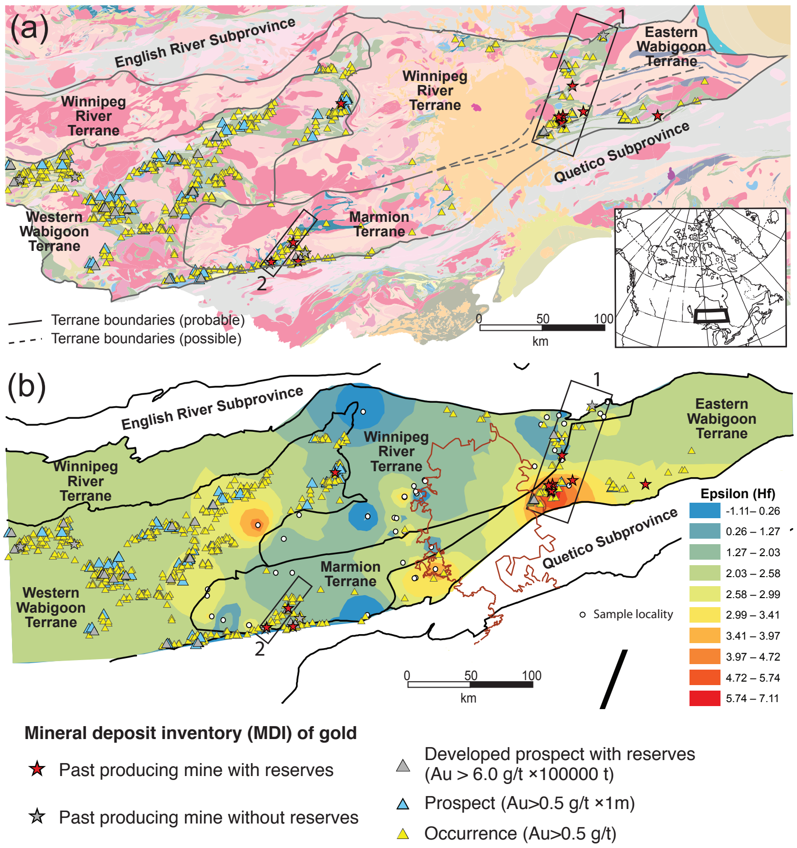


Figure 1. Spatial distribution of gold mineralisation and terrane boundaries within the Wabigoon Subprovince, Canada. (a) Geological map of the Wabigoon Subprovince showing terrane boundaries based on whole-rock Nd isotope data (Tomlinson et al., Precambrian Research 2004). Different colors represent different geological units. The inset shows the location of the study area. (b) Zircon Hf-isotope mapping of the Wabigoon Subprovince with the revised terrane boundaries after Stott, OGS, 2011. The contour bar shows the Epsilon Hf value of zircons studied. The rectangles labeled 1 and 2 highlight the two gold camps in Eastern Wabigoon and the Marmion terrane, respectively. The most economic gold mineralisation discovered to date is represented by red and grey stars.

The Marmion gold camp is intriguing as it occurs along a NE-trending zone within the Marmion Terrane (Fig. 1b). There are currently not enough zircon Hf data on both sides of this gold camp to reveal the isotopic signature of the lithosphere (Fig. 1b). However, Figure 2 shows a contrast in magnetic anomalies on both sides of this NE-trending structure within the Marmion terrane. The Hammond Reef deposit with 10 M oz of Au is close to this structure, highlighting the potential importance of this inferred terrane boundary (Fig. 2).

In summary, it appears that the spatial distribution of gold in the Wabigoon Subprovince is controlled by the terrane character (juvenile) and potentially their boundaries with ancient blocks (paleocraton margins), similar to the scenario in the Yilgarn Craton. Zircon isotopic mapping is a powerful tool to image the lithospheric boundaries and thus, can become a robust pathfinder to gold deposits.

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

Contacts: Cam McCuaig, Yong-Jun Lu, Katarina Bjorkman

Funded by: ARC ECSTAR Fellowship, CCFS Foundation Project 9

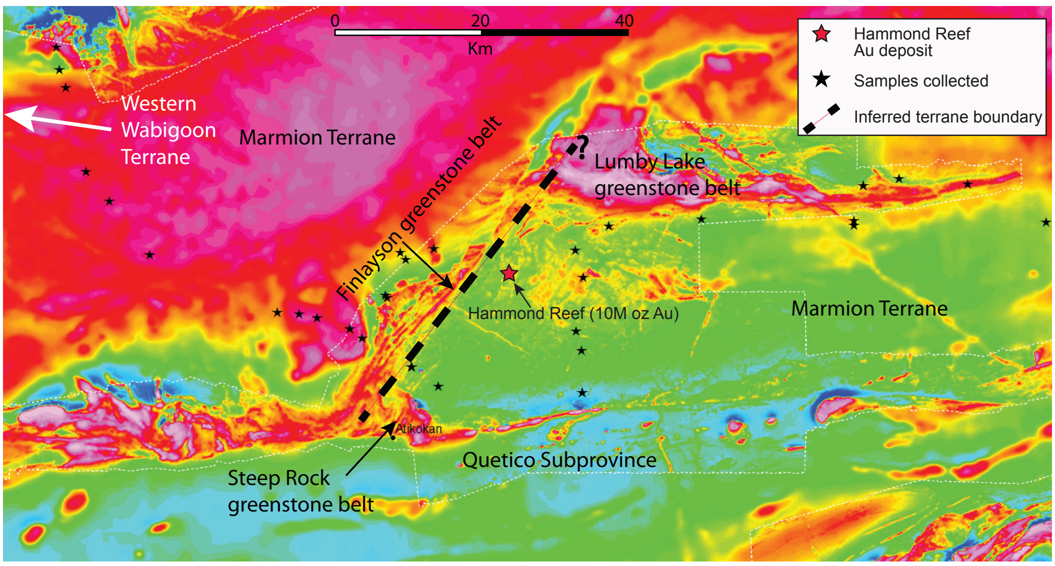


Figure 2. Residual total-field magnetic image of the Marmion Terrane. Warm and cold colors represent positive and negative magnetic anomalies, respectively. The magnetic character shows a marked change in the Marmion terrane across the NE-trending Finlayson greenstone belt, which can be inferred as a terrane boundary. The Hammond Reef deposit with 10 Moz Au is proximal to the inferred terrane boundary. However, this magnetic image probably only shows features down to about 20 km depth, and therefore does not image the deep lithosphere, unlike the isotopic data. The boundary between the Marmion and Western Wabigoon terranes is west of this map area, as indicated by the white arrow.

Diamond growth at the nanoscale – Mantle fluids at work

Diamondites are polycrystalline aggregates of diamond crystals with heterogeneous grain sizes and random orientation that formed in the Earth's mantle. They have a highly porous structure, which indicates that they precipitated from a volatile-rich medium strongly oversaturated in carbon. Gem-sized diamonds can contain a long history of growth and dissolution resulting in complex zonation patterns *(CCFS publication #168)*. In contrast, diamondites may form rapidly, presenting snapshots of diamond formation conditions that complement the information from slowly grown gem-sized diamond.

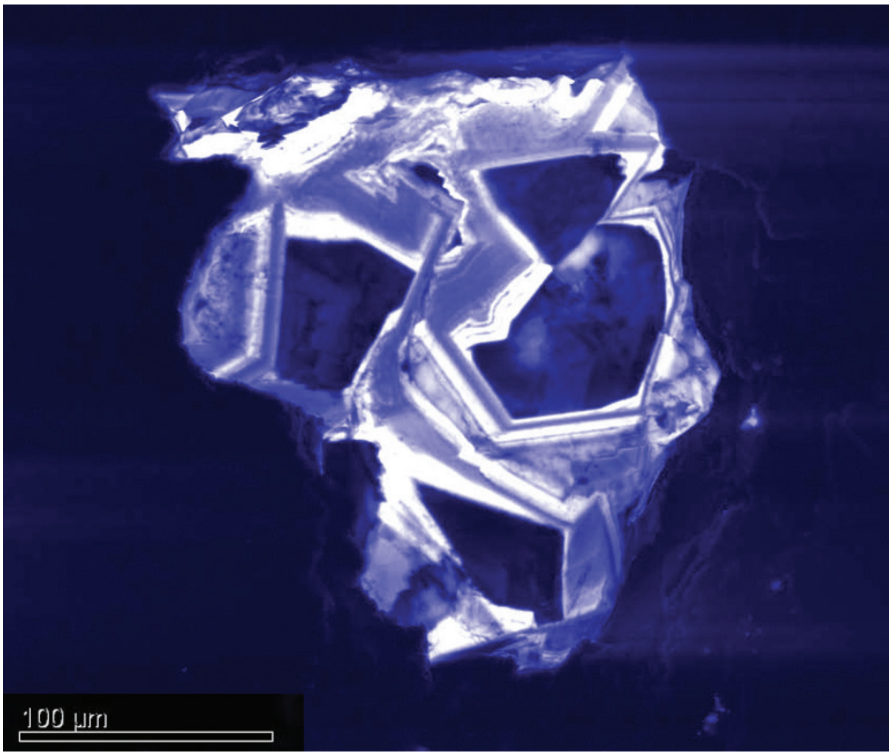


Figure 1. Cathodoluminescence image of diamondite showing complex zoning that most likely corresponds to episodic growth from a fluid dynamically changing in composition.

New microanalytical methods have allowed diamond studies to be carried to the next level, as submicron inclusions are now accessible, thus building on a solid foundation from studies of large inclusions, which are usually in the range of 200-300 µm. *In situ* analysis of diamonds and their inclusions is now able to span roughly six orders of magnitude in spatial resolution and draw critical complementary information from either end of this range. Large inclusions in diamondites are mostly intergrown with the diamond crystals rather than included. They record the general chemical environment of diamond formation, but can be subject to metasomatism that postdates diamond formation *(CCFS publication #210)*. In contrast, submicron-sized minerals included in the diamond crystals are shielded and contain the fluid from which the diamond precipitated.

To reveal more about the relationship between the diamond fluid and the growth mechanisms of the diamond crystals, we employed Transmission Electron Microscopy, enhanced with Focused-Ion Beam sample preparation, Transmission Kikuchi Diffraction Analysis and Nano-SIMS, enabling detailed analysis at the submicron scale and direct sampling of the diamonds' parental fluids included in the stones (*Jacob et al., Earth Science Reviews, in review*)

In situ sampling of diamond fluids reveals a large heterogeneity in redox conditions and chemical compositions at small scale, which is not reflected in the macro-inclusion suite. However, these fluids have compositions that correspond to the fluid end-members established by studies on fibrous diamonds; this suggests a universally important role for a limited number of basic ingredients, namely carbon, silicon, halogens and water.

Preliminary studies *(Rubanova PhD Thesis*, see *CCFS Postgraduates)* indicate that the crystals in diamondites may have grown not only by the octahedral (spiral/dislocation) mechanism, but also by cuboid (rough, adhesive type) growth. This suggests that other governing parameters, just beyond extreme carbon supersaturation, play an intrinsic role in their growth. Both growth mechanisms also occur in gem-sized diamonds, and the study of diamondites may tie these together in an integrated model and help define the impurities, oxygen fugacity, and episodic nature of these deep mantle fluids. Thus, diamondites could act as '*Rosetta Stones*' that can provide critical information about diamond growth and fluids in the Earth's mantle.

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

Contacts: Dorrit Jacob, Dan Howell, Bill Griffin, Sue O'Reilly, Sandra Piazolo
Funded by: CCFS

The leading edge in pits: the hole story for laser ablation ICP-MS

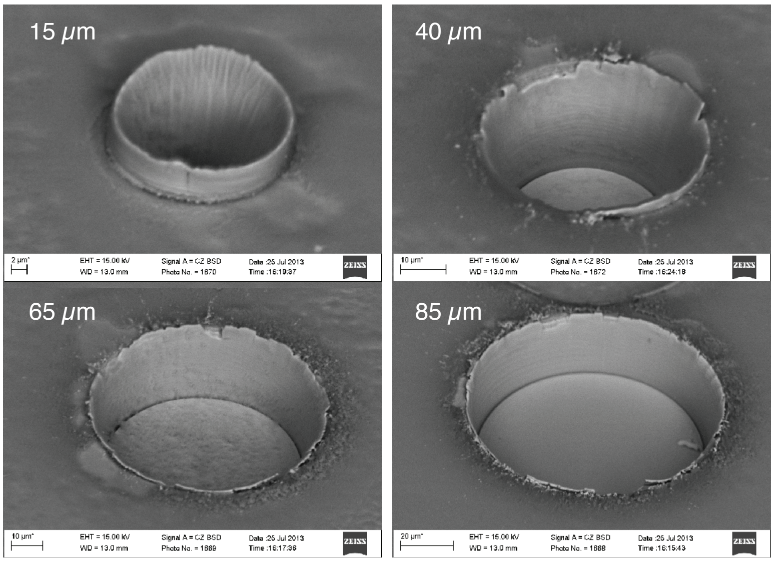


Figure 2. Back-scatter electron images of different laser spot sizes in GJ zircon. Note the marked development of the 'crown' of melt material on each pit, but especially the 15 μm diameter pit.

Conceptually, laser ablation is a simple process; material is removed from a solid (or liquid) sample by irradiation with a laser beam. In this sense laser ablation (LA) can be thought of as the micro-scale equivalent of taking a sledgehammer to an outcrop. However, the real power of laser ablation is that the sampled material can be directly transported into a plasma-source mass spectrometer, allowing rapid measurement of elemental abundances or isotope ratios. Researchers at Macquarie were among the pioneers in developing new analytical methods using laser ablation ICP-MS, and established early on, that the quantification of elemental abundances or isotope ratios is rather more complicated than a fantasy-world version of '*star-wars*' mass spectrometry. As part of the development of leading edge analytical methods involving new laser hardware, CCFS researchers are revisiting the basics of how a laser beam interacts with minerals.

The ablation behaviour of different minerals for specific wavelengths of light is well-documented in the literature. The degree of coupling between the laser beam and different minerals is indicated by the amount of material removed from the hole; in quantitative elemental analysis this is corrected by use of an independently determined internal standard (an element of known concentration). A more significant issue is the progressive change in the ratios of measured signals of certain element pairs or isotope pairs as the laser drills into the sample. This is referred to as '*down-hole fractionation*'. Elemental fractionation occurs because preferential ablation of some elements (low-volatility elements) in the sample results in non-stoichiometric sampling and analysis. Perhaps the best-documented example of laser-induced elemental fractionation is the changes in measured Pb/U and Pb/Th ratios in zircon as drilling proceeds.

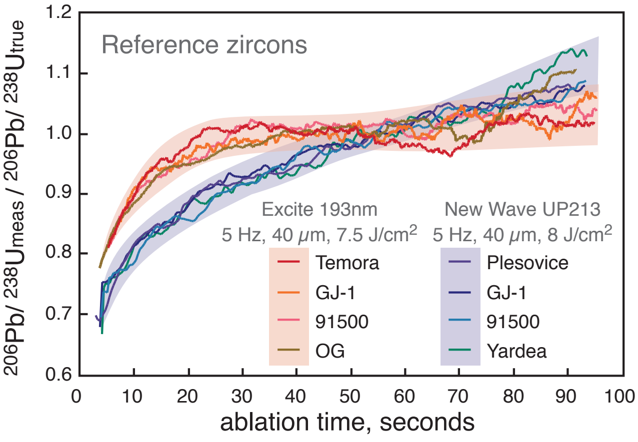


Figure 1. The plot of normalised $^{206}Pb/^{238}U$ (measured ratio relative to true ratio to remove the effect of age) vs time for selected reference zircons provides a comparison of 193 nm and 213 nm laser systems.

Down-hole laser-induced fractionation is one of the largest contributions to the uncertainty budget of LA-ICP-MS measurements of trace elements and isotope ratios. Efforts to improve the accuracy of analyses and to reduce the uncertainties associated with laser-induced fractionation have involved developments in both laser hardware and data-reduction software. Advances in cell design have improved the quantitative transport of material from the ablation site to the ICP, giving increased sensitivity and reduced fractionation. Rastering the laser, or using short acquisition times, are also commonly used to minimise downhole fractionation, but these compromise spatial resolution and depth information. Linear and exponential down-hole models are used in many data-reduction software packages and reflect the basic fractionation response for a wide range of laser specifications and operating conditions. In most models the fundamental assumption is that matrix-matched standards and samples ablate similarly with consistent time-depth relationships. However, further software advances are limited by our current understanding of the fundamental processes of ablation.

An investigation of the ablation characteristics of common minerals is part of the CCFS Foundation Project "*Frontiers in integrated laser-sampled trace-element and isotopic geoanalysis*". The aims are to assess the effect of laser wavelength, pulse width, spot size and fluence, in conjunction with laser-cell design and gas composition and flow rate. In the first phase of the study the focus has been on the ablation of zircon to establish the optimum set of hardware parameters and operating conditions to maximise spatial resolution, and to minimise ablation rate and U-Pb fractionation.

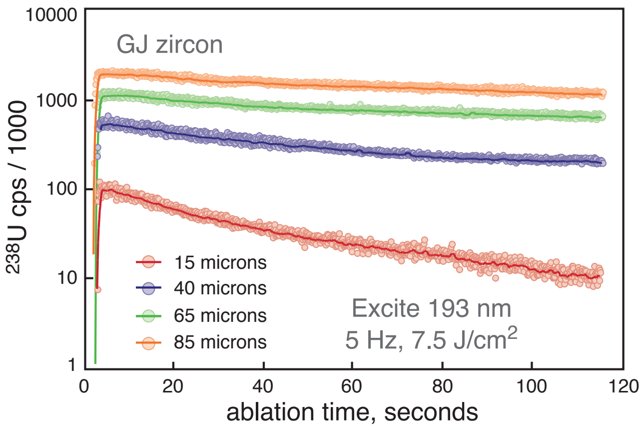


Figure 3. Plot of ^{238}U signal intensity (counts per second) versus time for 4 different spot sizes (15, 40, 65, 85 μm) in GJ zircon.

A distinctive down-hole fractionation of U and Pb is observed in ablation of zircon using 213 nm and 193 nm wavelength lasers (Fig. 1). The change in ratio from both systems is greatest in the first 150-200 laser pulses (20 to 30 seconds of ablation) but for the chosen operating parameters the 193 nm data show little further change with time, whereas the ratios produced by the 213 nm laser continue to increase with time.

Laser fluence and spot size have significant effects on ablation rate and fractionation. Ablation rate increases with fluence but more slowly for larger spot sizes. A series of images taken after a set number of laser pulses shows the development of a crater wall that forms from the initial laser pulse and grows in height with time by the addition of melt material extruded from the pit (Fig. 2). The development of this wall is more pronounced with small spot size and low fluence. There is also a significant decay in signal intensity with time, especially with small spot sizes, indicating that progressively less material is being removed from the hole and transported to the ICP (Fig. 3). The net effect is a greater fractionation of ^{206}Pb/^{238}U with small spot size due to the retention of melt and condensed material in and around the laser pit (Fig. 4).

One of the main drivers for investigating the fundamentals of the ablation process is to get higher spatial resolution but without compromising data quality. The results of the first stage of the study have produced a better understanding of how zircon ablates and the fractionation of U and Pb using a nano-second pulse laser system. This will form the benchmark for the next exciting experimental phase using the femto-second laser system.

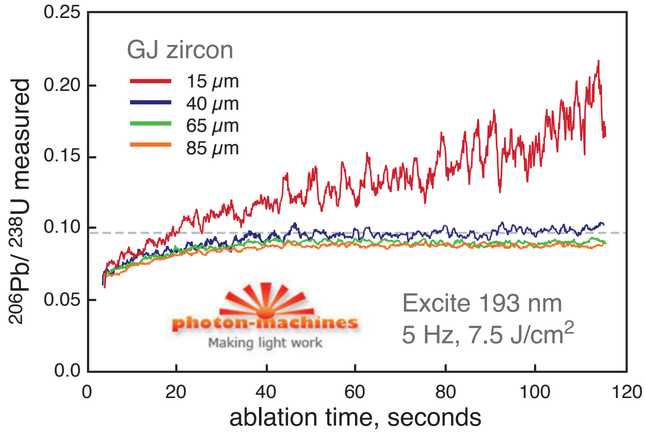


Figure 4. Plot of measured ^{206}Pb/^{238}U versus time for 4 different spot sizes (15, 40, 65, 85 μm) in GJ zircon.

This project is a Technology Development initiative in CCFS, contributes across all Themes (Early Earth, Earth Evolution and Earth Today), and contributes to understanding Earth's Architecture and Fluid Fluxes.

Contacts: Norman Pearson, Bill Griffin, Sue O'Reilly, Will Powell

Funded by: CCFS Foundation Project "Frontiers in integrated laser-sampled trace-element and isotopic geoanalysis"

Are ancient zircon ages real, or due to ancient element movement?

Zircons from the Tula Mountains, Napier Complex (East Antarctica), attracted scientific attention because they come from some of the oldest rocks on Earth (*Black et al., CMP, 1986*), which experienced high-temperature metamorphism at 2.8 Ga and ultra-high-temperature metamorphism at 2.5 Ga, with temperatures estimated at over 1100 ºC (*Hokada et al., Prec. Res., 2005*), some of the highest temperatures recorded in Earth's crust. Isotopic disturbance of zircons >ca 3.4 Ga old from the Napier Complex has been recognised for many years (*Williams et al., CMP, 1984*). To investigate this phenomenon further, we analysed zircon grains from three samples: one orthogneiss (from Gage Ridge) and two paragneisses (one each from Mount Sones and Dallwitz Nunatak). The analysis included U-Pb geochronology, oxygen isotopes, REEs, Raman spectroscopy and scanning ion imaging. All samples yielded reversely discordant data; the zircons from Mount Sones are significantly younger than those from the other two samples with an age range from 3.0 Ga to 2.5 Ga. Detrital zircons from Dallwitz Nunatak yield ages between 3.5 Ga and 2.5 Ga. The Gage Ridge sample contains four age groups with concordant data between 3.6 Ga and 3.3 Ga (*Kusiak et al., 2013a*) and a discrete population of ca 3.8 Ga zircon with reversely discordant data. The REE distribution in zircon from all three samples is generally similar, with steep MREE to LREE trends, consistent with an igneous origin. However, such patterns are also present in metamorphic zircon that grew in the absence of garnet. The sample from Mount

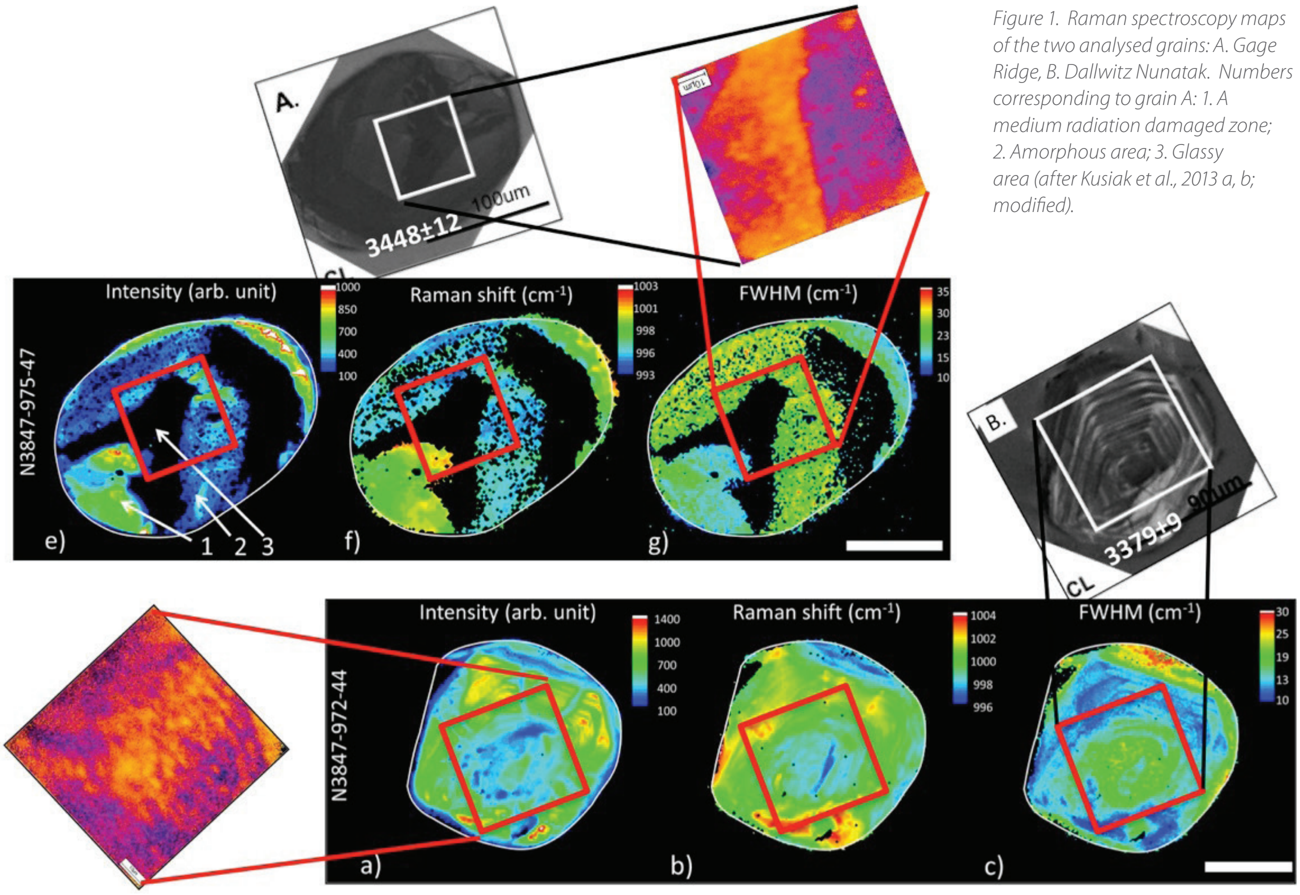


Figure 1. Raman spectroscopy maps of the two analysed grains: A. Gage Ridge, B. Dallwitz Nunatak. Numbers corresponding to grain A: 1. A medium radiation damaged zone; 2. Amorphous area; 3. Glassy area (after Kusiak et al., 2013 a, b; modified).

Sones contains garnet that grew during ultra-high temperature (UHT) metamorphism (ca 2.5 Ga), and, like Kelly and Harley (*CMP, 2005*), we suggest that 2.8 Ga zircon grew during metamorphism under high-temperature and low-pressure conditions in the absence of garnet.

To test for U/Pb disturbance during metamorphism we analysed oxygen isotopes in zircon from all three samples. Igneous zircons from Gage Ridge have lower $\delta^{18}O$ values (4.7-6.8‰) than zircons from the paragneisses. However, the Dallwitz Nunatak zircons give a scattering of ages, and $\delta^{18}O$ varies from 6.8-8.0‰ (average $\delta^{18}O$ – 7.4‰), as might be expected for detrital zircons. Low scatter in $\delta^{18}O$ in zircons from the Mount Sones paragneiss, together with high values (7.2-8.9‰, average $\delta^{18}O$ – 8.1‰), are consistent with growth during the earlier metamorphism at 2.8 Ga.

A novel high-resolution ion-imaging technique using the Cameca 1280 SIMS was used to generate maps of Pb-isotopic '*age*' for selected zircons. These record patchy variations in the isotopic ratios that result in spurious ages, including some that are Hadean (>4.0 Ga). Raman spectroscopy was used to determine the degree of metamictisation in the same zircon domains previously imaged by SIMS (*CCFS Publications #407, 429*). From our results (Fig. 1), it is evident that there is no correlation and that Pb is patchily distributed regardless of the degree of crystallinity.

From these results we conclude that there is no evidence that oxygen isotopes or REE in zircon were disturbed during the UHT metamorphism at 2.5 Ga. The reverse discordance in zircon from Gage Ridge, Mount Sones and Dallwitz Nunatak is related to ancient mobilisation of Pb and the most likely cause was polymetamorphism under dry conditions - two metamorphic events, one low-pressure at ca 2.8 Ga and a UHT event at ca 2.5 Ga.

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

The enigma of chromitites in the upper mantle resolved

The mantle sections and the crust-mantle transition zones of many ophiolites contain bodies of chromitite, almost monomineralic concentrations of Cr- and Al-rich spinel. They are important economically as a source of chromium, and scientifically because these rocks encapsulate information on the nature of ancient upper mantle, young oceanic mantle, mantle melt formation and percolation processes, and on large-scale geodynamic emplacement mechanisms.

During the last four decades there has been a hot debate about the origin of these type of chromitites, yielding a huge number of studies with diverse and passionately defended hypotheses. Forensic-type studies of individual chromitite bodies in isolation have led to a profusion of genetic models indicating that chromitites from different localities formed by different mechanisms. These models can be grouped into three broad categories: (1) Fractional crystallisation of basaltic melts in magma chambers or conduits in the upper mantle or around the crust-mantle boundary. Variants of this model include changing the composition of the melt by an external process such as melt-rock reaction or assimilation of pre-existing mafic rocks. (2) Mixing or mingling of melts within dunite channels. (3) Separation of volatile-rich fluid phases with an important role for oxygen fugacity.

Among the questions that these models have been not able to resolve satisfactorily are: (1) how can chromium, a minor element in a peridotite-derived basaltic melt, be concentrated to produce large monomineralic bodies of chromite?; (2) how does a chromitite body start to nucleate and grow?; (3) what factors control the size of individual chromitite bodies?

A major breakthrough in our understanding of the genesis of the chromitites has come during the development of this research project, through the *in situ* analysis of Os isotopes by laser-ablation MC-ICPMS analysis of single tiny PGMs (and larger base-metal sulfides), which are usually found as inclusions in the chromitites. The Os-isotope composition of individual PGMs can now be directly related to their microstructural setting, internal structure and bulk composition (*CCFS Publications #198, 334, 348, 349*).

The observation that the primary Os-rich PGMs in the chromitites are highly heterogeneous in terms of Os-isotope composition, even at the scale of inclusions in an individual chromite grain, suggests that the chromitite formed by the mixing/mingling of multiple basaltic melts that sampled different mantle sources, and have undergone variable degrees of fractionation. In the exposed mantle sections of several ophiolites, meso- and micro-structures of chromite suggest that the intersecting melt-filled dunitic channels were draining ascending basaltic melts in a suprasubduction mantle. This is the ideal framework to produce chromitites by mixing of basaltic melts of different provenance and degrees of fractionation. In our new model, the formation of a chromitite body, its size and the type of chromitite microstructures, are inferred to reflect focused melt flow within these high-porosity and high-permeability networks of channels at different melt/rock ratios, and different temperatures of melts and host peridotite. Melt/rock ratio controls the amount of crystallising chromite and the chromitite microstructures. Moreover, the observation that many chromitites cross-cut their host peridotites suggest that mixing of melts at the intersection between melt-filled dunite channels is not the unique '*physical*' trap inducing crystallisation of chromitites. Also, in relatively

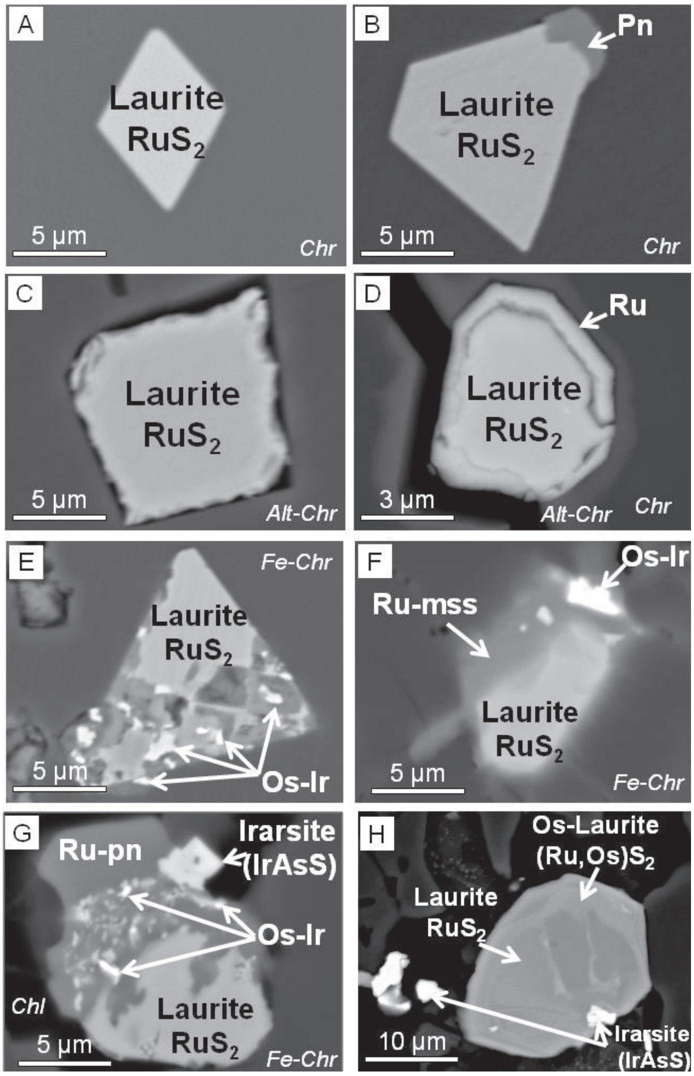
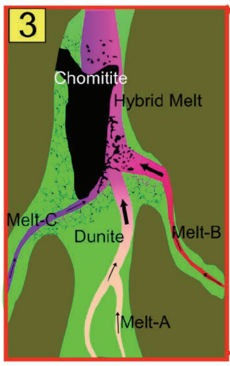
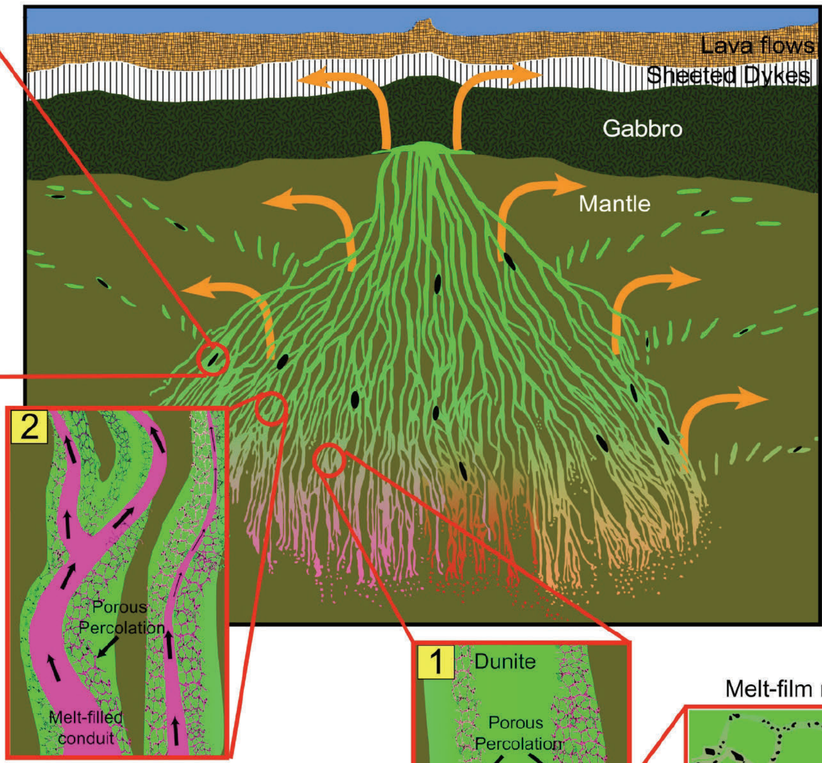


Figure 1. Backscattered electron images of Ru-Os sulfides and alloys from distinct microstructural positions in the Dobromirtsi chromitites. A and B: Primary (magmatic) laurite included in unaltered chromite. C and D: Partially corroded (secondary) laurite and Ru alloys in open fractures in chromite. E–G: Secondary assemblages showing distinct stages of alteration/replacement of laurite in ferrian chromite rims. H: Irregularly zoned laurite grain in the contact between a ferrian chromite rim and the interstitial matrix (for more details see CCFS Publication #42).





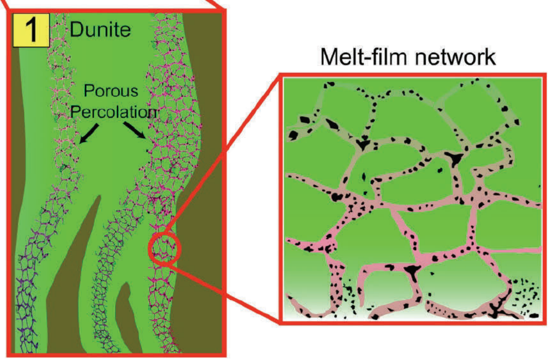


Figure 2. Formation of ophiolitic chromitites according to the new mechanism of crystallisation proposed in this work. A network of dunite channels drains melts ascending from different sources (marked with different colours) in the heterogeneous deeper mantle (modified from Kelemen, 2004). (1) Ascending melts move mainly by porous percolation through a melt-film network; in the zone of intersection between dunite channels mixing of basaltic melts with different SiO_2 promotes precipitation of chromite. The image is not to scale, as grains of olivine are generally from < 0.5 mm to a few centimeters. (2) Focused flow of melt produces melt-filled channels in dunite allowing the chemical isolation and rapid ascent of the melts. (3) Chemically isolated melts drained through different channels in the dunite meet and mix to produce hybrid melts able to precipitate volumes of chromitite. The size of the dunite network and the chromitite bodies can vary from a few metres to many kilometers.

cool mantle domains, chromitites may form in hydrofractures penetrating peridotites and infiltrated by interstitial chromite-bearing fluids. During these events of melt infiltration/injection, PGMs such as laurite or Os-Ir alloys already present in the mantle peridotite, or produced by the breakdown of PGE-bearing sulfides during the melt-rock reactions, can be also incorporated in a solid or crystal/melt mix into the parental melts of chromitites. This may explain why chromitites hosted in the mantle section of young ophiolites may contain PGM with Os-model ages > 2.5 Ga old.

On the other hand, the fact that some PGM grains in the chromitites are found along healed fractures cutting the primary chromite suggests that other populations of PGMs may have precipitated from metasomatic fluid/melts that infiltrated existing chromitites. The formation of this new generation of PGM can also explain the Os-isotopic heterogenity. The opening of the Os-isotopic system in PGMs associated with secondary chromite (produced by alteration of the magmatic chromite) also suggests that some PGMs that precipitated at mantle conditions, can be partly reacted and recrystallised during the infiltration of post-magmatic fluids. The recrystallisation of pre-existing PGM during polyphase metamorphism or '*recycling*' of the chromitite into deeper mantle levels can also explain the presence of micrometric PGMs with distinctly different Os-isotope compositions.

The results obtained in this project highlight the complex history that can affect the chromitites from their time of formation in the upper mantle, up to their surface emplacement. Chromitites may form at low pressures in the shallow mantle, but they can be later transported deep into the mantle (> 400 km) by subduction processes, and possibly integrated into the convecting mantle.

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

Contacts: José-María González-Jiminéz, Bill Griffin, Sue O'Reilly, Norman Pearson

Funded by: ARC ECSTAR Fellowship, ARC CoE CCFS Foundation Project 1 (TARDIS)

Transformation on Earth: the transition from ancient to modern Earth

Around 2.35 billion years ago (Ga), Earth's atmosphere and near-surface hydrosphere underwent perhaps the most fundamental revolution in Earth history since the Giant Moon-Forming Impact at 4.5 Ga: the rise in the concentration of atmospheric oxygen. This was a revolutionary event because of the effects it had on ocean chemistry and weathering: the oceans were scrubbed of iron (and soon after, manganese) and rusting of ferrous minerals in the continents released sulfate (and other elements) to the oceans through oxidative weathering. The resultant change in ocean chemistry is reflected in the rock record, with the disappearance of banded iron formations and the appearance of sulfates and phosphorites from 2.45-2.2 Ga. Eventually, the rise of atmospheric oxygen led to the evolutionary development (or at least, widespread flourishing) of eukaryotes, a more complex life form that depends on the extra energy available from oxygen. The rise of atmospheric oxygen coincided with climatic cooling to the extent that glacial deposits appear for the first time on many continents.

Only a few rock successions on Earth are preserved from across this period of Earth history, and almost all of those are plagued by an incomplete record with one or more unconformities, which are horizons of non-deposition, and/or erosion, where the history of change was not recorded, or preserved. However, there is one succession where a continuous sedimentary record is preserved across this interval of extraordinary change – the Turee Creek Group of Western Australia. In this succession, which is up to 4 km thick, we recently discovered the transition from ancient to modern Earth, recorded in a sequence of alternating banded iron formation, shale and chert, all of which gradually become less iron-rich up-section, recording the gradual oxidation of ferrous iron dissolved in seawater (Fig. 1: *Van Kranendonk et al., in review with Precambrian Research).* Further up-sequence, the appearance of stromatolites and rippled sandstones denote the progressive infilling of the Turee Creek Basin, and above that, we have discovered two glaciogenic successions, each marked by a period of rapid sea-level fall, when seawater volume was transferred into the developing ice sheets, followed by rapid sea-level deepening, as the glacial ice sheets melted (Fig. 2: *Van Kranendonk and Mazumder, in review with GSA Bulletin*).

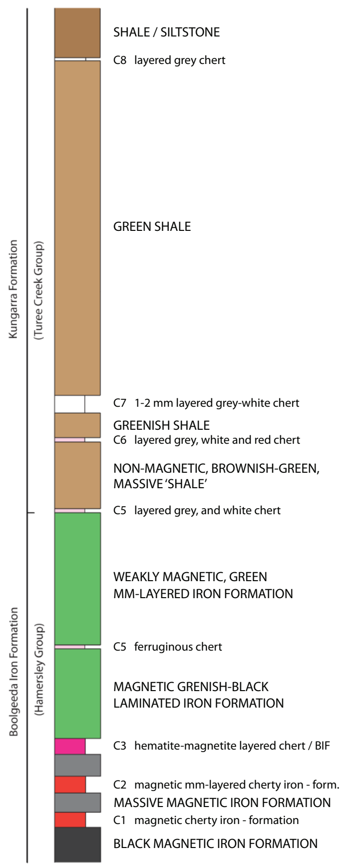


Figure 1. Stratigraphic section through the transition from the uppermost Boolgeeda Iron Formation of the Hamersley Group to the lowermost Kungarra Formation of the Turee Creek Group, here interpreted to occur at the base of the first non-magnetic unit. C1-C8 refers to chert layers from base to top across the section. (From Van Kranendonk et al., submitted).

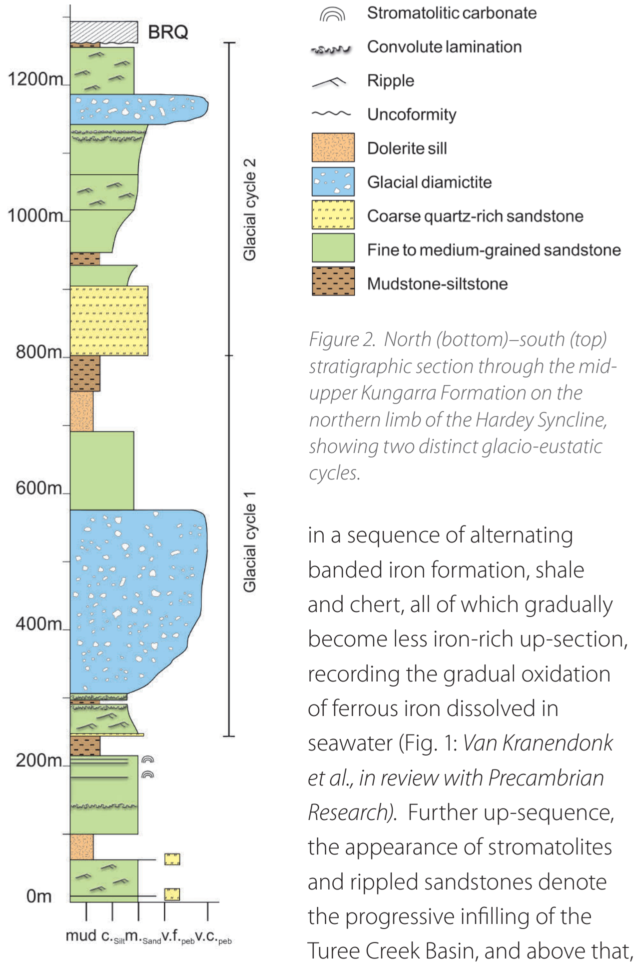


Figure 2. North (bottom)–south (top) stratigraphic section through the mid-upper Kungarra Formation on the northern limb of the Hardey Syncline, showing two distinct glacio-eustatic cycles.

In order to understand and quantify the nature of changes across this important interval, and to assess how the biosphere responded to this global climate change, Martin J. Van Kranendonk of the CCFS and his colleague from Paris, Professor Pascal Philippot, in collaboration with the Geological Survey of Western Australia, undertook a diamond drilling program to obtain fresh samples across each of the major transitions (Fig. 3). Three drill holes were obtained across different levels of the stratigraphy, including the basal contact with banded iron formations of the underlying Hamersley Group (ancient Earth), a full section through the lower of two glacial deposits and underlying stromatolites, and one through the upper part of the Turee Creek Group stratigraphy where the first sulfates might be expected to have been deposited, immediately above coastal to terrestrial sandstones of the Koolbye Formation (*Mazumder et al., in review, Precambrian Research*).

Preliminary results of drillcore inspection reveal that stromatolites have been intersected at several levels, and pyrite, of both authigenic and detrital origin, is common throughout the succession (Fig. 4). The basal transition from banded iron-

Figure 3. View looking over moderately dipping rocks of the Turee Creek Group, with the drillrig located on the flat ground in middle left. Lower slopes are glaciogenic diamictite.

formation to non-ferruginous chert was successfully recovered. A team of scientists from around the world will be analysing the cores to unlock their secrets and reveal more about the evolution of the ocean reservoir and the biosphere across the Great Oxidation Event.

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

Contact: Martin J. Van Kranendonk, University of New South Wales

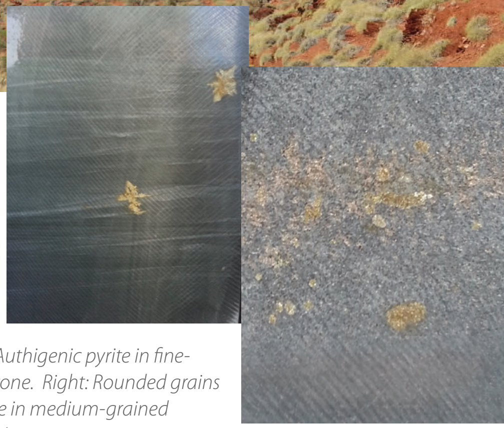


Figure 4. Left: Authigenic pyrite in fine-grained sandstone. Right: Rounded grains of detrital pyrite in medium-grained sandstone. Both views are 4 cm across.

Funded by: The University of New South Wales, Institute de Physique du Globe de Paris, the Agouron Institute

Isotopes reunite lost relatives in western Australia

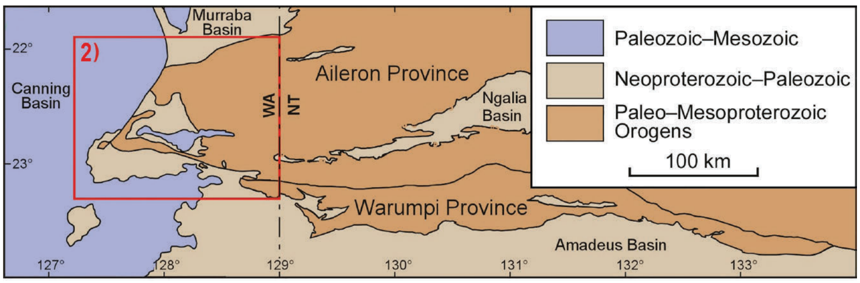
The Arunta Orogen of central Australia (Fig. 1) comprises a large part of the southern margin of the North Australian Craton and records episodic tectonic and thermal activity spanning almost 1.5 billion years of Earth's history, from the Paleoproterozoic to the Devonian. The 1690–1630 Ma Warumpi Province forms the southernmost part of the Arunta Orogen and is separated from the older, 1860–1700 Ma Aileron Province to the north by the Central Australian Suture (Fig. 2a). Both are unconformably overlain by Neoproterozoic to Paleozoic basins.

The Warumpi Province has been considered to be exotic to the North Australian Craton. However, Hf-isotope evidence for mixing between 1690–1630 Ma mantle-derived melts and older sources indicates that the history of the Warumpi Province involved interaction with significantly older crust of at least Mesoarchean age (Fig. 2b).

The ages and Hf-isotope compositions of inherited zircons in the 1677 Ma Pollock Hills Formation are consistent with this older crust being part of the Aileron Province. This suggests that the Warumpi Province represents a slice of Aileron Province crust rifted away from the southern margin of the North Australian Craton at, or prior to, 1690 Ma. The Warumpi Province then acted as a locus for the voluminous production of mantle-derived (juvenile) 1690–1660 Ma crust, both outboard of the southern Aileron Province margin, and during its accretion back onto the Aileron Province during and following the 1640–1635 Ma Liebig Orogeny.

Detrital zircons from Neoproterozoic units, including the Amadeus and Murraba Basins, which unconformably overlie the Aileron and Warumpi Provinces in the west Arunta region, record a history of distinct changes in erosional sources during their early depositional histories. Changes in detrital age components with stratigraphic level in the >840 Ma Kiwirrkurra Formation, the 1040–820 Ma Heavitree Quartzite, and the probably younger Munyu Sandstone, demonstrate marked changes from Warumpi-dominated to Musgrave-dominated detritus. This change in provenance over time probably relates to changes in tectonism in the region during the Neoproterozoic, possibly associated with breakup of the Rodinia supercontinent.
See *CCFS publication #436*

Figure 1. a) Location of the Warumpi Province on the southern margin of the Arunta region.



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

Contacts: Chris Kirkland, Michael Wingate
Funded by: CCFS, GSWA

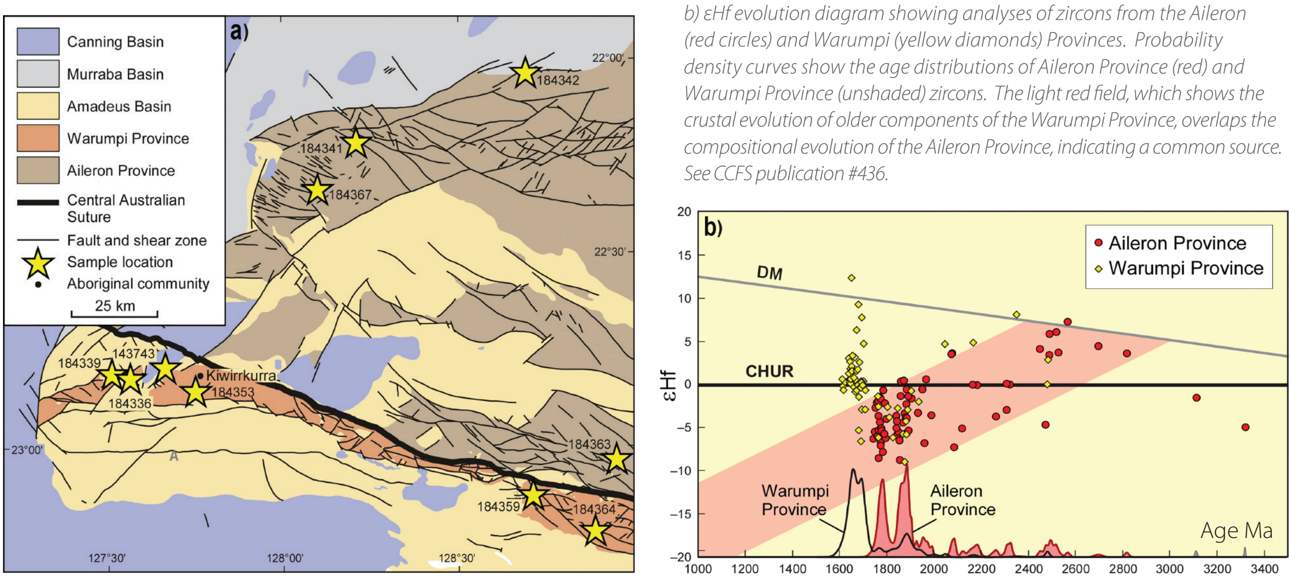


Figure 2. a) Simplified interpreted basement geology of the west Arunta region in Western Australia, showing the locations of analysed samples. b) εHf evolution diagram showing analyses of zircons from the Aileron (red circles) and Warumpi (yellow diamonds) Provinces. Probability density curves show the age distributions of Aileron Province (red) and Warumpi Province (unshaded) zircons. The light red field, which shows the crustal evolution of older components of the Warumpi Province, overlaps the compositional evolution of the Aileron Province, indicating a common source. See CCFS publication #436.

Tracking the birth and growth of the Central Asian Orogenic Belt

Most of the existing continental crust was generated by the end of the Archean (*CCFS Publication #342*), and the production of new crust has decreased markedly since that time (*Belousova et al., Lithos 2010*), except for some sporadic bursts of activity. One of these is the Central Asian Orogenic Belt (CAOB), a complex tectonic collage of microcontinental blocks, island arcs, and remnants of oceanic crust between the Siberian Craton to the north and the Tarim and North China cratons to the south. The CAOB is the world's largest Phanerozoic accretionary orogenic belts and is the most important site for juvenile crustal growth in the Phanerozoic. The challenge is to unravel the major magmatic events in the generation of the juvenile crust from this Phanerozoic accretionary orogenic belt, and to answer several major questions.

Why was the CAOB the locus of such extensive juvenile crustal growth in Phanerozoic? Is this related to the massive amount of oceanic crust that was subducted during closure of the Paleo-Asian Ocean, to subduction of the Mongol-Okhotsk arcs, or to the Siberian mantle plume? What was happening at the different continental margins (e.g. Siberian margin and North China Craton margin)? Was the pre-existing Paleozoic accretionary crustal architecture modified largely by Mesozoic magmatism? Our recent work (*Li et al. Earth-Science Reviews, 2013, Wang et al. American Journal of Science, 2014*) is beginning to provide plausible answers to these questions, from detailed regional geological, petrological and geochronological studies on the subduction-related, collision-related and intraplate

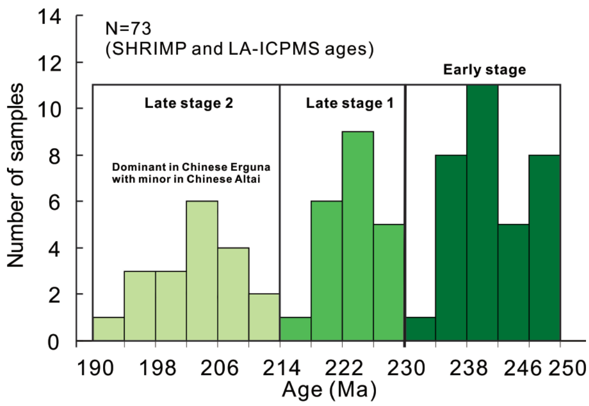


Figure 1. Histogram of Early Mesozoic zircon U-Pb ages in the CAOB. Only SHRIMP and LA-ICPMS zircon U-Pb data are used.

extensional magmatisms in the CAOB, tracing granite sources and origins to pinpoint crustal architecture and growth in the Early Mesozoic.

The numerous Early Mesozoic granitoids in the CAOB can be broadly classified into two groups on zircon U–Pb ages (Fig. 1): an early group from Early to Middle Triassic (250–230 Ma) and a late group emplaced during Late Triassic and Early Jurassic time (230-190 Ma). Early (250-230 Ma) granitoids are mainly distributed in the western Central Mongolia–Erguna Belt (CMEB), the western Altai Belt (AB), the South Mongolia–Xing'an Belt (SMXB) and the Beishan–Inner Mongolia–Jilin Belt (BIJB). They are mainly quartz-diorites, granodiorites and monzogranites, mostly of I-type, with minor mafic intrusions; some have adakite-like signatures and S-type features. Late (230-190 Ma) granitoids mainly occur in the North Mongolia–Transbaikalia Belt (NMTB), the eastern CMEB (Erguna massif) and the eastern Altai Belt (AB). They are mainly

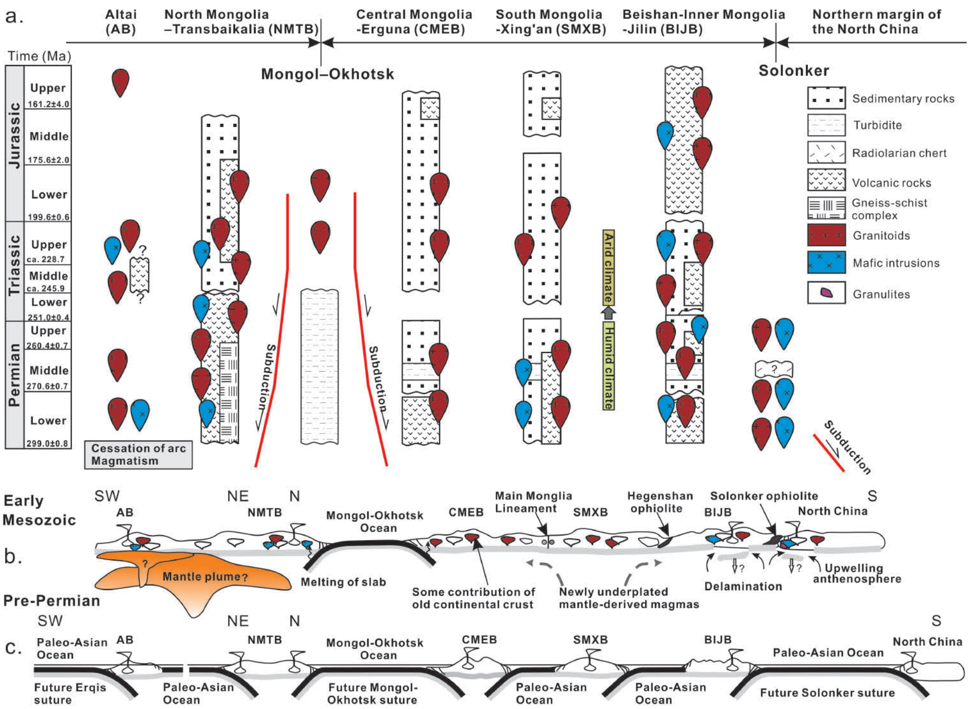


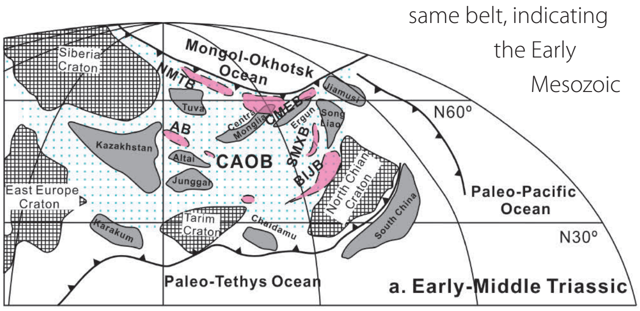
Figure 2. (a) Schematic space-time diagram showing major tectonic events affecting each belt in the CAOB. (b) Pre-Permian and (c) Early Mesozoic cross-section showing schematically the oceanic and arc/continent domains.

syenogranites, monzogranites and syenites, associated with many alkaline granites and mafic intrusions and are A-type and transitional I–A type or highly fractionated I-type granites.

Whole-rock Sr-Nd and zircon Hf isotopic data have been compiled for regional isotopic mapping. The $\varepsilon_{Nd}(t)$ values show large variations from –7.0 to +7.4 and Nd model ages (T_{DM}) from 0.46 Ga to 1.43 Ga; the initial Sr isotopic ratios (Sr_i) range from 0.7023 to 0.7174. The zircon $\varepsilon_{Hf}(t)$ values vary from -4.6 to +15.3 and give two-stage Hf model ages (T_{DM2}) from 0.30 Ga to 2.09 Ga. The extremely large variations of whole-rock Sr-Nd and zircon Hf isotopes imply heterogeneous source regions mainly dominated by juvenile components but with significant older crust as well. In the CAOB, the isotopic signatures (Nd-Hf) of the Early Mesozoic granitoids are similar to those of the Paleozoic granitoids in the same belt, indicating the Early Mesozoic crustal architecture retained its original Paleozoic continental signatures, which had not been modified by much juvenile mantle-derived material.

The older continental terrane was not thrust onto, or subducted beneath, the younger juvenile accretionary terranes, as seen in some collisional orogens. The crustal architecture in the CAOB is typical of an accretionary orogen that is characterised by horizontal accretion, not by vertical superposition of terranes. In contrast to the generation of massive juvenile crust in the Paleozoic accretionary stages of orogenic development, crustal recycling plays a more substantial role in the post-accretionary stages.

The generation of the Early Mesozoic granitoid magmas in the NMTB and the CMEB was dominated by the ongoing closure of the Mongol-Okhotsk Ocean and some were probably related to a mantle plume (Fig. 2). They may have been derived from melting of subducted materials or juvenile components with some probable contributions from ancient continental crust. Early Mesozoic granitoid magmas in the SMXB, the AB and the BIJB were generated in a post-/non-orogenic setting after the closure of the Paleo-Asian Ocean and were the results of partial melting of crustal components in response to underplating of mantle-derived magmas, most likely linked to lithospheric thickening, delamination and asthenospheric upwelling (Fig. 2). Early Mesozoic granitoid magmatism provides critical information on the Mesozoic post-accretionary tectonic evolution of the Paleo-Asian Ocean and transitional tectonic regimes from Early Mesozoic subduction to Late Mesozoic closure of the Mongol-Okhotsk Ocean as well as post-accretionary continental growth (Fig. 3).



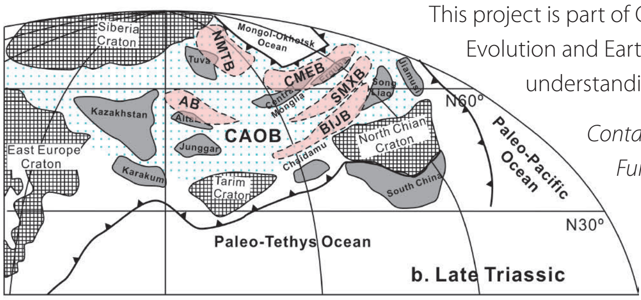


Figure 3. Schematic paleogeographic reconstruction of the Early Mesozoic ocean-continent framework of the CAOB and adjacent regions. The pink areas broadly represent the Early-Middle Triassic (a) and Late Triassic (b) granitoid belts in the CAOB.

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

Contacts: Shan Li, Tao Wang, Simon Wilde

Funded by: National Basic Research Program of China, National Natural Science Foundation of China, China Geological Survey

Ghosts of oldest bacterial colonies haunt Western Australia

Identifying and reconstructing Earth's earliest biosphere is challenging. Earth's oldest sedimentary rocks are not only rare, but almost always have been heated and deformed by tectonic activity so that former signs of life are destroyed or modified beyond recognition. A new study, however, has revealed the well-preserved remnants of a complex bacterial ecosystem in a 3.5 Ga sedimentary sequence from the Pilbara region of Western Australia (*CCFS publication #365*).

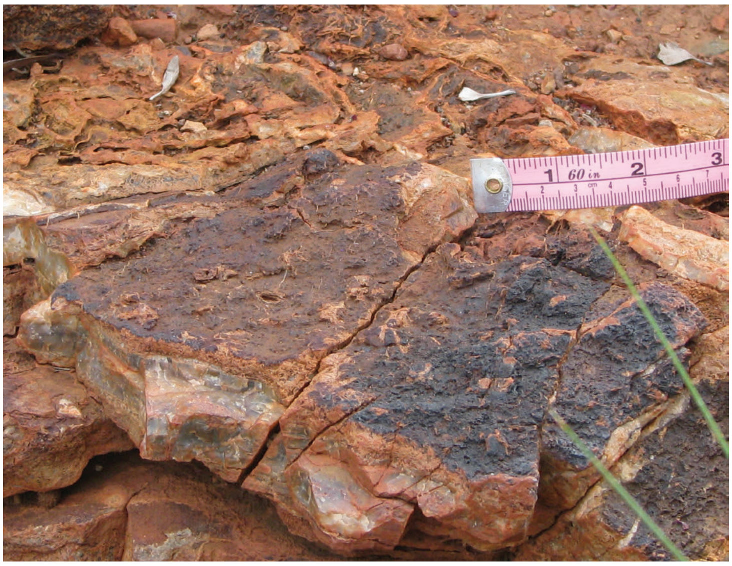


Figure 1. Microbial mat on rock surface from the 3.48 billion year old Dresser Formation, Pilbara, Western Australia.

The ancient core of the Pilbara terrane constitutes one of the rare geological areas that provide insights into the early evolution of life on Earth. Mound-like deposits (stromatolites) created by ancient bacteria, and rare microfossils of bacteria, have previously been described from this region. However, a phenomenon called microbially induced sedimentary structures, or MISS for short, had not previously been seen in rocks of this great age. Before our discovery the oldest MISS were ~ 3.2 billion years old.

MISS are created by communities of microorganisms, living in microbial mats, as they respond to changes in physical conditions such as erosion or sediment deposition in their immediate environment. A common example would be the binding together of sediment grains by microbes to prevent their erosion by water currents. MISS demonstrate not only the presence of life, but the presence of whole microbial ecosystems that could co-ordinate with one another and influence their environment.

MISS come in varied shapes and sizes. Some, such as crinkles and tufts on rock surfaces (Fig. 1), and eroded fragments of microbial mat, are on the millimetre to metre scale and can be seen with the naked eye. Other MISS are microscopic and typically include remnants of microbial filaments wrapping around sediment grains, or miniature versions of tufts (Fig. 2) and mat fragments. We have found at least ten distinct types of MISS from the 3.48 Ga Dresser Formation and demonstrated their close similarity in both morphology and preservation style to MISS found in the younger geological record. We also found that the structure and isotopic composition of carbon preserved in these MISS are consistent both with a biological origin and the known age of the samples.

As well as extending the geological record of MISS by almost 300 million years, our work shows that relatively complex mat-forming microbial communities probably existed almost 3.5 billion years ago. While it is arguable whether these MISS are the earliest signs of life on Earth, they certainly provide a new and robust source of evidence showing that large volumes of organisms were alive and well in these inhospitable conditions on the early Earth.

New discoveries of ancient life on Earth such as these can also be informative for the search for life on other planets, since the early histories of Earth and Mars are thought to have been similar. MISS could now be considered a prime target for Mars rovers, especially given that some MISS are of the centimetre scale and larger and may be visible to a rover camera.

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

Contact: David Wacey
Funded by: ARC CCFS CoE

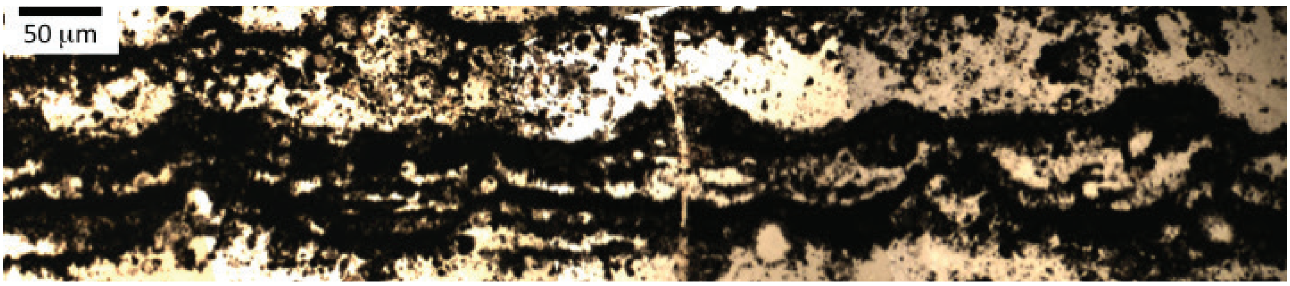


Figure 2. Cross-section through a tufted microbial mat from the Dresser Formation, viewed down the petrographic microscope. The black material is carbon and pyrite.

Trace elements in olivine are scouts for subducted continental crust in the source regions of magmas

Oceanic crust produced by sea-floor spreading at mid-ocean ridges is returned to the mantle by the process of subduction. This can be recognised by geophysical measurements that image sloping blocks of ocean crust beneath the surface, diving down beneath deep-sea trenches. For thirty years now, it has been debated how deeply these blocks are thrust into the mantle, and it is widely believed that some of this material reappears as chemical components in ocean islands such as Hawaii – thousands of kilometres from the position of any current subduction zone.

However, models for this recycling of crust usually deal with the basalts and gabbros that make up a thickness of about 7 km above the main mass of the ocean plate. It is much more difficult to characterise the recycling of the few hundred metres of sediments that were deposited on the ocean crust after its formation or during the collision process. Trace-element and isotopic compositions of volcanic rocks directly above the subduction zone indicate sediment subduction in some places, but in others the sediments are probably completely scraped off in the collision process, and do not follow the slab down into the subduction zone. The volumes of sediment involved are too small for the geophysical measurements to see.

Trace elements in olivine are a promising tool to solve this dilemma. Abundances of trace elements such as nickel, cobalt and manganese have been used to suggest the presence and melting of olivine-free rocks that originated from recycled oceanic crust beneath ocean islands (*Sobolev et al., 2007, Science*), but alternative explanations for these elements have also been put forward. No indicator for continental crust has been proposed as yet.

Our recent measurements in post-collisional volcanic rocks in the Mediterranean area have changed this. Many crustal blocks around the Mediterranean formed by a different subduction process, one that involved the collision and scrunching together of small ocean basins and blocks of continental crust – there is no deep subduction involved. These blocks are imbricated together and, after the lateral collision stops, the crust and lithosphere rise and melt, resulting in volcanoes that erupt 20-40 million years after collision ceases. These volcanic rocks contain large olivine crystals; some crystallised as the first minerals from the melts, and others were already present in the mantle and were torn off by the passing melt. These olivines have high concentrations of lithium and zinc (Fig. 1) - ten times as much lithium as is typical for mantle olivines, but similar to abundances seen in continental sediments. Coupled with previous results for lead isotopes in the volcanic rocks, which indicated input from continental crust, these lithium analyses in olivine clearly demonstrate the involvement of subducted continental sediments in the source regions of the melts. This process is widespread; the yellow points in Figure 1 are from Spain in the western Mediterranean, whereas the green points are from as far east as Turkey.

We will be pursuing research on this theme in the CCFS. The next questions are: [1] What are the olivines really '*seeing*'? We suspect that the lithium is concentrated by the formation of a different, intermediate rock type rich in mica and pyroxene, and this is what the olivines are really scouting for. [2] How important was subduction of continental crust earlier in Earth history? The suspicion here is that the accretionary type of collision involving small oceans and continental blocks, now seen in areas such as the Mediterranean and Indonesia, was much more widespread in the Archean, before all the continents had been formed.

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

Contact: Stephen Foley

Funded by: Geocycles Research Centre, University of Mainz - State of Rhineland Palatinate (Germany)

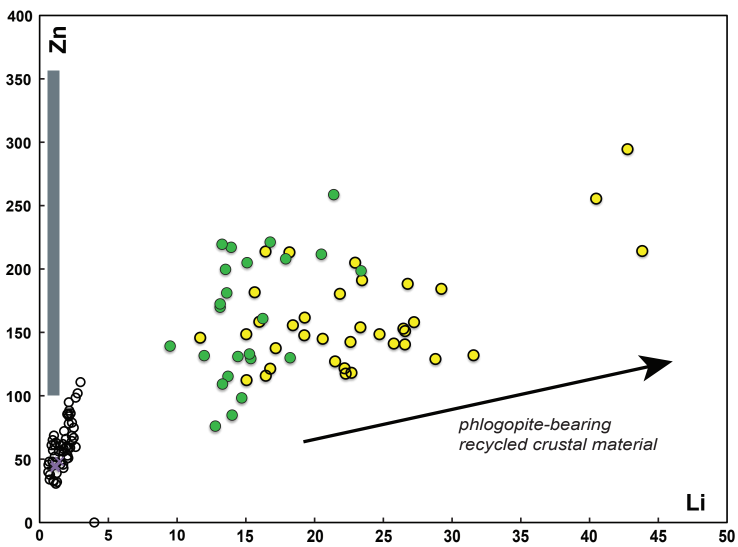


Figure 1. Both Li and Zn are enriched in olivines in Mediterranean post-collisional volcanic rocks (yellow and green circles) from source regions containing recycled continental crust, which is present in the source as phlogopite-bearing assemblages. Hawaiian olivines from sources containing recycled ocean crust lie in the grey box with variable Zn but low Li (1-2 ppm). Mantle olivines have almost exclusively less than 6 ppm lithium. From Foley, Prelevic, Rehfeldt and Jacob (2013) Earth and Planetary Science Letters Frontiers.

Auditioning zircons for perfecting performance

Zircon is a common U-rich accessory mineral recognised as a key geochronometer and premier geochemical tracer in terms of Hf and O isotopes because of its resistance to alteration and post-magmatic metamorphism. However, zircons with high uranium (U) contents commonly yield anomalous older apparent ages in ion microprobe analysis (commonly called the '*high-U matrix effect*') (*White and Ireland, Chem Geol, 2012*). Moreover, zircons with such discordant U-Pb ages usually also have disturbed oxygen-isotope compositions (Booth, GCA, 2005). Although these isotopic disturbances are commonly considered to be due to zircon metamictisation (the destruction of the crystal lattice by radiation damage), the discussion of data quality has mostly been qualitative. It is difficult to define a specific minimum U content that causes the '*high-U matrix effect*' or metamictisation, because the radiation damage is accumulated through time. This qualitative evaluation also has led most workers to overlook the different stability of zircon's U-Pb isotope system and oxygen-isotope system. For zircons in which the U-Pb system remains apparently undisturbed, the robustness of the oxygen isotope data is rarely questioned.

Raman spectra show that zircons with increasing degrees of radiation damage have gradually changing peaks and higher values of half-width height (Fig. 1), and the effects of radiation damage can be quantified, as displacements-per-atom, Ddpa

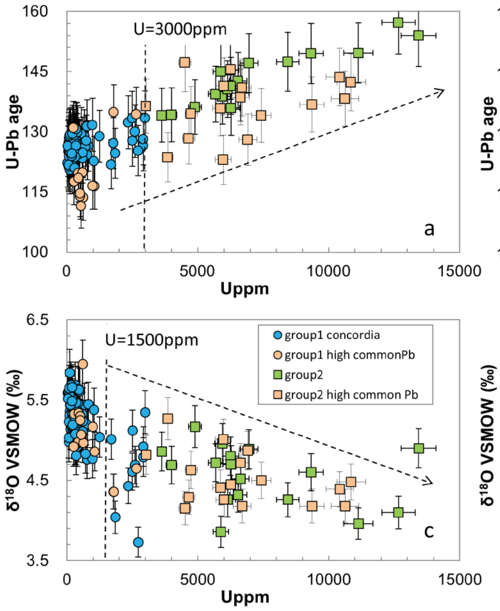


Figure 2. Plot of zircon U (or Ddpa) vs $^{206}Pb/^{238}U$ age (or $\delta^{18}O$); In-situ zircon U-Pb age and $\delta^{18}O$ data are obtained from SIMS analysis.

(*Palenik, Am Mineral 2003*). We have used this technique to assess the effect of varying U contents on the ion microprobe U-Pb and oxygen isotopic signatures of zircon-quartz pairs from the U-rich A-type granites of Suzhou (southern China). The results show that zircons with U concentrations ([U]) greater than 1500 ppm show a negative correlation between [U] and $\delta^{18}O$ values, while zircons with [U] greater than 3000 ppm show a positive correlation between [U] and U-Pb ages (Fig. 2). Oxygen-isotope analyses of coexisting quartz provide constraints for interpretation of zircon oxygen-isotope values, because the isotopic partitioning between quartz and zircon is well known. This relationship allows us

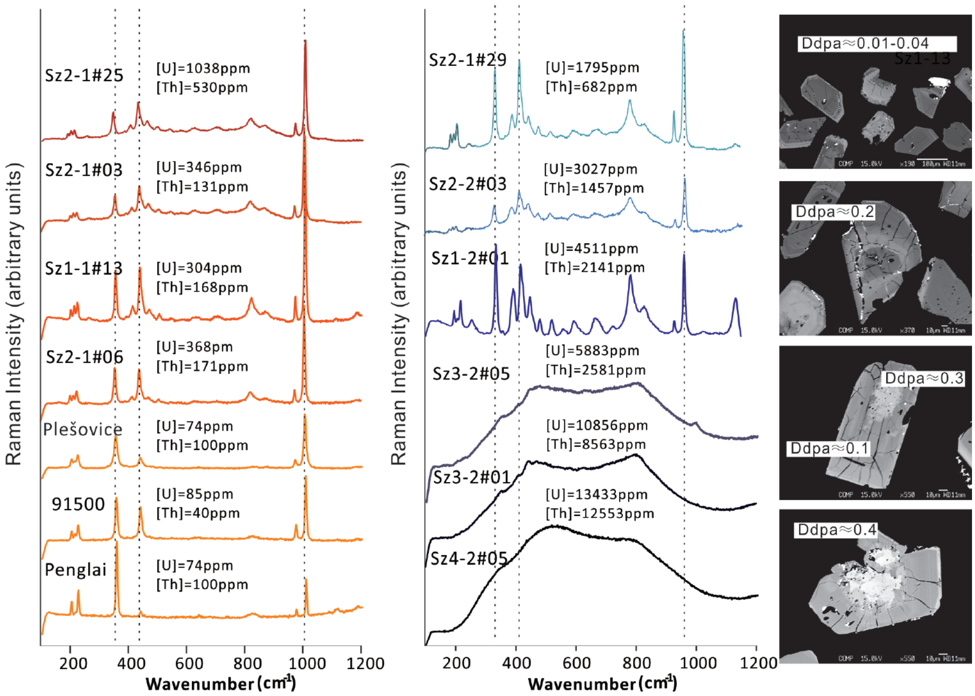


Figure 1. Raman spectra of zircons with different Ddpa values.

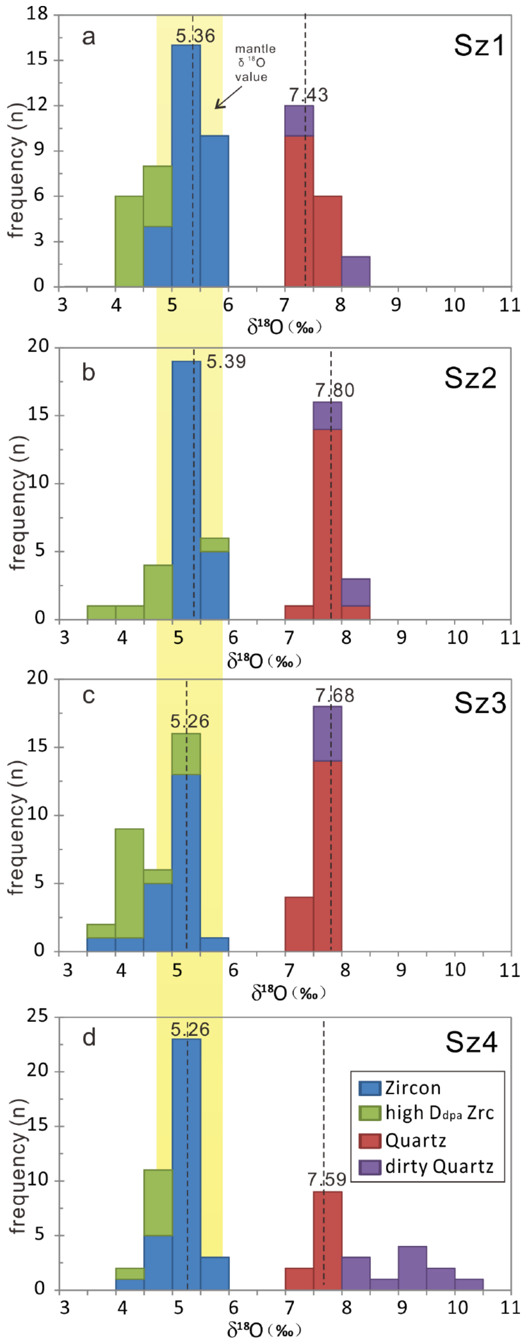


Figure 3. Histograms of δ^{18}O values for zircon-quartz pairs from the four representative Suzhou granite samples.

to recognise anomalous δ^{18}O values (Fig. 3), which are clearly common in high-U zircons.

The high U contents of the zircons thus produce two independent effects, linked by the radiation damage. Anomalously high SIMS U-Pb ages are a direct result of the matrix effect caused by metamictisation, whereas the low δ^{18}O values result from interaction with infiltration of OH-bearing fluid and fluid-facilitated diffusion in the radiation-damaged areas. Previous oxygen-isotope studies of bulk zircon separates from the Suzhou granites reported low δ^{18}O ratios; it is now clear that these represent anomalous values due to effects of radiation damage to the zircons.

This study shows how essential it is to evaluate the degree of radiation damage before/after carrying out dating or oxygen-isotope analysis on zircons with high U contents. Raman spectroscopy can be used to measure the degree of radiation damage of zircons, but, it is not always available, especially for pre-existing data and data from the literature. In the absence of Raman spectra, Ddpa calculated from the [U], [Th] and age can be used to estimate the highest degree of radiation damage and screening for reliable zircon U-Pb geochronology and oxygen isotope analysis (Fig. 4). The results indicate that for the Suzhou pluton, Ddpa <0.03 is a robust discriminant threshold to identify zircons with primary oxygen-isotope ratios and Ddpa<0.08 is a robust discriminant to screen for reliable U-Pb dating. These different screening values reflect the evidence that oxygen-isotope compositions show disturbance at a lower level of post-crystallisation zircon lattice disturbance than does the U-Pb system.

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

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Funded by: EPS postgraduate fund, iMQRES, MQ PGRF, CCFS, IGGCAS

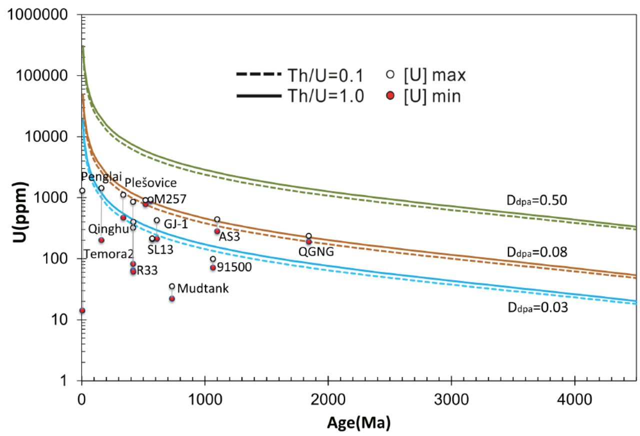


Figure 4. Correlation between U concentration and U-Pb ages, along with assigned Ddpa of 0.03, 0.08, and 0.5. Dashed lines Th/U = 0.1; solid lines Th/U = 1. The area between dashed and solid lines with same Ddpa, including all the zircons with Th/U = 0.1 ~ 1. Data sources for standard zircons: Penglai – Li, Geost. Geoan. Res, 2010; Qinghu – Li, Sci China Ser D, 2009; Plešovice – Slama, Chem Geol, 2008; Temora – Black, Chem Geol, 2003; R33 – Black, Chem Geol, 2004; M257 – Nasdala, Geost. Geoan. Res, 2008; SL-13 – Lee, Nature, 1997; GJ-1 – Jackson, Chem Geol, 2004; Mud tank – Black and Gulson, BMR J Aust Geol Geophys, 1978; 91500 – Wiedenbeck, Geostandards Newsletter,1995; AS3 – Paces and Miller, JGR,1993.

Why hasn't the Mediterranean Basin closed?

The Mediterranean Sea is the vestige of a large ocean that was closed by the northward movement of the African plate, creating the Alps as the leading edge of the African plate was subducted beneath Europe. But why did it stop there? Why does the Mediterranean exist at all? A growing body of data on U-Pb ages of magmatic zircons, Hf model ages of inherited zircons and whole-rock Nd model ages of crustal igneous and metamorphic rocks has provided many constraints on crustal evolution within the Mediterranean basin. However, there has been little robust information on the age of its underlying mantle, that would allow us to understand the deeper geological framework of the Mediterranean.

A synthesis of Re-depletion model ages (T_{RD}) for both whole-rock samples and *in situ* analyses of individual sulfides from mantle-derived rocks, including xenoliths and peridotite massifs that are widespread across the Mediterranean area, demonstrates the existence of different mantle domains *(CCFS Publication #234)*. A maximum T_{RD} age of 1.8 Ga is common to sulfides in mantle-derived peridotite xenoliths beneath Western Europe (Calatrava Volcanic Field, Spain; Languedoc and Massif Central, France) and to whole-rock samples from Azrou (North Africa) and the Pyrenees (France). A maximum at <1.4-1.3 Ga is seen in whole-rock samples from Central Europe (Bohemian and Rhenish Massifs) as shown in Figure 1.

In contrast, Os-bearing sulfides in xenoliths and sulfides and platinum-group minerals in peridotite massifs from the inner Mediterranean region (Hyblean Plateau in Sicily and Kraubath Massif in Austria) all show an oldest T_{RD} peak at ~ 2.3 Ga, equivalent to the oldest whole-rock T_{MA} of 2.2 Ga for rocks of Beni Boussera in northern Morocco and the 2.4 Ga peak in sulfides from peridotites of the internal Ligurides (Italy). A peak at 2.6 Ga is defined by sulfides in mantle xenoliths from the Tallante Volcanic Field in southern Spain.

These Re-Os data identify the existence of a common Paleo-Proterozoic (1.8 Ga) mantle on both sides of the Mediterranean realm, and an older (2.2-2.6 Ga) lithospheric mantle sitting inside the more recent Maghrebide-Appenine-Betic front generated during the Alpine-Betic orogeny. Thus, the Mediterranean basin may contain several buoyant Archean microplates, which could act like bollards, impeding the northward movement of Africa, and protecting the Mediterranean from closing.

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

Contacts: José María González-Jiménez, Bill Griffin, Sue O'Reilly

Funded by: CCFS ARC ECSTAR funds

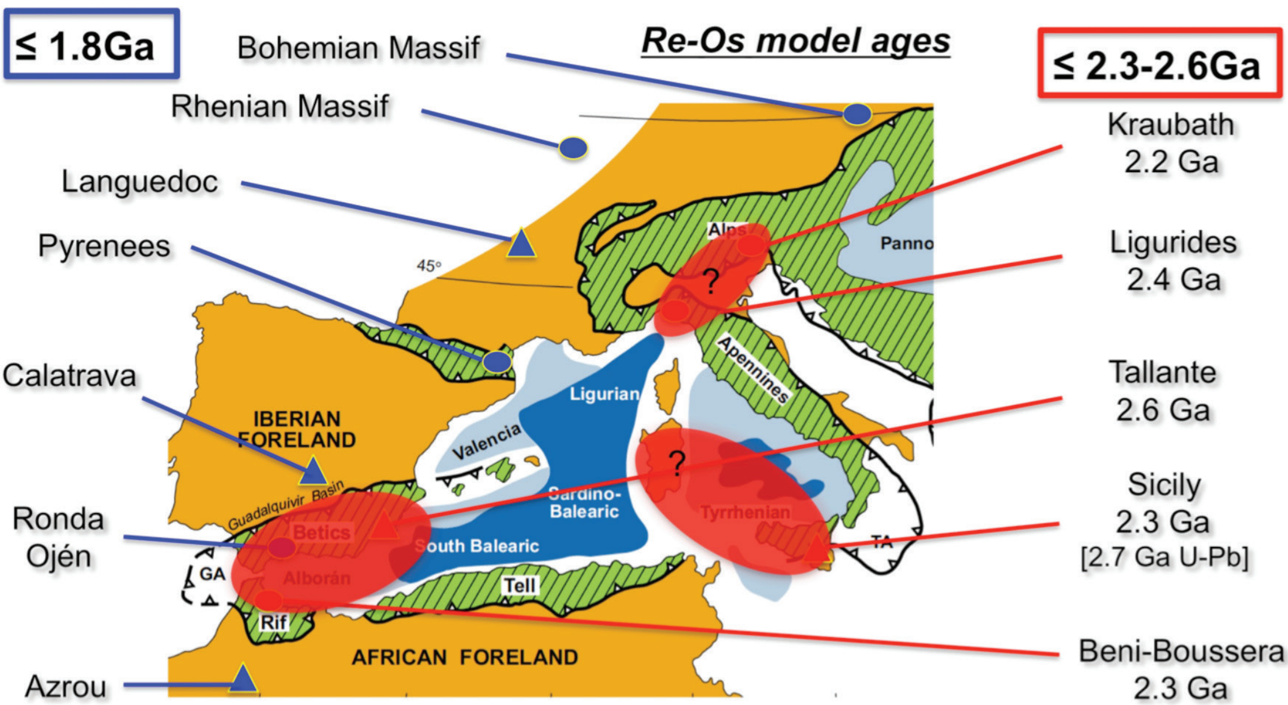


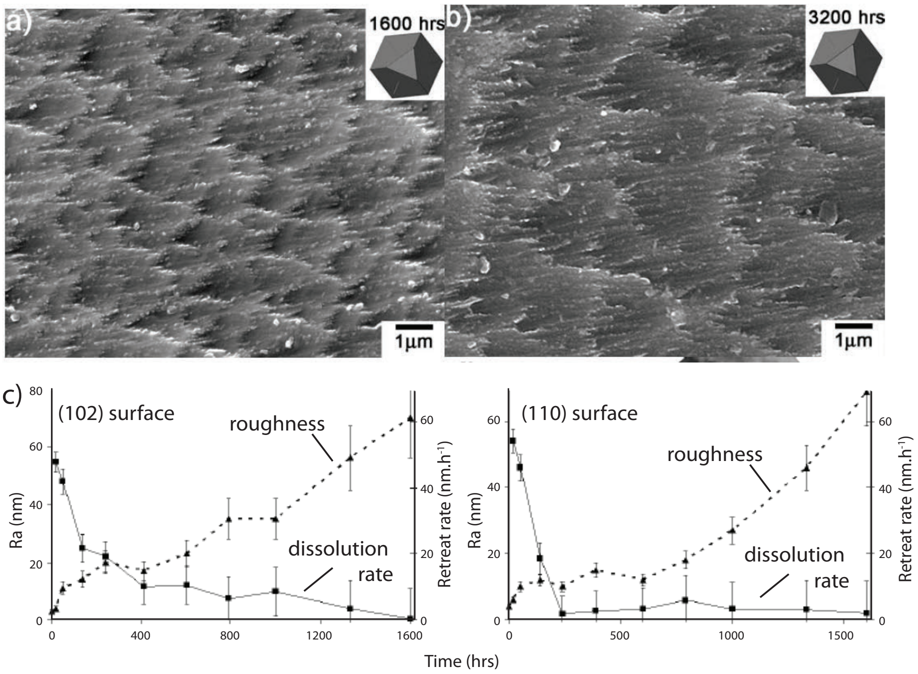
Figure 1. Distribution of maximum T_{RD} model ages across the Mediterranean region. The tagged line represents the Maghrebide-Appenine-Betic tectonic front. Red areas indicate possible Archean micro-plates.

Surface structures influence reaction rates of minerals

The rate at which minerals are dissolved and grow is crucial in our understanding of how Earth materials have changed in terms of physical and chemical properties through time. In recent years, it has been realised that many reactions that transform one mineral to another require fluid involvement. The first and often crucial step in this transformation is dissolution.

We have investigated the dynamics of dissolution and the time evolution of the (often assumed) parameter, dissolution constant, that determines at which rate a mineral dissolves under specific conditions. Classically, dissolution rates are calculated based on models of dissolution kinetics as a function of surface area, which is assumed to remain constant. However, this assumption ignores the changes occurring on the surface during the dissolution process. We examined how the topography of natural fluorite surfaces with different crystallographic orientations changed during up to 3200 hours of dissolution. The results were analysed in terms of changes in surface area, surface reactivity and dissolution rates.

We found that the dissolution rate is strongly time-dependent, while the value of the dissolution constant varies depending on the crystallographic orientation of the dissolving surface. All surfaces studied show rapid changes in topography and rapid dissolution rates during the initial 200 hours of dissolution. The factors controlling the development of topography are the stability of the step edges forming the initial surface and its inclination to the closest stable planes, which are specific for each surface orientation. The surface dynamics are accompanied by a significant decrease of dissolution rates after the initial rapid-dissolution regime. The time-dependent variation of dissolution rates is attributed to a decrease in the density of step edges on the surface and the continuously increasing exposure of more stable planes with time. During a second dissolution regime, some surfaces continue to show significant changes in topography, while on others the topography tends to remain approximately constant.



Change in dissolution rate, surface structure and topology / roughness as a function of time and surface orientation. (A) & (B) Examples of SE images showing topography of one studied surface after 1600 hrs and 3200 hrs dissolution. (C) Graphs showing that dissolution rates are initially high, while roughness/topography is low, subsequently dissolution rates decrease while roughness / topography increases. Two examples are shown, (left) surface (102), (right) surface (110).

Our observations suggest that the development of topography during the initial dissolution regime is kinetically driven, and therefore the surface may only reach a metastable state. The height and size of the topographic features initially developed, and the types of planes and step edges that constitute them, determine the changes during the second dissolution regime. Dissolution transforms the metastable surfaces formed during the initial dissolution stage towards a more stable topography. Importantly, our results show that, contrary to classic theory, dissolution rates decrease even though the total surface area increases. Therefore, calculations of dissolution rates that assume dissolution rates are directly proportional to surface area are not valid for the surfaces studied. Instead, to develop accurate kinetic-dissolution models and more realistic stochastic dissolution simulations the surface reactivity, as determined by the relative stability of the planes and type of edges that constitute a surface, must be taken into account.

Even though experiments were performed using fluorite, the same principles are predicted to hold for other crystal structures. This study may be the first step toward a quantitative characterisation of the often heterogeneous, fluid-mediated replacement of different minerals in the Earth's crust and Mantle (see *CCFS publication #364*).

This project contributes to the CCFS Theme 3, Earth Today, and furthers our understanding of Earth's Fluid Fluxes.

Contact: Sandra Piazolo
Funded by: ARC Future Fellowship, European Research Council

Different continent configurations around 800 – 500 million years ago give new clues about extreme climatic variations

The Neoproterozoic was one of the most dynamic times in Earth history, featuring the formation and breakup of the supercontinent Rodinia (e.g. *CCFS contribution #117*), repeated low-latitude glaciation at sea level (a Snowball Earth?), rapid oxidation of the atmosphere, and the end of the Precambrian explosion of complex life. To better understand the relationships between these dramatic events, we developed a set of revised global palaeogeographic maps for the 825–540 Ma time interval, accompanied by a compilation and graphical illustration of global data on sedimentary facies (*CCFS contribution #314*; see Fig. 1 for examples). These maps form the basis for an examination of the relationships between known glacial deposits, paleolatitude, positions of continental rifting, relative sea-level changes and major global tectonic events such as supercontinent assembly, breakup and superplumes.

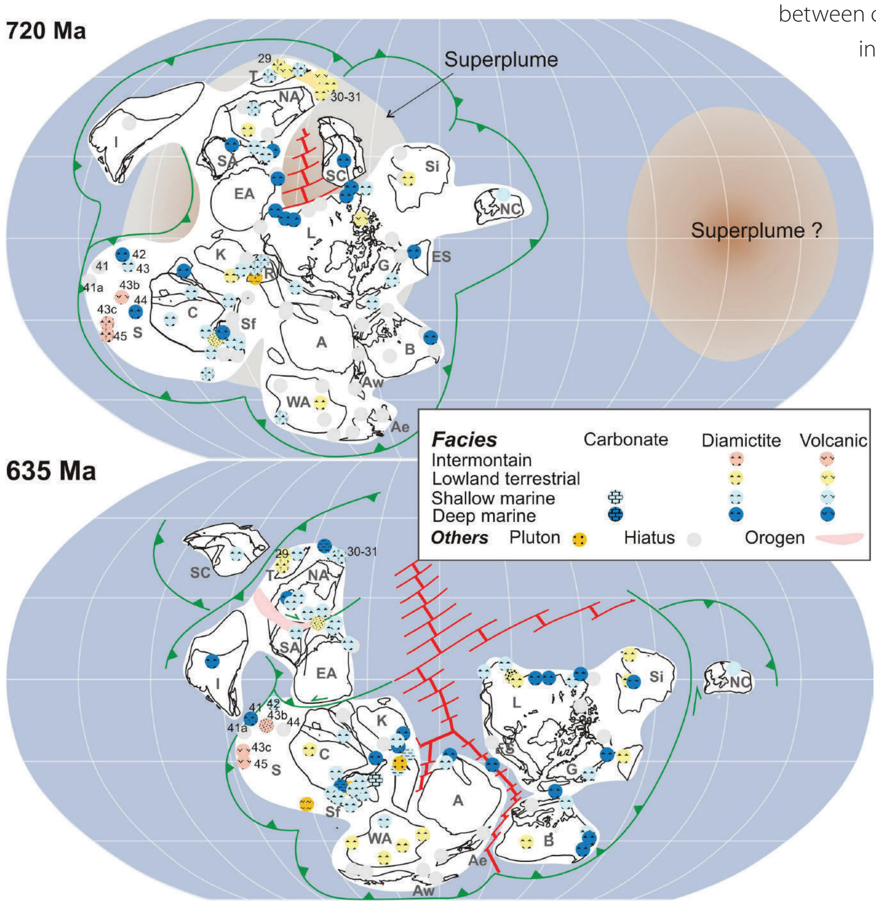


Figure 1. Revised global palaeogeographic reconstructions for 720 Ma and 635 Ma, with facies distributions featuring the occurrence of the "Sturtian" (ca. 720 Ma) and "Marinoan" (ca. 635 Ma) glaciations, respectively.

Our analysis reveals several fundamental palaeogeographic features that will help inform and constrain models for Earth's climatic and geodynamic evolution during the Neoproterozoic. First, whereas the latitudinal distribution of carbonate rocks appears to be in accord with a normal zonal global climate similar to that of the Phanerozoic (Fig. 2c), thus validating the palaeogeographic maps, glacial deposits at or near sea level appear to extend from high latitudes into the deep tropics for all three Neoproterozoic ice ages (720 Ma, ca 635 Ma, and ca 580 Ma), although the 580 Ma interval remains very poorly constrained in terms of both paleomagnetic data and global lithostratigraphic correlations (see Figs. 1 and 2b for latitudinal distributions of all three glacial events). This appears to be consistent with the predictions of the Snowball Earth model (e.g. Hoffman et al., 1998). Second, continental sedimentary environments were dominant in epicratonic basins within Rodinia (from >825 Ma to 750 Ma; Fig. 2a shows the low proportion of deep-marine facies for that time), possibly resulting from both plume/superplume dynamic topography and lower sea-level due to dominantly old oceanic crust. This was also the case at ca 540 Ma (Fig. 2a), but at that time the pattern reflects widespread mountain ranges formed during the assembly of Gondwanaland and the increasing mean age of global ocean crust. Third, deep-water environments were dominant during the peak stage of Rodinia break-up between ca 720 Ma and ca 580 Ma (Fig. 2a), probably indicating a higher sea level due to increased rate of production of newer oceanic crust, and perhaps the effect of continents drifting away from a weakening superplume. Such a geodynamic control of first-order global sea-level changes has also been observed during the evolution of the youngest supercontinent Pangaea (e.g. *Muller et al., 2008*), and agrees well with the hypothesised dynamic supercontinent-superplume coupling (see *Li and Zhong PEPI, 2009* for a review of the model). Finally, there is no clear association between continental rifting and the distribution of glacial strata, contradicting models that restrict glacial influence to those particular tectonic environments.

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

Contact: Zheng-Xiang Li
Funded by: CCFS Foundation Project 6

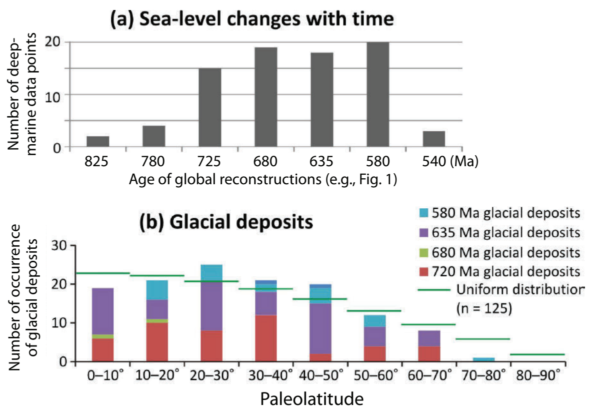
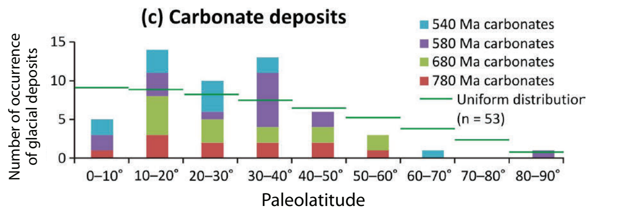


Figure 2. (a) Variations in the number of data points showing deep marine environments among seven palaeogeographic snap shots. (b) Paleolatitudinal distribution of glacial deposits, and (c) paleolatitudinal distribution of carbonate deposits according to the revised palaeogeographic reconstructions with facies distributions (see Fig. 1 for example).

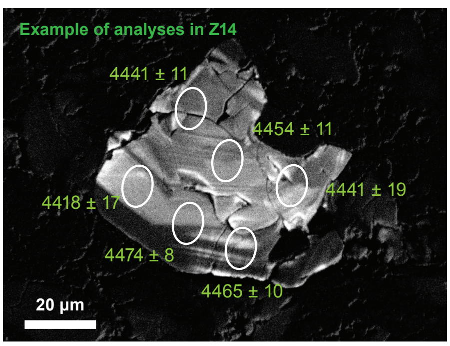


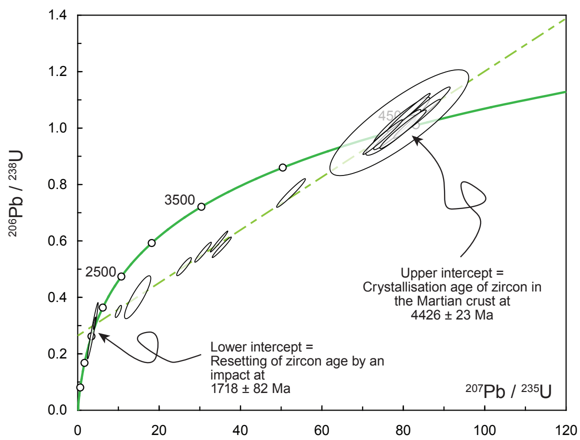
The first Martian crust

Mars is the closest planet to Earth after the Moon and mankind has long speculated about possible life on Mars. The science-fiction novels from the fifties depicting human colonies on the red planet certainly fed this curiosity and contributed to the modern development of the small robots now roving the surface of Mars (like NASA's Opportunity and Curiosity). These remotely-controlled rovers have been providing stunning images and data from the Martian surface and have massively improved our knowledge of the planet. The other way we can study Mars is by finding and collecting meteorites, first launched from its surface during impacts, and then delivered to Earth. While the rovers and their range of high-tech instruments concentrate on the study of the surface, Martian meteorites provide insight into the deeper part of the planet. Most of them are mafic and ultramafic rocks originating either from the mantle or from the young volcanic plains covering the northern hemisphere of Mars. The southern hemisphere of Mars, known as the Southern Highlands, is believed to be much older and to hold clues to the planet's early differentiation. Yet, so far, no samples are available from this part of the planet.

A Martian meteorite recently recovered from the north-western African desert and called NWA 7533 is strikingly different from the other known Martian meteorites: it is a fragment of Mars' regolith breccia, comprising a fine mixture of fragments of igneous rocks and clast-laden impact melt. Superficially, it appears quite similar to some Apollo samples but has the unique Martian compositional signature (as identified by oxygen isotopes). It also contains (i) high abundances of meteoritic siderophile elements (like Ni and Ir) suggesting it formed as a result of impact and (ii) fine-grained material with composition similar to soil analysed from the Gusev crater by the Spirit rover, suggesting the meteorite mainly consists of soil particles; hence its classification as a regolith breccia. NWA 7533 also contains small magmatic clasts, enclosing zircon grains.

Our part in this exciting project was to image and date these zircon grains, achieved by in situ U-Pb dating using the SHRIMP (ion microprobe) in the John de Laeter centre at Curtin University. The small meteorite slab we studied contained seventeen zircon grains; ten were large enough to be dated, and seven grains, representing eighteen ion-microprobe analyses, could be combined to define a Discordia line. The upper intercept age at 4426 ± 23 Ma (million years) is interpreted as the crystallisation age of the zircon grains. The lower intercept age at 1718 ± 82 Ma represents the time where the U-Pb system was disturbed, most likely by an impact. The discovery of such ancient zircon grains on Mars implies that the planet's early crust differentiated at about the same time as the Earth and the Moon crusts (*CCFS Publication #370*). This is of particular interest as it may point toward a similar mechanism for the differentiation of terrestrial planets, regardless of their present shape and overall mass.





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

Contacts: Alexander Nemchin, Marion Grange

Funded by: CCFS (Marion Grange salary)

Tracking deep fluid processes where continents collide: magmatic segregations in a Tibetan orogenic peridotite

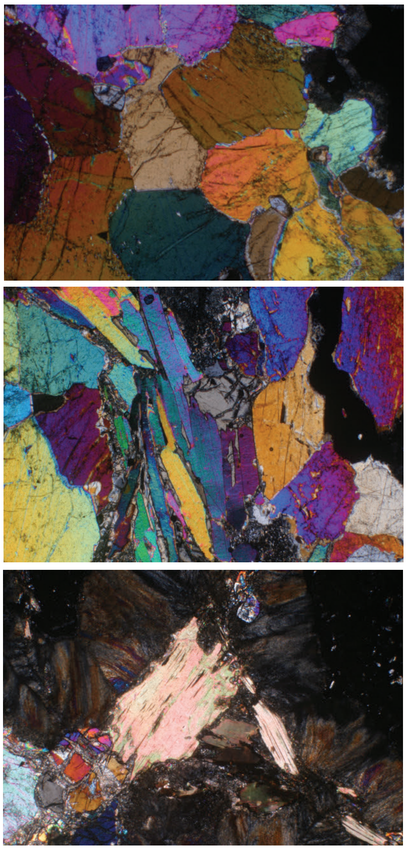


Figure 1. Thin-section photomicrographs of the Shenglikou pyroxenites, North Qaidam, NE Tibet.

Arc magmatism in subduction zones is a prime process controlling element recycling and continental growth at the convergent margins in the shallow Earth, but the early stages of magmatic processes at mantle depths remain unclear. Many previous studies have shown an andesitic average for the composition of the continental crust in contrast with the basaltic nature of primitive melts in plate collision zones, suggesting there is a complementary rock-type component at depth. Mafic to ultramafic pyroxenites hidden within the arc roots have been suggested as this complement (e.g. *Kay and Kay, GCA 1988; Dhuime et al., J Pet. 2009*). Thus, knowledge of the genesis and sources of these '*hidden*' pyroxenites is critical to understanding the dynamic processes of generation and migration of primitive arc magmas beneath active margins, and to linking the recycling of material between subduction slabs and erupted volcanics within a complete framework of plate convergence. This study examines the origin and history of pyroxenite dykes (interpreted to be magmatic segregations; Fig. 1) in the Shenglikou peridotite massif (North Qaidam Orogen, NE Tibet, China).

Major- and trace-element compositions of the pyroxenites indicate an origin as high-pressure (garnet-facies) cumulates and/or trapped melts, and the derivation of the parental magmas from the melting of a deep peridotite-dominated source. Bulk-rock trace-element patterns also show strong enrichment in fluid-mobile elements (Cs, Rb, Ba, U, Pb and Li) and marked negative anomalies in the high-field-strength elements relative to rare earth elements; overall they are geochemically similar to melts from a volatile-rich arc-type mantle. Initial Sr isotopic ratios (0.7152-0.7105) and Nd isotopic compositions (εNd(t) = -11.6 to -4.4) of clinopyroxene and garnet confirm the contribution of subducted sediments. However, the Hf isotopes of clinopyroxene, garnet and zircon show depleted-mantle isotopic values at 430 Ma; one garnet sample with depleted-mantle model age of 846 Ma shows minimum assimilation of the host peridotite during the pyroxenite intrusion. Oxygen isotopic signatures of garnet and zircon imply uncontaminated upper-mantle sources. These decoupled isotopic features further suggest that the melt source was a peridotite-dominated convective mantle wedge (controlling the Hf and O isotopes) that had been pervasively metasomatised by fluids from the subducted slab (controlling the Sr-Nd isotopes and highly-incompatible elements).

This study illustrates a detailed dynamic process of arc magmatism within the mantle wedge beneath an active continental margin (Fig. 2). A strongly metasomatised convective mantle moved as corner flow resulting from the early Cambrian subduction of the Proto-Tethys oceanic slab. The decompression and flux melting generated magmas that intruded into the overlying lithospheric mantle wedge as pyroxenite dykes. We suggest this is a significant process to allow the mafic-ultramafic complements of continental-arc lavas to escape delamination back to the convective mantle.

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

Contacts: Qing Xiong, Sue. O'Reilly, Bill Griffin, Norman Pearson, Jian-Ping Zheng (China University of Geosciences, Wuhan)

Funded by: ARC Discovery , Centre of Excellence Grants (S.Y.O'R and W.L.G.), NSFC (J.P.Z.), CSC scholarship, IMQRES, MQ PGRF, EPS postgraduate fund

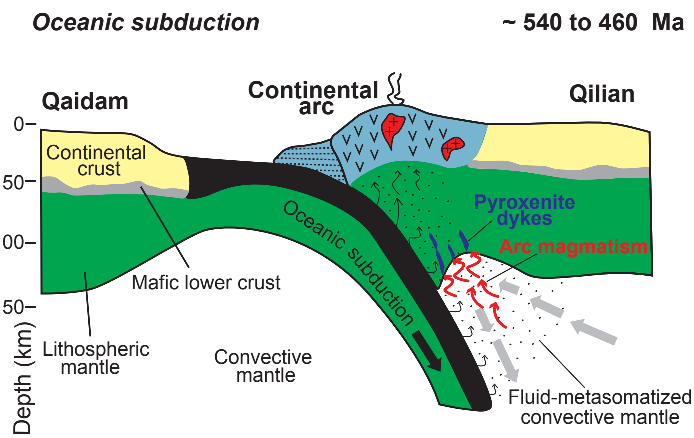


Figure 2. Cartoon representing our interpretation of the formation and evolution processes of the Shenglikou pyroxenite dykes within a tectonic framework of an early Paleozoic active continental margin, NE Tibet.

How soft is the lower crust? More ingredients to test the '*jelly sandwich*' model

Today, ancient rifting environments are important zones for the production of oil and minerals. Observations of rifted basement rocks, under the sediments that accumulate in the rifts, show they have experienced both shearing and extensional strain, often at lower-crustal depths. This project aims to develop a quantitative tool to determine the relative viscosity or '*resistance to flow*' of different rock types at lower-crustal levels. For such a study, '*boudins*' (French: a specific type of sausage; elongate sausage-shaped pieces of one rock layer aligned like a chain of pearls) can be used. Boudins occur where a harder, more competent layer in a weaker matrix is deformed by pure and/or simple shear, and at microscopic to landscape scales; they develop a variety of symmetric and asymmetric shapes. The temperature and pressure in the lower continental crust mean the rocks can flow and deform in ways unseen at the Earth's surface, and different rock types have different physical characteristics, melting temperatures, hardness, flow characteristics and viscosity. Our study adds more information about the rheological characteristics of the lower crust and will provide new data to assess details of the '*jelly sandwich*' model (e.g. Jackson GSA Today, 2002).

In this project, we combine detailed field work with numerical simulations. The Anita Shear Zone (ASZ) in Fiordland, New Zealand has been chosen as a field example; it is an excellent example of landscape scale, asymmetric ultramafic boudins formed at depth. The boudins are surrounded to the east by the Milford Orthogneiss and to the west by the Thurso Paragneiss. In the field, the first-order relative viscosities of the lithologies were determined, where the ultramafic layer is inferred to be the most viscous, followed by orthogneiss and then paragneiss. Field work uncovered a ~160m '*soft*', high-strain zone between the orthogneiss and the ultramafics and a much wider high-strain zone between the paragneiss and the ultramafics.

To investigate the impact of viscosity on boudin formation we used the Underworld software (*Moresi et al., J. Comp. Phys, 2003*) with, initially, three layers undergoing Newtonian flow with pure (extensional) shear, keeping the ultramafic:orthogneiss viscosity ratio at 5:3 and varying the paragneiss viscosity. Boudins started to form where the ultramafic:paragneiss viscosity ratio was 5:1, with better boudins forming as the ratio increased (5:0.5, 5:0.25 etc.). Subsequently, high-strain zones with a viscosity of 0.5 were added on either side of the more viscous ultramafic layer and the width of the high-strain zone on the orthogneiss side was varied. Boudin shapes similar to those of the ASZ were developed when the width of the paragneiss:orthogneiss high-strain zone was 4:1.

In general, the simulations show that individual boudins are more asymmetric where the paragneiss:orthogneiss high strain zone ratio is wider (4:1 cf 2:1) and the viscosity is asymmetric either side of the more viscous, boudinaging layer. A wider symmetric high-strain zone formed fewer, longer, more symmetrical boudins. This study highlights the importance of both high-strain zones and the relative viscosity of the lithologies for asymmetric boudin formation. Comparison of the symmetry and length of boudins measured in the field and those developed in numerical models allows quantitative determination of the relative viscosity ratio of the matrix and boudinaging layers.

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

Contacts: Robyn Gardner, Sandra Piazolo
Funded by: ARC Future Fellowship, MQ infrastructure funding, MQRES

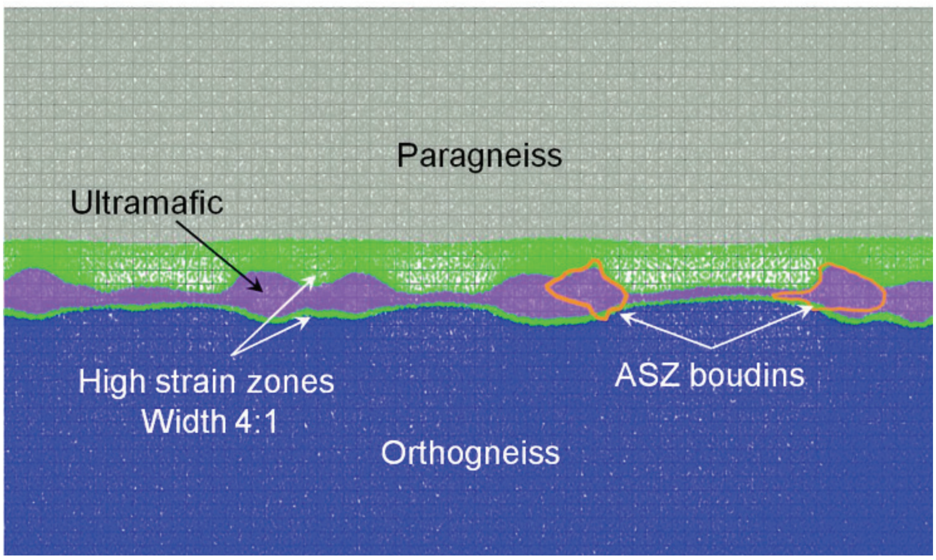


Figure 1. Simulated boudin formation where paragneiss:ultramafic:orthogneiss viscosity ratio is 1:5:3 with high strain zones with viscosity of 0.5 and paragneiss to orthogneiss zone width ratio of 4:1. The ASZ ultramafic boudins digitised from Google earth have been overlaid onto the simulated ultramafic boudins for comparison showing good agreement with the simulated shapes.

Is the Moho the Crust-Mantle Boundary? Evolution of an idea

The concept that the Mohorovicic Discontinuity (Moho) detected seismically does not necessarily coincide with the base of the continental crust as defined by rock-type compositions was introduced in the early 1980s (see *Griffin and O'Reilly, Geology 1987* and references therein). This had an important impact on understanding the nature of the crust-mantle boundary by integrating information from geophysics and the petrology and geochemistry of deep-seated samples brought to the surface either as fragments in magmas (xenoliths) or by tectonic activity.

The use of empirically-determined xenolith geotherms to plot the locus of the pressure-temperature curve with depth for specific lithospheric sections demonstrated that there is a variety of geotherms depending on tectonic environment. These geotherms range from very high near rift zones, through highly inflected but lower geotherms in active tectonic regions with basaltic volcanism (higher than *'oceanic'* geotherms), to very low geotherms in the most ancient cores of coherent cratons. These xenolith geotherms provided a robust framework for the construction of lithological sections through the lower crust and lithospheric mantle and revealed that the crust-mantle boundary is commonly transitional, over a depth range of 5 - 20 km or more, in off-craton regions. Early seismic-reflection data revealed that layering is common near the Moho and this correlates well with the petrological observation of multiple episodes of basaltic intrusion around the crust–mantle boundary. Petrologically, the crust-mantle boundary is defined as the depth at which peridotitic (mantle) wall rocks become dominant over mafic granulites and other deep-seated crustal rock types, and this boundary commonly lies 5 - 15 km above the seismically defined Moho, especially in off-craton regions.

Recent developments in seismological techniques, petrophysical laboratory measurements on natural rocks, and experimental petrology have refined interpretation of the formation of lower crust and uppermost mantle domains. The expansion of *in situ* geochronology (especially U-Pb ages and Hf-isotope composition of zircon and Os-isotope compositions of mantle sulfides) has allowed the recognition of linked tectonic events that have affected whole crust-mantle sections. These types of data reveal that the crust-mantle boundary has commonly changed in depth and thickness through time (*CCFS Publication #235*).

The main process effecting Moho depth variation is over- and under-plating of basaltic magmas at this major rheological boundary between peridotite and lower crustal rock types. This process is responsible for major crustal growth, resulting in a juvenile lower crust of mafic composition (which can then

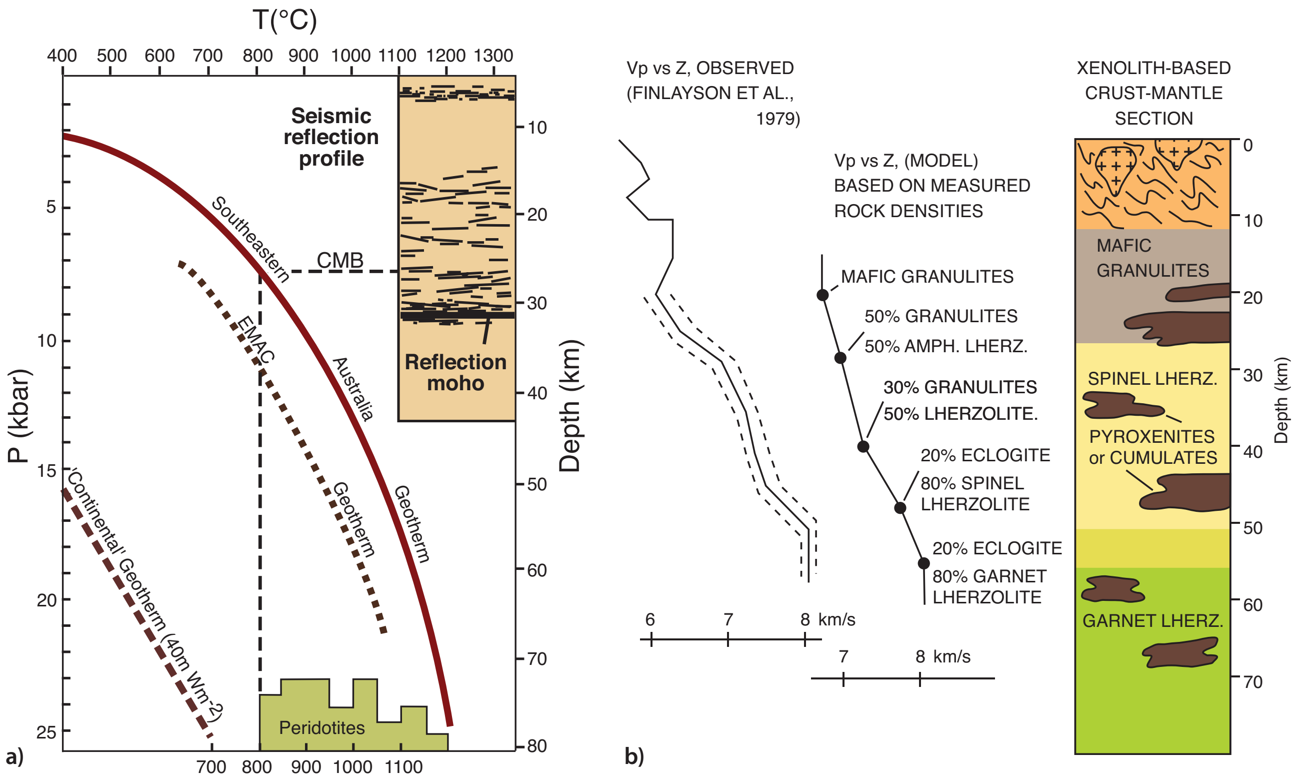


Figure 1. The geotherm generated by data from garnet+two-pyroxene xenoliths in alkali basalts of Eastern Australia. (a) Distribution of mantle peridotites beneath western Victoria, compared with the seismic reflection profile across the area (O'Reilly and Griffin, Geology, 1994); the crust-mantle boundary, as defined by the lowest temperature/depth estimates of abundant peridotite xenoliths, lies in the middle of the package of reflectors above the 'reflection Moho' "EMAC" is the Eastern Margin of the Australian Craton. (b) Crust-mantle stratigraphy reconstructed from xenoliths and thermobarometry calculations beneath the Bullenmerri locality, compared with the seismic-velocity profile of Finlayson et al. (BMR Jnl. 1979).

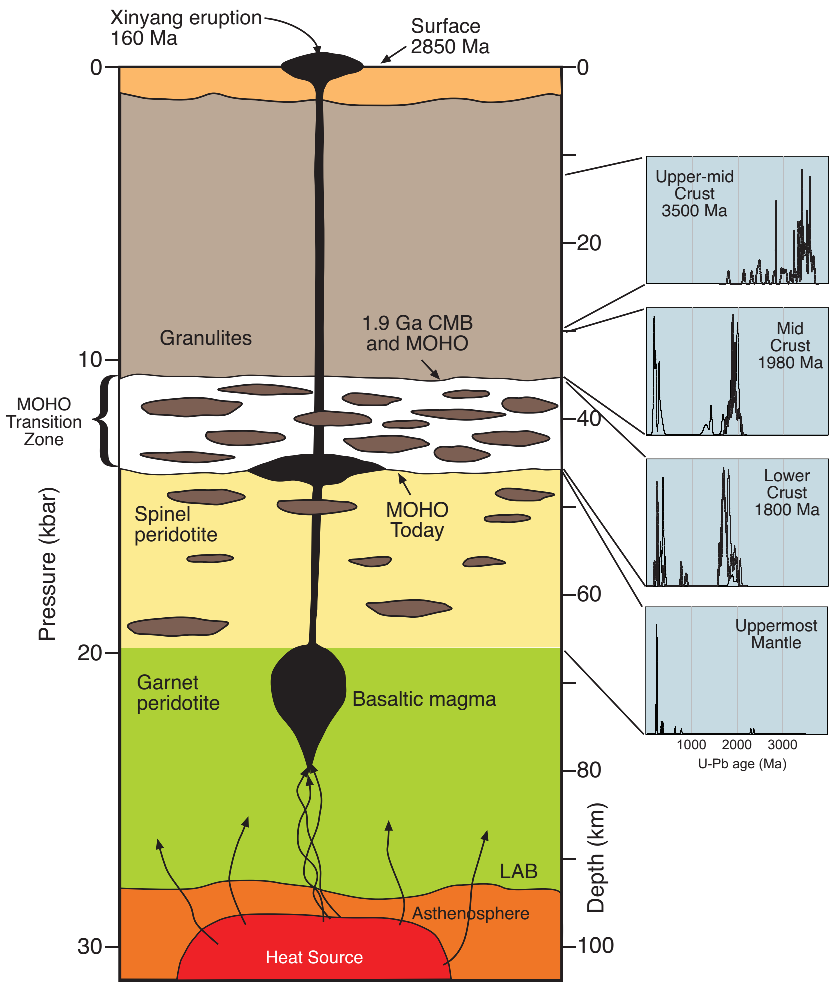


Figure 2. Crust-mantle section beneath the Xinyang area, on the southern edge of the North China Craton (after CCFS Publication #163). Histograms show U-Pb ages of zircons extracted from granulite, pyroxenite and peridotite xenoliths. The original 3.5 Ga crust was overplated at ca 2.85 Ga, and then underplated by mafic magmas at 1.9-2.0 Ga, and again at ca 1.6-1.8 Ga, lowering the crust-mantle boundary by ca 15 km. This lower crust and the subjacent upper mantle have been repeatedly intruded by mafic magmas from Paleozoic to Cenozoic time.

undergo melting and reworking to produce granitic magmas). In the alkali-basalt province of SE Australia the accumulated addition is approximately 5 km thick and occurred at a rate of about 900 m/Ma. This magma input is responsible for producing the characteristically high and inflected geotherm associated with such basaltic provinces before thermal decay occurs over about 30 million years.

However, the nature of the crust-mantle boundary in cratonic regions still remains enigmatic, mainly due to lack of key xenolith samples or exposed sections.

The observation that the Moho defined by seismic data may lie significantly deeper than the crust-mantle boundary has important implications for modelling the volume of the crust, especially in off-craton regions. Mapping of this crust using seismic techniques alone, without consideration of the petrological problems, may lead to an overestimation of crustal thickness by 15 – 30% and up to 50% in some areas. This will propagate to large uncertainties in the calculation of elemental mass balances relevant to crust-formation processes and the composition of the convecting mantle. For more details, refer to *CCFS Publication #235.*

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

Contacts: Sue O'Reilly, Bill Griffin

Funded by: ARC CoE CCFS Foundation Project 1 (TARDIS)

CCFS honours & MRes students

THE FOLLOWING HONOURS PROJECTS IN CCFS WERE COMPLETED IN 2013:

MACQUARIE

Mid 2013 Finish

Mark Eastlake: A petrographic and geochronological assessment of the Aileron Metamorphics, Mt Boothby Area, central Australia

Sarah Gain: The geochemistry of gem-quality zircons from the Mud Tank Carbonatite Complex

Kristina Gordon: Investigation of Tourmaline, Apatite and Monazite from a Low-Pressure High-Temperature Regional Aureole: Mount Stafford, Northern Territory, Australia

Patrick Sandor: A Re-evaluation of the Merrions Tuff '*Lavas*'

End of 2013 Finish

Vicki Beecher: Flow characteristics of lower crustal rocks: comparing two polyphase rock types

Rebecca Griffis: The volcanological and geochemical evolution of Waitomokia Tuff Ring, Auckland Volcanic Field, New Zealand

Blayne Murhall-Griffith: The volcanology and geochemistry of Pukeonake and Ohakune satellite vents and their relationship in the southern Taupo Volcanic Zone

Cameron Perks: Describing the basement rock of the Dimboola Subzone beneath EL5291, Victoria, Australia

UNIVERSITY OF WESTERN AUSTRALIA

Jonathon Cryer: The origin, alteration and mineralisation of dacites in the Jundee Goldfield, Western Australia

Fiona McCheyne: Mineralisation in the Zambia Copper Belt

Lei Shi: Mo mineralisation in the Central Asian Craton

Tom Watkins: '*Dropper*' base-metal mineralisation in the Broken Hill area

MASTERS OF RESEARCH

From 2013, the honours program at Macquarie University was replaced by a two-year Masters of Research (MRes). The MRes combines advanced coursework with research training to better prepare research students for further postgraduate study. The MRes aligns Macquarie's HDR program with those of many international universities and allows for a smoother transition into international postgraduate programs. From 2014, the MRes or equivalent will be the prerequisite for enrolling in Macquarie's postgraduate research (PhD) program. This change fulfils one of the CCFS goals – introducing high-level postgraduate coursework units.

THE FOLLOWING MRES PROJECTS IN CCFS WERE COMMENCED IN 2013:

Lauren Miller: The petrogenesis of fluorite in hydrothermal ore forming systems

Michael Nguyen: Understanding core formation through X-ray micro-computed tomography analysis of metal-silicate differentiation in natural and synthetic systems

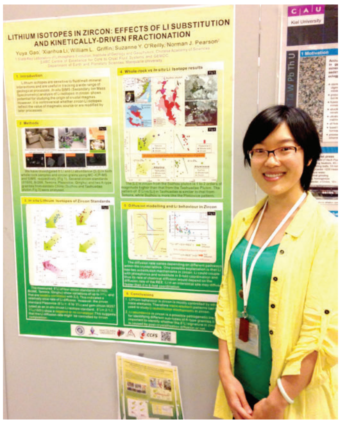
Cameron Piper: Remediation of contaminated sites in the Sydney region

Alastair Williams: Hydrothermal systems as open flow chemical reactors: New insights from a comparative geochemical and microstructural study of '*successful*' versus '*unsuccessful*' gold mineralisation at Sunrise Dam, Western Australia

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 2012/2013. Fifteen papers by CCFS postgraduates were published in high-profile international journals in 2013, including *Journal of Geology, Precambrian Research, Journal of Petrology, Lithos, G³, Gondwana Research and Chemical Geology*. 37 presentations were also given at 7 international conferences (see *Appendix 6*).

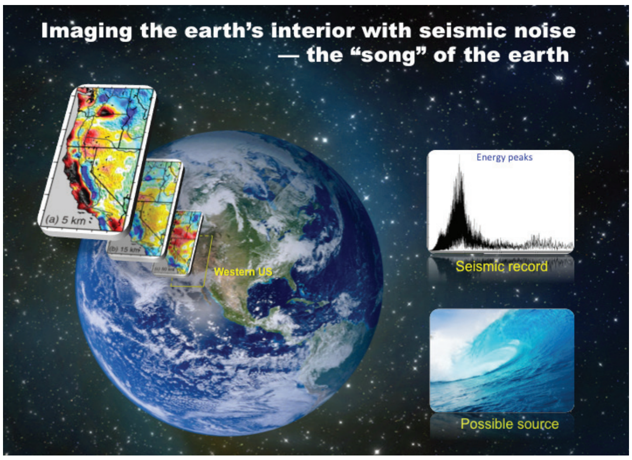
AWARDS



Yuya Gao (MQ) (*Pictured left*) won the prestigious European Mineralogical Union Poster Prize for the best student poster at the 2013 Goldschmidt Meeting.

Macquarie had six successful applicants from EPS for the PGRF travel grant in the 2013 second round (See *Research funding, p. 186*). **Yuya Gao** received the (equal) highest ranked application across the Faculty of Science, and was awarded a DVC-R commendation

Chengxin Jiang (MQ) won the Faculty competition for 3-minute thesis "*Imaging the Earth's interior with seismic noise - the 'song' of the Earth*" and represented the Faculty of Science in the University-wide final.



Margaux Le Vaillant (UWA) was awarded a 2013 SEG Student Research Grant as part of the 2013 SEG SRG program. Margaux was selected to receive a grant from the Hickok-Radford Fund in the amount of $US 5,000. The Hickok-Radford Fund, established by bequests from Bruce Hickok and Geoff Radford, supports field-based research projects and directly related laboratory studies as applied to metallic mineral deposits and is internationally recognised.

Qingtao Zeng (UWA) was awarded UWA's prestigious David Groves Prize for Postgraduate Research in Geology. This prize is awarded annually to the student who is considered by the Head of the School of Earth and Environment, to have made the most outstanding professional contribution to geology in the form of publication, research, organisation of lectures or seminars, or related activities.

Chris Grose (MQ) (*Pictured right*) was awarded "*Best Poster Presentation*" at the CCFS SAC meeting, June 2013.

COMPLETED

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 (UWA 2013)

Cara Danis (PhD): Geothermal state of the Sydney-Gunnedah-Bowen Basin system (Macquarie 2012)

Fiona Foley (PhD): Magmatic consequences of subduction initiation and its role in continental crust formation (Macquarie 2013)

Felix Genske (PhD): Assessing the heterogeneous source of the Azores mantle plume (Macquarie 2013)

Jin-Xiang Huang (PhD): Origin of eclogite and pyroxenite xenoliths in kimberlites and basalts (Macquarie 2012)

Huiqing Huang (PhD): The Petrogenesis of Jurassic Granitic Rocks in Western Nanling Ranges of South China and Tectonic Implications (Curtin 2013)

Shan Li (PhD): Early Mesozoic Magmatism and Tectonics in the Beishan area of Inner Mongolia, China (Curtin 2013) See *Research Highlight p. 74-75.*

Yongjun Lu (PhD): Controls on porphyry emplacement and Porphyry Au-Cu mineralisation along the Red River Fault, Hunnan Province, China (UWA 2012) See *Research Highlight p. 59-60.*

Kombada Mhopjeni (MSc): Investigating the Uranium potential in Namibia using GIS-based techniques (UWA 2013)

David Mole (PhD): Quantifying melt-lithosphere interaction in space and time: understanding nickel mineral systems in the Archaean Yilgarn craton (UWA 2013)

Melissa Murphy (PhD): A novel approach for economic uranium deposit exploration and environmental studies (Macquarie 2013)

Matt Pankhurst (PhD): Geodynamic significance of shoshonitic magmatism within the Andean Altiplano (Macquarie 2013)

Ekaterina Rubanova (PhD): Fluid processes in the deep mantle: Geochemical studies of diamonds and related minerals (Macquarie 2013)

Mingdao Sun (PhD): Late Mesozoic magmatism and its tectonic implication for the Jiamusi Block and adjacent areas of NE China (Curtin 2013)

Zoja Vukmanovic (PhD): A micromechanical and geochemical analysis of remobilisation of komatiite-hosted Ni sulfide ores (UWA 2013) See *Research Highlight p. 42-43.*

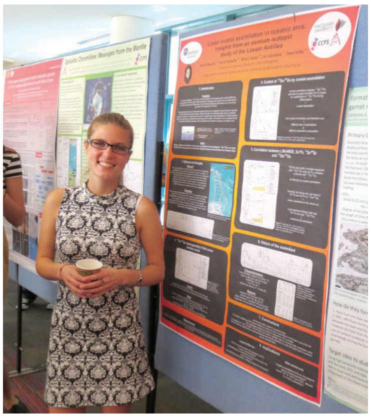
Qingtao Zeng (PhD): Regional controls on gold mineral systems in the western Qinling Belt, Gansu Province, China (UWA 2013)

Ganyang Zhang (PhD): Sb-Au mineralisation mechanism and exploration targeting prediction research in the Northern Himalaya Metallogenetic Belt, Tibet, China (UWA 2013)

Jianwei Zi (PhD): Igneous petrogenesis and tectonic evolution of Cretaceous plutons, eastern Tibetan Plateau (UWA 2013)

CONTINUING

MACQUARIE



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

Raul Brens Jr (PhD): Origin of silicic magmas in a primitive island arc: The first integrated experimental and short-lived isotope study of the Tonga-Kermadec system; *iMQRES* (commenced 2011)

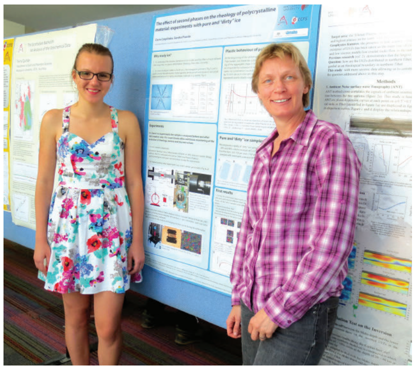
David Child (PhD): Characterisation of actinide particles in the environment for nuclear saftguards using mass spectrometric techniques (part-time, commenced 2007)

David Clark (PhD): Contributions to integrated magnetics - applications to the Earth Sciences (submitted 2013)

Bruno Colas (PhD): Why is the San Andreas Fault so weak?; HDRSCHOL, *iMQRES* (commenced 2013)

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

Daria Czaplinska (PhD): Flow characteristics of lower crustal rocks: Field studies and numerical modelling; *iMQRES* (commenced 2012) *Pictured right with Sandra Piazolo.*



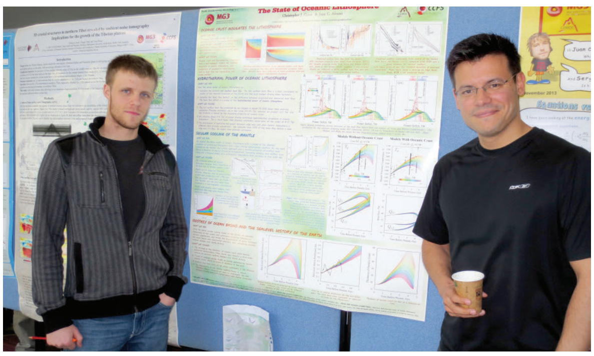
Eileen Dunkley (PhD): Hf isotopic behaviour in turbidites, migmatites and granites at Mount Stafford, central Australia (commenced 2010)

Christopher Firth (PhD): Integrating the volcanological and magmatic record of a young arc volcano: Yasur, Vanuatu; *APA* (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 Cotutelle* (commenced 2012) *Pictured left with Bill Griffin.* See *Research Highlight p. 79.*

Robyn Gardner (PhD): The nature of the lower crust: New insights from field compilations, experiments and numerical modelling; *MQRES* (commenced 2012) See *Research Highlight p. 85.*

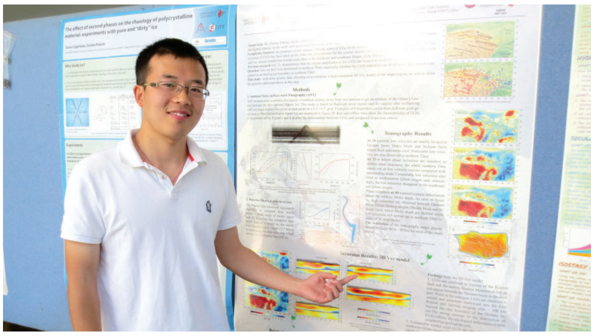
Christopher Grose (PhD): Geodynamics of oceanic lithosphere; *iMQRES* (commenced 2011) *Pictured below with Juan Carlos Afonso.*



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

Kim Jessop (PhD): Fluids and metamorphism: New insights from field mapping, metamorphic petrology and thermodynamic modelling; *APA* (commenced 2013)

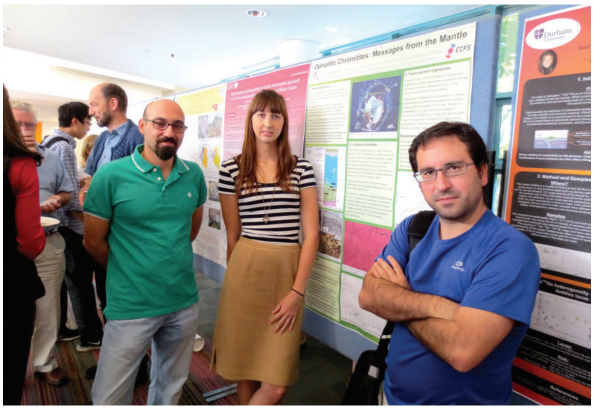
Chengxin Jiang (PhD): Combining seismic tomography and sedimentology to understand the deep structure and evolution of the northern edge of Tibetan Plateau; *iMQRES* (commenced 2012) See *Research Highlight p. 40*. *Pictured below.*



Elizabeth Keegan (PhD): Measurement of Protactinium-231 (part-time, commenced 2011)

Pablo Lara (PhD): Late Neoproterozoic granitoid magmatism of the southernmost section of the Dom Feliciano Belt in Uruguay: Regional geology, geochemistry, geochronology and its significance for the geotectonic evolution of the Region; *iMQRES Cotutelle* (commenced 2010)

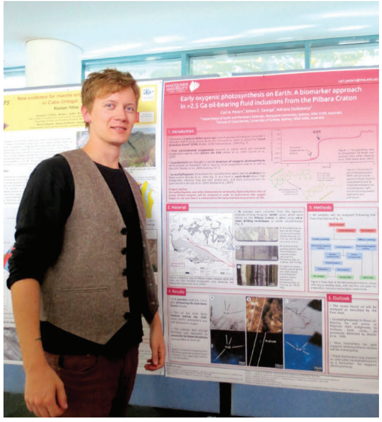
Nicole McGowan (PhD): Messages from the mantle: Geochemical investigations of ophiolitic chromites; *APA* (commenced 2012) *Pictured below (centre) with Mehmet Akbulat, (Dokuz Eylul University, Turkey) and José María Gonzaléz Jiménez.*



Rosanna Murphy (PhD): Stabilising a craton: the origin and emplacement of the 3.1 Ga Mpuluzi batholith (South Africa / Swaziland); *MQRES* (commenced 2010)

Beñat Oliveira Bravo (PhD): Multicomponent and multiphase reactive flows in the earth's mantle; *iMQRES* (commenced 2013) See *Research Highlight p. 61*.

Carl Peters (PhD): Biomarkers and fluid inclusions of early Earth using samples from Australia; *iMQRES* (commenced 2013) *Pictured right.*



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

James (Ed) Saunders (PhD): The nature, abundance and mobility of gold in the mantle; *APA* (submitted 2013) See *Research Highlight p. 53*.

Elyse Schinella (PhD): Processes sculpting the surface of Venus; *APA* (submitted 2013)

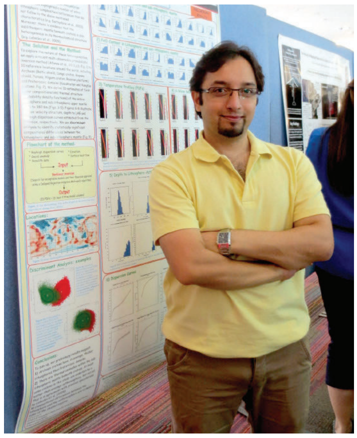
Liene Spruzeniece (PhD): Fundamental Link between Deformation, Fluids and the Rates of Reactions in Minerals; *iMQRES* (commenced 2012)

Catherine Stuart (PhD): Flow characteristics of lower crustal rocks: In depth analysis of xenoliths and experimental studies; *MQRES* (commenced 2012)

Rajat Taneja (PhD): The origin of seamount volcanism in the Northeast Indian Ocean; *iMQRES* (submitted 2013)

Romain Tilhac (PhD): Peridotite Massifs from North-Western Iberia; *iMQRES Cotutelle* (commenced 2013)

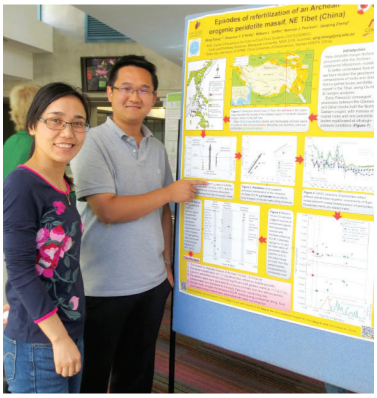
Mehdi Tork Qashqai (PhD): Inversion of multiple geophysical data for composition and thermal structure of Earth's upper mantle; *iMQRES* (commenced 2012) *Pictured right.*



Irina Tretiakova (PhD): The nature, extent and age of the lower crust and underlying subcontinental lithospheric mantle (SCLM) beneath the Siberian Craton (Russia); *iMQRES* (commenced 2013) *Pictured p. 98.*

Yu Wang (PhD): Melting process in recycled continental crust; *iMQRES, China Science Council* (commenced 2013)

Jonathon Michael Wasiliev (PhD): Two-phase flow within the Earth's mantle: Implications for flat subduction settings; *MQRES* (commenced 2013)



Qing Xiong (PhD): Origin of the Sheng Likou garnet peridotite massif, North Qaidam, western China; *iMQRES top-up, China Scholarship Council* (commenced 2011) *Pictured left with Jin-Xiang Huang.*

Yao Yu (PhD): The evolution and water inventory of the subcontinental lithospheric mantle: a new perspective from periodotite xenoliths (SE China) and zircon megacrysts from basalts; *iMQRES Cotutelle* (submitted 2013)

Commencing 2014

Katherine Farrow (PhD): In-situ melt generation and thermal origin of the Nagadarunga Granite: Implications for the geochronology and tectonic evolution of the eastern Arunta Region, Central Australia

Louise Goode (PhD): Volcanological and geochemical evolution of East Javanese Volcanoes, Indonesia; *iMQRES*

Jianggu Lu (PhD): Nature and evolution of the lithospheric mantle beneath the South China block; *iMQRES Cotutelle, China Scholarship Council, iMQRES top-up*

Samuel Matthews (PhD): Tracking CO_2 sequestration using gravity gradiometry; *CO_2CRC Scholarship*

Jun Xie (PhD): Imaging the lithosphere structure of Australia using dispersion curve receiver functions and Rayleigh waves A/H ratio; *iMQRES Cotutelle*

UWA

Raphael Baumgartner (PhD): Ore deposits of the future; magmatic Ni-Cu-PGE sulphide mineral systems on Mars; *IPRS* (commenced 2013) *Pictured p. 93.*

Jonathan Bell (PhD): Risk Adjusted Evaluation of Mineral Asset Using Transactions Based Statistical Models (commenced 2013)

Katarina Bjorkman (PhD): 4D lithospheric evolution and controls on mineral system distribution: Insights from Marmion Terrane, Western Superior Province, Canada; *UWA SIRF* (commenced 2013) See *Research Highlight p. 65*. *Pictured p. 93.*

Raphael Doutre (PhD): Spatial periodicity, self-organisation and controls on large ore deposits; *International Sponsorship, Teck Resources Ltd* (commenced 2013)

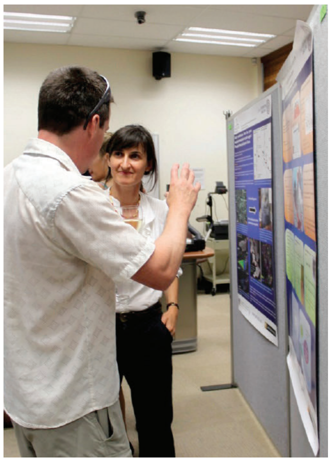
Alex Eves (MSc): Geology, mineralogy and geochemistry of the newly discovered Speewah Dome V-Ti-Fe Deposit, East Kimberley; *Niplats Australia Limited* (commenced 2012)

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

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

Erin Gray (PhD): Deformation of Earth's upper mantle: Insights from naturally occurring fabric types (submitted 2013)

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, APA* (commenced 2010)



Linda Iaccheri (PhD): Petrogenesis of the plutonic rocks in the Granites-Tanami Orogen; *UWA SIRF* (commenced 2013) *Pictured right.*

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 grant, ARC DP* (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 sulphide deposit systems. Implications for exploration targeting; *MERIWA, UWA SIRF, ARC linkage grant* (commenced 2011)

Erwann Lebrun (PhD): 4D structural modelling and hydrothermal evolution of the sediment hosted Siguiri gold deposit (Guinea) and implication on Paleoproterozoic gold targeting in West Africa; *International Sponsorship* (commenced 2011)

Ben Li (PhD): Evolution of fluid associated with gold mineralisation in the Paleoproterozoic Granites–Tanami Orogen; *UWA 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; *RTS* (commenced 2010)

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

Quentin Masurel (PhD): Controls on the Genesis, Geometry and Location of the Sadiola-Yatela Gold Deposit, Republic of Mali; *IPRS* (commenced 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; *UWA SIRF, UIS, Ad Hoc Safety-Net Top-Up Scholarship, ARC Linkage grant* (commenced 2012) *Pictured right with Katarina Bjorkman.*

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

Aileen Robert (PhD): Field characterisation of Australian gold deposits; *IPRS* (Commenced 2013)

Christian Schindler (PhD): Petrogenesis of intrusive rocks in the Telfer region, Patterson Orogen, Western Australia: implications for gold mineralisation; *UWA SIRF, UIS, Newcrest Mining Ltd.* (commenced 2010)

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

James Warren (PhD): 4D evolution of the Ora Banda and Coolgardie Domains; *RTS* (commenced 2012)

CURTIN

Timmins Erickson (PhD): Resolving the bombardment history of the early Earth using ancient zircons (commenced 2013)

Rongfeng 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* (commenced 2012)

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)

CCFS PhD students at the 2013 SAC meeting, June 2013.

Yingchao Liu (PhD): Recognising gold mineralisation zones using GIS-Based modelling of multiple ground and airborne datasets; *APRA* (commenced 2010)

Vicky Meier (PhD): Metamorphic evolution of the Kerala Khondalite belt, India (commenced 2013)

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)

Ni Tao (PhD): Thermochronological record of tectonic events in central and southeastern South China since the Mesozoic; *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)

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)

A highlight of CCFS postgraduate activity in 2013...

... was a series of extended exchange visits by international postgraduate students for collaborative studies with CCFS research groups.

Exchange visits by international PhD students

Celia Guergouz (2013 Masters student visiting from Nancy, France): Thermal evolution of the lower crust at the transition from crustal thickening to lithospheric thinning: Metamorphic petrology, geochemistry and U/Pb geochronology on zircon and monazite from metapelites of the Ivrea zone (Italy).

Mr Jun Xie, a PhD candidate from University of Science and Technology of China, who visited Macquarie from March to June 2013. During his visit, Jun worked with Yingjie Yang on the accuracy of long period surface waves from ambient noise.

Ms Montgarri Castillo I Oliver, from Barcelona University, visited CCFS at Macquarie to work on geochemical studies of minerals in carbonatites and alkaline rocks from Angola. Montgarri's visit is part of a collaboration with Professor Malgarejo at Barcelona University.

Vanessa Colás Ginés, (*pictured right with Dr José María González Jiménez*) from the Departamento Ciencias de la Tierra, Universidad de Zaragoza, Spain visited Macquarie to work on her project entitled *"Distribution and mobility of major, minor and trace elements in metamorphosed and unmetamorphosed chromite deposits from ophiolites."*

Peter Kollegger from the University of Leoben, Austria, visited UWA to work on his project *"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, visited UWA to work on his project *"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, and facilities for experimental mineralogy and petrology are being built up at Macquarie and Curtin.

CCFS/GEMOC INFRASTRUCTURE, LABORATORIES AND INSTRUMENTATION

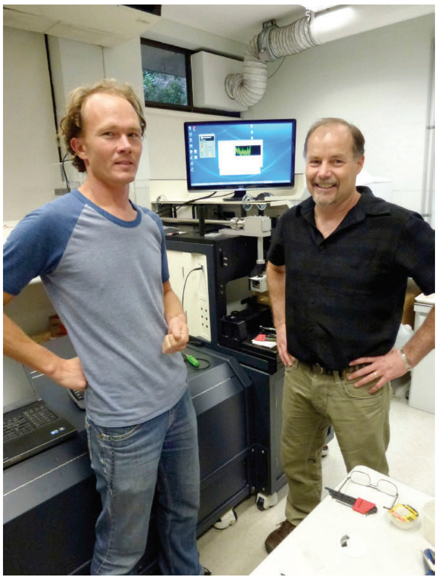
The analytical instrumentation and support facilities of the Macquarie University Geochemical Analysis Unit (GAU) represent a state-of-the-art geochemical facility.

The GAU contains:

- a Cameca SX-100 electron microprobe
- a Zeiss EVO MA15 Scanning electron microscope (with Oxford Instruments Aztec Synergy EDS/EBSD)
- four Agilent quadrupole ICPMS (industry collaboration; two 7500cs; two 7700cx)
- a Nu Plasma multi-collector ICPMS
- a Nu Plasma high resolution multi-collector ICPMS
- a Nu Attom high resolution single-collector sector field 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 Analyte G2 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

GEMOC is continuing to develop a unique, world-class geochemical facility, based on *in situ* imaging and microanalysis of trace elements and isotopic ratios in minerals, rocks and fluids. The Facility for Integrated Microanalysis now consists of four different types of analytical instrument, linked by a single sample positioning and referencing system to combine spot analysis with images of spatial variations in composition ('*micro-GIS*'). All instruments in the FIM have been operating since mid-1999. Major instruments were replaced or upgraded in 2002-2004 through the $5.125 million DEST Infrastructure grant awarded to Macquarie University with the Universities of Newcastle, Sydney, Western Sydney and Wollongong as partners. In late 2009 GEMOC was awarded an ARC LIEF grant to integrate the two existing multi-collector inductively-coupled-plasma mass spectrometers (MC-ICPMS) with 3 new instruments: a femtosecond laser-ablation microprobe (LAM); a high-sensitivity magnetic-sector ICPMS;



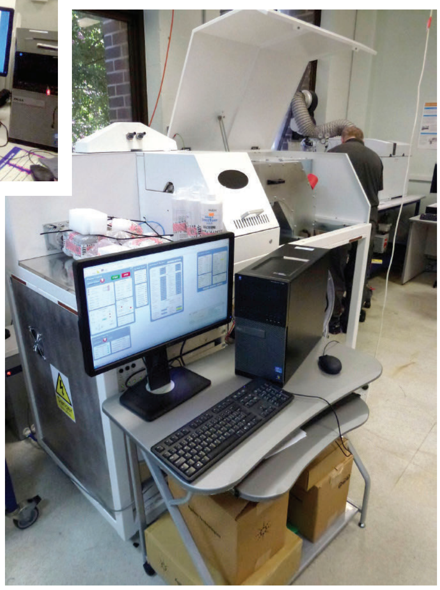
Will Powell and Jamie Barbula, (Photon Machines) during the installation of the Femto-second laser.

a quadrupole ICPMS. The quadrupole ICP-MS was purchased and installed in 2010; a Photon Machines femtosecond laser system was installed in June 2012; and a Nu Attom ICP-MS was installed in January 2013. In 2012 GEMOC was awarded ARC LIEF funding for a second generation MC-ICPMS. Evaluation of the current instruments on the market was undertaken in 2013 and an order will be placed in early 2014.

Raymond Jones visited Simon Clark in March - April -2013 to help set up the high pressure lab.

EQUIPMENT FOR HIGH-PRESSURE EXPERIMENTATION

Expansion of the facilities for high-pressure experimentation at GEMOC began in 2013. The laboratories now house two piston-cylinder presses (pressures to 3 GPa), a Griggs apparatus and a multi-anvil apparatus for (pressures to 27 GPa). Funding for the purchase of a diamond-anvil apparatus for use at much higher pressures, and an additional large-volume multi-anvil apparatus were acquired in 2013, expanding the experimental capability for mantle studies.



PROGRESS IN 2013:

1. Facility for Integrated Microanalysis

a. 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, PGM in chromitites and experimental petrology. The Oxford Instruments AZtec Synergy combined Energy Dispersive System and Electron Back-Scatter Diffraction detector installed in 2012 has enabled simultaneous elemental and crystal orientation mapping. This capability has enabled new research directions in the study of deformation processes in mantle and crustal rocks, including melt/rock interaction in high-grade metamorphic rocks and metasomatism of mantle-derived peridotites, pyroxenites and chromitites. The Cameca SX100 electron microprobe continued to service 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 Bruker Energy Dispersive Spectrometer system was installed on the SX100 and was purchased with funding provided by a MQSIS 2013 Faculty of Science Infrastructure Fund grant.

b. Laser-ablation ICPMS microprobe (LAM): In 2013 the LAM laboratory was used by 12 Macquarie PhD thesis projects, eleven international visitors, two Honours students, nine users from other Australian institutions and several in-house funded research projects and industry collaborations. Projects included the analysis of trace elements in the minerals of mantle-derived peridotites, pyroxenites and chromitites, 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),

Will Powell, Mark Chandler (Nu Instruments) and Norman Pearson (Photon Machines) oversee the installation of the Nu Attom.

New Zealand, Algeria, Australia, Bostwana, Brazil, Indonesia, Laos, PNG and Russia. Method development was also undertaken for the U-Pb dating of baddeleyite and rutile. 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.

c. MC-ICPMS: The high demand for LAM MC-ICPMS time for in-situ high-precision ratio measurements was again led by the analysis of Lu-Hf isotopes in zircon as a major strand of the *TerraneChron®* activities (see *http://www.gemoc.mq.edu.au/TerraneChron.html*) 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, Australia, Bostwana, Brazil, Indonesia, Laos, PNG and Russia. Re-Os studies were undertaken on xenoliths from eastern China, Siberia, Mongolia, Italy, Spain and South 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 refinement was undertaken of methods for whole-rock Re-Os isotopes of basaltic rocks and the adaptation of conventional techniques for Rb-Sr and Nd-Sm isotope separation to the nano-scale to process small sample sizes.

Further development of *'non-traditional'* stable isotopes was carried out in 2013 and focused on Mg isotopes in mantle minerals and for the separation and analysis of Li isotopes in granitic rocks and in clinopyroxene from mantle-derived eclogites and peridotites.

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 real-time interactive data reduction for LAM-ICPMS analysis, allowing inspection and evaluation of each result before the next analysis spot is chosen. GLITTER's capabilities include the on-line reduction of U-Pb data. Sales of GLITTER are handled by Access MQ and GEMOC provides customer service and technical backup. During 2013 a further 11 full licences of GLITTER were sold bringing the total number in use to more than 220 worldwide, predominantly in earth sciences applications but with growing usage in forensics and materials science. Dr Will Powell continued in his role in GLITTER technical support and software development through 2013. The current GLITTER release is version 4.4.4 and is currently available without charge to existing customers and accompanies all new orders.

2. X-Ray Fluorescence Analysis

In November 2012 a PANalytical Axios 1 kW X-ray Fluorescence Spectrometer was installed (see *photo below*). This instrument is a wavelength spectrometer system and replaced the Spectro XLAB2000 energy-dispersive X-ray spectrometer, which was installed in November 2000. The Axios instrument is used routinely to measure whole-rock major element compositions on fused glass discs and trace-element concentrations on pressed-powder pellets. In 2013 the sample preparation equipment was upgraded and included a new furnace to make high-quality cast glass beads.

3. Whole-rock solution analysis

An Agilent 7500cs ICPMS produces trace-element analyses of dissolved rock samples for the projects of CCFS/GEMOC researchers and students and external users, supplementing the data from the XRF.

The ICPMS dedicated to solution analysis is also used to support the development of *'non-traditional'* stable isotopes with the refinement of separation techniques and analytical protocols (see *1. d above*).

4. Diamond preparation and analysis

The GEMOC laser-cutting system (donated by Argyle diamonds in 2008) was used during 2013 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 2013 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 2013 on the CNT Hydroseparator for the separation of small volumes of ultrafine material (e.g. alloys in chromitites).

6. Computer cluster

The cluster Enki has continued to be a workhorse for the geodynamics group, supporting two funded research projects, 3 PhD projects, a postdoc, and numerous masters-level projects. Recent developments have included the migration of the new mantle convection code Aspect (based on the deal.II finite element libraries) to Enki, and continued development of this code, led by Siqi Zhang, has led to a number of capability breakthroughs, including coupled core-mantle simulations, integrated mantle melting/convection simulations, and coupled plate/fluid flow models.

José María González Jiménez and Irina Tretiakova working on the LA-ICPMS.

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 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 (Skyscan 1176)
- 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 CAMECA IMS 1280 and NanoSIMS 50 are flagship instruments of the Australian Microscopy & 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 NanoSIMS 50, installed in 2003, was funded through the Federal Government's NCRIS-precursor, the Major National Research Facility scheme (NANO-MNRF).

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 2013:

Recent successes in ARC LIEF funding will update the electron microscopy facilities, with the addition of a FEI Titan TEM and a FEI Verios 460 SEM. The CMCA will also receive funding for a new Cameca NanoSIMS 50L ion probe through CSIRO's Science and Industry Endowment Fund (SIEF). The new instrument will be part of the tripartite Advanced Resources Characterisation Facility, along with a Geo-Atom Probe to be located at Curtin University, and the in-house development of a MAIA mapping facility at CSIRO. The NanoSIMS 50L represents a considerable technological advance over the existing NanoSIMS, with a seven-FC/EM multicollector array and a new oxygen ion source allowing high-resolution isotope measurements on geological samples.

In 2013, the Ion Probe Facility has continued to contribute to various projects in the context of CCFS. These have included a wide range of topics, from the characterisation of mantle metasomatism (O isotopes in garnet, J Huang), the origin of diamonds (C isotopes in diamond: W Griffin and Z Spetsius), magmatic processes and crustal growth (O isotopes in zircon; E Belousova), the origin of ore deposits (S isotopes in sulfides; M Fiorentini). In addition, the NanoSIMS has also been involved in the measurement of element diffusion across mineral interfaces, trace element transportation along grain boundaries, and S isotopes (D. Wacey, M. Fiorentini).

High-precision isotope measurement with SIMS requires calibration against known standards to correct for instrumental mass fractionation between analysis sessions. This varies significantly between different 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 pyroxene and olivine (O isotopes) as well as a range of Si-bearing materials (SiC, Si metal, silicates) for Si isotopes. Development continues on diamond (C isotopes), lawsonite, pyroxene, garnet and olivine (O isotopes), tourmaline and serpentine (B isotopes), pentlandite, pyrrhotite and chalcopyrite (S and Fe isotopes). The development of standards for unknown isotope systems aims to identify potentially new geochemical tools.

Personnel:

2013 saw a number of staff changes at the CMCA. Laure Martin and John Cliff continued to develop standards and analytical protocols for isotopic measurement using the Cameca IMS 1280 ion probe. Matt Kilburn spent six months on sabbatical at Harvard University, learning about the intricacies of applying NanoSIMS to biomedical research. David Wacey returned from overseas to work full time on CCFS Foundation Project 5. Rong Liu left the CMCA to take up a position running the SIMS lab at the University of Western Sydney. His position was filled by Paul Guagliardo. David Adams left CMCA to take up a similar position as EPMA operator at GEMOC, Macquarie University and was replaced by Malcolm Roberts.

CMCA RESEARCH HIGHLIGHTS:

Once again the Ion Probe Facility at CMCA was highly productive during 2013, contributing to a number of projects across the whole CCFS. Highlights include:

Metasomatism in the mantle (Jin-Xiang Huang, Yoann Gréau, Bill Griffin, Suzanne O'Reilly, Norman Pearson, John Cliff, Laure Martin)

The garnets from a key Roberts Victor eclogite (RV07-17) were analysed for oxygen-isotope compositions by SIMS (CAMECA IMS 1280) on the grain mounts. The $\delta^{18}O$ value of the garnet decreases from 8.2 to 5.7 ‰ as the MgO content increases from one side to the other of the hand specimen, providing important evidence for progressive metasomatism, further constraining the origin of xenolithic eclogites.

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

The CAMECA IMS 1280 has been used to analyse several sets of Precambrian sulfides in order to determine sulfur sources during the pyritisation of potential organisms in deep time. Here we have measured all 4 stable sulfur isotopes. Samples range from pyritised Ediacaran (560 Ma) macrofossils, to 1.9 Ga pyritised microfossils from the Gunflint chert, to possible pyritised microfossils in a 3.2 Ga black smoker type deposit. This high-spatial resolution *in situ* data is giving unique insights into Precambrian biological cycling of sulfur. One paper has been published in PNAS in 2013 (Wacey et al. 2013) and there are a further 3 manuscripts containing IMS 1280 data in review.

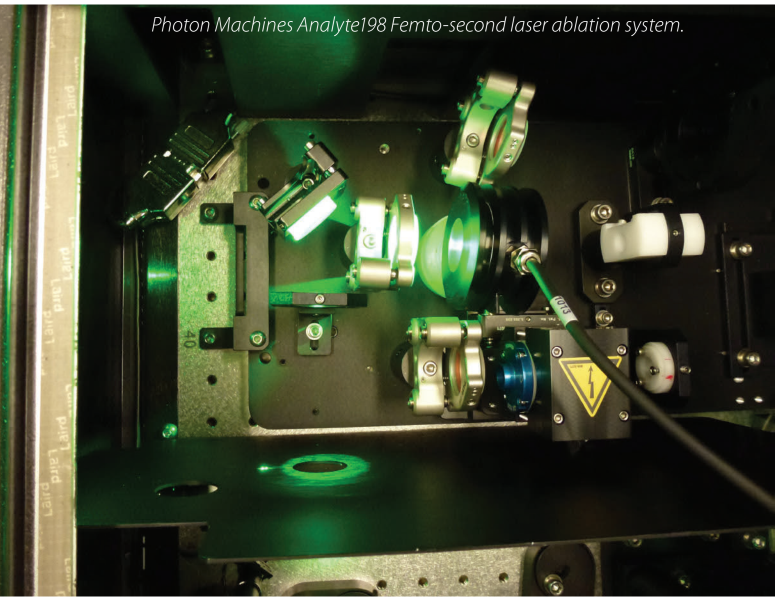
Isotopic standards development (John Cliff, Laure Martin)

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, the testing of new standards extend our capabilities into hitherto unexplored isotope systems. Recent development has included Si isotopes in silicates, SiC and Si metal, as well as Zr isotopes in zircon crystals from different provenance.

Ultra-fine resolution diffusion studies (Matt Kilburn, Marco Fiorentini, Zoja Vukmanovic)

The NanoSIMS proved once again that size does matter as a number of projects employed the ultra-high spatial resolution to determine diffusion profiles across mineral interfaces. One study, published in Chemical Geology (Saunders et al., 2014), demonstrated how such an increase in our ability to measure diffusion profiles could be used to better constrain the timing of volcanic processes on the order of days to years. Similarly, high-resolution imaging with NanoSIMS combined with EBSD and LA-ICPMS imaging revealed the presence of trace elements along twin boundaries in pyrrhotite. These data, published in *Lithos* (*Vukmanovic et al., 2014*) are interpreted as intragrain diffusion during syn- and post-deformation.

For further information on CMCA facilities please consult http://www.cmca.uwa.edu.au/



Photon Machines Analyte198 Femto-second laser ablation system.

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 ~400m² 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 µm 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 named Project Manager and Chief Investigator on the ARC grant) has been set up and approved by all Collaborating and Partner Organisations.

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.

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.

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, badeleyite, 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.

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 Facility: A new SelFRAG facility has been completed within the JDLC at Curtin University. The facility provides electric pulse dissagregation methodologies for mineral separation that allow pristine mineral grains to be separated from rock samples without the damage associated with standard crushing techniques.

Electron Microscopy Facility (EMF): The EMF is a new node of the John de Laeter Centre located at Curtin University and is a state of the art facility for microanalysis using electron microscopes. The facility has three scanning electron microscopes, all with EBSD capability, and a transmission electron microscope. The suite of instruments facilitates high quality research across a range of disciplines including Earth sciences, materials science, engineering, chemistry and biology.

The following is a summary of the capabilities of our major instruments;

Zeiss NEON 40 EsB - The Neon is a dual beam focused ion beam scanning electron microscope (FIB-SEM) equipped with a field emission gun and a liquid metal Ga+ ion source. This instrument combines high resolution imaging with precision ion beam ablation of focused regions which allows for site specific analysis of the surface and subsurface of samples in 2D or 3D.

Key Capabilities

- High resolution imaging using SE, BSE and inlens detectors (resolution is 1.1 nm at 20 kV to 2.5 nm at 1 kV)
- Energy Dispersive X-ray Spectroscopy (EDS) point analysis and mapping
- Electron Backscatter Diffraction (EBSD) mapping, including 3D EBSD
- Focused Ion Beam (FIB) milling
- Transmission Electron Microscope (TEM) lamella, Transmission Kikuchi Diffraction (TKD) foil and atom probe tip preparation
- High resolution 3D tomography

Tescan MIRA3 XMU with Oxford AZTEC EBSD-EDS system

The MIRA is a variable pressure field emission scanning electron microscope (VP-FESEM) equipped with a comprehensive range of detectors suitable for researchers in the fields of Earth science, forensics, life science and materials science.

Key Capabilities

- High resolution SE and BSE imaging of 1-3 nm (depending upon conditions used)
- Fast Electron Backscatter Diffraction (EBSD) mapping
- Energy Dispersive X-ray Spectroscopy (EDS) point analysis and mapping
- High quality cathodoluminescence (CL) imaging
- Electron Beam Induced Current (EBIC) imaging
- Low vacuum secondary electron imaging up to 500 Pa
- Scanning Transmission Electron Microscope (STEM) imaging
- Beam Deceleration Mode (BDM) for low voltage imaging of beam sensitive samples
- Simultaneous EBSD and EDS mapping
- Large area autonomous data collection
- Stereoscopic imaging

Zeiss EVO

The Zeiss EVO 40XVP is a variable pressure scanning electron microscope (VP-SEM) equipped with a tungsten filament. The microscope is suitable for general-purpose microstructural analysis at high vacuum, or for the analysis of non-conductive/hydrated samples at lower vacuum.

Key Capabilities

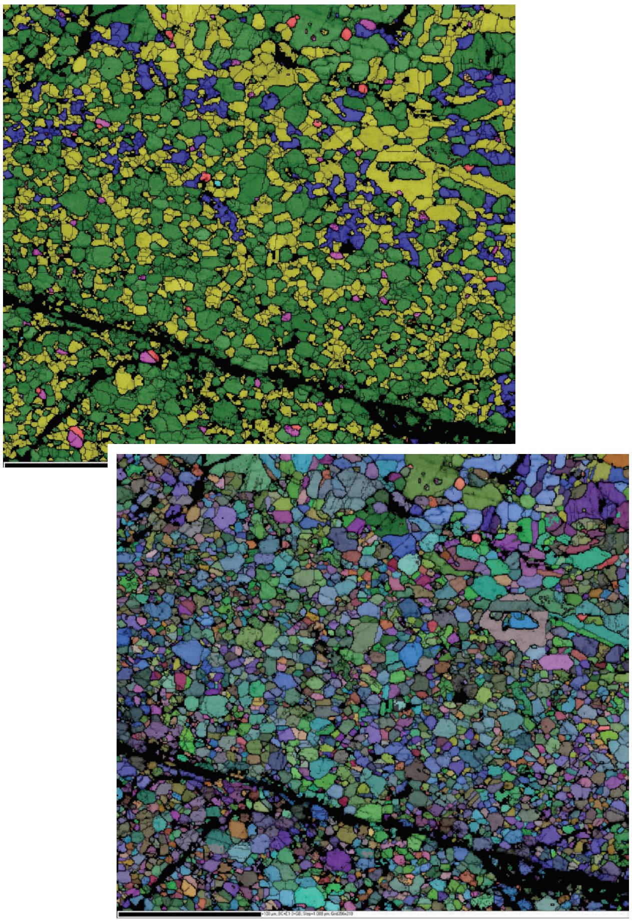
- Secondary Electron (SE) imaging
- Backscattered Electron (BSE) imaging
- Cathodoluminescence (CL) imaging
- Low vacuum secondary electron imaging
- Energy Dispersive X-ray Spectroscopy (EDS) point analysis and mapping
- Electron Backscatter Diffraction (EBSD) mapping

Jeol JEM 2011

The JEM-2011 is a transmission electron microscope (TEM) with a LaB6 filament. The TEM is equipped with an energy dispersive x-ray spectroscopy detector and a scanning transmission electron microscope attachment. This combination allows for comprehensive elemental and microstructural analysis at very high magnifications.

Key Capabilities

- High resolution bright field and dark field imaging
- Scanning Transmission Electron Microscope (STEM) imaging
- Selected Area Electron Diffraction (SAED)
- Energy Dispersive X-ray Spectroscopy (EDS) analysis



Phase map and an all-Euler orientation map of a basaltic achondrite meteorite. Thick black lines are phase boundaries, thin black lines are grain boundaries (same phase). The colours in the phase map are blue (quartz); yellow (anorthite); green (augite); brown (enstatite); aqua (olivine); fuchsia (ilmenite); red (chromite); orange (zircon). Black areas indicate no indexing and represent sample damage most likely associated with formation of the meteorite. Data was collected on the Tescan Mira XMU. Number of points (diffraction patterns) = 113,208. Collection time ~50mins (EBSD and EDS data collected).

For further information on JDLC facilities please consult http://jdlc.curtin.edu.au/facilities/

WESTERN AUSTRALIA PALEOMAGNETIC AND ROCK-MAGNETIC FACILITY

The Western Australia Paleomagnetic 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, paleoclimates, and recent environmental pollution.

Program 1: Regional and Global Tectonic Studies

Paleomagnetism 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 paleoclimate 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).

CCFS supports the national UNCOVER initiative:
http://www.science.org.au/policy/uncover.html/

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 2013

- *TerraneChron*® studies (see *p. 106* and http://www.gemoc.mq.edu.au/TerraneChron.html) have enjoyed 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 in 2013. This formally involved project collaboration with five industry partners.
- An ARC Linkage project continued, 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.

- Two new linkage projects commenced in 2013 "*Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions*" (ANU, GSWA) CIs: Tkalcic, Kennett, Spaggiari, Gessner and "*Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems*" (Curtin, GSWA) CIs: Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate
- The Distal Footprints of Giant Ore Systems: UNCOVER Australia, Supported by CSIRO ex Science & Industry Endowment Fund (SIEF), MERIWA, Industry Collaborators, CSIRO, University of Western Australia, Curtin University, Geological Survey of Western Australia, CIs: Hough, Reddy, McCuaig, Tyler, Dentith, Shragge, Miller, Fiorentini, Aitken. This project aims to develop a toolkit with a workflow to identify the distal footprints of the Giant Ore Systems. The project aims to overcome the fundamental limitation in current exploration methodologies; Australia's thick cover of weathered rock and sediment.
- 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 with Minerals Targeting International accommodates 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 2013 as part of the close collaborative working pattern for this project. This project was further supported by a DVC(R) Discretionary Grant in 2013.

Professor Vadim (Dima) Kamenetsky (University of Tasmania) visited with Elena Belousova during June 2013 for discussions about Olympic Dam zircons.

- 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 2013 by CCFS Foundation Project 8 and 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 collaborative projects.
- The application of U-series isotopes to groundwater studies for both exploration and investigation of palaeoclimate continued in 2013. 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 and the Thompson Orogen.
- A collaborative research project continued in 2013 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.
- Following Professor Bill Griffin's Noumea workshop on new approaches to exploration and minor-element exploitation in ophiolitic complexes for SLN, who operate the large Ni mines on New Caledonia, a collaborative project has resulted involving the BRGM and a PhD student from the Sorbonne (France).
- CET held their annual "*Corporate Members Day*" on the 9th of December 2013, to showcase its research to its Corporate Members. The day provided an audience of


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
www.gemoc.mq.edu.au/ www.ccfs.mq.edu.au/
MACQUARIE UNIVERSITY
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

over 60 representatives from CET Member companies 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). Posters and poster presentations by CET staff and students showcased the width and breadth of research activities.

- Industry visitors spent varying periods at Macquarie, Curtin and UWA (CET) in 2013 to discuss our research and technology development (see visitor list, *Appendix 7*). 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, and convening relevant sessions at national and international industry peak conferences in 2013.

See Appendix 6 for abstract titles and Appendix 5 for recent publications.

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

CURRENT AND 2014 INDUSTRY-FUNDED COLLABORATIVE RESEARCH PROJECTS

These are brief descriptions of 2013 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*® 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.

CCFS PROJECTS FUNDED BY INDUSTRY (INCLUDING ARC LINKAGE)

Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	***Linkage Project*** ***Industry Collaborator: Geological Survey of Western Australia*** ***CIs: Tkalcic, Kennett, Spaggiari, Gessner*** ***Summary:*** The objective of this work is to achieve new, synergistic techniques for delineating the three-dimensional structure of the east Albany-Fraser Orogen in Western Australia, and the lithospheric structure below it. These methods will guide understanding of the potential for mineral resources in this region with little surface geological exposure.
Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	***Linkage Project*** ***Industry Collaborator: Geological Survey of Western Australia*** ***CIs: Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate*** ***Summary:*** The application of innovative age dating techniques with field mapping and a new deep seismic survey across the Capricorn Orogen by this project will help construct a vastly improved geological framework for understanding large mineral systems. Outcomes of this project will reduce uncertainty and risk in exploration, thereby improving the discovery rate of natural resources.

The applicability of Ru-chromite signatures in the exploration for picrite-hosted Ni-Cu-PGE sulfide deposits	***Industry Collaborator: Rio Tinto*** ***CIs: Fiorentini, Locmelis, Pearson, Agnew, Kobussen*** ***Summary:*** The collaborative project aims to develop reliable heavy mineral indicators in the exploration for magmatic mineral systems. A pilot study is being undertaken with Rio Tinto to test the applicability of the Ru-chromite method of Locmelis et al. (2011; 2013; in review) in picritic systems. The method currently enables the discrimination between mineralised and barren komatiites, komatiitic basalts and ferropicrites. The study will further develop the use of laser ablation ICP-MS analysis to determine Ru abundance in chromite from a selected range of mineralised and barren picritic intrusions.
The Distal Footprints of Giant Ore Systems: UNCOVER Australia	***Supported by CSIRO ex Science & Industry Endowment Fund (SIEF)*** ***Industry Collaborator: CSIRO, University of Western Australia, Curtin University, Geological Survey of Western Australia*** ***CIs: Hough, Reddy, McCuaig, Tyler, Dentith, Shragge, Miller, Fiorentini, Aitken*** ***Summary:*** Australia is an old continent with much of its remaining mineral wealth masked by a thick cover of weathered rock and sediments that pose a formidable challenge for future mineral exploration. This project aims to develop a toolkit with a workflow to identify the distal footprints of the Giant Ore Systems to address a fundamental limitation in current exploration methodologies.
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.

Four-dimensional lithospheric evolution and controls on mineral system distribution in Neoarchaen 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.
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.
PaleoplateGIS quantification of the latitude and tectonic triggers for CD deposits in ancient passive margins	***Supported by the Minerals and Metal Group*** ***CIs: Leach, Li, Pisarevsky, Gardoll*** ***Summary:*** This a pilot study to examine the possible paleolatitudinal and plate kinematic controls on global clastic-hosted lead-zinc mineralisation (or CD deposits) in the past 1000 Ma, and use the identified criteria to develop a prospective map for such deposits. To achieve this we revised our global plate motion model using the latest knowledge and developed GIS tools to determine various plate-motion parameters such as paleolatitude, plate motion speed and directions etc. Utilising and prioritising empirically key controlling factors identified in this study, we were able to develop a set of criteria for identifying favourable passive margins for CD deposits, and use it to make global prospectivity maps.

Multiscale dynamics of hydrothermal mineral systems	***Supported by MERIWA*** ***Industry Collaborators: Integra Mining, First Quantum Minerals, AngloGold Ashanti, SIPA Resources, GSWA, Newmont, Goldfields, Barrick Gold, OZ Minerals*** ***CI's: Ord, Gorczyk, Gessner, Hobbs, Micklethwaite*** ***Summary:*** The project aims to produce an integrated framework for the origin of giant hydrothermal deposits. The study crosses all the length scales from lithospheric down to thin section. The goal is to define measurable parameters that control the size of such systems and that can be used as mineral exploration criteria. In particular the emphasis is on: (i) criteria that distinguish a '*successful*' from a '*failed*' mineral system and (ii) vectors to mineralisation within a successful system.
Hydrothermal footprints of magmatic nickel sulfide deposits	***Supported by MERIWA, WA State Government (commenced 2011)*** ***CI's: Fiorentini, Barnes, Miller*** ***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.

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 eclectic, but demonstrates the global network with targeted leaders in core research areas in CCFS.

FUNDED COLLABORATIVE ACTIVITIES AND PROJECTS COMMENCED OR ONGOING IN 2013 INCLUDE:

Macquarie

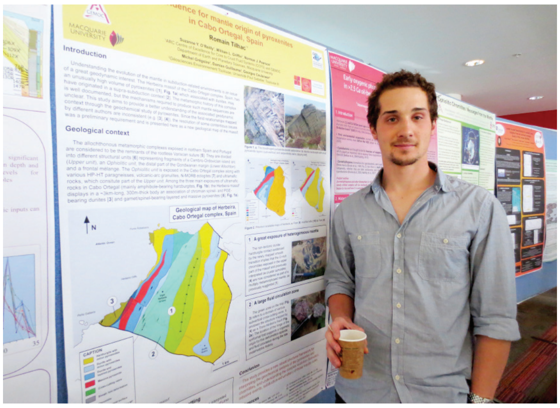
- Sue O'Reilly was awarded the Copernicus Visiting Professorship at the University of Ferrara in 2013. A 4-week visit by Sue O'Reilly and Bill Griffin at the University of Ferrara continued collaboration with with Professors Massimo Coltorti and Costanza Bonadiman starting a new project on the nature of the mantle beneath Sardinia. Fruitful interaction also took place with the instrument laboratory at the University of Modena.
- 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 with a project funded by the China Academy of Sciences for 5 years from 2013 with Bill Griffin, Sue O'Reilly and Elena Belousova as CIs. Bill Griffin, accompanied by Drs Jin-Xiang Huang and Ming Zhang, joined them for fieldwork in Tibet led by Dr Shi in May 2013 as part of this large project.

Fieldwork in Tibet; Top: Badunzhu and Ming Zhang, Centre: Prayer flags on the River. Botom: Bill Griffin, Jin-Xiang Huang, Xiaohan Gong and Qishuai Huang.

- Sue O'Reilly and Bill Griffin are formal collaborators on a five-year project titled *"Geological Evolution and Mineral Resources in South China"* funded as a Key Project from the Ministry of Education of China. This project is led by Professor Shao-Yong Jiang, Director of the State Key Laboratory for Mineral Deposits Research, Nanjing University and also involves Professor Xisheng Xu, a CCFS Honorary Associate. This project involves joint visits of researchers between Nanjing and Macquarie Universities over the term of the Project.

- Collaboration continued on a related project with Professor Yang Jing-Sui at the China Academy of Geological Sciences (CAGS, Beijing), funded by CAGS, examining the trace minerals in ophiolitic peridotites along the Yarlung-Zhangbo Suture Zone in Tibet, and similar massifs in the Polar Urals. These minerals carry evidence for subduction of shallow rocks to the Transition Zone and their re-exhumation and emplacement in the crust during the India-Asia collision. Studies were started on the isotopic composition of metal and alloy phases, to examine isotopic fractionation under extreme conditions. This collaboration extends resources and expertise for FP1 (TARDIS).
- 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). The Consortium promotes research collaboration and exchange as well as undergraduate training exchange and joint postgraduate programs.
- The first IUCES Summer School for postgraduates, "*Water in Geological Processes*" is scheduled in September 8-13 2014.
- 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 continued in their role as as Guest Professors at CUG (Wuhan). The first cotutelle student (Mr Qing Xiong) continued at GEMOC/CCFS during 2013, and Dr Huayun Tang was awarded a 12-month fellowship by the China Scholarship Council for research at Macquarie. Two new cotutelle PhD projects were set up, bringing Jianggu Lu to CCFS/GEMOC in December 2013 for a project focused on the nature of the lithospheric mantle under the South China Block, with support from the China Scholarship Council, and Jun Xie to study the accuracy of long period surface waves from ambient noise. 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 with Dr Yingjie Yang and postgraduate student, Chengxin Jiang from CCFS/GEMOC.
- Following the signing of a formal MOU in 2011 with the Institute of Geology and Geophysics (IGG; China Academy of Science, Beijing), collaboration expanded in 2013 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 CCFS Foundation 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.
- Following the formal MOU signed in 2012 with the University of Science and Technology, Hefei, to promote collaborative research and postgraduate joint projects, Dr Jin-Xiang Huang (TARDIS-E CCFS Foundation Project) visited Hefei to undertake stable-isotopic work.
- A new collaboration with Profesor Zeng-qian Hou (Director of the Institute of Geology, China Academy of Geological Sciences (CAGS)) and his group, including a cotutelle between MQ and China University of Geosciences Beijing (CUGB) for a project titled "*The study of enclaves in Gandese Belt, Tibet*". This project is part of the internationally funded IGCP project "*Metallogenesis of collisional orogens in the East Tethyside domain*", with Professor Hou as a CI, and in particular, is relevant to the Tibet geodynamics research within Professor Hou's group in CAGS, and enhances the Tibet-related projects addressing a wide range of large geodynamic questions; this also interfaces with related research strands at the UWA and Curtin nodes, and with China-based work of the GSWA.
- As a result of collaborative connections initiated by Dr José María Gonzáles-Jiminéz, collaborations commenced with the Universities of Barcelona and Zaragoza (Spain), with research study periods at CCFS/GEMOC by Montgarri Castillo Oliver and Vanessa Colás respectively. These successful interactions resulted in the setting up of relevant cotutelle agreements for PhD studies involving "*Evolution of indicator minerals in Angolan kimberlites: applications in diamond exploration*" and "*Thermodynamic modelling of the fluid mobility of transition elements in Earth's lithosphere using chromite geochemistry*".

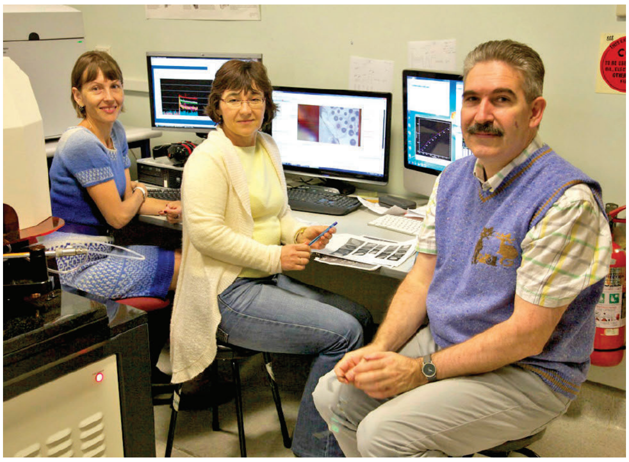
- Professor Bill Griffin continued interaction with SLN Doniabo, the French company that mines the ophiolitic laterites of Numea to extract Ni. The purpose of the project is to advise the company and the BRGM on the potential to expand the metallurgical processes to produce scandium. A project proposal involving a collaboration with French synchrotron researchers has been approved.
- Studies of trace elements and fluids in diamonds and their 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 2013 as an external advisor to this PhD, and for analytical work connected with the links between eclogites, metasomatism and diamonds.
- A study involving detailed 2-D and 3-D structure of the Kaapvaal Craton in several time slices, using mantle-derived xenocrysts, was continued as 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, continued as a collaborative project with Minerals Targeting International, BHP Billiton and Professor Steve Grand (University of Texas at Austin).
- 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.
- Projects on the nature of the lithosphere in Mongolia, Vietnam and Russia continued 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).
- 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 (*pictured below*) commenced a joint PhD at Macquarie University in early 2013, with a project titled "*Peridotite massifs from 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, and submitted her thesis in 2013.
- A collaborative research project continued with the University of Witwatersrand, South Africa. 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 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 publication 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 Professor Carlos Villaseca from the Complutense University of Madrid, Spain provided further insights into the age, nature and composition of the lower continental crust in central Spain. This resulted in a Geology paper concerning the architecture of the European-Mediterranean Lithosphere (see *CCFS publication #234 and Research Highlight p. 80*).
- A 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 Mountans, Russia. The new integrated results on trace-element compositions and Rb-Sr, Sm-Nd, U-Pb, Lu-Hf isotope data were published in Mineralogy and Petrology in 2013 (See *CCFS Publication #399*).



- Several collaborative projects continued with Drs Kreshimir N. Malitch and Inna Yu Badanina, Dept of Geochemistry and Ore-Forming Processes, A.N. Zavaritsky Institute of Geology and Geochemistry, Uralian Division of Russian Academy of Sciences, Ekaterinburg, Russia (*pictured above with Elena Belousova, (centre)*). They provide a unique collection of samples from a range of ultramafic massifs (from different regions of Russia, South Africa, Italy, UK), with separates of zircons, baddeleyites, Ru-Os sulfides and Ru-Os-Ir alloys available for collaborative studies.
- This collaboration aligns with strands of the TARDIS Project focusing on a better understanding of the osmium and hafnium isotope composition of the Earth's mantle through studies of Ru-Os sulfides and Ru-Os-Ir alloys, with special focus on Hf-isotope composition of zircon and baddeleyite derived from globally distributed ultramafic massifs. These contribute to our knowledge about: (1) the Os-isotope evolution of the Earth's mantle exemplified by Proterozoic to Mesozoic ultramafic complexes, (2) Os-isotope sources for PGE mineralisation and Hf-isotope sources for zircon/baddeleyite in the oceanic and subcontinental mantle environments and (3) timing of formation of ultramafic protoliths hosting PGE mineralisation.
- This collaborative study also contributes to the aims of the ARC Future Fellowship project of Dr Elena Belousova entitled "*Dating Down Under: Resolving Earth's Crust - Mantle Relationships*". Integrated isotopic information (U-Pb, Lu-Hf and Re-Os) to be collected from several minerals should provide a highly effective set of tracers for crust-mantle interactions. The sources of magmas and the relative proportions of different possible contaminants should be readily distinguishable using these isotopic systems, while the U-Pb data and Os model ages provide constraints on the timing of these interactions.
- Studies on the geochemical signatures of Mesozoic granites as indicators of geodynamic processes in southeastern China continued with Professor Jinhai Yu (collaborative project with Nanjing University).
- *TerraneChron*® analysis of Proterozoic terrains in Africa, Australia, South America, South East Asia and Europe were undertaken with several mineral-exploration companies.
- 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.
- CCFS/GEMOC continued active relationships with the newly established International Precambrian Research Centre of China (IPRCC); Bill Griffin is on the Board and was involved in organising the very successful 2013 meeting in Beijing in October: "*The International Meeting on Precambrian Evolution and Deep Exploration of the Continental Lithosphere*" that also coincided with the opening of the new SHRIMP Centre in

Participants at the SHRIMP Conference, Beijing, October 2013.

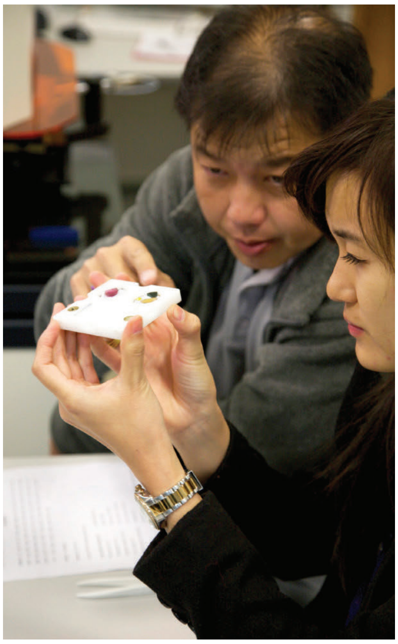
Beijing under the directorship of Dunyi Liu. This meeting was attended by several (cross-node) CCFS participants including Bill Griffin, Sue O'Reilly, Sergei Pisarevsky, Simon Wilde (also on the Board) and Craig O'Neill, who attended the post-conference field trip.

- 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 (Novosibirsk, currently at 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. This has led to the arrangement of a formal cotutelle PhD project for Nóra Liptai between Eotvos Lorand University, Budapest (Hungary) and MQ. The project is titled "*Nature of the Mantle beneath the Carpathian-Pannonian region, Hungary: a mantle xenolith study*".
- Collaboration continued between Associate Professor Sandra Piazolo and Professor P. Bons (University of Tuebingen, Germany) on the numerical simulations of ice microstructures using the numerical modelling platform Elle.
- Collaboration continued between Associate Professor Sandra Piazolo and Dr D. Koehn (University of Glasgow, Scotland) on the numerical simulations of fracture – fluid systems using the numerical modelling platform Elle.
- Collaboration was initiated between Associate Professor Sandra Piazolo and Professors C. Teyssier and D. Whitney (University of Minnesota, USA) on the deformation microstructures of eclogitic shear zones in the Bergen Arc, Norway.
- Collaboration continued between Associate Professor Sandra Piazolo and Professor M. Mantami (Indian Institute of Technology, India) on the deformation mechanism of magnetites and their magnetic signature.
- Collaboration continued between Associate Professor Sandra Piazolo and Professor A. Putnis (University of Muenster, Germany) on the effect of deformation on reaction rates in fluid mediated phase transformations.
- Collaboration continued between Associate Professor Sandra Piazolo and Dr M. Peternell (University of Mainz, Germany) on the experimental deformation of ice.
- Collaboration continued between Associate Professor Sandra Piazolo and Dr V. Luzin (Bragg Institute, ANSTO, Australia) on (a) the experimental deformation of ice. This included a joint two week experiment at ANSTO in Nov. 2013, and (b) textural and residual stress measurements of diamondites including 5 days of analysis at ANSTO throughout the year.
- Collaboration was initiated between Associate Professor Sandra Piazolo with Dr Venter (Pretoria, South Africa) on residual stress measurements of diamondites, including 5 days of analysis at ANSTO throughout the year.
- Continued collaboration of Associate Professor Sandra Piazolo with Dr J. Godinho (Oak Ridge National Laboratory, USA) on the dissolution behaviour of minerals – experiments and numerical simulations.
- Collaboration was initiated between Associate Professor Sandra Piazolo and Professor M. Jacobsson (Stockholm University, Sweden) on the application of ice flow law research to large scale geomorphological phenomena in glaciated areas.
- Collaboration was initiated between Associate Professor Sandra Piazolo and Dr B. Almquist (Uppsala University, Sweden) on the seismic anisotropy of metamorphic mobile belts.
- Continued collaboration of Associate Professor Sandra Piazolo with Professor J. Wheeler and Dr E. Mariani (Liverpool University, UK) on superplasticity in rocks – numerical simulation, experiment and nature.
- Associate Professor Simon Clark continued his collaboration with Professor David Walker, University of Columbia, on the study of excess volumes in garnet solid solutions.
- Associate Professor Simon Clark visited Lawrence Livermore National Laboratory this year as part of a continued collaboration with Dr Joe Zaug, Lawrence Livermore National Laboratory, on the study of materials at high-pressures and temperatures using resistively heated diamond anvil cells.
- Associate Professor Simon Clark visited Lawrence Berkeley National Laboratory as part of a continued collaboration with Dr Bora Kalkan on polyamorphism in natural and synthetic materials.
- Dr Juan Carlos Afonso continued collaborating with Professors Ivone Jimenez-Munt, M. Fernandez, J. Verges and D. Garcia-Castellanos from the 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 Juan Carlos Afonso continued collaborating with Professor Alan Jones from the Dublin Inst. for Advanced Studies (Ireland) on the characterisation of the lithospheric mantle beneath Ireland, funded by IRETHERM (Science Foundation Ireland).

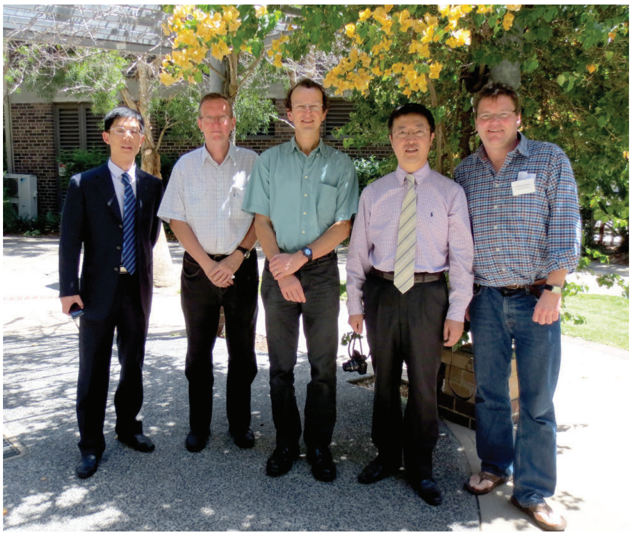
- Dr Juan Carlos Afonso collaborated with Professors James Connolly (ETH Zurich), Nicholas Rawlinson (Univ. Aberdeen), Derek Schutt (Colorado State Univ.), Alan Jones (DIAS), Professors Bill Griffin and Sue O'Reilly, and Dr Yinjie Yang on the development of 3D multiobservable probabilistic inversion methods for the thermochemical structure of the lithosphere and sublithospheric upper mantle. This project is funded by ARC DP project 120102372.
- Dr Juan Carlos 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 Manel Fernandez (CSIC, Barcelona) visited MQ to work with Dr Afonso (*pictured below*) on the application of LitMod2D to study the lithospheric structure of several mountain chains in Europe and Asia.

- Dr Juan Carlos Afonso collaborated with Professor Sergei Lebedev from the Dublin Inst. for Advanced Studies (Ireland) on the charaterisation of Pre-Cambrian lithospheric regions based on multi-observable probabilistic inversions.
- Dr Juan Carlos Afonso started a collaboration with Professor Gianluigi Rozza (SISSA MathLab, Switzerland) on the applications of reduced basis methods to probabilistic geodynamic inversions.
- Dr Javier Fullea (CSIC, Madrid) visited MQ to work with Dr Afonso on further developments of the LitMod software and application to the Iberian Peninsula.
- Professor Sergio Zlotnik (*pictured right (right)*) (UPC, Barcelona) visited MQ to work with Dr Afonso and PhD Student Beñat Oliviera-Bravo (*pictured right (centre)*) on the development of LitMod software and its application to the Iberian Peninsula.
- 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*".
- Dr Yingjie Yang continued collaboration with Professor Yinhe Luo from China University of Geosciences (Wuhan), on a project "*Imaging crustal anisotropy of the Dabie Orogenic Belt using ambient noise tomography*", funded by the Chinese National Science Foundation.
- Dr Yingjie Yang visited Professor Michael Ritzwoller (University of Colorado at Boulder) to continue collaboration on imaging the seismic anisotropy of the Tibet plateau and understanding the deformation mode of Tibetan lithosphere.
- Dr Yingjie Yang continued to collaborate with Dr Yong Zheng the institute of Geodesy and Geophysics of China Academy of Sciences on a project "*Using two-plane wave tomography method to map the upper mantle structure of Tian Shan*".
- Dr Yingjie Yang continued to collaborate with Professor Jieyuan Ning's group at Beijing University to work on surface wave tomography in northeast China.
- Dr Yingjie Yang visited China University of Geosciences (Beijing) to build collaboration with Associate Professor Hongyi Li on a project "*Studying the seismic lithospheric structure of the lower Yangtze River metallogenic belt in east central China and its possible relationship with the metallogenic processes*" funded by China National Science Foundation.
- 2013 saw the continuation 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 Associate Professor Mehmet Akbulat. The observations and samples collected during fieldwork on the ophiolites in Atalya (2012) form part of Nicole McGowan's PhD project, while Jose González Jiménez concentrated on Platinum Group Minerals in the chromitites. Mehmet Akbulat visited CCFS/GEMOC in 2013 for an extended period to collaborate on this research.
- CCFS/GEMOC hosted Dr Narong Praphairaksit and Ms Thidarat Muangthai, from the Gem and Jewellery Institute

of Thailand (*pictured right*) Dr Praphairaksit is Assistant Professor in the Department of Chemistry, Chulalong University, Bangkok. His research has focused on the development of sample preparation techniques for the trace element analysis of petrochemical and environmental samples by ICP-OES and ICP-MS. Ms Muangthai is a Precious Metal Assayer at the Gem and Jewelry Institute of Thailand, Bangkok. She operates the laser ablation ICP-MS at GIT and has been using this technique to investigate impurities in natural and synthetic corundums. The purpose of the visit is to gain more experience in laser ablation ICP-MS (in which CCFS/GEMOC has frontline experience) and specifically trace-element analysis of gemstones.



- In January 2013, CCFS/GEMOC hosted visitors, Professors Li Menlou, Head of the Education Department Graduate School, Su Longtao, Vice Head of the overseas Graduate Education Department from the China University of Geosciences, Wuhan, and Dr Wolfgang Roeher, University of Hamburg (*pictured below with Norman Pearson and Simon George*) for a tour of through the GEMOC/CCFS research laboratories to showcase Macquarie's research excellence.



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 Associate 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 had an ongoing collaboration with CCFS PI Professor Robert Kerrich from University of Saskatchewan, Canada, with studies ranging from potassic intrusions in SW China and porphyry magmatism in the Philippines, to greenstone belts in the Yilgarn Craton and western Africa. Despite Professor Kerrich's untimely passing in 2013, this research will continue within CCFS.
- Professor Cam McCuaig has an ongoing collaboration with Dr David Leach from the U.S. Geological Survey on the evolution of mineral systems within the context of the Earth's evolving atmosphere, hydrosphere and biosphere, which led to a paper in 2013 "*Banded Iron Formation to Iron Ore: Implications for the Evolution of Earth Environments*".
- A new collaborative project began between Dr David Wacey, Professors Mark Barley and James Farquhar (University of Maryland) using multiple sulfur isotopes to investigate sulfur cycling in the early Archean Dresser Formation of Western Australia.
- Dr David Wacey continued his collaboration with Martin Brasier (Oxford University, UK) investigating the biodiversity of the 1900 Ma Gunflint Formation of Cananda, and extended this collaboration to working on the Ediacara biota of Newfoundland.
- Dr David Wacey continued his collaboration with Nicola McLoughlin (University of Bergen, Norway) studying life in ancient volcanic rocks.
- Professors Mark Barley and Marco Fiorentini continued their collaborations with international leaders in multiple sulfur isotope geochemistry (James Farquar, Boz Wing, Shuhei Ono, Doug Rumble, Sue Golding, Jay Kaufman) to determine how results from the range of methods compare, and implications for the evolution of the early Earth.

- 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, Associate Professor Marco Fiorentini has an ongoing collaboration with scientists from the Geological Survey of Denmark and Greenland (lead by Professor Jochen Kolb). In December 2013 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, Associate Professor Marco Fiorentini has an ongoing collaboration with scientists from the University of Leoben (Austria). In particular, Marco 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.
- Associate Professor Marco Fiorentini was awarded two prestigious Post-Rouge Visiting Professorships, one from Toulouse, France and one from Grenoble, France, which allowed him to undertake research at these institutions within the framework of his ongoing ARC Future Fellowship.
- Professor Cam McCuaig was awarded a visiting professorship in Nancy (France) from the University de Lorraine, which he is undertaking in 2013-2014 to collaborate with the Georesources21 and Labex projects dealing with the genesis of mineral systems and industry application of research.

Curtin University

- Dr Xuan-Ce Wang is collaborating with Dr Chao-Feng Li (Institute of Geology and Geophysics, Chinese Academy of Sciences, Guangzhou, China) on early Earth differentiation processes using ^{146}Sm-^{142}Nd and ^{147}Sm-^{143}Nd isotope system (National Natural Science Foundation of China) and 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 (UWA) 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).
- Collaboration continued for Professor Zhen-Xiang Li with a large group of researchers from around the world, including Professor D.A.D. Evans (Yale University), Dr Richard Ernst (Carleton University), Professor 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 magmatism and tectonics of South China is part of an ongoing collaborative research with Professor X.H. Li (Chinese Academy of Sciences (CAS), Beijing), Professor W.X. Li (CAS, Guangzhou), Professor X. Xu (Nanjing University), and Professor S.L. Chung and Dr Q.H. Lo (National Taiwan University). In addition, his ARC-CAS jointly-funded project on Mesozoic vertical tectonic movements in South China and subduction dynamics involves collaboration with Professors Y.G. Xu and W.X. Li (CAS, Guangzhou), and Dr M. Danisik (University of Waikato, NZ).
- Professor Li collaborated with Professor Q. Wang (CAS, Guangzhou) and Dr C.L. Zhang (China Geological Survey, Nanjing) on the tectonic evolution of Tibet and NW China, and with Professor X.D. Jiang (China Ocean University) on a NSF-China project on the development and evolution of the Red River Fault System.
- 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 and two papers have been submitted for publication in 2014. Collaboration with the Guangzhou Institute of Geochemistry has continued and a major review of crustal growth in the southern North China Craton with Professor Xiao-Long Huang was published. Professor Touping Peng spent 12 months working at Curtin supported by the Chinese Science Council and the Chinese Academy of Sciences.
- Professor Wilde's ongoing collaboration with Professor Santanu Bhowmik of the Indian Institute of Technology at Kharagpur focused on the application of U-Pb and Lu-Hf isotopic work on zircon and dating of monazite in high-grade metamorphic rocks.
- Professor Wilde'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 continued and ongoing collaboration with Profs Dunyi Liu and Yusheng Wan at the Institute of Geology at the Chinese Academy of Geological Sciences (CAGS) in Beijing has focused on examining events in the Western Block of the North China Craton. Work has now re-commenced the Anshan area, where the oldest segments of the North China Craton are preserved.

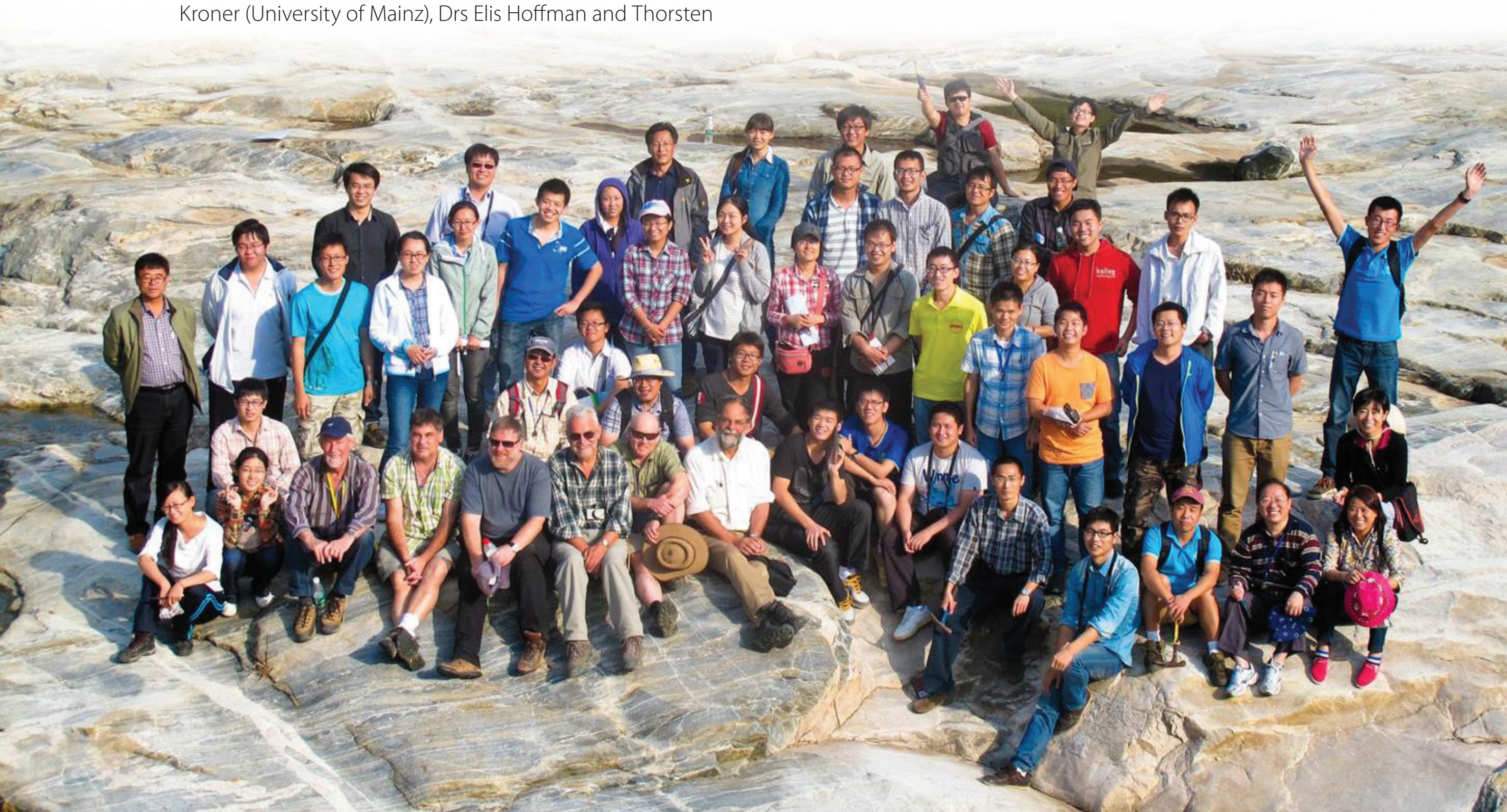
- Professor Wilde's is also collaborating with Professor Alfred Kröner from the University of Mainz on several projects, including the eclogites of the Escambray in Cuba, the Precambrian rocks along the Namibia-Angola border, and several studies in the North China Craton.
- A Tectonic History of South China in Nine Days, a CCFS Joint Field Workshop with Chinese Partners, is a biannual field workshop on the tectonic history of South China and 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. 7–15 December 2013, Zhejiang University, China.
See *photo below.*

GSWA

- Dr Klaus Gessner continued international research collaboration with: Dr Virginia Toy (Otago University, Dunedin) and Dr Xianghui Xiao (Argonne National Laboratories, USA), and Jens-Erik Lund Snee at Stanford University on the Alpine Fault in New Zealand, and with Professor 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), Drs Elis Hoffman and Thorsten Nagel (University of Bonn) and Professor Carsten Munker (University of Cologne). He is collaborating with Professor Clark Johnson (University of Wisconsin at Madison) and Dr K. Williford (Jet Propulsion Laboratory) on projects including: in-situ investigation of kerogen of microfossils from the 2.3 Ga Turee Creek Group, and Fe-isotope investigation of oxide and sulfide phases within rocks deposited across the Great Oxidation Event (GOE) in Western Australia. The same transition is being investigated for whole rock geochemical changes together with Professor Balz Kamber (Trinity College, Dublin). A detailed investigation of the entire Turee Creek Group is being undertaken together with Professor Pascal Philippot (Institute de Physique du Globe de Paris) using fresh drill core obtained through a diamond drilling program completed in 2013. A collaborative research project with Professor John Valley (University of Wisconsin at Madison, oxygen isotopes) and Professor Robert Hazen (Carnegie Institution of Science, carbonaceous matter) is investigating the nature and compositional variations of hydrothermal fluid flow in the 3.5 Ga volcanic caldera setting of the Dresser Formation in the Pilbara Craton of Western Australia, the site of Earth's oldest convincing evidence of life. In the same area, an ongoing project with Professor Joachim Reitner and Dr Jan-Peter Duda (University of Göttingen) is investigating the variable composition of carbonate minerals and their role as biomarkers and/or source for kerogenous material in hydrothermal veins. The changing composition of seawater across the GOE is being investigated in collaboration with Professor Martin Wille (Universität Tübingen). Precambrian microfossils are the subject of research conducted in collaboration with Professor Bill Schopf (University of California, Los Angeles).



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
- Applications to funding schemes for matching funds for new infrastucture purchases and partner co-investment
- 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
- Providing input into future NCRIS (especially AuScope) policies, using CCFS research concentration and leading directions to inform national priorities

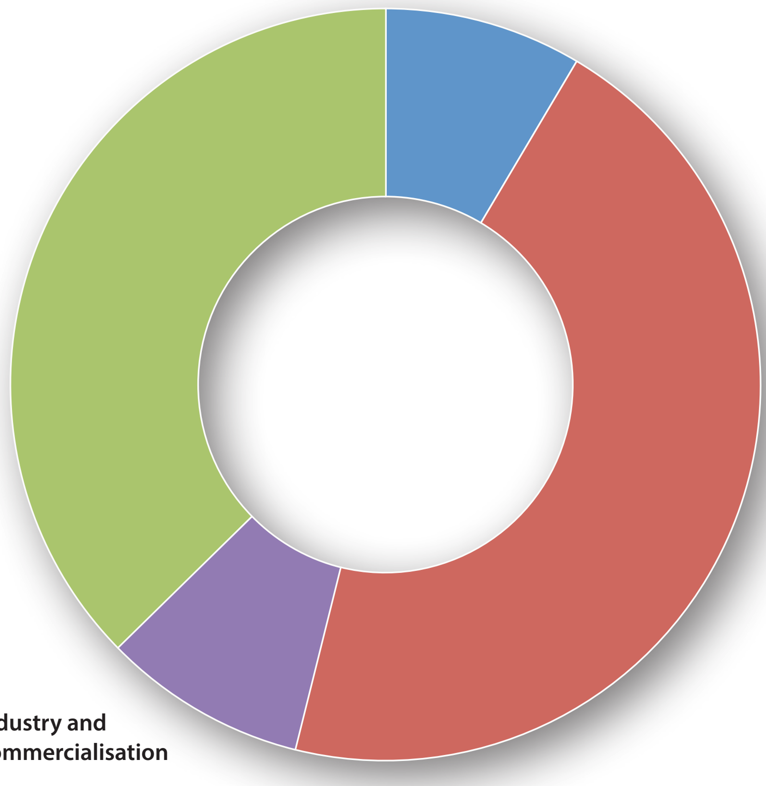
This is an unaudited summary of 2013 income and expenditure. A full, audited statement of detailed expenditure and income is prepared by Macquarie University. No in-kind support is included here.

INCOME		
Accumulated ARC funds at the end of 2012		*$2,079,941*
*Accumulated Institutional cash Contributions at the end of 2012 **		*$3,315,258*
ARC Centre of Excellence Grant		**$1,971,746**
Cash contributions from Nodes and Australian Partner		
Macquarie University **	$600,000	
The University of Western Australia	$320,000	
Curtin University	$250,000	
GSWA	$150,000	
		$1,320,000
Other Income	Interest	**$21,908**
Total Income		**$3,313,654**

EXPENDITURE	
Salaries	**$2,007,227**
Scholarships	**$91,037**
Travel	**$262,795**
Laboratory	**$172,500**
Conference Fees	**$15,996**
Maintenance/Consumables	**$455,998**
Total Expenditure	**$3,005,553**
Accumulated ARC funds at the end of 2013	*$2,069,230*
** Accumulated Institutional cash Contributions at the end of 2013 ***	*$3,634,070*

** Includes carry forward of $908,707 for 2011 lump sum payments for Science Leverage Fund and ARC Post Award*
*** Includes $100,000 of 2014 commitment received in 2013*

INCOME SOURCES 2013



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

- 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
- 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.

Appendix 1: Foundation Project summaries and progress in 2013

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

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

AIMS:

The most robust record of the Os isotope composition of the Earth's convecting mantle is provided by Platinum Group Minerals in ophiolites and komatiites. From these, fundamental information on the origin of the Earth and the evolution of its core-mantle system can be obtained. In this project, an international team of leading mantle researchers uses a unique combination of techniques to provide new insights into deep mantle processes with the following specific objectives: (a) to define the initial composition and evolution of Earth's convecting mantle using the Re-Os isotopic systematics of platinum-group minerals and sulfides from ophiolites and komatiites; (b) to understand the origins of ophiolitic chromitites; (c) to understand the relation of Os-isotope heterogeneity in the convective mantle to major events in Earth's evolution; (d) to evaluate the evidence for the preservation of large volumes of ancient continental mantle within the ocean basins.

PROGRESS IN 2013:

During 2013 we continued our work on a large collection of chromitites from ophiolite localities worldwide; this collection continues to grow, especially through our active collaboration with groups at the Universities of Barcelona and Granada. The chromites (and associated silicates) were analysed for major- and trace-elements, and were surveyed petrographically to locate and identify any platinum-group minerals (PGM) or base-metal sulfides (BMS) residing in them. Those that were found were then analysed by LA-MC-ICPMS to determine their Os-isotope compositions. Approximately 300 Os-isotope analyses of PGM have been carried out; a larger number (>1000) of BMS analyses was carried out, with ca 20% containing enough Os to give reliable results. Dr González Jiménez finalised his PGM-based projects before leaving to take up a senior teaching and research post at the University of Santiago; he will continue to collaborate with the project, expanding our network in this field with colleagues in Chile.

Field work in Tibet (collaboration with Dr Rendeng Shi, CAS, and Professor Jingsui Yang, CAGS) added more sample sets. This collaboration has turned much of the activity in the project toward trying to understand the highly reduced UHP assemblage enclosed in the chromitites and peridotites of the '*ophiolites*' along the Yarlung-Zangbo Suture Zone in Tibet. A major achievement during the year was the discovery of minerals derived from the Transition Zone, implying that some of the Tibetan '*ophiolites*' have been subducted to depths of at least 500 km, and then been rapidly exhumed to be emplaced in the crust, bringing in the geodynamic modelling strand with Dr Juan Carlos Afonso. Application of new methodologies for mineral separation using the selFrag, as described in Technology Development Project 3, were critical for this.

U-Pb dating of zircons from the chromitites (by Dr Elena Belousova), and Re-Os dating of laurites in similar samples, suggest that the peridotites in the suture had resided in the Transition Zone for several hundred million years before their exhumation. EBSD studies of the chromitites by Takako Satsukawa are yielding spectacular and unexpected information on deformation and recrystallisation in the Transition Zone.

To provide comparative material for the ophiolite work, we have continued studies of PGM and BMS in xenoliths from the subcontinental mantle. Dr Jin-Xiang Huang continued her work on metasomatism in mantle-derived eclogites, SIMS analysis of O isotopes in metasomatised rocks, and the development of

Qing Xiong, Tibet.

standards for O-isotope analysis of Cr-rich garnets. She began a large project on Mg and Fe isotopes and their behaviour in mantle metasomatic processes, involving work in CAS Beijing laboratories with 2-way technology transfer.

Mr Qing Xiong, a cotutelle student with the China University of Geosciences, Wuhan, is working on ophiolites and ultramafic complexes in two parts of Tibet. During 2013 his work focused on the Zedang complex in the Yarlung-Zangbo Suture Zone. Mr Ed Saunders completed his PhD thesis on the mobility of gold in the mantle. Ms Nicole McGowan continued her multi-isotopic study of chromitites and their host rocks in direct collaboration with Dr Rendeng Shi (Institute for Tibetan Research, Chinese Academy of Sciences) who has provided her with key samples from three Tibetan ophiolites; her work also includes ophiolites in Spain and Turkey.

Published outputs:

CCFS 2013 Publications #198,199, 200, 215, 212, 234, 235, 236, 237, 239, 281, 320, 324, 334, 344, 348, 349, 352, 361, 362, 375

Conference Presentations:

21 International conference presentations including 4 Keynote

Nicole McGowan examining the Antalya ophiolite, Turkey.

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

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

AIMS:

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, at the P-T conditions of the lithospheric mantle 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.

PROGRESS IN 2013:

In 2013, considerable progress was achieved in two areas; firstly, the generation of new experiments, and secondly, new analyses from both the Ivrea Zone in Italy and the Thrym Complex in Greenland.

After overcoming numerous technical difficulties in the first year of the project in setting up the new methodology that would permit measurement of the compositions of hydrous fluids in equilibrium with mantle rocks, progress has been made on experiments with various water contents. Twenty new experiments have been performed on H_2O-saturated basanite compositions that extend the range of investigated conditions from 0.5 to 4.0 GPa and 950 to 1200 °C. These augment experiments on both dry and H_2O-undersaturated mixes for the purpose of determining the dry and H_2O-saturated liquidii of the basanite, as well as the solubility of H_2O in the basanite melt. In combination, these studies provide important information about the likely distribution and compositional characteristics of H_2O-fluids in the Earth's mantle and lower lithosphere. They also provide the basis for more advanced experimental studies on S-bearing aqueous fluids under mantle conditions that are planned for the coming year.

The key successful experiments have now been submitted for publication in an international peer-reviewed journal. These experiments reveal that although most incompatible elements and chalcophile metals are sparingly soluble in H_2O-fluids at low pressures and temperatures (i.e. 950 °C at ≤ 1.0 GPa), they become increasingly soluble at higher temperatures and (more particularly) pressures. H_2O-fluids and basanitic melts were found to be completely miscible by 4.0 GPa at 1100 °C. The new data also reveal that, relative to silicate melts, H_2O-fluids preferentially incorporate alkalis, Ba and Pb. In contrast, rare earth elements have much lower solubilities. This is consistent with previous predictions for the role of H_2O-fluids during arc processes and continental crust production. However, the experiments also reveal that high-field-strength elements (Nb, Ta, Zr, Hf, Ti) are relatively soluble in H_2O-fluids (contrary to previous expectations) and thus residual rutile is a necessity if H_2O-fluids are to be a key element of arc magma and continental crust development.

Since this project began in August 2011, 3 Honours and 1 Masters students have been supervised and trained to work in challenging, remote and complex environments. Three field seasons have now been completed both in the Ivrea-Verbano Zone (IVZ) and in the Thrym Complex. Research concentrated initially on the genesis of several nickel-copper sulfide deposits that occur in enigmatic mafic/ultramafic, alkaline and volatile-rich pipes that intruded into rocks of the deep lithosphere in the IVZ. In order to identify the source and composition of the parental magma and the fluid that was evidently involved in the formation of the pipes and metal sulfide deposits, analyses comprised (1) whole rock studies (XRF, NiS fire assay, solution ICP-MS), (2) in-situ major, minor and trace element analysis of silicates, oxides, and sulfides (electron microprobe, laser ablation ICP-MS), and (3) analysis of water of pyroxene (SHRIMP-SI).

In 2013 we organised a very successful field trip in the Ivrea Zone between the Biennial Meeting of the Society for Geology Applied to Mineral Deposits in Uppsala, Sweden, and the Goldschmidt Conference in Florence, Italy, where the outcomes of this project were presented. This allowed a group of ten experts in nickel-copper sulfide systems from the University of Western Australia, Macquarie University, CSIRO and Minerals Targeting International to attend the field trip and to discuss topics related to metal transport and concentration in the deep lithosphere and upper mantle (Fig. 1).

In terms of analytical work, in 2013 we carried out detailed isotopic studies on samples from both the Ivrea Zone and the Thrym Complex with the aims of (1) identifying the source region of the sulfur that formed the sulfide deposits (i.e. crustal vs. mantle sulfur), and (2) better constraining the timing of events in the mineralised areas. While the work in Greenland is still under way and is planned for completion in 2014, work in the Ivrea Zone has already showed interesting results. Sulfur isotope studies conducted using the SIMS at UWA indicate that sulfides from the pipes yielded $\delta^{34}S$ values of 0 ± 2 which is indicative of a mantle source. The geochronological studies included (1) U-Pb dating of zircon and apatite using laser ablation ICP-MS at UWA and Macquarie, respectively, and (2) ^{40}Ar-^{39}Ar dating of phlogopite using a noble gas mass spectrometer with laser probe and resistance furnace at Curtin University. Zircons separated from the pipe rocks suggest a crystallisation age of the pipes of 277 ± 6 Ma, which is slightly, but significantly, younger than the previously reported age of 287 ± 3 Ma. The younger age is in better agreement with field relationships and confirms a genetic link between emplacement of the pipes and widespread mantle metasomatism in the lithospheric mantle in this area during the late Carboniferous. The apatite yielded an age of 235 ± 20 Ma, whereas the phlogopite gave an age of 188.9 ± 1.3 Ma. These young ages likely reflect lower closing temperatures of apatite and phlogopite and/or regional cooling. However, there is some structural evidence that the phlogopite ages reflect a reopening of the system due to a small thermal spike that has not affected higher closure temperature phases, suggesting that part of the exhumation history of the Ivrea Zone is associated with extension at the continental margin rather than being completely Alpine. This question will be addressed in a new foundation project.

Published outputs:

CCFS 2013 Publications #32, 162, 174, 222, 228, 272, 310, 333, 389, 413, 419, 447, 448

Conference Presentations:

11 International conference presentations

See *Research Highlight "Metals flow in mantle streams" p. 47.*

Figure 1. Participants of the 2013 CET-CCFS Field trip in the Ivrea Zone (Italy). From left to right: Marek Locmelis, Marco Fiorentini, John Adam, Steve Barnes, John Owen, Bob Loucks, Steve Denyszyn, Elena Belousova, Graham Begg, Nicolas Thébaud. In the background, the glaciers of the Monte Rosa.

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

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

AIMS:

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 decipher the processes structuring the lithosphere. This project explores the upper mantle from rifting to ocean-continent transition environments. We have studied several localities that provide a progressive history from rift initiation to subduction including the East-African Rift (Marsabit, Kenya), Sardinia and Platta-Totalp-Tasna massifs (Alps) to find how the deformation was initiated, localised and evolved in these geological settings. We also study the structural and geochemical relationships amongst fluids and/or melts during mantle deformation. We have characterised the microstructure and the deformation mechanisms recorded by mantle minerals, such as olivine and pyroxenes, with the EBSD technique and combine microstructural observations with geochemistry to refine our understanding of the mantle processes.

PROGRESS IN 2013:

The study of the East-African rift (Marsabit-Kenya) is now finalised with the publication of a paper in Tectonophysics. We confirmed the activation of the E-type slip-system in a rifting environment and provide the first evidence of [001] slip in such an environment. Decompression and cooling from high-pressure and high-temperature could be the major factor influencing the localisation of deformation and the change in the dominant slip direction in olivine.

During 2013, we focused our work on Platta-Totalp-Tasna (Alps) peridotites sampled in 2012. These massifs represent a type example of a zone of exhumed continental mantle, and offer a complete sequence across an ocean-continent transition. We analysed major elements of primary minerals using the electron microprobe in 12 samples in Platta and Totalp massifs at the University of Lausanne, Switzerland. This was not possible in Tasna samples, which are highly retrogressed. We have undertaken the first EBSD analyses on these rocks. Moreover, the sample collection has been upgraded with a new field session by Mary-Alix Kaczmarek at the end of September 2013.

Clinopyroxene compositions from Totalp and Platta are distinct with a higher Na_2O (wt%) content in Totalp than in Platta suggesting melt percolation and crystallisation of plagioclase in Platta peridotite. Within the Platta sequence, there is a slight variation of the Na_2O content between two localities permitting a relative positioning within the ocean continent transition section. We focused our study on the highly deformed peridotites to characterise the mechanism activated during the deformation and to understand the influence of fluid/melt during deformation. The presence of high temperature amphibole (pargasite and kaersutite) in Totalp testifies to the relevance of the fluid percolation model. The peridotite and the ultramylonite contain porphyroclastic amphiboles (rounded in the ultramylonite), as well as the fine-grained matrix with an evolution of its chemical composition. The amphibole started to crystallise before the initiation of the deformation (large porphyroclasts) and continued to grow during the localisation of the deformation within the ultramylonite and the chemical evolution of the fluid/melt, which became focused in the mylonite. Our first EBSD results show an evolution of the deformation mechanisms from the host peridotite to the fine-grained matrix in the ultramylonite in Totalp with a possible slip change within the olivine from [100] to [001] slip, which might be related to the presence of fluid during deformation. For details and figures on our Alps research see *Research Highlight p. 62-63).*

Published output:

CCFS 2013 Publication #335

Conference Presentation:

M-A Kaczmarek and S. Reddy. Fluid percolation within an Ocean-Continent Transition, AGU 2013

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

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

AIMS:

This 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. It involves isotopic studies of zircons from ancient terrains and deep-crustal xenoliths worldwide, and a continued search for the oldest mantle samples beneath cratonic areas. Targeted field studies will provide a basis for static and dynamic modelling of the rheology of the crust before, during and after melt extraction.

This project is closely linked with the research of Future Fellow Dr Elena Belousova, involving regional surveys (*TerraneChron®* approach) of zircons (U-Pb, Hf isotopes, O isotopes) from old continental areas, to pick up the signatures of the oldest crust. Two areas are being investigated to look at some of the processes of crustal stabilisation: [1] the 3.1 Ga Mpuluzi batholith (Swaziland/RSA), and [2] 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.

PROGRESS DURING 2013:

Dr Belousova carried out studies of the Archean crust of the Volgo-Uralia region of the East European Craton, using both surface samples and material from super-deep drill holes. This has demonstrated the presence of crust older than expected, and detailed information on the structure of the crust.

The charnockitic lower crust in southern Volgo-Uralia consists of Eo- to Paleoarchean crust re-worked in the Mesoarchean (ca. 3.1 Ga). Hf model crustal ages of up to 3.9 Ga found for this region and farther northeast suggest that this Eo- to Paleoarchean continental crust was widespread in Volgo-Uralia. A back-arc setting along an active continental margin may explain the high-T, '*dry*' and '*ferroan*' magmatism of the Volgo-Uralian charnockites. An alternative interpretation is that deep mantle-plume activity at 3.1 Ga caused mantle underplating, extension of the Paleoarchean crust and high-T magmatism.

The ultramafic–mafic Noril'sk-1 intrusion in Polar Siberia (Russia) was another focus of Dr Belousova's research. Despite the long-term study of the Noril'sk-type intrusions their origin remains controversial. Hf-isotope data on zircons, which serve as an explicit constraint on source regions, have been rarely applied to Noril'sk-type intrusions. We have explored the isotope systematics of hafnium in zircon and baddeleyite from variously mineralised rocks of the economic Noril'sk-1 intrusion. *In situ* Hf-isotope data for zircon and baddeleyite, combined with whole-rock Nd-isotope results, identify three distinct clusters of Hf-Nd isotope values typical of different lithological units (e.g. unmineralised gabbroic rocks, mineralised portions represented by ultramafic and taxitic-textured rocks with disseminated PGE-Cu-Ni sulfide and low sulfide ores, and gabbro-diorite). Our findings are consistent with a model that involves interaction of three distinct magma sources during protracted evolution of the Noril'sk-1 intrusion. The outcomes of this study suggest that a prolonged period for concentration of the ore components in staging chambers during this interaction may be a key factor for formation of such economic deposits.

Work continued on identifying major tectonic events associated with crustal magma genesis to track patterns in crustal evolution for comparative benchmarks with the Archean tectonic regimes.

Large granite bloom, Western Australia.

PhD student Yuya Gao (cotutelle with CAS, Beijing, a CCFS Partner) completed a study of Li isotopes in A-type granites and their zircons. She demonstrated that diffusion of Li in zircons during cooling from magmatic temperatures produces large isotopic fractionation. However, if large-enough grains (>100 microns across) are used, the Li-isotope compositions in their cores may be used to trace magmatic processes. Ms Gao has also produced a detailed evaluation of the processes of U-Pb-isotope disturbance related to the metamictisation of zircons, complete with a '*recipe*' for recognising zircons whose U-Pb systematics cannot be trusted. The A-type granites, on which she has concentrated, are typically the latest components in '*granite blooms*' and this work will be directly relevant, as an analogue, to the aims of the project.

Rosanna Murphy presented her work at international conferences in 2013; she has produced a detailed regional characterisation of the Barberton granite bloom at 3.15 Ga. The Sr-Nd-Hf isotopic data demonstrate the involvement of older crust (>3.5 Ga) in the genesis of the granites, which both constrains the tectonic setting (heat sources) and suggests that the high-degree melting of the lower crust at this time was the stabilising factor. Modelling of these processes has begun in collaboration with Dr Craig O'Neill.

Published outputs:

CCFS 2013 Publications #205, 213, 215, 214, 233, 311, 313, 319, 330, 344

Conference Presentations:

7 International conference presentations including 2 Keynotes.

Large granite bloom, South Africa.

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.

AIMS:

The overarching goal of this project is the development and application of 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 2013:

This project is a long-timescale undertaking designed to operate over the lifetime of the centre, and lay the substrate for substantial numerical improvement in code capabilities. It consists of a three-pronged approach to numerical modelling and imaging of the deep Earth [1] Long-term development of codes towards a more complete geodynamic and geochemical description of mantle processes, led by Juan Carlos Afonso; [2] shorter-term applications, particularly in early Earth and planetary processes, involving the further development of existing codes, led by Craig O'Neill; [3] development and application of advanced seismic imaging techniques, led by Yingjie Yang.

The development of new multi-component multi-phase reactive flow formulations has been progressing with the PhD research of Beñat Oliviera. Some low-lying problems in the advection of chemical boundaries and reaction fronts have been resolved, with publications pending. We plan to integrate this with a multi-scale FEM framework within the next year to model sub-grid scale flow, which will then be coupled with concurrent developments in Aspect.

A number of publications using the multicomponent flow capabilities of CitcomS code to model chemical heterogeneities within the mantle have been produced, applying these modelling techniques to deep Earth recycling in the Hadean (first 500 million years of Earth history), the tectonothermal evolution of small planetary bodies such as terrestrial planets, moons and exoplanets, and the internal dynamics of Venus.

We have developed a new global convection capability using the new Aspect framework (dealii.org), and have extended it to include our own plate motion models, compositionally distinct particle formulation, and evolving boundary condition formulation. This work has been spearheaded by CCFS postdoctoral fellow Siqi Zhang. We have recently been successful in obtaining extra computation time at the larger resources at Intersect (the NSW high performance computing consortium), and the National Computing Facility.

Two new seismic imaging methods called Ambient noise tomography (ANT) and Multiple Plane Wave Tomography (MPWT) are being used to construct 3D seismic models on the basis of seismic data from the extensive broadband Transportable Array component of EarthScope/USArray, which are archived in IRIS/DMC and open for public download. The targeted areas are Western U.S.A and south China. We will augment these with seismic data from the Chinese Seismic Network, which will be obtained via collaboration with the Institute of Geodesy and Geophysics (an institute under Chinese Academy of Sciences). The combination of these two methods provides higher resolution information than traditional methods of surface wave tomography, with ANT producing information about the crust and uppermost mantle and MPWT generating information about the mantle. The cutting-edge nature of these studies was recognised with the award of a Future Fellowship to Yingjie Yang in 2013.

Meetings have been held in late 2013 to plan the integration of the new experimental mineralogy expertise in the CCFS into the optimisation of input into the geodynamic models; this will be developed further during 2014.

Published outputs:

CCFS 2013 Publications #196, 217, 218, 237, 315, 325, 330, 340, 414, 440, 441, 442, 883

Conference Presentations:

7 International conference presentations

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:

This projects seeks to define the nature of the first life in the early Archean, to discover links between the early evolution of life and the rise of atmospheric oxygen in the Neoarchean, and to understand the evolution of the Earth's oceanic and atmospheric composition during the Archean and Paleoproterozoic. Links between the evolution of the sulfur cycle and the formation of important Archean submarine ore deposits will be evaluated.

PROGRESS DURING 2013:

Work has continued on the three main streams of the project during 2013: [1] David Wacey and Mark Barley focused on establishing the nature of the first life in the early Archean; [2] Marco Fiorentini and PhD student Carissa Isaac focused on evaluating the links between the evolution of the sulfur cycle and the formation of important Archean submarine ore deposits, principally komatiite systems; and [3] Martin Van Kranendonk concentrated on the adaptation of life to the rise of atmospheric oxygen and cooling of the atmosphere during the Paleoproterozoic Great Oxidation Event (GOE), in addition to continuing studies on the geological setting of the earliest convincing evidence of life the 3.5 Ga Dresser Formation of the Pilbara Craton. Ongoing work is also looking at documenting the sulfur isotope signature of a wide range of VMS systems in Western Australia.

The work on establishing the nature of the first life in the early Archean includes the discovery and documentation of ecosystems of bacteria in ~3.5 billion-year-old rocks from Western Australia, extending the geological range of such complex ecosystems to around 300 million years further back than known previously. In addition, we have found supporting evidence for a volcanic caldera setting for the earliest convincing evidence of life from a detailed study of hydrothermal alteration facies associated with the 3.5 Ga Dresser Formation. We also developed a new hypothesis that the volcanic rock pumice may have provided the ideal environment in which life could have evolved, and followed this up with a detailed study of some of Earth's oldest pumice deposits from the ~3.5 billion year old Apex Basalt of Western Australia. Work in this project also identified consortia of 1,900 million-year-old fossils from rocks around Lake Superior, Canada, providing the first ever snapshot of organisms eating each other and outlining the types of microbial metabolisms were present on the ancient Earth.

Evaluation of the links between the evolution of the sulfur cycle and the formation of komatiite-hosted ore deposits have led researchers to identify sulfur dioxide degassing from komatiite volcanoes as a single process that explains two major heretofore unrelated conundrums about the Archean Earth System: (1) why are komatiite-hosted nickel deposits so well endowed? and; (2) why did the mass-independent record of S isotopes suddenly blossom 200 million years before the GOE? In terms of conceptual understanding, the demonstration that sulfur dioxide degassing can lead to economic Ni deposits is as exciting the proposal that earthquakes cause gold deposits. We have identified a volcanic pulse of sulfur dioxide that fundamentally restructured Earth's S cycle. This provides a solid geologically based hypothesis for the bloom in S-MIF at 2.7 Ga that contrasts with model-based suggestions of changing CH_4/O_2 ratios at this time.

In 2013, Martin Van Kranendonk and colleagues undertook detailed mapping of the 2.4-2.3 Ga Turee Creek Group, deposited as a conformable succession throughout the period during which atmospheric oxygen rose. Major discoveries include [1] a second unit of glaciogenic diamictite, [2] an expanded transitional section across the GOE in which the change from anoxic to oxygenic conditions are preserved, [3] new units of stromatolitic carbonates from below and above the transition, and [4] a set of microfossil-iferous black chert units. All of these document the adaptation of life to changing atmospheric conditions (composition, temperature). A scientific drilling program was completed across three intervals of the group to obtain fresh drill core samples aimed at documenting the adaptation of life to this major revolution in Earth history.

The three key aims of the Foundation Project have been fulfilled. Research on the evolution of the Earth's oceanic and atmospheric composition through the Precambrian has led to some important new insights. A study on S-isotopic variation across the rise in atmospheric oxygen from the Paleoproterozoic succession of Western Australia identified the largest yet recorded swing in $\delta^{34}S$ isotopic compositions and the rise of seawater sulfate concentrations. The work on earliest life has shown that there are still new discoveries to be made on potential habitats where life signatures may be discovered.

The compilation of geotectonic and biogeological data across the Precambrian revealed long-wavelength cyclical changes in atmospheric composition tied to the supercontinent cycle, whereby periods of rapid crust formation immediately preceding supercontinent amalgamation events were followed by precipitation of banded iron-formations during the dénouement of the supercontinent cycle, and then followed, in turn, by periods of widespread (or even global) glaciation as the supercontinent cycle restarted. Earth's supercontinent cycle evolved in a way previously undocumented, peaking at ca. 1.1 Ga and decreasing in intensity thereafter, paving the way for a new look at how life evolved and responded to changing conditions through time. With associated changes in the biosphere linked to these geological changes through a successive, causative series of events tied to mantle dynamics, this study will form the conceptual basis for the realignment of this Foundation Project.

Published outputs:

CCFS 2013 Publications #22, 232, 321, 329, 421

Conference Presentations:

4 International conference presentations

6. DETECTING EARTH'S RHYTHMS: AUSTRALIA'S PROTEROZOIC RECORD IN A GLOBAL CONTEXT

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

AIMS:

By investigating targeted Australian Proterozoic mafic igneous rocks, we aim to (1) push our knowledge of the Earth's paleogeographic and geodynamic history back to the Paleoproterozoic, and (2) test a ground breaking hypothesis that the birth and death of a supercontinent on the 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.

PROGRESS DURING 2013:

The project made major progress in three aspects during 2013.

In terms of revising late Precambrian global paleogeography and pushing our understanding of supercontinent evolution back to the Paleoproterozoic, we published two milestone papers. One was accomplished with colleagues from Yale and McGill universities (*CCFS contribution #314*), in which we presented a updated set of 825–540 Ma global paleogeography that illustrates not only the global continental distributions from the breakup of the supercontinent Rodinia to the assembly of Gondwanaland, but also the accompanying sedimentary facies patterns. We were able to use these data to examine the Snowball Earth and competing hypotheses as well as the geodynamic controls on global sea-level changes (see *Research highlight, p. 82*).

Also, we published a new comprehensive paleomagnetic examination of Nuna evolution in collaboration with the Nordic Paleomagnetic Working Group (*CCFS contribution #309; featured in* *Research highlight, p. 54*). Instead of the widely held ca. 1.8 Ga formation for the pre-Rodinia supercontinent Nuna/Columbia (for example, s*ee CCFS contribution #197*), the supercontinent could have been formed as late as between 1.65 and 1.58 Ga by amalgamation of West Nuna (Laurentia/Greenland, Baltica, Cathaysia, Rockall and possibly India), East Nuna (North, West and South Australia, Mawson Craton of Antarctica and North China) and the juxtaposed Siberia and Congo-São Francisco cratons. Nuna broke apart at ~ 1.45–1.38 Ga through the separation of Australia/East Antarctica from Laurentia/Cathaysia. In CCFS contribution #386, we reported high-quality results for the 2.41 Ga Widgiemooltha dyke swarm of the Yilgarn craton, and produced provocative Archean-Paleoproterozoic reconstructions.

We finalised the paleomagnetic and geochronological study of the 1.2 Ga Ravensthorpe dykes (WA), with a manuscript reporting the results now submitted for publication. We also completed the analysis of the ca. 1.46 Ga sills and two undated dykes in the Bangemall Basin through collaboration with Professor S. Zhang (China University of Geosciences, Beijing). One of the dykes yielded a stable and well-grouped remanence with a direction very close to that of the 1.07 Ga Bangemall Sills (*Wingate et al., 2002*), suggesting that this dyke is related to the Warakurna large igneous province (*Wingate et al., 2004*). However, ca. 1.46 Ga sills yielded a scattered and internally inconsistent secondary remanence only, so further paleomagnetic study on this target is not warranted. We sampled a new paleomagnetic collection from the Mesoproterozoic Morawa Lavas (WA) during the 2013 field season.

A field photo of pahoehoe structures in the 2 Ga Girvas volcanic edifice, Russian Karelia.

We have continued our collaborations with Russian, Swedish and Canadian colleagues. A field trip to the 1.97 Ga Girvas intrusions, Karelia (Russia) in collaboration with the Russian Karelian Research Centre finalised our previous study; a manuscript is in preparation. New paleomagnetic data resulted in a new model for the Cryogenian-Ediacaran opening of the Paleo-Asian Ocean between Laurentia and Siberia (*CCFS publication #302*, in collaboration with the Institute of the Earth's Crust in Irkutsk, Russia). New paleomagnetic and geochronological data from Sweden led to a revision of the history of the assembly of Rodinia (*CCFS publication #345*). New constraints on the reconstruction of the final breakup of Rodinia (the opening of the Iapetus Ocean) have been provided by precise 548 ± 1 Ma (U-Pb; baddeleyite) dating and a paleomagnetic study of the St Simeon mafic dykes in Quebec, carried out in collaboration with our Canadian and Swedish colleagues. In collaboration with Canadian, Portuguese and Brazilian colleagues, we proposed a new Mesoproterozoic reconstruction of Siberia and Congo/Sao Francisco constrained by LIPs barcode and paleomagnetic data (*CCFS publication #221*).

In terms of petrogenetic examination of possible plume events during the Proterozoic, we published our findings on the 1.2 Ga Ravensthorpe dykes (*CCFS publication #371*), collected mafic dyke and sill samples from the Bangemall Basin for analysis, and conducted petrographic examinations and major element analyses on these samples. Our work on the Ravensthorpe dykes led us to conclude that the dyke swarm was likely linked to a mantle plume (the Marnda Moorn LIP), and that the geochemical and emplacement characteristics of the dykes are attributed to relief in the lithosphere–asthenosphere boundary across the Yilgarn craton and complex interplay between the plume, a heated sub-continental lithospheric mantle, a normal asthenosphere, and recycled components. Our plume-lithosphere interaction model is consistent with the occurrence of synchronous ultrahigh-temperature events in the Musgrave Province of central Australia and the large volume of mafic magma in the Marnda Moorn LIP.

Published outputs:

CCFS 2013 Publications #32, 162, 186, 195, 219, 221, 223, 224, 250, 278, 293, 297, 299, 300, 302, 307, 314, 336, 353, 354, 386, 387, 422

7. FLUID REGIMES AND THE COMPOSITION OF THE EARLY EARTH

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

AIMS:

The first aim is to characterise the earliest crust on Earth, and identify additional localities where evidence for ancient crust may still be preserved. This is achieved by working on newly-discovered samples of ancient zircon, and acquiring a full geochemical and isotopic data set to compare with the huge inventory already obtained from Jack Hills and Mt Narryer in the Narryer Terrane of Western Australia. We aim to determine why so few Hadean rocks survived on Earth. The second subproject adds constraints from extra-terrestrial samples, including work on Martian meteorites and lunar samples in order to characterise any fluid present and their interaction with minerals. This involves a combination of geochemical and microstructural techniques, including SEM imaging, electron and ion microprobes, EBSD (Electron Backscatter Diffraction) and Raman spectroscopy.

PROGRESS DURING 2013:

Zircon grains extracted from both ortho- and paragneisses from the ultra-high temperature rocks of the Napier Complex, Enderby Land, Antarctica, were dated by SHRIMP and ion imaged by Cameca IMS 1280 using a single collector for Ti, Y, Hf, Pb, Th and U and a multi-collector for Pb isotopes. The patchy distribution of Pb that was previously identified in these samples was substantiated and found to be unrelated to zoning or crystal imperfections and has the ability to affect the $^{207}Pb/^{206}Pb$ age. This redistribution of Pb (and Ti) was further characterised by Raman spectroscopy and the Australian Synchrotron, and is attributed to the 2.5 Ga high-grade metamorphic event that affected the Napier Complex. Lu-Hf data from selected zircons were also obtained through collaboration with our Partner Organisation, the Institute of Geology and Geophysics at the Chinese Academy of Sciences in Beijing.

Work has commenced on samples obtained from the Australian Geological Survey from Aker Peaks in Kemp Land to the east of Enderby Land in Antarctica. Some of these yielded ages in excess of 3.5 Ga and also revealed ancient Hf model ages that extend back to 4.45 Ga, making this only the third locality on Earth where such ancient model ages have been consistently obtained.

Work completed last year on the re-investigation of >3.9 Ga zircon in the North Qinling Orogenic Belt in Central China was published in 2013 in Gondwana Research. This is the second locality after Jack Hills where Hf crustal model ages extend back to 4.4-4.5 Ga. The zircons occur in an Ordovician volcanic rock, establishing that ancient continental crust was present in the basement of the North China Craton during the Paleozoic. Additional samples from the Anshan district of the North China Craton were collected and will be studied in association with Yusheng Wan at the Chinese Academy of Geological Sciences.

Further work was completed on the Dharwar Craton of India, including the acquisition of Lu-Hf data at the Chinese Academy of Sciences. TTG components as old as 3.3 Ga are present in the eastern part of the craton, although the major events occurred in the Neoarchean, with two pulses of magmatism at ~2.55 and ~2.15 Ga. Work has also commenced on granitoids of the Bundlekhand Craton in India, with SHRIMP U-Pb age data and ICP-MS Lu-Hf data on zircon acquired during 2013.

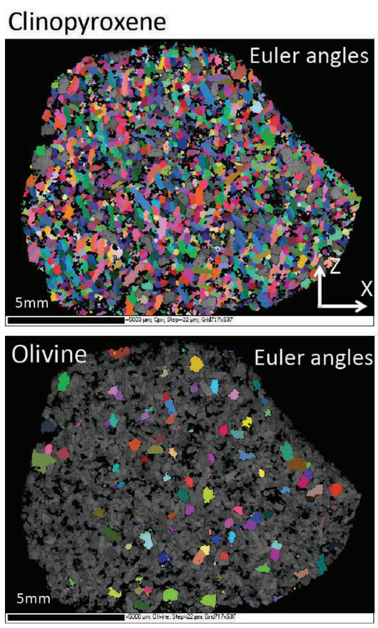
The collection of data from a detailed traverse across the Jack Hills Belt was completed and the data are being prepared by Qian Wang as part of her doctoral studies at Curtin University. Both SHRIMP and MC-ICP-MS zircon data were collected for U-Pb and Lu-Hf study, respectively. In addition all suitable samples and investigated for rutile, monazite and xenotime in order to constrain the timing of metamorphism across the belt. Initial sampling of the Ilarra Greenstone Belt in the central Yilgarn Craton was undertaken and zircons extracted from a number of fuchsite quartzite horizons.

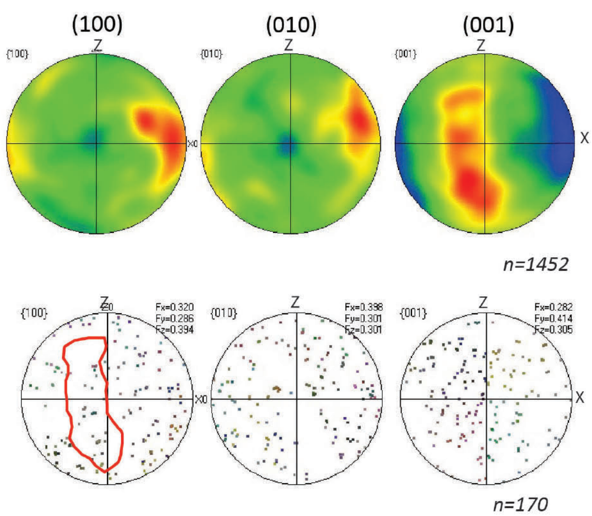
In extra-terrestrial work, we performed a detailed study of Zagami and Nakhla samples, combining EBSD and geochemistry. Nakhla is an olivine-bearing clinopyroxenite mildly shocked at 20 GPa. The analyses of major elements of minerals have been undertaken using an electron microprobe at the University of Lausanne (Switzerland). The clinopyroxenes are zoned from augitic to pigeonitic from core to rim and Mg# decreases from core (0.65) to rim (0.31). The Mg# of cpx rim is in equilibrium with the olivine Mg# (0.305-0.312) suggesting late crystallisation of the olivine. Zagami, which comprises clinopyroxene and maskelynite has been shocked at 27-31 GPa and 60-80 GPa (Stoffler et al. 1986; Lambert, 1995; Langenhorst et al. 1991) with the formation of melted shear-zones. Zagami clinopyroxenes display similar chemical zoning from core to rim as Nakhla, but is more irregular.

The analyses of preferred crystallographic orientation (CPO) of Nakhla clinopyroxenes show a weak fabric with the dominant activation of (100)[001] slip (Fig. 1). Olivine CPOs show a dispersed distribution, which is discordant to clinopyroxene CPOs where <001> cpx axes are not parallel to <100> olivine axes (Fig. 1). These observations, combined with the geochemistry, suggest that Nakhla clinopyroxenes crystallised under weak flow conditions and later the olivine crystallised in a more static, cumulate regime. Clinopyroxene CPOs of Zagami have a maximum concentration on <001> parallel to the observed foliation, inferring the dominant activation of the {110}[001] slip system. This is interpreted as the primitive deformation related to a weak flow. The intra-grain deformation in Zagami clinopyroxenes is complex with the dominant activation (100)[001] slip. Combining clinopyroxene geochemistry and microstructural data highlights two generations of twinning. The first generation of grain boundaries and twin planes acted as melt pathways illustrated by Fe enrichment. The second generation of twinning shows no chemical variation, suggesting a late activation. It is possible that Zagami records a double shock impact.

Both Nakhla and Zagami samples record primitive igneous processes, yet these have been partially overprinted by shock metamorphism. The combination of geochemistry and deformation provides a more detailed understanding of the texture and propose a relative timing of these events on Mars.

Carbonate phases present in Antarctic meteorite ALH84001 are Fe-Mg-Mn-Ca carbonates. New backscatter images document the carbonates that had been analysed with an ion microprobe in July 2012. These pictures are the basis for detailed chemical profiles of the carbonates with electron microprobe. We are preparing carbonate standards that need to be analysed with the electron microprobe.





Published outputs:

CCFS 2013 Publications #278, 301, 403, 404, 405, 406, 407, 408, 409, 412, 420, 426, 427, 428, 429, 430, 431, 432

Conference Presentations:

2 International conference presentations

8. DIAMOND GENESIS: CRACKING THE CODE FOR DEEP-EARTH PROCESSES

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

AIMS:

This project combines 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. The causes of isotopic variability of carbon, oxygen, nitrogen and sulfur in diamond-forming fluids will be constrained; are these primary signatures, or do they reflect isotopic fractionation during diamond growth? We work towards understanding the links between diamond formation and the redox state of the lithospheric and asthenospheric mantle, and to developing new exploration and evaluation methodologies for application to kimberlites by defining the trace element signatures of mantle minerals that have been exposed to diamond-bearing fluids. Finally, different types of mantle fluids and their interactions with mantle rocks will be characterised.

PROGRESS DURING 2013:

Extensive work on mixed-habit diamonds demonstrated the sectorial partitioning of trace elements and in some cases C isotopes, during growth of these unusual diamonds. N isotopes were analysed in collaboration with R. Stern (Edmonton) and demonstrated that while there is little change in isotopic composition from core to rim, there is a small but significant fractionation between the different sectors. The trace-element analyses have applied the new high-precision, high-sensitivity analytical techniques developed through 2012, and have confirmed the difference in fluid compositions involved in the formation of gem diamonds versus fibrous diamonds. This work has led to a new model for diamond crystallisation, and a clearer definition of the position of mixed-habit diamonds in the scheme of diamond formation.

Related comparative studies on mantle xenoliths revealed further information on the sources and compositions of deep mantle fluids. Of particular note is the multi-isotope study on the isotopic characteristics of LIMA minerals from the Jagersfontein kimberlites, identifying a HIMU reservoir mantle source for the parental fluids.

Dr Howell travelled to Beijing in 2013 to select a representative sample of the diamonds extracted from peridotite massifs and their chromitites in Tibet and the Polar Urals. A detailed characterisation of this sample suite is in progress; this has required the development (in collaboration with colleagues in Physics) of new micro-milling techniques to obtain undisturbed cross sections through the centres of these tiny (100-200 micron) diamonds.

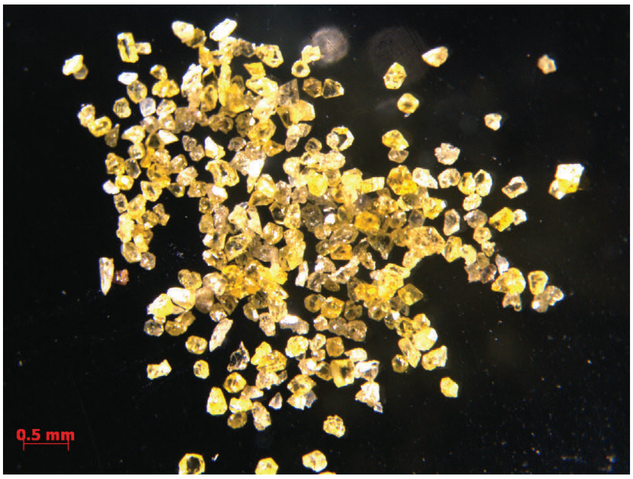
PhD student Ekaterina Rubanova completed her thesis and graduated in 2013. Her thesis work has provided new insights into diamond crystallisation and its links to other metasomatic processes in the cratonic lithosphere. In particular, the presence of both diamondites (polycrystalline aggregates, from rapid crystallisation) and zoned monocrystalline diamonds in the same samples has allowed an assessment of the relative time-scales and changes in fluid composition involved in the growth of the two types of diamond.

Published outputs:

CCFS 2013 Publications #210, 328, 332, 211, 236, 320

Conference Presentations:

4 International conference presentations



Micro-diamonds from Tibet.

9. 4D LITHOSPHERIC EVOLUTION AND CONTROLS ON MINERAL SYSTEM DISTRIBUTION: THE WESTERN SUPERIOR-YILGARN COMPARISON

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

AIMS:

This project is the first case study to obtain the full range of zircon multi-isotopic data and spatially map it over the Superior Province. Traditionally researchers have taken isotopic and whole-rock geochemical data and presented them as a few data points in chart form. In contrast, we undertake an order of magnitude more analyses in order to effectively map the data spatially.

The project aims specifically to (1) apply multi-isotopic (U-Pb, Lu-Hf, O) analyses in zircon to map deep 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 criteria for targeting exploration for various Archean mineral systems at the craton to terrane scale.

PROGRESS DURING 2013:

A new PhD candidate Katarina Bjorkman started in February 2013 to study the Marmion Terrane in detail. Fieldwork in 2013 was focused on regional sampling, stratigraphic and structural study of greenstone belts, and localised study of mineralisation. A total of 222 samples were collected for whole-rock analyses and thin sections. Of these samples, 100 will be selected for zircon U-Pb, Lu-Hf, and O isotope analyses. Field investigations targeted areas poorly understood or with conflicting observations and/or interpretations in order to put the mapping and observations of previous workers in context and to interpret the tectonic history of the terrane. Structural observations, both at the regional and outcrop scale, support final NW-SE compression for the area, and stratigraphic observations support autochthonous development of the greenstone belts. This interpretation will be tested by a spatially constrained multi-isotopic study. In most instances, contacts between the greenstone belts and the underlying, marginally younger TTG are intruded by mafic dykes and young tonalite. Deformation is concentrated in the contact areas. Gold mineralisation occurs near NE-trending sinistral structures and contrasting lithology but within a variety of host rocks and with variably altered mineral assemblages. The 10.7 M oz Hammond Reef gold deposit is located within the 3.0 Ga Marmion Intrusive Complex along intersecting structures. These observations will be integrated with isotopic and geochemical analyses, will be used to constrain the crust-mantle evolution of the Marmion Terrane and related mineralisation. In 2013, 63 samples were dated by zircon SHRIMP method and 30 samples were analysed for LA-MC-ICPMS Lu-Hf isotopes. Zircon oxygen isotopic analysis was not available due to technical difficulties with the Cameca IMS 1280 in 2013. In addition, whole-rock major and trace element analysis was done for 112 samples.

This project has attracted strong collaborations and leverages in 2013. The concept and methodology of this project has now been expanded to Tibet and the Uchi/North Caribou Terranes in Canada, in collaboration with the Chinese Academy of Geological Sciences (CAGS) and Lakehead University, respectively. The zircon multi-isotopic mapping in Tibet has led to an exciting discovery, showing that porphyry copper systems cluster exclusively within the juvenile domain and not in the ancient block, which could potentially become an effective regional targeting tool for the exploration industry. Moreover, these data are revealing the underlying structure of the Tibetan plateau and its evolution through time. A new NSFC project was also established together with CAGS to study the lithospheric architecture and mineral systems in the Eastern Tethyan belt, focusing in Tibet and Iran, which successfully attracted ¥3.3 million and will run from 2014 to 2018. A self-funded visiting professor Hooshang Asadi Haroni from Iran has joined CET for one year, forging a stronger collaboration in the study of Iranian mineral systems. Moreover, the Ontario Geological Survey in Canada has offered to conduct whole-rock geochemistry for over 200

Field work in Wabigoon. Cam, Yongjun and Katarina are with colleagues from Lakehead Uni., OGS and Bjorkman prospector family.

samples at no cost to this project. Industry has also shown great interest in this project; we have been approached by companies such as De Beers Canada and Chalice Gold Mines to integrate our research with their practical exploration.

There have been about 200 samples collected from this study for the zircon multi-isotopic analysis, which is the largest and most complete such dataset in Superior Province collected to date. Results have shown that the lithospheric architecture wielded strong control on the location of gold mineralisation in the Wabigoon Subprovince. The concepts and methods of this project are now being actively applied in other parts of the world, which places CCFS as the world leader in applying multi-isotopic mapping globally.

Published outputs:

CCFS 2013 Publications #32, 162, 206, 222, 243, 350

Conference Presentations:

4 International conference presentations

10A. 3D ARCHITECTURE OF THE WESTERN YILGARN CRATON

Theme 2 and 3, Earth Evolution and Earth Today, contributing to understanding Earth's Architecture.

AIMS:

This project aims to develop an integrated 4-dimensional, 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 Goldfields Superterrane in the eastern part of the craton.

PROGRESS DURING 2013:

Significant steps have been taken to address crustal evolution of the western Yilgarn Craton, including the release of the deep seismic reflection and magnetotelluric surveys over the Youanmi, South Carnarvon, and Yilgarn Craton-Officer Basin-Musgrave Provinces, the holding of a CCFS project definition meeting, targeted field work in several locations in the Yilgarn, and the planning and partial deployment of passive seismic arrays. Three individual seismic lines (YU1, YU2 and YU3) and complementary magnetotelluric data were acquired across the northern Yilgarn Craton in 2010, with acquisition, processing and interpretation managed by Geoscience Australia. The lines are located in the northern part of the Yilgarn Craton from the Narryer Terrane in the northwest, crossing major bounding and internal structures of the Youanmi Terrane and proceeding into the Kalgoorlie Terrane of the Eastern Goldfields Superterrane. The northwestern end of YU1 is east of the southern end of line CP3 from the 2010 Capricorn seismic survey. The two surveys are linked by the Southern Carnarvon Basin seismic survey, acquired by Geoscience Australia in 2011. The eastern end of YU2 crosses major structures on the western side of the Eastern Goldfields Superterrane, augmenting the images from the 2001 Geoscience Australia seismic line about 120 km to the southeast. The Youanmi and Southern Carnarvon and the Yilgarn Craton – Officer Basin – Musgrave Province deep seismic reflection surveys add to the existing network of deep-crustal seismic surveys, and have closed a major data gap in the crustal structure of Western Australia, providing a traverse around 1800 km long across almost the entire southern half of Western Australia.

A major paper was released in 2013 on the tectonic development of the Murchison Domain of the Youanmi Terrane, Yilgarn Craton, providing a holistic framework for the history of the western Yilgarn craton and tying it in with development of the Eastern Goldfields Superterrane, highlighting overlaps in development that predate proposed terrane accretion. This summary presents a major compilation of map, structural, geochronological, and geochemical data that, when combined with isotopic and geochemical data provides a framework for future research of this heavily mineralised terrane.

Targeted field work has been carried out in the western Yilgarn, including mapping and sampling in the Murchison and Narryer terranes. Nd-isotope data suggest that the Youanmi Terrane has behaved as a coherent crustal block since at least 3000–2900 Ma ago. It is bounded by crustal-scale fault zones that dip away from the nucleus. The accretion of the Eastern Goldfields Superterrane, which may be either an exotic terrane or an extended margin of the Youanmi Terrane, marked the amalgamation of the composite Yilgarn Craton by about 2655 Ma ago. The Narryer Terrane is generally interpreted to have accreted onto the Youanmi Terrane in the northwest, but further work is required to better define the nature of the Narryer Terrane–Youanmi Terrane boundary.

The Youanmi seismic reflection survey release workshop on 27 February 2013 was very successful and attracted a capacity crowd of more than 90 attendees at the WA Department of Mines and Petroleum Mineral House Auditorium. Attendees from the Resources Industry, Academia and Government provided very positive feedback and engaged in fruitful discussions.

The passive source (Earthquake) component of the project started in the second half of 2013 after Dr Huaiyu Yuan joined the program from UC Berkeley. Dr Yuan's specialities are crustal and lithospheric structural imaging using earthquake imaging methods.

Careful planning of the Capricorn Orogen Passive Array (COPA) passive source study has been carried out during the second half of the year with seismic waveform dataset available already, and also with data that will become available in the coming years. A list of passive source methods have also been planned in conjunction with the deployment in March 2014. In parallel to the COPA development, in order to develop a technical template for revolving seismic anisotropy structure for long-operating stations, Dr Yuan and his US colleague targeted several permanent sites in the US, and observed promising anisotropic signals that may be related to fossil rifting processes and the current plate-asthenosphere coupling. The newly developed technique will be applied to the previously collected seismic waveform data and data from the semi-permanent sites in Western Australia in the coming year.

Published outputs:

CCFS 2013 Publications #248, 355

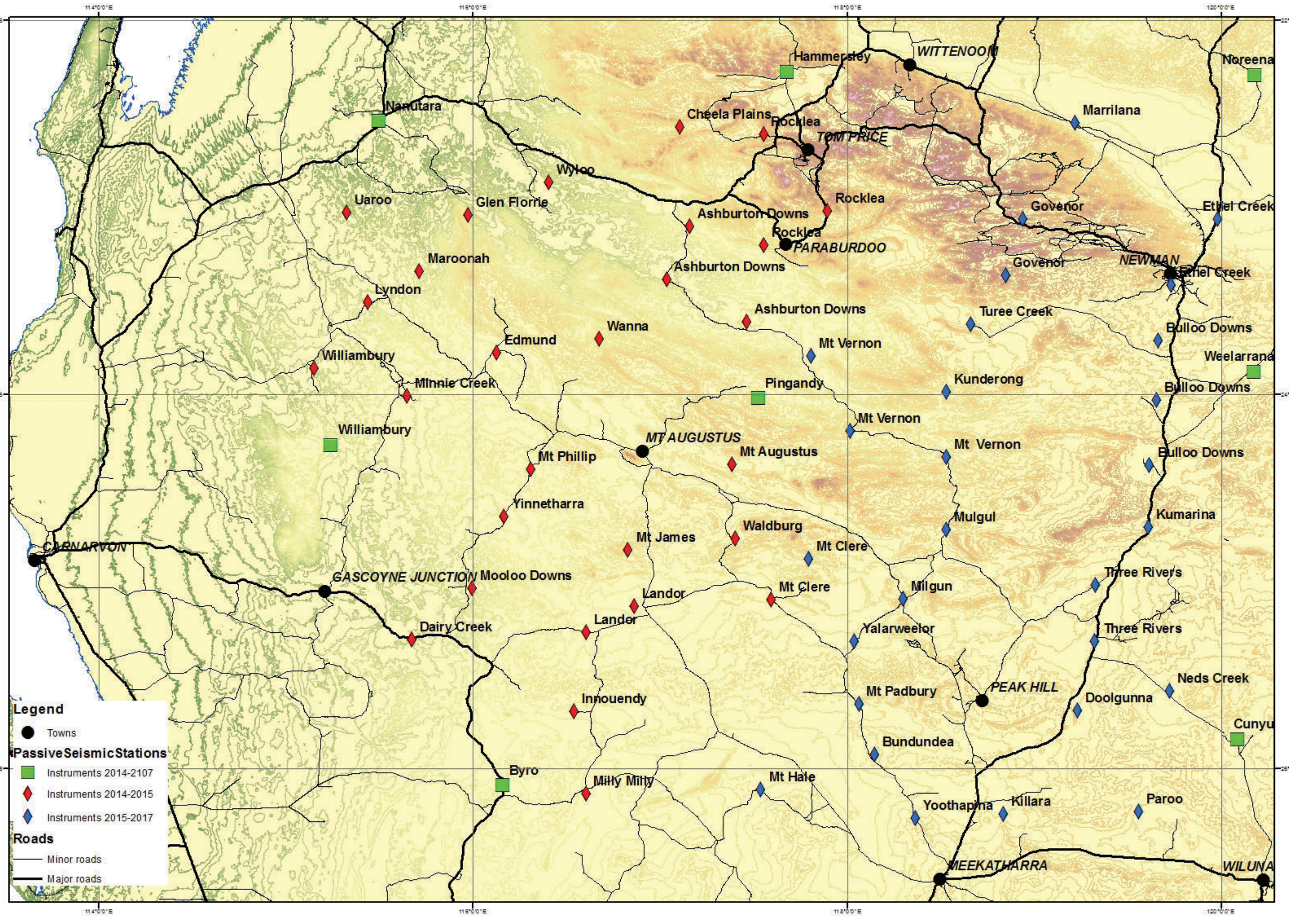


Figure 1. Capricorn seismic sites.

10B. ZIRCON LU–HF CONSTRAINTS ON PRECAMBRIAN CRUSTAL EVOLUTION IN WESTERN AUSTRALIA

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

AIMS:

The project aims to generate Lu–Hf isotope data, and integrate them with geological, geochemical, and geophysical information to understand the evolution of continental crust in Western Australia. Efforts will be directed at addressing specific geological questions in key areas, particularly along new geophysical transects, as well as in under-explored *'greenfield'* regions, where the new information will improve the targeting of mineral exploration.

PROGRESS DURING 2013:

More than 1400 zircon analyses from 59 samples were selected for Lu–Hf analysis during 2013, so that over 200 samples (ca. 4000 zircons) have been analysed since the start of the project. The samples were drawn from the Pilbara Craton, Murchison Domain, Kimberley and Amadeus Basins, and the Gascoyne Province. Unfortunately, data collection was adversely affected in 2013 by instrument instability, although significant progress was made with interpretation of previous data. This project has made excellent progress in integrating zircon Lu–Hf isotope data with geological, geochemical, geophysical, and other isotope information to understand the evolution of continental crust in Western Australia.

Searching for a suture to the east of the Albany–Fraser Orogen

The Arid and Barren Basins are remnants of two major sedimentary basins within the Albany–Fraser Orogen. The Barren Basin comprises Paleoproterozoic metasedimentary rocks that overlie the Yilgarn Craton, Northern Foreland, the Biranup Zone (itself intruded by certain Biranup Zone magmas), and the Nornalup Zone. Barren Basin samples yield late Archean and Paleoproterozoic detrital zircons with a median εHf of +1 and a range of +6 to -18. Two-stage model ages reveal similarities with magmatic rocks of the Biranup Zone and Yilgarn Craton. The Arid Basin consists of metasedimentary rocks that have maximum depositional ages younger than the ca.1660 Ma Biranup Orogeny, but were intruded by Stage I magmas. Detrital zircons in the Arid Basin samples indicate latest Paleoproterozoic to mid-Mesoproterozoic age components, and yield a median εHf of 0 and a range from +12 to -17. Two-stage model ages show similarities with model ages in the Biranup Zone of the Yilgarn Craton, and include a new 2.0 Ga model-age component not seen in the Barren Basin. Importantly, the youngest detrital zircons, at 1455–1375 Ma, dominate the Arid Basin samples, but do not correspond to any known sources within the Albany–Fraser Orogen. They also have the most juvenile Lu–Hf isotope signatures of any detrital zircons in the orogen. The source of this material is thought to be juvenile rocks of probable oceanic affinity in the Madura Province. The exciting tectonic and geodynamic implications of these results are currently being assessed.

Links between the Warumpi and Aileron Provinces, west Arunta region

The Arunta Orogen comprises a large part of the southern margin of the North Australian Craton (NAC) and records episodic tectonothermal activity spanning almost 1.5 billion years from the Paleoproterozoic to the Devonian. The Warumpi Province forms the southernmost part of the Arunta Orogen and is separated from the older, 1860–1700 Ma Aileron Province to the north by the Central Australian Suture. The Warumpi Province has been considered exotic to the NAC. However, Hf-isotope evidence for mixing between 1690–1630 Ma mantle-derived melts and older sources indicates that the history of the Warumpi Province involved interaction with significantly older crust of at least Mesoarchean age (Fig. 1). The ages and Hf-isotope compositions of inherited zircons in the 1677 Ma Pollock Hills Formation are consistent with this older crust being part of the Aileron Province. This suggests that the Warumpi Province represents a slice of Aileron Province crust, rifted away from the southern margin of the NAC at, or prior to, 1690 Ma.

Published outputs:

CCFS 2013 Publications #209, 275, 324, 337, 362, GSWA Reports 120, 122, GSWA Record 2013/9

Conference Presentation:

1 international conference presentation

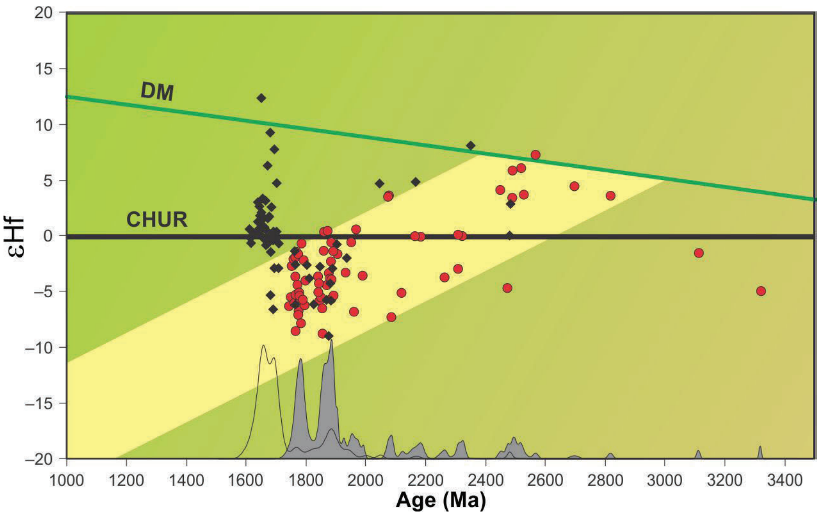


Figure 1. Age- Hf data for zircons from the Arunta region.

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

AIMS:

The Centre for Microscopy, Characterisation and Analysis (CMCA) 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.

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 plays 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 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 2013:

Recent successes in ARC LIEF funding will update the electron microscopy facilities, with the addition of a FEI Titan TEM and a FEI Verios 460 SEM. The CMCA will also receive funding for a new Cameca NanoSIMS 50L ion probe through CSIRO's Science and Industry Endowment Fund (SIEF). The new instrument will be part of the tripartite Advanced Resources Characterisation Facility, along with a Geo-Atom Probe to be located at Curtin University, and the in-house development of a MAIA mapping facility at CSIRO. The NanoSIMS 50L represents a considerable technological advance over the existing NanoSIMS, with a seven-FC/EM multicollector array and a new oxygen ion source allowing high-resolution isotope measurements on geological samples.

2013 saw a number of staff changes at the CMCA. Laure Martin and John Cliff continued to develop standards and analytical protocols for isotopic measurement using the Cameca IMS 1280 ion probe. Matt Kilburn spent six months on sabbatical at Harvard University, learning about the intricacies of applying NanoSIMS to biomedical research. David Wacey returned from overseas to work full time on Foundation Project 5. Paul Guagliardo replaced Rong Liu at the CMCA, and Malcolm Roberts replaced David Adams, who made an inter-node move to take up the position of EPMA operator at GEMOC (Macquarie).

The Ion Probe Facility at CMCA was highly productive during 2013, contributing to a number of projects across the whole CCFS. Highlights include:

[1] Metasomatism in the mantle (Jin-Xiang Huang, Yoann Gréau, Bill Griffin, Suzanne O'Reilly, Norman Pearson, John Cliff, Laure Martin). Garnets from a key Roberts Victor eclogite were analysed for oxygen-isotope compositions by SIMS (CAMECA IMS 1280) on grain mounts. The $\delta^{18}O$ values of the garnet decrease from 8.2 to 5.7 ‰ as the MgO content increases from one side of the hand specimen to the other, providing important evidence for progressive metasomatism, further constraining the origin of xenolithic eclogites.

[2] Textural and spatial variability in multiple sulfur isotope biosignatures (David Wacey, John Cliff, Mark Barley). The CAMECA IMS 1280 has been used to analyse several sets of Precambrian sulfides in order to determine sulfur sources during the pyritisation of potential organisms in deep time. Here we have measured all 4 stable sulfur isotopes. Samples include pyritised Ediacaran (560 Ma) macrofossils, 1.9 Ga pyritised microfossils from the Gunflint chert, and possible pyritised microfossils in a 3.2 Ga black smoker type deposit. This high-spatial resolution *in situ* data provides unique insights into Precambrian biological cycling of sulfur. One paper has been published in PNAS in 2013 (*Wacey et al. 2013*) and a further 3 manuscripts containing IMS 1280 data are in review.

[3] 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, the testing of new standards extends our capabilities into hitherto unexplored isotope systems. Recent development has included Si isotopes in silicates, SiC and Si metal, as well as Zr isotopes in zircon crystals from different provenance. Standards are in constant development at CMCA and currently include a range of Si-bearing materials (SiC, Si metal, silicates) for Si isotopes. Development continues on diamond (C isotopes), lawsonite, pyroxene, garnet and olivine (O isotopes), tourmaline and serpentine (B isotopes), pentlandite, pyrrhotite and chalcopyrite (S and Fe isotopes). The development of standards for unknown isotope systems aims to identify potentially new geochemical tools.

[4] Ultra-fine resolution diffusion studies (Matt Kilburn, Marco Fiorentini, Zoja Vukmanovic). The NanoSIMS proved once again that size does matter as a number of projects employed the ultra-high spatial resolution to determine diffusion profiles across mineral interfaces. One study, published in Chemical Geology (*Saunders et al., 2014*), demonstrated how our increased ability to measure diffusion profiles can be used to better constrain the timing of volcanic processes on the order of days to years. Similarly, high-resolution imaging with NanoSIMS combined with EBSD and LA-ICPMS imaging revealed the presence of trace elements along twin boundaries in pyrrhotite. These data (*Vukmanovic et al., 2014*) are interpreted as intragrain diffusion during syn- and post-deformation.

A number of CCFS projects featuring data from the Ion Probe Facility were published during 2013, including two papers in the prestigious Proceedings of the National Academy of Science.

Published outputs:

CCFS 2013 Publications #32, 162, 275, 321, 362, 426, 437, 438, 439.

Conference Presentations:

5 international conference presentation

2. FRONTIERS IN INTEGRATED LASER-SAMPLED TRACE-ELEMENT AND ISOTOPIC GEOANALYSIS

AIMS:

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-ICP-MS 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.

PROGRESS DURING 2013:

The past year saw the installation of three new pieces of cutting-edge instrumentation:

[1] Femtosecond Laser Microprobe: A Photon Machines fs198 laser system was installed in June 2012. Due to recurring damage to optics, the beam delivery system was redesigned and replaced in January 2013 (and commissioned in July 2013).

[2] SF-ICP-MS: A Nu AttoM high resolution sector field (SF)-ICP-MS was installed in January 2013. The features of this instrument include the continuously variable high-resolution capabilities, fast electrostatic scanning/jumping and a fully laminated, high-scan-speed magnet. Activity on the Nu AttoM in 2013 has concentrated on the transfer of in-situ methodologies from the quadrupole ICP-MS with an emphasis on U-Pb geochronology of zircon.

[3] Excimer Laser systems: In addition to the femto-second laser, a Photon Machines Excite 193 nm excimer laser system was installed in June 2012 and was followed by a Photon Machines Analyte G2 193 nm excimer laser system in January 2013. The Excite has been used with the Agilent 7700 for all in-situ U-Pb and trace-element analytical work. The Photon Machines Analyte G2 excimer has enabled the first phase of an experimental program to investigate fundamental properties of nanosecond and femtosecond ablation processes in geological materials, focusing on laser-induced isotopic fractionation. The first phase has focused on the ablation characteristics of zircon and the fractionation of U-Pb.

Due to issues with the femto-second laser system and the delays in the delivery of the Nu AttoM, the planned development of the split-stream methods was put on hold. In its place a program was established to evaluate a range of new methods (proof-of-concept) and to refine and improve existing procedures.

Evaluation of standard reference materials (silicate) for combined measurement using laser ablation ICP-MS and MC-ICP-MS

The development of potential microbeam standards for combined laser ablation ICP-MS and MC-ICP-MS requires characterisation of the chemical (major and trace elements) and isotopic compositions. Studies undertaken include the following:

(i) the suitability of gem-quality zircon from the Mud Tank carbonatite as a reference standard for trace element and U-Pb and Lu-Hf isotopes. The results demonstrated the uniformity of U-Pb and Hf isotopes, but the trace-element compositions varied with the colour of the stone.

(ii) the on-going development of garnet standards for the in-situ measurement of Mg (laser ablation MC-ICPMS and SIMS) and O isotope composition (SIMS development in collaboration with UWA-CMCA)

(iii) the assessment of a variety of accessory minerals (baddeleyite, apatite, rutile) for U-Pb geochronology; this has lead to the development of new methods for U-Pb geochronology

(iv) the evaluation of osmiridium, Pt-rich alloys and laurite for in-situ Re-Os isotope analysis

(v) refinement of in-situ Sr and Nd isotope ratio measurement of perovskite and apatite

Incorporation of operating protocols for combined measurement using laser ablation ICP-MS and MC-ICP-MS into GLITTER data reduction software

GLITTER is software for ICPMS Laser-ablation data reduction developed at GEMOC, Macquarie University and commercialised through AccessMQ. Revision of GLITTER has commenced to expand its capabilities and functionality, with the primary goal of enabling the simultaneous treatment of combined trace-element and isotope ratio measurements. Additional emphasis has been placed on the identification and propagation of uncertainties for isotope ratio and the treatment of short duration transient signals (laser shot or '*burst*' analyses).

New features in the GEMOC lab '*beta-testing*' include automatic loading of new data; loading of internal standard data from a user-defined file; user defined plotting; entry of internal standard values as oxide or ppm; mouse control for the selection of the rise-time indicator; improved support for Agilent's MassHunter output (automatic loading of dwell-time information). Features currently under development include multi-stage fitting to the standards; user-defined uncertainties on individual uncertainties for standard ratios; choice of calculation by '*mean of ratios*' or '*ratio of means*' in isotope ratio routines; support for output from Nu AttoM and Nu Plasma mass spectrometers; support for the output from Thermo Neptune and Qtegra.

Development of new sample preparation methods for geochemical and isotope analysis in the GAU

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 and underpins many of the CCFS projects. The development projects listed below were undertaken in support of CCFS-funded research programs and to lay the foundations for future split-stream applications.

(i) New sample preparation methods for the separation and purification radiogenic isotopes (Rb-Sr and Sm-Nd radiogenic isotope systems and preliminary experiments have commenced for Lu-Hf) have involved the adaptation of conventional '*macro*' techniques to micro sample volumes. This has been driven by the production of '*contamination-free*' mineral separates using selFrag and the New Wave Micromill.

(ii) refinement of Li isotope methodologies for ultramafic rocks and adaptation to other applications (A-type granites, corals)

(iii) development of whole-rock trace element analysis of fused glasses by laser ablation ICPMS.

Published output:

CCFS 2013 Publications #306

Conference Presentations:

3 international conference presentations

3. OPTIMISING MINERAL PROCESSING PROCEDURES: FROM ROCK TO MICRO-GRAINS

AIMS:

Liberation and recovery of the accessory mineral components from any type of rock for geochemical and geochronological analysis. 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.

PROGRESS DURING 2013:

selFrag is now routinely used for the defragmentation of a wide variety of different rock types and is the critical first stage in mineral separation procedures in GEMOC. The routine use of selFrag marks a significant achievement in method development and transfer of the established procedures to all users. In the past 3 years the defragmentation of each new rock type has required the development and refinement of experimental procedures depending on grain size, mineralogy and the amount of sample. One of the most important products of the intensive development phase of selFrag is a handbook of experimental conditions for a wide variety of rock types. This is a valuable resource for users with all levels of experience and has contributed to the efficient operation of the facility. The cumulative experience and expertise of the user group continues to grow and underlies the importance of the training program undertaken by all users as an important aspect of technology transfer. In 2013 selFrag was used to process 183 samples for 16 different research projects, including CCFS research projects (TARDIS; PhD projects; Honours), *TerraneChron*® and users from other institutions (ANU, CSIRO, University of Wollongong, NSW Geological Survey).

Since its installation the primary application of selFrag has been for the extraction of zircon grains for U-Pb geochronology and in 2013 this accounted for more than 90% of the samples processed. 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 (e.g. chromitites, peridotites). Other applications include the analysis of grain size and shape of phenocrysts and glass shards 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), and archeological provenance studies using zircon ages from potshards. These applications highlight the advantages of selFrag over conventional comminution methods with the use of a small volume cell to extract mineral inclusions and the use of '*sandwich-sieve*' to improve the yield of ultra-fine materials (see *Research Highlight Tibet Chromitites*).

selFrag is the centrepiece of the facility for mineral separation at GEMOC, but for most samples it is just the first stage in the separation process. The following further separation methods using material produced by selFrag have been developed and are being refined:

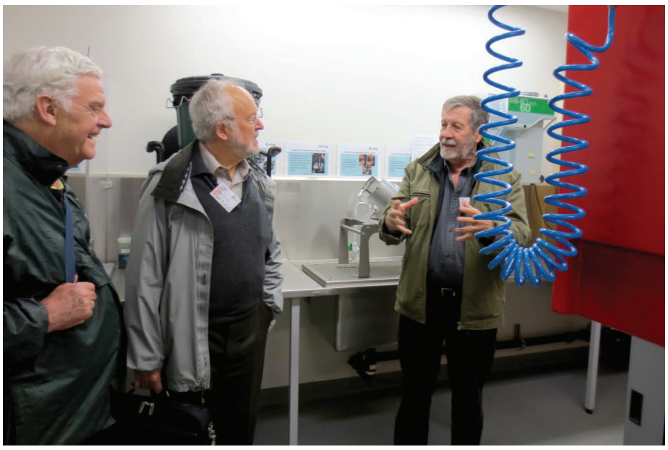
(i) sample sieving using disposable plastic/nylon sieves to prevent (cross-) contamination of samples

(ii) heavy liquid mineral separation using aqueous solutions of the nontoxic chemical sodium polytungstate (SPT) for heavy-mineral separation.

(iii) magnetic/paramagnetic separation using Frantz® Magnetic Barrier Laboratory Separator for separation of dry materials according to magnetic susceptibility, exploiting either paramagnetic or diamagnetic properties, resulting in three output fractions: magnetic, paramagnetic and non-magnetic.

(iv) 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. The hydroseparator has been successfully used 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.



Members of the 2013 CCFS Science Advisory Committee, Rob van der Voo and Giorgio Ronalli taking a guided tour of the selFrag lab with Bill Griffin.

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, Xuan-Ce Wang, Takako Satsukawa was appointed in 2012 and Yongjun Lu in 2013.

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 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** in the field.*

Nodular chromitites in dunite.

PROGRESS DURING 2013:

The strategic plan for 2013 has been fully accomplished, and the analysis of the samples collected by Dr González-Jiménez during 2012 from the ophiolites of the Coolac Serpentinite Belt in southern Australia, the Vizcaino Peninsula in northern Mexico and Dobromirtsi in southern Bulgaria have been completed. The results obtained from the study of the Dobromirtsi chromitites have been published in a paper submitted to a special volume of *Gondwana Research* on "*Ophiolitic Peridotites, Ultrahigh Pressure Minerals and Podiform Chromitites: Their Origin and Evolution*" (*CCFS publication #348*). In April, Dr González-Jiménez was invited by colleagues from the Dokuz Eylul University in Turkey to carry out fieldwork on the ophiolites of the Lycian Nappes. During this fieldwork Dr González-Jiménez and his colleagues recognised new styles of chromitite mineralisation in the ophiolitic mantle, and collected new samples of PGM-bearing chromitites. The identification of new styles of chromitite mineralisation led to the development of a new model for the formation of chromitites in ophiolites. The results of this research were published in two invited review papers hosted in a special volume of *Lithos* entitled "*Lithosphere and Beyond*" (*CCFS publications #334 and #349*).

During September-December Professor Mehmet Akbulut (Dokuz Eylul University, Turkey) and PhD candidate Vanessa Colás (University of Zaragoza, Spain) visited CCFS. Prof. Akbulut carried out in-situ Re-Os analyses on PGMs from chromitites of the ophiolites of the Lycian nappes. Visiting PhD, Vanessa Colás, carried out in-situ analyses of minor and trace-elements in chromitites from a suite of metamorphosed ophiolites, including Tehuitzingo (Mexico), Los Congos (Argentina) and Coolac Belt (Australia). The results obtained in her work show that alteration of chromite can only be produced during the infiltration of hydrothermal fluids at temperatures between 500-700˚C.

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 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 2013:

The most significant contribution of this project during 2013 was to provide a potential breakthrough hypothesis that links the generation, preservation, and sampling of early reservoirs into a self-consistent Earth system. In this year, we discovered that an ancient mantle reservoir formed at 4.5-4.4 Ga had been tapped by the ca 60 Ma old Baffin Bay high-magnesium lavas (*CCFS publication #354*) and late Cenozoic basalts from the Hainan-Leizhou peninsula, the Indochina peninsula and South China Sea seamount (*CCFS publication #336*). An in-depth analysis demonstrated that this ancient mantle reservoir is chemically heterogeneous, containing at least two (depleted and enriched) end-member components (*CCFS publication #354*). This implies that chemical effects of early differentiation can persist in mantle reservoirs to the present day, and challenges an enduring tenet of modern chemical geodynamics, that the Earth started as a well-mixed or homogeneous body which evolved progressively over the geological time into several chemically distinct domains. Consequently, the observable chemical heterogeneity in mantle-derived rocks cannot be simply linked directly to the chemical and physical structure and evolution of the solid Earth over the past 4.5 Ga. We proposed a new hypothesis that illustrated how global differentiation of the early silicate Earth from 4.55-4.40 Ga may have produced depleted and enriched

Xuan-Ce Wang in the field.

dense melts in an undegassed deep Earth (*CCFS publication #354*). Such an early Earth differentiation would have occurred in two independent layers at >1,800 km and ≤1,800 km depths. The crystallisation of a transient magma ocean would produce an enriched denser liquid phase at >1,800 km depth. The denser melts may be further modified by metal-silicate segregation to produce coupled high Hf/W, Re/Os, and Pt/Os ratios at the base of a primordial magma ocean or in a partially molten zone at or near the core-mantle boundary. In contrast, within the upper layer (≤1,800 km), as the crystallisation proceeded, the residual liquid would rise buoyantly until a small fraction (≤1%) of melt ultimately formed a protocrust at the Earth surface, depleting 60% of the silicate Earth. The depleted dense melt may have been generated by high-degree partial melting of peridotite at about 300-410 km depths, shortly after magma ocean crystallisation. These two types of dense melts would result in materials constituting the present-day thermo-chemical piles hosted within the two large low-shear-wave-velocity provinces above the core-mantle boundary, that have been protected from complete entrainment by subsequent mantle convection currents. We argue that although such dense melts may exhibit some '*primordial*' geochemical signatures, they are not representative of the bulk silicate Earth.

How such a dense chemical layer can be sampled and brought to the surface is another important question. Geological evidence related to supercontinent-superplume cycling shows that the location and formation of superplumes were dominantly controlled by the first-order geometry of global subduction zones. Recent studies have proposed that sinking subducted slabs not only can push the dense chemical layer upward, but at the same time push the thermal boundary layer to form thermal-chemical domes, enhancing or triggering thermal instability (*CCFS publication #336*). Our studies show that the late-Cenozoic less-contaminated and synchronous basaltic samples from the Hainan-Leizhou peninsula, the Indochina peninsula and South China Sea seamount occur above a seismically detected thermal plume adjacent to deep subducted slabs (*CCFS publication #336*). Thus, we proposed that young avalanched slabs may push up such a thermal-chemical pile to form a thermal plume. Such an ancient denser chemical layer therefore would continue to be sampled by mantle plumes (*CCFS publications #336 and 354*).

Published outputs:

2013 CCFS publications #19, 297, 336, 338, 343, 347, 354, 369, 371

AIMS AND WORK PLAN FOR 2014:

In 2014, the core task will be to conduct extensive analyses of Re-Os, Sm-Nd isotope and PGE abundance data obtained in 2013 from the mantle xenoliths hosted by the Hainan alkalic basalts, to constrain the evolution of the sub-continental lithospheric mantle and compare it with those of Cathaysia Block and Yangtze Craton. The specific aims in 2014 are:

(1) To conduct comprehensive in-situ olivine-oxygen and electronic microprobe analyses to examine the proportion of recycled components;

(2) To conduct whole rock major-trace element analysis on high-magnesium synchronous basalts of southeast China collected in 2013, to test whether or not they derived from high-temperature primary melts;

(3) To conduct analyses of short-lived ^{146}Sm-^{142}Nd isotopes to further test the relative roles of early Earth processes versus subsequent dynamic processes in shaping the Earth's chemical architecture.

(4) To finish the manuscripts focusing on mantle xenoliths and submit in the middle of 2014;

(5) To prepare a paper focusing on the drill-core samples from the Hainan CFBs.

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 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.

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.

PROGRESS DURING 2013:

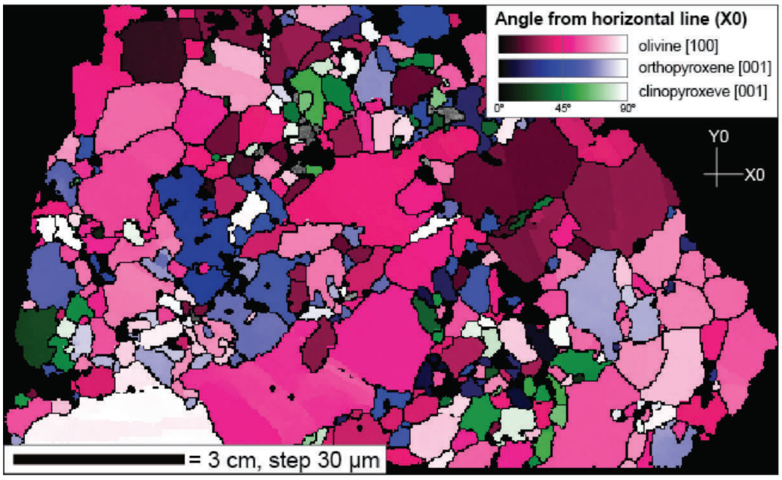
The Japan Sea is one of the back-arc basins distributed around the western rim of the Pacific. Its floor is composed of oceanic crust, rifted continental crust and stretched continental crust. However, the evolution of the back-arc spreading is not fully understood; for example, the cause of formation, processes of evolution, similarity and differences to the mid ocean ridge are yet to be fully described. Moreover, evolution of ocean basins is a fundamental component and they are particularly important for producing crust, deformation of the lithosphere, asthenospheric flow, partial melting, and melt/fluid rock interaction. To constrain these interactions, we studied the microstructural development in the uppermost mantle associated with melt-rock interactions in peridotite xenoliths from Shingu (SW Japan) and Seifu seamount (Japan Sea).

The Shingu peridotite xenoliths are hosted by a lamprophyre dike on Shikoku Island, Japan, which has a K-Ar age of 17.7 ± 0.5 Ma (Uto et al., 1987), before the formation of the Japan Sea. Thus, these peridotites may preserve features of the uppermost mantle prior to the back-arc spreading, whereas peridotite xenoliths in alkali basalt dredged from Seifu seamount, which has a K-Ar age of 8.09 ± 0.31 (Ishii personal comm.), represent direct samples of Japan Sea oceanic mantle.

The peridotite xenoliths have equigranular to porphyroclastic texture, with grain boundaries that range from triple junctions to smoothly curving boundaries. Some olivine grains are cut by pyroxenes. The mineral chemistry of the Shingu peridotites reveal a sequence of metasomatic events; 0) partial melting, 1) Fe-enrichment, 2) refertilisation with Ti and Al enrichment, 3) Al and REE (Rare Earth Element) enrichment. The Seifu peridotites can be classified into two types in terms of REE patterns of clinopyroxene; one shows slight enrichment in LREE and the other has high-REE cpx with flat to slightly LREE-enriched patterns.

The olivine CPO of Shingu peridotite is dominantly (010)[100] and subordinate {0kl}[100]. The sample, which was only influenced by the first metasomatism (Fe-enrichment), shows a (010)[100] slip system in olivine and (100)[001] in orthopyroxene. Other samples show no significant relationships among the minerals. This indicates that deformation was completed by the early stage of metasomatism. In contrast, the olivine CPO of Seifu peridotites is consistent with slip on (010)[100] and {0kl}[100]. In most samples, orthopyroxene crystals have irregular grain boundaries and are interstitial to the olivine grains. In spite of their grain shape, the slip system of orthopyroxene is consistent with that of the neighbouring olivine crystals, indicating that deformation of olivine and orthopyroxene occurred at the same time.

Combined with petrological and microstructural observations, we argue that the suite of the peridotite xenoliths records a rare snapshot of the uppermost mantle flow related to the initial stage of back-arc spreading. Geochemical characteristics reveal that fundamental melt percolation occurred both before and during back-arc spreading, suggesting that asthenospheric flow and deformation occurred in the presence of small melt fractions.



EBSD map of a peridotite xenolith from Seifu seamount (SW Japan).

AIMS AND WORK PLAN FOR 2014:

1. 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.

2. To calculate CPO-derived seismic properties which will provide a unique basis for comparison with the detailed seismological data available in these areas.

3. To reveal the deformation history of chromitites in peridotite massifs. Chromite is nicely preserved indicating it was more resistant to fluid-related processes than the silicates of the peridotitic host rocks; this distinctive property makes chromitites very useful to track the evolution of Earth's mantle convection.

Appendix 2: CCFS workplan 2014

AIMS AND WORKPLAN FROM 2014

Two years after commencement of the CCFS Foundation Projects, individual projects have matured, cross-node communications have developed, and new research directions and collaborations have emerged. The research already completed has identified new perspectives and asks new questions: synergies between Foundation Projects and the Technology Development Projects have grown, fulfilling the original strategy. The new project descriptions are given in detail here.

Most Foundation Projects (FP) have proven robust research anchors core to CCFS goals and have developed new aims and directions; some have been completed and others have conceptually converged so align (and merge) with other Foundation Projects, together defining creating new and exciting goals. For example, original FP projects on large granite blooms (FP 3) and Dynamics of Earth's mantle (2b) are completed as envisaged, whereas aspects of understanding the nature of deep Earth fluids through diamond research (FP 8) have been combined into FP 1 (TARDIS II) and 4-D lithospheric evolution (FP 9) into FP 2 (Multi-scale four-dimensional genesis). There have been major re-alignments of several Foundation Projects, adjusting their scope to achieve the new scientific goals. Aspects of geodynamic processes and fluid effects, at micron to macro scales, during subduction processes have taken on increased importance, and are now integral to most in projects.

FOUNDATION RESEARCH PROJECTS FROM MID 2014	Coordinator and main Centre personnel
1. TARDIS II: project: Deep-Earth fluids in subduction zones, ophiolites and cratonic roots	O'Reilly, Griffin, Pearson
2. Multi-scale four-dimensional genesis, transfer and focus of fluids and metals	Fiorentini, McCuaig, Reddy
3. Two-phase reactive flow in multi-component deformable media	O'Neill, Afonso, Yang, Foley
4. A planetary driver of atmospheric, environmental and biological evolution through time	Van Kranendonk, Foley, Fiorentini, Kilburn
5. Detecting Earth's rhythms: Australia's Proterozoic record in a global context	Li, Wingate
6. Fluid regimes and the composition of the early Earth	Wilde, Nemchin
7. 3D architecture and Precambrian crustal evolution in the Western Yilgarn, Australia	Gessner, Wingate, Tyler, Belousova
WHOLE OF CENTRE TECHNOLOGY DEVELOPMENT	
Cameca Ion microprobe development: maximising quality and efficiency of CCFS activities within UWA Ion Probe Facility	Kilburn, Cliff, Griffin,
Frontiers in integrated laser-sampled trace-element and isotopic geoanalysis	Pearson, Cliff, Griffin, Kilburn, Belousova

As this Annual Report goes to print, details of these projects (including titles and funding allocations) are being finalised for implementation from mid 2014 as the original 3-year projects are completed.

FP 1: TARDIS II: DEEP-EARTH FLUIDS IN SUBDUCTION ZONES, OPHIOLITES, AND CRATONIC ROOTS

The newly designed TARDIS project incorporates the previously independent Foundation Project Diamond genesis: Fluids in deep Earth processes, with an added specific goal of following up and explaining intriguing discoveries about the process of ultra-deep subduction in continental collision zones. The former projects converged toward studies of the super-reducing, ultra-high-pressure (SuR-UHP) diamond-bearing mineral assemblages found in ophiolites from Tibet and the Polar Urals. The SuR-UHP assemblage includes a wide range of alloys, native metals, oxides, carbides, and some silicates.

The nature of the SuR-UHP environment and the tectonic setting and evolution of the UHP ophiolites will be constrained by analyses of the contents and aggregation state of N in the nitrogen rich ophiolitic diamonds, supplemented by *in situ* FTIR measurements of N contents and aggregation states, isotopic analysis of N and C by SIMS, and measurements of $^{3}He/^{4}He$ ratios and other noble gases. These will help to establish the origin of the diamonds, following up initial indications that the rocks experienced a short burial and exhumation history and rapid cooling to low temperatures. Studies of diamonds, their inclusions, and the amorphous carbon will include techniques such as NMR and FIB-TEM, benefitting from the broadened base of expertise in CCFS with the new AI Dorrit Jacob, CI Yingjie Yang (Beijing) and R. Wirth at Potsdam. The investigation of the *'amorphous C'* will have a high priority to follow up the suggestion that this material may represent a natural occurrence of a polymer-based ceramic material.

In situ measurements of the isotopic ratios of a number of elements in their oxidised and reduced forms using a mixture of SIMS and LA-MC-ICPMS will test the possibility that the exceptionally reducing conditions may have caused isotopic fractionations between phases such as native metals, carbides, oxides and silicates. The analysis of Si isotopes in SiC from several environments has been funded as a pilot sub-project as a new Technology Development initiative. Small-scale variations in Fe^{3+}/Fe^{2+} and Cr^{2+}/Cr^{3+} will be ascertained by XANES mapping at the Australian Synchrotron. These *in situ* and mapping techniques will improvements on the currently available bulk analyses by Mössbauer spectroscopy.

Indications of extreme pressures will be intensively investigated. Trace-element spot analyses of olivines will check them for signs of inverted wadsleyite or ringwoodite, and the suggestion that olivines in the massive chromitites have shorter bond lengths (Mg-O, Si-O) than in shallow environments will be re-investigated. If confirmed, this could become a *'fingerprint'* that could be applied to other ophiolites to detect similar UHP histories. Dynamic modelling of deep subduction and collision will cross-check the conclusions from the geochemical and mineralogical investigations, integrating this work with FP 3 (Two-phase flow). Petrological and improved Os isotope geochronological studies will constrain rock properties, including density and its changes during exhumation. Experimental studies will be introduced in the last half of the project, following installation of the new high-pressure laboratory. Aims could be the investigation of the formation of baiwenjiite by subduction-dehydration of antigorite at Transition Zone conditions, and element partitioning in the high-P polymorphs of chromite under variable redox conditions.

FP 2: MULTI-SCALE FOUR-DIMENSIONAL GENESIS, TRANSFER AND FOCUS OF FLUIDS AND METALS

A combination of the two previous Foundation Projects on metal sources and transport mechanisms and 4D lithospheric controls on mineral system distribution, FP 2 has been re-aligned to bring the separate studies of fertility, architecture and geodynamics into a single umbrella project. Previous CCFS experiments on melt/fluid pairs have demonstrated the success of the experimental technique. These studies will now be expanded to look at the role of other volatiles (S, Cl, CO_2, Br) in the transport of metals, and to add PGE and Au to the existing suite of base metals. The range of conditions will also be expanded to additional pressure-temperature windows and oxidation states. This will in turn expand the applicability of the experiments to a greater range of mineral systems including Ni-Cu-PGE, Cu-porphyry systems and PGE layered intrusions, with the goal of resolving the debate whether these result from sulfide segregation or fluid metasomatism. A new branch of studies will integrate the now-diverse CCFS expertise in investigating the role of ultrapotassic-potassic rocks in the redistribution of metals and volatiles from mantle to crust in collision zones.

Recent CCFS work has emphasised the role of lithospheric architecture in the localisation of magmatic provinces prospective for a wide range of mineral systems, including orogenic gold and Cu-(Au) porphyries, Ni-Cu-PGE, and Cu-Mo-Au porphyry systems. The key pathways that connect geochemical reservoirs and permit efficient fluid flux will be further investigated in field studies in the Ivrea Zone, Southeast Greenland and Tibet. The critical tectono-metamorphic events that favour the efficient extraction of metals from a fertile source will be investigated by targeting the peridotites of Zabargad (Red Sea), which represent mantle rocks exhumed by hyper-extension during rifting. These rocks provide the key to establishing the relationship between continental-margin processes and mantle metasomatism and provide a unique opportunity to tease out the importance of extension in fertility enhancement before subsequent modification associated with basin closure. Expanded use of

EBSD will strengthen our knowledge of the key relationship between deformation at the micro-scale and the transfer of key fluids and metals.

FP 3: TWO-PHASE REACTIVE FLOW IN MULTI-COMPONENT DEFORMABLE MEDIA

This project incorporates novel self-consistent thermodynamic modelling and new seismic tomography methods to constrain the thermal and fluid content of the upper mantle. A thermodynamically consistent scheme that couples deformation, self-generation and migration of porosity (or damage), mass transfer between phases, and reaction within phases is under development in only a few Institutions, and is widely regarded as the frontier of geodynamical methods. This will enable the CCFS geodynamics group to address problems of significant relevance to the geochemical community, given the clear importance of percolative fluid flow within the solid mantle.

Progress in the investigation of multi-component multi-phase reactive flow (MPMCRF) systems involves overcoming technical difficulties in solving complex numerical problems, analytical, experimental and field studies to constrain important parameters, and understanding the strong scale-related variability in the behaviour of the system of equations. Two prongs of a three-pronged approach to developing computational tools (Cartesian tool development [Underworld] and CitcomS spherical code capability) have been adopted, and we are currently working on the new code-development aspects. Underworld's modelling capabilities will be further developed using Nectar funding. Applications of this modelling initially will be primarily in areas of flat subduction, where fluid release makes two-phase flow problems of particular importance. The Farallon slab in the western U.S.A. and a similar situation in South China will be used as examples.

We will adopt the two new methods of Ambient noise tomography and Multiple Plane Wave Tomography in seismic imaging to construct 3D seismic models using data from the extensive broadband Transportable Array component of EarthScope/USArray, which are publicly available.

The thermodynamic modelling will benefit from the expansion of high-pressure experimental facilities at Macquarie over the next two years. Immediate relevant questions that can be approached experimentally are the mineralogy of material formed by melts and fluids that solidify under lower lithosphere conditions, and the reactions that occur between infiltrating melts and fluids and the lower lithospheric mantle.

FP 4: A PLANETARY DRIVER OF ATMOSPHERIC, ENVIRONMENTAL AND BIOLOGICAL EVOLUTION THROUGH TIME

This re-vamped project incorporates the work already conducted on multiple sulfur isotopes into a coherent, integrated plan with a much broader scope that links the previous work into a global framework of changing tectonics through time. Specifically, we have added three new modules that link ore deposits and life, to investigate how these interact with the lithosphere-hydrosphere boundary through time, and tie changes in these systems to the evolving geodynamic framework of our planet.

The early Earth was a fundamentally different planet: environments, habitats, and atmosphere and ocean compositions have all evolved in concert with changes in the biosphere, and at least some of these coincide with changes in the tectonic style of Earth. New work modules address [1] Vital pathways: how mantle-derived ultramafic magmas incorporate sulfur to produce ore deposits and how the compositions of these systems have evolved through time. A continuation of this work will be applied to Mars, as a way of comparing the developmental history of these terrestrial planetary neighbours. [2] Critical interfaces: what occurs where the lithosphere meets the exosphere when and where life appears? The low-metamorphic grade rocks of the Turee Creek Group, Western Australia, preserve a conformable record of the transition from early Earth (anoxic exosphere, warm climate, hotter mantle) to more modern Earth (oxidised exosphere, cold climate, cooler mantle). [3] Global element cycles: chemical proxies of microbial metabolism are preserved in the cycles of C, S, Fe and N isotopic systems. Here two specific intervals, the Mesoarchean, when modern-style plate tectonics appears to have begun, and the Neoarchean to early Proterozoic transition, when atmospheric oxygen rose and chaos appears to have reigned in the biosphere. [4] Planetary driver: How do crust formation and episodic rapid subduction affect heat flow and life environments at a global scale? We will elaborate on the causative drivers, undertaking whole-Earth modelling of the effects of subduction and its effects on atmospheric composition and temperature.

FP 5: DETECTING EARTH'S RHYTHMS: AUSTRALIA'S PROTEROZOIC RECORD IN A GLOBAL CONTEXT

This Foundation project maintains its previous aims, and will build on its solid base of results from the first two years, concentrating during the next period on paleomagnetic analysis of the Mesoproterozoic Morawa Lavas of Western Australia, and the 2.4 Ga Erayinia mafic dykes in the southwestern Yilgarn Craton. Additional sequential targets are the Bangemall Basin, sampled in 2013, and Paleoproterozoic rocks of the Kimberley region. International collaborative work will be continued, including a number of offshore targets, and results will be published as further syntheses of Proterozoic paleomagnetism and paleogeography.

FP 6: FLUID REGIMES AND THE COMPOSITION OF THE EARLY EARTH

Further work on both early Archean terrestrial samples and meteoritic material representative of the terrestrial planets will continue. Terrestrial samples from several continents will be studied: Antarctic samples from both Enderby Land and Kemp Land will be further investigated to resolve the origin of the '*patchy*' distribution of Pb and Ti, and will include additional synchrotron and Raman analyses. The Jack Hills traverse will be interpreted and published, focusing on the distribution of Proterozoic sedimentary rocks and the timing of metamorphism. Analytical work will be undertaken on the Illarra Greenstone Belt samples that contain components older than 4.0 Ga, and work will continue on zircons extracted from the oldest rocks in Canada and Greenland. The work on the North Atlantic Craton will be augmented in the future by samples from key localities in Labrador, to which a field excursion is planned for 2014. A thorough investigation of the oldest rocks in the North China Craton will continue in association with the Chinese Academy of Geological Sciences.

As regards extra-terrestrial samples, the geochemical and micro-structural data obtained on Zagami and Nakhla sub-samples will be completed, and a new focus will be placed on the composition and significance of carbonates within ALH84001-83, which will require development of suitable carbonate standards. We will continue our investigations on ALH84001-104, emphasising variations in microstructure and geochemistry across the sample.

FP 7: 3-D ARCHITECTURE AND PRECAMBRIAN CRUSTAL EVOLUTION IN WESTERN AUSTRALIA

Two previous Foundation projects dealing with the evolution of the crust in Western Australia are now folded into one. Future work on the Western Australian crust will involve more than 20 CCFS scientists, interlinking with several Foundation Projects, as well as independently funded initiatives such as ARC-Linkage funding of a three-year passive-array deployment across the south-eastern margin of the Yilgarn, and a similar passive array for the Capricorn Orogen on the Yilgarn Craton's northern margin in association with the Distal Footprint Science Investment and Education Fund. The craton-scale 3D seismic passive-source deployment will greatly improve lithospheric imaging. Ambient-noise imaging and receiver-function CCP stacking have intermediate resolution in the crust compared with active-source studies, but unprecedented resolution in the cratonic lithosphere.

Collaborative research on the lithospheric evolution and related significant mineralisation of the Yilgarn Craton and its margins, will also be developed in geochemistry, geochronology, geodynamics and modelling. U-Pb, Hf, and Nd isotope studies will be continued in the northeastern Yilgarn, and extended to the southwest of the craton. These will be supplemented by Os and Nd isotopic data to develop a mantle-signature database that will assist in determining the relative roles of juvenile mantle and continental lithosphere in mafic/ultramafic rocks and in crustal isotopic mapping. Testing of existing geodynamic concepts that have been put forward for the Yilgarn Craton will be prioritised, beginning with relatively well-described time slices such as the 2800–2600 Ma tectonic evolution of the eastern Yilgarn Craton.

The project will continue to acquire and interpret zircon Lu–Hf isotope data, integrating them with other geoscience datasets. The research will continue to be focused in '*greenfields*' areas, concentrating on the western Yilgarn Craton, the Albany–Fraser and Capricorn Orogens, the Kimberley region, and basement rocks of the Eucla Basin from 2014. Additional new samples will be collected during the normal course of GSWA fieldwork to address specific geological problems. In 2013 more than 1400 analyses were performed despite considerable instrument down-time; it is hoped to surpass this number in the coming years.

TECHNOLOGY DEVELOPMENT PROJECTS

TDP 1: CAMECA ION-MICROPROBE DEVELOPMENT

The ion microprobe has enjoyed increasing usage within CCFS and has become an important entity in the cross-fertilisation of research ambitions, leading to an increased number of applications planned in the near future. Work on standards and analytical protocols is ongoing, and currently includes multiple sulfur isotopes in sulfide minerals, oxygen and hydrogen isotopes and zirconium isotopes in zircon. The new pilot projects will extend this to the isotopes of silicon, carbon and nitrogen.

The installation of the new NanoSIMS 50L will likely occur in late 2014, with testing extending into 2015. Testing the new oxygen ion source should prove to be exciting as this has the potential to increase the spatial resolution for positive secondary ions by an order of magnitude.

TDP 2: FRONTIERS IN INTEGRATED LASER-SAMPLED TRACE ELEMENT AND ISOTOPIC GEOANALYSIS

Further advancement of geochemical methodologies and techniques, particularly involving the new Femtosecond laser microprobe, the Nu AttoM Sector field ICP-MS and the Excite 193nm excimer laser, will continue to play a significant role in the creation of new research initiatives and to be a major factor in attracting new research collaborators. The development of potential microbeam standards for combined laser ablation ICP-MS and MC-ICP-MS requires characterisation of major and trace elements and isotopic compositions; these are being developed in collaboration with UWA in TP 1. A new technological initiative involves adaptation of conventional '*macro*' techniques to micro sample volumes, driven by the availability of '*contamination-free*' mineral separates using selFrag and the New Wave Micromill (TP 3). Research into fundamental properties of femtosecond ablation processes in geological materials (firstly silicates, then sulfides, oxides, phosphates, carbonates) focusing on laser-induced isotopic fractionation, will be expanded, and split-stream laser ablation analysis using Q-ICP-MS (U-Pb isotopes) and MC-ICP-MS (Hf isotopes) will be developed. Work on Li and Mg isotopes will be continued and optimised.

PILOT PROJECTS 2014-2015: A NEW INTITATIVE

In addition to the Foundation Projects, CCFS is providing limited funding for pilot projects for one or two years, commencing in 2014. These pilot projects were conceived with the aim of '*seeding*' small project ideas that are not yet far enough developed to compete successfully for grants to conduct the fully-fledged projects. The aim of the pilot projects is to nurture excellent, risky research ideas and bring them to the stage where they are either competitive for outside funding or become a new strand of a Foundation Project. The pilot projects were awarded in a competitive proposal round with a view either to folding them into Foundation projects at a later stage, or to giving them from one to two years to unfold their potential with preliminary results to demonstrate that they are competitive to apply for independent funding. Three of these pilot projects (5, 6, 7) address technology development, particularly new types of in situ analysis. All involve inter-node collaboration.

Pilot Project	Coordinator and main Centre personnel
1. Hydrating the Earth's deep, dry crust	C. Clark, Martin, Griffin, Reddy, Cliff, Rushmer, Brown, Jacob
2. The isotopic architecture of komatiite flow fields in the Yilgarn Craton of Western Australia	Fiorentini, McCuaig, Griffin, O'Reilly, Pearson, Kirkland
3. Trace element partitioning during hydrous melting of lower crust and volatile redistribution by shoshonite: implications for genesis of post-collisional porphyry Cu deposits in Tibet	Lu (Y-J), McCuaig, Fiorentini, Ciff, Li, Turner, Foley, Rushmer, Pearson
4. Diamond growth at the nanoscale: mantle fluids at work	Jacob, Kilburn, Howell, Piazolo, Griffin
5. How to make the invisible visible: exploring the use of isotopic labelling for the visualisation of fluid/rock interaction in experimental and natural samples	Kilburn, Fiorentini, Piazolo, Rushmer, Locmelis, Adam, Reddy
6. Fluid fluxes and architecture in subduction zones: insight from O and H isotopes in lawsonite	Martin, Cliff, Reddy, Pearson, Griffin, Foley, Turner, Rushmer
7. Isotopic composition of SiC and Si from continental roots and subducted oceanic mantle: redox processes in the deep Earth	Griffin, Cliff, Pearson, Martin, Huang, O'Reilly
8. Probing the deep nitrogen cycle	Foley, Kilburn, Cliff, Pearson, Fiorentini, George, S. Clark

Appendix 3: 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. 107.*

Unravelling the geodynamics of eastern Australia during the Permian: the link between plate boundary bending and basin formation	G. Rosenbaum, **S.A. Pisarevsky**, C.R. Fielding, F. Speranza: *Supported by ARC Discovery (commenced 2013)* ***Summary:*** The Permian evolution of eastern Australia is poorly understood. It involved bending of the southern New England Orogen and simultaneous development of widespread sedimentary basins. This project will combine palaeomagnetic and structural investigations to unravel the palaeogeography and plate kinematics of eastern Australia during the Permian. We will generate a comprehensive database on palaeolatitudes, block rotations and magnetic fabric, and will link, for the first time, the process of oroclinal bending with the development of the east Australian rift system. Outcomes will elucidate the fundamental tectonic process of oroclinal bending and will fill a knowledge gap in our understanding of the evolution of the Australian continent.
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.
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.
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.
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.

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.
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.
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.
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.

How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	**Y. Yang**: *Supported by ARC Future Fellowship (commenced 2013)* ***Summary:*** The concept of small-scale convection currents from about 100-400 km below the Earth's surface is a model proposed to explain the origins of intraplate volcanoes and mountains. However, direct evidence for the physical reality of small-scale convection cells is generally weak. This project will develop a novel seismological approach combining both ambient noise and earthquake data that can image such small-scale upper mantle convection. The outcomes of this project will help to fill the gap left in the Plate Tectonic paradigm by its inability to explain intraplate geological activity (volcanoes, earthquakes, mountains), which would be a significant step towards unifying conceptual models about how the Earth works.
A new approach to quantitative interpretation of paleoclimate archives	**D. Jacob**: *Supported by ARC Future Fellowship and MQ (commenced 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.
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.
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.

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.
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 as 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
Residual stress investigations of polycrystalline natural diamond aggregates	Venter, **S. Piazolo**, Luzin: *Suported by Braggs Institute, ANSTO (commenced 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.
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. Clark**, **M. Fiorentini**, **Z.-X. Li**, **N. Daczko**: *Supported by ARC LIEF (commenced 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 (commenced 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 geosciences over the next decade.
Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	H. Tkalcic, B. Kennett, C. Spaggiari, **K.Gessner**: *Supported by ARC LIEF (commenced 2013)* ***Summary:*** The objective of this work is to achieve new, synergistic techniques for delineating the three-dimensional structure of the east Albany-Fraser Orogen in Western Australia, and the lithospheric structure below it. These methods will guide understanding of the potential for mineral resources in this region with little surface geological exposure.

Australian membership of the International Ocean Discovery Program	R.J. Arculus, E.J. Rohling, A.P. Roberts, N.F. Exon, C.J. Yeats, **S.Y. O'Reilly**, **S.C. George**, D. Muller, J.C. Aitchison, J.M. Webster, M.F. Coffin, P.M. Vasconcelos, K.J. Welsh, **T.C. McCuaig**, A.D. George, C.G. Skilbeck, A.T. Baxter, J.M. Hergt, S.J. Gallagher, C.L. Fergusson, C.R. Sloss, A.D. Heap, W.P. Schellart, J.D. Stilwell, J.D. Foden, A.P. Kershaw, W.R. Howard, M.B. Clennell, J.J. Daniell, L.B. Collins: *Supported by ARC LIEF (commencing 2014)* ***Summary:*** This project is for an Australian membership of the International Ocean Discovery Program. The Program will recover drill cores, situate observatories, and conduct down-hole experiments in all the world's oceans from lowest to highest latitudes to address fundamental questions about Earth's history and processes within four high-priority scientific themes: climate and ocean change - reading the past and informing the future; biosphere frontiers - deep life, biodiversity, and environmental forcing of ecosystems; earth connections - deep processes and their impact on earth's surface environment; earth in motion - processes and hazards on a human time scale.
A digital mineralogy and materials characterisation hub for petrology, mineralogy, exploration, metallurgy and reservoir characterisation research	B.I. McInnes A. van Riessen, P.A. Bland, S. Iglauer, J.J. Eksteen, A.I. Kemp, J.R. Muhling, **M. Fiorentini**, N.J. Thébaud, **M.T. Wingate**, **C. Kirkland**, G. Senanayake, A.N. Nikoloski: *Supported by ARC LIEF (commencing 2014)* ***Summary:*** This project will establish a digital mineralogy and materials characterisation hub for applications in petrology, geometallurgy, reservoir characterisation, environmental science, soil science, mineral processing and extractive metallurgy research. An automated mineral analysis instrument would complement the mineral separation (selFrag HV pulse fragmentation) and microanalytical facilities (SHRIMP/Cameca ion microprobes and ELA-ICP-MS) available to the participants via the John de Laeter Centre for Isotope Research. The instrument and software package making up the FEI QEMSCAN 650F model is the most advanced configuration on the market, and ideally suited for the high level research projects undertaken by the partner institutions.
A new view on diamonds: Deformation textures of polycrystalline diamond	**S. Piazolo**, Griffins, Venter, Luzin: *Supported by Braggs Institute, ANSTO (commenced 2013)* ***Summary:*** In-depth knowledge of the orientation characteristics of diamondites will allow us to interpret these rocks in terms of their deformation history.
GSWA-CET Targeting Products	M. Dentith, **T.C. McCuaig**, J. Miller, S. Beresford, L. Gallardo, E.-J. Holden, A. George, S. Hagemann, A. Porwal, A. Joly: *Supported by GSWA (commenced 2012* ***Summary:*** The GSWA is seeking to improve delivery of exploration-relevant geoscience datasets to industry to attract industry investment in WA as an exploration destination and thereby maintain a pipeline of mineral deposit discoveries that will underpin the revenue base of the State Government into the future. In order to achieve a step change in the exploration relevance of GSWA datasets, it has been recognised that a series of targeting products that help junior to mid-sized exploration companies translate the geoscience datasets into actual ground acquisition and drill target decisions will be critical.
Mineral Systems Flagship Cluster	**T.C. McCuaig**: *Supported by CSIRO Flagship Collaboration Fund (commenced 2013)* ***Summary:*** As Australian mineral exploration moves into areas of deep cover, the expense of exploration drilling wil increase dramatically. Explorers will demand increasingly sophisticated targeting tools to plan drilling programs and an improved understanding of the processes that influence the transport and deposition of metals by ore-forming fluids. The cluster has 3 Themes to deliver on each of the advertised requirements notably: Theme 1: An experimental program to assess the behaviour of meta-stable organic compounds in targeting mineral systems and validate thermodynamic models and interpretations. Theme 2: A complementary field program aimed at providing data from key mineral systems to support the thermodynamic and experimental programs. Theme 3: An integrated thermodynamic treatment of organic and inorganic systems that includes recently documented organometallic complexes.

Appendix 4: Participants list

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	Dr Belinda Godel (CSIRO, Australia)
	Professor Sue Golding (University of Queensland, Australia)
	Dr Nikolai Goriacev (University of Magadan, Russia)
	Dr Giovanni Grieco (University of Milano, Italy)
	Professor Eero Hanski (University of Oulu, Finland)
	Professor Peter Hollings (Lakehead University, Thunder Bay, Canada)
	Professor Zeng-qian Hou (Institute of Geology, Chinese Academy of Geological Sciences (CAGS) Beijing, PR China)
	Dr Rob Hough (CSIRO, Australia)
	Dr Alexei Ivanov (Irkutsk Institute for Crustal Evolution, Russia)
	Professor Alan Jay Kaufman (University of Maryland, USA)
	Dr David Leach (U.S. Geological Survey USGS, USA)
	Dr Liu Liu (CSIRO, Australia)
	Professor Wolfgang Maier (Cardiff University, UK)
	Dr John Mavrogenes (Australian National University Research School of Earth Sciences, Australia)
	Dr Nicola McLoughlin (University of Bergen, Norway)
	Dr Marilena Moroni (University of Milano, Italy)
	Assist Professor Shuhei Ono (Earth, Atmospheric, and Planetary Sciences Massachusetts Institute of Technology, USA)
	Adjunct Professor Franco Pirajno (Geological Survey of Western Australia, Australia)
	Dr Olivier Rouxel (European Institute for Marine Studies Technopôle Brest-Iroise, France)
	Dr Doug Rumble (Carnegie Institution of Washington, USA)
	Associate Professor Herbert Sigmund (International Atomic Energy Agency, Austria, Austria)
	Professor Oskar Thalhammer (University of Leoben, Austria)
	Assistant Professor Ingunn Thorseth (University of Bergen, Norway)
	Dr Kirsty Tomlinson (Ontario Geological Survey, Canada)
	Dr Jon Wade (University of Oxford, UK)
UWA	Dr Boswell Wing (McGill University, Canada)
	Professor Bernard Wood (University of Oxford, UK)
	Dr Federica Zaccarini (University of Leoben, Austria)
	MTEC group (Australia)
GSWA	Professor James Connolly (Institute of Mineralogy and Petrography, Swiss Institute of Technology ETH, Switzerland)
	Professor Taras Gerya (ETH, Zurich, Switzerland)
	Dr Jens-Erik Lund Snee (Stanford University, USA)
	Professor Uwe Ring (Stockholm University, Sweeden)
	Dr Stuart Thomson (University of Arizona, Tucson, USA)
	Dr Virginia Toy (Otago University, Dunedin, NZ)
	Dr Xianghui Xiao (Argonne National Laboratories, USA)
NSW	Dr Jan-Peter Duda (University of Göttingen, Germany)
	Professor Robert Hazen (Carnegie Institution of Washington, USA)
	Dr Elis Hoffman (University of Bonn, Germany)
	Professor Clark Johnson (University of Wisconsin, USA)
	Professor Balz Kamber (Trinity College, Dublin, UK)
	Professor Alfred Kröner (Institute of Geosciences Johannes Gutenberg University Mainz, Germany)
	Professor Carsten Munker (University of Cologne, Germany)
	Dr Thorsten Nagel (University of Bonn, Germany)
	Professor Pascal Philippot (Institute de Physique du Globe de Paris, France)
	Professor Joachim Reitner (University of Göttingen, Germany)
	Professor Bill Schopf (University of California, Los Angeles, USA)
	Dr Steven Shirey (Geophysical Lab. Washington, USA)
	Professor John Valley (University of Wisconsin, USA)
	Professor Martin Wille (Universität Tübingen, Germany)
	Dr K. Williford (University of Wisconsin, USA)

Appendix 5: 2013 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.J., Shellnutt, J.G. and Iizuka, Y. 2013. Microcontinents among the accretionary complexes of the Central Asia Orogenic Belt: *In situ* Re-Os evidence. *Journal of Asian Earth Sciences, 62, 37-50.*

22. **Van Kranendonk, M.J.** and **Kirkland, C.L.** 2013. Orogenic climax of Earth: The 1.2-1.0 Ga Grenvillian Superevent. *Geology, 41, 735-738.*

27. Adams, C.J., Mortimer, N., Campbell, H.J. and **Griffin, W.L.** 2013. The mid-Cretaceous transition from basement to cover within sedimentary rocks in eastern New Zealand: evidence from detrital zircon age patterns. *Geological Magazine, 150, 455-478.*

28. Adams, C.J., Mortimer, N., Campbell, H.J. and **Griffin, W.L.** 2013. 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. *Geological Magazine, 150, 89-109.*

32. **Lu, Y.-J.**, **Kerrich, R.**, Kemp, A.I.S., **McCuaig, C.**, Hou, Z.-Q., Hart, C.J.R., **Li, Z.-X.**, Cawood, P.A., **Bagas, L.**, Yang, Z.M., **Cliff, J.**, **Belousova, E.A.**, Jourdan, F. and Evans, N. 2013. Intracontinental Eocene-Oligocene porphyry Cu mineral systems of Yunnan, Western Yangtze Craton, China: Compositional characteristics, sources, and implications for continental collision metallogeny. *Economic Geology*, *108*, *1541-1576*.

36. Lu, J.G., Zheng, J.P., **Griffin, W.L.** and Yu, C.M. 2013. Petrology and geochemistry of peridotite xenoliths from the Lianshan region: Nature and evolution of lithospheric mantle beneath the lower Yangtze block. *Gondwana Research*, *23*, *161-175*.

161. Pan, S.K., Zheng, J.P., Chu, L.L. and **Griffin, W.L.** 2013. Coexistence of the moderately refractory and fertile mantle beneath the eastern Central Asian Orogenic Belt. *Gondwana Research*, *23*, *176-189*.

162. **Lu, Y.J.**, Kerrich, R., **McCuaig, T.C.**, **Li, Z.X.**, Hart, C.J.R., Cawood, P.A., Hou, Z.Q., **Bagas, L.**, **Cliff, J.** **Belousova, E.A.** and Tang, S.H. 2013. Geochemical, Sr-Nd-Pb, and zircon Hf-O isotopic compositions of Eocene-Oligocene shoshonitic and potassic adakite-like felsic intrusions in Western Yunnan, SW China: Petrogenesis and tectonic implications. *Journal of Petrology, 54, 1309-1348.*

172. Badanina, I.Y., **Belousova, E.A.** and Malitch, K.N. 2013. Hafnium isotope composition of zircons from dunites of the Nizhny Tagil and Guli Massifs (Russia). *Doklady Earth Sciences, 448, 38-42.*

174. **Locmelis, M.**, **Fiorentini, M.L.**, Barnes, S.J. and **Pearson, N.J.** 2013. Ruthenium variation in chromite from komatiites and komatiitic basalts - a potential mineralogical indicator for nickel sulfide mineralization. *Economic Geology*, *108*, *355-364*.

178. **Howell, D.**, **Griffin, W.L.**, **Piazolo, S.**, Say, J.M., Stern, R.A., Stachel, T., Nasdala, L.,Rabeau, J.R., **Pearson, N.J.** and **O'Reilly, S.Y.** 2013. A spectroscopic and carbon-isotope study of mixed-habit diamonds: Impurity characteristics and growth environment. *American Mineralogist, 98, 66-77.*

186. Murphy, J.B., **Pisarevsky, S.A.** and Nance, R.D. 2013. Potential geodynamic relationships between the development of peripheral orogens along the northern margin of Gondwana and the amalgamation of West Gondwana. *Mineralogy and Petrology, 107, 635-650.*

187. Balić-Žunić, T., **Piazolo, S.**, Katerinopoulou, A. and Schmith, J.H. 2013. Full analysis of feldspar texture and crystal structure by combining X-Ray and Electron techniques. *American Mineralogist*, *98*, *41-52*.

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195. **Pisarevsky, S.A.**, Biswal, T.K., **Wang, X.C.**, De Waele, B., Ernst, R., Soderlund, U., Tait, J.A., Ratre, K., Singh, Y.K. and Cleve, M. 2013. Palaeomagnetic, geochronological and geochemical study of Mesoproterozoic Lakhna Dykes in the Bastar Craton, India: Implications for the Mesoproterozoic supercontinent. *Lithos*, *174*, *125-143*.

196. Jiang, M., Ai, Y., Chen, L. and **Yang, Y.** 2013. Local modification of the lithosphere beneath the central and western North China Craton: 3-D constraints from Rayleigh wave tomography. *Gondwana Research*, *24*, *849-864*.

198. **Gonzalez-Jimenez, J.M.**, Marchesi, C., **Griffin, W.L.**, Gutierrez-Narbona, R., Lorand, J.P., **O'Reilly, S.Y.**, Garrido, C.J., Gervilla, F., **Pearson, N.J.** and Hidas, K. 2013. Transfer of Os isotopic signatures from peridotite to chromitite in the subcontinental mantle: Insights from *in situ* analysis of platinum-group and base-metal minerals (Ojen peridotite massif, southern Spain). *Lithos*, *164*, *74-85*.

200. Wang, Q., Xia, Q.K., **O'Reilly, S.Y.**, **Griffin, W.L.**, Beyer, E.E. and Brueckner, H.K. 2013. Pressure- and stress-induced fabric transition in olivine from peridotites in the Western Gneiss Region (Norway): implications for mantle seismic anisotropy. *Journal of Metamorphic Geology*, *31*, *93-111*.

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206. Evans, K.A., **McCuaig, T.C.**, Leach, D., Angerer, T. and Hagemann, S.G. 2013. Banded iron formation to iron ore: A record of the evolution of Earth environments? *Geology*, *41*, *99-102*.

207. **Griffin, W.L.**, Begg, G.C. and **O'Reilly, S.Y.** 2013. Continental-root control on the genesis of magmatic ore deposits. *Nature Geoscience*, *6*, *905-910*.

209. **Van Kranendonk, M.J.**, Ivanic, T.J., **Wingate, M.T.D.**, **Kirkland, C.L.** and Wyche, S. 2013. Long-lived, autochthonous development of the Archean Murchison Domain, and implications for Yilgarn Craton tectonics. *Precambrian Research, 229, 49-92*.

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217. **Afonso, J.C.**, Fullea, J., **Griffin, W.L.**, **Yang Y.**, Jones, A.G., Connolly, J.A.D. and **O'Reilly, S.Y.** 2013. 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. I: *a priori* petrological information and geophysical observables. *Journal of Geophysical Research: Solid Earth*, *118*, *2586-2617*.

218. **Afonso, J.C.**, Fullea, J., **Yang Y.**, Connolly, J.A.D. and Jones, A.G. 2013. 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. II: General methodology and resolution analysis. *Journal of Geophysical Research: Solid Earth*, *118*, *1650-1676*.

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227. Mazzoli, S., Martín-Algarra, A., **Reddy, S.M.**, López Sánchez-Vizcaíno, V., Fedele, L. and Noviello, A. 2013. The evolution of the footwall to the Ronda subcontinental mantle peridotites: insights from the Nieves Unit (western Betic Cordillera). *Journal of the Geological Society, 170, 385-402*.

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234. **Gonzalez-Jimenez, J.M.**, Villaseca, C., **Griffin, W.L.**, **Belousova, E.**, Konc, Z., Ancochea, E., **O'Reilly, S.Y.**, **Pearson, N.J.**, Garrido, C.J. and Gervilla, F. 2013. The architecture of the European-Mediterranean lithosphere: A synthesis of the Re-Os evidence. *Geology*, *41*, *547-550*.

235. **O'Reilly, S.Y.** and **Griffin, W.L.** 2013. Moho vs crust-mantle boundary: Evolution of an idea. *Tectonophysics*, *609*, *535-546*.

237. **Griffin, W.L.**, Sturt, B.A., **O'Neill, C.J.**, **Kirkland, C.L.** and **O'Reilly, S.Y.** 2013. Intrusion and contamination of high-temperature dunitic magma: the Nordre Bumandsfjord pluton, Seiland, Arctic Norway. *Contributions to Mineralogy and Petrology*, *165*, *903-930*.

238. **Foley, F.V.**, **Pearson, N.J.**, **Rushmer, T.**, **Turner, S.** and **Adam, J.** 2013. Magmatic evolution and magma mixing of Quaternary adakites at Solander and Little Solander Islands, New Zealand. *Journal of Petrology*, *54*, *703-744*.

240. Dolgopolova, A., Seltmann, R., Armstrong, R., **Belousova, E.**, Pankhurst, R.J. and Kavalieris, I. 2013. Sr–Nd–Pb–Hf isotope systematics of the Hugo Dummett Cu–Au porphyry deposit (Oyu Tolgoi, Mongolia). *Lithos*, *164-167*, *47-64*.

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243. Zi, J.W., Cawood, P.A., Fan, W.M., Tohver, E., Wang, Y.J., **McCuaig, T.C.** and Peng, T.P. 2013. Late Permian-Triassic magmatic evolution in the Jinshajiang orogenic belt, SW China and implications for orogenic processes following closure of the Paleo-Tethys. *American Journal of Science* , *313*, *81-112*.

245. Adams, C.J., Korsch, R.J. and **Griffin, W.L.** 2013. Provenance comparisons between the Nambucca Block, Eastern Australia and the Torlesse Composite Terrane, New Zealand: connections and implications from detrital zircon age patterns. *Australian Journal of Earth Sciences*, *60*, *241-253*.

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248. **Gorczyk, W.**, Hobbs, B., **Gessner K.** and Gerya, T. 2013. Intracratonic Geodynamics. *Gondwana Research*, *24*, *838-848*.

250. Gladkochub, D.P., **Pisarevsky, S.A.**, Mazukabzov, A.M., Soderlund, U., Sklyarov, E.V., Donskaya, T.V., Ernst, R. and Stanevich, A.M. 2013. The first evidence of Paleoproterozoic late-collision basite magmatism in the near-Sayan salient of the Siberian craton basement. *Doklady Earth Sciences*, *450*, *583-586*.

262. Angerer, T., **Kerrich, R.** and Hagemann, S.G. 2013. Geochemistry of a komatiitic, boninitic, and tholeiitic basalt association in the Mesoarchean Koolyanobbing greenstone belt, Southern Cross Domain, Yilgarn craton: Implications for mantle sources and geodynamic setting of banded iron formation. *Precambrian Research*, *224*, *110-128*.

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272. Godel, B., Barnes, S.J., Gurer, D., Austin, P. and **Fiorentini, M.L.** 2013. Chromite in komatiites: 3D morphologies with implications for crystallization mechanisms. *Contributions to Mineralogy and Petrology*, *165*, *173-189*.

275. **Kirkland, C.L.**, Smithies, R.H., Woodhouse, A., Howard, H.M., **Wingate, M.T.D.**, **Belousova, E.A.**, **Cliff, J.B.**, **Murphy, R.C.** and Spaggiari, C.V. 2013. Constraints and deception in the isotopic record; the crustal evolution of the west Musgrave Province, central Australia. *Gondwana Research*, *23*, *759-781*.

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278. Zhu, K.-Y., **Li, Z.-X.**, Xu, X.-S. and **Wilde S.A.** 2013. Late Triassic melting of a thickened crust in southeastern China: Evidence for flat-slab subduction of the Paleo-Pacific plate. *Journal of Asian Earth Sciences*, *74*, *265-279*.

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284. Wang, L.J., **Griffin, W.L.**, Yu, J.H. and **O'Reilly, S.Y.** 2013. U-Pb and Lu-Hf isotopes in detrital zircon from Neoproterozoic sedimentary rocks in the northern Yangtze Block: Implications for Precambrian crustal evolution. *Gondwana Research*, *23*, *1261-1272*.

293. Fan, H.P., Zhu, W.G., **Li, Z.X.**, Zhong, H., Bai, Z.J., He, D.F., Chen, C.J. and Cao, C.Y. 2013. Ca. 1.5 Ga mafic magmatism in South China during the break-up of the supercontinent Nuna/Columbia: The Zhuqing Fe-Ti-V oxide ore-bearing mafic intrusions in western Yangtze Block. *Lithos*, *168-169*, *85-98*.

294. **Glen, R.A.**, Korsch, R.J., Hegarty, R., Saeed, A., Poudjom Djomani, Y., Costelloe, R.D. and **Belousova E.** 2013. Geodynamic significance of the boundary between the Thomson Orogen and the Lachlan Orogen, northwestern New South Wales and implications for Tasmanide tectonics. *Australian Journal of Earth Sciences*, *60*, *371-412*.

297. Li, X.H., **Li, Z.X.**, Li, W.X., **Wang, X.C.** and **Gao, Y.** 2013. Revisiting the '*C-type adakites*' of the Lower Yangtze River Belt, central eastern China: In-situ zircon Hf-O isotope and geochemical constraints. *Chemical Geology*, *345*, *1-15*.

299. **Liu, Y.C.**, **Li, Z.X.**, Laukamp, C., West, G. and Gardoll, S. 2013. Quantified spatial relationships between gold mineralisation and key ore genesis controlling factors, and predictive mineralisation mapping, St Ives Goldfield, Western Australia. *Ore Geology Reviews*, *54*, *157-166*.

300. Ma, L., **Wang, Q.**, **Li, Z.X.**, Wyman, D.A., Jiang, Z.Q., Yang, J.H., Guo, G.N. and Guo, H.F. 2013. Early Late Cretaceous (ca. 93 Ma) norites and hornblendites in the Milin area, eastern Gangdese: Lithosphere-asthenosphere interaction during slab roll-back and an insight into early Late Cretaceous (ca. 100-80 Ma) magmatic '*flare-up*' in southern Lhasa (Tibet). *Lithos*, *172-173*, *17-30*.

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302. **Pisarevsky, S.A.**, Gladkochub, D.P., Konstantinov, K.M., Mazukabzov, A.M., Stanevich, A.M., Murphy, J.B., Tait, J.A., Donskaya, T.V. and Konstantinov, I.K. 2013. Paleomagnetism of Cryogenian Kitoi mafic dykes in South Siberia: Implications for Neoproterozoic paleogeography. *Precambrian Research*, *231*, *372-382*.

304. Ping, X.Q., Zheng, J.P., Zhao, J.H., Tang, H.Y. and **Griffin, W.L.** 2013. Heterogeneous sources of the Triassic granitoid plutons in the southern Qinling orogen: An E-W tectonic division in central China. *Tectonics, 32, 396-416*.

305. **Fiorentini, M.**, Bach, A., Stromgaard, K., Kastrup, J.S. and Gajhede, M. 2013. Interaction partners of PSD-93 studied by X-ray crystallography and fluorescence polarization spectroscopy. *Acta Crystallographica Section D - Biological Crystallography*, *69*, *587-594*.

306. Payne, J.L., **Pearson, N.J.**, **Grant, K.J.** and Halverson, G.P. 2013. Reassessment of relative oxide formation rates and molecular interferences on *in situ* lutetium-hafnium analysis with laser ablation MC-ICP-MS. *Journal of Analytical Atomic Spectrometry, 28, 1068-1079*.

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312. Yaxley, G.M., Kamenetsky, V.S., Nichols, G.T., Maas, R., **Belousova, E.**, Rosenthal, A. and Norman, M. 2013. Diamonds in Antarctica? Discovery of Antarctic kimberlites extends vast Gondwana Cretaceous kimberlite province. *Nature Communications, 4, Article #2921*.

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Appendix 6: 2013 Abstract titles

A FULL LIST OF CCFS ABSTRACTS FOR CONFERENCE PRESENTATIONS IS AVAILABLE AT: http://www.ccfs.mq.edu.au/

Granulites & Granulites 2013, Hyderabad, India, 16-20 January 2013	The Pan-African granulites of Madagascar and southern India **I.C.W. Fitzsimons**, **C. Clark**, A. Collins and R. Taylor Generating TTGs in Nuvvuagittuq Fold Belt: implications for the origin of the Earth's early continental crust **T. Rushmer** **Keynote** Implications of Late Archean magmatism and almost coeval high-grade metamorphism in the North China Craton at the Archean/Proterozoic boundary **S.A. Wilde** **Keynote**
37th Annual Condensed Matter and Materials Meeting, Wagga Wagga NSW, Australia, 5-8 February 2013	Polyamorphism: Fact or Fiction? **S. Clark** **Invited**
44th Lunar and Planetary Science Conference, Texas, 18-22 March 2013	What Lunar Zircon Ages Can Tell? **M.L. Grange**, **A.A. Nemchin**, **R.T. Pidgeon**, R.E. Merle and N.E. Timms Stratigraphy of the Fra Mauro Formation Defined by U-Pb Zircon Ages of Breccia Samples from Apollo 14 Landing Site R.E. Merle, **A.A. Nemchin**, **M.L. Grange** and M.J. Whitehouse Constraining the Flux of Impactors Postdating Heavy Bombardment Using U-Pb Ages of Impact Glasses **A.A. Nemchin**, M.L. Norman, R.A. Zeigler and **M.L. Grange** 1950 Ma Annealing of Radiation Damage in a Complex Zircon from an Apollo 15 Breccia **R.T. Pidgeon**, **M.L. Grange** and **A.A. Nemchin** Applications of electron backscatter diffraction to lunar and other extraterrestrial samples N.E. Timms, **S.M. Reddy**, **A.A. Nemchin**, **M.L. Grange**, **R.T. Pidgeon**, P.A. Bland, G. Benedix, K.A. Dyl, **M.-A. Kaczmarek** and F. Jourdan
European Geosciences Union General Assembly, Vienna, Austria, 7-12 April 2013	What lies beneath: Unveiling the fine-scale 3D compositional and thermal structure of the lithosphere and upper mantle **J.C. Afonso** **Keynote** Evaluating the extent of microbial mediation in volcanic glass alteration by nanoSIMS: Insights from recent and Archean metabasaltic pillow lavas N. McLoughlin, E.G. Grosch, **D. Wacey**, **M.R. Kilburn**, I.H. Thorseth and R.B. Pedersen Structure of the New England Orocline (eastern Australia): evidence from magnetic fabrics T. Mochales, G. Rosenbaum, **S.A. Pisarevsky** and F. Speranza U-Pb geochronology and paleomagnetism of the Neoproterozoic St Simeon dolerite dykes, Quebec: an eastern Laurentian perspective of Ediacaran Rodinia breakup **S.A. Pisarevsky**, J.B. Murphy, M. Hamilton, U. Söderlund and J. Hodych Lithospheric mantle heterogeneities within the Tibetan Plateau: Results from a geophysical-petrological approach L. Tunini, I. Jimenez-Munt, M. Fernandez and **J.C. Afonso** The post-collisional stage of the Yenisey Ridge orogeny (Siberia): geological, geochemical, geochronological and paleomagnetic data V.A. Vernikovsky, A.E. Vernikovskaya, A.Y. Kazansky, N.Y. Matushkin, D.V. Metelkin, I.V. Veyalko, **Z.-X. Li**, **M.T.D. Wingate** and **S. Wilde**

International Workshop in Advanced EBSD Techniques, Wollongong, 3 May 2013	EBSD and Numerical Modelling: Current Status, Challenges and Opportunities **S. Piazolo** **Invited**
5th International Conference on Recrystallization and Grain Growth, Sydney, 5-10 May 2013	Numerical modelling of textures and recrystallization microstructures in ice with insights from in-situ deformation experiments L. Evans, **S. Piazolo**, A. Giera, M. Peternell and C.J.L. Wilson Dynamic recrystallization at high Th: New insights from *in situ* neutron diffraction and see-through experiments of polycrystalline ice **S. Piazolo**, C. Wilson, V. Luzin, C. Brouzet and M. Peternell Effect of temperature on the development of microstructures during and after deformation: In-situ experiments and EBSD, Burgers vector and time lapse analysis **S. Piazolo**, J. Wheeler and M.R. Drury The distinction of grain microstructures formed by triple junction kinetics and grain boundary kinetics: Insights from *in situ* and ex situ experiments in aluminium **S. Piazolo**, V.G. Sursaeva and L. Evans Deformation and recrystallization processes in polycrystalline diamond aggregates: Monitors of mantle processes **S. Piazolo**, **E. Rubanova**, **W. Griffin** and **S.Y. O'Reilly** Deformation and recrystallization of ice using *in situ* experiments C. Wilson, **S. Piazolo**, M. Peternell and V. Luzin
Rodinia 2013: Supercontinent Cycles and Geodynamics Symposium, Moscow State University, Moscow, Russia, 20-24 May 2013	Proterozoic Baltica: major stages of block reorganization and supercontinent reconstruction S.V. Bogdanova, N.V. Lubnina and **S.A. Pisarevsky** **Keynote** Petrology and geochemistry of Proterozoic mafic intrusions in the southern part of the Siberian craton and Proterozoic supercontinents T.V. Donskaya, D.P. Gladkochub, A.M. Mazukabzov, M.N. Shokhonova and **S.A. Pisarevsky** When Siberia broke up from Rodinia? Evidence from detrital zircon geochronology D.P. Gladkochub, **S.A. Pisarevsky**, A.M. Stanevich, T.V. Donskaya and A.M. Mazukabzov New U-Pb age data on detrital zircons from Upper Ediacaran sandstones, south-east White-Sea region: Implications for tectonic models for the Late Ediacaran evolution of the north-eastern margin of the East-European Craton N.B. Kuznetsov, A.S. Alexeev, **E.A. Belousova** and T.V. Romanyuk Neoproterozoic glaciations in a revised global palaeogeography from the breakup of Rodinia to the assembly of Gondwanaland **Z.X. Li**, D.A.D. Evans and G.P. Halverson Australia's 40° twist during Rodinia breakup and a revised Neoproterozoic global palaeogeography **Z.X. Li** and D.A.D. Evans **Keynote** Pre-Rodinian supercontinents: how "super" were they? **S.A. Pisarevsky** **Keynote**
FUTORES Noel White Symposium, Townsville, Queensland, 2-5 June 2013	Intra-plate tectonics and melting processes **W. Gorczyk** and K. Vogt Genesis of porphyry Cu deposits in collisional orogens **Y.-J. Lu**, **R.R. Loucks** and **M.L. Fiorentini** Multiscale structural controls on mineral systems **T.C. McCuaig**
YOM Seismic and MT Workshop, GSWA, June 2013	Numerical modelling of the west Musgrave Province **W. Gorczyk** and H. Smithies

MPE2013 Workshop - Recycling Rocks: Understanding Sustainability in a Dynamic Earth, Melbourne, Australia, 5-16 July, 2013	In-situ studies of granular materials under deformation **S. Clark**, **T. Rushmer**, **B. Colas**, R.L.L. Jones and D.Y. Parkinson **Invited** Coupling global systems in geodynamic earth models **C. O'Neill** **Invited**
GSA Biennial Conference of the Specialist Group in Geochemistry, Mineralogy and Petrology, Mission Beach, Queensland, 14-19 July 2013	Melting mantle migmatites **S.F. Foley**
76th Annual Meeting Of The Meteoritical Society, Edmonton, Canada, 29 July -2 August 2013	Petrology of NWA 7533: Formation by Impacts on Ancient Martian Crust R.H. Hewins, B. Zanda, M. Humayun, J.-P. Lorand, D. Deldicque, S. Pont, C. Fieni, **A. Nemchin**, **M. Grange**, A. Kennedy, C. Göpel and E. Lewin The Age and Composition of the Martian Crust from NWA 7533 M. Humayun, **A. Nemchin**, **M. Grange,** A. Kennedy, B. Zanda, R.H. Hewins, J.-P. Lorand, C. Göpel, E. Lewin, S. Pont and D. Deldicque U-Pb Ages and Compositions of Apollo 14 Regolith Glasses M.D. Norman, **A.A. Nemchin**, **M.L. Grange**, R.A. Zeigler, M.J. Whitehouse, J.R. Muhling and R.E. Merle
12th SGA Biennial Meeting, Uppsala, Sweden, 12-15 August 2013	Compositional diversity in chromitites from Eastern Rhodopes (SE Bulgaria): petrogenesis and tectonic implications **V. Colas,** I. Fanlo, F. Gervilla, **J.M. Gonzalez-Jimenez** and T. Kerestedjian Multistage mineralization of the giant Obuasi gold deposit, Ghana **D. Fougerouse,** S. Micklethwaite, J. Miller, **T.C. McCuaig** and S. Ulrich Sulfur degassing and nickel sulfide ore forming process in Archean komatiite volcanoes **C. Isaac**, **M.L. Fiorentini** and B. Wing The chromite-bearing ultramafic-mafic complexes of the Vizcaíno Peninsula (Baja California Sur, Mexico), revisited for platinum-group minerals L.A. Jimenez-Galindo, **J.M. Gonzalez-Jimenez**, A. Camprubi, M. Martini, E. Centeno-Garcia, J.A. Proenza, **W.L. Griffin**, **S.Y. O'Reilly** and **N.J. Pearson** Ore dating by Shrimp II proxy analyses, Fe-Ni-Cu-PGE sulphide deposits, Ivrea Verbano Zone, Northern Italy P. Kollegger, **M.L. Fiorentini,** F. Zaccarini, G. Garuti and O.A.R. Thalhammer Potential role of a buoyant CO_2 vapour phase in the formation of the Mount Isa copper ore deposit M. Kühn and **K. Gessner** Hydrothermal footprints around magmatic nickel-sulfide deposits: a case study at the Miitel deposit, Yilgarn craton, Western Australia **M. Le Vaillant**, **M.L. Fiorentini**, J. Miller, S.J. Barnes and D. Paterson Structural framework and evolution of the world class Siguiri orogenic gold district (Guinea, West Africa) E. Lebrun, J. Miller, N. Thébaud, **T.C. McCuaig** and S. Ulrich Geology, geochemistry and petrogenesis of the Twin Bonanza intrusion-related gold deposit: Implications for a post-collisional lithospheric mantle source for the Granites-Tanami gold province, North Australian Craton **B. Li**, **L. Bagas** and **T.C. McCuaig** Zircon multi-isotopic mapping in Wabigoon Subprovince, western Superior Craton: Implications for lithospheric architecture and controls on orogenic gold mineral systems **Y.-J. Lu**, **T.C. McCuaig**, P. Hollings, K. Ketchum, **R. Kerrich**, M. Smyk, **J. Cliff** and **L. Bagas** Genesis of fertile hydrous adakite-like melts in post-subduction porphyry Cu systems of Tibet **Y.-J. Lu**, **R.R. Loucks** and **M.L. Fiorentini** Structural setting and mineralisation of the carbonate hosted Sadiola gold deposit, Mali, West Africa **Q. Masurel**, J. Miller, N. Thébaud, **T.C. McCuaig** and S. Ulrich

12th SGA Biennial Meeting, Uppsala, Sweden, 12-15 August 2013 *cont...*	The orogenic gold mineral system **T.C. McCuaig** and **J.M.A. Hronsky** **Keynote** Intra-cratonic architecture and the localisation of mineral systems **D. Mole**, **M. Fiorentini**, N. Thébaud, **T.C. McCuaig**, K. Cassidy, **C. Kirkland**, S. Romano, M. Doublier, **E. Belousova** and S. Barnes Crust-mantle interaction and genesis of the Kidston goldrich breccias pipe deposit in north-east Australia: U–Pb, Hf and Os isotope evidence V. Murgulov, **W.L. Griffin** and **S.Y. O'Reilly** Age constraints on host rocks for gold mineralisation in the Ashanti Belt, Ghana **L.A. Parra**, **M.L. Fiorentini**, J. Miller, **T.C. McCuaig**, Y. Bourassa and S. Perrouty The orogenic and not so orogenic gold deposits of the Agnew Gold Camp (Yilgarn Craton, Western Australia) N. Thébaud, J. Miller, **T.C. McCuaig**, L. Fisher and I. Sonntag Origin of Bushveld magmas via new constraints from Pb-Hf zircon systematic M. Yudovskaya, J. Kinnaird, **E. Belousova**, **N. Pearson**, J. Kramers and D. Kuzmin Platinum group elements and Re minerals in the magmatic Ni-Fe-Cu sulfide deposits of the Ivrea Verbano Zone (Italy) F. Zaccarini, G. Garuti, **P. Kollegger**, O.A.R. Thalhammer and **M. Fiorentini**
Goldschmidt 2013 Conference, Florence, Italy, 25-30 August 2013	Crystal/melt partitioning of volatiles during near-solidus melting of peridotite **J. Adam**, M. Turner, E. Hauri and **S. Turner** Multi-observable thermochemical tomography: A new framework in integrated studies of the lithosphere **J.C. Afonso**, J. Fullea, J. Connolly, N. Rawlinson, **Y. Yang** and A.G. Jones **Invited** Trace elements in olivine characterize the mantle source of subduction related potassic magmas E. Ammannati, **S.F. Foley**, R. Avanzinelli, **D.E. Jacob** and S. Conticelli Time-related changes in the Si-isotopic composition of Palaeo- to Mesoarchaean granitoids K. Abraham, **S.F. Foley**, A. Hofmann, D. Cardinal, L. André Ancient fragments in the subcontinental lithospheric mantle beneath the Carpathian-Pannonian Region L.E. Aradi, C. Szabó, **J.-M. González-Jiménez**, **W. Griffin**, **S.Y. O'Reilly** and K. Hattori U-Pb and Hf isotope characteristics of zircon from chromitites at Finero I.Yu. Badanina, K.N. Malitch and **E.A. Belousova** Archean andesites as products of plume/crust interaction? S.J. Barnes, **C. Isaac** and **M.L. Fiorentini** Ore deposits and lithosphere evolution in the early Earth G.C. Begg, **W.L. Griffin**, **S.Y. O'Reilly** and **J.M.A. Hronsky** **Keynote** New insights into the history of an ophiolite from zircons **E.A. Belousova**, **J.M. González-Jiménez**, I.T. Graham, **W.L. Griffin** and **S.Y. O'Reilly** Assimilation of sediments embedded in the oceanic arc crust: myth or reality? **R. Bezard**, J.P. Davidson, **S. Turner**, C.G. Macpherson, J.M. Lindsay and A.J. Boyce Zircon from Mesoarchean enderbites of Volgo-Uralia: U-Pb age, REE, Hf and O-isotope compositions S.V. Bogdanova, **E.A. Belousova**, B. De Waele and A.V. Postnikov Lithium isotopic composition of the Tonga-Kermadec arc and its constraints on subduction recycling **R. Brens Jr**., X.-M. Liu, R. Rudnick, **S. Turner** and **T. Rushmer** Evidence of sulfur degassing in komatiite-hosted Ni-PGE ores S. Caruso, M. Moroni, **C. Isaac**, **M.L. Fiorentini**, S.J. Barnes, B. Wing and **J. Cliff** U-Pb geochronology and source constraints for late S-type Variscan magmatism related to Sn-W metallogeny: The Logrosán granite pluton (Central Iberian Zone) E. Chicharro, C. Villaseca, P. Valverde-Vaquero, **E. Belousova** and J.A. López-García The Gangdese batholith, southern Tibet is the largest of the Transhimalayan batholiths produced by the Neo-Tethyan subduction M.-F. Chu, S.-L. Chung, X.-H. Li, H.-Y. Lee and **S.Y. O'Reilly** Garnet, zircon and monazite as monitors of high-temperature metamorphic events: How useful are they? **C. Clark**

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$^{16}O^{1}H$ signal as an indication of metamict O-contamination in zircon
J. Cliff, **R.T. Pidgeon** and **A.A. Nemchin**

Trace-element fingerprints of chromites link ultramafic massifs of the Bulgarian Rhodopes
V. Colas, **J.M. González-Jiménez**, I. Fanlo, W.L. Griffin, F. Gervilla, **S.Y. O'Reilly**, **N.J. Pearson** and T. Kerestedjian

Sr-Nd-Hf-Pb isotope mapping of Tien Shan in Uzbekistan
A. Dolgopolova, R. Seltmann, R. Armstrong, **E. Belousova**, R. Pankhurst, D. Konopelko and R. Koneev

A comparison of shocked zircon and quartz from the Reis impact structure, Germany
T.M. Erickson, **S.M. Reddy**, N.E. Timms and **A.A. Nemchin**

Li isotopes in zircon: Effects of Li substitution and kinetic fractionation
Y.-Y. Gao, X.-H. Li, **W.L. Griffin**, **S.Y. O'Reilly** and **N.J. Pearson**

Constraining the nature of the western Azores mantle source using Pb-Hf-Os isotope systematics
F.S. Genske, C. Beier, **S.P. Turner**, A. Stracke and K.M. Haase

On the origins of Platinum-Group Minerals in ophiolitic chromitites
F. Gervilla, **W.L. Griffin**, **J.M. González-Jiménez**, J.A. Proenza, **S.Y. O'Reilly** and **N.J. Pearson**

Direct observations of structures developed on fluorite surfaces after contact with an aqueous solution
J.R.A. Godinho, C.V. Putnis and **S. Piazolo**

Neo-Archean domains in the Mediterranean and their implications
J.M. González-Jiménez, C. Villaseca, **W.L. Griffin**, **E. Belousova**, Z. Konc, E. Ancochea, **S.Y. O'Reilly**, **N.J. Pearson**, C.J. Garrido and F. Gervilla

Intra-Plate tectonics and magmatisim as a consequence of mantle lithosphere delamination
W. Gorczyk, K. Vogt, K. and B. Hobbs

A Second Lunar Magma Ocean?
M. Grange and **A. Nemchin**

Going up or going down? Diamonds and Super-Reducing UHP assemblages in ophiolitic mantle
W.L. Griffin, J.S. Yang, P. Robinson, **D. Howell**, R.D. Shi, **S.Y. O'Reilly** and **N.J. Pearson**

"*Garnet signature*" systematics and the structure of oceanic lithosphere
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**, C. Macpherson and R. Gertisser

Nitrogen isotope systematics and origins of mixed-habit diamonds
D. Howell, R.A. Stern, **W.L. Griffin**, R. Southworth, S. Mikhail, T. Stachel, A.B. Verchovsky, A.P. Jones, **S.Y. O'Reilly** and **N.J. Pearson**

Unmasking enigmatic xenolithic eclogites: Progressive metasomatism on a key Roberts Victor sample
J.-X. Huang, **W.L. Griffin**, **Y. Greau**, **N.J. Pearson** and **S.Y. O'Reilly**

Deformation mechanisms in Martian Shergottites
M.-A. Kaczmarek, **M. Grange**, **S.M. Reddy** and **A. Nemchin**

High-resolution imaging and quantification of Au in sulphide minerals using NanoSIMS
M.R. Kilburn and R. Liu

Ancient mobilisation of radiogenic Pb and Ti during high-grade metamorphism
M.A. Kusiak, M.J. Whitehouse, **S.A. Wilde**, D.J. Dunkley, **A.A. Nemchin**, R. Wirth and K. Marquardt

Mass Transfer of Fluids and Metals in the Deep Earth
M. Locmelis, **M.L. Fiorentini**, **T. Rushmer**, **J. Adam**, F. Zaccarini, G. Garuti, M. Turner and **S. Turner**

Distinctive Composition and Genesis of Copper Ore-forming Arc Magmas
R.R. Loucks

Speciation and thermodynamic properties of palladium chloride and bisulfide complexes: insights from experiments and ab-initio molecular dynamics simulations
Y. Mei, T.M. Seward, J. Brugger, S.J. Barnes and **M.L. Fiorentini**

Crustal sources of peraluminous granites: the Montes de Toledo batholith, Iberian Hercynian Belt
E. Merino, C. Villaseca, C. Pérez-Soba, D. Orejana, **E. Belousova** and T. Andersen

Rates of Natural silica precipitation through time
R. Merle, **A. Nemchin**, S. Simons, F. Tomaschek and T. Geisler

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Trace-element fingerprints of chromites and sulfides from the Archean Nuggihalli greenstone belt, western Dharwar craton, India
R. Mukherjee, S.K. Mondal, **J.M. González-Jiménez**, **W.L. Griffin**, **N.J. Pearson** and **S.Y. O'Reilly**

Stabilising a craton: The 3.1 Ga Mpuluzi batholith (Swaziland / RSA)
R.C. Murphy, **W.L. Griffin**, **N.J. Pearson** and **S.Y. O'Reilly**

Fractionation of $^{238}U/^{235}U$ by reduction during low T uranium mineralisation processes
M.J. Murphy, C.H. Stirling, A. Kaltenbach, **S.P. Turner** and **B.F. Schaefer**

Crustal recycling during the Neoarchaean; SE Greenland
T. Næraa and **L. Bagas**

Zircon U-Pb-ages, Hf isotope and trace element composition in the evolution of the IVAC Complex (Urals, Russia)
I.L. Nedosekova, **E.A. Belousova**, B.V. Belyatsky and **N. Pearson**

What does Hadean mantle mixing tell us about Hadean geodynamics?
C. O'Neill, V. Debaille and **W.L. Griffin**

Archean lithospheric mantle: The fount of all ores?
S.Y. O'Reilly, **W.L. Griffin**, G.C. Begg, **N.J. Pearson** and **J.M.A. Hronsky** **Invited**

The Thrym Complex of southeastern Greenland: Evolution of Ni-Cu-Sulfide mineralization in the lower crust
J. Owen, **L. Bagas**, **J. Kolb**, **M.L. Fiorentini**, B.M. Stensgaard and N. Thébaud

Mafic potassic volcanics from the Altiplano, South America: indication of a dynamic A-type magma source under construction?
M.J. Pankhurst, **B.F. Schaefer** and **S.P. Turner**

New Zircon U-Pb and Hf-isotope data of the Birimian Terrane of the West African craton
L.A. Parra, **M.L. Fiorentini**, **E. Belousova**, A.I.S. Kemp, J. Miller, **T.C. McCuaig** and N. Said

A forward modelling approach to understanding continental growth
J.L. Payne, K.M. Barovich, **N.J. Pearson** and M. Hand

The hole story about laser ablation ICP-MS
N.J. Pearson, **W.J. Powell**, K.J. Grant, J.L. Payne, **R.C. Murphy**, **E. Belousova**, **W.L. Griffin** and **S.Y. O'Reilly** **Invited**

On the hunt for a Gondwanan suture zone in South India
D. Plavsa, A.S. Collins, J.F. Foden, **C. Clark** and M. Santosh

Os-isotope constraints on the dynamics of orogenic mantle: the case of central Balkans
D. Prelevic, G. Brugmann, M. Barth, M. Bozovic, V. Cvetkovic and **S.F. Foley**

Growth medium and carbon source of unusual rounded diamonds from alluvial placers of the North-East of Siberian Platform
A.L. Ragozin, V.S. Shatsky, D.A. Zedgenizov and **W.L. Griffin**

Origin of Earth's Earliest Continental Crust: A Combination of Partial Melting and Fractional Crystallization?
T. Rushmer and **J. Adam**

Heterogeneity of the uppermost mantle in back-arc settings: Insights from trace-element compositions and water contents in Japanese peridotite xenoliths
T. Satsukawa, M. Godard, S. Demouchy and K. Michibayashi

Mobility of Au in the mantle
J.E. Saunders, **N.J. Pearson**, **S.Y. O'Reilly** and **W.L. Griffin**

A Pilot Br Isotopic Study of Arid Playa Lakes and Ordinary Chondrites
B.F. Schaefer

Geodynamic constraints on the recycling of ancient SCLM and genesis of Tibetan diamondiferous ophiolites
R.D. Shi, **W.L. Griffin**, **S.Y. O'Reilly**, X.R. Zhang, Q.S. Huang, X.H. Gong and L. Ding

Timing of ultra-high temperature (UHT) metamorphism and formation of incipient charnockites in the Kerala Khondalite Belt (KKB), southern India
R. Taylor, **C. Clark** and **I.C.W. Fitzsimons**

Extremely young melt infiltration of the continental lithospheric mantle
S. Turner and M. Turner

Recycling of water between the mantle and crust/hydrosphere
M. Turner, **S. Turner**, T. Ireland and **J. Adam**

Goldschmidt 2013 Conference, Florence, Italy, 25-30 August 2013 *cont...*	Tomography at Single-Atom Scale of ^{207}Pb and ^{206}Pb in a 4374 Ma Zircon J.W. Valley, T. Ushikubo, A.J. Cavosie, D.A. Reinhard, D. F. Lawrence, I. Martin, D.J. Larson, P.H. Clifton, T.F. Kelly, **S.A. Wilde**, D.E. Moser and M.J. Spicuzza Microstructural control on trace element diffusion in pyrrhotite from komatiite hosted massive Ni sulphides, Yilgarn Craton **Z. Vukmanovic**, **S.M. Reddy**, B. Godel, S.J. Barnes, **M.L. Fiorentini** and S.-J. Barnes Geochemistry and nano-structure of putative filamentous microbes from the 3.24 Ga Sulfur Springs Group, Pilbara, Western Australia **D. Wacey**, M. Saunders, **M.R. Kilburn**, **J.B. Cliff**, C. Kong and **M.E. Barley** Geochemical fingerprints in Siberian mantle xenoliths reveal progressive erosion of an Archean lithospheric root K.-L. Wang, Y.-H. Chien, M.I. Kuzmin, **S.Y. O'Reilly**, **W.L. Griffin**, A. Vorontsov and **N.J. Pearson** Lawsonite as a potential repository of Th and REE in subduction zones: Blueschists from Tavsanlı (Turkey) **Y. Wang**, D. Prelevic, **S. Foley**, S. Buhre, T. Johnson and T. Häger Diamond-forming fluids: The trace-element perspective Y. Weiss, **W.L. Griffin** and O. Navon Delamination of the North China Craton: A widespread phenomenon or a one-off situation? **S.A. Wilde** Multistage refertilization of an Archean peridotite massif, N. Qaidam orogen (NE Tibet, China) **Q. Xiong**, **S.Y. O'Reilly**, **W.L. Griffin**, **N.J. Pearson** and J.-P. Zheng Parental growth media of Siberian diamonds – Relation to kimberlites D.A. Zedgenizov, A.L. Ragozini, V.S. Shatsky and **W.L. Griffin**
Building Strong Continents, Metamorphic Studies Group, University of Portsmouth, UK, 2-4 September 2013	Crustal recycling during the Neoarchaean; SE Greenland T. Næraa and **L. Bagas**
The Electron Microscopy and Analysis Group Conference, York, UK, 3-6 September 2013	Electron microscopy reveals unique microfossil preservation in 1 billion-year-old lakes M. Saunders, C. Kong, S. Menon and **D. Wacey**
6th International Symposium on Hydrocarbon Accumulation Mechanisms and Petroleum Resources Evaluation, Beijing, PR China, 26-28 September 2013	Re-Os dating of the Shengli River marine oil shale, North Tibet: A development method for direct dating crude oil. **X.-C. Wang** and J. Li **Invited**
19th International Conference on Deformation Mechanisms, Rheology and Tectonics, Leuven, Belgium, 16-18 September 2013	Microstructural evolution of polycrystalline ice using *in situ* deformation experiments and FAME M. Peternell, C.J.L. Wilson, M. Dierckx, D.M. Hammes and **S. Piazolo** **Keynote** Dynamics of ice mass deformation: Linking processes to rheology, texture and microstructure **S. Piazolo**, C.J.L. Wilson, V. Luzin, C. Brouzet and M. Peternell Melt migration in the lower crust by melt induced fracturing and reaction: insights from field studies combined with numerical modelling **S. Piazolo**, D. Koehn, A. Vass and **N. Daczko** The role of reaction progression and annealing on shear localization: Initiation of paired shear zones in the lower crust of Fiordland, New Zealand **S. Piazolo**, J. Smith, **N. Daczko**

19th International Conference on Deformation Mechanisms, Rheology and Tectonics, Leuven, Belgium, 16-18 September 2013 *cont...*	Rheology of Dirty Ice: First Results and Future Perspectives **S. Piazolo**, C.J.L. Wilson, V. Luzin, C. Brouzet and M. Peternell **Invited** Natural constraints on the dynamics of the uppermost mantle evolution during the initial stage of back-arc spreading **T. Satsukawa**, T. Mizukami and T. Morishita
13th Australian Space Science Conference, Sydney, 30 September - 2 October 2013	The tectonics of exoplanets **C. O'Neill** **Keynote** Venusian Admittance and Correlation: Clues to Topographic Compensation Mechanisms and Mantle Dynamics **E. Schinella** and **C. O'Neill**
International Meeting on Precambrian Evolution and Deep Exploration of the Continental Lithosphere, Beijing, PR China, 6-9 October 2013	The World Turns Over: Hadean – Archean crust-mantle evolution **W.L. Griffin**, **E. Belousova,** V. Malkovets, Z. Spetsius, **S.Y. O'Reilly**, **N.J. Pearson** and others **Keynote** Spurious ages and ancient mobilisation of radiogenic Pb and Ti in zircons from the Napier Complex, Antarctica **M. Kusiak**, M.J. Whitehouse, **S.A. Wilde**, D.J. Dunkley, **A. Nemchin**, R. Wirth and K. Marquardt Was Earth stagnant in the Hadean? **C. O'Neill**, V. Debaille and **W.L. Griffin** A saga of crust-mantle relationships and evolution since Archean times: Geophysical and geochemical evidence tracked in mantle xenoliths from Arctic Norway and Cape Verde (Atlantic Ocean) **S.Y. O'Reilly**, **W.L. Griffin**, **N.J. Pearson** and G. Begg **Keynote** Thirty years of progress in Precambrian paleomagnetism and continental reconstructions **S. Pisarevsky** **Invited** What do we really know about conditions in the Hadean? **S. Wilde**
The GSA 125th Anniversary Annual Meeting and Expo, Denver, Colorado, USA, 27-30 October 2013	Solving CCW granulite–UHT metamorphism: a model for the tectonic evolution of the Eastern Ghats Province, India–Rayner Province, East Antarctica M. Brown, **C. Clark** and F.J. Korhonen Peridotite-pyroxenite relationships in orogenic peridotites from Liverpool Land, Eastern Greenland caledonides: chemical metasomatism or mechanical mixing? H. Brueckner, L.G. Medaris Jr., **W.L. Griffin**, S.M. Johnston, R. Bubbico and E.H. Hartz Establishing peak temperature in UHT metamorphic terranes **C. Clark**, M. Brown, F.J. Korhonen and R. Taylor Multiple melting events in polycyclic high-T terranes defined using geochemically constrained dating of zircon and monazite N.M. Kelly, J.A. Matthews, A.R.C. Kylander-Clark, A.E. Koenig, S.L. Harley and **C. Clark** Is plate tectonics a phase in the evolution of Earth-like planets? **C. O'Neill** **Invited** Development of regional stratigraphic frameworks and geological implications in Upper Devonian carbonates using integrated chronostratigraphy, Canning Basin, Western Australia T.E. Playton, D.A. Katz, K. Hillbun, E. Tohver, R. Hocking, P. Haines, K. Trinajstic, P. Montgomery, J. Hansma and **S.A. Pisarevsky** Rare earth element behavior in orthopyroxene, zircon and garnet during UHT metamorphism R. Taylor, **C. Clarke** and **I.C.W. Fitzsimons**
ICE Microstructure, Rheology and Physical Properties, University of Otago, Dunedin, NZ, 29-30 October 2013	Dynamics of ice mass deformation: Linking processes to rheology, texture and microstructure **S. Piazolo**, C.J.L. Wilson, V. Luzin, C. Brouzet and M. Peternell Numerical simulation of ice processes **S. Piazolo** **Invited** Rheology of Dirty Ice: First Results and Future Perspectives **S. Piazolo**, C.J.L. Wilson, V. Luzin, C. Brouzet and M. Peternell **Invited**

IGCP581 4th Annual Meeting, Hanoi, Vietnam, 10-15 November 2013	A thermochronological record of vertical tectonic movements in southern South China since the Mesozoic **N. Tao**., **Z.-X. Li**, M. Danišík, N.J. Evans, Y.G. Xu, W.X. Li and C.J. Pang South China's connection with North India in Gondwanaland – Basin and detrital provenance analyses W.H. Yao, **Z.-X. Li**, W.X. Li, X.H. Li and J.H. Yang
Swiss Geosciences Meeting, Lausanne, Switzerland, 15-16 November 2013	Deformation mechanisms in Martian meteorites **M.-A. Kaczmarek**, **M. Grange**, **S. Reddy** and **A. Nemchin**
AGU Fall Meeting, San Francisco, USA, 9-13 December 2013	The compositions of hydrous fluids in equilibrium with the Peridotitic Mantle **J. Adam**, **M. Locmelis**, **M. Fiorentini** and **T.A. Rushmer** Multi-observable thermochemical tomography of the lithosphere and upper mantle beneath the Western/Central US **J.C. Afonso**, **Y. Yang**, N. Rawlinson, D. Schutt, J. Fullea and A.G. Jones Lower crustal assimilation in oceanic arcs: insights from an osmium isotopic study of the Lesser Antilles **R.C. Bezard**, **B.F. Schaefer**, **S. Turner**, J. Davidson and D.S. Selby Constructing a starting 3D shear velocity model with sharp interfaces for SEM-based upper mantle tomography in North America M. Calo, T. Bodin, **H. Yuan**, B.A. Romanowicz, C.S. Larmat and M. Maceira Decarbonation and carbonation processes in the slab and mantle wedge – insights from thermomechanical modeling C.M. Gonzalez, **W. Gorczyk**, J.A. Connolly, T. Gerya, B.E. Hobbs and A. Ord Majorite Garnet and Lithosphere Evolution: Kaapvaal Craton **W.L. Griffin**, S. Tessalina and **S.Y. O'Reilly** **Invited** Garnet Signatures in Geophysical and Geochemical Observations: Insights into the Thermo-Petrological Structure of Oceanic Upper Mantle **C.J. Grose** and **J.C. Afonso** Molecular marker and stable carbon isotope analyses of carbonaceous Ambassador uranium ores of Mulga Rock in Western Australia C. Jaraula, L. Schwark, X. Moreau, K. Grice and **L. Bagas** The crustal structure in north Tibet revealed by joint inversion of receiver functions and ambient noise tomography: implications for the growth of the Tibetan Plateau **C. Jiang**, **Y. Yang** and Y. Zheng Fluid percolation within an ocean-continent transition **M.-A. Kaczmarek** and **S.M. Reddy** Isotropic and anisotropic shear velocity model of the NA upper mantle using EarthScope data J. Leiva, P. Clouzet, S.W. French, **H. Yuan** and B.A. Romanowicz Upper Mantle Texture Patterns In Eastern North America From Seismic Anisotropy And Global Mantle Flow Calculations V.L. Levin, R. Moucha and **H. Yuan** The effect of grain boundary sliding on the rheology of polymineralic rocks: Nature and numerical experiments J.M. Nevitt, **S. Piazolo**, L. Evans and V.G. Toy Was the Hadean Earth stagnant? Constraints from dynamic mixing models **C. O'Neill**, V. Debaille and **W.L. Griffin** Geochemical Evolution of cratonic lithospheric mantle: A 3.6 Ga story of persistence and transformation **S.Y. O'Reilly**, **W.L. Griffin** and **N.J. Pearson** **Invited** Developing and testing models for creep of polycrystalline ice: new laboratory approaches D.J. Prior, T.E. Caswell, W.B. Durham, N. Golding, D.L. Goldsby, K. Lilly, **S. Piazolo,** M. Seidemann, M. Vaughan and C. Wilson Source stacking for numerical wavefield computations: application to continental and global scale seismic mantle tomography B.A. Romanowicz, S.W. French, F. Rickers and **H. Yuan**

AGU Fall Meeting, San Francisco, USA, 9-13 December 2013 *cont...*

Chondrules as Natural Analogs for Metal Segregation: Analyses from 3D Synchrotron Imaging
T.A. Rushmer, **S.M. Clark** and D. Parkinson

An N-TIMS Br Isotopic Study of Australian Playa Lakes
B.F. Schaefer

From Gabbro to Granulite to Kyanite- and bimineralic Eclogite: A petrological, geochemical and mass balance approach to mantle eclogites
H. Sommer and **D. Jacob**

Looking at the roots of the highest mountains: the lithospheric structure of the Himalaya-Tibet and the Zagros orogens. Results from a geophysical-petrological study
L. Tunini, I. Jimenez-Munt, M. Fernandez, A. Villasenor, **J.C. Afonso** and J. Verges

Mantle flow, volatiles, slab-surface temperatures and melting dynamics in the north Tonga Arc – Lau Backarc Basin
S. Turner, J. Caulfield, R.J. Arculus, C.W. Dale, F.E. Jenner, J.A. Pearce, C. Macpherson and **H.K. Handley**

Interactions among plumes, mantle circulation and mid-ocean ridges
J.M. Whittaker, S. Williams, S.M. Masterton, **J.C. Afonso**, M. Seton, T.C. Landgrebe, M.F. Coffin and D. Müller

Modelling terrestrial planet evolution with practical mineral physics and mantle-core coupling
S. Zhang and **C. O'Neill**

Imaging lithosphere structures using long period surface waves from ambient noise: a case study in western USA
Y. Yang

The collision of South China with NW India to join Gondwanaland in the Cambrian: Provenance constraints from foreland basins
W. Yao, **Z.-X. Li**, W. Li, X.-H. Li and J. Yang

Azimuthal anisotropy layering in the Pacific upper mantle
H. Yuan, S.W. French and B.A. Romanowicz

Evidence for large sulfur isotope fractionation in carbonate hosted Neoarchean pyrites
I. Zhelezinskaia, A.J. Kaufman, J. Farquhar and **J. Cliff**

Appendix 7: CCFS visitors & GAU users

CCFS VISITORS 2013
(Excluding participants in conferences and workshops)

Macquarie

VISITOR	ORGANISATION	COUNTRY
Associate Professor Mehmet Akbulut	Department of Geological Engineering, Dokuz Eylül University	Turkey
Dr Aharon Arakel	Geo-Processors USA, Inc	USA
Dr Inna Badanina	A.N. Zavaritsky Institute of Geology and Geochemistry	Russia
Mr Jamie Barbula	Photon Machines Inc, Bozeman, MT	USA
Dr Graham Begg	Minerals Targeting International Pty Ltd, West Perth, WA	Australia
Ms Montgarri Castillo	Dept. of Crystallography, Mineralogy and Ore Deposits, Universitat de Barcelona	Spain
Mr Mark Chandler	Nu Instruments, Wrexham	UK
Professor Geoff Clarke	University of Sydney	Australia
Ms Vanessa Colas	Departamento Ciencias de la Terra, University of Zaragoza, Zaragoza	Spain
Professor Rhodri Davies	Research School of Earth Sciences, Australian National University	Australia
Dr Guillaume Duclaux	Minerals Down Under Flagship, Earth Science and Resource Engineering, CSIRO	Australia
Professor Manel Fernandez	Institute of Earth Sciences Jaume Almera - CSIC, Barcelona	Spain
Dr Javier Fullea	Dublin Institute of Advanced Studies, Institute of Geosciences (IGEO) CSIC-UCM, Madrid	Ireland/Spain
Professor Joseph Hamilton	Lithicon	Australia
Professor Dan Harlov	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum - GFZ	Germany
Dr Christian Heine	School of Geosciences, University of Sydney	Australia
Dr Su Hongtao	Vice Head of Overseas Graduate Education Dept, China University of Geosciences	PR China
Ms Tracy Howe	University of Auckland	New Zealand
Dr Huiqing Huang	University of Newcastle	Australia
Mr Ray Jones	Photonics Group, Daresbury Labs (retired)	UK
Dr Vadim Kamenetsky	CODES, University of Tasmania	Australia
Dr Penny King	Research School of Earth Sciences, Australian National University, ACT	Australia
Professor Stephan Klemme	Institut für Mineralogie, University of Münster	Germany
Dr Giampiero Laffaldano	Research School of Earth Sciences, Australian National University, ACT	Australia
Dr Miak Lang	University of Michigan	USA
Professor Nick Petford	Vice-Chancellor, University of Northampton	UK
Dr Narong Praphairaksit	Gem and Jewelry Institute of Thailand	Thailand
Professor Kreshmir Malitch	A.N. Zavaritsky Institute of Geology and Geochemistry, Uralian Division of Russian Academy of Sciences	Russia
Professor Vladimir Malkovets	Pheasant Memorial Laboratory, Institute for Study of the Earth's Interiors, Okayama University, Misasa	Japan
Dr Li Menlou	Head of Education, Dept Graduate School, China University of Geosciences	China
Ms Thiodarat Muangthai	Gem and Jewelry Institute of Thailand	Thailand
Professor Hans-Joachim Müller	Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum, Potsdam	Germany
Mr Jose Alberto Padron Navarta	Research School of Earth Sciences, Australian National University, and Montpellier	Austrailia/ France

	VISITOR	ORGANISATION	COUNTRY
Macquarie	Dr Paula Piilonen	Mineral Sciences, Canadian Museum of Nature, Ottawa	Canada
Macquarie	Associate Professor Patrice Rey	School of Geosciences, University of Sydney	Australia
Macquarie	Dr Wolfgang Roehr	University of Hamburg	Germany
Macquarie	Dr Chris Ryan	CSIRO and University of Melbourne	Australia
Macquarie	Dr Tristan Salles	Minerals Down Under Flagship, Earth Science and Resource Engineering, CSIRO	Australia
Macquarie	Dr Simon Shee	Independent Mining and Metals Professional, Melbourne	Australia
Macquarie	Dr Zdislav Spetsius	Geology of Diamond Deposits, NIGP Alrosa Co Ltd	Russia
Macquarie	Dr Koya Suto	Terra Australis Geophysica Pty Ltd	Australia
Macquarie	Dr Huayun Tang	Earth Sciences, China University of Geoscience	PR China
Macquarie	Dr Kuo-Lung Wang	Institute of Earth Sciences Academia Sinica, Taipei	Taiwan
Macquarie	Professor Yanzhang Wang	College of Instrumentation and Electrical Engineering, Jilin University	PR China
Macquarie	Dr Fred Watson	Astronomer-in-Charge, Australian Astronomical Observatory	Australia
Macquarie	Professor Rudy Wenk	Dept of Earth and Planetary Sciences, University of California, Berkeley	USA
Macquarie	Mr Jun Xie	University of Science and Technology of China, Hefei	PR China
Macquarie	Professor Shengbao Yu	College of Instrumentation and Electrical Engineering, Jilin University	PR China
Macquarie	Professor Jianping Zheng	State Key Lab of Geological Process & Mineral Resources, China University of Geosciences	PR China
Macquarie	Associate Professor Song Zhiguang	State Key Lab of Organic Geochemistry, Guangzhou Institute of Geochemistry, CAS	PR China
Macquarie	Associate Professor Sergio Zlotnik	LaCaN, Tech, University of Catalonia, Barcelona	Spain
University of Western Australia	Professor Hooshang Asadi	Iran and Mining Department, Isfahan University of Technology	Iran
University of Western Australia	Dr Steve Barnes	CSIRO, Kensington, WA	Australia
University of Western Australia	Dr Graham Begg	Minerals Targeting International, West Perth, WA	Australia
University of Western Australia	Dr Martin Bromann Klausen	Department of Earth Sciences, University of Stellenbosch	South Africa
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	Professor David Groves	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, WA	Australia
University of Western Australia	Dr Julie Hollis	Geological Survery 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 Allan Jones	School of Cosmic Physics, Dublin	Ireland
University of Western Australia	Dr Asko Käpyaho	Geologian tutkimuskeskus, GTK (Senior Scientist, Geological Survey of Finland)	Finland
University of Western Australia	Mr Peter Kollegger	University of Leoben, Leoben	Austria
University of Western Australia	Dr David Leach	U.S. Geological Survey (USGS)	USA
University of Western Australia	Dr Robert Loucks	Geoscience Research	USA
University of Western Australia	Dr Tomas Næraa	Department of Geology, Lund University	Sweden
University of Western Australia	Dr Bo Møller Stensgaard	Dept. Petrology & Economic Geology, Geol. Survey of Denmark & Greenland (GEUS)	Denmark

	VISITOR	ORGANISATION	COUNTRY
UWA	Dr Franco Pirajno	University of Western Australia, Faculty of Science, Crawley, WA	Australia
	Dr Andrew Rate	University of Western Australia, Faculty of Science, Crawley, WA	Australia
	Professor Thomas Seifert	Technical University Bergakademie Freiberg, Freiberg	Germany
	Mr Herbert Siegmund	International Atomic Energy Agency	Austria
	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	Research School of Earth Sciences, Australian National University, ACT	Australia
	Dr Svetlana Tessalina	Department of Applied Geology, Curtin University, Bentley, WA	Australia
	Dr Nick Timms	Department of Applied Geology, Curtin University, Bentley, WA	Australia
	Dr Ian Tyler	Geological Survey of Western Australia, East Perth, WA	Australia
	Professor Dan Wood	University of Queensland, WH Bryan Mining and Geology Research Centre, St Lucia	Australia
	Dr Roberto Xavier	Dept. Geology & Natural Resources, Universidade Estadual de Campinas, São Paulo	Brazil
Curtin	Associate Professor Galen Halverson	Dept of Earth and Planetary Sciences, McGill University	Canada
	Zhiqiang Kang	College of Earth Sciences, Guilin University of Technology	PR China
	Associate Professor Adam Maloof	Department of Geosciences, Princeton University	USA
	Professor Stefano Mazzoli	Dipartimento Scienze della Terra, Università di Napoli Federico II, Naples	Italy
	Dr Touping Peng	Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou	PR China
	Professor Weiguang Zhu	Institute of Geochemistry, Chinese Academy of Sciences, Guiyang	PR China

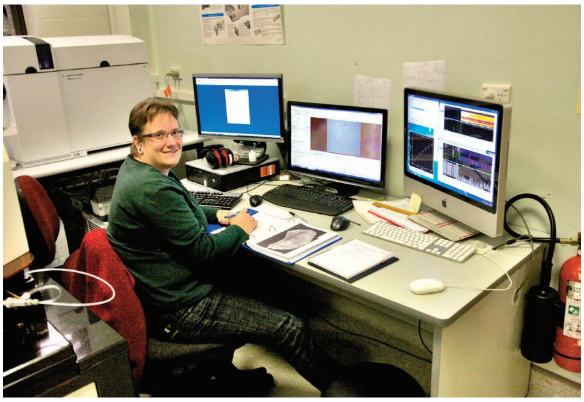
EXTERNAL USERS OF THE GEOCHEMICAL ANALYSIS UNIT FACILITIES IN 2013

(Note: this does not include contract work)

	USER	ORGANISATION	COUNTRY
Macquarie	Dr Mehmet Abulkut	Dept of Geological Engineering, Dokuz Eylul University, Izmir	Turkey
	Dr Chris Adams	Institute of Geological & Nuclear Science, Lower Hutt	New Zealand
	Dr Inna Badanina	A.N. Zavaritsky Institute of Geology and Geochemistry	Russia
	Dr Chris Clark	Curtin University	Australia
	Professor Geoff Clarke	School of Geosciences, University of Sydney	Australia
	Ms Montgarri Castillo Oliver	Faculty of Geology, Barcelona University, Barcelona	Spain
	Mr Tim Chapman	School of Geosciences, University of Sydney (*see photo p 173)*	Australia
	Ms Vanessa Colas	University of Zaragoza	Spain
	Ms Venera Espanon	School of Earth & Environmental Sciences, University of Wollongong	Australia
	Mr Andrea Giuliani	School of Earth Sciences, University of Melbourne	Australia
	Mr Matthew Hill	CET, University of Western Australia, Crawley, WA	Australia
	Ms Tracy Howe	School of Environment, University of Auckland	New Zealand
	Dr Irina Nedosekova	Urals Division of Russian Academy of Science (UDRAS), Ekaterinburg	Russia
	Dr Huiqing Huang	Newcastle Institute for Energy and Resources, University of Newcastle	Australia
	Dr Andrew Lee	Department of Physics and Astronomy, Macquarie University	Australia
	Ms Jocelyn Liu	Department of Physics and Astronomy, Macquarie University	Australia
	Professor Kreshmir Malitch	A.N. Zavaritsky Institute of Geology and Geochemistry	Russia
	Professor Vladimir Malkovets	Pheasant Memorial Laboratory, Institute for Study of the Earth's Interiors, Okayama University, Misasa	Japan

Macquarie

USER	ORGANISATION	COUNTRY
Associate Professor Allan Nutman	University of Wollongong, NSW	Australia
Mr Luis Parra	CET, University of Western Australia, Crawley, WA	Australia
Ms Bernadette Phu	School of Biological, Earth and Environmental Sciences, UNSW, Kensington	Australia
Dr Paula Piilonen	Canadian Museum of Nature, Ottawa	Canada



USER	ORGANISATION	COUNTRY
Ms Adrianna Rajkumar	School of Geosciences, University of Sydney (*see photo below*)	Australia
Dr Phil Schmidt	Independent Consultant, Sydney	Australia
Dr Zdislav Spetsius	Geology of Diamond Deposits, NIGP Alrosa Co Ltd	Russia
Ms Isabella Stephenson	School of Geosciences, University of Sydney	Australia

Adrianna Rajkumar, Isabella Stephenson and Tim Chapman (School of Geosciences, University of Sydney).

USER	ORGANISATION	COUNTRY
Dr Huayun Tang	Earth Sciences, China University of Geoscience	PR China
Ashley Uren	Research School of Earth Sciences, Australian National University, Canberra, ACT	Australia
Dr Kuo-Lung Wang	Academia Sinica, Nankang, Taipei	Taiwan
Dr Kira Westaway	Department of Environment and Geography, Macquarie University	Australia

Appendix 8: Research funding

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
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
Collins, Belousova, Murphy, Hand	ARC Discovery Project	Supercells and the supercontinent cycle	$18,500 ($80,000)
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	$14,000 ($140,000)
Rosenbaum, Pisarevsky, Fielding, Speranza	ARC Discovery Project	Unravelling the geodynamics of eastern Australia during the Permian: the link between plate boundary bending and basin formation	$46,226 ($137,195)
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
Schaefer	ARC Discovery Project	Bromine isotopic evolution of the Earth and solar system	$50,000
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 ($120,000)
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

Investigators	2013 Funding Source	Project Title	Amount
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
Yang	ARC Future Fellowship	How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	$93,537
Clark (C)	ARC DECRA	How does the continental crust get so hot?	$125,000
Griffin, Pearson, O'Reilly, Belousova, Collins, Aitchison, Clarke, Fiorentini, Li, Daczko	ARC LIEF	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, Collins, Aitchison, Clarke, Fiorentini, Li, Daczko	ARC LIEF (MQ contribution)	New horizons in geochemical isotopic analysis with a new-generation multicollector plasma mass spectrometer: towards unravelling the deep earth system	$500,000
Griffin, Pearson, O'Reilly, Belousova, Collins, Aitchison, Clarke, Fiorentini, Li, Daczko	ARC LIEF (collab Inst.)	New horizons in geochemical isotopic analysis with a new-generation multicollector plasma mass spectrometer: towards unravelling the deep earth system	$110,000
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
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
Gessner, McCuaig, Hobbs, Cawood, Gorczyk, Connolly, Gerya, O'Neill, Lester	ARC Linkage Project	Multiscale dynamics of ore body formation	$95,000
Gessner, McCuaig, Hobbs, Cawood, Gorczyk, Connolly, Gerya, O'Neill, Lester	ARC Linkage Project (state cont.)	Multiscale dynamics of ore body formation	$100,000
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
Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate	ARC Linkage Project	Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	$85,000
Tkalcic, Kennett, Spaggiari, Gessner	ARC Linkage Project	Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	$50,000

Investigators	2013 Funding Source	Project Title	Amount
Tkalcic, Kennett, Spaggiari, Gessner	ARC Linkage Project (GSWA cont.)	Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	$50,000
Piazolo, Griffins, Venter, Luzin	Braggs Institute, ANSTO	A new view on diamonds: Deformation textures of polycrystalline diamond	$60,000
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
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
Foley	DVC(R) Core Start up	DVC Core Start up	$250,000
Dentith, McCuaig, Miller, Beresford, Gallardo, Holden, George, Hagemann, Porwal, Joly	Geological Survey of Western Australia	GSWA-CET Targeting Products	$267,060
McCuaig, Greenwood, McCulloch	CSIRO Flagship Collaboration Fund	Mineral Systems Flagship Cluster	$268,532
Fiorentini, Barnes, Miller	MERIWA M413	Hydrothermal footprints of magmatic nickel sulphide deposits	$128,000
Ord, Gorczyk, Hobbs, Micklethwaite	MERIWA	Multiscale dynamics of hydrothermal mineral systems	$70,000
Le 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
Fiorentini, Locmelis, Pearson, Agnew, Kobussen	Rio Tinto Industry collaboration	The applicability of Ru-chromite signatures in the exploration for picrite-hosted Ni-Cu-PGE sulfide deposits	$92,381
Venter, Piazolo, Luzin	Braggs Institute, ANSTO	Residual stress investigations of polycrystalline natural diamond aggregates	$30,000
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (Minerals Targeting International Pty Ltd)	Lithospheric architecture mapping in Phanerozoic orogens	$60,000
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (DVCR allocation)	Lithospheric architecture mapping in Phanerozoic orogens	$20,000
O'Reilly	MQSIS Research Infrastructure Special Reserve Fund	Energy dispersive x-ray system for Cameca SX100 Electron Microprobe	$150,000
Afonso	RIBG	Cluster computing for 21st-century Geophysical simulations	$90,587
Pearson	RIBG	Front-line microscope imaging for Geosciences	$91,522
Gore, Taylor, Fryirs, Pearson, Belousova, Handley, Sheedy, Shoat	RIBG	A hand-held portable XRF analyser	$97,522
George, Turner, Rushmer, Schaefer, Brock	RIBG	Precision saw for finely cutting and slicing geological samples	$60,487

Investigators	2013 Funding Source	Project Title	Amount
Jacob	MQ Academic Non-Discretionary Fund	Start-up funds for Future Fellowship FT120100462	$130,000
Wacey	SEED project grant, Bergen University	Multiple sulfur isotope analysis of microbially-mediated mineral sulfides at the micron scale	$18,737
Bezard	PGRF	Assimilation of sediments embedded in the oceanic arc crust: myth or reality?	$3,936
Gao	PGRF	Comparative study of origin and petrogenesis of A-Type granites in eastern China and southeastern Australia: Evidence from Hf-O-Li isotopes	$5,462
Hoshino	PGRF	Demonstrating the syngeneity and interpreting the palaeobiology of hydrocarbon biomarkers in the Fortescue Group (2.7 Ga)	$5,000
Murphy, R	PGRF	Stabilising a craton: the origin and emplacement of the 3.1 Ga Mpuluzi batholith (South Africa / Swaziland)	$4,971
Xiong	PGRF	Shenglikou and Zedand peridotite massifs, Tibet (China): Upper mantle processes and Geodynamic significance	$5,000
Colas, Gardner, Murphy, Pankhurst, Stuart, Wasillev	MQRES	MQ	$106,829
Firth, Jessop, McGowan, Murphy, Saunders, Schinella	APA	MQ	$112,985
Brens Jr, Czaplinska Foley, Genske, Grose, Hoshino, Jiang, Oliveira Bravo, Peters, Ramzan, Rubanova, Spruzeniece, Taneja, Tork Qashqai, Tretiakova	iMQRES & tuition	MQ	$723,003
Bezard, Gao, Lara, Tilhac, Wang, Xiong, Yu	iMQRES Cotutelle	MQ	$135,591
Bjorkman, Gonzalez, Iaccheri, Le Vaillant, Li, Markov, Mirasol-Robert, Owen, Parra Avila, Schindler	SIRF & tuition	UWA	$470,756
Masurel, Baumgartner	IPRS & tuition	UWA	$87,177
Macquarie University	GLITTER software	Core to Crust Fluid Systems	$68,744
Macquarie University	Access MQ	Core to Crust Fluid Systems	$140,539

GRANTS AND OTHER INCOME FOR 2014

Investigators	2014 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
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

Investigators	2014 Funding Source	Project Title	Amount
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
Collins, Belousova, Murphy, Hand	ARC Discovery Project	Supercells and the supercontinent cycle	$19,500 ($80,000)
Nemchin, Grange	ARC Discovery Project	Investigation of the early history of the Moon	$70,000
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	$13,000 ($130,000)
Rosenbaum, Pisarevsky, Fielding, Speranza	ARC Discovery Project	Unravelling the geodynamics of eastern Australia during the Permian: the link between plate boundary bending and basin formation	$45,626 ($130,007)
Schaefer	ARC Discovery Project	Bromine isotopic evolution of the Earth and solar system	$50,000
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 ($100,000)
Jacob	ARC Future Fellowship	A new approach to quantitative interpretation of paleoclimate archives	$205,358
Jacob	ARC Future Fellowship startup grant (MQ)	A new approach to quantitative interpretation of paleoclimate archives	$150,000
Belousova	ARC Future Fellowship	Dating down under: resolving earth's crust - mantle relationships	$177,912
Fiorentini	ARC Future Fellowship	From Core to Ore: emplacement dynamics of deep-seated nickel sulphide systems	$167,632
Handley	ARC Future Fellowship	The timescales of Earth-system processes: extending the frontiers of uranium-series research	$160,207
O'Neill	ARC Future Fellowship	Strength and resistance along oceanic megathrust faults: implications for subduction initiation	$70,844
Piazolo	ARC Future Fellowship	Flow characteristics of lower crustal rocks: developing a toolbox to improve geodynamic models	$203,682
Yang	ARC Future Fellowship	How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	$187,584
Clark (C)	DECRA	How does the continental crust get so hot?	$125,000
Arculus, Rohling, Roberts, Exon, Yeats, O'Reilly, George, Muller, Aitchison, Webster, Coffin, Vasconcelos, Welsh, McCuaig, George, Skilbeck, Baxter, Hergt, Gallagher, Fergusson, Sloss, Heap, Schellart, Stilwell, Foden, Kershaw, Howard, Clennell, Daniell, Collins	ARC LIEF	Australian membership of the International Ocean Discovery Program	$1,800,000

Investigators	2014 Funding Source	Project Title	Amount
McInnes, van Riessen, Bland, Iglauer, Eksteen, Kemp, Muhling, Fiorentin, Thébaud, Wingate, Kirkland, Senanayake, Nikoloski	ARC LIEF	A digital mineralogy and materials characterisation hub for petrology, mineralogy, exploration, metallurgy and reservoir characterisation research	$700,000
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	$432,844
Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate	ARC Linkage Project	Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	$170,000
Tkalcic, Kennett, Spaggiari, Gessner	ARC Linkage Project	Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	$100,000
Tkalcic, Kennett, Spaggiari, Gessner	ARC Linkage Project (GSWA contrib.)	Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	$100,000
Luzin, Piazolo, Rushmer, Bland, Tomkins	Braggs Institute	Texture measurements in meteorites - a pilot study (ID 3201)	$53,600
Abily	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
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
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
Griffin, O'Reilly, Pearson, Belousova	DVCR allocation	Lithospheric architecture mapping in Phanerozoic orogens	$20,000
McCuaig, Fiorentini, Aitken, Dentith, Hagemann, Miller, George, Bagas, Micklethwaite	UNCOVER Australia Project	The Distal Footprints of Giant Ore Systems	$237,917
McCuaig, Greenwood, McCulloch	CSIRO Flagship Collaboration Fund	Mineral Systems Flagship Cluster	$272,688
Aitken, Dentith, Lindsay, McCuaig	Geological Survey of Western Australia	Second Generation Regional Targeting Products	$272,688
Hough, Reddy, McCuaig, Tyler, Dentith, Shragge, Miller, Fiorentini, Aitken	Science and Industry Endowment Fund (SIEF) c/o CSIRO	The Distal Footprints of Giant Ore Systems: UNCOVER Australia	$4,000,000

Investigators	2014 Funding Source	Project Title	Amount
Hough, Reddy, McCuaig, Tyler, Dentith, Shragge, Miller, Fiorentini, Aitken	MERIWA	The Distal Footprints of Giant Ore Systems: UNCOVER Australia	$2,600,000
Hough, Reddy, McCuaig, Tyler, Dentith, Shragge, Miller, Fiorentini, Aitken	Industry	The Distal Footprints of Giant Ore Systems: UNCOVER Australia	$900,000
Hough, Reddy, McCuaig, Tyler, Dentith, Shragge, Miller, Fiorentini, Aitken	GSWA	The Distal Footprints of Giant Ore Systems: UNCOVER Australia	$2,600,000
Jacob	MQSIS	High Spectral Resolution Confocal Raman Micro-Spectrometer	$150,000
Foley	MQSIS	High-Pressure experimental equipment: cubic multi-anvil apparatus	$150,000
George, Goodwin, Armand, Jacob, Westaway, Leefmann	RIBG	Facility for large lipid analysis of geological and environmental samples, including new ability to derive important palaeothermometers	$67,000
Clark, Afonso, O'Neill, Jacob, Pearson, Rushmer, Foley, Griffin, O'Reilly, Turner	RIBG	Core to Crust Experiments: Establishment of a High-pressure, High-temperature Diamond Anvil Cell facility	$100,000
O'Reilly	NCRIS Auscope	A4.45; Macquarie University Project - Earth Composition and Evolution	$175,000
Fitzgerald, Dunlop, Hool, Hodgetts, Kilburn	NHMRC	Optimising combinations of calcium channel inhibitors for treatment of secondary degeneration after neurotrauma	$657,562
Piazolo	AINSE Research Award	Neutron Activation Analysis of natural polycrystalline diamond aggregates	$1,360
McGowan	PGRF	Messages from the Mantle: Geochemical Investigations of Ophiolitic Chromitites	$5,000

Note: Amounts in brackets are for total funding for relevant grants administered by external institutions.

Appendix 9: Standard performance indicators

All values maximised at double target

RESEARCH

Number & quality of publications	R1	*Research outputs*	*Actual*	144
			Target	40
	R2(a)	*Journals with Impact Factor >2.5*	*Actual*	83%
			Target	70%
	R2(b)	*Journals with impact Factor >3*	*Actual*	68%
			Target	50%
	R2(c)	*Journals with specific target audiences*	*Actual*	15%
			Target	20%
	R2(d)	*Book chapters / international conference proceedings*	*Actual*	4%
			Target	10%
	R3(a)	*Number of presentations / talks / papers / lectures given at major international meetings*	*Actual*	186
			Target	30
	R3(b)	*Number of invited or keynotes given at major international meetings*	*Actual*	26
			Target	8
	R4	*Number & nature of commentaries on Centre's achievements in general/specialist publications*	*Actual*	>100
			Target	6
	R5	*Citation data for publications*	*Actual*	To be set at Review
			Target	
Research training and professional education	R6	*Number of attended professional training courses for staff and postgraduate students*	*Actual*	19
			Target	10
	R7	*Number of Centre attendees at all professional training courses*	*Actual*	97
			Target	20
	R8	*Number of new postgraduates working on core Centre research, supervised by CoE staff (PhD, MRes)*	*Actual*	20
			Target	8
	R9	*Number of new postdoctoral researchers recruited to the CoE working on core Centre research*	*Actual*	4
			Target	4
	R10	*Number of new Honours students working on core Centre research & supervised by CoE staff*	*Actual*	9
			Target	6
	R11(a)	*Number of postgraduate completions working on core Centre research and supervised by CoE staff*	*Actual*	13
			Target	6
	R11(b)	*Postgraduate completion times: students working on core CoE research, supervised by Centre staff*	*Actual*	3.5
			Target	3.5
	R12	*Number of Early Career Researchers (within 5 years of completing PhD) working on core CoE research*	*Actual*	11
			Target	6
	R13	*Number of students mentored*	*Actual*	99
			Target	24
	R14	*Number of mentoring programs*	*Actual*	3
			Target	3
Build int. national and regional links/networks	R15	*Number of international visitors and visiting fellows*	*Actual*	58
			Target	20
	R16	*Number of national and international workshops held / organised by Centre*	*Actual*	6
			Target	3
	R17	*Number of visits to overseas laboratories and facilities*	*Actual*	26
			Target	20
	R18	*Examples of relevant interdisciplinary research supported by the Centre*	*Actual*	93%
			Target	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	6	
				Target	5	
		R21	Currency of information on the Centre's website	Actual	6	
				Target	4	
		R22	Number of website hits	Actual	9544	
				Target	8,000	
		R23	Number of public talks given by centre staff	Actual	5	
				Target	4	
ORG SUPPORT	Generate cash & in-kind contributions from partners & other sources & build collab. & infrastrucutre support	O1	Annual new and existing cash contributions from collaborating organisations	Actual	1,790,000	
				Target	1,790,000	
		O2	Annual in-kind contributions from collaborating organisations	Actual	12,564,157	
				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	1,229,300	
				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	43	
				Target	6	
		O7	Level and quality of infrastructure provided to the Centre	Actual	To be set	Assessed at Review
				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	Assessed at Review
				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 Science	N1	Industry Seminars	Actual	4	
				Target	4	
			Number of industry / end-user collaborations		16	
		N2	Postgraduate units established by end year 3	Actual	6	
				Target	2	
			Number of honours and Postgraduate students		92	

CCFS KPI	Outcomes	C1	*Linkage of geochemical / petrologic / geological data with geophysical datasets / modelling* *2013 - Submit first results to international journals*	*Actual*	Complete	
				Target	Complete	
		C2	*Technology & method development related to NCRIS infrastructure* *2013 -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*	Assessed at Review	
				Target		
	End-user	C4	*Establishment of linkages and collaborative projects with end-users relevant to external core business of the Centre* *2013 - proceed with projects*	*Actual*	Complete	
				Target	Complete	

Appendix 10: 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).
- **UWA Scholarship for International Research Fees (SIRF)**: available to eligible overseas candidates for higher degrees by research (HDR) at The University of Western Australia (http://spe.publishing.uwa.edu.au/latest/scholarships/postgraduate/sirf)

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. 21* 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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Australian Government
Australian Research Council

Glossary

AINSE	Australian Institute of Nuclear Science and Engineering
AMIRA	Australian Mineral Industry Research Association
AMMRF	Australian Microscopy and Microanalysis Research Facility
(RSES) ANU	(Research School of Earth Sciences) Australian National University
APA	Australian Postgraduate Award
ARC	Australian Research Council
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
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
ERA	Excellence in Research for Australia
FIM	Facility for Integrated Microanalysis
FTIR	Fourier Transfer Infrared Spectroscopy
GA	Geoscience Australia (formerly AGSO)
GAC	Geological Association of Canada
GAU	Geochemical Analysis Unit (DEPS, Macquarie University)
GEMOC	Geochemical Evolution and 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
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
MIM	Greenland Ministry of Industry and Mineral Resources
(i)MQRES	(International) Macquarie University Research Excellence Scholarships
MQSIS	Macquarie University Strategic Infrastructure Scheme
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
SAC	Science Advisory Committee
SEM	Scanning Electron Microscope
SIRF	UWA 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

GEOLOGICAL SURVEY WESTERN AUSTRALIA

ARC Centre of Excellence
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