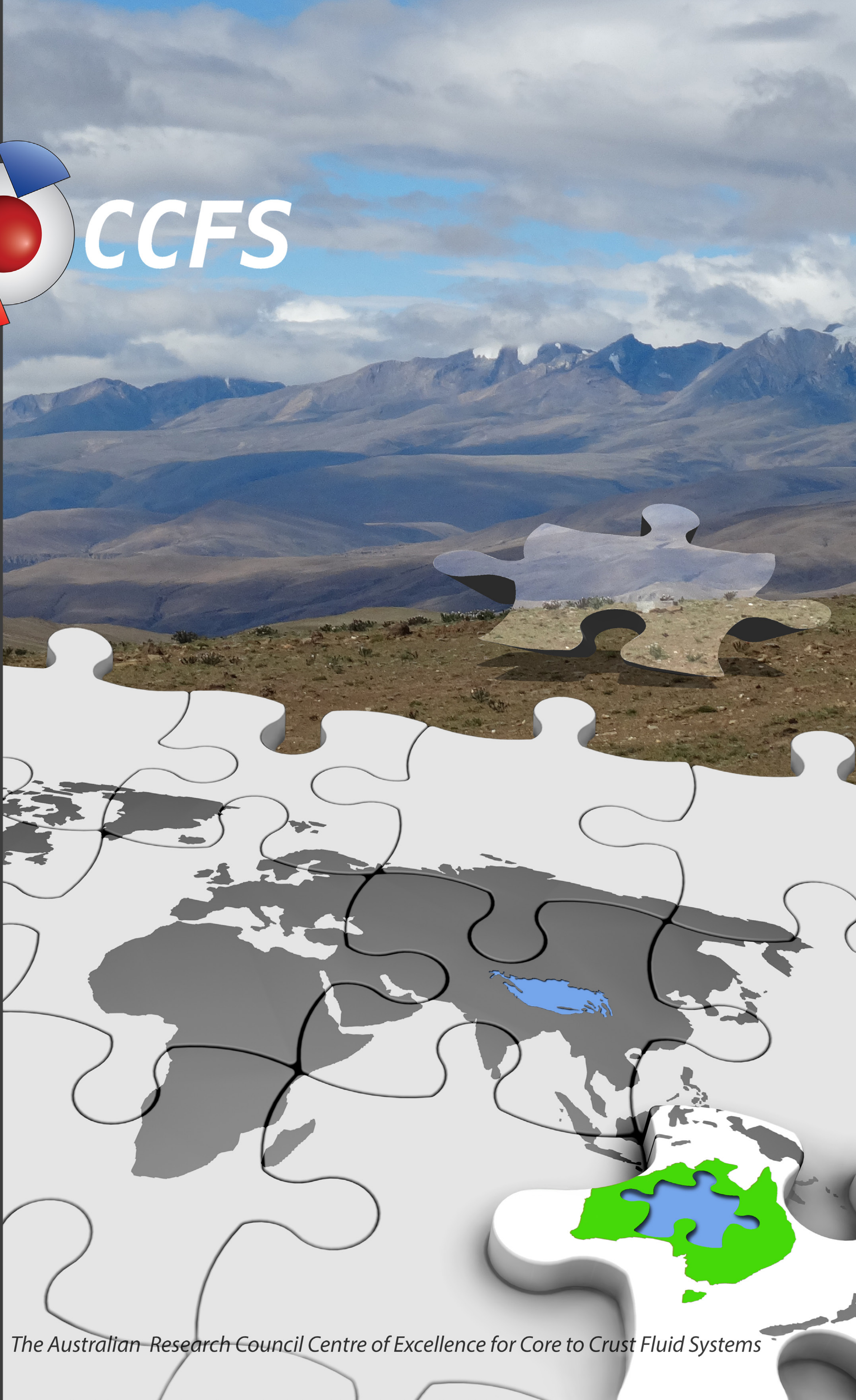
CCFS

2014 Annual Report



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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  ccfs.admin@mq.edu.au

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: The giant 4-dimensional Earth puzzle being solved by CCFS. Global analogues provide key pieces to solve the lithosphere structure in covered Australian regions, potentially revealing the mineral and energy resources buried beneath our continent's vast weathered surface. Image by Sally-Ann Hodgekiss.

Contents

Australian Government
Australian Research Council

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

Director's preface

This report summarises the activities and achievements of the Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS) in 2014 (commenced mid 2011). Activities include research, technology development, stakeholder engagement, 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. Our strong formal international partnerships and growing networks leverage our resources across intellectual, infrastructure and funding bases.

The formal ARC Mid-Term Review and Site Visit were major features of 2014. The preparations confirmed the strong collaborative and collegial spirit that has developed across researchers within CCFS at all levels and showcased the world-leading scientific outcomes and impact of the research program. The ARC Report from the Review Panel (Professors Martin Hand and Brian Yates and Dr Erica Smythe) emphasised the transformational research that had resulted, and praised the global recognition, the culture of the Centre that encourages exploration of innovative ideas, its mentorship at all levels, its governance and its leadership, illustrated by the following excerpts.

"The Centre is building critical mass of PhD students and postdoctoral researchers … working collaboratively across disciplines. The Panel views this capacity building as one of the Centre's strengths and lasting legacies, and a major advantage for Australia"

"The Centre is undertaking original, innovative and transformational research and is making important advancement of capabilities and knowledge … [and has] achieved important breakthroughs in geoscience research (e.g. new synthesis of early Earth tectonics, and identification of both cubic Mg-silicates in peridotites in Tibet and the slab roll-back mechanism to extract material) … The Panel found the Centre's 3-D/4-D work particularly transformational … and considered this work as the most exciting, interdisciplinary and cross-functional part of the Centre's program."

"The Centre's research is innovative and is generating interest in the research community … one example being the Centre's interpretation of lower crust formation … the paper has had over 6000 downloads.

"… the Centre Director was … a fantastic mentor for personnel across the nodes and experience levels, was accessible, provided invaluable guidance and experience, … whose leadership was critical to the Centre. The Centre Director was seen as having an overarching view of the Centre, as an effective communicator and a leader who brings people together."

"Nationally, Centre researchers are being recognised for the excellence of their research, with a number receiving research support through competitive schemes for commencement in 2013 and 2014, including ARC Discovery Projects, Future Fellowships … as well as non-ARC awards"

2014 was also a year of review and program restructuring to identify the most productive research directions relevant to fulfilling the CCFS vision of ***"Delivering the fundamental science needed to sustain Australia's resource base."*** All the research programs were scrutinised, reassessed and realigned (following advice from the Science Advisory Committee). This resulted in 7 Flagship Programs (see *p. 20*) based on the benchmark outcomes of the first 3 years and extending in new directions; programs that had come to fruition in the first three years were finalised. These Flagship Programs will target the research goals through to 2018, providing a new focus and realigned strategies to deliver more transformational outcomes and leave a legacy in knowledge, new technology and methodologies, and vital new knowledge about Australia's geological evolution to guide smart new mineral exploration. They are underpinned by two Technology Development Programs designed to deliver more leading-edge geochemical breakthroughs, capitalising on the outstanding geochemical instrumental infrastructure across CCFS.

The continuing success in gaining external leverage of resources is exemplified by the award of two more Future Fellowships to David Wacey and Xuan-Ce Wang - a total of nine Future Fellowships have been awarded to researchers in CCFS. The postgraduate cohort keeps burgeoning with 73 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 and was highlighted in the Review Report.

Our postgraduates are producing world-class research with authorship of 28 publications in high-impact journals in 2014 and 53 presentations at peak international workshops and conferences. Beñat Oliveira deserves particular mention not only for being awarded the prestigious La Caixa Spanish scholarship for study in a foreign country, but also for his top ranking in that cohort.

The Research Highlights section again showcases the outstanding research in CCFS, reflected in the 2014 outputs including publications. Following from our reflections for the mid-term Review about the scientific and stakeholder impact of CCFS research, and new knowledge contributions to understanding the Earth on which we live, 2015 is starting with high energy in the exciting new research framework defined by its Flagship Programs.

We are eagerly anticipating building on our fundamental knowledge expansion and new tools from our successes in the first three years, to further explore Earth's inner space and workings since its formation over 4.5 billion years ago. The ultimate goal is to continue to lead the way to Australia's future mineral security, ensuring economic health for our society through fundamental, high-impact research discoveries.

Professor S.Y. O'Reilly

Participants at the CCFS Research meeting, 3-4 July 2014.

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

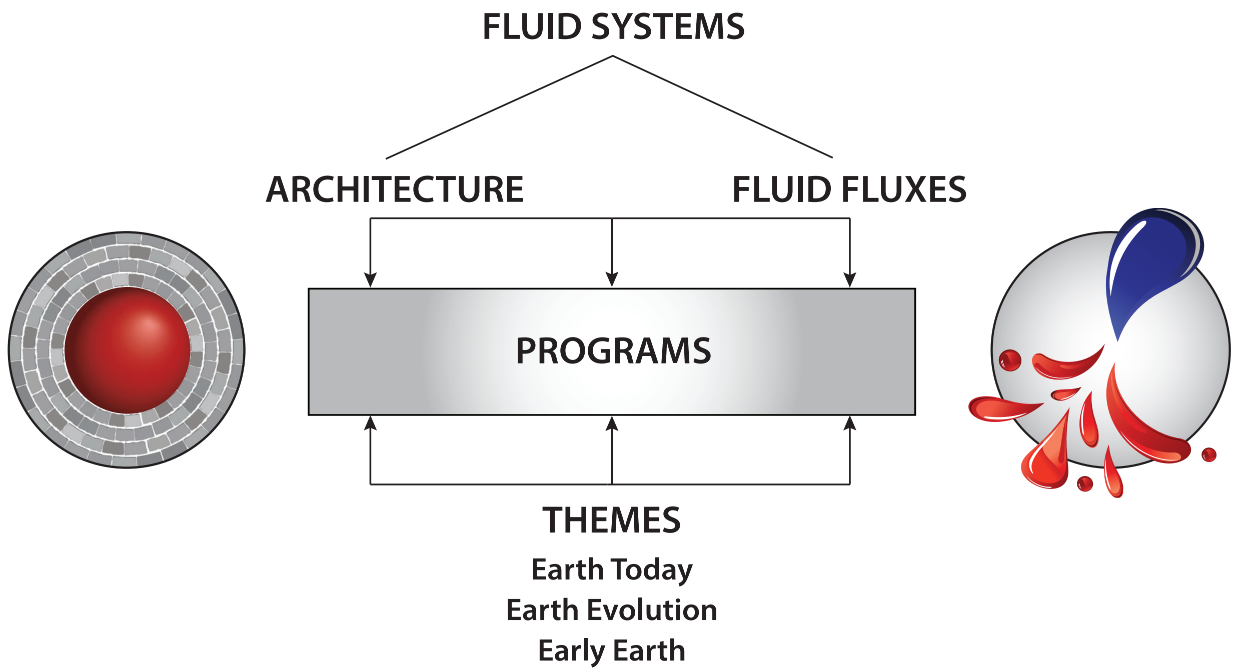
Research programs within the Centre are focused to provide maximum synergy for the scope enabled by the resource base. As it is not possible to encompass the full range of research about the Earth's fluid cycle and deep Earth dynamics, all applied and mature strategic research is carried out in parallel, supported by other funding sources. The Research Program structure was revised in 2014 to ensure the overarching goals were being fulfilled. The resulting Flagship Programs (see *p. 20*) were put in place as cross-node streams contributing to the three global Themes (Early Earth, Earth Evolution and Earth Today).

These are structured to capitalise on the people and resource context of the Centre in a way not possible with a shorter timeframe, or without the critical mass of research expertise, depth and breadth. More detailed information is given in *"The CCFS Research Program"* and *"Research Highlights"*.

In order to track the input of coalescing strands, the concept of programs contributing to understanding ***Earth Architecture*** and/or ***Fluid Fluxes*** helps track the pieces of the giant 4-dimensional Earth puzzle being solved by CCFS and encapsulates the relationship of all the CCFS programs to Earth *'fluids'*.

> ***"Architecture" is the 'roadmap' for fluids***
>
> ***"Fluid Fluxes" represents the 'traffic report'***

All Research Highlights and Programs are now keyed to this framework shown diagrammatically below:



Kimberly, Western Australia.

2014 CENTRE RESEARCH MEETING, 3-4 JULY

A successful and productive CCFS Research Meeting was held on 3-4 July 2014. The meeting provided the opportunity for participants, as well as members of the CCFS Board, to hear research presentations from CCFS researchers, including postgraduates and ECRs.

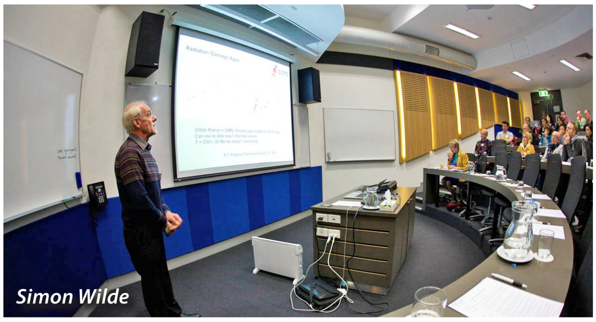
This forum is a catalyst for new, exciting ideas and cements collaboration among researchers of the Centre's nodes and partner institutions.

The meeting also provided an opportune time for a CCFS Board Meeting.

Nicole McGowan delivering her presentation on Tibetan Chromitites.

Sue O'Reilly

Cam McCuaig



Simon Wilde

CCFS Board meeting, 3 July 2014.

Matt Kilburn, Sandra Piazolo, Dorrit Jacob

CCFS Postgrads

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

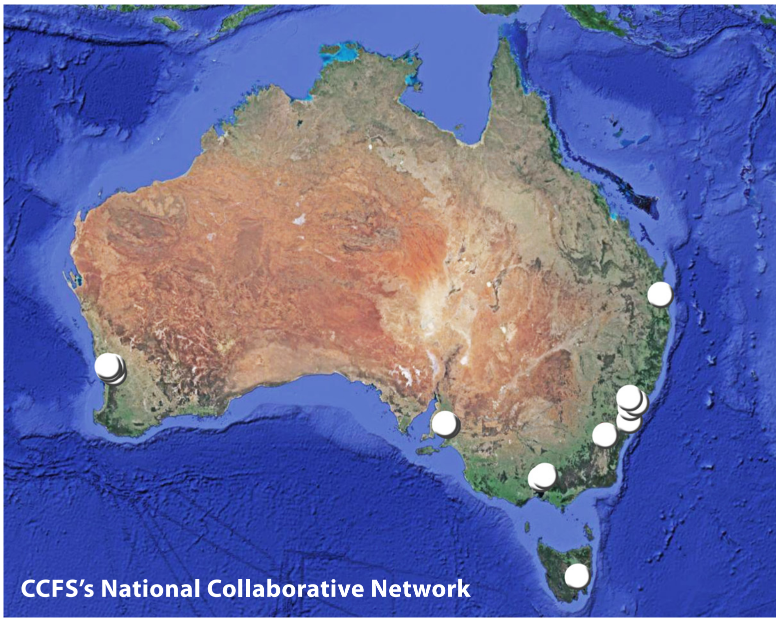
Earth Today - Dynamics, decoding geophysical imaging, and Earth resources. Geophysical imagery gives us a snapshot of the current status of the deep Earth but also carries the imprints of past processes. Realistic interpretation of these data will give us new insights into Earth's internal dynamics and 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.

1.8 Ga ripple marks, Kimberly, Western Australia.

Structure

CCFS builds on a world-class infrastructure base, and multiplies the capabilities of three internationally recognised centres of research excellence: Macquarie University (Administering Institution), Curtin University and the University of Western Australia. The Geological Survey of Western Australia is a Partner Institution and researchers from Melbourne University and the University of New South Wales are formally affiliated. The overseas nodes led by Partner Investigators in France, China, Germany and the USA are contributing resources and provide access to a wide variety of expertise and instrumental capabilities. Memoranda of Understanding (MOU) for research collaboration and postgraduate exchange and joint programs, provide formal affiliations with four additional global institutions with leading reputations in the field. CCFS also has formal Cotutelle MOU with a further 15 global institutions (see *p. 87*). 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.



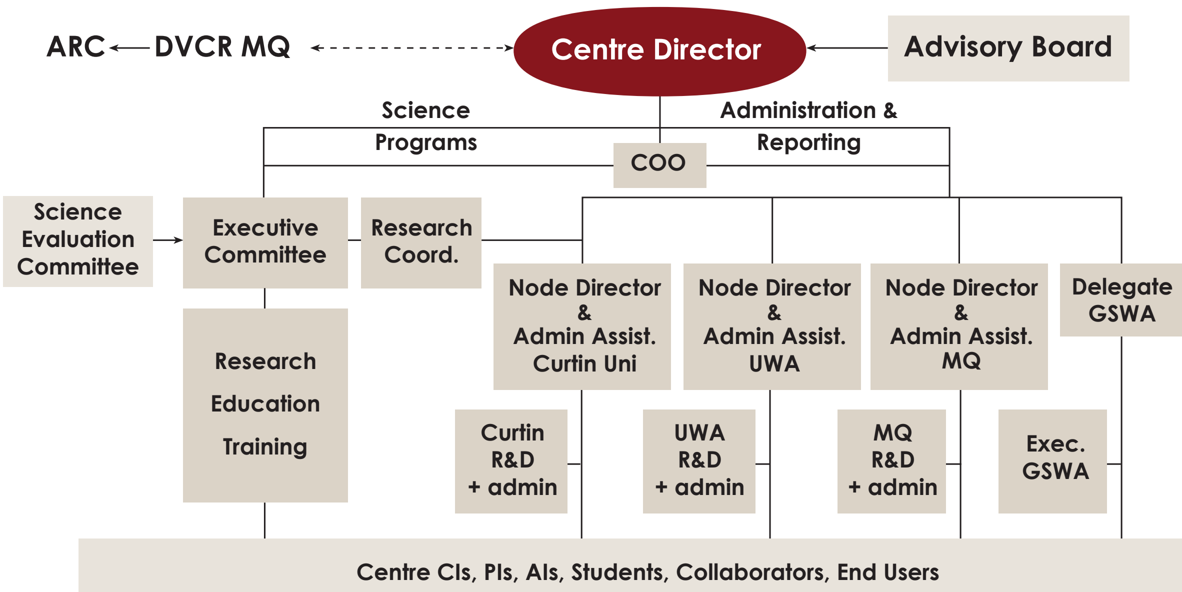
CCFS's National Collaborative Network

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 programs 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*).

MACQUARIE University

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieve International Excellence

Curtin University



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 the targeted MQ appointment of 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 at least annually to provide advice on the research program and governance, and any other matters relevant to CCFS. The six external members of the Advisory Board are actively 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

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

Magdalene Wong-Borgefjord - COO
Department of Earth and Planetary Sciences
Macquarie University

Advisory Board

Dr Ian Gould
Chancellor
University of South Australia

Dr Andy Barnicoat
Chief, Community Safety & Earth Monitoring Division
Geoscience Australia

Dr Paul Heithersay
Chief Executive Olympic Dam Task Force, and Deputy Chief Executive, Resources and Energy Group, Department of State Development

Dr Jon Hronsky
Principal
Western Mining Services

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

Dr Roric Smith
VP Discovery / Chief Geologist
Evolution Mining

plus the Executive Committee

Participants

Organisations

Administering Organisation

Macquarie University (MQ)

Collaborating Organisations

Curtin University (CU)

University of Western Australia (UWA)

Partners

Australian Partner

Geological Survey of Western Australia (GSWA)
Dr Ian Tyler - CCFS Leader GSWA

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

Dr Elena Belousova - MQ

Associate Professor Simon Clark - MQ

Professor Marco Fiorentini - UWA

Professor Stephen Foley, Research Coordinator - MQ

Professor William Griffin - MQ

Professor Matt Kilburn - UWA

Professor Zheng-Xiang Li - CU

Professor T. Campbell McCuaig, Node Leader - UWA

Associate Professor Alexander Nemchin - CU

Associate Professor Craig O'Neill - MQ

Professor Suzanne Y. O'Reilly, Director - MQ

Associate Professor Norman Pearson - MQ

Professor Martin Van Kranendonk - University of NSW

Professor Simon Wilde, Node Leader - CU

Partner Investigators

Australian Partner Investigator

Dr Klaus Gessner - GSWA

International Lead Partner Investigators

Professor Michael Brown - Maryland

Dr David Mainprice - Montpellier

Professor Catherine McCammon - Bayreuth

Professor Fuyuan Wu - CAS Beijing

Associate Investigators

Dr Juan Carlos Afonso - MQ

Dr Olivier Alard - Universite de Montpellier, France

Dr Leon Bagas - CET, UWA

Professor Mark Barley - UWA

Dr Christopher Clark - CU

Assistant Professor John Cliff - CMCA UWA

Associate Professor Nathan Daczko - MQ

Professor Simon George - MQ

Dr Richard Glen - Honorary Associate

Dr Masahiko Honda - Australian National University

Associate Professor Dorrit Jacob - MQ

Dr Chris Kirkland - GSWA (2014, CU 2015)

Professor Jochen Kolb - Geological Survey of Denmark and Greenland

Professor Louis-Noel Moresi - University of Melbourne

Associate Professor Sandra Piazolo - MQ

Professor Steven Reddy - CU

Associate Professor Tracy Rushmer - MQ

Dr Bruce Schaefer - MQ

Professor Paul Smith - MQ

Professor Simon Turner - MQ

Dr Michael Wingate - GSWA

Dr Yingjie Yang - MQ

Professor Shijie Zhong - University of Colorado, Boulder, USA

CCFS early-mid career researchers at the July CCFS Research Meeting.

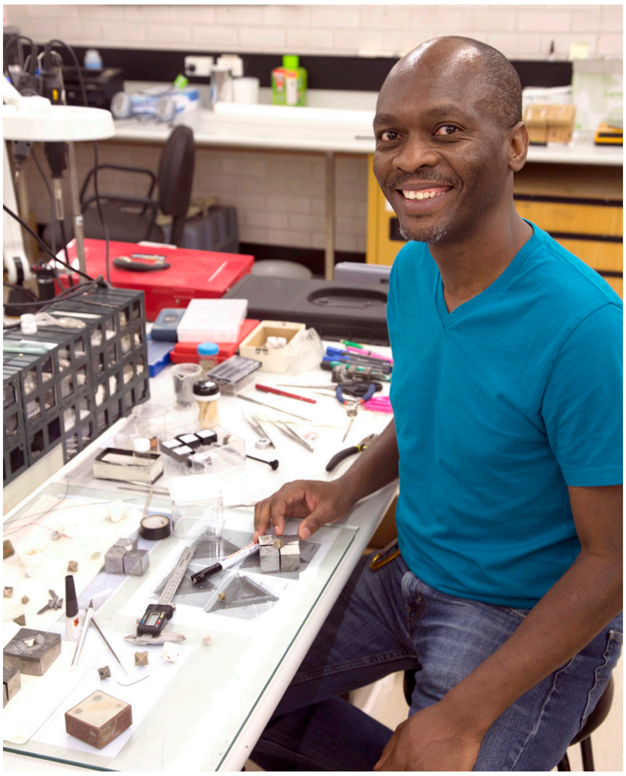
ECSTARS	
	Dr Bénédicte Abily - MQ
	Dr Xuan-Ce Wang - UWA
	Dr Takako Satsukawa - MQ

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 Yongjun Lu - UWA
	Dr David Mole - CU
	Dr Edward Saunders - MQ
	Dr Zoja Vukmanovic - CU
	Dr Weihua Yao - CU
	Dr Siqi Zhang - MQ
	Dr Andrea Giuliani - MQ (announced as DECRA to commence 2015)
	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

Dr George Amulele joined the CCFS in December 2014 as an ARC funded Research Associate after six years at Yale University,



working as a laboratory manager in the Department of Geology and Geophysics. Prior to this, he completed his PhD in physics (University of the Witwatersrand, Johannesburg) and went on to complete two postdoctoral fellowships at the University of Hawaii and Stanford University.

During his time at Yale, George contributed to a number of successful research projects (in the laboratories of Professor Shun Karato and Professor Kanani Lee), in multi-anvil deformation and diamond anvil high-pressure and temperature systems up to conditions similar to those proposed in the lower mantle. He will be working closely with Associate Professor Simon Clark, Professor Stephen Foley and Associate Professor Tracy Rushmer to develop high-pressure facilities at the CCFS as well as engage in research on the physics and chemistry of mantle and deep earth minerals. His research interests include deformation, behaviour of volatiles and electrical conductivity in mantle minerals.

Ms Magdalene Wong-Borgefjord joined CCFS in July 2014 as Chief Operating Officer. Magdalene has more than 15 years experience in administrative and customer-focused roles in the Higher Education Sector. Magdalene spent the last four years managing the start up of two research centres at the University of Western Sydney. Her experience also includes financial, human resources, project and research management, coordinating new international academic programs and international relationships as well as providing administrative support to student, academics and senior executives. Magdalene also has four years overseas experience, coordinating the opening of international hotels in Hong Kong.

Magdalene has a Master of Education and Work from Macquarie University as well as a Bachelor of Business Degree with majors in Marketing and Management from the Australian Catholic University.

Other new staff *(featured on p. 12 of our ECR section)*

Dr Bénédicte Abily

Dr Weihua Yao

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. Seven Future Fellows, Dr Elena Belousova, Professor Marco Fiorentini, Dr Heather Handley, Associate Professor Dorrit Jacob, Associate Professor Craig O'Neill, Associate Professor Sandra Piazolo and Dr Yingjie Yang 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). Two Future Fellowships were awarded in 2014 to Dr Xuan-Ce Wang and Dr David Wacey.

Dr Xuan-Ce Wang is a geochemist. He took his Master of Science at the China University of Geosciences in 2004 and completed his PhD in 2008 at the Guangzhou Institute of Geochemistry, Chinese Academy of Science. In 2008, Xuan-Ce joined the Institute of Geology and Geophysics, Chinese Academy of Science, as a postdoctoral fellow. He then held a senior research fellow position and was an ARC CCFS ECSTAR at Curtin University at Perth. In 2015, he took up an ARC Future Fellowship. His primary research interests lie in: (1) Understanding the origin and evolution of the Earth's crust and mantle by using isotope and major and trace element geochemistry, petrology, field geology and simple geodynamic models and by investigating the relationships between intra-continental geotectonic phenomena, plate tectonics, mantle plumes, deep-Earth fluid cycling, and supercontinents;

(2) Examining roles of deep-Earth fluid cycling in intra-continental magmatic and tectonic events by studying continental flood basalts and rift-related basalts; (3) Deciphering early Earth processes and subsequent mantle evolution by studying Archean komatiite and associated TTG; and (4) Integrating multi-isotope systems for direct dating of oil generation and charge in key oil-rich basins in Australia and China.

In his Future Fellowship project, he will test a provocative and potentially ground-breaking hypothesis that links fluid cycling, large-scale intra-continental magmatism, volcanic volatile flux, climate changes, mantle chemical geodynamics, plate tectonics, and slab stagnation in a self-consistent geodynamic system. This research will integrate geochemistry, petrology, geophysics, global tectonics and thermodynamical modelling to reach a new level of understanding of fluid cycling and Earth's dynamics through time. The outcomes will fill the knowledge gap of how fluids work in the Earth's system, and will help us to understand how deep-Earth's geodynamic processes influence paleoclimate changes. This work will also help us to identify ways to improve future mineral exploration success. See *Research Highlights* *p. 48, 57.*

Dr David Wacey is a geologist and palaeobiologist who combines geological fieldwork, high spatial resolution morphological studies and geochemical analysis to investigate

fossil life in the Precambrian rock record. He obtained his BA in Earth Sciences from Oxford University in 1998 and remained at Oxford for his PhD (awarded 2004) and first postdoctoral position (2005-2008). In 2008, he won a three-year University Research Fellowship at the University of Western Australia. In 2011-2012, David spent time working at the University of Bergen, Norway, before returning to UWA as part of the ARC CCFS. David will take up his Future Fellowship from June 2015.

In his Future Fellowship project, David will aim to provide new insights into the origin of life on Earth, life's diversification *cont...*

through the Precambrian, and the co-evolution of life and early Earth environments. The project will be unique in that it will take the study of early life to the sub-micrometre and hence sub-cellular level. This will facilitate new opportunities for identifying the types of life present during early Earth history, their metabolisms, cellular chemistry and interactions with their environment. It will also provide new search engines and more robust assessment criteria for life on other planets, and help to resolve specific scientific controversies, for example, the validity of claims for cellular life from 3.5 billion-year-old rocks. Finally, it will also refine new nano-scale analytical techniques that can be applied across academic disciplines and in industrial and environmental problem solving.

EARLY CAREER RESEARCHERS (ECR)

The second primary goal of CCFS (see *p. 3*) concerns the recruitment, development and mentoring of Early Career Research (ECR) staff *"for the development of the next generation of Australia's geoscientists"*.

The following profiles present 2014 ECRs and summarise their expertise and research areas.

New 2014

Dr Bénédicte Abily joined CCFS in 2014 as a research associate in the CCFS ECSTAR program. Previously, she was a postdoctoral researcher at the French National Centre for Scientific Research (CNRS) carrying out her research in the Géosciences Environement Toulouse (GET) laboratory, France. Prior to this, she completed her BSc at the University of Brest, France in 2005, her MSc at the University of Clermont-Ferrand, France in 2007 and her PhD on the "*Characteristics petrographic, geochemical and structural deep crustal section of the Oman ophiolite: Implications for magma genesis and operation of magma chambers at the base of a center oceanic expansion*" at the Université Paul Sabatier in Toulouse, France in 2011.

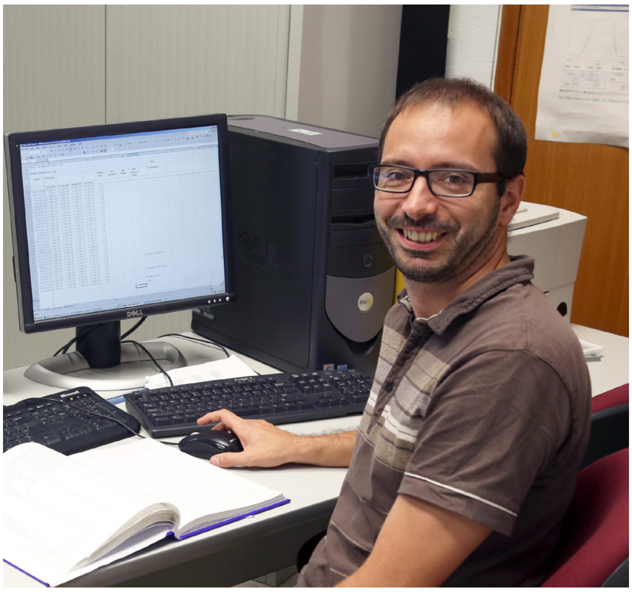
The goal of her research at CCFS is to better understand the migration of fluids (magma, seawater, hydrothermal fluid) and the interplay between magmatic, metasomatic and tectonic processes in the lithosphere at mid-ocean ridges. To achieve this she will carry out detailed petrographic observations and various geochemical analyses (major, trace and rare-earth elements, radiogenic isotopes) on crustal and mantle rocks collected from present-day mid-ocean ridges and exposed fossil oceanic ridges (ophiolites), especially the Oman ophiolite (Sultanate of Oman). In this framework, she had the opportunity to participate in a two-month international drilling expedition in the Pacific Ocean (IODP Expedition 335).

Dr Weihua Yao (*pictured above*) completed her BSc and MSc with a Petroleum Geology major at China University of Geosciences (Wuhan).
After working in the Chinese oil industry for a year as a petroleum geologist, she commenced her PhD study at Curtin University in 2010, investigating the tectonostratigraphic evolution of the Ediacaran-Silurian Nanhua Basin and the nature of the lower Paleozoic Wuyi-Yunkai orogeny in South China in relation to the assembly of Gondwanaland. The results of her research suggest an Ediacaran-Cambrian collision between South China and northern India, leading to the formation of the Ediacaran-Silurian Nanhua foreland basin and the Wuyi-Yunkai intraplate orogeny. Her work, completed in early 2014, led to the publication of four papers and more are in the pipeline.

Weihua commenced her employment at Curtin University in 2014 as a Research Associate with TIGeR and CCFS. Her current research, as a part of CCFS Flagship Program 5, focuses on the examination of Ediacaran-Silurian paleogeographic connections between the Indian-Australian margin of Gondwanaland and Asian continents/terranes, including the South China and Indochina blocks. See *Research Highlight p. 50-51*.

Continuing

Dr Leon Bagas completed his PhD at UWA in 2010 on the Evolution and tectonic setting of the Paleoproterozoic Granites-Tanami Orogen, Western Australia. He joined the CET 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.



Dr Yoann Gréau (*pictured above*) 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.

Since 2013 Yoann has 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 2014, *TerraneChron®* imaged and analysed 3605 grains of zircons for a total of 17 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. 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 program by documenting the characteristics of diamonds found in Tibetan ophiolites, and understanding their formation conditions in this new environment for diamond occurrences.

Dr Jin-Xiang Huang (*pictured above*) 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 studying metasomatism and origins of xenolithic eclogites from the Roberts Victor kimberlite, South Africa. This provided her with extensive experience in the clean labs, on state-of- *cont...*

art instruments producing precise geochemical data, and 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, therefore, evidence from these can no longer 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 stable isotopes and water contents 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 2014, she developed high-Cr garnet standards for *in situ* oxygen-isotope analysis by SIMS. She also measured the water content of well-characterised Roberts Victor eclogites and found that eclogite-rich horizons near the base of the lithospheric mantle can represent a significant, previously unrecognised reservoir of water. This work contributes to our understanding of the global water cycle, metasomatic processes and the generation of melts near the base of the lithospheric mantle.

Dr Marek Locmelis is a Research Assistant Professor in the CET working on the CCFS Foundation Program "*Metal sources and transport mechanisms in the deep lithosphere*".

In 2014, Marek continued his research on the processes that lead to mass transfer of fluids and metals between the mantle and the crust. His work integrated (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.

In mid 2014 Marek left CCFS to take up a position at NASA in the Solar System Exploration Division.

Dr Yongjun Lu (*pictured left*) is a Research Assistant Professor funded by CCFS. He is undertaking the CCFS Foundation Program, "*4D lithospheric evolution and controls on mineral system distribution: The Western Superior-Yilgarn comparison*". He has been supervising PhD student Katarina Bjorkman since 2013, who is studying the 4D crust-mantle evolution of the 3.0 Ga Marmion Terrane as part of the Foundation Program. Yongjun has ongoing collaboration with Chinese Academy of Geological Sciences on the investigation of Tibetan porphyry systems, which has resulted in publications in high-impact journals such as *Geology* and *Journal of Petrology*. Yongjun is also leading a Rio Tinto-funded project titled "*The mineral chemistry of zircon as a pathfinder for magmatic-hydrothermal copper and gold systems*", in keeping with the vision of CCFS to deliver the fundamental science needed to sustain Australia's resource base. Yongjun was invited in 2014 to be the Associate Editor for SEG 2016 special publication on Tethys volume and to be a keynote speaker in the SEG 2016 conference in Turkey. He is Deputy Theme Leader for the Magmatic Mineral Systems theme at CET and member of the Geoconferences Main Committee and the Strategic Planning and Implementation subcommittee of Geoconferences. He also serves as reviewer for international journals such as *Journal of Petrology, Chemical Geology*, *Economic Geology, Lithos, Gondwana Research, Mineralium Deposita* and *Ore Geology Reviews*.
See *Research Highlights pp. 35-36, 59-60.*

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 Masters 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 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

Steve Barnes and David Mole sampling drill-core at the Forrestania komatiite-hosted Ni-Cu-PGE camp.

understanding to the evolution of multiple geological systems within a given terrane, such as structural regimes, volcanism, sedimentary facies and mineral systems. 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.

In mid 2014, David moved to CSIRO as an OCE Postdoctoral Fellow. He continues his close association with CCFS through his contribution to the Pilot Project, "*The isotopic architecture of komatiite flow fields in the Yilgarn Craton of Western Australia*" which aims to map mantle source, crustal ages and magma-lithosphere interactions using multiple isotopic systems in komatiites from the Yilgarn Craton of Western Australia.

Dr Takako Satsukawa joined CCFS/GEMOC in October 2012 as an ECSTAR (Early-Career Start-up 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 also 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, geochemical analyses, analysis of water contents, and numerical modelling of the seismic properties of peridotite xenoliths and chromitite from different lithospheric levels which have experienced different degrees of melt-fluid-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 2014, she characterised the microstructure of mantle-derived rocks from the southwest Japan arc to investigate the uppermost mantle evolution during back-arc spreading. She also investigated fluid-present deformation preserved in chromitite from Golyamo Kamenyane, southeast Bulgaria. She presented her work at the 6th Orogenic Lherzolite Conference in Marrakech (Morocco), the American Geophysical Union Fall Meeting 2014 in San Francisco (USA), and 2014 Annual Meeting of Japan Association of Mineralogical Sciences in Kumamoto (Japan). This project is part of CCFS Themes 2 and 3, Earth Evolution, and Earth Today. See *Research Highlight p. 55.*

Dr Edward Saunders completed his PhD with CCFS/GEMOC in 2013. His thesis investigated the petrography and geochemistry of sulfides hosted in mantle peridotites and pyroxenites, with an emphasis on their gold concentration. This research increases our understanding the nature, abundance and mobility of Au in the lithospheric mantle, as well as sulfide metasomatism more generally. This has important implications for understanding the fluid flux within lithospheric mantle.

In 2014, Ed commenced employment at Macquarie University as a lecturer and is an early career researcher in CCFS. *cont...*

He has been expanding on the research that he started during his PhD investigating the mobility of chalcophile elements in the mantle, and the role these processes might have in ore deposit genesis. This has included using data collected during his PhD to create quantitative geochemical models to explore how gold behaves during mantle melting.

Dr Zoja Vukmanovic joined Curtin University after completing her PhD at UWA 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 Masters degree from the Free University, Amsterdam, Netherlands.

As a research associate, she investigated 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 examined the relationship between intragrain and intergrain deformation processes and chemical reactions associated with hydration of the mantle, with the goal of improving 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.

Dr Siqi Zhang (*pictured below*) 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.

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 mantle-core coupling models to study the early evolution of Mars. By exploring a range of uncertainties with different model settings, the results suggest that mobile-lid may exist in early Martian history, and it is the likely cause of an early dynamo. He is also exploring the construction of an Earth mantle-flow model constrained by the plate motion in the past few hundred million years to recover the mantle structure and to track its evolution over that time. In addition, he is developing new treatments of magmatism in global mantle flow models, making it possible to also recover melting history. Recently, he has become involved in improving high performance SPH (smoothed particle hydrodynamics) code using Intel Xeon Phi co-processors to study the formation of the moon. See *Research Highlight p. 54*.

VALE

STIRLING EDWARD SHAW 25/3/33 - 12/12/13

Stirling completed his honours degree in geology at UWA in 1959 and in his third year was awarded the Edward de Courcy Clarke Prize in Geology and the Edward Sydney Simpson Prize (shared with Ian Martin).

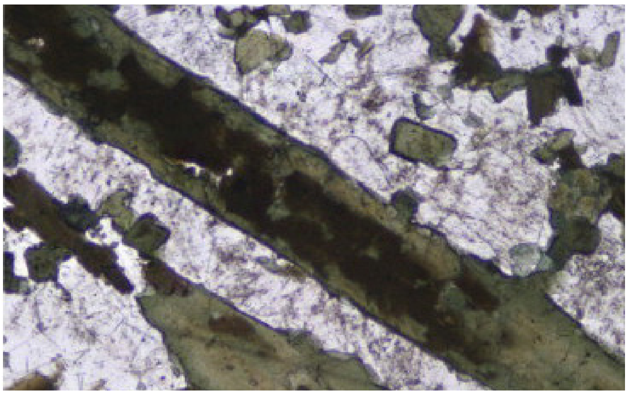
In 1960 Stirling accepted a demonstrators position at the University of New England and by 1964 had completed a PhD on the granitic rocks of the Tenterfield area in northern NSW. His mapping of over 2000 sq km detailed a large number of granitic units as well as recognising the Demon Fault and its right lateral displacement of about 30 km. The results of the mapping were published in the Geology of NSW (1969). To generate the geochemical data for his thesis he first had to establish a geochemical laboratory in the Geology Department to analyse his rocks and minerals. This effort produced a thesis with a wealth of geochemical data.

A short while after completing his PhD, Stirling took up a lectureship with the University of NSW at their Broken Hill College. He was the only geologist and taught the full breadth of subjects. With funding from the Mine Managers Association he also conducted research on both the mine sequence rocks and the granites further north at Tibooburra.

In 1966 Stirling accepted a position at Macquarie University where it is believed he was the first non-professorial academic appointment. He always taught with infectious enthusiasm and the Department still has many of the teaching samples Stirling collected for these first classes.

In his research, Stirling recognised the value of XRF instruments for rock analysis and was able to purchase a Siemens XRF in the first year of his appointment at Macquarie. A little later he automated the XRF by building the interface to a small computer that also computed the results. This was the first major step in the development of the geochemical facilities at Macquarie. A few years later he obtained funding for the purchase of an ETEC electron microprobe/scanner which gave Macquarie the state-of-the-art facilities needed to analyse minerals as well as rocks. Most importantly, Stirling kept all this equipment going with little outside assistance. This early foresight and tremendous personal effort laid the foundations of the present Geochemical Analysis Unit, one of the best such facilities in Australia. Just before he retired he went to Newfoundland to arrange the purchase of the first of the laser analysis systems that are now the key to much of what is done in the Geochemical Analysis Unit. The important part of his enormous contribution was that what he did, he did for everyone.

Stirling's research output of fifty papers and a similar number of abstracts cover a broad range of research but the majority involve geochemical and isotopic studies, especially related to granitic rocks. His publications include a significant number on the New England region, the northern parts of the Lachlan Fold Belt and the Sydney Basin. He has also produced important papers with colleagues in the USGS on the granitic rocks of southern California including one of two CCFS papers published in 2014 (*CCFS#205 and 435*).



CCFS #435 - Figure 3. Enclave LX14.

Stirling Shaw was a great ambassador for Earth Sciences and Macquarie University and a man of the highest honour. He was always totally straight forward, hard working, the best-mannered person you would ever meet, a fantastic family man and a great colleague. He led by example and was the first to roll up his sleeves. He will be remembered for having made vital and lasting contributions to Macquarie University and our understanding of the geology of eastern Australia.

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 Programs described below.

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

FOUNDATION RESEARCH PROGRAMS

Foundation Programs for 2011-2014 were funded from the ARC Centre funds allocation, and include components from the Universities' funding support. The first tranche of Foundation Programs 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 Programs are designed to be interdisciplinary, cross-node and to foster early-career/postgraduate researchers participation.

The research directions of the Foundation Programs were designed to contribute to the overarching three major Themes identified to bring about a new level of understanding of Earth and its resource dispersion. They include three integrated projects targeted at Technology Development required to deliver the research goals.

Summaries and progress are detailed in *Appendix 1*.

***Appendix 2* presents the Flagship Programs set up from 2014, and the 2015 workplan**

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

FOUNDATION RESEARCH PROGRAMS

Program	Coordinator and main Centre personnel
1. The TARDIS program: 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) Castillo, Lu, McGowan, Saunders, Tilhac, Xiong, Xu, Yao (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 Kollegger, Davies, Owen (PhDs), Guergouz (MSc)
2b. Dynamics of Earth's mantle: assessing the relative roles of deformation and magmatism	Reddy, Kaczmarek and Gray (PhD)
3. Generating and stabilising the earliest continental lithosphere - Late granite blooms	Griffin, O'Reilly, O'Neill, Pearson, Van Kranendonk, Belousova, Gréau (ECR) and Murphy, Gao, Tretiakova (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, Huang, Wasiliev, Matthews (PhDs)
5. Early evolution of the Earth system and the first life, from multiple sulfur isotopes	Barley, Fiorentini, Kilburn, Wacey, Van Kranendonk, Wilde, Nemchin, Griffin, Isaac (PhD), Djokic (MPhil)
6. Detecting Earth's rhythms: Australia's Proterozoic record in a global context	Li, Pisarevsky, Wingate, Wang, (ECR, ECSTAR) Huang, Zhu, Yao, Pang, Tao, L. Liu, Y. Liu, Meng (PhDs), Niu (MSc)
7. Fluid regimes and the composition of the early Earth	Wilde, Nemchin, Grange, Barley, Kusiak, Kaczmarek, Pidgeon Wang, Ge, Sun, Li (S) (PhDs)
8. Diamond genesis: Fluids in deep-Earth processes	Griffin, O'Reilly, Pearson, Cliff, Martin, Kilburn, Howell (ECR) Rubanova, 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, Parra-Avila, Stevenson, Iaccheri (PhDs)
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 and Mole (PhD)

TECHNOLOGY DEVELOPMENT

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) and Gao, Xiong (PhDs)
Frontiers in integrated laser-sampled trace-element and isotopic geoanalysis	Pearson, Cliff, Griffin, O'Reilly, Kilburn, Huang (ECR), Gréau (ECR) and Gao, Genske, McGowan, Xiong (PhDs)
Optimising mineral processing procedures: From rock to micro-grains	Pearson, Belousova, Daczko, wide spectrum of Centre researchers

2014 FLAGSHIP PROGRAMS

Program	Coordinator and main Centre personnel
1. Deep Earth fluids in collision zones and cratonic roots (TARDIS II) Themes 1, 2, 3 Earth Fluids, Earth Architecture	**O'Reilly**, **Griffin**, Pearson, Cliff, RA (TBA), Kilburn, Martin, Huang (ECR), Satsukawa (ECSTAR, ECR), Abily(ECSTAR, ECR), Gréau, Saunders (ECR's) McGowan, Xiong, Xu, Tilhac, Colas, Lu, Liptai (PhDs)
2. Genesis, transfer and focus of fluids and metals Themes 2 and 3 Earth Fluids	**Fiorentini**, McCuaig, Foley, O'Reilly, Griffin, Reddy, Rushmer, Adam, Turner, Lu (ECR), Bagas, Gorczky, Piazolo, Kilburn, Clarke Thébaud, Guergouz, Bjorkman, Xu (PhDs) Arting, Burley, Johannesen (MSc)
3. Modelling fluid and melt flow in mantle and crust Themes 2 and 3 Earth Fluids, Earth Architecture	**O'Neill**, Afonso, Yang, Li, Foley, Clark, S. Zhang (ECR), Shan, Gorczky, Smith, O'Reilly, Griffin Wasilev, Ramzan, Oliveira, Grose, Jiang (PhDs)
4. Atmospheric, environmental and biological evolution Theme 1 Earth Fluids, Earth Architecture	**Van Kranendonk**, Wacey, Fiorentini, Foley, McCuaig, Cliff, Kilburn, Grange, Kirkland, Alard Baumgartner (PhD), Djokic (MPhil)
5. Australia's Proterozoic record in a global context Themes 2 and 3 Earth Architecture	**Li**, Pisarevsky, Wang, Yao (ECR), Wingate, O'Reilly, Griffin, Pearson, Belousova, McCuaig, Wang (ECR) Tao, I. Liu, Y. Liu (PhDs)
6. Fluid regimes and composition of early Earth Themes 1 and 3 Earth Fluids, Earth Architecture	**Wilde**, Nemchin, Grange, Martin, O'Neill Gu, Ge (PhD)
7. Precambrian architecture and crustal evolution in WA Themes 1, 2 and 3 Earth Architecture	**Kirkland**, Belousova, Gréau, Gessner, Yuan, Merdie, Wingate, Tyler (ECR) PhD/ECR 2015 (TBA)

TECHNOLOGY DEVELOPMENT

Cameca Ion microprobe Themes 1, 2 and 3 Earth Fluids, Earth Architecture	**Kilburn**, Cliff, Martin, Fiorentini, McCuaig, Wacey, Wilde, Griffin Students of CIs and ECRs utilising the Ion Probe Facility are active in the program
GAU multi-instrument development Themes 1, 2 and 3 Earth Fluids, Earth Architecture	**Pearson**, Griffin, O'Reilly, Cliff, RA (TBA), Kilburn, Martin, Huang (ECR), Saunders (ECR) McGowan, Gao, Xiong (PhDs)

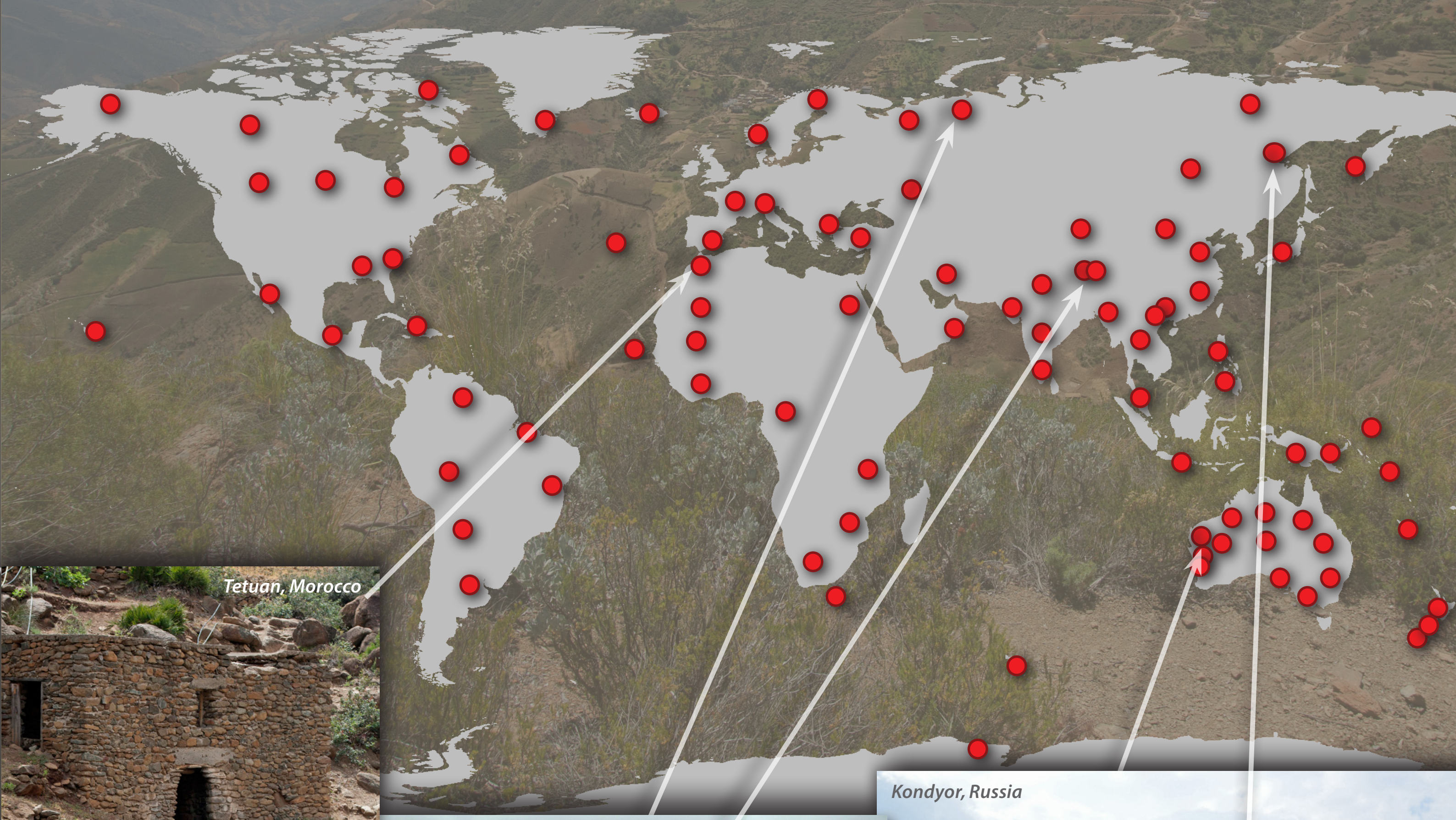
Where out of this world is CCFS?

As part of our quest to better understand the processes that led to the formation of the early Earth, CCFS has been investigating the early history of both the Moon and Mars.
See *Research Highlights p. 33, 54.*


Moon


Mars

WHERE IN THE WORLD IS CCFS?



Tetuan, Morocco

Qulong porphyry copper mine, China

Kondyor, Russia

Polar Urals-Ekaterinburg

Kimberly Region, Australia

Communications 2014

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 2014 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.

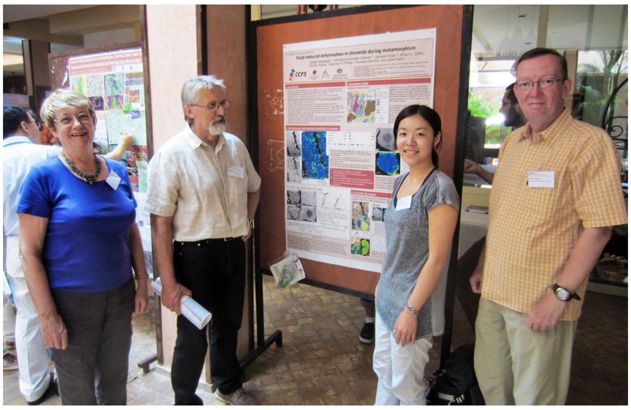
CCFS publications for 2014 are given in Appendix 5.

The 151 CCFS publications that were published in 2014 are mainly in high-impact international journals (Thomson ISI).

PARTICIPATION IN WORKSHOPS, CONFERENCES AND INTERNATIONAL MEETINGS IN 2014

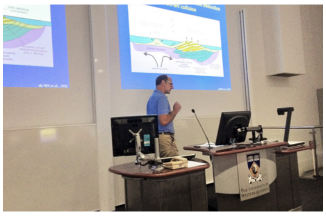
CCFS Investigators, associated staff, early-career researchers and postgraduates had a high profile at 38 peak geophysical, metallogenic, geodynamic and geochemical conferences as convenors, invited speakers, or presenters, with 227 presentations including:

- UHNAI-Nordic Winter School "Water and the Evolution of Life in the Universe", Hawaii, 1-14 January 2014
- IGG-CAS 2014 Annual Meeting, 16-17 January 2014
- Biennial meeting of the Specialist Group in Tectonics and Structural Geology (SGTSG), Thredbo NSW, 2-8 February 2014
- Workshop on Advanced Development on *In Situ* and WR High-Precision Elemental and Iisotopic Analyses, Academia Sinica Taipei, Taiwan, 10-12 March 2014
- 45th Lunar and Planetary Science Conference, The Woodlands, TX, USA, 17-21 March 2014
- UNCOVER Summit 2014 Adelaide Convention Centre, SA, Australia, 31 March - 02 April 2014
- International Workshop on: Ophiolites, Mantle Processes and Related Ore Deposits, Beijing, 14-15 April 2014
- European Geosciences Union General Assembly 2014, Vienna, Austria, 27 April - 02 May 2014
- 6th Orogenic Lherzolite Conference, Morocco, 4-15 May 2014



Sue O'Reilly, Professor Csaba Szabó (Eötvös University Budapest), Takako Satsukawa and Norm Pearson at the 6th Orogenic Lherzolite Conference.

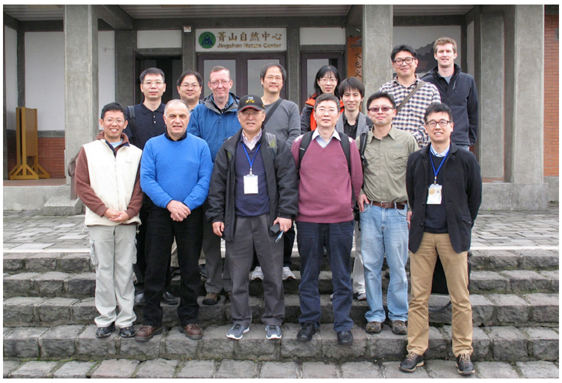
- Biosignatures Across Space and Ttime, Joint Meeting - Nordic Network of Astrobiology and the Centre of Geobiology, Bergen, Norway, 20-22 May 2014
- GAC-MAC Annual Meeting, Fredericton, Canada, 21-23 May 2014
- XIX Geological Congress of Argentina, Córdoba, Argentina, 2-6 June 2014
- Goldschmidt 2014 Conference, Sacramento, USA, 8-13 June 2014
- Sydney Space Society, NSW, Australia, 16 June 2014
- AESC Australian Earth Sciences Convention, Sustainable Australia, Newcastle, NSW, Australia, 7-10 July 2014
- XXXIV Reunión de la Sociedad Española de Mineralogía, Granada, 2 July 2014
- Gondwana 15, Madrid, Spain, 14-18 July 2014
- AOGS 11th Annual Meeting, Royton Sapporo Hotel, Japan, 28 July to 1 August, 2014
- Australian Institute of Geoscientists Minerals Systems Workshop, Perth, Australia, 11 August 2014
- 12th International Platinum Symposium, Yekaterinburg, Urals, Russia, 11-14 August 2014
- Gordon Research Conference: Rock Deformation, Andover, New Haven, USA, 17-22 Aug, 2014
- Ninth International Mining Geology Conference, Adelaide, SA, Australia, 18-20 August 2014
- IMA 2014, Gauteng, South Africa, 1-5 September 2014
- 77th Annual Meeting of the Meteoritical Society, Casablanca, Morocco, 8-12 September 2014


CCFS presenters at the Archean Tectonics Debate and Symposium, November 2014.

- 14th International Conference on Thermochronology, Chamonix, 8-14 September 2014
- Kimberley Diamond Symposium and Trade Show, The Big Hole, Kimberley, South Africa, 11-14 September 2014
- 2014 Annual Meeting of Japan Association of Mineralogical Sciences, Kumamoto University, Japan, 17-18 September 2014
- 2014 EMAS Regional Workshop, Leoben, Austria, 21-24 September 2014
- SEG 2014: Building Exploration Capability for the 21st Century, Keystone, CO, USA, 27-30 September 2014
- SEISMIX 2014, 16th International Symposium on Multi-scale Seismic Imaging of the Earth's crust and Upper Mantle, Castelldefels, Spain, 12-17 October 2014
- Nordic Supercontinent Workshop, Haraldvangen, Norway, 13-19 October 2014
- Dating Origin of Life: Present-Day Molecules and First Fossil Record, Göttingen, Germany, 16-18 October 2014
- GSA 2014, Vancouver, British Columbia, Canada, 19-22 October 2014
- Symposium on International Safeguards, IAEA, Vienna, 20-24 October 2014
- 24e Réunion des Sciences de la Terre (24th Earth Sciences Meeting), Pau, France, 27-31 October 2014
- Archean Tectonics Debate and Symposium "Plumes or Plates in the Late Archaean: How Far Does Uniformitarianism Apply in Archaean Tectonics?" CSIRO, Kensington, WA, Australia, 27-28 November 2014
- 1st Australian Workshop for EMC Geoscientists, Macquarie University, NSW, Australia, 1-2 December 2014
- AGU Fall meeting, San Francisco, CA, USA, 15-19 December 2014

INVITED TALKS AT MAJOR CONFERENCES AND WORKSHOPS IN 2014



IGG-CAS 2014 Annual Meeting, 16-17 January 2014	Seismic images of craton margins and adjacent orogens and tectonic implications **H. Yuan Invited**
Workshop on Advanced Development on *In Situ* & WR High-Precision Elemental and Isotopic Analyses", Academia Sinica Taipei, Taiwan, 10-12 March 2014	Back to basics: quantitative elemental and isotope ratio analysis by laser ablation ICP-MS **N. Pearson Keynote** *Norman Pearson with some of the workshop's participants.*
UNCOVER Summit 2014 Adelaide Convention Centre, SA, Australia, 31 March - 2 April 2014	Isotope geology through space and time: a tool for understanding crustal evolution. Case studies from the Yilgarn Craton and its margin **C.L. Kirkland Keynote**
International Workshop on: Ophiolites, Mantle Processes and Related Ore Deposits, Beijing, 14-15 April 2014	Transition-Zone mineral assemblages in peridotite massifs, Tibet: Implications for collision-zone dynamics and orogenic peridotites **W. Griffin Invited**
European Geosciences Union General Assembly 2014, Vienna, Austria, 27 April - 02 May 2014	Long hard road from Nuna to Rodinia **S.A. Pisarevsky Invited**
Sydney Space Society, Australia, 16 June 2014	The tectonics of exoplanets **C. O'Neill Invited**

AESC Australian Earth Sciences Convention, Sustainable Australia, Newcastle, NSW, Australia, 7-10 July 2014	Metal sources and transport mechanisms at crust-mantle boundary conditions: new search space for deep-seated magmatic mineral systems **M.L. Fiorentini**, **M. Locmelis**, **T. Rushmer**, **J. Adam** and **S. Turner** **Keynote** Formation of horizontally layered Archean crust: examples from the Pilbara, Kaapvaal, and Yilgarn Cratons **M.J. Van Kranendonk** **Keynote** Was the Early Earth Stagnant? **C. O'Neill** and V. Debaille **Invited** Innovation in Australian geochronology and thermochronology A. Gleadow, B. McInnes and **N. Pearson** **Keynote**
Gordon Research Conference: Rock Deformation, Andover, New Haven, USA 17-22 August 2014	Strain heterogeneities and dynamic recrystallization in anisotropic materials: Insights from ice and ice mixture deformation experiments and modeling **S. Piazolo** **Keynote**
Ninth International Mining Geology Conference, Adelaide, SA, 18-20 August 2014	Mines versus mineralisation - Deposit quality, mineral exploration strategy and the role of '*Boundary Spanners*' **T.C. McCuaig** J.E. Vann and J.P. Sykes **Keynote**
14th International Conference on Thermochronology, Chamonix, 8-14 September 2014	Earthquake seismology: Exploring the cratonic crust in Western Australia **H. Yuan** **Invited**
2014 EMAS Regional Workshop, Leoben, Austria, 21-24 September 2014	*In-situ* quantitative determination of PGE concentrations in komatiitic chromites: application to nickel-sulphide targeting **M.L. Fiorentini** **Invited**
SEG 2014, Keystone, CO, USA, 27-30 September 2014	The mineral system concept: Key to exploration targeting under cover **T.C. McCuaig** and J.M.A. Hronsky **Invited**
2014 GSWA Kimberley Workshop, 21 November 2014	The geochemical architecture of the Hart Dolerite at Speewah Dome, Western Australia **M.L. Fiorentini** **Invited**
Archean Tectonics Debate and Symposium, CSIRO, Kensington, WA, 27-28 November 2014	No plate tectonics in the Archaean? **C. O'Neill** **Invited** Internal seismic structure of the cratonic lithosphere **H. Yuan** **Invited**
AGU Fall Meeting, San Francisco, CA, USA, 15-19 December 2014	Thermochemical structure and stratification of the Hudson Bay lithosphere, Northern Canada: Evidence from multi-observable probabilistic inversion F.A. Darbyshire and **J.C. Afonso** **Invited**

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

OTHER CONFERENCE ROLES

European Geophysical Union, Vienna, Austria, 27 April - 2 May 2014	*Session Co-convenor:* **Klaus Gessner** - ERE31./GMPV14S9.6 - Structural Interpretation and Evolution of Mineral Systems from Geological and Geophysical Data

Goldschmidt 2014 Conference, Sacramento, USA, 8-13 June 2014	*Theme Co-coordinator:* **Tracy Rushmer** - 22: Early Earth: Earth's History Before the Phanerozoic *Session Co-convenor:* **Mike Brown** - 18e: Models for Continental Growth Four Decades On *Session Co-convenors:* **Tracey Rushmer** and **Martin Van Kranendonk** - 22d: Mantle Thermal Peaks, Crustal Growth and the Inception of Plate Tectonics
AESC Australian Earth Sciences Convention, Sustainable Australia, Newcastle, NSW, Australia, 7-10 July 2014	*Organising committee:* **Craig O'Neill** and **Martin Van Kranendonk** *pictured right* *Theme Convenor:* **Martin Van Kranendonk** - Living Earth (Life and Habitats) *Session Convenors:* **Martin Van Kranendonk** - LE1 Recent Advances in the Evolution of Life Through the Archean **Ian Tyler** and **Michael Wingate** - P03 Precambrian Geochronology **Martin Van Kranendonk** and **Stephen Foley** - DP05 Fluids and Melts from Core to Crust *Session Co-convenors:* **Klaus Gessner** - DP07 Archean and Proterozoic Hot Orogens: Rocks, Models, Mechanisms, and Resources **Norman Pearson** - DP08 Understanding the Composition and Evolution of the Earth: Australian Innovation in Geochronology, Thermochronology and Isotope Geochemistry **Klaus Gessner** - RE13 3D Geoscience: Methods, Applications and Challenges in Imaging and Analysing Solid Earth systems at different scales
AOGS 11th Annual Meeting, Sapporo, Japan, 28 July - 1 August, 2014	*Session Co-convenor:* **Yingjie Yang** - SE31 - Seismic Imaging and Tomography of Multi-scale Earth Structure
AGU Fall meeting, San Francisco, CA, USA, 15-19 December 2014	*Session Co-convenors:* **Zheng-Xiang Li** - T33B: Linking Plate Tectonics and Mantle Convection to Wilson Cycles: Constraints from the Geological Record and Surface Processes **Kelsie Dadd** - Marginal Sea Tectonic, Volcanic, and Oceanic Processes: Ocean Drilling of the South China Sea and Recent Investigations

SELECTED WORKSHOP ROLES

Activity	Details & Participant/s	Date
CET Seminar Series	**Cam McCuaig**	2014
CCFS/EPS Seminar Series	**Richard Flood**	2014
International Workshop on: Ophiolites, Mantle Processes and Related Ore Deposits, Beijing, China	**Bill Griffin** was a member of the scientific organising committee	14-15 April 2014
TeamWA workshop: Iron Oxide Copper Gold IOCG deposits, Perth, WA, Australia	**Cam McCuaig** was part of the discussion panel	29 May 2014

SELECTED WORKSHOP ROLES *cont...*

Activity	Details & Participant/s	Date
Australian Earth Science Convention, Newcastle, Post-conference workshop "*Recent advances on the interpretation of the global multiple sulphur isotope record: implications for the evolution of the Early earth and a wide range of ore-forming processes*"	Organised by **Marco Fiorentini** Attended by more than 15 students and researchers	29 May 2014

This workshop brought together the sulfur isotope community, including several global leaders in this discipline (Sue Golding, Boswell Wing) to present the latest advances in our understanding of the multiple sulfur isotope signature record and to identify the greatest knowledge gaps that should be addressed in the short term future. The debate focused on the processes that lead to genesis and preservation of mass independent sulfur isotope signatures in the global geological record. In the last two decades the discovery and measurement of non-mass dependent sulfur isotope signatures in sedimentary, igneous and metamorphic rocks has permitted the formulation of new hypotheses on the evolution of the Early Earth. The precision of analytical techniques, both for whole-rock and *in situ* analysis of a wide range of S-bearing phases, including sulfides, sulfates and phosphates, have dramatically improved, yet our ability to interpret this data still lags. Sulfur is a crucial element that is involved in numerous biological processes and is a critical ligand that complexes, transports and concentrates a wide range of metals in hydrothermal fluids and silicate melts. As a result, sulfides play a key role in the formation of numerous world-class mineral systems, including gold, nickel, copper and the platinum group elements. However, even if the scientific community broadly agrees that sulfur most likely played a crucial role in the establishment of the first forms of proto-life, the relationship between the global sulfur cycle and the evolution of the biosphere-atmosphere-hydrosphere-lithosphere in the Early Earth is still a hot topic of debate. The entire day was a great success.

Activity	Details & Participant/s	Date
CCFS Centre Research Meeting	**CCFS MQ** hosted the Centre-wide Research meeting (See *p. 5*)	3-4 July 2014
Short Course for Precambrian Centre in Beijing, China	**Sue O'Reilly** and **Bill Griffin** were appointed Short Course presenters for Geochemistry	September 2014
IUCES Summer School "*Water in Geological Processes*" at China University of Geosciences, Wuhan	**Sue O'Reilly** and **Bill Griffin** were presenters	8-15 September 2014
Postgraduate Seminar Day	Organised by the MQ Department of EPS featuring presentations and posters from EPS and **CCFS PhD students**	19-20 November 2014
Laser Ablation Split Stream Petrochronology Workshop	Hosted by **CCFS CU node**	29 September - 1 October 2014
Plumes or Plates in the Archean: How far does uniformitarianism apply in Archean tectonics? Archean Tectonics Debate and Symposium	Organised by **Weronika Gorcsyk** and Steve Barnes (CSIRO) Well attended with over 80 participants	27-28 November 2014

Dr Weronika Gorcsyk and Dr Steve Barnes (CSIRO) organised a very well attended and exciting debate on Archean tectonics. It has long been debated how far back in Earth's history plate tectonic processes have operated. Until the late 1980's, many geologists considered that plate tectonic activity only operated in the past 1 Ga. Since then, new discoveries have pushed back the envelope to the early Archean. This is a matter of continued dispute and is currently unresolved. Understanding of dynamic Archean tectonics is critical for comprehending the evolution of the Australian continent, and processes that led to the formation of world-class gold and base metal provinces. Recent advances in geophysics, geochronology and geochemistry have opened up new ideas and interpretation of tectonic evolution in the Archean. These were discussed and debated during the two day event.

SELECTED WORKSHOP ROLES *cont...*

Activity	Details & Participant/s	Date
CET Corporate Members Day	Organised by **Cam McCuaig** and **Marco Fiorentini**	9 December 2014
1st Australian Workshop for Early and Mid-Career Geoscientists	Hosted at **CCFS MQ node** and **sponsored by CCFS** Organised by **Juan Carlos Afonso**, Fabiao Capitanio (Monash), **Chris Clark**, **Heather Handley**, Giampiero Iaffaldano (ANU), Stephan Thiel (U. Adelaide) Attended by ~85 participants	1-2 December 2014

The workshop brought together Australian Early and Mid-Career Geoscientists (EMCG) working in universities, government institutions, and the industry sector to discuss current and future challenges and opportunities for EMCGs in Australia. The overarching goals of the workshop were to harness the potential of EMC geoscientists in Australia and to 1) Establish a national network of EMCGs to foster collaboration and provide support and guidance to ECRs. 2) Discuss the role of EMC geoscientists in contributing to the development of community-based research objectives that address current Australian needs (both industry and academic). 3) Discuss strategies for funding to improve geoscience research capacities in Australia. 4) Promote opportunities for recruitment support and advancement within Australia and abroad. 5) Discuss Mid- and long-term research strategies to maintain the productivity, originality and success of the Australian Geoscience community at the highest level.

AWARDS

Activity	Participant/s
MQ Vice Chancellor's Citation for Excellence in Learning and Teaching	**Kelsie Dadd**
The 2014 UWA Vice-Chancellor's Mid-Career Research Award	**Marco Fiorentini**
CET Science Day - Awarded Best student poster	**Christopher Gonzalez**
Awarded the Clark Medal from the Royal Society of New South Wales	**Bill Griffin**
Only Australian Geoscientists listed in Thomson-Reuters Highly-Cited Researchers, 2014: http://highlycited.com	**Bill Griffin, Zheng-Xiang Li, Simon Wilde**
Tall Poppy Award	**Heather Handley**
Visiting Professorship, University of Lorraine, Nancy, France	**Cam McCuaig**
Nominated for UWA Vice-Chancellor's Award in Research Mentorship	**Cam McCuaig**
Nominated by UWA for the Western Australian Scientist of the Year Award	**Cam McCuaig**
Awarded AESC student scholarships from GSA - NSW division	**Nicole McGowan**
Elected to Australian Academy of Sciences Council	**Sue O'Reilly**
2014 Macquarie University's 3MT (3 Minute thesis) - won Faculty competition and the People's Choice award in the University final	**Irena Tretiakova**
Distinguished Professor Award recipient	**Simon Turner**
2014-2018 - ARC Future Fellows	**Xuan-Ce Wang, David Wacey**
2013 Curtin Early Career Research Highest Research Performance Index Award	**Xuan-Ce Wang**
Geophysics Journal International: Outstanding Reviewers 2014	**Yingjie Yang**
Awarded 2015 Anton Hales Medal for research in earth sciences	**Yingjie Yang** *(right)*

OUTREACH

Forum	Participant/s	Date
Public lecture entitled *"Archean komatiite volcanism and ore genesis controlled by the evolution of early continents"*, held within the forum of the IS Grand Terre public monthly seminars at the University of Grenoble, France	**Marco Fiorentini**	January
Lecture at UWA's School of Earth and Environment's *"DEE-TALKS"* about working in Canada's Yukon Territory as an exploration geologist - *"Fear and Loathing in the Land of the Midnight Sun"*	**David Stevenson**	April
Spoke at *Women in Science* careers night, Macquarie University	**Kelsie Dadd**	May
Participated in *My Science* mentoring program at West Epping School	**Kelsie Dadd**	May
Public lecture *"Sulfur degassing and nickel-sulfide ore-forming process in Archean komatiite volcanoes"*, UWA	**Marco Fiorentini**	May
Australian Earth Sciences Convention, Newcastle, Public talk, Newcastle Museum: Van Kranendonk, M.J., *"Making the sky blue: The early history of life and the rise of complex life"*	**Martin Van Kranendonk**	July
Australian Earth Sciences Convention, Newcastle, Organiser, Geological Society of Australia sponsored Public Forum on *"Energy 2050: The Future of Energy in Australia"*	**Martin Van Kranendonk**	July
Participated in *"Girls in Science Night"* at Seaforth Public School aimed at enhancing science in education at the secondary level	**Tracy Rushmer**	August
Public Lecture - Knox Grammar School, *"The geologist"*	**Sandra Piazolo**	September
Invited talk at *"Young Mineralogist Organisation"* - *"How mantle is attractive - The research life in France and Australia."* This talk was provided for young people interested in Earth Sciences.	**Takako Satsukawa**	September
CET Member's Day Presentation *"Isotopic mapping and paleogeophysics"*	**Marco Fiorentini**	December
Geological Survey public outreach though numerous stakeholder meetings and direct public engagement	**Chris Kirkland**	2014

2014 APPOINTMENTS AND POSITIONS

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**)
Chris Clark	Invited Early-Mid career representative, Australian Academy of Science National Committee for Earth Sciences
Ian Fitzsimons	Fellow of the Geological Society, London Fellow of the Mineralogical Society
Bill Griffin	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), 2014
Matt Kilburn	Visiting Professorship, Technische Universität München Dec 2014
Yongjun Lu	Appointed Associate Editor for SEG 2016 Special Publication on Tethys

Craig O'Neill	International University Consortium in Earth Science (IUCES) MQ colleague
Catherine McCammon	President, Volcanology, Geochemistry and Petrology section of the American Geophysical Union
Cam McCuaig	Invited member, Science Committee, UNCOVER
Sue O'Reilly	Member of the ARC ERA Reference Working Group 2013-2014 Chair, Australian Academy of Sciences National Committee, Earth Sciences Member Executive Committee, UNCOVER national initiative (auspices of the Australian Academy of Sciences) Appointed member NSW Minerals Council Taskforce for the Minister for Resources and Energy (for the Hon Anthony Roberts MP, 2014) Member of the Academy of Sciences Working Party for the Chief Scientist on the Economic Value of STEM to Australia (2014) Member, 2015 ERA Research Evaluation Committee
Tracy Rushmer	Appointed member of the Program Advisory Committee - Australian Synchrotron Appointed as Associate Dean of Higher Degree Research at Macquarie University
Martin Van Kranendonk	Chair of the Precambrian Subcommission of the International Commission on Stratigraphy Co-Director, Australian Centre for Astrobiology
Xuan-Ce Wang	Appointed as an Adjunct Research Professor - Guangzhou Institute of Geochemistry, Chinese Academy of Sciences

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


Kondyor, Russia

MEDIA

Activity	Participant/s	Date, Forum	Web address
Geotalk: The mantle and models and measurements, oh my! Talking geophysics with Juan Carlos Afonso	**Juan Carlos Afonso**	27/03/2014, GEOLOG (The Official Blog of the European Geosciences Union)	http://geolog.egu.eu/2014/03/27/geotalk-the-mantle-and-models-and-measurements-oh-my-talking-geophysics-with-juan-carlos-afonso/
Rocks get super-heated to 1000°C under new mountains	**Chris Clark & Mike Brown**	20/11/2014, BBC	http://www.bbc.com/earth/story/20141120-the-hottest-part-of-earths-crust
QS World - Macquarie University was the only university to achieve two top five positions in philosophy and earth and marine sciences University Ranking by Subject - MQ with 2 x top 5	**MQ - EPS**	26/02/2014, The Australian	The Australian, Australia, by Julie Hare, Higher Education, p. 25
Mars prospectivity	**Marco Fiorentini**	June Issue, CET Quarterly News	
Hottest lava eruption linked to growth of first continents	**Marco Fiorentini**	24/06/2014, UWA media release	http://www.news.uwa.edu.au/201406246782/research/hottest-lava-eruption-linked-growth-first-continents
Hydrothermal remobilisation of nickel-sulfide systems	**Marco Fiorentini**	September Issue, CET Quarterly News	
Frontiers in Mineral Exploration	**Marco Fiorentini, Raphael Baumgartner, David Wacey**	7/11/2014, UWA media release	http://www.news.uwa.edu.au/201411077104/business-and-industry/frontiers-mineral-exploration
De gisements de metaux sur Mars	**Marco Fiorentini**	11/11/2014, IRD media release	http://www.obs-mip.fr/actualites/actualites-scientifiques/gisements_metaux_mars
Red rovers meet the ultimate outback challenge	**Simon George**	8/09/2014, The Age	http://www.theage.com.au/national/education/red-rovers-meet-the-ultimate-outback-challenge-20140905-10cth7.html
Finding the world's oldest fossils the Flinders Ranges	**Simon George**	9/09/2014, 639 ABC North and West	http://www.abc.net.au/local/photos/2014/09/09/4083966.htm
Four of our best make World's Most Influential Minds list	**Bill Griffin, Simon Wilde, Zheng-Xiang Li**	14/07/2014, This Week at MQ	http://mq.edu.au/thisweek/2014/07/14/four-of-our-best-make-worlds-most-influential-minds-list/#.VGltm1OUeiM
Young tall-poppy science awards for astronomer and volcanologist	**Heather Handley**	11/11/2014, MQ Newsroom	http://mq.edu.au/newsroom/2014/11/11/young-tall-poppy-science-awards-for-astronomer-and-volcanologist/
Light and lava	**Heather Handley**	16/11/2014, This Week at MQ	http://mq.edu.au/thisweek/2014/11/16/light-and-lava/
World's oldest rocks spark discussion on origin of life	**Craig O'Neill**	11 April 2013, ABC News in Science	http://www.abc.net.au/science/articles/2013/04/11/3734009.htm
Expert reaction: Earthquake in California, Australian Science Media Centre	**Craig O'Neill**	25/08/2014, aus/SMC Australian Science Media Centre	http://www.smc.org.au/2014/08/expert-reaction-earthquake-in-california-experts-respond/

Promoting service and engagement	**Craig O'Neill**	16/11/2014, This Week at MQ	http://mq.edu.au/thisweek/2014/11/16/promoting-service-and-engagement/#.VGlcnlOUeiM
Eminent geologist joins Australian Academy of Science Council	**Sue O'Reilly**	14/11/2014, MQ Newsroom	http://mq.edu.au/newsroom/2014/11/14/eminent-geologist-joins-australian-academy-of-science-council/
Eminent geologist joins Australian Academy of Science Council	**Sue O'Reilly**	14/11/2014, Australian Academy of Science News	https://www.science.org.au/news/eminent-scientists-join-academy-leadership-1
Early start for plate tectonics	**Simon Turner**	14/01/2014, Chemistry World	http://www.rsc.org/chemistryworld/2014/01/early-start-plate-tectonics-subduction
Study of Earth's crust tells of first plate tectonics and life on Earth	**Simon Turner**	30/01/2014, MQ Newsroom	http://www.mq.edu.au/newsroom/2014/01/30/study-of-earths-crust-tells-of-first-plate-tectonics-and-life-on-earth/
Old rocks open new debate on life's origins	**Simon Turner**	4/02/2014, The Australian	http://www.theaustralian.com.au/higher-education/old-rocks-open-new-debate-on-lifes-origins/story-e6frgcjx-1226816899290?nk=e7382f281f6dfa8292380c1a0dd72db3
Earth's crust tells a different story	**Simon Turner**	7/02/2014, Science Alert	http://www.sciencealert.com.au/news/20140702-25223.html
The Dawn of Plate Tectonics	**Simon Turner**	19/02/2014, Science Magazine - Latest News	http://news.sciencemag.org/earth/2014/02/dawn-plate-tectonics
World's oldest rocks spark discussion on origin of life	**Simon Turner**	21/02/2014, Iowa Now	http://now.uiowa.edu/2014/02/worlds-oldest-rocks-spark-discussion-origin-life
Analysis of rock sequences in Quebec and Japan -continental drift	**Simon Turner**	26/02/2014, 702 ABC Sydney	702 ABC Sydney
Conditions for Creation	**Simon Turner, Tracy Rushmer and colleagues**	1/07/2014, Australasian Science	http://www.australasianscience.com.au/article/issue-julyaugust-2014/conditions-creation.html
Distinguished Professor Simon Turner	**Simon Turner**	24/10/2014, Research Impact MQ	http://mq.edu.au/research-impact/2014/10/24/distinguished-professor-simon-turner/#.VGlxZ1OUeiN
Filmed part of a documentary for PBS USA - on "*The evolution of Minerals*", together with Professor Bob Hazen, Carnegie Institution of Washington	**Martin Van Kranendonk**	to be aired in 2015, PBS USA	N/A to be aired in 2015
Academy awards recognise outstanding science researchers	**Yingjie Yang**	25/11/2014, MQ Newsroom	http://mq.edu.au/newsroom/2014/11/25/academy-awards-recognise-outstanding-science-researchers/#ixzz3K8ZRGTol

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*.

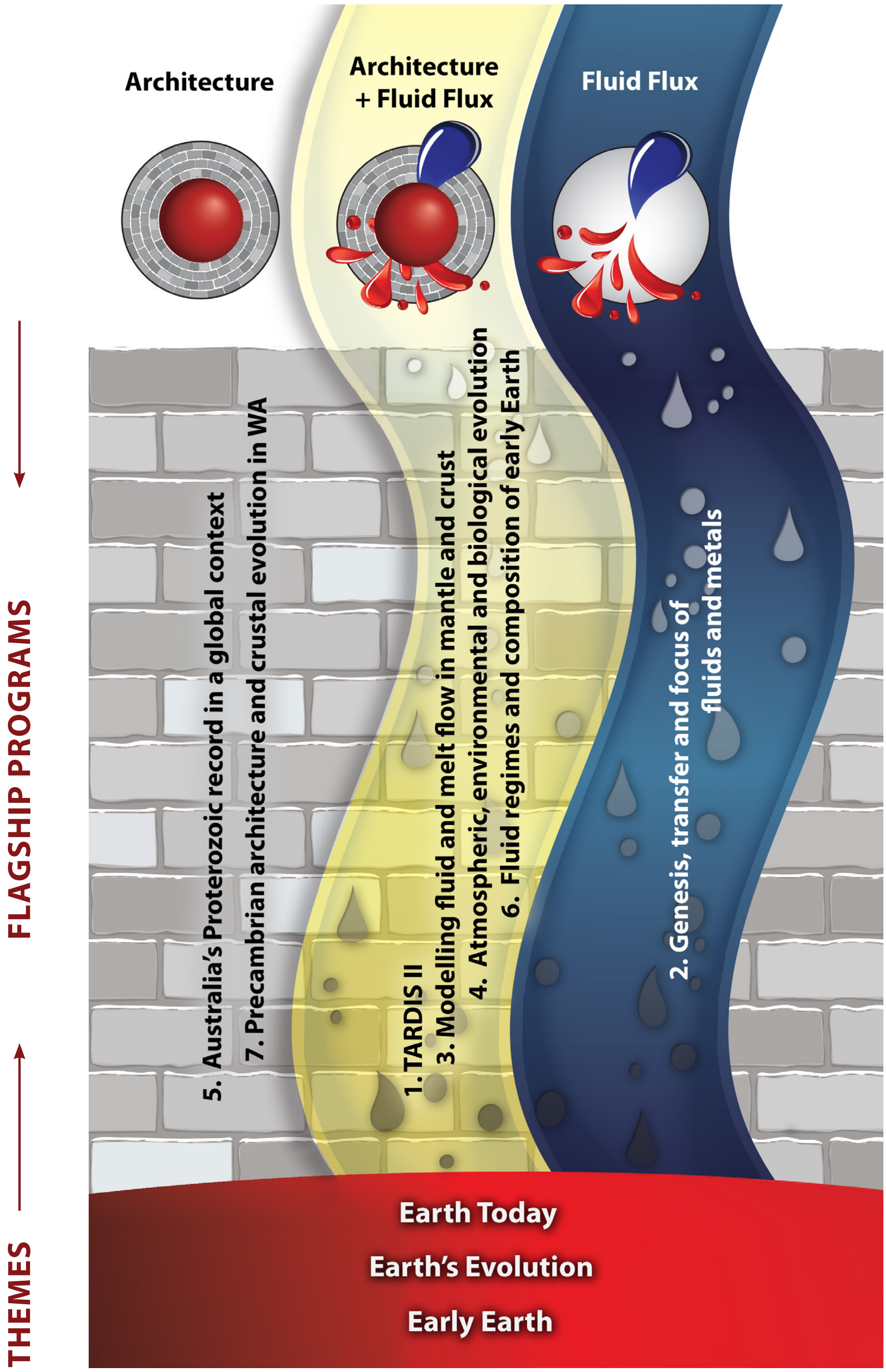
They have participated in:

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

Martin Van Kranendonk during filming of a PBS documentary to air in 2015.

Research highlights 2014

Following the new conceptual framework outlined on *page 4*, 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 Programs, see *Appendix 1* and for the Flagship programs see *Appendix 2*.



Mineral exploration - Out of this world

Evaluating whether magmatic sulfide mineralisation exists on Mars can enhance our fundamental understanding of the processes that govern the evolution of such mineral systems on Earth - thus improving the scientific foundation upon which mineral exploration models are built. Understanding how and where potential ore-forming processes occurred on Mars is relevant both to long-term planning for future missions to the planet, and to designing exploration criteria for certain sample-return programs.

Widespread volcanic activity, showing striking mineralogical, petrographical and chemical similarities to terrestrial komatiites and ferropicrites, reshaped and buried the primary Martian crust. We have evaluated (CCFS *publication #508*) whether this igneous activity may have led to the formation of orthomagmatic Ni-Cu±(PGE) sulfide mineralisation similar to that associated with terrestrial komatiites and ferropicrites. Particular emphasis was focused on two different components of the Martian Ni-Cu±(PGE) sulfide mineral system: 1) the potential metal and sulfur fertility of mantle sources and derived melts, and 2) the physicochemical processes that enable sulfide supersaturation and batch segregation of metal-rich sulfide liquids.

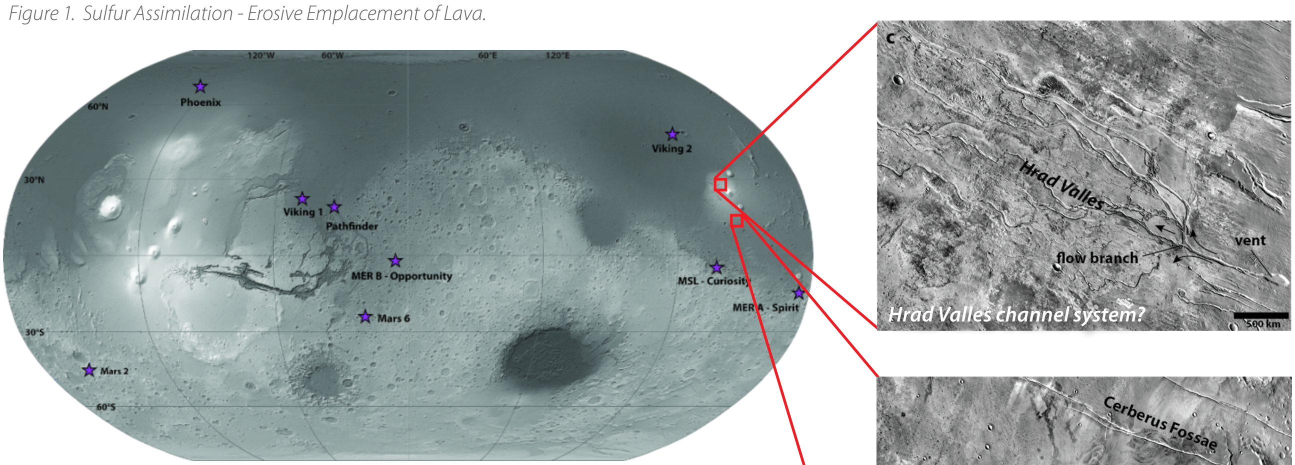
We found that potentially metal-rich Martian mantle melts probably reach sulfide saturation within 30 wt% crystal fractionation. This value is comparable to that calculated for the mineralised ferropicrites at Pechenga, Russia. However, most known world-class Ni-Cu±(PGE) sulfide deposits associated with terrestrial komatiites and ferropicrites originated due to the assimilation of crustal sulfur-rich substrates. This assimilation promoted sulfide supersaturation and batch segregation of metal-rich sulfide liquids during the early stages of magma evolution. Given the high sulfur inventory of Martian crustal reservoirs, ranging from sulfide-bearing magmatic rocks to sulfate-rich soils, regoliths and sedimentary deposits, mantle-derived melts could have assimilated significant amounts of crustal sulfur during ascent and emplacement. We therefore have proposed that channelled lava flows, which were potentially emplaced on and incised into sulfur-rich crustal lithologies, may have led to the formation of orthomagmatic Ni-Cu±(PGE) sulfide mineralisation on Mars.

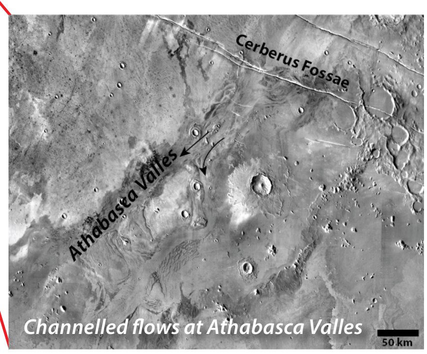
This project is part of CCFS Theme 1, Early Earth, and contributes to understanding Fluid Fluxes.

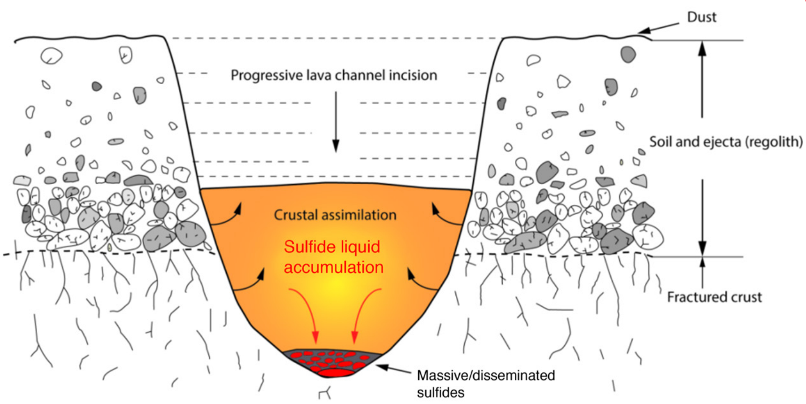
Contact: Marco Fiorentini

Funded by: CCFS Flagship Program: Atmospheric, environmental and biological evolution

Figure 1. Sulfur Assimilation - Erosive Emplacement of Lava.







Cross section through a Martian lava channel.

Scoping heat and composition in the depths below Central-Western US

Despite many geological and geophysical studies, the tectonic evolution of the Central-Western US region remains contentious. One of the major questions is the cause and timing of the uplift of the Colorado Plateau. Does the Plateau reflect mainly deep processes (e.g. large-scale dynamic topography) or shallow convection and heating? At least part of the controversy stems from the fact that studies of very different types (i.e. inversion of seismic data, numerical simulations, geochemical studies, electromagnetic studies), with different resolutions and sensitivities to the thermochemical structure of the Earth's interior have been used in isolation to explain the same observations. There is no *a priori* reason, however, why the results from these diverse studies should be strictly comparable, consistent or compatible, despite the fact that they all sample the same structure. Vastly different mechanisms can explain some observations (e.g. plateau elevation) equally well, and this does not inspire confidence in our understanding of important features of the Earth's interior. This raises the question as to what extent different models are actually supported or required by independent geophysical, geological, and geochemical evidence.

Here we apply an innovative 3D multi-observable probabilistic inversion method ("*thermochemical tomography*") using high-quality geophysical, geochemical and geological datasets to image the thermochemical structure of the Central-Western US. Working within this internally and thermodynamically consistent framework allows us to move beyond traditional methods and jointly use P-wave and S-wave teleseismic arrival times, Rayleigh wave phase dispersion data, Bouguer anomalies, long-wavelength gravity gradients, geoid height, absolute (local and dynamic) elevation, and data on surface heat flow. In our methodology, all physical and chemical parameters controlling model predictions are linked together by fundamental thermodynamic relations; the only independent variables in the inversion are therefore temperature, pressure and major-element composition. Accordingly, traditional tomographic images and models (e.g. S-wave velocity) are a by-product of our inversion rather than the main result.

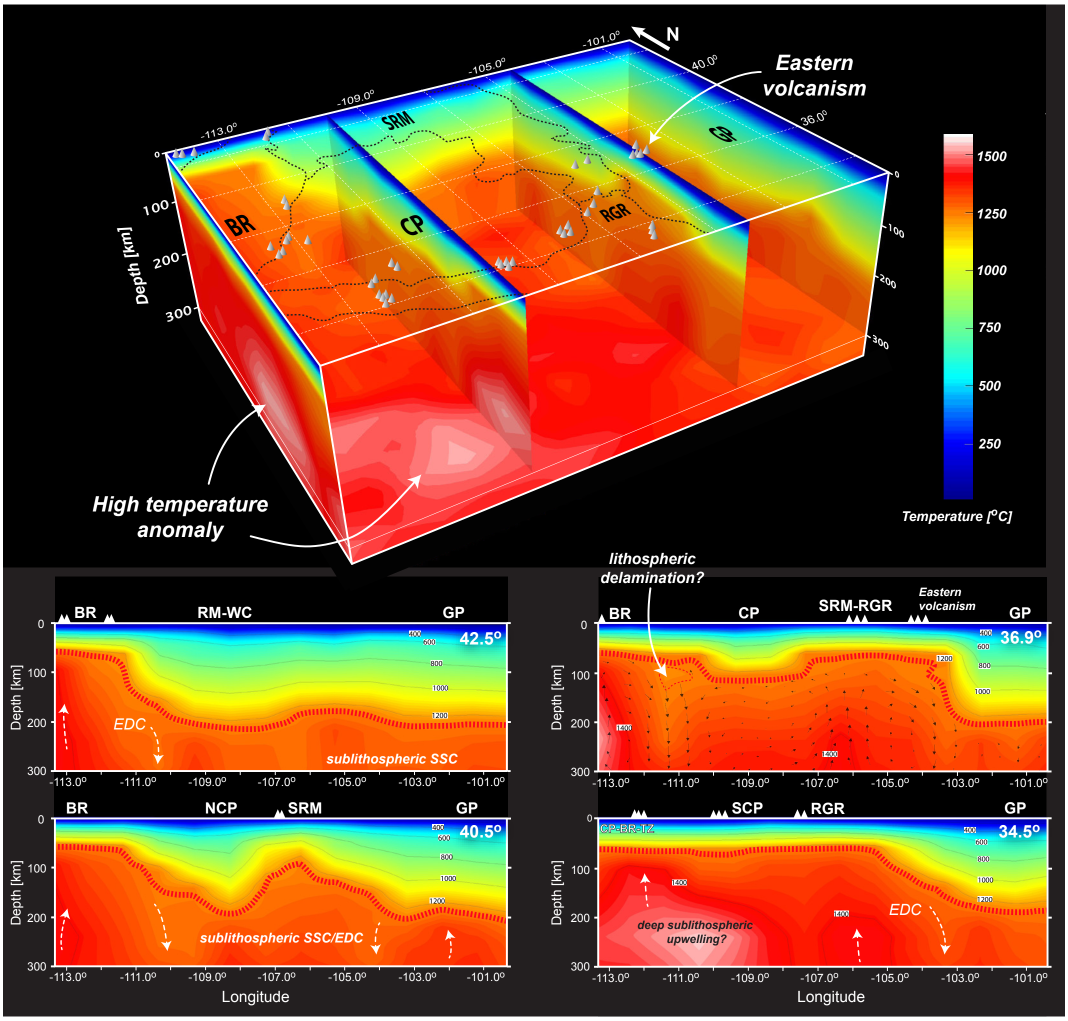


Figure 1. Top: Three-dimensional rendering of the thermal structure beneath Central-Western US. Major volcanic localities are indicated as white cones. Bottom: Temperature structure along four transects. The LAB is indicated by the thick red dashed line. Clear indications of both edge-driven convection (EDC) and sublithospheric small-scale convection (SSC) are visible in these transects. Cross-section at 36.9° includes the full instantaneous sublithospheric flow (as transparency); a clear downwelling is imaged beneath the western edge of the CP. SRM-WC = Southern Rocky Mountains-Wyoming Craton; NCP = Northern Colorado Plateau; SCP = Southern Colorado Plateau; BR = Basin and Range; RGR = Rio Grande Rift; GP = Great Plains.

We emphasise here that the thermal (and compositional) structure outcome is driven entirely by the constraining datasets. Thus, although we solve the 3D Stokes equations to obtain the instantaneous mantle flow and dynamic pressures arising from specific thermochemical structures required by data fits, small-scale convection patterns emerge only from the inversion of data, and are not imposed by flow computations. That makes it remarkable that cells of small-scale upwelling and downwelling (particularly beneath the Colorado Plateau region) with wavelengths of 200-300 km are recovered in the inversion (Fig. 1). These are the natural wavelengths of convection cells in the upper mantle. Our results demonstrate that the edges of the Colorado Plateau are being eroded by delamination and/or edge-driven downwellings. These downwellings transfer material from the lower parts of the lithospheric mantle to the upper sublithospheric mantle, changing its mean temperature and composition. This explains why the highly depleted nature of the uppermost lithospheric mantle becomes more obvious in regions where the Colorado Plateau lithosphere has been thinned or eroded by downwellings without associated volcanism.

Most of the present-day elevation in the Colorado Plateau area can be explained by a combination of lithosphere composition, crustal thickness and density structure, and thermal state, with only moderate localised contributions from sublithospheric upper-mantle convection. This analysis does not preclude the existence of deeper dynamic components, but it shows that large dynamic effects are not required to explain the available data. Our results therefore support models that require a net gain of lithospheric buoyancy since Laramide times.

The results reported here demonstrate that multi-observable thermochemical tomography described here, offers a robust method to characterise the fine-scale thermochemical structure of the lithosphere and upper mantle and opens new opportunities for deep-Earth imaging. The probabilistic nature and internally-consistent use of a number of key constraining datasets, all linked through a thermodynamic framework, gives the new method a unique sensitivity to thermal and chemical signatures that are otherwise difficult to assess unambiguously. This method allowed us to capture the complex interaction of structure and processes responsible for the present-day elevation of the Colorado Plateau, as well as directly imaging the dynamic behaviour of the upper mantle beneath the Central-Western US which, until now, has only been speculated upon, based on indirect proxies.

The intricate thermochemical structure of the lithospheric mantle seems to be linked more closely to interactions with the sublithospheric mantle via small-scale convection, melt production, and refertilisation of the lithospheric mantle rather than to physiographic or surface structures. Such interactions are likely to be key global and recurrent factors controlling the tectonic evolution of continental interiors and intra-plate epeirogenesis.

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

Contacts: Juan Carlos Afonso, Yingjie Yang
Funded by: ARC Discovery Project (DP120102372)

Giant porphyry copper deposits on the roof of the world

The Gangdese porphyry copper belt in southern Tibet, the roof of the world, is the most metal-rich porphyry copper system known from a continental collision zone. Numerous porphyry copper-molybdenum-gold (Cu-Mo-Au) deposits in this region contain over 20 million tons (Mt) of copper.

These porphyry Cu deposits are genetically associated with dacitic-rhyolitic (SiO_2>63 wt%) magmas with unusually high Sr/Y ratios (>40), which have been attributed to dehydration melting (no free water) of garnet amphibolites in a thickened lower crust beneath Tibet. To test this hypothesis and examine the hydration state of these magmas, we developed a geohygrometer for granitoid rocks, combining zircon-saturation thermometry and H_2O-dependent phase equilibria (Fig. 1).

The results show that the Tibetan high-Sr/Y ore-forming magmas had dissolved H_2O contents >10 wt% (Fig. 1). This is far more water than can be supplied by dehydration melting of basaltic amphibolites (maximum of 6.7 ± 1.4 wt%; Fig. 2).

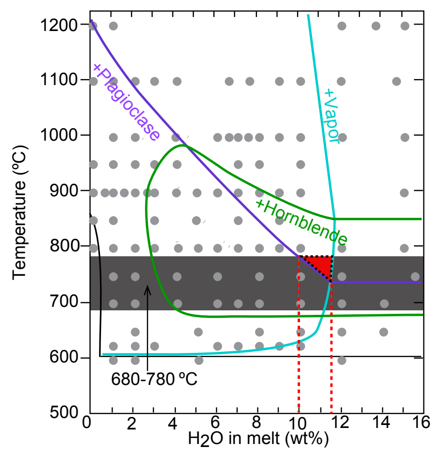


Figure 1. Temperature vs H_2O plot. Each grey circle represents an experiment in which the stable mineral phases were identified in run products by Naney (1983; American Journal of Science, 283, 993-1033). Only the plagioclase (blue), hornblende (green) and vapour (turquoise) saturation curves are shown for clarity. The grey band is the range of zircon-saturation temperatures for Tibetan ore-forming high Sr/Y porphyries and the dashed red triangle is the field of the Tibetan ore-forming dacitic porphyries. The H_2O contents in these ore-forming magmas are thus estimated to be at 10-12 wt% (red dashed lines).

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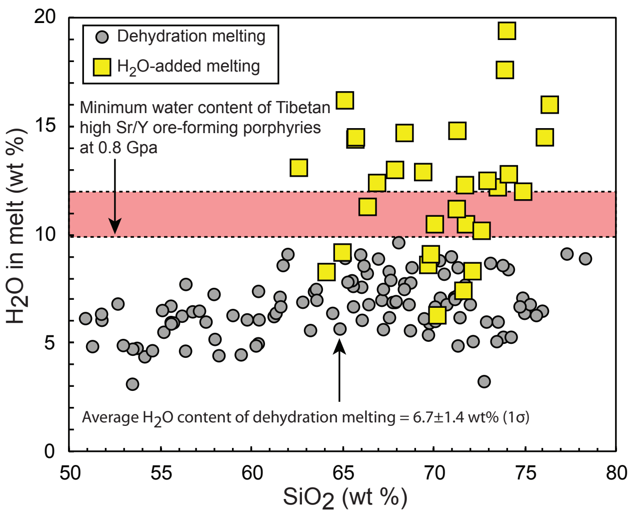


Figure 2. H_2O vs SiO_2 (wt %) in melts from H_2O-absent and H_2O-added experimental melting of basaltic amphibolite. The pink band highlights the minimum water content (10-12 wt %) of Tibetan copper-ore-forming porphyries.

Melting basaltic amphibolites in the presence of H_2O can produce high Sr/Y hydrous dacitic-rhyolitic melts (Fig. 2), but only with lower Mg# (>50), MgO and Cr contents than the Tibetan ore-forming porphyries (Fig. 3). Mafic microgranular enclaves (MMEs) have been reported from several Miocene porphyry Cu-Mo deposits in southern Tibet, which have much higher Mg#, MgO and Cr contents than partial melts of mafic lower crust (Fig. 3). These cognate enclaves, derived from metasomatised Tibetan mantle, represent quenched mafic magmas, injected into the porphyry-forming felsic magmas. They typically define fractionation trends and Sr-Nd-Hf isotopic compositions that relate them to the Tibetan ore-forming porphyries.

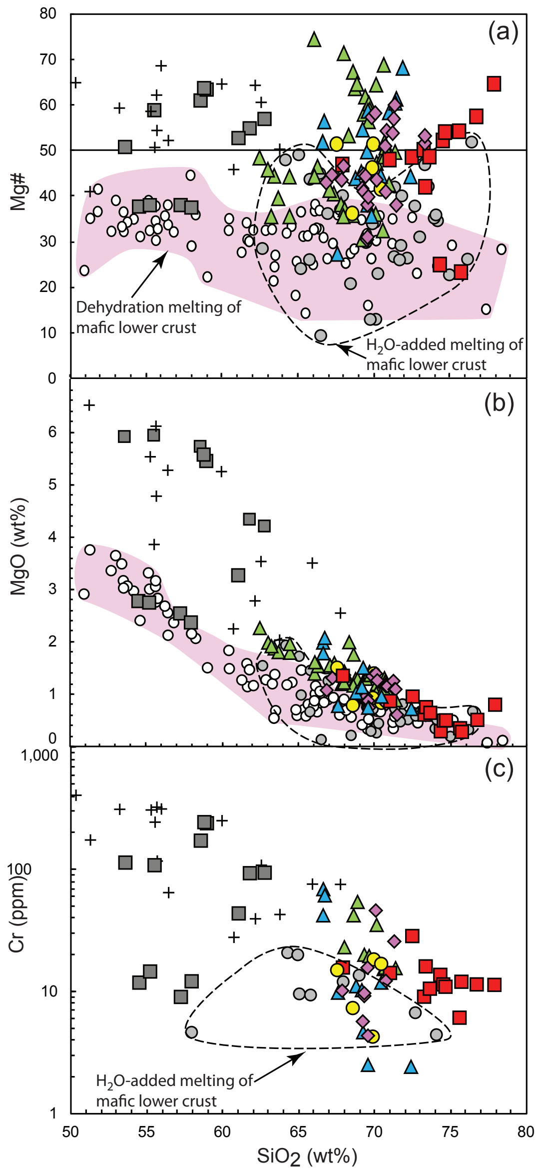
These observations suggest an alternative model for the genesis of copper-rich high-Sr/Y magmas: they are residually H_2O-enriched, high-pressure differentiation products of hydrous mafic partial melts of Tibetan mantle. The mid-Miocene stress regime was more compressive in the eastern portion of the Gangdese belt (where these porphyry copper deposits form) than in the western parts, where Miocene N-S trending rifts are abundant. The mafic magmas thus would tend to underplate the crust and differentiate and assimilate there until relatively silicic, hydrous residual melts have acquired sufficient buoyancy to overcome the compressive stress regime. During the high-pressure differentiation of mafic magmas, the resultant felsic magmas become rich in copper and water, so when they eventually reach the upper crust, they can form giant copper deposits.

Our new model implies that porphyry Cu deposits in continental collision zones have similar origins to those in other tectonic settings such as the circum-Pacific magmatic arcs. Therefore, a universal exploration model may be applied to search for porphyry deposits all over the world.

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: Yongjun Lu, Marco Fiorentini

Funded by: ARC CCFS ECSTAR funds, CCFS pilot project.



Legend

Miocene ore-forming porphyry in E. Gangdese belt, S. Tibet:

- Qulong
- Jiama
- Nanmu
- Chongjiang
- Tinggong

Mafic Microgranular Enclave (MME) in E. Gangdese belt, S. Tibet:

- Miocene MME within ore-forming porphyry (Yang, 2008; Wu et al., 2014)
- + Oligocene MME within granodiorite and monzogranite (Zheng et al., 2012)

Experimental melts:

- Dehydration melting of mafic lower crust (Sen and Dunn, 1994; Rapp et al., 1991; Rapp and Watson, 1995; Rushmer, 1991,1993)
- H_2O-added melting of mafic lower crust (Winther and Newton, 1991; Winther, 1996; Qian and Hermann, 2013)

Figure 3. (a) Mg# vs SiO_2, (b) MgO vs SiO_2, and (c) Cr vs SiO_2 plots for high Sr/Y Cu-ore-forming porphyries in southern Tibet.

A tale of two rheologies - deformation with and without fluid

Although the amount of free fluid in the Earth's crust is very small, it plays a fundamental role in many geodynamic and geochemical processes. Field studies demonstrate that fluid circulation through the crust mainly occurs through localised sites of intense deformation, such as faults and shear zones. Although in recent years fluid-rock interaction during deformation has been much studied, it is still one of the least understood aspects in crustal tectonics.

The hydrated mid-crustal shear zones in the Wyangala Granite (SE Australia) displays a very localised infiltration of external syn-tectonic fluids, limited to the central domains, while the shear zone margins have remained relatively *'dry'* during the deformation allowing identification of the particular effects fluid exert on the rock rheology (flow behaviour during deformation).

Two cases can be distinguished: (1) the *'fluid-deprived'* shear zone margins preserve many similarities with the wall rock granite, chemically, mineralogically and structurally. The most deformed mineral in these domains is quartz displaying crystallographic preferred orientation and dynamic recrystallisation microstructures, which indicate the dominance of dislocation creep regime (described by a power-law function), which is consistent with the predictions of current theoretical models for the Earth's crust. (2) In the highly hydrated central domains of the shear zone, the granitic host rock is transformed into a fine grained quartz-muscovite phyllonite. During deformation feldspar breaks down into fine-grained muscovite-quartz-epidote aggregates, deformation occurs by pressure-solution creep and grain boundary sliding in the feldspar reaction products, as well as basal slip of muscovite, while remaining quartz porphyroclasts experienced very little deformation. All of these processes are facilitated by fluid and are characterised by a linear creep function resulting in extreme softening and strain localisation.

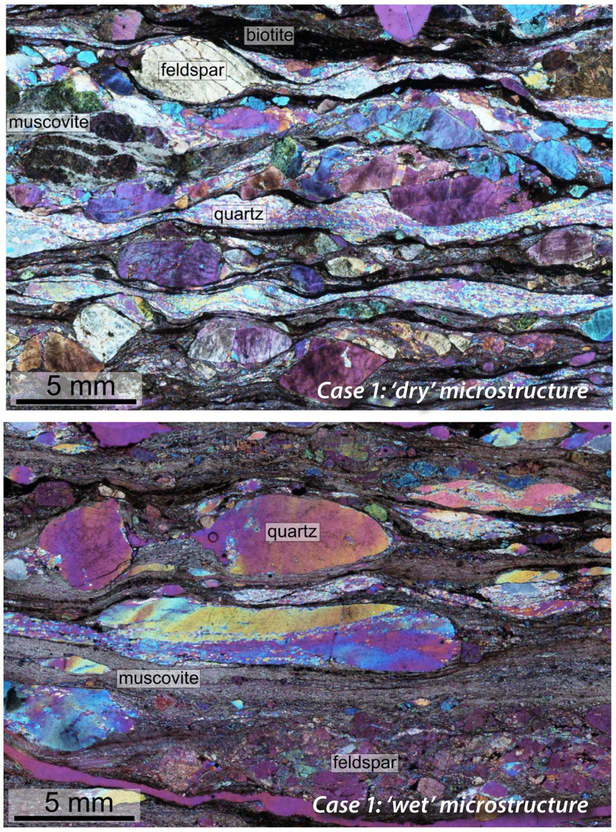


Figure 2. Optical photographs (through gypsum plate) of microstructures developed in a case of (1) 'dry' deformation on the shear zone margins and (2) 'wet' deformation in the shear zone centre.

This study demonstrates the dramatic softening fluids induce on rock rheology, and points out the limited applicability of theoretical models based on dry rheologies for deformation in the Middle crust, where metasomatic fluids are common.

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

Contacts: Liene Spruzeniece, Sandra Piazolo

Funded by: ARC Discovery Project (DP120102060)

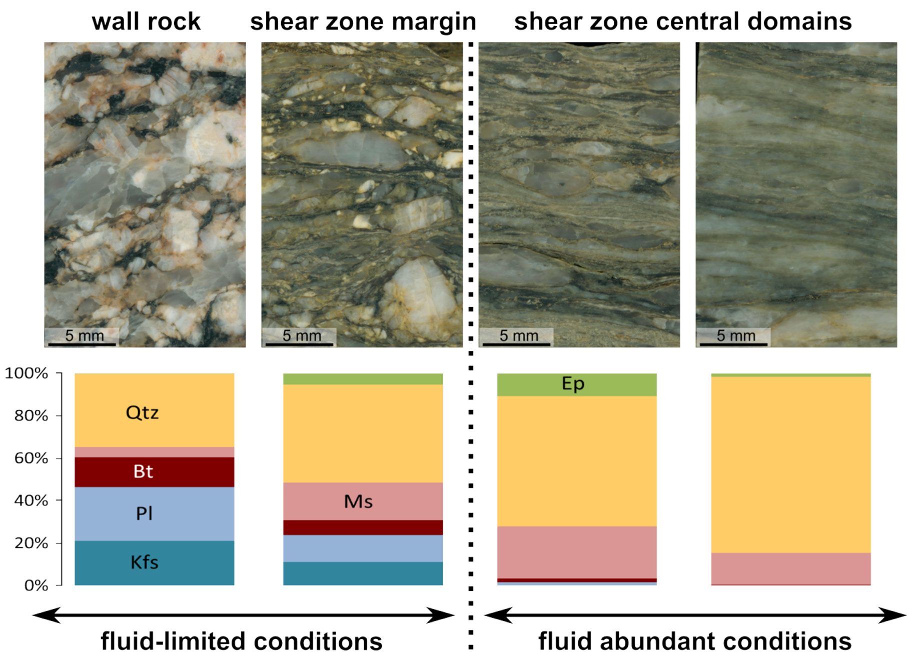


Figure 1. The structural and mineralogical evolution of fabrics across the shear zone.

Dating kimberlites and mantle evolution below southern Africa

Kimberlite magmas represent our best source of information on the composition and evolution of the deep continental lithosphere, but extracting that information can be difficult, because kimberlites typically are jumbled mixtures of the original magma and debris carried up from the mantle. However, perovskite ($CaTiO_3$, with extensive substitution by Sr, U and REE) occurs in many kimberlites as a groundmass phase, early-crystallising in most cases. Its chemistry allows not only U-Pb dating of the kimberlite's emplacement, but Sr- and Nd isotopes carry information on the source(s) of the magma (*CCFS Publication #466*). We have dated groundmass perovskite by LA-ICPMS U-Pb techniques in 135 kimberlites and related

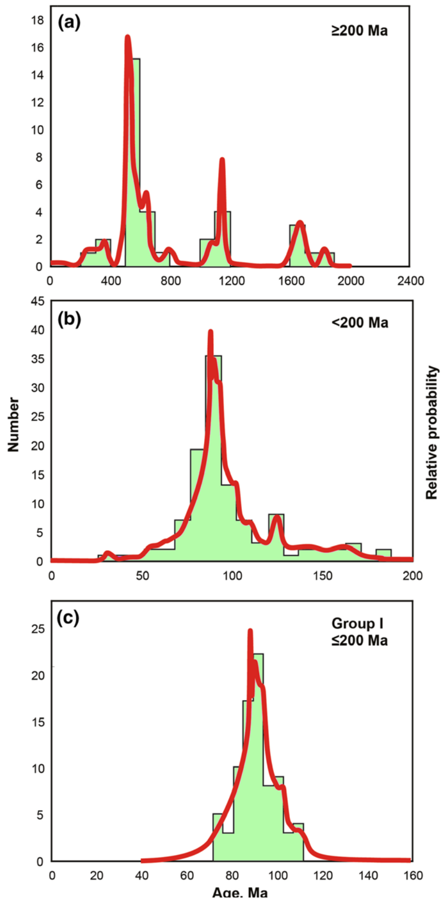


Figure 1. Cumulative-probability plots and histograms for U-Pb ages on perovskites. (a) ages >200 Ma; (b) ages <200 ma, showing buildup to main peak; (c) Group I kimberlites with ages <110 Ma (main pulse) showing abrupt cut-off at <80 Ma.

rocks from 110 localities across southern Africa. Sr and/or Nd isotopes have been analysed by LA-MC-ICPMS in a subset of these; combined with published data this gives ^{89}Sr-age datasets and ^{85}Nd-age datasets. The age distribution (Fig. 1) shows peaks at 1600-1800 Ma, 1000-1200 Ma, 500-800 Ma and 50-130 Ma. The major '*bloom*' of Group I kimberlites at ~90 ±10 Ma was preceded by a slow buildup in magmatic activity that began at ~70 Ma. The main pulse of the cluster of kimberlites at 120-130 Ma (called "*Group II*") was a distinct major episode within this buildup.

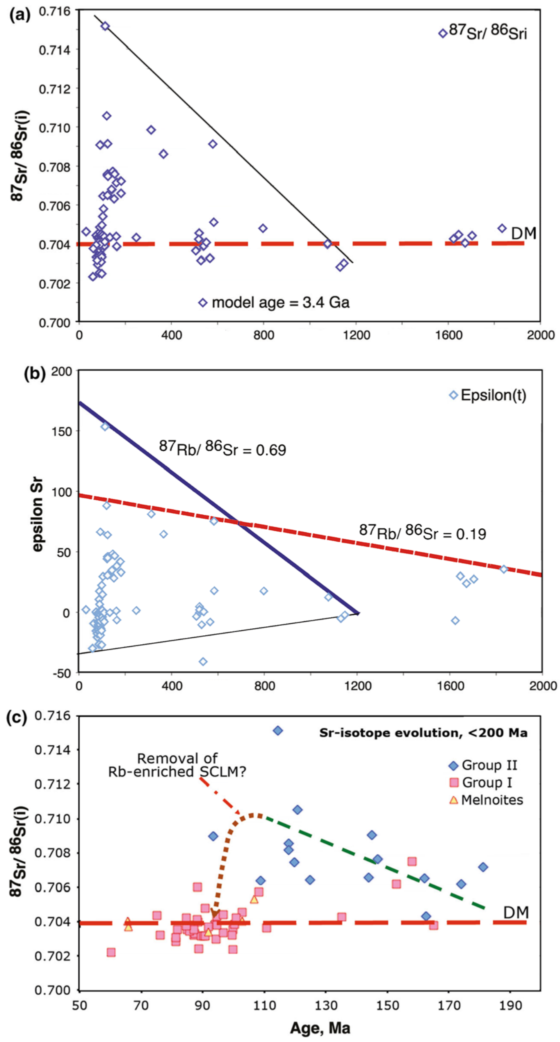


Figure 2. Sr-isotope data for perovskite in the analysed kimberlites, plotted vs time, to show the increased variability of the isotopic signatures of kimberlites toward the present. Heavy lines in (b) show the evolution of the radiogenic Reservoir 1 that could have contaminated the younger kimberlites, assuming that the necessary metasomatism occurred at ca 1.2 Ga or ca 2.0 Ga. Light line in (b) shows the depletion in Rb/Sr (relative to DM) that would be required to produce Reservoir 2 with low $^{87}Sr/^{86}Sr$. (c) shows details of the data for the last 200 Ma, with an interpretation of the data in terms of the destruction of reservoir (1).

The Sr- and Nd-isotope data (Figs. 2 and 3) show that the subcontinental lithospheric mantle (SCLM) sampled by the younger kimberlites was isotopically heterogeneous, and that this heterogeneity reflects a metasomatic refertilisation that may have begun as early as 1.2 Ga ago, but probably was episodic. This metasomatically modified mantle was sampled extensively by the Group II kimberlites that erupted at 120-130 Ma. However, the latest major bloom of Group 1 kimberlites (~90 ±10 Ma) sampled a much more strongly metasomatised mantle.

Figure 4 shows the spatial distribution of εNd and εSr overlain on the seismic-tomography image of southern Africa generated by the Kaapvaal Seismic Project (*Fouch et al., 2004*). The most striking observation from these maps is that the samples with the lowest εNd and the highest εSr are concentrated in three areas: around the low-Vs feature that marks the intrusion path of the Bushveld Complex, along the Kimberley belt, and in the off-craton '*tail*' of kimberlites. The geochemical signature implies long-term geochemical enrichment in the LREE relative to the HREE (and hence low Sm/Nd) and high Rb/Sr. There is an obvious correlation between this clearly metasomatic signature and low Vs, as would be predicted from studies of xenoliths, where this type of trace-element enrichment is associated with higher Fe/Mg, Ca and Al, and lower calculated seismic velocities (*Griffin et al. 2009*).

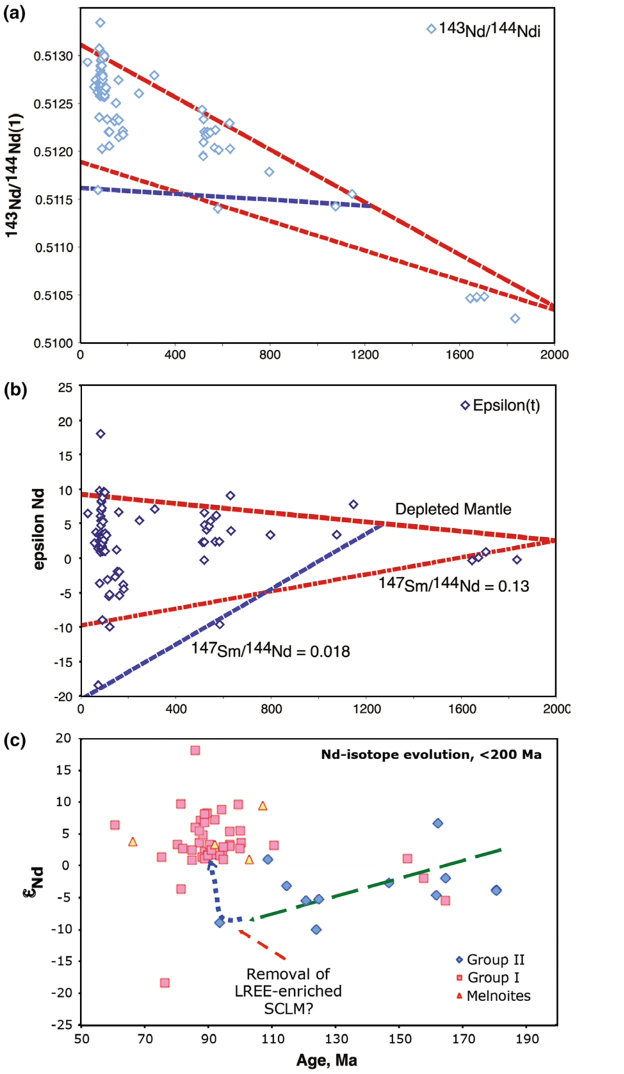


Figure 3. Nd-isotope data from perovskite in the analysed kimberlites, plotted against intrusion age. Dashed lines show the evolution of the depleted mantle, and of volumes metasomatised at ca 1.2 Ga or 2.0 Ga, labeled with the Sm/Nd ratio that would be needed for these volumes to evolve unradiogenic Nd-isotope compositions like those seen in some of the samples. (c) shows details of the data for the last 200 Ma, with an interpretation of the data in terms of the destruction of reservoir (1).

These maps suggest that volumes of metasomatised SCLM with very low εNd and high $^{87}Sr/^{86}Sr$, (the characteristic isotopic signature of Group II kimberlites (~120-130 Ma)), were confined to low-Vs zones along trans-lithospheric structures. These include the locus of the Bushveld intrusion, major faults and craton boundaries. Such metasomatised zones existed as early as 1800 Ma, but were only sporadically tapped until the magmatic buildup began at ca 170 Ma, and apparently were mostly gone by ca 110 Ma. We suggest that these metasomatised volumes resided mainly in the deep SCLM, and that their low-melting-point components were '*burned off*' by rising temperatures, presumably due to an asthenospheric upwelling that led to SCLM thinning and a well-documented rise in the ambient geotherm between 120 Ma and 90 Ma. The younger Group I kimberlites therefore rarely interacted with such SCLM, but had improved access to shallower volumes of differently metasomatised, ancient SCLM with low $^{87}Sr/^{86}Sr$ and intermediate εNd (0-5). The kimberlite compositions therefore record the slow evolution of the SCLM of southern Africa, from 1.8 Ga through a refertilisation event around 1 Ga ago, and a major thermal and compositional change at ca 110 Ma.

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

Contact: Bill Griffin

Funded by: CCFS

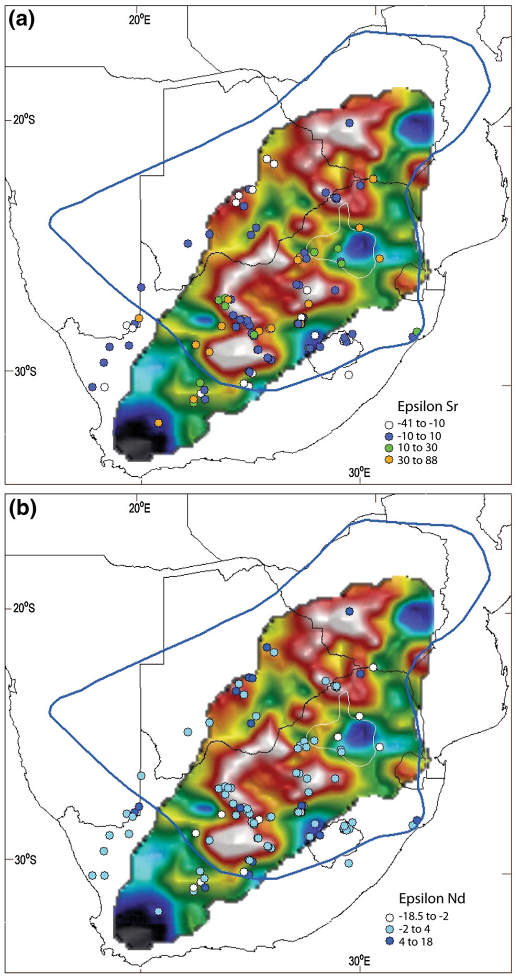


Figure 4. Values of εSr (upper) and εNd (lower) superimposed on the Vs tomography for the 150 km depth slice (after Begg et al., 2009), illustrating the association of metasomatic signatures (high εSr and low εNd) with low-Vs zones and trends. See Figure 2 for discussion of the velocity scales and interpretation of major tomographic features.

The growth of the Tibetan Plateau: the last 25 Myr

The spectacular topography of the Tibetan Plateau (Fig. 1) is the result of collision between India and Eurasia over some 50 Myr, but how did the plateau grow to its present size? Previous work along the eastern Longmenshan margin (LM in Fig. 1) of the Tibetan Plateau suggests a two-stage uplift (thus growth of the plateau) since ~30 Myr: one from 30-25 Myr, and another from 15-10 Myr. Was this just a local feature, or does it reflect plateau-wide episodic lateral growth? We have used high-resolution seismic reflection and drill core data from the southern Tarim Basin to analyse the pattern of plateau growth along the West Kunlun margin (WK in Fig. 1) of the northwestern Tibetan Plateau. The work was carried out through collaboration with Professor Xiao-Dian Jiang of Ocean University of China and published in *Nature Communications* (*CCFS contribution #496*).

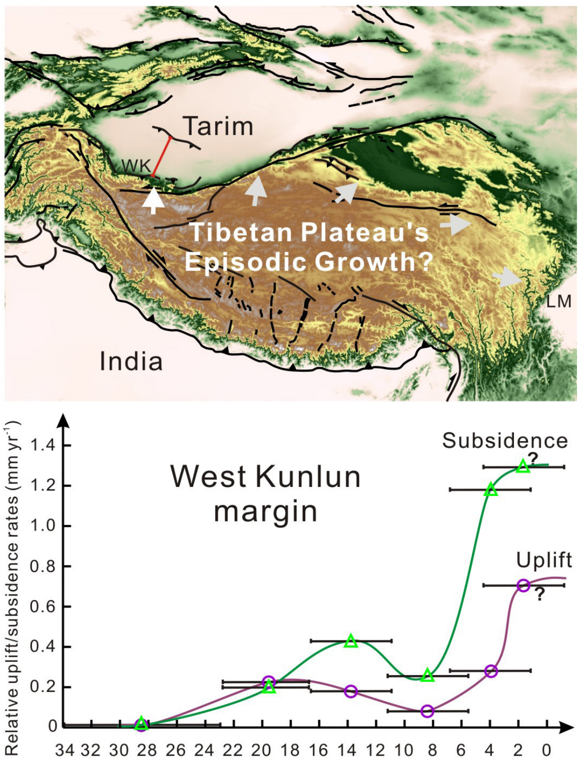


Figure 1. Location of the West Kunlun Range (WK) at the northwestern margin of the Tibetan Plateau, and time variations in estimated relative subsidence and uplift rates. The location of the seismic profile is shown as a red line. LM - the Longmenshan Range.

The continental lithosphere of the Tarim Block underthrusted northern Tibet to its south, with up to 12 km of Cenozoic foreland basin deposits accumulated along the southern Tarim due to the loading of the plateau. These deposits provide a unique record of the history of the mountain building. Seismic reflection and drill hole data were acquired in the foothills of the West Kunlun Range and the southwestern Tarim foreland basin by the Shengli Oilfield Company (location of seismic profile shown by red line in Fig. 1), and were made available for our research. The change in sedimentary environment from a marine carbonate platform in the Oligocene to a clastic tidal flat in the early Miocene marks the beginning of foreland-basin development due to the formation of the proto-West Kunlun Range at the northern edge of the proto-Tibetan Plateau. The temporal variation in the deposition/subsidence rate is taken as reflecting changes in the orogenic loading on the lithosphere of the Tarim Block, which would have resulted in isostasy-driven surface uplift at the present northwestern margin of the Tibetan Plateau. Rate estimates for the depocentre (green curve in Fig. 1) indicate that there have been two episodes of rapid uplift along the West Kunlun Range: one in the mid-Miocene (~16-11 Myr), and the in the last ca 5 Myr; the latter has been significantly faster. Using the differences in thickness between strata on the two sides of a frontal thrust, we calculated the relative uplift rate on the hanging wall as a function of time; this analysis also indicates two episodes of rapid uplift (purple curve in Fig. 1).

Our data thus suggest that the uplift of northern Tibet started from near sea level at ~23 Myr; the first episode ended by ~10 Myr, followed by rapid uplift along the present plateau margin over the last 5 Ma. The contrast in the intensity of the two episodes probably indicates that during the first episode, the front of the proto-West Kunlun orogen at the edge of the plateau was off from its present position, and it only propagated to its present position during the second episode. This two-episode uplift history is comparable to that reported along the eastern margin of the Tibetan Plateau, suggesting that the growth of the Tibetan Plateau after the Eocene likely has been episodic in nature, and near-synchronous along both eastern and northern margins.

Recent work on both margins also suggests that brittle thickening of the upper crust plays the dominant role in plateau propagation along those margins (see *CCFS contribution #223*). There is thus a case for synchronous episodic plateau expansion, dominantly through brittle thickening of the upper crust rather than mechanisms like crustal channel flow.

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

Contact: Zheng-Xiang Li

Funded by: NSFC (40772124 and 41176038), CGS (GZH200900504)

Modelling mantle melting: New horizons

One of the great goals of Geosciences is the explanation of geochemical data consistent with models of the Earth. Models are constrained by physical laws, so successful modelling explanations not only give multifaceted support to our stories about the formation and evolution of rocks, but simultaneously constrain the properties of the deep Earth from which they originate. Our project attempts to develop a new generation of detailed models for grain-scale microstructural evolution and chemical transport in the framework of classical irreversible thermodynamics. We have so far applied the current version of the models to the explanation of Rare-Earth Elements (REE) and Uranium-series isotopes in Ocean Island Basalts (OIB's). Figure 1a illustrates an example of the microstructure showing the 2D distribution of 5 phases (olivine, opx, cpx, garnet, and melt) around the garnet transition, and Figures 1b and 1c show the corresponding distributions of Sm/Yb and $^{228}Ra/^{232}Th$ ratios throughout the microstructure. Because different trace elements are characterised by different partition and diffusion coefficients, very different diffusive features can be seen.

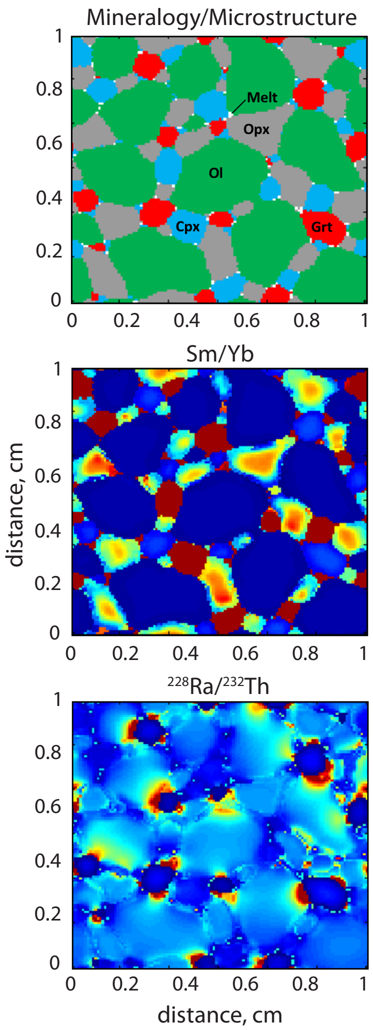


Figure 1.

One success of our modelling efforts is the explanation of REE ratios in OIBs. As shown in Figure 2, if REE ratios are plotted against the age of the lithosphere on which OIB's are erupted, we see step-like features in La/Sm and Sm/Yb ratios, separating low values over young (thin) lithosphere, and higher values on old (thick) lithosphere. The thin black line is a moving average of the data and the bold green line is our best model compared to the data. The fit is impressive, and by inspection of the properties of the model, we can infer the origin of the step-like feature. The step in La/Sm is caused by the onset of anhydrous melting, where melt productivity as a function of depth substantially increases. Sm/Yb, on the other hand, reveals a garnet signature: when oceanic lithosphere is about 15 million years old, it is ~50 km thick, which happens to be the depth at which garnet is stable. As garnet preferentially holds heavy rare earth elements (e.g. Yb) during melting, Sm/Yb is high in magmas derived by melting beneath older lithosphere, and low otherwise.

An interesting consequence of these explanations is that the source of OIB must be at a temperature <1400°C, about the temperature of ambient mantle. If the source were warmer, the models cannot fit the data. In other words, thermal mantle plumes do not appear to be consistent with our analysis. On the other hand, classical thermal plumes may be a rare source of intra-oceanic volcanism.

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

Contacts: Christopher Grose, Juan Carlos Afonso

Funded by: ARC Discovery Project (DP120102372), ARC IPRS

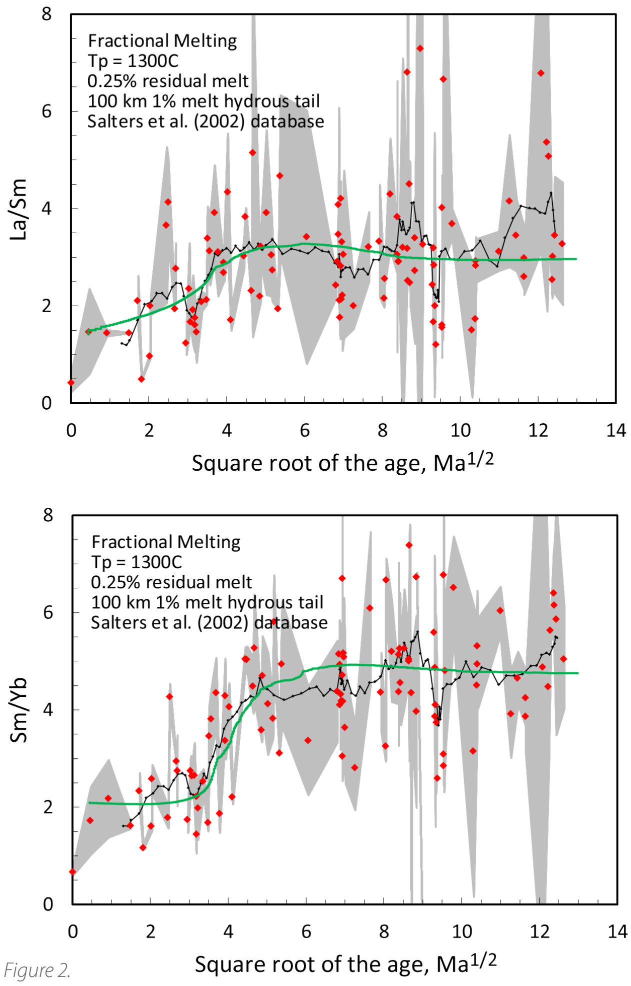


Figure 2.

Mesozoic flat-slab subduction and the opening of the South China Sea - clues from thermochronology

The South China Block (SCB) constitutes a major continental segment in the Western Pacific region (Fig. 1). Revealing the tectonothermal history of the region is fundamental to establishing the timing and kinematics of flat-slab subduction, foundering, and the opening of a marginal South China Sea.

We have carried out the first comprehensive thermochronological analysis of four areas in the southeastern SCB, making up a SE-NW traverse from the coast to the inland (A-D in Fig. 1). Late Triassic muscovite and biotite $^{40}Ar/^{39}Ar$ ages (220-200 Ma) in the northwest are clearly older than the Late Jurassic ages from the southeast (165-155 Ma; Fig. 2a). Among forty-one zircon (U-Th-[Sm])/He ages, four ages are pre-Middle Jurassic (253, 245, 220 and 176 Ma) and the remaining ages range from the Late Jurassic (152 Ma) to the Late Cretaceous (75 Ma). The four pre-Middle Jurassic ages are all from the northwest (area D) and the southeast is dominated by Cretaceous ages (Fig. 2b). Apatite fission track ages cluster at 70-30 Ma; two older ages (90 Ma) are from samples in the northwest (Fig. 2c). Like the apatite fission- track dates, apatite (U-Th-[Sm])/He ages form a tight Late Cretaceous-Eocene cluster at 70-30 Ma (Fig. 2d).

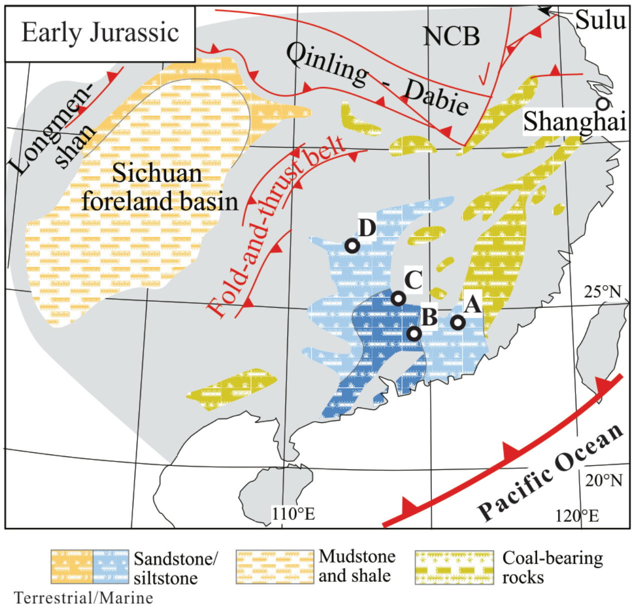


Figure 1. Paleogeographic map of the southeastern South China Block (SCB) showing areas studied in this project.

According to the time-temperature trajectories extracted from both forward and inverse modelling of thermochronological data, area D records rapid cooling related to orogenic uplift and related erosion during the Late Triassic. This orogenic uplift is interpreted as a result of the approaching flat subduction of a paleo-Pacific oceanic plateau from the southeast. At the same time, regions to the southeast were sagging and receiving terrestrial and shallow-marine sediments during the Late Triassic and Early Jurassic (Fig. 1 and 3). This may have resulted from the gravitational pull of the eclogitised oceanic flat slab (*Li and Li, 2007*, Fig. 3). Significant magmatic reheating occurred first in area B in the Middle Jurassic and generated a thermal peak of ~300 °C. Subsequently, in the Late Jurassic, a thermal peak of 250-300 °C was recorded in areas C and A, to the northwest and east of area B, respectively. This spatial distribution of Jurassic reheating is consistent with slab break-off as in a flat-slab model (Fig. 3).

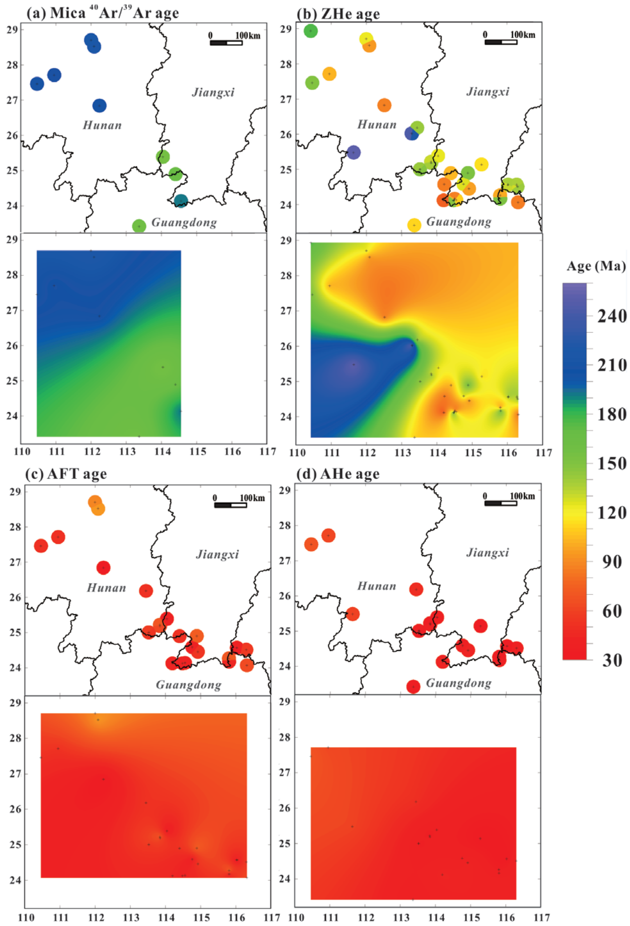


Figure 2. Database of new thermochronological ages in the southeastern SCB from this project. X-axis is longitude and y-axis is latitude. Mica $^{40}Ar/^{39}Ar$ = muscovite and biotite $^{40}Ar/^{39}Ar$ ages, ZHe = zircon (U-Th-[Sm])/He, AFT = apatite fission track ages, AHe = apatite (U-Th-[Sm])/He. Ages are expressed in Ma as circles; age values are indicated by the colour of circles. The pattern of ages was obtained by interpolation and smoothing of the data set. Previous data points are shown as black crosses in interpolated maps. Note that linking between areas without data points is by interpolation. The maps show the spatial distribution of ages and general trends; geology and faults are ignored.

The southern SCB was subjected to slow exhumation and cooling during the Cretaceous. The relatively quiescent, low temperature (200-100 °C) conditions reflect long-term thermal relaxation after the Middle-Late Jurassic magmatic heating. Such a protracted slow cooling is consistent with lithospheric rebound in the flat-slab model. Intensive Cretaceous magmatism in the coastal regions during the Cretaceous, interpreted as reflecting the roll-back of the remaining paleo-Pacific oceanic slab (Fig. 3; e.g. *CCFS Publication #16*), can account for the reheating recorded in area A.

The Pacific subduction zone had migrated to the south of the present continental margin of SCB by ~90 Ma (Fig. 3; e.g. *CCFS Publication #31*). Rapid cooling from ~150 °C to surface temperatures started as early as latest Cretaceous time and lasted until the late Eocene, coinciding with rifting in the southeastern SCB that has been linked to the rollback of the subducting western Pacific oceanic plates. This rifting event ultimately led to the opening of the South China Sea (Fig. 3; e.g. *CCFS Publication #31*).

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

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Funded by: CCFS, ARC Discovery Project (DP110104799)

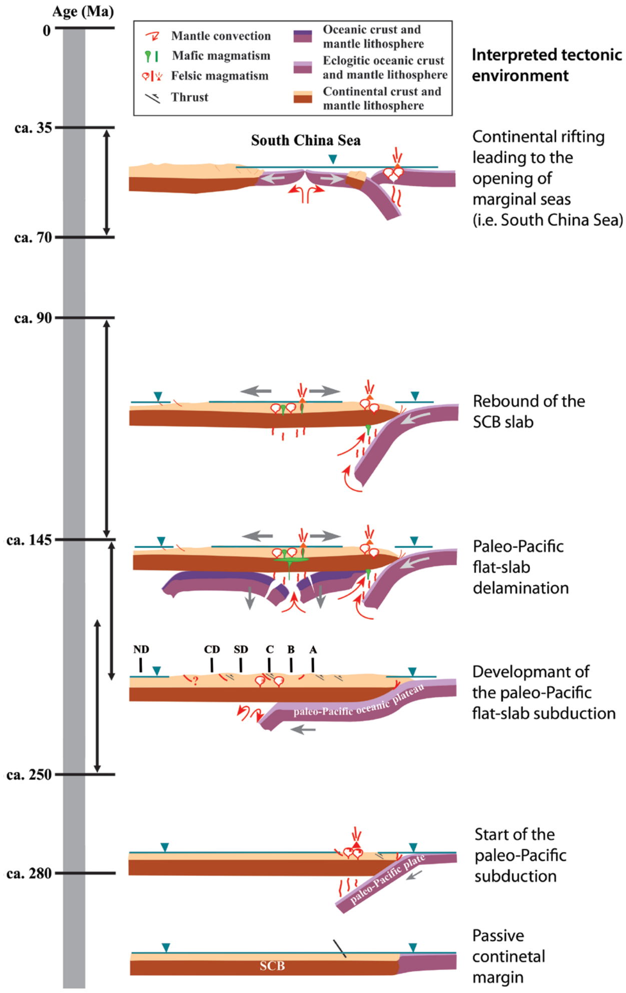

Figure 3. Schematic diagram showing the tectonic evolution of southeastern SCB, modified from Li and Li (2007); Li et al. (2012). Arrow bars on the left show the heat/cooling ages. ND = northern area D; CD = central area D; SD = southern area.

Migrating ridges link the deep and shallow mantle

It has long been recognised that mid-ocean ridges (MORs) migrate in an absolute sense relative to the underlying mantle. Present-day MOR migration rates affect seafloor morphology and the physical state of the upper mantle, and these migration rates correlate with asymmetric seafloor spreading, lava generation at ridge crests, asymmetry in melting depths and geochemical discontinuities, and ridge morphology. However, the effects of long-term variations in MOR migration and the resulting non-uniform sampling of the upper mantle have not been studied, although there is growing evidence from MORB geochemistry and upper mantle seismic tomography, mantle convection simulations and laboratory models, to support close linkages between slowly migrating MORs and plumes in the present oceans.

Here, we use Large Igneous Provinces (LIPs) that have formed since the Early Cretaceous to demonstrate that ridge-plume interactions can continue for up to 180 Ma and strongly influence ridge migration rates. These long-standing MOR migration patterns and ridge-plume interactions influence the thermal structure of the upper mantle and the geochemistry of the ocean crust vs spreading segments (Fig. 1a) and their full spreading rates. To assess the relationships of slowly migrating ridges caused by plume-ridge interactions to the thermal structure of the upper mantle, we have developed and implemented a novel methodology to construct a global map of the relative volume of upper mantle material extracted through partial melting at MORs since the Early Cretaceous. Our map (Fig. 1b) is a proxy for the Volume of Extracted Mantle (VEM) and is calculated as a function of the residence time (i.e. the duration for which a MOR lies above an area of upper mantle) of the global MOR system and the rate at which material is extracted from the mantle (i.e. spreading rate).

Regions with high VEM values indicate prolonged melt extraction and mantle focusing/processing by a relatively stationary MOR system with moderate to fast spreading rates, e.g. the Eastern Pacific. In contrast, rapid MOR migration, even with rapid spreading rates, does not result in high *cont...*

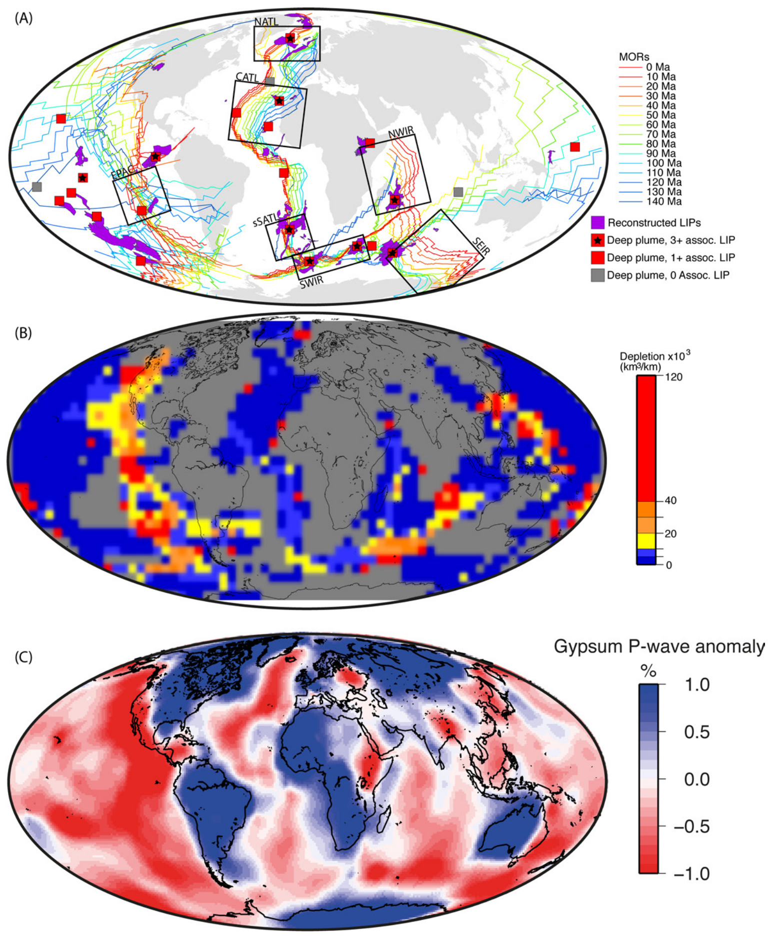

Figure 1. (A) Reconstructed mid-ocean ridges for the past 140 Myr in 10 Myr intervals. Black boxes show regions where ridge migration distances were computed along flow lines. CATL - Central Atlantic, EPAC - East Pacific Rise, NATL - North Atlantic, NWIR - Northwest Indian Ridge, SEIR - Southeast Indian Ridge, sSATL - southern South Atlantic, SWIR - Southwest Indian Ridge. LIP formation locations (purple) cluster around hotspots coinciding with slow ridge migration rates. (B) Estimated upper mantle VEM (km³/km of ridge). (C) 100-175 km S-wave velocities.

VEM values. We observe particularly slow MOR migration rates over the past 100 Ma at three ridges that currently exhibit ridge-plume interactions, namely the East Pacific Rise, the Southwest Indian Ridge, and the southern South Atlantic Ridge. On average, these three MOR systems have migrated <500 km in an absolute sense in the last 100 Ma, compared with absolute migration distances of >1500-2000 km for the Central and North Atlantic, and Northwest and Southeast Indian Ridges. We see evidence for higher upper mantle temperatures beneath slowly migrating ridges through global correlations between VEM and perturbations in both P- and S-wave velocity at depths 100-200 km. This is consistent with recent observations of higher upper mantle temperatures beneath spreading ridge segments located near deeply-sourced plumes. Together, patterns of MOR migration, LIP formation, and correlations of VEM with seismic tomography and MOR basalt geochemistry suggest a strong feedback between the dynamics of slowly migrating ridges and deeply-sourced plumes at global scale, which produce a self-sustained system over time scales up to 180 Ma.

In our proposed model, ridges at intermediate distances from plumes best represent the feedback mechanism. On the one hand, plume material will preferentially flow laterally towards areas with shallower lithosphere-asthenosphere interfaces (i.e. beneath MORs), with the effect of stabilising the MOR segment. On the other hand, the suction effect produced by the MOR will drain hot material from the plume and help stabilise the deeply-sourced plume.

These interactions result in a perturbation of the isotherm directly beneath the MOR, as hotter mantle is drawn towards the surface, a model supported by correlations between VEM, MOR basalt geochemistry and seismic tomography. Ridge segments located farther from the ridge-plume interaction are not affected by the ridge-plume interaction and are able to migrate more rapidly. These rapidly-migrating MORs do not perturb the upper mantle structure to any significant extent, nor focus large volumes of upper mantle towards the MOR. The plumes we have identified as participating in long-standing ridge-plume interactions are probably sourced from Large Low Shear Velocity Provinces. If these provinces are stable for very long periods of geological time, then it is possible that the relationships we observe between plume ridge interactions and slow MOR migration, and their effect on the thermal structure of the upper mantle are similarly stable. The stabilisation of MOR over time periods >180 million years, facilitated by ridge-plume interactions has significant implications for the way we model the plate-mantle system, and for understanding observed patterns of ridge morphology and geochemistry.

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

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Funded by: CCFS Foundation Program 4, Two phase flow within the Earth's mantle.

Deformation behaviour in polymineralic rocks

Deformation in rocks can be mainly localised in large ductile shear zones, broadly distributed into several smaller high-strain zones or dynamically change from one system to the other. One of the main reasons for strain localisation is a switch from Power-law flow, in which dislocation creep is a dominant deformation mechanism to Newtonian flow, in which deformation is dominated by diffusion or dislocation glide accommodated grain boundary sliding (GBS). A switch between these two types of flow will result in a marked weakening and strain localisation, because it lowers the effective viscosity of the rock by at least two orders of magnitude.

We have investigated the controls on the deformation behaviour of polymineralic rocks using a granitic pegmatite deformed at medium P and T conditions *(CCFS Publication #501)*. The chosen plagioclase, next to initially large K-feldspars deformed in the brittle regime; (ii) fracturing coupled with grain-size reduction through the interface-coupled dissolution and reprecipitation replacement of coarse-grained K-feldspar by fine-grained albitic plagioclase. Strain is localised in the newly formed, fine-grained plagioclase and causes advanced recrystallisation of adjacent K-feldspar.

Once the grain size is sufficiently small, grain-boundary sliding becomes the dominant deformation mechanism. Consequently, once micro- and mesoscale high-strain zones are interconnected, the rheology of the rock is controlled by Newtonian flow. Phase mixing and continuous high strain rates help to maintain small enough grain sizes to allow Newtonian flow over long periods, '*stabilising*' the high-strain zones.

Our study shows that, in polymineralic rocks, the variation in initial and developing grain size, as well as mineral distribution, governs the dynamic rheological behaviour of the rock as a whole.

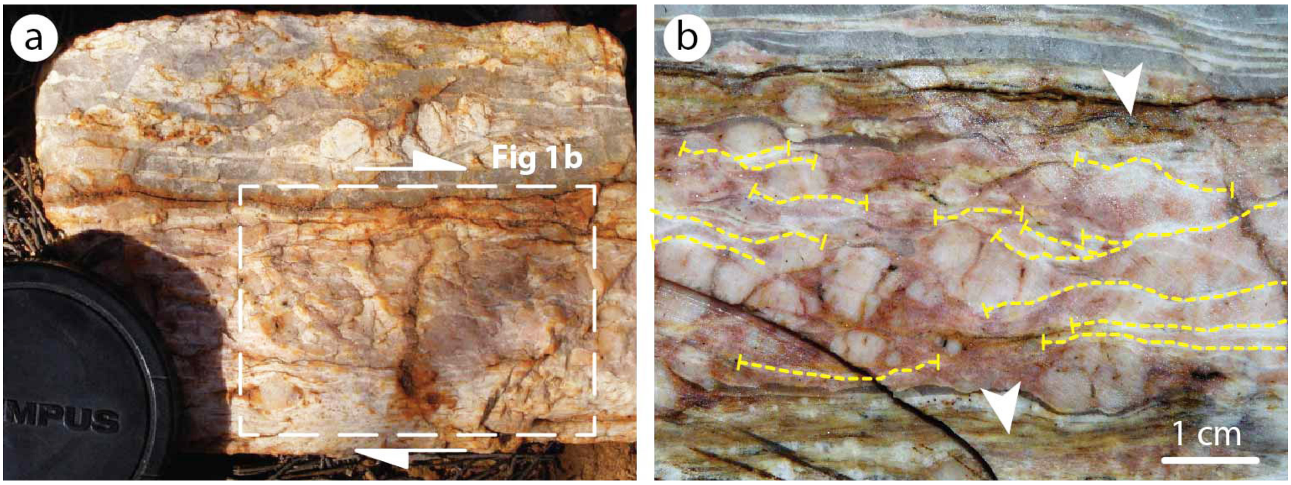

Figure 1. General characteristics of the studied sample: (a) hand specimen showing two main domains in pegmatite; (b) close-up of zone dominated by K-feldspar (pink) with several discontinuous microscale shear zones (yellow dashed lines) and two mesoscale zones of strain localisation below and above (white arrows).

sample is an example of a mesoscale system where several minerals with different rheological behaviour were deformed together and strain was localised in a complex system of high-strain zones at different scales.

The sample shows visible zonation in the distribution and grain size of the minerals (Fig.1a). In the initially coarse-grained, K-feldspar-dominated lower part of the sample, several microscale shear zones developed; two mesoscale shear zones separate this zone from the upper, quartz-rich part of the sample and the wall rock (Fig. 1b).

Microstructural observations, and chemical and EBSD data, show that mesoscale shear zones form at the boundary between zones with different mineral assemblages, especially between the initially K-feldspar-rich and quartz-rich zones. Microscale shear zones in the initially coarser-grained, feldspar-rich zone form by (i) intense recrystallisation in originally smaller grains of

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

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Tibetan chromitites: Excavating the slab graveyard

Large peridotite massifs are scattered along the 1500 km length of the Yarlung-Zangbo Suture Zone (southern Tibet, China), the major suture between Asian and Gondwana-derived terranes. Diamonds occur in the peridotites and chromitites of several massifs, together with an extensive suite of trace phases that indicate extremely low fO_2 (SiC, nitrides, carbides, native elements) and/or ultra-high pressures (diamond, possible stishovite, coesite). Physical and isotopic (C, N) studies of the diamonds confirm they are natural, crystallised in a disequilibrium environment, and spent only a short time at

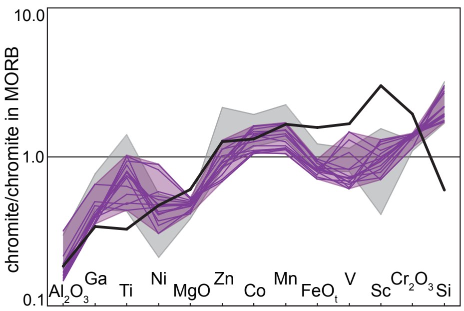
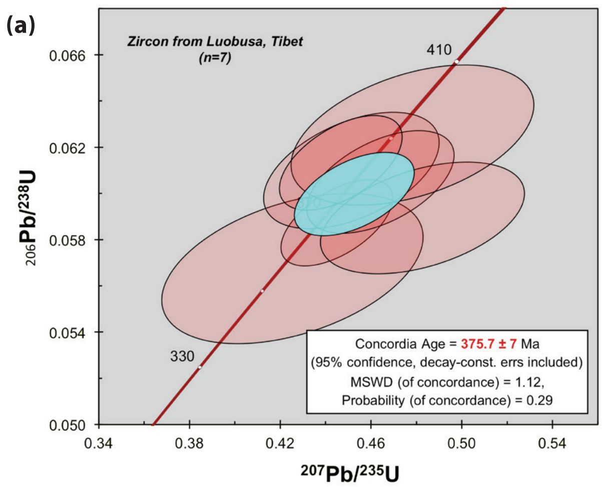


Figure 1. Major element oxide and minor/ trace-element plot (normalised to MORB chromite (Page and Barnes 2009)) for chromites from Luobusa, Tibet (purple), the Antalya ophiolite complex, Turkey (grey), and chromite hosted in boninite-lavas from Bonin Island (black; Pagé and Barnes, 2009). Luobusa (Tibet) chromites have Cr# from 0.60-0.78 and Mg# 0.58-0.73; Antalya (Turkey) chromites have Cr# from 0.59-0.73 and Mg# from 0.55-0.69.

mantle temperatures before exhumation and cooling (*Howell, Griffin et al., submitted*). These constraints are difficult to reconcile with previous models for the history of the diamond-bearing rocks. However, new investigations are providing evidence that these peridotite massifs have experienced a remarkable journey in time and space (*CCFS Publication #522*).

We have uncovered evidence that strongly suggests some of these peridotites have undergone metamorphism in or near the upper part of the Transition Zone, around 400-600 km deep. This includes the discovery that many of the chromites contain exsolved pyroxenes and coesite, consistent with inversion from the high-pressure polymorph (calcium-ferrite structure) of chromite, which is stable in the Mantle Transition Zone. This high-P polymorph structure, unlike the



normal spinel structure of chromite, can accommodate ions such as Ca^{2+} and Si^{4+}; however, these elements are ejected (exsolved) when chromite is emplaced at shallow, (lower pressure) levels. This evidence, and the presence of diamonds, coesite and other high-pressure phases recorded in both the peridotites and the chromitites, suggest that the peridotite bodies have indeed risen from the Transition Zone. But how did they get there?

An answer comes from CCFS' extensive work on the trace-element geochemistry of chromites from many different geotectonic settings. The trace-element data for the Luobusa chromitites (Fig. 1) show that they are typical of chromitites formed above subduction zones by magma mixing, at shallow depths (tens of km) in the oceanic mantle. Euhedral, oscillatory-zoned zircons in the chromitites (Fig. 2), formed in this magma-mixing environment, give U-Pb ages of 376 ±7 Ma, εHf = 9.7±4.6, and $\delta^{18}O$ = 4.8 to 8.2; the isotopic data are consistent with mingling of magmas derived from the oceanic mantle and a subducting slab. Os-Ir nuggets in the chromitites have Re-Os model ages (TRD) of 234±3 Ma, while TRD of in situ Ru-Os-Ir sulfides range from 290-630 Ma, peaking at ca 325 Ma. All of these ages are significantly older than the emplacement of the peridotites into the Yarlung-Zangbo suture zone (ca 130 Ma).

A proposed P-T-t path (Fig. 3) traces the original formation of chromitites in mantle-wedge harzburgites, subduction of these harzburgites at ca 375 Ma, residence in the upper Transition Zone for >200 Ma, and rapid exhumation at ca 130 Ma. The Os-isotope data suggest that the subducted mantle consisted of previously depleted subcontinental lithosphere, dragged down by a subducting oceanic slab. Thermo-mechanical modelling (Fig. 4) shows that rollback of a younger subducting slab would produce a high-velocity channelised upwelling that could exhume

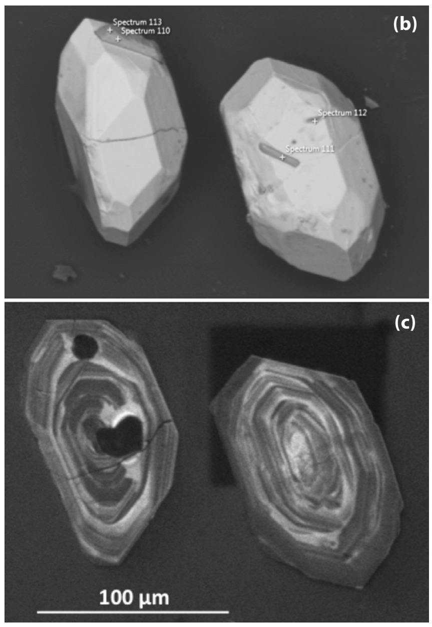


Figure 2. (a) Inverse $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}U$ concordia plot for zircon from Luobusa ophiolite, Tibet (n=7). Zircons from a Luobusa chromitite: (b) BSE image; (c) CL image. Dark inclusions are F-apatite; prisms of apatite are visible on both grains in (a).

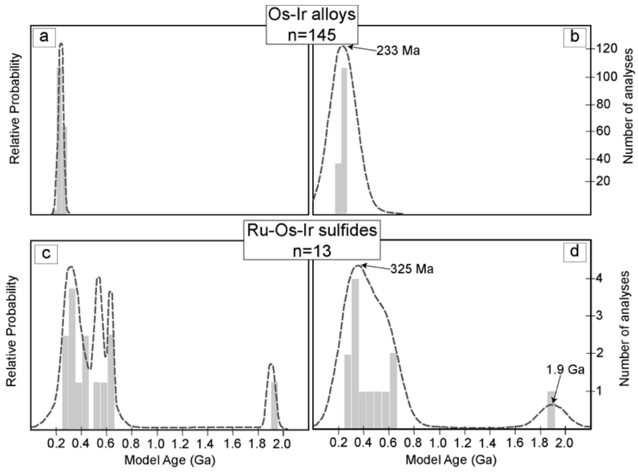


Figure 3. Model age ranges for b) Os-Ir alloys (Shi et al., 2007), and d) laurite. (a) and (c) show the data with the analysed analytical errors; in (b) and (d) the uncertainties have been expanded to a uniform 0.1 Ga.

the buoyant harzburgites (and their chromitites) from the Transition Zone in <10 Ma. This rapid upwelling could be the mechanism that brought some massifs to the surface in back-arc basins, forming parts of the oceanic crust basement. This model reconciles many apparently contradictory petrological and geological datasets. It also introduces a previously unrecognised, geodynamic process that may have operated in large collisional zones.

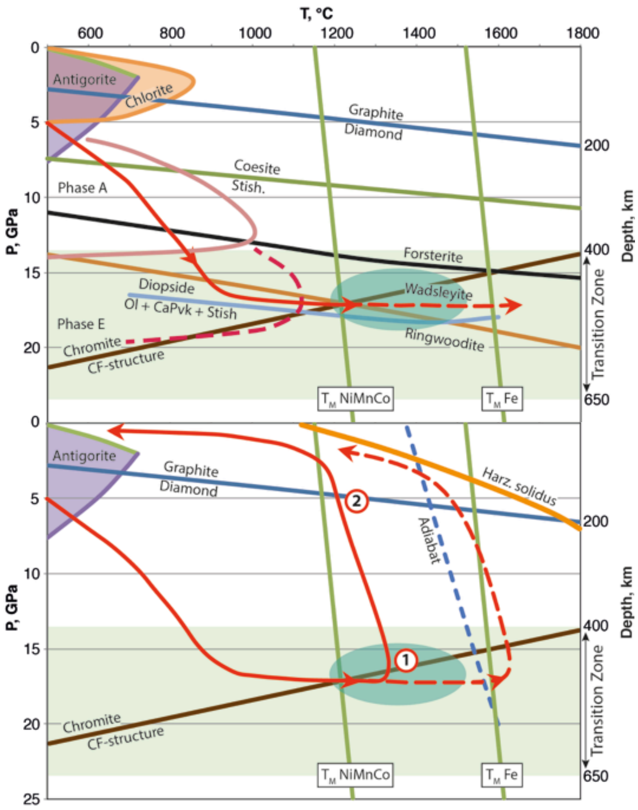


Figure 4. Reconstructed P-T-t path for the Luobusa-Kangjinla peridotite body. (a) stability fields of hydrous phases, and curves for relevant reactions and T constraints (see text); green oval outlines a probable P-T region for coexistence of wadsleyite, CF-structured chromite, and majoritic garnets. Red arrow illustrates subduction of mantle-wedge material into the Transition Zone, followed by heating to at least 1300 °C (constrained by the melting point of alloy inclusions in diamonds at TZ depths), or to >1500 °C (melting point of Fe). (b) Two end-member (low-T, high-T) adiabatic uplift paths are illustrated. Formation of diamonds is possible at point (1), but formation near point (2) would be more consistent with the lack of nitrogen aggregation in the diamonds.

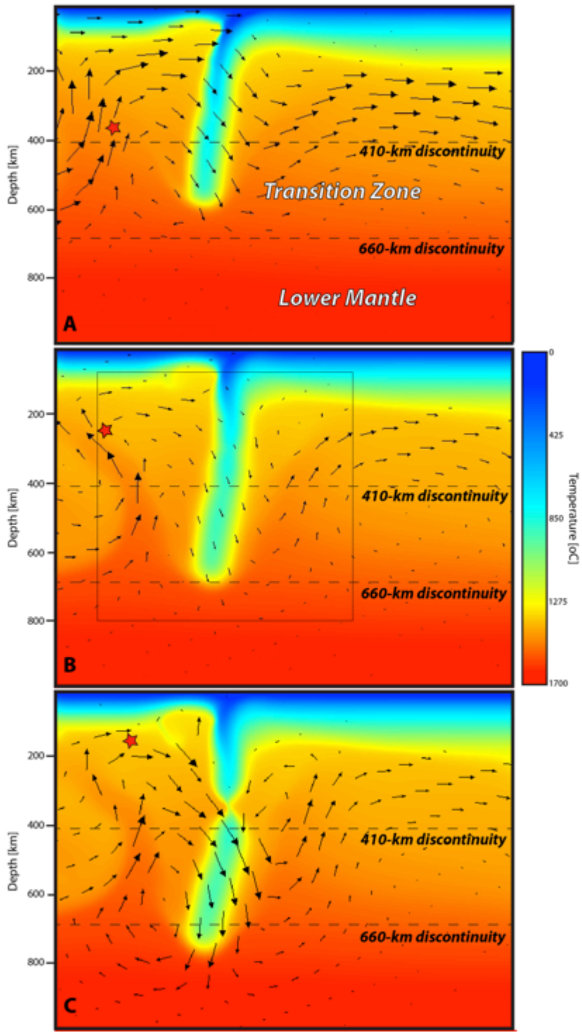


Figure 5. Ascent of TZ material in a thermo-mechanical simulation of continental collision involving slab roll-back and break-off. The simulation begins with a 400 km-long slab subducting at an angle of 45°. No boundary conditions are imposed on velocities, which are controlled entirely by the balance between internal forces (e.g. buoyancy, shear resistance, etc). More details can be found in Afonso & Zlotnik (2012). A) The verticalisation of the slab under the action of gravity generates a large-scale upwelling down to the TZ. B) This broad upwelling evolves into a narrower 'channel' (favoured by a non-linear rheology) with velocities of 3-8 cm yr^{-1}. C) Once the continental plate arrives at the trench, subduction slows down and a slab break-off occurs. At this point, material from the TZ has been brought up to lithospheric depths in <10 Ma, to become part of smaller-scale lithospheric tectonic processes. Red star indicates the path of a low-density passive tracer, which is at a depth of 520 km at the beginning of the simulation.

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

Contacts: Nicole McGowan, Bill Griffin

Funded by: CCFS Foundation Program; TARDIS: Tracking ancient residues distributed in the silicate Earth; APA, MQ PGRF

New Ce-Nd separation techniques improve our ability to detect early silicate differentiation of planetary bodies

Sm and Nd have two different radiogenic decay systems that can be useful for evaluating the hypothesis that the Earth and chondrites have the same Sm/Nd ratio: ^{146}Sm decays to ^{142}Nd (T1/2 = 68 Ma) and ^{147}Sm decays to ^{143}Nd (T1/2 = 106 Ga). The short-lived ^{146}Sm-^{142}Nd radioactive nuclides are ideal tools for constraining the early silicate differentiation of planetary bodies and the early history of the Earth's mantle. Because of its low initial abundance, ^{146}Sm is effectively extinct after 4-5 half-lives, so that ^{142}Nd/^{144}Nd anomalies can only be related to the differentiation of silicate reservoirs during the first few hundred million years of Earth's history. However, ^{142}Nd anomalies are expected to be extremely small (less than 40 ppm) and require ultra-precise measurements because the variation of ^{142}Nd/^{144}Nd is very small (<50 ppm). New-generation thermal-ionisation mass spectrometry (TIMS) has produced published reproducibilities of ^{142}Nd/^{144}Nd ca 5 to 7 ppm (2 RSD). For ultra-high-precision ^{142}Nd/^{144}Nd isotopic measurements the complete separation of Nd from the matrix and the isobaric interfering elements Ce and Sm is indispensable. During TIMS analysis, ^{140}Ce/^{144}Nd and ^{147}Sm/^{144}Nd must be lower than 0.000010.

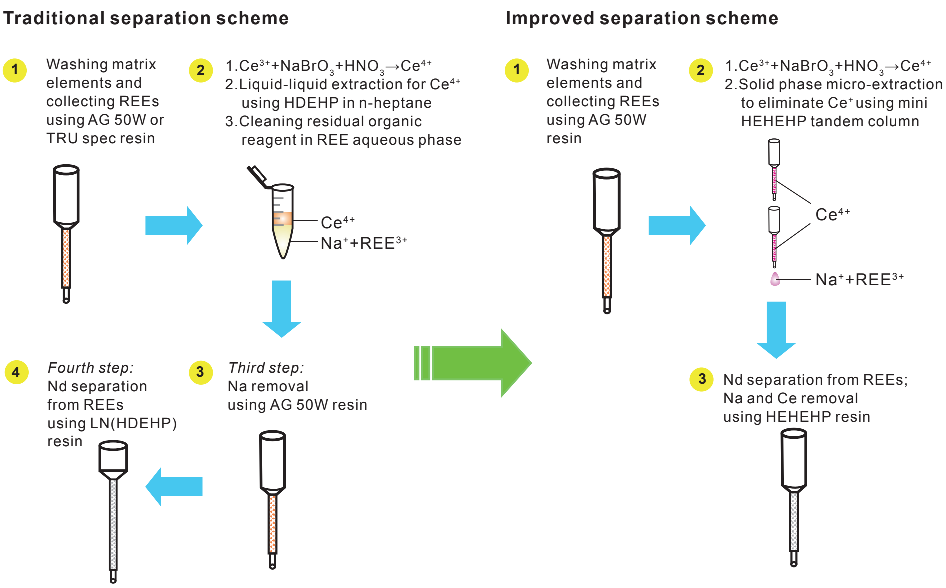


Figure 1. The new rapid solid-phase microextraction technique separation protocol compared with traditional methods.

A rapid solid-phase microextraction technique, using HEHEHP resin, has been developed to completely separate Ce from rare earth element (REE) mixtures, including Nd (Fig. 1), and has been applied to ultra-high-precision measurement of ^{142}Nd/^{144}Nd in geological materials (Fig. 2). In contrast to the traditional liquid-liquid micro-extraction technique, the benefits of the SPME tandem column techniques are high Nd recovery, low residual Ce (Ce/Nd <10-6), and ease of operation. A single HEHEHP resin column, replacing the traditional two-column scheme (AG 50W + HDEHP resins), is used to further purify Nd by removing Na salt and Sm isobaric interferences. All mean values of ^{140}Ce/^{144}Nd of geological samples after separation are <0.000010, even though the Ce/Nd ratio of geological materials is >3.0. Thus, ^{142}Ce interferences on ^{142}Nd never exceed 1.3 ppm. Ultra-high-precision TIMS analyses of silicate standards show that the internal precision of all runs is better than 4 ppm (2 RSD) for ^{142}Nd/^{144}Nd values. Values of ^{142}Nd/^{144}Nd for JNdi-1, JR-3, and BCR-2 have external precisions of ±4.8, ±4.4, and ±3.9 ppm (2 RSD), respectively. The external reproducibility is sufficient to resolve 5 ppm anomalies in ^{142}Nd/^{144}Nd.

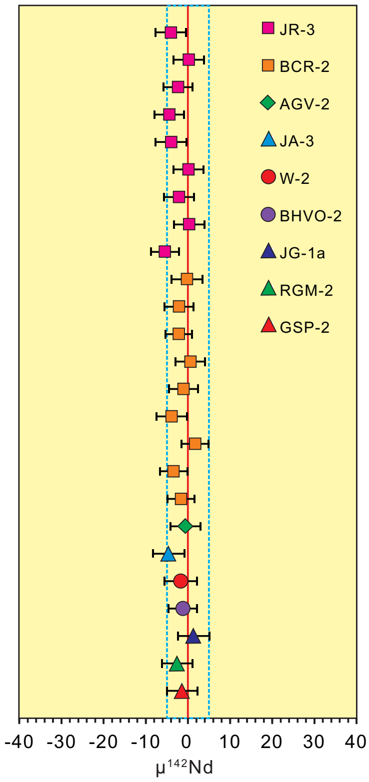


Figure 2. ^{142}Nd/^{144}Nd data for the CRM samples are plotted as deviations in ppm (μ^{142}Nd) from the JNdi-1 standard relative to the terrestrial Nd standard JNdi-1. $\mu^{142}Nd = ((^{142}Nd/^{144}Nd)_{sample}/(^{142}Nd/^{144}Nd)_{JNdi\text{-}1\text{-}1}) \times 106$, where the ^{142}Nd/^{144}Nd value of JNdi-1 is the average value in this study (1.1418367 ± 0.0000055, 2 SD, n = 37). The dashed lines delimit the external error of 5 ppm (2 RSD) of the repeated measurements of the JNdi-1 standard (n = 37). Error bars are 2 SE errors of individual measurements.

Compared to the traditional methods, the new separation procedure has advantages in terms of simplicity, Nd recovery, and miniaturisation.

This project is part of CCFS Theme 1, Early Earth

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Funded by: National Science Foundation of China (No. 41373020)

The thermochemical structure of the lithosphere and upper mantle beneath South China

South China is an ideal natural Earth laboratory for testing ideas about lithospheric structure and evolution. South China experienced major changes in the thermochemical structure of its lithospheric mantle throughout the Phanerozoic. Existing lithospheric models for this region are inconsistent with each other, but recently, abundant geophysical data (topography, geoid, surface heat flow and dense regional seismic arrays) and petrological/geochemical data on mantle-derived xenoliths have become available, and we have used these new data to test the competing lithospheric models.

By jointly inverting Rayleigh-wave dispersion data, geoid height, topography and surface heat flow with a probabilistic (Bayesian) Monte Carlo method, we have defined the thermal and compositional structure of South China. Our inversions show marked differences in the depth to the lithosphere-asthenosphere boundary between the eastern and western regions of South China. The lithosphere is thin (85-150 km) beneath the South China Fold system and thickens beneath the Yangtze Craton, reaching maximum thicknesses of up to 250 km beneath the Sichuan Basin. The average lithospheric composition predicted by our inversion is significantly fertile (Mg# ~88-90), in agreement with independent geochemical observations on mantle xenoliths in the volcanic rocks of East China. Such fertile compositions, together with the relatively thin lithosphere thickness, point towards a widespread metasomatism/refertilisation event. We suggest, as others have, that a flat-subduction episode and subsequent slab removal may have triggered both the delamination of the lowermost part of the subcontinental lithosphere and the generation of asthenospheric melts that metasomatised (refertilised) the remaining lithospheric mantle. Inconsistencies among geophysical observations and the anomalously fertile compositions derived from the Sichuan Basin indicate that this region may currently be affected by small-scale convection or delamination processes. Alternatively, the anomalous observations may be associated with the eastward push of Tibetan lithosphere beneath the Yangtze Craton.

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

Contacts: Bin Shan, Juan Carlos Afonso, Yingjie Yang
Funded by: ARC Discovery Project (DP120102372)

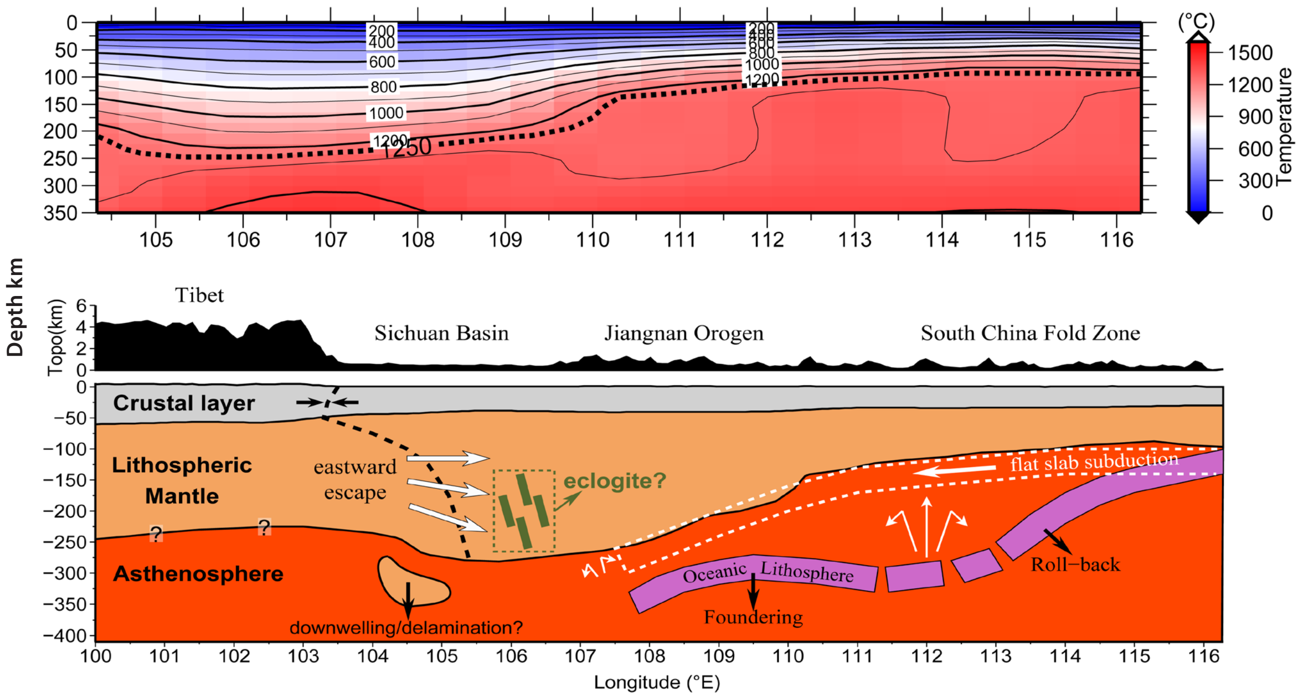


Figure 1. Temperature cross section obtained by interpolating the 1-D temperature structures; b) Cartoon illustrating a possible scenario for the thermochemical evolution of South China.

South China's collision with northern India 580-470 million years ago to join Gondwanaland

The position of the South China Block (SCB) relevant to Gondwanaland during late Precambrian and early Palaeozoic remains a challenge to geoscientists. One peculiar observation has been that prior to the Ordovician-Silurian Wuyi-Yunkai intraplate orogeny, the Yangtze half of the SCB was dominated by platform carbonate deposits whereas the Cathaysia half received almost exclusively siliciclastic deposition. What caused such contrasting depositional environments over the same continent?

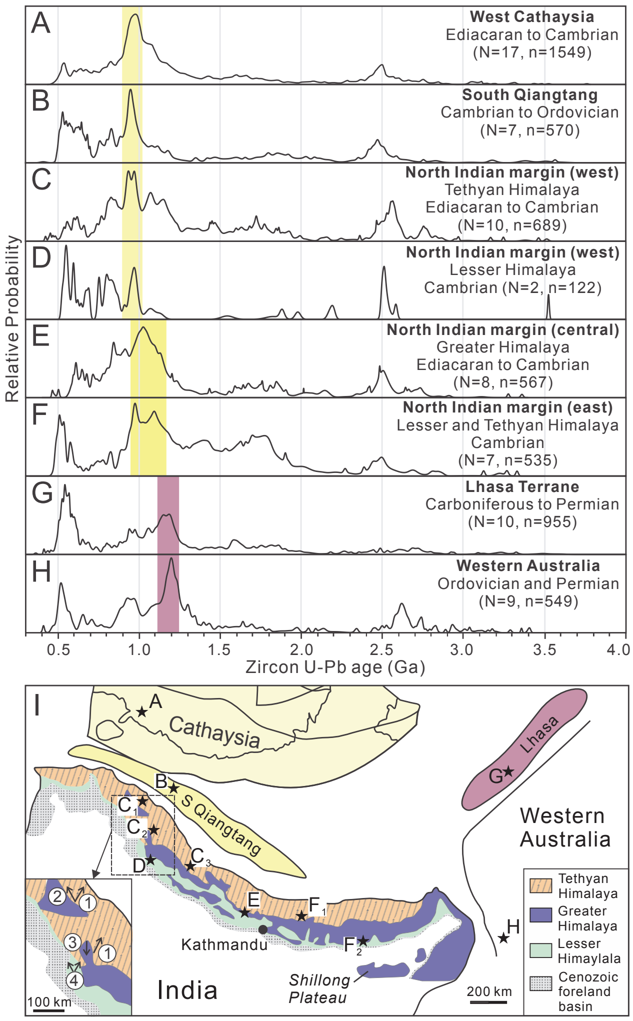


Figure 1. Provenance variations of Ediacaran-Cambrian sedimentary rocks along the northern margin of India, and comparisons with southwestern South China and adjacent terranes. Age spectra in (A)-(H) correspond to data points A-H in the location cartoon (I), where data points C1-C3 and D represent the western North Indian margin, data points E represent the central North Indian margin, and data points F1 and F2 represent the eastern North Indian margin. Sources of detrital zircon age spectra can be found in Yao et al. (2014; Am. J. Sci.).

LA-ICP-MS U-Pb dating of detrital zircons from Cambrian sedimentary rocks in southwestern South China has revealed four major age populations with a predominant peak at 980 Ma (*CCFS publication #366*). Zircon Hf-O isotopes suggest three Precambrian episodes of juvenile crustal growth for the source areas, with major crustal reworking at 580 Ma. The source provenance as defined by the U-Pb and Hf-O analyses is distinctly different from the known tectonomagmatic record of the SCB, hinting at an external source. The sedimentary facies and modal composition of the Cambrian clastic rocks further show that the clastics were derived from a source southeast of the present-day South China mainland.

Possible candidates for this source, such as western Australia and western Laurentia fail to match the zircon U-Pb patterns of the South China rocks. In contrast, zircon U-Pb patterns and Hf isotopes of Ediacaran-Cambrian clastic sedimentary rocks and granites in northwestern Indian Himalaya match well with those of the South China clastic rocks (Fig. 1). In addition, the strongest provenance connection with the SCB, which started from 580 million years ago, appears to be with northwestern India, and weakens eastward along the Himalaya toward western Australia (Fig. 1). Terranes such as Qiangtang and Lhasa show provenance affinities with the Indian and Australian sections of the Gondwana margin, respectively.

Together with a regional tectonostratigraphic analysis, our new results lead to a reconstruction of the tectonic evolution of the NE Gondwana margin for the late Neoproterozoic and earliest Paleozoic (Fig. 2). We propose that after breaking away from central Rodinia, South China started to approach northern

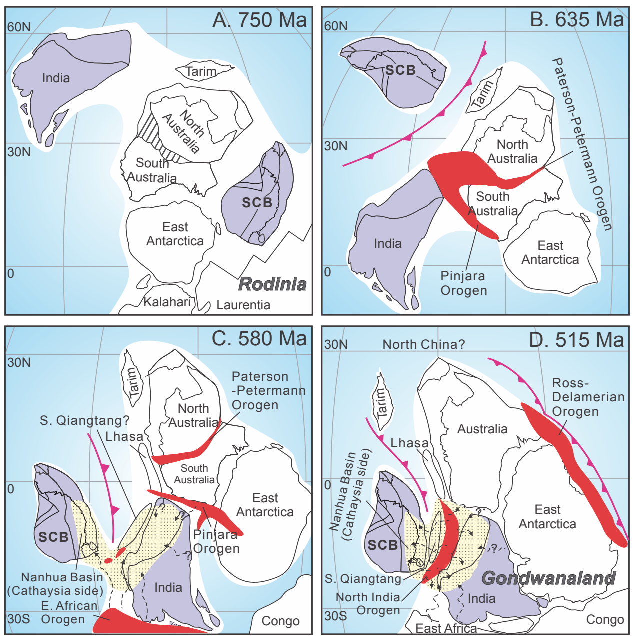


Figure 2. Paleogeographic reconstructions showing the position of South China (A) before the break-up of Rodinia in the mid-Neoproterozoic (750 Ma); (B) after Rodinia broke up, but prior to its collision with India during the assembly of Gondwanaland (635 Ma); (C) beginning of collision with NW India at ca 580 Ma during the assembly of Gondwanaland; (D) colliding with India to join Gondwanaland (515 Ma).

India at about 580 million years ago during the assembly of Gondwanaland. Continental collision occurred between 580 and 440 million years ago, causing not only the so-called "*Pan-African*" orogeny at the northern margin of India but also the intraplate Wuyi-Yunkai orogeny in South China. The collision started with northwestern India, and finished with northestern India. The resulting orogens shed vast amounts of Ediacaran-Cambrian clastic sedimentary rocks to an evolving foreland basin (the Nanhua foreland basin) in the SE South China Block.

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: Wei-Hua Yao, Zheng-Xiang Li
Funded by: CAS SAFEA(KZCX2-YW-Q04-06), NNSFC(41173039) and ARC Discovery Project (DP110104799). This project is part of CCFS Foundation Program 5: Earth rhythms

Volatiles and mantle melting: An experimental study

Mineral/melt partitioning of volatiles (in particular H_2O) in the mantle is a first-order problem because of its influence on the distribution of melts and fluids in the mantle as well as the creation of the Earth's hydrosphere. Melts and fluids also play a key role in both fractionating and transporting metals and incompatible elements between the mantle and crust/hydrosphere. Thus, experimental data on the partitioning of volatile and non-volatile elements between peridotite minerals and melts can be related to the broader issues of the Earth's deep volatile cycle and its influence on mantle fractionation and evolution. The partitioning data generated within the framework of CCFS Foundation Program 2a define conditions under which relatively water-rich fluids and/or melts can exist in equilibrium with water-poor mantle host rocks. It also is relevant to the calculation of solidus temperatures for water-undersaturated mantle rocks.

Figure 1.

Our new experimental data for the basanite UT-70489 include: H_2O-saturated liquidus and subliquidus phase equilibria (Fig. 2); H_2O-solubility data for 2.5 GPa, plus estimates of the 2.5 GPa liquidus of basanite under dry, and H_2O-saturated (~28 wt % dissolved H_2O) conditions (Fig. 3).

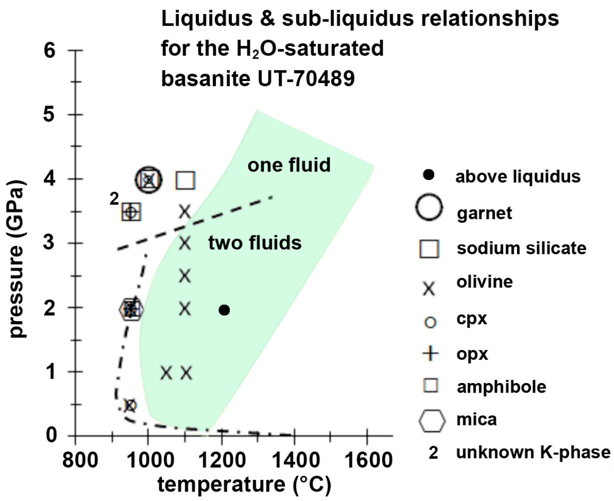


Figure 2. H_2O-saturated liquidus and subliquidus phase equilibria for basanite bulk composition.

These can be combined with published data for volatile-undersaturated basanite and for similar compositions (Fig. 3). The results fit to a polynomial that allows calculation of the effects of even small H_2O concentrations on liquidus temperatures. Initially this effect is large but then tails off as concentrations increase. This integrated information can be used to calculate solidus temperatures for H_2O-undersaturated mantle peridotites, which is probably the most common composition in the convecting asthenosphere.

Earlier studies have underplayed the role of low-degree melts in the asthenosphere. Earlier experiments on the liquidus of basanite showed that it is in equilibrium with garnet lherzolite at ~2.7 GPa and 1200 °C with 4.5 wt % of dissolved H_2O and 2 wt% of dissolved CO_2. These conditions are close to those estimated for oceanic geotherms. Using the D values for H_2O from this study, it is also possible to calculate a concentration of ~230 ppm H_2O for the residue. This is within the range of estimates for the MORB source. In this light, the presence of migratory solidus melts within the ordinary convecting asthenosphere seems both feasible and probable.

Currently, these results are being extended to 4.0 GPa by looking at liquidus equilibria for another potential primary melt composition (Laughing Jack Marsh melilitite). The initial results show that at 1400 °C, close to estimates of the *cont...*

mantle T at 4 GPa, this melilitite begins to melt with only 5 wt% of dissolved H_2O (plus a small but unknown amount of CO_2).

For H_2O-saturated conditions, the basanite results require greater interpretation. Olivine is the liquidus phase up to at least 3.5 GPa

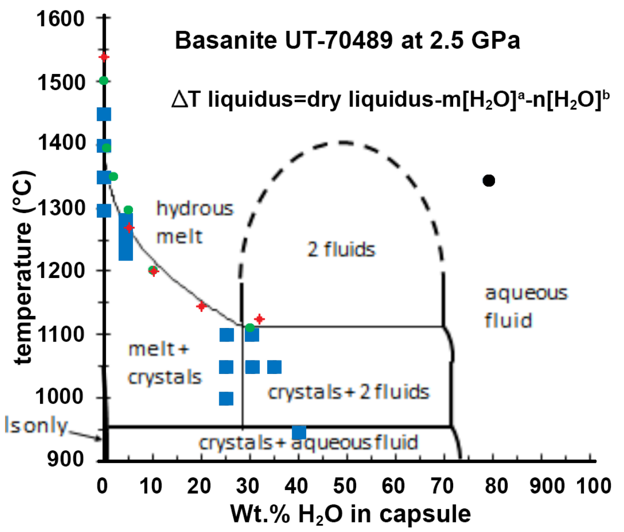


Figure 3. Water solubility at 2.5 GPa for basanite bulk composition in this study (blue squares) and the Mt. Leura basanite (red points) and Laughing Jack Marsh olivine melilitite (green points). See text for discussion.

and T close to 1100 °C. This is ~100 °C above the water-saturated peridotite solidus. In this case, the basanite is not an exact match to the H_2O-saturated solidus melt. But from phase equilibria and mineral/melt partitioning, the H_2O-saturated melt can be predicted to be less olivine-normative, but more SiO_2- and Na_2O-rich than the basanite at the same pressure (2.7 GPa).
At pressures above those where complete miscibility occurs between basanitic melts and H_2O (~3.5 GPa at 1100 °C), conditions can also be bracketed (3.5-4.0 GPa and 950-1000 °C) for the equilibration of a basanite-like melt/fluid (containing ~50 wt% H_2O) with garnet lherzolite.

Because of the strong influence of pressure on solute concentrations in hydrous fluids, our results favour relatively high temperatures for the water-saturated peridotite solidus (1000 °C at 2.0-3.0 GPa) rather than the very low temperatures advocated by some workers (as low as 850 °C at 2.0 GPa).

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

Contacts: John Adam, Tracy Rushmer
Funded by: CCFS Foundation Project; 2a Metal sources

Heterogeneous crust in the WA Craton

Recent seismic compilations show there is a global change in the characteristics of continental crust that was formed between 3.0 Ga and 2.5 Ga: older cratons have a thin, more felsic and less deformed crust with a very flat and sharp Moho; younger cratons have a thicker crust, more intermediate in composition and more deformed, usually with a diffuse Moho. These differences suggest a secular change in the processes of crustal growth in the late Archean.

Using the seismic receiver function technique, we have examined the crust in the Archean Western Australian (WA) Craton. We focused on its mean crustal properties and looked for possible links to its nearly 1 Ga history of early crustal formation. The crust in the constituent Pilbara and Yilgarn cratons is a typical mixture of plutonic rocks (granites) and supracrustal greenstone-facies rocks. The surface expression of these rocks are different across the two cratons: in the eastern and central Pilbara, granitoid domes and greenstone belts form a dome-and-keel pattern, while in the Yilgarn the granite-greenstone terranes are more elongated (Fig. 1), suggesting different tectonic processes during the growth and assembly of the two cratons.

Seismic records from available WA stations gave a fairly uniform coverage of the whole region. Receiver functions, the structural responses (functions) beneath a seismic station (receiver), were computed and stacked to derive the most coherent values for bulk crustal thickness (H) and the Vp/Vs ratio (k). The Vp/Vs ratio is closely related to crustal composition (Christensen, JGR 1996). It can be constrained robustly using the free-surface multiples of the Moho receiver function phase, which travel differently in P- and S-waves in the crust.

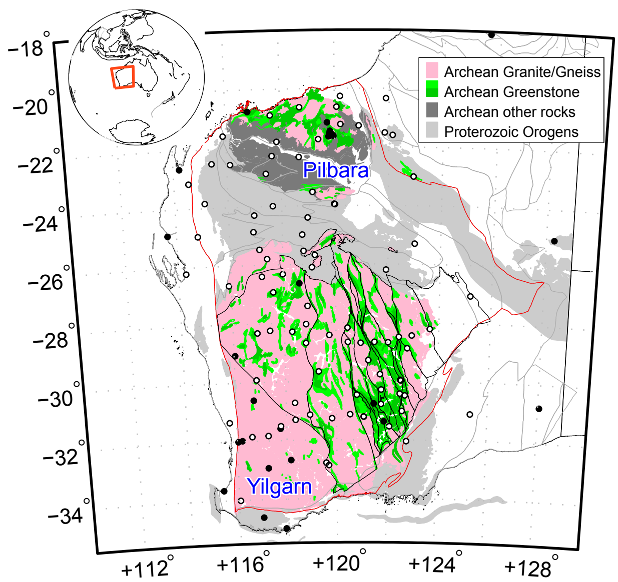


Figure 1. Seismic stations, rock ages and greenstone belts in the WA craton. Open and filled circles are temporary and permanent seismic stations. Red line contours the WA craton. Inset shows the location of the study region.

The crust in the WA craton is seismically heterogeneous (Fig. 2). While the Pilbara crust seems nearly uniform, the Yilgarn crust is spatially clustered into regions which correlate well with the surface tectonic units. The crustal density anomalies (*Aitken et al., Tectonophys, 2013*) and the mean crustal velocities (*Salmon et al., GJI 2013*) all indicate a similar pattern. The clustering in these observations indicates that the tectonic units in the WA craton are unique entities with deep-rooted geophysical signatures.

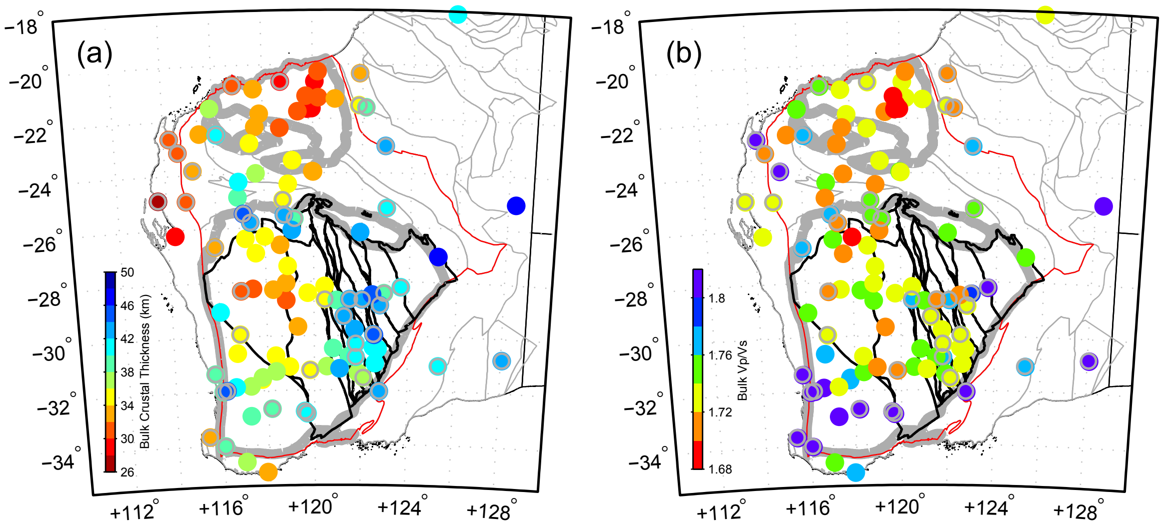


Figure 2. Bulk crustal properties in the WA craton. (a) Crustal thickness; (b) Vp/Vs ratio. Circles are stations.

Close inspection indicates that there is a weak correlation between the mean crustal thickness and the Vp/Vs ratio (Fig. 3), from the oldest crust in the Pilbara craton (formed ~3.6 Ga ago) to younger domains in the Yilgarn (<3.2 Ga). The Eastern Goldfields Superterrane, the youngest unit in the Yilgarn, is an outlier, which lies anomalously away from the trend.

Vertical tectonics has been proposed as responsible for the crustal structure of the Pilbara, especially in the >3.2 Ga mid- to eastern regions. The associated processes of plume impingement, melt differentiation, partial convective overturn, and delamination of lower crustal restites (*van Kranendonk et al., Geological Society London Special Publication 2014*), may have produced this extremely thin and felsic Pilbara crust.

Van Kranendonk et al. (2014) suspected that a transition towards accretional tectonics began about 3.2 Ga ago, as seen in linear trends of geological structures in the western Pilbara. In the Yilgarn. most crust is believed to have formed after 3.2 Ga (*Griffin et al., Precambrian Research 2004*). Most published crustal-genesis models favour arc accretion, as responsible for the elongated pattern defined by large-scale faults and greenstone belts. The processes associated with horizontal tectonics may have significantly contributed to the greater crustal thickness and more intermediate composition.

Much older crustal components (3.1-3.5 Ga; *Griffin et al. 2004*) have been recognised in the Murchison portion of the Yilgarn craton. These pieces of extraneous thin and felsic crust may have formed as in the Pilbara. Alternatively, late Archean plume activity in the region (*Ivanic et al., AJES 2010*) may have reworked the crust substantially. Younger plumes in the Eastern Goldfields Superterrane, as evidenced by the 2.7 Ga komatiites along the western margin, may have dominated the thick and intermediate crust concentrated in this region.

Seismic observations show a heterogeneous crust in the WA Craton. The spatial correlation with the Archean tectonic domains indicates the spatial heterogeneity may be deeply rooted, extending through the whole cratonic lithosphere. The temporal correlation suggests that the early crustal-formation processes may have worked differently through time, but have left distinct seismic signatures in the crust.

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

Contact: Huaiyu Yuan

Funded by: CCFS foundation Program 10a, 3D Architecture of the western Yilgarn Craton

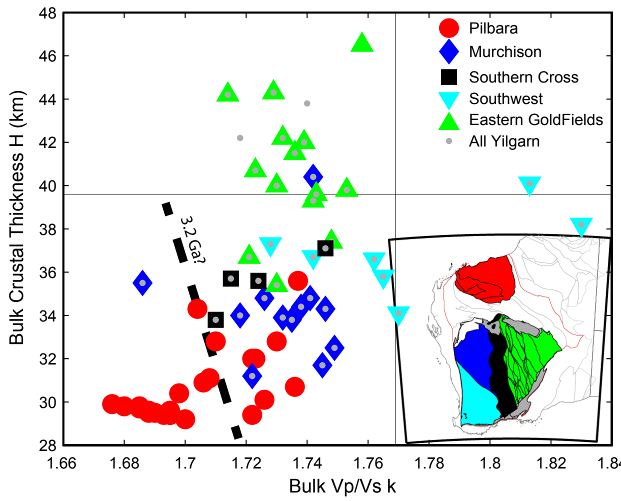
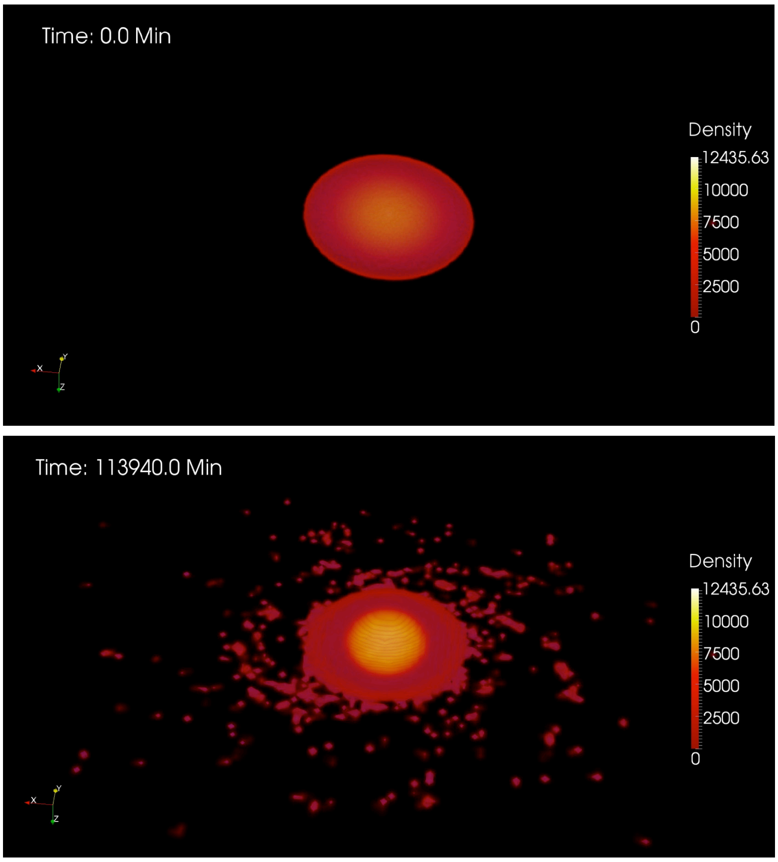


Figure 3. Clustering of bulk seismic properties in the WA crust. Thin lines show the global continental average. Thick dashed line shows a possible 3.2 Ga separation among all the measurements.

The origin of the Moon: spin-up during core formation?

The origin of the Moon is an ancient problem. The leading theory in recent decades has been a giant impact hypothesis, where a Mars-sized impactor - dubbed Theia - hit the protoEarth in a glancing impact in the late stages of accretion, ejecting a circum-planetary disk from which the Moon formed. The canonical models, however, predict that up to 60% of the Moon forms from material from the impactor Theia. However, the Moon and Earth's mantle have essentially identical oxygen and titanium isotopic signatures, distinct from any other planetary body, so a large contribution from Theia seems unlikely.



As a result, the impact community has moved towards special classes of impacts, with either a smaller impactor colliding with a rapidly-spinning proto-Earth, or two similarly-sized impactors in a head-on collision. Both require substantial loss of angular momentum in the Earth-Moon system and imply initial spin rates for the Earth of 1-4 hours, in line with recent accretion modelling.

We have developed an alternative scenario to explain the isotopic similarity of the Earth and Moon. Using parallel smoothed-particle hydrodynamic simulations, and a code developed within CCFS, we found that core formation in a rapidly rotating proto-Earth increases the angular momentum and results in a spin-up of the body. An analogy would be a twirling ice skater, increasing her rate of spin by pulling her arms in to her body. For fast initial rotations, this can result in mass being ejected along the equatorial plane. The magnitude of this effect depends on the initial spin, but for plausible rotation rates derived from accretion scenarios, the mass of disk ejected is between 0.2-3.5 lunar masses. The mass of the Moon predicted in the example shown is 0.6 Lunar masses, which compares well with the Moon. It also explains the Moon's low iron content, as the event was preceded by a major stage of core formation, removing much iron from the mantle. While the angular momentum is larger than in the current Earth-Moon system, modelling has shown this momentum would rapidly be lost due to orbital resonance effects soon after Moon formation.

The timing is broadly consistent with the geochronology of the Moon and core formation - the oldest anorthosites on the Moon show that the Moon formed within the first 150 Myr of solar system history. Likewise Earth's core formation is constrained to be within the first 45-140 Myr by U-Pb systematics, or 70-100 Myr from Rb-Sr data. This timescale also is consistent with large-scale atmospheric blow-off ~100 Myr after solar system formation, as recorded in Xe- isotope systematics. Recent analysis of the water content of the Moon suggest up to 1410 ppm of water in mantle olivines; this is difficult to reconcile with a giant impact, but would be a natural consequence of this mechanism.

Figure demonstrates the ejection of mass from the equatorial plane of a rapidly rotating proto-Earth, as a result of core formation. Using 50,000 interacting particles in a smoothed particle hydrodynamics simulation, we modelled the density re-distribution within a previously stable planet (top) during core formation, and track the increase in spin rate as a result of this, and the ejection of mass into a circum-planetary disk (bottom). The mass of this disk is sufficient to form Earth-sized Moons.

Finally, Venus has a slow retrograde rotation, and accretion modelling suggests this is a consequence of the last few large impacts in its accretion history. Despite these orbit-altering impacts, Venus does not have a moon, and has retained its primordial contingent of radiogenic noble gases, suggesting that the large-scale atmospheric blow-off that affected Earth did not occur. Our mechanism suggests that Venus' slow initial rotation made it difficult for core formation to spin the planet up enough to cause significant equatorial flattening. As a result, Venus never formed a Moon and did not experience the massive atmospheric loss expected during a mass spin-off event.

This project is part of CCFS Theme 1, Early Earth.

Contacts: Craig O'Neill, Siqi Zhang
Funded by: CCFS Foundation Program 4; Two phase flow within the Earth's mantle.

Fluid-present deformation aids chemical homogenisation in chromite

The deep Earth water cycle is strongly coupled to the dynamics of Earth's interior. Oceanic crust descending into the deep mantle carries relatively little water, but even trace amounts of water affect physical and chemical properties, including melting temperature, rheology, deformation mechanism, electrical conductivity, etc. Ophiolitic chromitites are commonly regarded as resistant to fluid-related processes, and the chemical signatures of chromitites have been used to study processes in Earth's mantle. However, modification during deformation may have important implications for the interpretation of chemical signatures in chromite. We have studied how deformation promotes chemical homogeneity in chromite hosted in the serpentinite body of Golyamo Kamenyane, in south Bulgaria (*Gervilla et al., 2012; Colás et al., 2014*). These chromitites have undergone deformation together with fluid-rock interaction during metamorphism, and previous work suggested that these chromitites are one of the most chemically modified and deformed examples known (*Colás et al., 2014*). We have documented how chromite has deformed and homogenised under fluid-present amphibolite-facies conditions, providing new insights on the microstructural evolution of chromite during retrograde metamorphism.

We measured crystallographic orientation relationships using Electron Back-Scattered Diffraction (EBSD) and electron microprobe analysis. Chromites show porphyroclastic textures with coarse-grained porphyroclasts (ca 0.2 ~5 mm) and fine-grained neoblasts (< 200 μm) (Fig. 1a). Large chromite grains are chemically zoned in terms of major elements from core to rim, preserving an initial igneous feature (CIa, CIb), while outer rims show a metamorphic signature (CII) (Fig. 1e). Large chromite grains also exhibit distinct intra-crystalline deformation including continuous crystal bending and subgrain boundaries, and chemical modification in their outer, deformed parts (CII; Fig. 1a, d). Two types of fine-grained chromite, F1 and F2, are recognised. F1 exhibits a well-developed polygonal texture, straight grain boundaries and low intercrystal misorientation (<1º); F2 shows low-angle boundaries and significant intercrystalline misorientation (2 ~8º) (Fig. 1a). Both F1 and F2 have higher Fe^{3+} and Cr and lower Mg# values than the cores of large grains (Fig. 1e). We interpret F1 and F2 to represent chromite recrystallised by heterogeneous nucleation and subgrain rotation recrystallisation, respectively.

Crystallographic preferred orientation (CPO) and misorientation data on the well-developed low-angle (subgrain) boundaries in coarse grains and F2 grains indicate that deformation in chromite was accommodated mainly by dislocation creep, dominantly activating the {111}<100> slip system. The retrograde P-T exhumation path defined by thermodynamic and chemical modelling suggests that these fine-grained chromites were produced when the initial chromitites reacted with oxidising fluids during retrograde metamorphism (~1.0 GPa and 500-700 ºC). Our results show that deformation in the dislocation-creep regime in a chemically-open system induced chemical modification and homogenisation within chromite aggregates as well as strain localisation. This close physicochemical link offers new avenues for the interpretation of chemical signatures in chromites, linked to their microstructurally-controlled variation.

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

Contacts: Takako Satsukawa, Bill Griffin, Sue O'Reilly, Sandra Piazolo

Funded by: CCFS Foundation Program 1, TARDIS-E

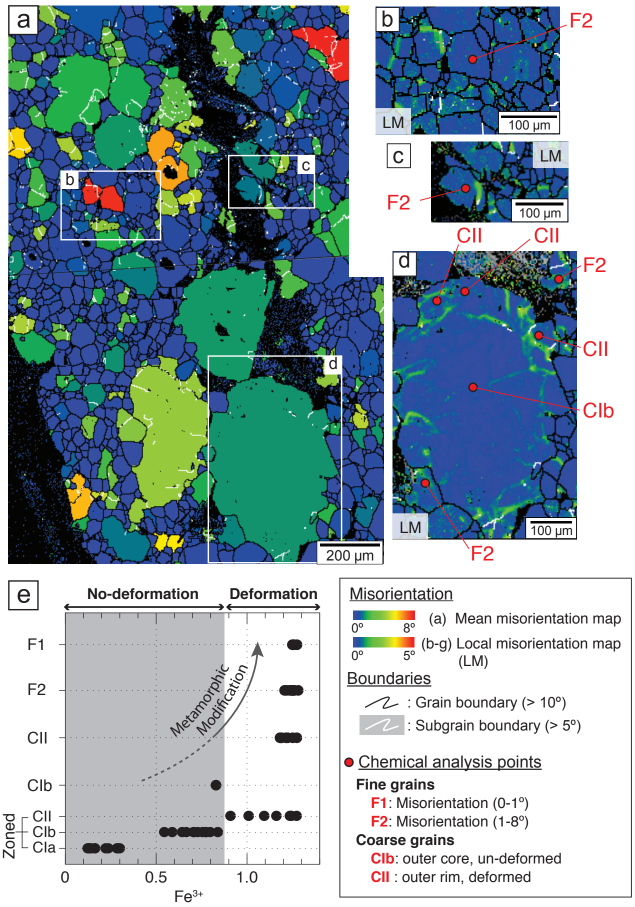


Figure 1. Orientation relationships as well as chemical composition of chromite porphyroclasts and adjacent fine grains. Step size of the map is 3 μm. (a) Colour coded EBSD map depicting the mean misorientation per grain (mean misorientation map). (b-d) EBSD maps showing local misorientations (LM) to identify crystal bending and subgrain boundaries below 5º. Fine grain types F1 and F2 are depicted. Chemical compositions at each red point are categorised according fine grain type (F1, F2) and coarse grain domain (CII, CIb). (e) Differences in chemical composition (Fe^{3+}) of different coarse-grained chromite domains (CIa, CIb and CII) and fine chromite grain types (F1 and F2), note that coarse grains have a general Fe^{3+}-poor composition relative to the fine grains.

Mean plate velocity and the frequency of orogens: Secular changes in the supercontinent cycle?

We have used two sets of data for the last 2.5 Gyr to address the question of secular changes in the supercontinent cycle: the timing and locations of collisional and accretionary orogens, and average plate velocities as deduced from paleomagnetic and paleogeographic data. This analysis has been done in collaboration with Kent Condie (New Mexico Tech), Jun Korenaga (Yale University) and Steve Gardoll (Curtin University) (*CCFS publication #468*).

One of the main problems in counting orogens is: what constitutes a single orogeny? Collisional orogens of short strike length could be parts of a longer orogen, now displaced by supercontinent breakup. Therefore we have used '*orogen segments*' in our analyses. In some cases an orogen segment may represent a complete orogen, whereas in others, it may represent only part of a much more extensive orogen. We also have distinguished between collisional and accretionary orogens. Accretionary orogens do not always end with a continent-continent collision, but collisional orogens always do.

Paleomagnetic data provide a quantitative tool for paleogeographic reconstructions. However, the number of high-quality paleomagnetic results is limited, especially for the Early-Middle Paleozoic and the Precambrian. The most complete and reliable global paleogeographic reconstructions for the last 2 Gyr are constrained by both geological and paleomagnetic data. To calculate the average angular velocities of tectonic plates, we used published post-1800 Ma global paleogeographic reconstructions that fulfil the following criteria: (i) all major continental block positions are shown in the reconstructions; (ii) evolving block positions are known in time slices or animations; (iii) reconstructions are made using spherical geometry; and (iv) each reconstruction is made with Euler rotation parameters. Pre-1800 Ma paleogeographic reconstructions are rare and rather controversial. Unfortunately, only the paleomagnetic data from the Superior craton are sufficient for the estimation of mean angular velocities between 2500 and 1800 Ma. As the sizes of continents vary significantly, we calculated the mean angular velocity (in degrees/100 Myr) for each 100-Ma bin by normalising to continental area. We analysed only the movement of continental plates, because the data from oceanic plates are not available for most of the period of interest (≤2.5 Ga).

Peaks in the number of orogens, which probably reflect craton collisions, occur at 1850 and 600 Ma, with smaller peaks at 1100 and 350 Ma (Fig. 1). Distinct minima occur at 1700-1200, 900-700 and 300-200 Ma. Angular plate velocities as weighted by cratonic area vary greatly from about 20 to 80 deg/100 Myr with two peaks at 450-350 Ma and 1100 Ma (60-80 deg/100 Myr). However, the overall trend suggests a gradual speed up of plate tectonics with time. There is no simple relationship in the frequency of cratonic collision or average plate velocity between supercontinent assemblies and breakups. The assembly of Nuna at 1700-1500 Ma correlates with very low collision rates, whereas the assembly of Rodinia and Gondwana at 1000-850 and 650-350 Ma, respectively, correspond to moderate to high rates. Very low collision rates occur during supercontinent breakup at 2200-2100, 1300-1100, 800-650, and 150-0 Ma. A peak in plate velocity at 450-350 Ma correlates with early growth of Pangea, and another at 1100 Ma with the initial stages of Rodinia's assembly following the breakup of Nuna.

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

Contact: Sergei Pisarevsky
Funded by: CCFS Foundation Program 6: Detecting Earth's rhythms: Australia's Proterozoic record in a global context

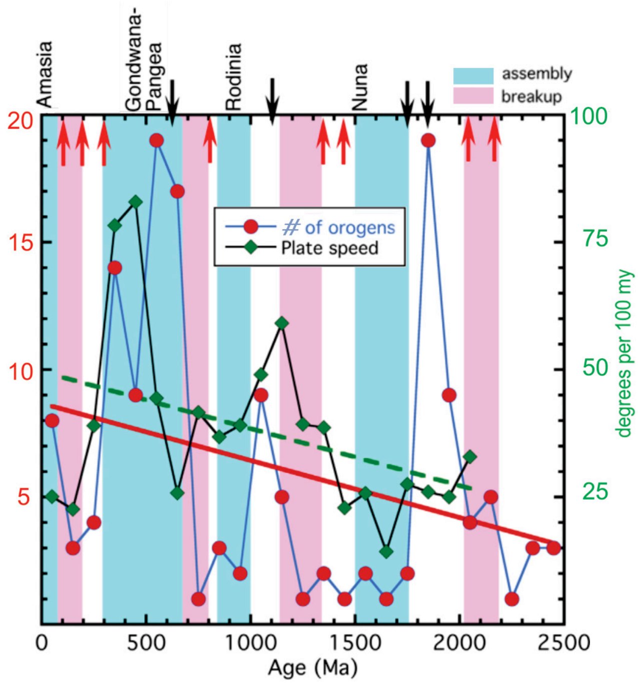


Figure 1. Secular changes in craton collision frequency and average area-weighted plate speed (deg/100 Myr). Collision frequency between cratons is expressed as number of orogen segments per 100-Myr bin moving in 100 Myr increments. Lines are linear regression analysis: n = 8.68-0.00224a, r = 0.287; s = 9.927-0.00223a, r = 0.393 (n, number of orogens; s, plate speed divided by five; a, age). Also shown are supercontinent assembly (blue stripes) and breakup (pink stripes) times. Major LIP (large igneous provinces) events: red arrows correspond to LIPs associated with supercontinent breakup, black arrows correspond to other LIPs.

Highly siderophile elements in the Emeishan LIP

Highly magnesian lavas (picrite) potentially preserve information about the origin and thermochemical state of the mantle sources of large igneous provinces (LIPs). We have carried out high-precision analysis of highly siderophile elements (HSE) in picrites from the ca 260 Ma Emeishan large igneous province

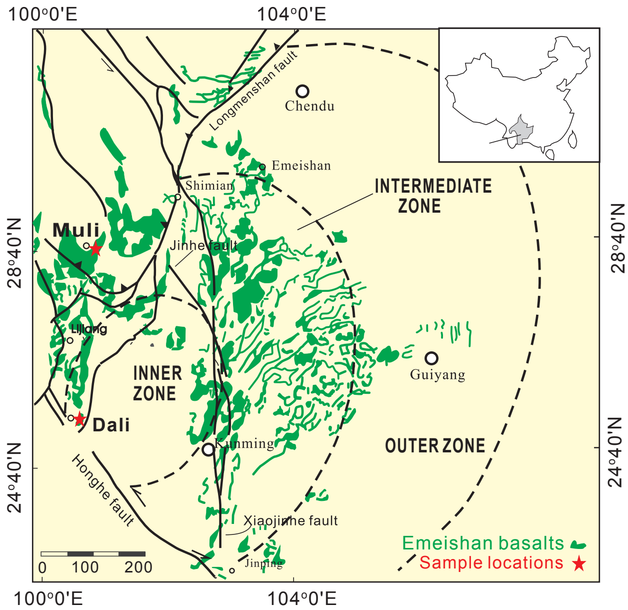


Figure 1. Distribution of the various components of the Emeishan Large Igneous Province, showing sample locations.

(Fig. 1). The absolute abundances of HSE in the Emeishan picrites are greater than those in MORB and in parental melts of Hawaiian picrites, and similar to the concentrations observed in komatiites (Fig. 2). The CI chondrite-normalised HSE patterns of the studied samples can be divided into two types (Fig. 3). Type 1, represented by the Muli picrites, is similar to that of the primitive upper mantle. Type 2, represented by the Dali picrites, has patterns similar to those of East Greenland and Iceland picrites; more fractionated Pt/Ir (8.6-34.5 with an average of 15.9 ± 8.4) and Pd/Ir (1.3-12.1 with an average 6.6 ±3.0) ratios relative to Type 1. The primary melt compositions of the studied samples were estimated using back addition of equilibrium olivine into

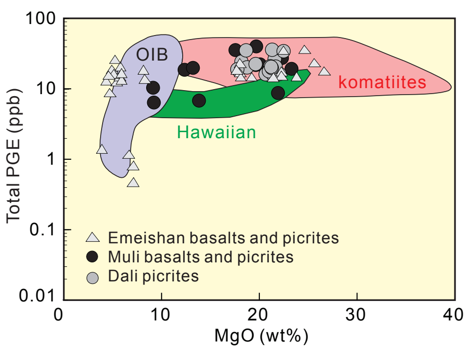


Figure 2. Total PGE contents versus MgO. The reference fields are after Ely and Neal, (2003), the Emeishan basalts and picrites data from Li et al. (2012).

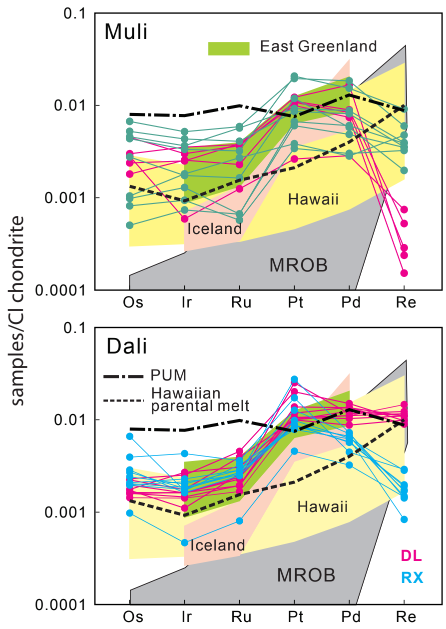


Figure 3. CI-chondrite normalised HSE patterns for (a) Muli and (b) Dali picrites. Primitive upper mantle (PUM) is thought to be representative of fertile peridotites, prior to the removal of material from the upper mantle (Becker et al., 2006). The reference MORB field is modified after Dale et al. (2008). The primitive melt for Hawaiian picrites is an average of individual suite parental melts (Ireland et al., 2009). The normalising values are from McDonough and Sun (1995). Data sources are as follows: east Greenland picrites are from Momme et al. (2006) and Momme et al. (1997); Iceland picrites from Momme et al., (2003); Hawaiian picrites from Bennett et al. (2000), Ireland et al. (2009) and Pitcher et al. (2009).

selected whole rock compositions (Fig. 4). The estimated HSE abundances in the parental melts of the Dali and Muli picrites are higher than estimates of Hawaiian parental melts. The large range of HSE abundances in the picrites reflects the integrated effects of source heterogeneity, plume-SCLM interaction, partial melting and early fractionation of olivine (± chromite). Together with existing isotopic data, this study shows that the source of the Emeishan plume mantle was chemically heterogeneous.

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

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Funded by: National Science Foundation of China (No.40903007) and CCFS ESTAR Fellowship

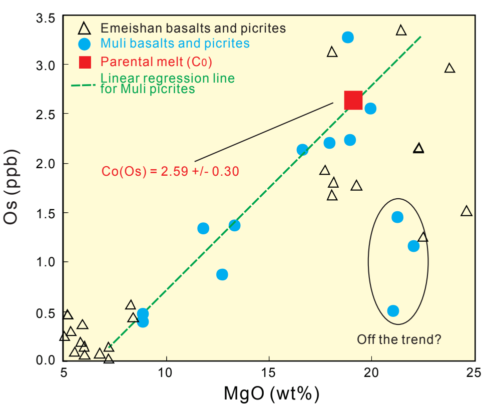

Figure 4. Example of how the HSE content in a parental melt was estimated, using Os abundances of the Muli picrites. The parental melt is assumed to contain 19 wt% MgO, and its Os abundance is determined by linear regression of the data. There are three samples that fall off the regression trend.

From core to ore: Localisation of Earth's hottest lavas

Volcanic eruptions are as old as the planet itself and have inspired awe, curiosity, and sometimes fear since the dawn of the first humans. These dynamic systems are the surface expression of the Earth's internal heat engine, and demonstrate that our planet is alive internally, as well as externally.

Despite the impressive impact of modern volcanoes, these eruptions and their flows pale in comparison to those that affected our planet in the past. The rarest and most evocative type of volcano is that of the ancient komatiites. These lavas are restricted to the early history of Earth around, 3.4-1.8 billion years ago when the mantle was much hotter. Erupted at temperatures above 1600 °C, they produced hose-like fire fountains, and lava flows that travelled at over 40 kilometres an hour as bluish-white, turbulent lava rivers. These crystallised to form some of the world's most spectacular igneous rocks, as well as giant nickel deposits, mainly in Western Australia and Canada.

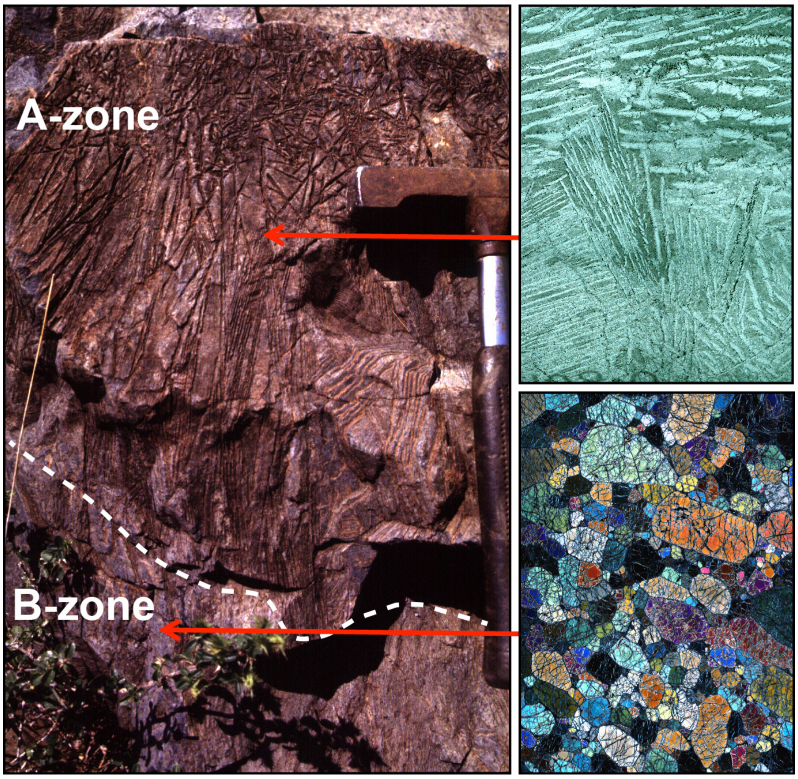

Figure 1. 3.4 billion year old komatiite flow from the Barberton greenstone belt in South Africa, where these ultra-high temperature lavas were first recognised. These lava flows consist of two zones; the A-zone (upper) is dominated by fine, needle-like crystals of olivine called 'spinifex texture', while the B-zone (lower) consists of a solid matrix of olivine crystals, which mark the base of the komatiite lava river.

These volcanic rocks have been studied for over 60 years and have been fundamental in developing our knowledge of the thermal and chemical evolution of the planet. However, until recently we did not understand why they formed where they did. Komatiites are found in ancient pieces of crust, called cratons, preserved from the Archean Eon 3.8-2.5 billion years ago. These cratons contain belts of preserved volcanic and sedimentary material, called greenstone belts. One of the largest cratons is Western Australia's Yilgarn Craton, which hosts most of the gold and nickel ever mined in Australia. This craton contains many greenstone belts but only a few contain major komatiite flows. The uneven distribution of ultra-high temperature lavas is not only a puzzling academic problem, but also is relevant to exploration for nickel ore deposits.

Previous research has demonstrated that komatiites form from mantle plumes - upwelling pipes of hot material that stretch from the outer core to the base of the crust; the modern equivalent is the mantle plume that is forming the Hawaiian island chain. Around 2.7 billion years ago, in a huge global event referred to as a '*mantle turnover*', multiple mantle plumes formed, and one impacted the base of the Yilgarn Craton, forming the hottest lavas ever erupted on Earth. When plumes first hit the base of the lithosphere - the 50-250 km thick rigid outer shell of the Earth - they spread out into discs of hot material more than 1000 kilometres in diameter. If the plume covered such a large area, why are komatiites confined to specific linear belts?

CCFS researchers in collaboration with CSIRO and the Geological Survey of Western Australia, set out to answer this question, not by looking at the komatiites, but by studying the slightly younger granites that make up most of the craton. They used Hafnium isotopes in zircon to constrain the age of the rocks that were melted to form the granites and whether they had a mantle or a crustal source. Mapping out the isotopic compositions of the granites revealed a jigsaw pattern in the crust, defined by regions where the granites formed by melting pre-existing, much older crustal rocks, and younger areas where the crust was newly created from sources in the deeper mantle.

Comparing the nature and shape of the ancient continent with the location of the major komatiite events, we found a remarkable correlation. The major komatiite belts and their ore deposits are located at the edge of the older continental regions. This is because of the shape of the base of the ancient Australian continent. As the plume rises, it impacts the older lithosphere first; this is thick and as a result the plume cannot generate much magma. However, the plume flows upwards along the base of the lithosphere, into the shallower, younger areas. Here, huge volumes of magma are generated at the boundary between the old, thick and young, thin areas of the lithosphere. Subsequently, komatiites, and their nickel deposits, are located at the margins of Earth's early continents.

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

Contact: Marco Fiorentini

Funded by: This study was started through ARC Linkage Projects (LP0776780, LP110100667) and finished within the framework of CCFS Flagship Program 2: Genesis, transfer and focus of fluids and metals

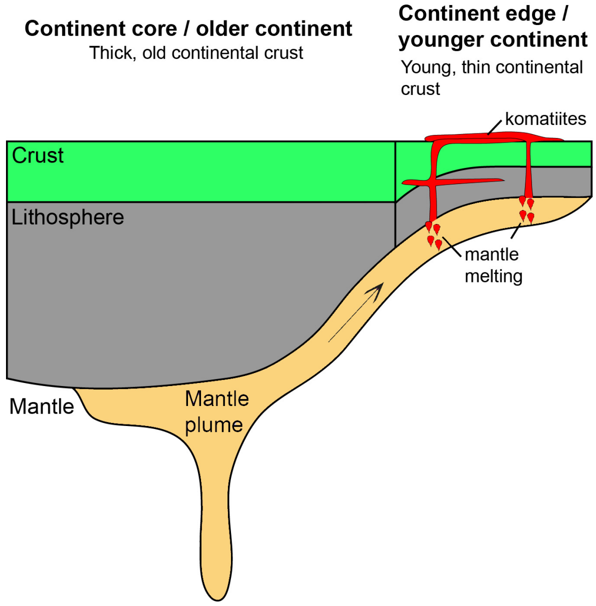

Figure 2. This cartoon demonstrates the main findings of our study. By imaging the older, thicker and younger, thinner areas of ancient lithosphere in the Yilgarn Craton, we were able to map the three-dimensional architecture of the craton and explain why komatiites are localised in specific belts. Plume melts are 'channeled' into the younger, thinner continental areas, resulting in a concentration of komatiites and their associated ore deposits in these areas.

Zircon signposts for base metals

Zircon 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 and the Superior Craton in Canada. Such maps combine *in situ* zircon U-Pb and Lu-Hf isotopic analyses. The isotopic mapping serves as a form of '*paleogeophysics*' for imaging ancient lithospheric architecture through time, even when it may not be visible in seismic data

There is a strong spatial correlation between lithospheric boundaries and the concentration of gold in Archean cratons. However, it is unknown whether this is the case for ore deposits in younger orogenic belts such as the world's largest - the Indo-Asian continental collision zone. Therefore, we have chosen the Lhasa Terrane in southern Tibet to examine the relationship between lithospheric architecture and various types of ore deposits in such orogens.

The Lhasa Terrane is the most metal-rich tectonic unit within the Indo-Asian collision zone with a variety of base metal deposits: copper, molybdenum, iron, lead and zinc (Fig. 1). It previously has been subdivided into northern, central, and southern subterranes, based on the differing sedimentary covers and metamorphic basements (Fig. 1). These three subterranes are separated by the Shiquan River-Nam Tso Melange Zone (SNMZ) and the Luobadui-Milashan Fault (LMF) (red lines on Fig. 1).

The zircon Hf-isotope mapping reveals more complex patterns than that defined by surface geology (Fig. 1). In the northern Lhasa subterrane, the western and eastern segments have high and low Epsilon Hf values, respectively, suggesting a juvenile block in the west and an ancient block in the east. The central

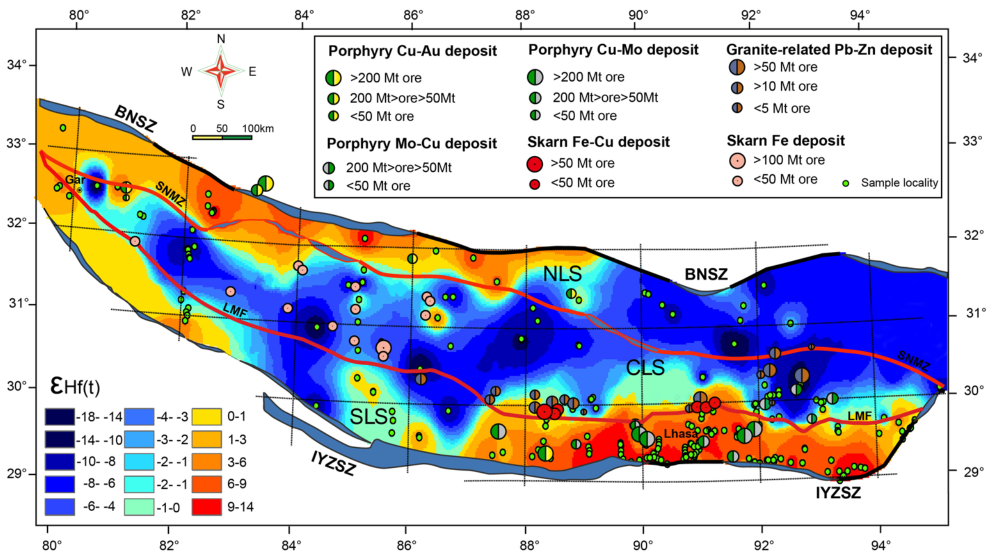

Figure 1. Zircon Hf isotopic mapping of the Lhasa Terrane in Tibet. The colour bands show the Epsilon Hf value of zircons studied. The ore deposits and zircon sample localities are also shown. The warm colours represent relatively juvenile blocks with higher Epsilon (Hf) values, whereas the cold colours represent relatively ancient blocks with lower Epsilon (Hf) values. Abbreviations: IYZSZ = Indus-Yarlung-Tsangpo Suture Zone; BNSZ = Bangong-Nujiang Suture Zone; LMF = Luobadui-Milashan Fault; SNMZ = Shiquanhe-Nam Tso Melange Zone; NLS = Northern Lhasa Subterrane; CLS = Central Lhasa Subterrane; SLS = Southern Lhasa Subterrane.

cont...

Lhasa subterrane is dominated by low Epsilon Hf values, consistent with it being an ancient Precambrian microcontinent. The southern Lhasa subterrane consists of two isotopically juvenile blocks in the west and east, withan ancient block in the middle (Fig. 1). A time slice map at 215-66 Ma, i.e. the period of orogenic accretion before India collided with Asia, reveals the same pattern for the Lhasa Terrane, suggesting that the lithospheric architecture of the Lhasa Terrane formed in the Mesozoic when two juvenile arcs accreted onto an ancient Precambrian microcontinent (Fig. 2a). A time slice map at 65-12 Ma, during the collision, shows that the eastern segment of the southern Lhasa subterrane is very juvenile, consistent with underplating of mantle-derived magmas generated during the Cenozoic collision (Fig. 2b).

The Mesozoic subduction-related porphyry Cu-Au deposits and Cenozoic collision-related porphyry Cu-Mo deposits are exclusively located in juvenile crust with high Epsilon Hf values (Figs. 1 and 2). The granite-related Pb-Zn deposits cluster in the oldest crustal regions or are developed along the margin of the old crustal block bounded by lithospheric faults (Fig. 1). The porphyry Mo-Cu deposits are localised along the reworked margins of the old crustal block. Skarn Fe-Cu ore deposits are typically localised along a terrane-boundary fault, through which crustally-derived felsic melts mixed with ascending Cu-rich mantle-derived mafic magmas. Skarn Fe deposits are exclusively located in the ancient crustal region (Fig. 1).

These zircon Hf-isotope maps show temporal-spatial relationships between lithospheric architecture and the location of ore deposits, and demonstrate that the structure, nature and composition of the lithosphere controlled the localisation of ore deposits and the migration of ore-forming metals into the crust. Zircon isotopic mapping is a powerful tool to image the lithospheric architecture of an orogenic terrane, and thus may become a robust pathfinder to base-metal deposits.

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

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Funded by: ARC ECSTAR Fellowship, CCFS Foundation Program 9: 4D Lithosphere evolution, CAGS

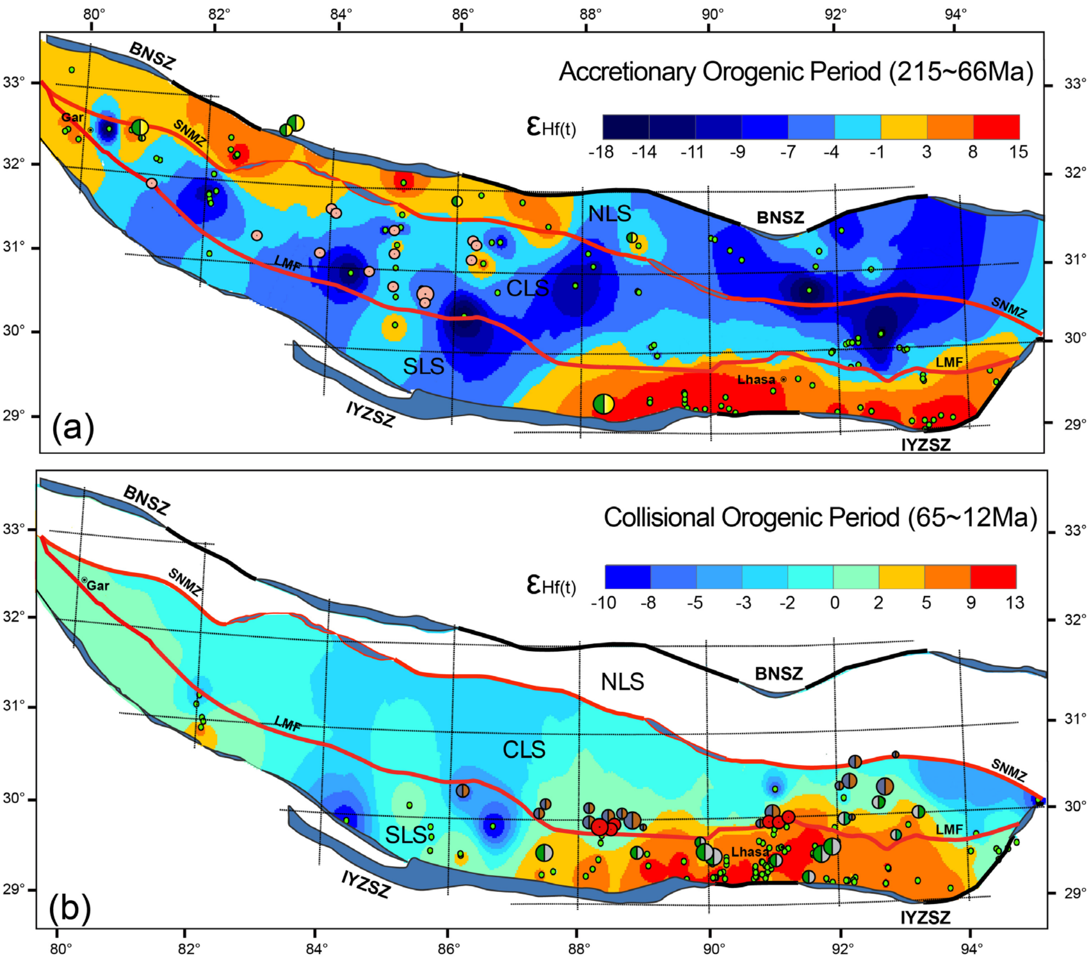
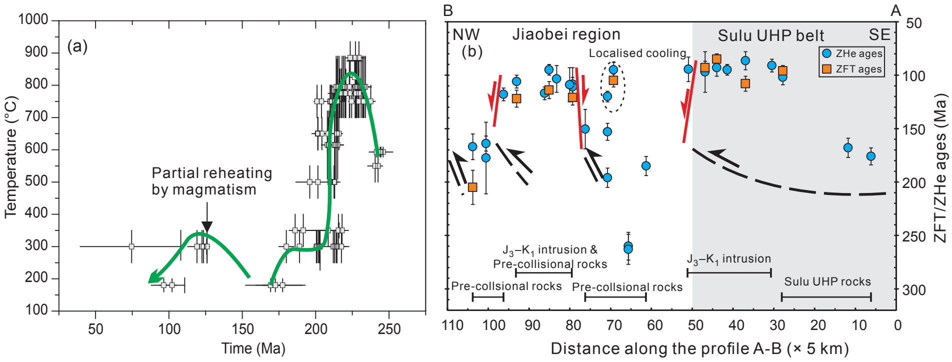


Figure 2. Time slices of zircon Hf isotopic mapping at 215-66 Ma (a) and 65-12 Ma (b). See Figure 1 for Legends.

Dissecting a continental collision with thermochronology

How are ultrahigh pressure metamorphic (UHM) rocks exhumed to the surface from mantle or lower-crustal depths? What happens after two continents collide? The clue could lie in the cooling history of UHP belts and the surrounding rocks, and one of the best-exposed and best-studied UHP terranes is the Dabie-Sulu orogenic belt in eastern China.



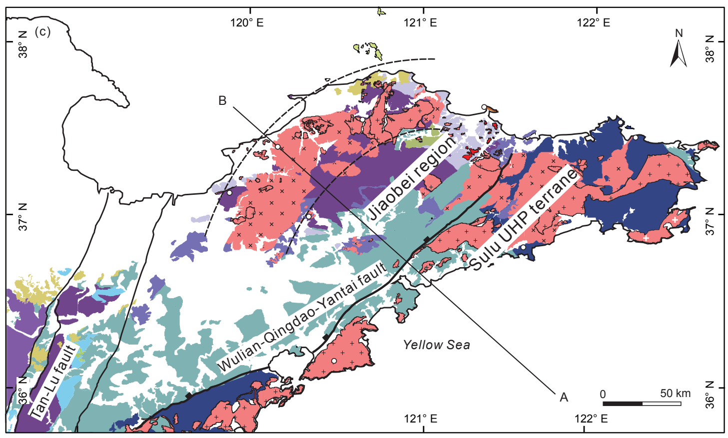


Figure 1. a) Temperature-time path based on zircon U-Pb, and hornblende and mica ^{40}Ar-^{39}Ar ages. b) Profile of ZHe and ZFT ages along the A-B cross section. Ages were projected along the dashed curves in Figure 1c. c) Geological map showing A-B section location.

The Dabie-Sulu orogenic belt formed during the collision of the South China Block (SCB) with the North China Block (NCB) in early Mesozoic time. However, a lack of unambiguous kinematic constraints has made it difficult to verify competing models for the mechanisms of continental collision and exhumation of the UHP rocks. We have applied mica and hornblende $^{40}Ar/^{39}Ar$, zircon and apatite fission tracks, and zircon (U-Th)/He dating to both the metamorphic rocks and syn- to late-orogenic granitic intrusions in the Sulu UHP belt and the adjacent Jiaobei region. $^{40}Ar/^{39}Ar$ and zircon (U-Th)/He data show that the UHP rocks experienced a prominent cooling event at ca 210-160 Ma (Fig. 1a). The Jiaobei region, underlain by the Archean basement of the NCB and located immediately north of the Sulu UHP belt, experienced a localised exhumation at ~260 Ma as well as a Jurassic (196 ± 9 Ma to 164 ± 7 Ma), westward-younging exhumation (Fig. 1b) that overlaps with the exhumation age of the Sulu UHP belt. The ca 260 Ma exhumation probably reflects tectonic erosion at the southern margin of the NCB in response to the initial continental collision, whereas the Jurassic exhumation may be related to an episode of NW-SE tectonic compression. Hence, the 210-160 Ma exhumation in both the Sulu UHP belt and the Jiaobei region is interpreted to reflect erosion in response to northward thrusting of the UHP rocks and the Jiaobei Archean basement. Overall, our results lend strong support to the continental-collision model of Li (1994) in which both the Sulu UHP rocks and the upper crust of the Jiaobei region moved northward along a mid-crustal detachment plane after the UHP rocks were exhumed to upper-crust levels (Fig. 2).

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: Li-Ping Liu, Zheng-Xiang Li

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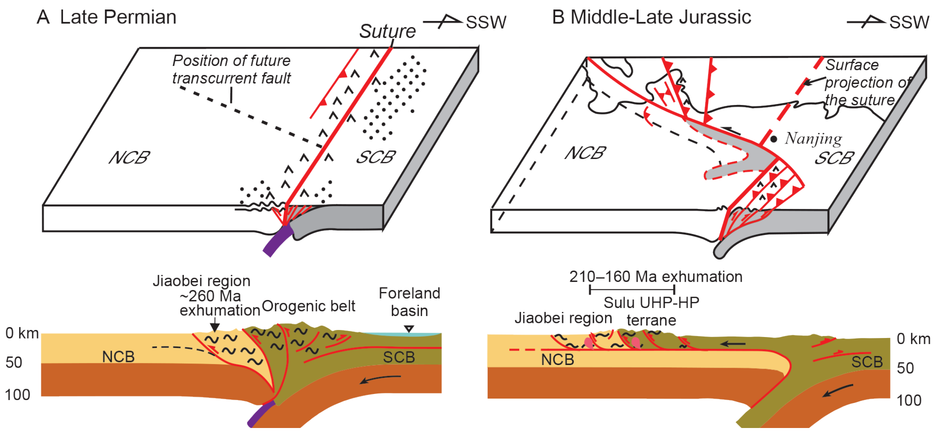


Figure 2. The crustal detachment model that is compatible with observed exhumation events. A) With initial continental collision at ~260 Ma, the Jiaodong region underwent crustal thickening and exhumation. B) By ~210 Ma, the UHP-HP rocks had been exhumed back from the mantle depths to crustal depths. Continuous compression led the UHP-HP rocks to detach from underlying SCB lower crust and move northward along a horizontal detachment until finally climbing the frontal thrust ramp at ~160 Ma. This movement also caused folding and thrusting in the Jiaobei region and exhumation of both the Sulu UHP rocks and the upper crust of the Jiaobei region.

Cryptic chemical fingerprints identify different origins for ancient regions of Western Australia

CCFS, through close collaboration with the Geological Survey of Western Australia, has produced a world-leading isotopic dataset that integrates U-Pb ages and Lu-Hf data from zircons with geological, geochemical, and geophysical information from across Western Australia. This expansive dataset has refined our understanding of the Proterozoic evolution of Australia. One of the most critical, yet controversial, issues relating to Proterozoic reconstructions of the Australian Continent is the nature, or even existence, of Mesoproterozoic links between the Musgrave Province and the Albany-Fraser Orogen.

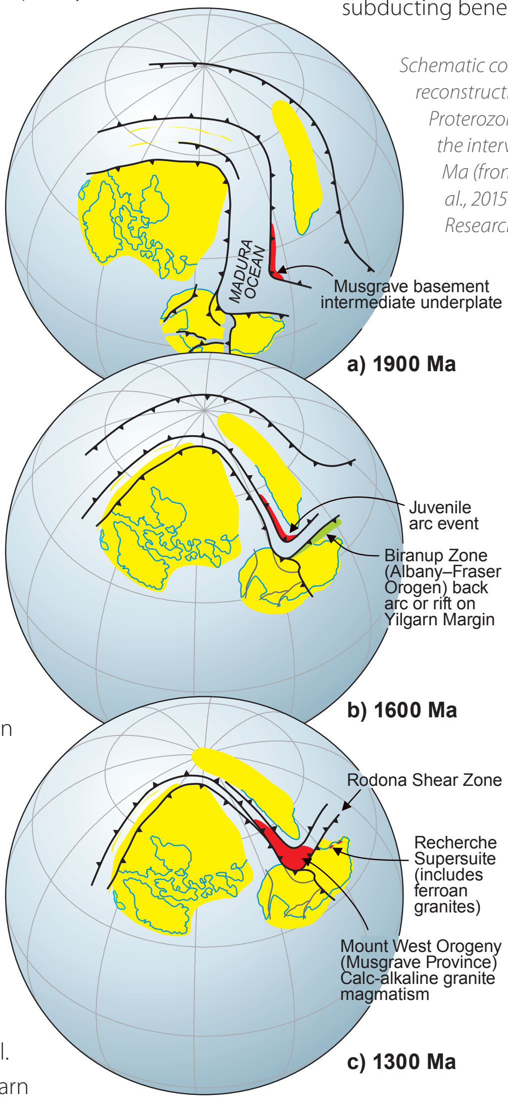
The Musgrave Province lies between the North and South Australian Cratons, whereas the Albany-Fraser Orogen lies along the southern and southeastern margin of the Archean Yilgarn Craton. These two belts evolved through temporally similar Mesoproterozoic orogenies at 1345-1260 and 1215-1140 Ma, but on completely different basement. The West and North Australian Cratons amalgamated before the 1345-1260 Ma event, which is interpreted to result from the collision of those combined cratons with the South Australian Craton.

The Paleoproterozoic and Mesoproterozoic history of the Albany-Fraser Orogen involved the reworking of the Yilgarn Craton's margin, accompanied by significant juvenile mantle input. The orogen's profile of zircon ages and its Hf- and Nd-isotopic signature reveals an Archean component incorporated into rocks of all ages, which is unequivocally derived from the Yilgarn Craton. The age and isotopic signature of the Albany-Fraser Orogen thus suggests it is an indigenous component of the Yilgarn Craton, rather than an accreted terrane.

This program strand has produced well-defined Nd- and Hf-isotope arrays that track the evolution of the Musgrave Province, through distinct 1950-1900 and 1600-1550 Ma crustal-formation events. Rare non-radiogenic material in the Musgrave Province is only seen in detritus and in magmas that assimilated this material. This evolved detritus, derived from non-Yilgarn and reworked Archean sources, was added to sedimentary basins developed over the Musgrave Province basement from ca 1400 Ma onward. However, the pre-Mesoproterozoic isotopic composition and zircon-age profile for the Musgrave Province is distinctly different from that of the Albany-Fraser Orogen.

If the basement to the Musgrave Province is neither Archean nor part of the West Australian Craton, then what is it? The Madura Province, which lies south of the Musgrave Province, has a radiogenic signature similar to the Musgrave Province and the two provinces probably are contiguous beneath the younger cover sequences. We have found that the crust of the Madura Province contains zircons with 2.0-1.4 Ga mantle extraction ages, and is dominated by juvenile rocks related to oceanic crust that was consumed to the north of the South Australian Craton and east of the West Australian Craton. It appears that the Musgrave Province was formed by modification of Madura-Province crust along the edge of the North Australian Craton. Together, the Musgrave Province and the Madura Province represent Proterozoic Australia's most juvenile crustal remnant.

The new data indicate that the Musgrave Province developed on a juvenile substrate of Madura Province crust that was subducting beneath, and accreting to, the North Australian-West Australian Craton. During the Mount West Orogeny / Albany-Fraser Orogen at ca 1300 Ma, the Musgrave Province was not an along-strike equivalent of the Albany-Fraser Orogen. At that stage, the Musgrave was an active subduction zone, while the Albany-Fraser Orogen was undergoing orogenic collapse following the earlier accretion of the Loongana arc of the Madura Province to the West Australian Craton.



Schematic continental reconstruction of Proterozoic Australia for the interval 1900-1300 Ma (from Howard et al., 2015 Gondwana Research).

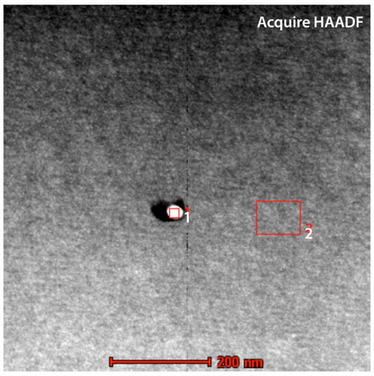
This project is part of CCFS Theme 2, Earth Evolution, and contributes to understanding Earth's Architecture.

Contacts: Chris Kirkland, Elena Belousova

Funded by: CCFS Foundation Program 10b

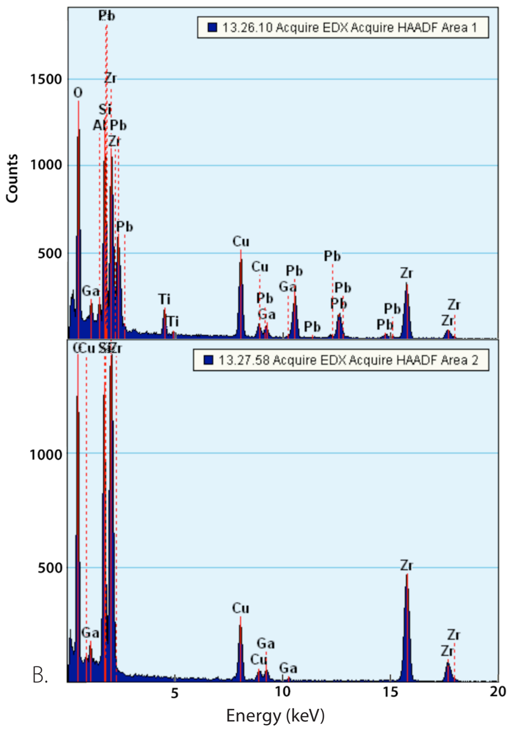
Mobile lead and spurious zircon ages

Zircons from metasedimentary and metaigneous gneisses in the Napier Complex (East Antarctica) preserve zircon U-Pb ages greater than 3.8 Ga (*Black et al., 1986; Harley, 1997*). The complex underwent two metamorphic events; high-temperature metamorphism at ca. 2.8 Ga (*Kelly and Harley, 2005*) and ultra-high-temperature (T >1100 ºC) at ca 2550-2480 Ma (*Harley, 2000*). The earliest zircon SHRIMP (Sensitive High Resolution Ion MicroProbe) study of the Napier Complex (*Williams et al., 1984*) described isotopic disturbance of >3.4 Ga zircons, defined by reversely discordant analyses (i.e. U-Pb ages older than $^{207}Pb/^{206}Pb$ ages) and within-run instability of Pb during analysis. These results were confirmed recently by ion imaging utilising a Cameca ims 1280 (*CCFS Publications #407, 429*). These studies revealed the patchy distribution of Pb and Ti and identified the presence of unsupported Pb with anomalously high (>4 Ga) $^{207}Pb/^{206}Pb$ ages.



A.

Figure 1. A: High-angle annular dark-field TEM image showing Pb nanosphere. B: EDX spectra of nanosphere rich in Pb and Ti (top) and zircon (bottom).



B.

Following this discovery, we analysed zircons from three samples: one orthogneiss (from Gage Ridge) and two paragneisses (one each from Mount Sones and Dallwitz Nunatak) by TEM (Transmission Electron Microscopy) applying the site-specific focused-ion-beam (FIB) technique at GeoForschungsZentrum (GFZ) Potsdam in Germany. TEM images revealed that zircon grains from the Napier Complex contain randomly distributed, spherical metallic lead nano-inclusions 5-30 nm in diameter (*Kusiak et al., under revision*). They occur either as individual droplets (Fig. 1) or together with unidentified phases rich in Ti and silica, which together constitute melt inclusions ca 20-80 nm in diameter. The occurrence of metallic Pb nanospheres in zircons that underwent UHT metamorphism explains the unusual U-Pb behaviour of such grains during SIMS (Secondary Ion Mass Spectrometry) analysis. Further studies are continuing to determine how the nanospheres may have formed. See *CCFS Publications #407, 429*.

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

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The Hadean - Archean crust-mantle revolution: How should we divide the Archean?

When and how did the continents on which we live form and stabilise in the torrid early history of our evolving planet? We have used the mineral zircon as time capsules to record the history of events in the Earth's crust from trace-element and isotopic data (U-Pb and Lu-Hf). Sulfide minerals and metal alloys from mantle-derived samples (brought to the Earth's surface by magmas from 50 to 600 km deep), record the history of fluid, melting and formation events in the mantle using the Re-Os isotopic system. The combination of these two powerful tools allows time travel back to early Earth times and has produced some rare insights, changing our understanding of the timing of significant ancient upheavals that shaped Earth's crust.

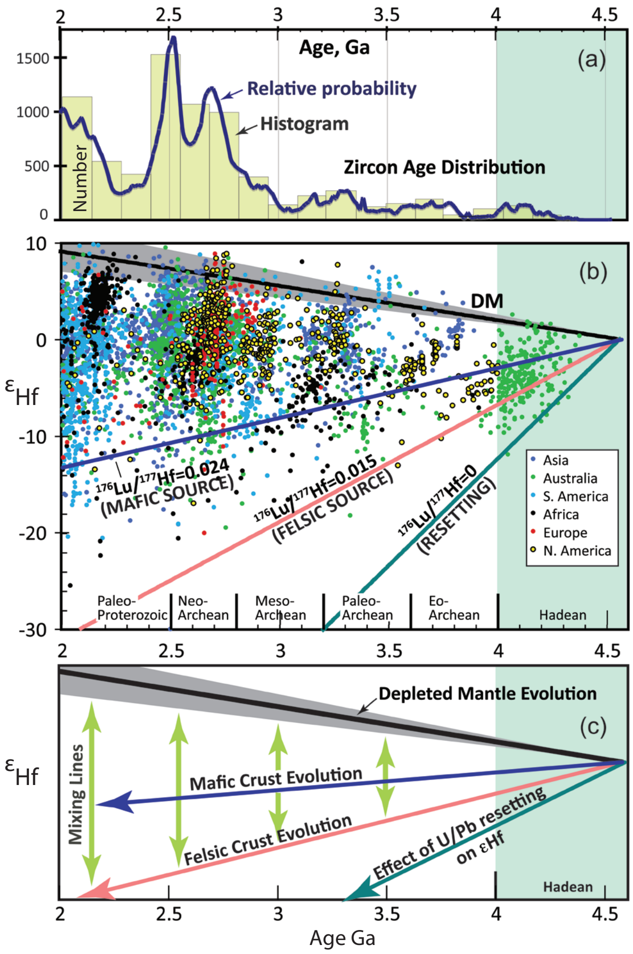


Figure 1. εHf vs age for zircons worldwide, divided by region. The database (n=6699) builds on the data of Belousova et al. (2010) updated with >2000 analyses published, and/or produced in our laboratories, after 2009. The conventional subdivision of the Hadean and Archean is shown along the X axis. (a) zircon age distribution shown as a histogram and a cumulative-probability curve. (b) distribution of Hf-isotope data. The "juvenile band", defined as ±0.75% of the εHf of the Depleted Mantle line at any time, is shown as a grey envelope. Evolution lines from 4.5 Ga are shown for reservoirs corresponding to typical mafic rocks ($^{176}Lu/^{177}Hf = 0.024$), the average continental crust ($^{176}Lu/^{177}Hf = 0.015$), and zircons, approximated by $^{176}Lu/^{177}Hf = 0$. (c) shows these evolution lines.

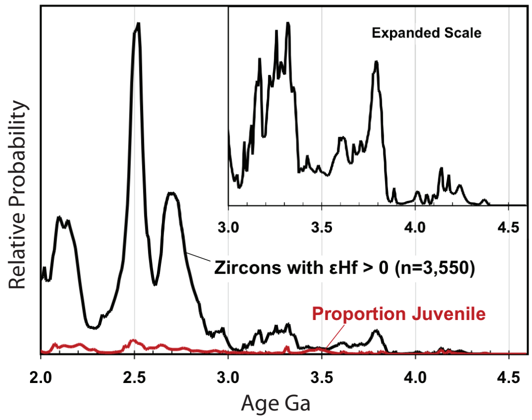


Figure 2. (a) Cumulative-probability curve and age histogram for all zircons with εHf falling within 0.75% of the Depleted Mantle curve in Figure 1. Inset uses an expanded scale to show detail in the oldest datasets.

We have integrated a worldwide compilation of the ages of crust and mantle events from 2 billion years ago until nearly the time of formation of planet Earth at ~4.5 billion years, allowing us to track patterns of evolution of the crust, and interaction between the mantle and crust. These data show that from about 4.5 to 3.4 billion years ago, the Earth's crust was essentially stagnant (like a lid on a hot cauldron), and was mainly basaltic in composition.

Data suggest that some zircons crystallised from magmas that were possibly generated by impact melting from bombarding planetary bodies (meteorites large and small). Pulses of magmatic activity at about 4.2, 3.8, and 3.3-3.4 billion years, possibly representing mantle convective overturns or rising mantle plumes, broke this quiescent state.

Between these pulses, there is evidence of resetting of zircon U-Pb ages (by impact?) but the Hf-isotope data (Fig. 1) allow us to see back through such events and imply that there was no further generation of new crust. There is thus no evidence of plate-tectonic activity, as described for the Earth in the state we know it today (i.e. through the Phanerozoic Era), before about 3.4 billion years ago. Previous modelling studies indicate that the early Earth may have been characterised by an episodic-overturn, or a stagnant-lid, regime. New thermodynamic modelling (*CCFS Publication #488*) confirms that an initially hot Earth could have a stagnant lid for ca 300 million years, and then experience a series of massive overturns at intervals on the order of 150 Ma, until the end of the EoArchean Period (earliest Archean time). The lack of older Os model ages (Fig. 2) suggests that subcontinental lithospheric mantle (SCLM) sampled on Earth today did not exist before about 3.5 billion years ago.

A lull in crustal production around 3.0 billion years coincides with the rapid buildup of Mg0-rich, buoyant SCLM, which peaked around 2.7-2.8 billion years; this pattern is consistent with one or more major mantle overturns. The generation of continental crust peaked later in two main pulses at about

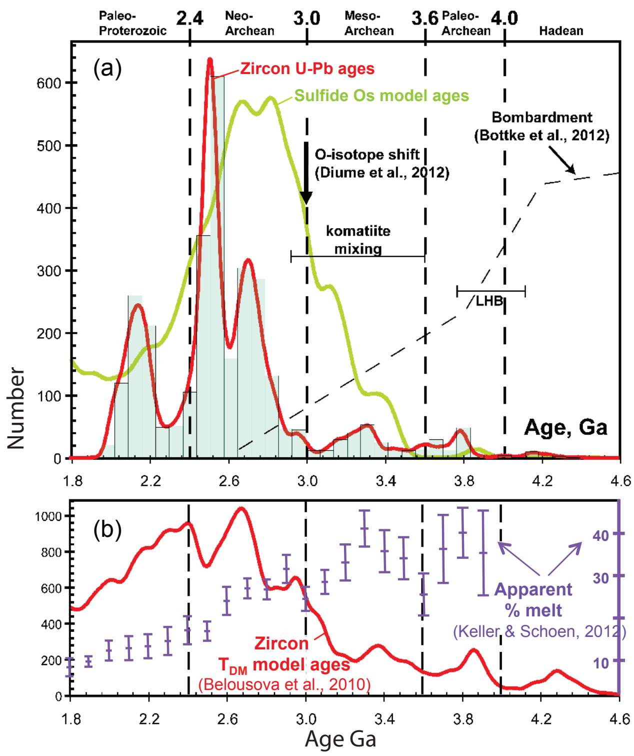


Figure 3. Summary of crust-mantle evolution. Grey histogram shows distribution of all zircons in the database for the time period shown; red line shows the probability distribution of these ages. Green line shows distribution of Re-Os TRD model ages for sulfides in mantle-derived xenoliths and xenocrysts. The revised distribution of meteorite bombardment intensity (Bottke et al., 2012) and a generalized summary of older interpretations of the "Late Heavy Bombardment" is shown as LHB. The homogenization of PGE contents in komatiites from 3.5-2.9 Ga (Maier et al., 2010) may mark the major mantle-overturn/circulation events discussed in the text. The O-isotope shift noted by Dhuime et al. (2012) marks the beginning of a quiescent period, or perhaps the destruction of the crust during the major overturns from 3.5-2.9 Ga.

2.75 and 2.5 billion years ago (*Belousova et al., 2010*). The age/Hf-isotope patterns of the crust generated from 3.0-2.4 billion years are similar to those in old tectonic regions of the Gondwana supercontinent, implying the existence of plate tectonics at the time of assembly of the ancient supercontinent (Kenorland) ca 2.5 billion years ago. We have demonstrated a clear link in these data between the generation of the SCLM and the emergence of modern plate tectonics; we consider this link to be causal, as well as temporal.

The *International Geologic Time Scale* sets the Hadean-Archean boundary at 4.0 Ga and divides the Archean into four approximately equal time slices (Fig. 1): Eo-Archean (4.0-3.6 Ga (Ga = billion years ago)), Paleo-Archean (3.6-3.2 Ga), Meso-Archean (3.2-2.8 Ga) and Neo-Archean (2.8-2.5 Ga). There is no apparent evidence in the present datasets for these divisions, and we suggest a simplified subdivision, based on the changes in tectonic style (Fig. 3) at identifiable times.

In the absence of better data, we accept the Hadean-Archean boundary at 4.0 Ga, although we suggest that the stagnant-lid regime may have continued for another 500-800 million years.

We propose that the term *Eo-Archean* be discarded, since there is little preserved evidence of magmatic activity between 4.2 and 3.8 billion years, and that the term *PaleoArchean* be used for the period 4.0-3.6 billion years; this timespan contains the oldest preserved crust, and inferred evidence for one major overturn. *MesoArchean* could be applied to the period 3.6-3.0 billion years, during which overturns became more prominent, ending with the buildup toward the major 2.8-2.55 billion years, magmatism that accompanied the building of the bulk of the Archean SCLM. NeoArchean can be usefully applied to the period 3.0-2.4 billion years, which marks a *new tectonic style* with frequent plume activity, the beginning of some form of plate tectonics, and the preservation of large volumes of continental crust. The zircon data suggest that this activity continued up to about 2.4 billion years ago, and then ceased quite abruptly, marking a natural end to the Neo-Archean period, and heralding a new geotectonic regime for Earth.

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

Contacts: Bill Griffin, Elena Belousova, Sue O'Reilly

Funded by: CCFS Foundation Program; TARDIS: Tracking ancient residues distributed in the silicate Earth, Future Fellowship (Elena Belousova)

CCFS honours & postgraduates

HONOURS

COMMENCING 2015

Jack Adams
Haydn White

MASTERS OF RESEARCH, MQ

From 2013, the honours program at Macquarie University was replaced by a two-year Masters of Research (MRes) combining 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 is 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.

COMPLETED 2014

Lauren Miller: Fluorite in hydrothermal vein systems: Reconstructing fluid evolution

Michael Nguyen: Understanding the evolution of planets through X-Ray micro-computed tomography analysis of metal-silicate differentiation in the meteorite Bijurbole

Cameron Piper: Direct comparison of bore purge and low-flow groundwater sampling techniques in rapid recharge areas

Alastair Williams: A microstructural and geochemical study of the Sunrise Dam Gold Deposit, Western Australia: Hydrothermal history and its relation to gold mineralisation

CONTINUING 2015

Anthony Lanati: Determining the role of water in mantle conductivity

Alexandre Lemenager: Geothermal modelling of the Sydney Basin using temperature dependent measurements

Uvana Meek: Reactive fluid flow in the lower crust

Josephine Moore: Grain boundary characterisation of Alpine Fault rocks

COMMENCING 2015

Victoria Elliott

Jean-Antoine Gazi

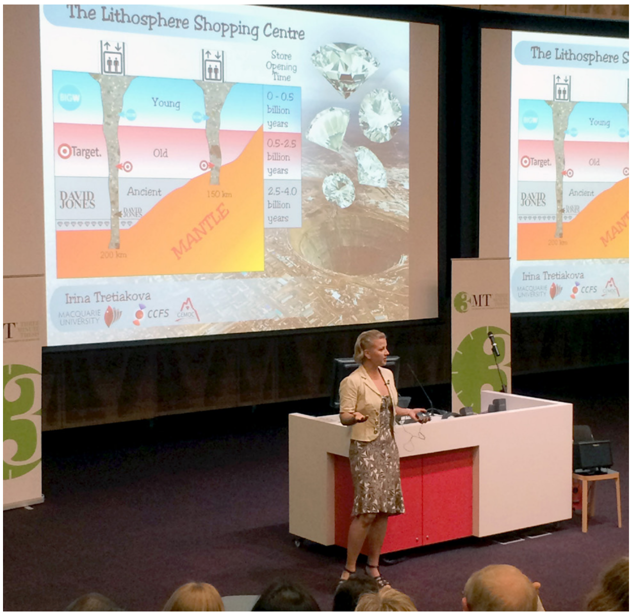
Mitchell Gerdes

Colleen McMahon

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 2012-2014. 28 papers by CCFS postgraduates were published in high-profile international journals in 2014, including *Proceedings of the National Academy of Sciences, Precambrian Research, American Journal of Science, Journal of Petrology, Earth and Planetary Science Letters, Lithos, Chemical Geology, Tectonics and Journal of Geophysical Research*. 53 presentations were also given at 11 international conferences (see *Appendix 6*).

HIGHLIGHTS



Irina Tretiakova and **Romain Tilhac** won their way through to the Macquarie University wide final for 3-Minute Thesis as representatives of the Faculty of Science. Competitors were allowed three minutes to deliver an engaging and dynamic talk on their thesis topic and its importance. Talks were limited to a single slide and needed to be language appropriate for an intelligent but inexpert audience. Both gave exceptional presentations, with Irina securing the People's Choice award for her talk entitled "*The Lithosphere shopping centre*" *(pictured above).*

Their presentations may be viewed at http://ccfs.mq.edu.au/NewsArchive/NewsArchive.html.

Christopher Gonzalez was awarded the best student poster at the CET Science Day.

Nicole McGowan was awarded an AESC student scholarships from the NSW division of the GSA.

Beñat Oliveira Bravo was awarded the most prestigious Spanish postgraduate award: "*la Caixa*". Grants cover the full cost of matriculation, travel expenses and monthly allowances that can be extended up to 24 months. The award ceremony will take place in Barcelona, 10 April 2015, in the presence of the King and Queen of Spain.

Chengxin Jiang and **Beñat Oliveira Bravo** *(pictured right)* were given the opportunity to participate in an elite PhD coarse, "*Anisotropy and mantle deformation*," organised by the Copenhagen School of Solid Earth Geophysics. The workshop, held on 14-18 June, provided students with the unique opportunity to learn about anisotropy and mantle deformation from world leading researchers and interact with other international PhD students.

COMPLETED

Rachel Bezard (PhD): Impact of crustal assimilation on the Lesser Antilles arc lava geochemistry (MQ 2014)

David Clark (PhD): Integrated magnetics: Contributions to improved processing and interpretation of magnetic gradient tensor data, new methods for source location and estimation of magnetisation, and predictive magnetic exploration models (MQ 2014)

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 (MQ 2012)

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

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

Erin Gray (PhD): Deformation of Earth's upper mantle: insights from naturally occurring fabric types (UWA2014)

Celia Guergouz (MSc): Study of the dynamic emplacement of Nickel mineralisation, as well as the geodynamics of the lithosphere (UWA/Nancy, 2014)

Jin-Xiang Huang (PhD): Origin of eclogite and pyroxenite xenoliths in kimberlites and basalts (MQ 2012, see *profile, p. 13-14*)

Huiqing Huang (PhD): The petrogenesis of Jurassic granitic rocks in Western Nanling Ranges of South China and tectonic implications (CU 2013)

Shan Li (PhD): Early Mesozoic magmatism and tectonics in the Beishan area of Inner Mongolia, China (CU 2013)

Yongjun Lu (PhD): Controls on porphyry emplacement and Porphyry Au-Cu mineralisation along the Red River Fault, Hunan Province, China (UWA 2012, see *profile, p. 15-16*)

WHERE ARE THEY NOW?

In 2013, **Dr Matthew Pankhurst** completed his PhD investigating the source regions of post-orogenic magmatism. While at CCFS he was trained in major, trace and isotope geochemistry and developed analytical skills including ICPMS, (both solution and laser ablation) TIMS, EMPA and EBSD. His thesis linked the production of small degree mantle partial melts during orogenesis to lithospheric crisis and thermal response producing A-type granites and termination of the local orogeny.

In 2013, Matt commenced a Post-Doc fellowship at Leeds in the School of Earth and Environment investigating the timescales of magmatic and eruption processes of the 2010 eruptions of the Eyafjallajökull volcano. Matt believes this research will play an important role in eventually improving civil disaster management strategies.

In November 2014, Matt visited CCFS to use the instruments housed in the GAU at MQ *(pictured left).*

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, see *profile, p. 14-15*)

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

Chongjin Pang (PhD): Basin record of Mesozoic tectonic events in South China (CU 2014)

Matthew Pankhurst (PhD): Geodynamic significance of shoshonitic magmatism within the Andean Altiplano (MQ 2013, *See feature, p. 67*)

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

James (Ed) Saunders (PhD): The nature, abundance and mobility of gold in the mantle (MQ 2014, see *profile, p. 15-16*)

Elyse Schinella (PhD): Constraining the contribution of isostasy and dynamic uplift at Venusian volcanic rises and tessera terrain: implications for rifting and volcanism (MQ 2014)

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

Zoja Vukmanovic (PhD): A micromechanical and geochemical analysis of remobilisation of komatiite-hosted Ni sulfide ores (UWA 2013)

Weihua Yao (PhD): Lower Palaeozoic basin record in Southern South China: Nature of the Cathaysia basement and evolution of the Wuyi-Yunkai Orogeny (CU 2014, see *profile, p. 12*)

Yao Yu (PhD): The evolution and water inventory of the subcontinental lithospheric mantle: A new perspective from peridotite xenoliths (SE China) and zircon megacrysts from basalts (MQ 2014)

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)

Kongyang Zhu (PhD): Petrogenesis and tectonic setting of Phanerozoic granitic rocks in eastern South China (CU 2014)

CONTINUING

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

Katarina Bjorkman (PhD): 4D lithospheric evolution and controls on mineral system distribution: Insights from Marmion Terrane, Western Superior Province, Canada; *UWA SIRF* (UWA, commenced 2013)

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* (MQ, commenced 2011)

Montgarri Castillo Oliver (PhD): Compositional evolution of indicator minerals: Application to diamond exploration; *iMQRES Cotutelle* (MQ, commenced 2014)

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

Bruno Colas (PhD): Why is the San Andreas Fault so weak?; HDRSCHOL, *iMQRES* (MQ, commenced 2013, *pictured p. 71*)

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

Daria Czaplinska (PhD): Flow characteristics of lower crustal rocks: Field studies and numerical modelling; *iMQRES* (MQ, commenced 2012, *pictured below*) See *Research Highlight p. 45.*

Tara Djokic (MPhil): Life in the Dresser Formation: The relationship between early life and hydrothermal fluids at c. 3.5 Ga in the North Pole Dome, Pilbara Craton, Western Australia (UNSW, commenced 2014)

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

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

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

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

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 (MQ, part time, commenced 2014)

Christopher Firth (PhD): Integrating the volcanological and magmatic record of a young arc volcano: Yasur, Vanuatu; *APA* (MQ, commenced 2011)

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

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* (MQ, commenced 2012)

Robyn Gardner (PhD): The nature of the lower crust: New insights from field compilations, experiments and numerical modelling; *MQRES* (MQ commenced 2012)

Robyn Gardner and Cait Stuart in Fiordland, New Zealand.

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* (CU, commenced 2012)

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

Louise Goode (PhD): Volcanological and geochemical evolution of East Javanese Volcanoes, Indonesia; *iMQRES* (MQ, commenced 2014)

Christopher Grose (PhD): Geodynamics of oceanic lithosphere; *iMQRES* (MQ, commenced 2011) See *Research Highlight p. 41.*

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* (UWA, submitted 2014)

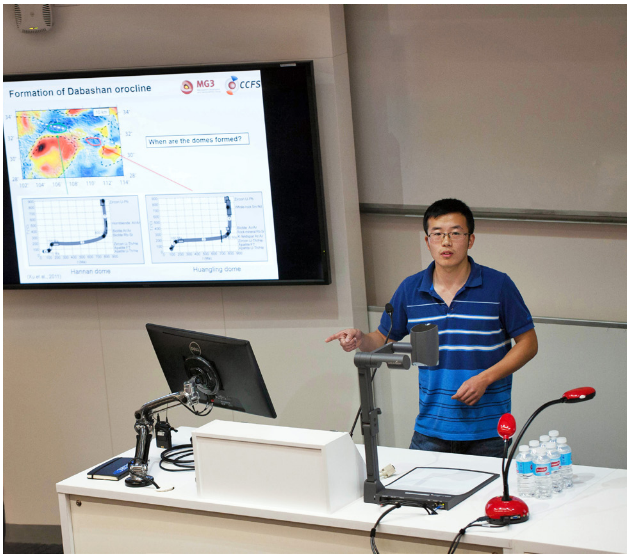
Yosuke Hoshino (PhD): Investigation of hydrocarbon biomarkers preserved in the Fortescue Group in the Pilbara Craton, Western Australia; *iMQRES* (MQ, submitted 2014)

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

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* (UWA, submitted 2014)

Kim Jessop (PhD): Fluids and metamorphism: New insights from field mapping, metamorphic petrology and thermodynamic modelling; *APA* (MQ, 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* (MQ, commenced 2012, *pictured below*)



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

Heta Lampinen (PhD): Mineral system footprints, Edmund Basin, Capricorn Orogen, Western Australia; *SIEF* (UWA, commenced 2014)

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* (MQ, part time, commenced 2010)

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* (UWA, submitted 2014, *pictured below*)

Vikram Selvaraja, Celia Guergouz, Dr Laure Martin and Margaux Le Vaillant at the CCFS Research meeting, July, 2014.

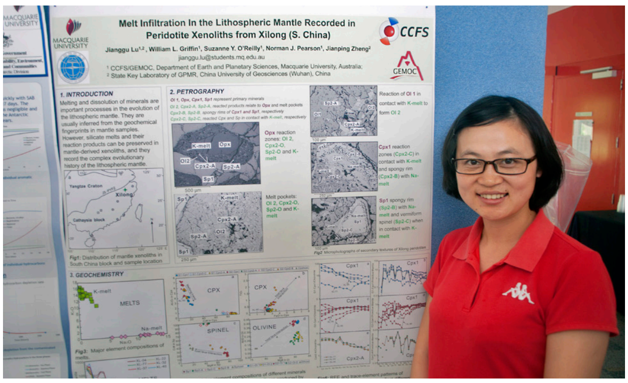
Erwann Lebrun (PhD): 4D structural modelling and hydrothermal evolution of the sediment hosted Siguiri gold deposit (Guinea) and implication on Paleoproterozoic gold targeting in West Africa; *International Sponsorship* (UWA, commenced 2011)

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

Li-Ping 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* (CU, submitted 2014) See *Research Highlight p. 61.*

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

Jianggu Lu (PhD): Nature and evolution of the lithospheric mantle beneath the South China block; *iMQRES Cotutelle, China Scholarship Council, iMQRES top-up* (MQ, commenced 2014, *pictured below*)



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

Quentin Masurel (PhD): Controls on the genesis, geometry and location of the Sadiola-Yatela Gold Deposit, Republic of Mali; *IPRS* (UWA, commenced 2012)

Samuel Matthews (PhD): Tracking CO_2 sequestration using gravity gradiometry; *CO_2CRC Scholarship* (MQ, commenced 2014)

PhD student Sam Matthews on field work to the Carsulae archeological site, Umbria, Italy.

Nicole McGowan (PhD): Messages from the mantle: Geochemical investigations of ophiolitic chromites; *APA* (MQ, commenced 2012, *pictured p. 5*) See *Research Highlight p. 47.*

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

Aileen Mirasol-Robert (PhD): Field characterisation of Australian gold deposits; *IPRS* (UWA, commenced 2013)

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

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

Beñat Oliveira Bravo (PhD): Multicomponent and multiphase reactive flows in the Earth's mantle; *iMQRES* (MQ, commenced 2013)

Luis Parra-Avila (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* (UWA, commenced 2011)

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

Jonathon Poh (MSc): Numerical investigation of the driving forces of Archean fluid and heat transfer flows (UWA, commenced 2014)

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

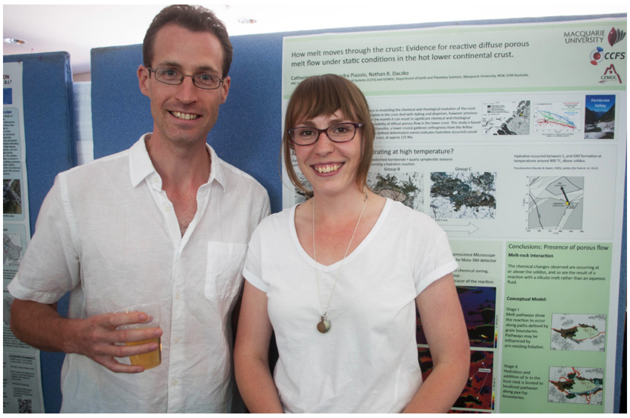
Farshad Salajegheh (PhD): 3D multivariable probabilistic inversion for thermochemical structure of Earth (MQ, commenced part time 2014)

Vikram Selvaraja (PhD): Mineralisation in the Capricorn Orogen: Where, when and how (UWA, commenced 2014, *pictured p. 70*)

Liene Spruzeniece (PhD): Fundamental link between deformation, fluids and the rates of reactions in minerals; *iMQRES* (MQ, commenced 2012) See *Research Highlight p. 37.*

Camilla Stark (PhD): Decoding mafic dykes in the southern Yilgarn Craton: Significance to Australia's position in supercontinent-superplume cycles (CU, commenced 2014)

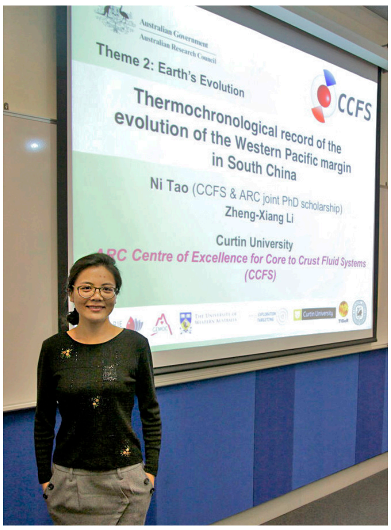
David Stevenson (PhD): 4D modelling of the Tanami Inlier, Northern Territory (UWA, commenced 2012)



Catherine Stuart (PhD): Flow characteristics of lower crustal rocks: In depth analysis of xenoliths and experimental studies; *MQRES* (MQ, commenced 2012, *pictured above with Bruno Colas*)

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

Ni Tao (PhD): Thermochronological record of tectonic events in central and southeastern South China since the Mesozoic; *ARC DP scholarship* (CU, commenced 2011, *pictured left*) See *Research Highlight p. 42-43.*



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

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

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

Janet Tunjic (PhD): Terranes, volcanoes and gold: relationship of gold mineralisation to stratigraphic domains and terranes in the East Yilgarn Craton, Western Australia (UWA, commenced 2014)

Qian Wang (PhD): A geological traverse across the Jack Hills Metasedimentary Belt, Western Australia: isotopic constraints on the distribution of Proterozoic rocks and the evolution of Hadean crust; *China Scholarship Council* (CU, commenced 2010)

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

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

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

Jun Xie (PhD): Imaging the lithosphere structure of Australia using dispersion curve receiver functions and Rayleigh waves A/H ratio; *iMQRES Cotutelle* (MQ, commenced 2014)

Qing Xiong (PhD): Origin of the Sheng Likou garnet peridotite massif, North Qaidam, western China; *iMQRES top-up, China Scholarship Council* (MQ, commenced 2011, *pictured right*)

Bo Xu (PhD): Mantle xenoliths and lamprophyres in Tibet: mineralisation and tectonic implications; iMQRES Cotutelle (MQ, commenced 2014)

Commencing 2015

Jason Bennett (PhD, UWA)
Lauren Burley (MSc, UWA)
Stefano Caruso (PhD, UWA)
Matthieu Chasse (PhD, MQ)
Greg Derring (PhD, UWA)
Xiowen Gu (PhD, CU)
Hadrien Henry (PhD, MQ)
Jelte Keeman (PhD, MQ)
Nora Liptai (PhD, MQ)
Mr Yebo Liu (PhD, CU)
Antoine Neaud (MSc, UWA)
Greg Poole (PhD, UWA)
Valerie Roy (MSc, UWA)
Kai Wang (PhD, MQ)

A highlight of CCFS postgraduate activity in 2014...

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

Exchange visits by international PhD students

Ms Montgarri Castillo Oliver, from the faculty of Geology, University of Barcelona, Barcelona, Spain, visited CCFS to undertake geochemical studies of minerals in carbonatites and alkaline rocks from Angola. Montgarri later returned to commence a cotutelle PhD at MQ.

Mr Mathieu Chassé, a research student at the Université Pierre et Marie Curie (UPMC), France, is undertaking a project on the scandium geochemistry in mantle-derived rocks including sampling and analysis of lateritic profiles on ultramafic bodies from central-west New South Wales, to understand the mechanisms of enrichment of Sc during lateritic weathering. Mathieu visited CCFS in July 2014 and will be returning in 2015.

Mr Zhen Guo, from Peking University, visited for three months from March 2014 to June 2014 to work with Dr Yingjie Yang on surface wave tomography in imaging the lithospheric structure in northeast China (*pictured below*).

Mr Guoliang Li, from the China Petroleum University (Beijing), China, visited CCFS in September-November 2014 to undertake training in ambient noise tomography with Yingjie Yang and CCFS team members (*pictured below*).

Mr Xi-yao Li visited CCFS from the State Key Lab of Geological Process and Mineral Resources at China University of Geosciences, Wuhan. Xi-yao is working on the Hunan and Guangxi deep lithosphere (south China), as well as mantle xenoliths from eastern and Central Guanxi Province basalts and crustal xenoliths (garnet gneiss) from southern Hunan (Daoxian) basalts.

Mr Lei Liu visited from the State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, China, to further his studies of Late Mesozoic volcanism in SE China.

Mr Qiang Ma from the Faculty of Earth Sciences, China University of Geosciences, Wuhan, visited CCFS to work on the nature and evolution of the lower crust beneath the northern North China Craton using evidence from xenoliths in igneous rocks.

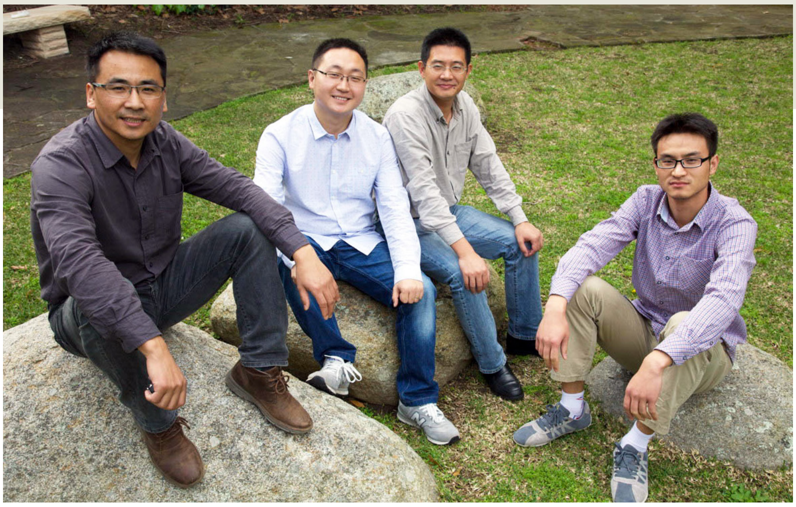
Mr Leandre Ponthus from Géosciences-Environment-Toulouse, Observatoire Midi-Pyrénée, Universite Paul Sabatier, France, is studying Plutonic Alkaline complexes and zircons from Kerguelen syenite. Whilst at CCFS, Leandre analysed zircons in the GAU.

Mr Kai Wang visited CCFS from the Institute of Geophysics & Gematics China University of Geosciences Wuhan, China. Kai is using ambient noise tomography to monitor hydrocarbon reservoirs.

Ms Laurène-Marie Wavrant is undertaking a PhD at the Université du Québec, Chicoutimi. Laurène-Marie visited CCFS to carry out *in situ* Os isotope analyses of laurite from the Stillwater complex.

Mr Kaifeng Zhao visited MQ from China University of Geosciences (Wuhan) from April 2014 until June 2014. Kaifeng worked with Dr Yingjie Yang on developing teleseismic methods to image the radial anisotropy of the lithosphere.

Ms Xueyao Zhou is undertaking a PhD at the State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, China. Xueyao's research focuses on the Precambrian basement in North Vietnam and the consistency of boundaries between South China and Indochina, and the Cathaysia and Yangtze Blocks.



Yingjie Yang with visitors, Mr Zhen Guo (Peking University), Professor Yinhe Luo, (China University of Geosciences, Wuhan) and Mr Guoliang Li (China Petroleum University, Beijing).

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
- a JY Horiba LABRAM HR Evolution confocal laser raman 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; 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 and a Nu Plasma II is scheduled for delivery in April 2015.

EQUIPMENT FOR HIGH-PRESSURE EXPERIMENTATION

In 2013, a period of expansion of the high-pressure experimental facilities began which continued through 2014. The experimental laboratories already housed two old piston-cylinder apparatuses for experiments primarily on melting and fluids to pressures of 4 GPa, a Griggs apparatus for deformational studies at crustal pressures, and a multi-anvil apparatus for

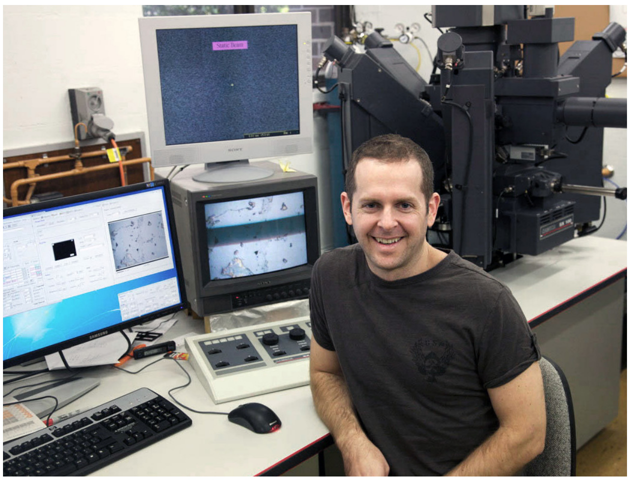
Simon Clark and Stephen Foley in the high pressure lab.

pressures up to 27 GPa. An additional multi-anvil apparatus is scheduled for delivery in 2015 and funds for the acquisition of a diamond-anvil experiments at pressures of the lower mantle have been secured. Dr George Amulele joined the team in December 2014 from Yale University, and brings in extensive experience in experimentation at deep mantle pressures.

PROGRESS IN 2014:

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 provides 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



GAU Geochemist David Adams at the EMP.

interaction in high-grade metamorphic rocks and metasomatism of mantle-derived peridotites, pyroxenites and chromitites. The Cameca SX100 electron microprobe (fitted with 5 wavelength dispersive spectrometers and a Bruker Energy Dispersive Spectrometer system) 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.

b. Laser-ablation ICPMS microprobe (LAM): In 2014 the LAM laboratory was used by ten Macquarie PhD thesis projects, eleven international visitors, 6 Masters Research students, three 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), New Zealand, Algeria, Bostwana, Brazil, Indonesia, Chile, Laos, PNG and Russia. Method development was also undertaken for the U-Pb dating of baddelyite 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.

Visitors Dr Justin Payne and Mr Henry Chalk (University of Adelaide), with GAU Director Norman Pearson, using the LA-ICP-MS.

c. MC-ICPMS: The high demand for LA 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, Bostwana, Brazil, Indonesia, Laos, PNG, Russia and Tibet. 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 undertaken on Mg isotopes in mantle minerals, including chromite.

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 2014 a further 12 full licences of GLITTER were sold bringing the total number in use to more than 250 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 2014. 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 and through 2014 produced major and trace-element data for a wide spectrum of rock compositions. The Axios 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 2014 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 iN10 FTIR 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 has been 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.

6. Spectroscopy

Investment in spectroscopy infrastructure started with the purchase of an FTIR microscope (ThermoFisher iN10 FTIR microscope) in 2008 followed by a confocal laser Raman microscope in 2014 (co-funded by MQSIS and Future Fellowship funding to A/Prof Dorrit Jacob). The FTIR is used to measure H abundance in a range of nominally anhydrous minerals (e.g. olivine, pyroxene, garnet) and H and N contents in diamond. Raman spectrometry delivers information for non-destructive phase-identification and characterisation at one micrometre spatial resolution. In developing the spectroscopy capability an emphasis has been placed on hyperspectral mapping to produce integrated datasets and multi-layered information in a spatial context. In 2014 MQSIS funds were granted for a CL monochromator to be attached to the Zeiss EVO SEM. The distribution of CL is a powerful tool in geological research; it provides textural evidence of crystal growth, overgrowths and replacement, deformation, diagenesis and provenance. The monochromator system will provide imaging of individual emitting species and their distribution in a sample, and semi-quantitative estimates of the individual CL activators; the system will be purchased and installed in 2015.

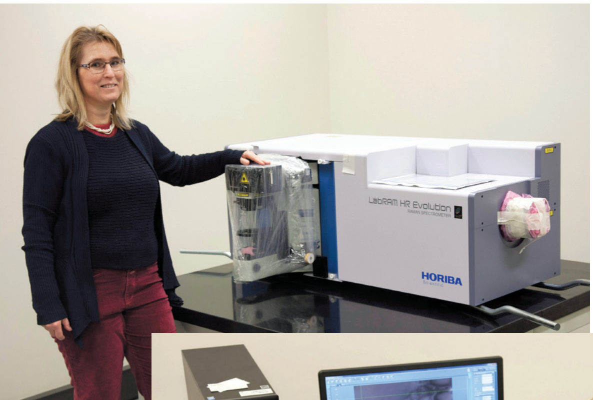
7. Computer cluster

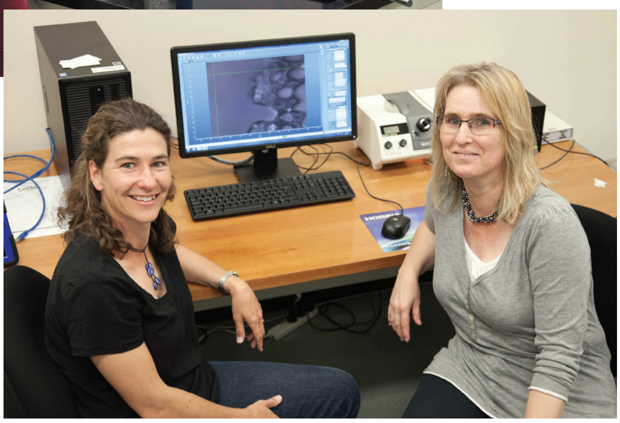
The cluster Enki has continued to be a powerhouse for the geodynamics group, supporting two funded research projects, 3 PhD projects, a postdoc, and numerous Masters-level projects. Recent developments have included the development of planetary evolution capability of the mantle convection code Aspect (based on the deal.II finite element libraries), led by Siqi Zhang. In addition O'Neill and Zhang have developed a new smoothed-particle hydrodynamic code to simulate early solar-system processes, and have been utilising Enki for these simulations. A recent RIBG round to expand the lithosphere/seismic cluster "*Toto*" was successful (led by JC Afonso). In addition, a GPU Tower (supplied by Xenon systems) continues to act as a development machine for GPU-capable code, including the recent SPH code, and a Xeon-Phi server (supplied by Dell) has recently been installed, enabling the modelling group to start development and migration of their codes onto this next generation hardware.

8. Raman spectrometry

The purchase of a confocal Micro-Raman spectrometer (JY Horiba Labram Evolution, 514 and 623 nm wavelength lasers), with outstanding spectral and spatial resolution as well as fast imaging capabilities, extended the analytical capabilities of the CCFS this year. It is only the third instrument with this setup at an Australian University and the first of its kind in Australian Earth Sciences. The instrument is central to the ARC Future Fellowship project of A/Prof Dorrit Jacob where it will be used for imaging and accurate characterisation of the ephemeral phases present in biominerals.

The instrument was delivered, installed and commissioned in July 2014 and was immediately functional.





Dr Ulrike Troitzsch (ANU, below left) and Dorrit Jacob putting the Raman through its paces.

In addition to being used by Jacob and her students, the instrument has been used intensively by postgraduate students from CCFS, EPS, other Departments at Macquarie University (Dept. Physics, Dept. Biological Sciences) as well as by visitors from the Research School of Earth Sciences at ANU.

Overall the new instrumentation has extended the spectroscopy capabilities and intensive interest in its use shows Raman spectrometry and its applications are readily accepted and already form an integral part of the instrumental analytical possibilities at EPS/CCFS.

For further information on GAU facilities please consult http://ccfs.mq.edu.au/Tech/Tech.html/

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:

- Secondary Ion Mass Spectrometry (CAMECA IMS 1280 and CAMECA NanoSIMS 50)
- Electron probe microanalysis (JEOL JXA 8530F)
- Transmission electron microscopy (FEI Titan, JEOL 2100)
- Scanning electron microscopy (FEI Verios XHR, Zeiss 1555, Tescan Vega3)
- X-ray powder diffraction (Panalytical Empyrean)
- X-ray micro-CT (Xradia)
- Confocal Raman imaging with AFM (WiTec Alpha 300RA+)
- NMR spectroscopy (2 Bruker Avance and 2 Varian spectrometers)
- X-ray crystallography (Oxford Diffraction)
- GC and HPLC mass spectrometry
- Bioimaging, flow cytometry, cell sorting, and laser micro-dissection
- Optical and confocal microscopy
- Biological sample cryo-preparation and ultramicrotomy

THE AMMRF FLAGSHIP ION PROBE FACILITY

The CAMECA IMS 1280 and NanoSIMS 50 are flagship instruments of the 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, and secondary ion imaging 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 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.

The Ion Probe Facility is also a member of the International Atomic Energy Agency's (IAEA) Network of Analytical Laboratories (NWAL), performing U isotope analyses on environmental dust particles for Nuclear Safeguards.

PROGRESS IN 2014:

Recent successes in ARC LIEF funding have updated the electron microscopy facilities at CMCA, with the installation in 2014 of a FEI Titan TEM, a FEI Verios XHR high resolution SEM, and Confocal Raman with AFM. Further success in the 2014 LIEF round will see the installation in 2015-16 of a Focused Ion Beam (FIB) platform for the preparation of TEM, NanoSIMS and atom probe samples.

The CMCA has also received funding for a new Cameca NanoSIMS 50L ion probe through CSIRO's Science and Industry Endowment Fund (SIEF) via the National Resources Science Precinct (NRSP). The new instrument will be part of the tripartite Advanced Resources Characterisation Facility, along with a Cameca LEAP4000 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 2014, 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 magmatic processes and crustal growth, the origin of ore deposits (O isotopes in zircon, E. Belousova and Y. Lu; S isotopes in sulfides, M. Fiorentini) and the exploration of redox processes in the deep Earth (Si and C isotopes in moissanite; J. Huang and W. Griffin). 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 potential new geochemical tools.

CMCA RESEARCH HIGHLIGHTS:

Once again the Ion Probe Facility at CMCA was highly productive during 2014, contributing to a number of projects across the whole CCFS. Highlights include:

Zircon analysis

Zircon is a robust mineral whose chemical and isotopic composition has the ability to preserve information about its growth environment. The analysis of oxygen isotope in zircon is thus a powerful tool to identify the magmatic origin of these crystals. E. Belousova and co-authors have conducted an integrated isotopic (U-Pb, Hf and O) study of zircon crystals from upper-mantle rocks from the Tumut ophiolite complex. Their study shows that crustally-derived zircons can be introduced into mantle rocks even after their obduction onto the continental crust, thus proposing an alternative explanation for the presence of this mineral in ultramafic rocks from ophiolite complexes. This work has been published in the journal Geology [Belousova, E., Gonzáles-Jiménez J.-M., Graham I., Griffin, William L., O'Reilly S.Y., Pearson

N., Martin L., Craven S., Talavera C. (2015). The enigma of crustal zircons in upper-mantle rocks: Clues from the Tumut ophiolite, southeast Australia. *Geology, vol. 43, p. 119-122*].

Sulfur isotope analysis

The ability to measure all 4 stable sulfur isotopes in sulfide minerals *in situ*, makes the CAMECA IMS1280 one of the most powerful techniques available for S isotope analysis. During 2014, the IMS1280 was used to analyse several sets of Precambrian sulfides in order to determine sulfur sources in deep time. One project, led by CCFS SAC member James Farquhar at the University of Maryland, measured S isotopes in 2.5 billion year old carbonate rocks from Brazil to investigate S sources in the Neoarchean ocean. The data revealed that bacteria were metabolising sulfate even when the ocean contained 1000 times less sulfate than today. The results were published in the prestigious journal Science (see CCFS publication# 568).

Isotopic Standard development

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, C isotopes in SiC, Zr isotopes in zircon crystals from different provenance. O isotope analysis in garnet is in constant development in order to cover the complex chemistry of this mineral. The development of a Cr-rich garnet standard is underway in collaboration with J. Huang and aims to provide a better characterisation of mantle-derived garnets. The combined development of Li and O isotope measurements in olivine and clinopyroxene is also in progress.

Ultra-fine resolution diffusion

The NanoSIMS proved once again that size does matter as a number of projects utilising the ultra-high spatial resolution and sensitivity to determine diffusion profiles across mineral interfaces. One study, published in Chemical Geology (Saunders et al., *Chem. Geol., 364, 20-33*), demonstrated how the ability to acquire high-resolution diffusion profiles could be used to better constrain the timing of volcanic processes on the order of days to years. Similarly, experimental studies on Ni and Co revealed that the activity of SiO_2 has a significant effect on the diffusion rates of these elements in olivine from magmas with different compositions (Zhukova et al., *Contrib. Mineral. Petrol., 168, 1029*).

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

JOHN DE LAETER CENTRE

The John de Laeter Centre (JDLC) is a collaborative research venture involving Curtin University, the University of Western Australia, CSIRO and the Geological Survey of Western Australia. It hosts over $28M in infrastructure supporting research in: geosciences (geochronology, thermochronology and isotope studies); environmental science; isotope metrology; forensic science; economic geology (minerals and petroleum); marine science; and nuclear science. Highlights for the 2014 period include:

- Success in 5 Australian Research Council LIEF proposals resulting in the commissioning of $3,460,000 in high-technology research facilities in 2013 and 2014.
- National leadership of the AuScope Earth Composition and Evolution program; the award of $800,000 in NCRIS funding to create a laboratory information management system (LIMS) for mineralogical data and a prototype for the national geochemistry community in cooperation with the Australian National Data Service (ANDS).
- A $12,400,000 Science and Industry Endowment Fund grant will create a collaborative Advanced Resources Characterisation Facility (ARCF) in 2015; JDLC will be responsible for managing the ARCF Geoscience Atom Probe and accessory equipment worth $4,200,000.
- A major funding agreement with the Chinese Academy of Geological Sciences permitting remote operation of the JDLC Sensitive High Resolution Ion MicroProbe (SHRIMP) from Beijing.
- The commercialization of JDLC technology was boosted by a four-year R&D agreement with Australian Scientific Instruments (ASI) to advance the commercial potential of the RESOchron laser ablation mass spectrometry instrument platform developed at Curtin, and to develop integrated U-Th-Pb-He geochronology and thermochronology applications. In 2013, ASI delivered RESOchron systems, based on the JDLC prototype, to labs in China and Canada.
- High-profile publications, including:
    - The oldest age yet obtained for samples from Mars and the first evidence of the composition of the ancient Martian atmosphere.
    - The oldest age yet obtained for samples from the Apollo Moon missions with implications for understanding the bombardment history of the early Earth.
    - A 200-year climate record for NW Australia obtained from Ningaloo reef corals and a greater understanding of the variability of the Leeuwin warm current.
    - A major study of multiple ice cores confirmed widespread Pb pollution of the Antarctic continent in 1889, almost 22 years before human exploration began. This date coincides with the onset of base metal smelting activities at Broken Hill and Point Pirie, Australia.

- A study linking high CO_2 contents in the Triassic atmosphere to sea level rise, anoxic oceans and the mass extinction of marine and terrestrial species.

The components of the JDLC are organised into thirteen major facilities.

1. The Advanced Ultra-Clean Environment (ACE) Facility: This consists of a ~400m^2 class 1000 containment space housing 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 filtration at each stage.

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

- TJA (VG/Fisons) PlasmaQuad 3 Quadrupole ICP-MS.
- TJA (VG/Fisons) Laserlab high resolution 266 nm (Frequency quadrupled Nd-YAG) laser, capable of 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.

3. 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 spatial resolution up to 10 μm 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 are on order.

4. Joint ANU-John de Laeter Centre for Mass Spectrometry (JdLC) Argon Facility: The new instrument enables work on rare extra-terrestrial sample materials, such as micrometer-size grains recovered from the Itokawa asteroid (see below) by the Japanese spacecraft Hayabusa.

David Adams (GAU), John Cliff and Matt Kilburn (CMCA) at the June CCFS Research Meeting.

5. A Thermo Argus VI multi-collector noble gas mass spectrometer was installed in November 2012 with funding from a 2012 ARC LIEF grant. This 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 muticollector design allows simultaneous measurement all five Ar isotopes leading to reduced analysis time and greater productivity.

6. Organic Geochemistry Facility: This facility is located in 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)

7. 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 that was remodelled in 2014. 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 zircon and other U-bearing minerals, including monazite, xenotime, titanite, allanite, rutile, apatite, baddeleyite, cassiterite, perovskite and uraninite where multiple growth zones commonly require analyses with high spatial resolution.

8. Stable Isotope Ratio Mass Spectrometry (SIRMS) Facility: The West Australian Biogeochemistry Centre (WABC) at UWA is associated with the JdLC. The WABC currently operates three isotopic ratio mass spectrometers (IRMS) and additional analytical instrumentation (GC, HPLC, CE autoanalyser) for biogeochemical studies. A fourth IRMS (especially for small-sample $\delta^{13}C$ and $\delta^{18}O$ and carbonate analysis) is now being commissioned. The IRMS are coupled with a variety of sample preparation modules to facilitate analysis of a broad range of sample matrices.

9. 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 geochemistry (Re/Os, U/ Pb, Pb/Pb, Sm/Nd, Rb/Sr) the TIMS instruments can be applied to a variety of isotope fingerprinting, such as forensics and the environmental impact of human activities. The TIMS instruments are also used for the calibration of isotopic standards and the calculation of isotopic abundances and atomic weights.

10. 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. 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. It now operates 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 the 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.

11. 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

12. selFrag Facility: A new selFrag facility, supported by an ARC LIEF grant, has been installed within the Department of Applied Geology at Curtin University. The facility provides electric pulse disaggregation for mineral separation, which allows mineral grains to be separated from rock samples without the damage associated with standard crushing techniques.

13. Electron Microscopy Facility (EMF): The EMF is a new node of the JdLC located at Curtin University; it has three scanning electron microscopes, all with EBSD capability, and a transmission electron microscope, for applications across Earth sciences, materials science, engineering, chemistry and biology.

The following is a summary of the capabilities of the 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 range of detectors suitable for research in 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. It is equipped with an EDS detector and a scanning transmission electron microscope attachment, allowing for 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

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 kappa bridge was installed in 2011. In 2014, a national consortium consisting of Curtin University, The University of Western Australia, the Australian National University, Macquarie University and University of Queensland was awarded an ARC LIEF grant to purchase a new 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system) and other accessories (ovens etc.), to be housed in a purposely built magnetic shielded room at Curtin University's Bentley campus. This new system is expected to be installed in early 2016. We have also ordered an AGICO JR-6A spinner magnetometer and a TD-48SC thermal demagnetiser, expect to be delivered in May 2015 to the Bentley laboratory.

The joint WA facility is one of three similar laboratories in Australia. The new purchases will build on existing instruments in the facility, including:

- 2G cryogenic magnetometer upgraded (LE0668377) to a 4K DC SQUID system (currently back to 2G for a minor upgrade and for repair of the lightning-damaged cold head)
- 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/

UNCOVER
AUSTRALIAN EXPLORATION GEOSCIENCE RESEARCH

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 2014

- *TerraneChron*® studies (see *p. 84* 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 30,000 zircon U-Pb and Hf-isotope analyses) in the Macquarie laboratory allows unparalleled contextual information in the interpretations and reports provided to industry. Six major Industry Reports were completed for collaborative industry projects related to *TerraneChron*® at CCFS/GEMOC in 2014. This formally involved project collaboration with six industry partners.
- A new ARC Linkage Project was commenced in 2014, taking the total active projects to four (see *p. 87*)
- The Distal Footprints of Giant Ore Systems: UNCOVER Australia, (supported by CSIRO ex Science & Industry Endowment Fund (SIEF), MERIWA and industry collaborators) continued. The project aims to develop a toolkit with a

workflow to identify the distal footprints of the Giant Ore Systems in order 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 (*pictured below*) spent significant research time at GEMOC through 2014 as part of the close collaborative working pattern for this project.

- On-going collaboration with BHP Billiton (Dr Kathy Ehrig) and University of Tasmania (Professor Vadim Kamenetsky) looking for evidence of younger magmatic events (e.g. Grenville-age events) in the magmatic evolution of the Gawler Craton, with a particular focus on the region around the giant Olympic Dam deposit.
- A new colaborative project funded by Rio Tinto Limited was commenced in 2014. Marco Fiorentini and Yongjun Lu (UWA) will investigate "*The mineral chemistry of zircon as a pathfinder for magmatic-hydrothermal copper and gold systems*". The project aligns with the goals of Flagship project 2, Genesis, transfer and focus of fluids and metals and will run for two years.
- 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 2014 by CCFS Foundation Program 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.
- 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 2014 with the GSWA as a formal CCFS Foundation Program, 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, a collaborative project was established with Jervois Mining, involving a co-tutelle PhD student (Matthieu Chasse) jointly supervised by Professor George Callas, Pierre et Marie Curie University, Paris, France.
- CET held their annual "*Corporate Members Day*" on the 9th of December 2014, to showcase its research to its Corporate Members. The day provided an audience of 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 2014 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.

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)

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MACQUARIE UNIVERSITY

What is *TerraneChron*®?

The methodology was developed by GEMOC to provide rapid, cost-effective characterisation of crustal history on regional (10-1000 km^2) 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

- CCFS publications, preprints and non-proprietary reports are available on request for industry libraries.
  A full list of previous GEMOC publications is available at http://www.GEMOC.mq.edu.au
- CCFS participants were prominent in delivering keynote and invited talks and workshop modules, and convening sessions relevant to mineral exploration at national and international industry peak conferences in 2014 (see Abstracts, *Appendix 6*).

CURRENT AND 2015 INDUSTRY-FUNDED COLLABORATIVE RESEARCH PROJECTS

These are brief descriptions of 2014 and current CCFS projects that have direct cash support from industry, most with combinations from ARC, internal University or State Government support. Projects are both national and global. In addition to these formal projects, many shorter projects are directly funded by industry, 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 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 integrated with tectonic analyses and large-scale datasets (including geophysical) 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 (*TerraneChron*®) are being developed as a regional isotopic mapping tool 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)

Reducing 3D geological uncertainty via improved data interpretation methods	***Linkage Project*** ***Industry Collaborators: Western Mining Services Australia Pty Ltd, Geological Survey of Western Australia*** ***CIs: Jessell, Holden, Baddeley, Kovesi, Ailleres, Wedge, Lindsay, Gessner, Hronsky*** ***Summary:*** The integrity of 3D geological models heavily relies on robust and consistent data interpretation. This project proposes an innovative workflow for 3D modelling to minimise geological uncertainty. Advanced visualisation and intelligent decision support methods will be combined to assist geological interpretation. Feedback on interpretation will be provided based on data evidence and consistency with expert knowledge and previous interpretations. The process can be considered as a spelling and grammar checker for geological interpretation. The outcome of this study aims to achieve an improved workflow that reduces model uncertainty, resulting in a broad and significant impact on the management of Australian mineral, energy and water resources.
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.

Four-dimensional lithospheric evolution and controls on mineral system distribution in Neoarchean to Paleoproterozoic terranes	***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.
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	***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.
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*** ***CIs: 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*** ***CIs: 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.

FORMAL MEMORANDA OF UNDERSTANDING (MOU)

Formal MOU between international institutions promote the Centre's collaborative research and facilitate visits by Centre staff and postgraduates as well as joint PhD research projects. CCFS has agreements with the following international institutions:

- China University of Geosciences (Wuhan) - 2011 (& Cotutelle)
- University of Science and Technology of China, Hefei - 2012 (& Cotutelle)
- Institute of Geology and Geophysics, China University of Geosciences (Beijing) - 2014
- Institute of Tibetan Plateau Research, CAS (Beijing) - 2014

COTUTELLE MOU

Cotutelle MOU aim to establish deep, continuing relationships with international research universities through joint research candidate supervision. CCFS has agreements with the following international institutions:

- China University of Petroleum, Beijing, China
- Durham University, United Kingdom
- Eötvös Loránd University, Hungary
- Friedrich-Alexander-University of Erlangen, Nuremberg, Germany
- Institute of Geology and Geophysics, Chinese Academy of Sciences, China
- Nanjing University, China
- Peking University
- Universidad de la Republica, Uruguay
- Université Montpellier 2, France
- Université Paul Sabatier, France
- University Jean Monnet, France
- University of Barcelona, Spain
- University of Zaragoza, Spain

2014 COLLABORATIVE ACTIVITY

INTERNATIONAL LINKS - 2014 HIGHLIGHTS

A formal Memorandum of Understanding was signed with the Institute of Geology and Geophysics, China University of Geosciences (Beijing).

Planned programs include the exchange of staff, joint research activities and the exchange of students.

Professor Jim Lee, DVC International (MQ), Sue O'Reilly, Professor Jun Deng, Professor Zhang Shouting and Professor Chuanheng Zhang (CUG, Beijing).

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. CCFS participants, Professor Marco Fiorentini, Dr Robert Loucks and Dr Yongjun Lu (CET) are actively collaborating with CAGS under this IGCP framework. This collaboration between CET/CCFS and CAGS involves multi-isotopic mapping in Tibet, experimental and field studies of adakites and associated porphyry Cu systems in Tibet, Pakistan and Iran.

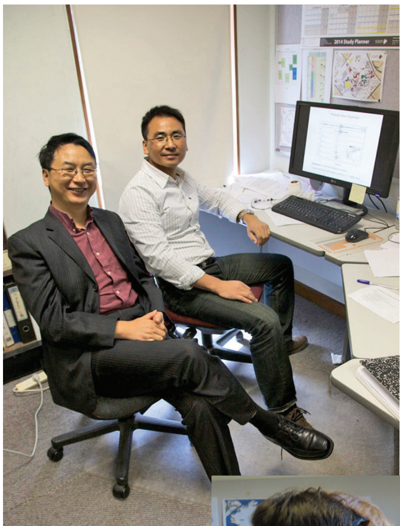
Jump at 4500 m: PhD students and researchers from CAGS in Beijing in Tibet. From left to right, Dr Liming Zhou (CAGS), Dr Rui Wang (CSIRO), Ms Qiuyun Li (PhD, CAGS), Yongjun Lu, Associate Professor Zhiming Yang (CAGS) and Ms Maoyu Sun (MSc, CAGS).

A field session was conducted in Tibet from the 25th August - 10th September 2014 as part of the CCFS Pilot Project "*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*".

Professor Simon Wilde, Professor Alfred Kröner (University of Mainz) and Dr Kamal Ali (King Abdulaziz University, Saudi Arabia) are collaborating on a project aimed at understanding the range of processes that contribute to crustal growth in the Eastern Desert of Egypt (see *field photo above*).

Elena Belousova and Dr Victor Kovach with zircon mounts from the Dunzhugar ophiolite complex.

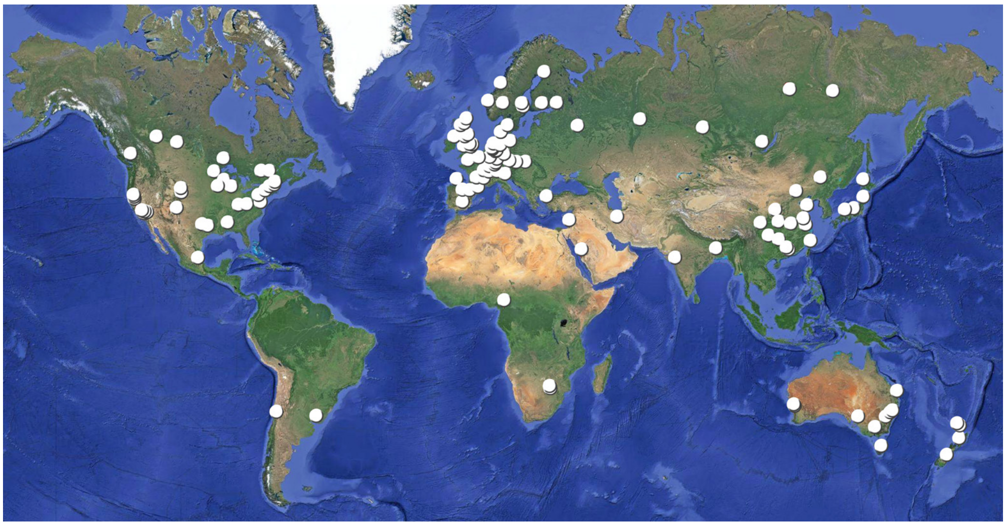
Dr Viktor Kovach from the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg visited CCFS (MQ) in July 2014. The main aim of the visit was to conduct geochronological (U-Pb LA-ICPMS) and Hf isotopic analyses on zircons from plagiogranites and gabbros from the Dunzhugur ophiolite complex, Eastern Sayan, Russia. The Dunzhugur ophiolite complex of the East Sayan region is thought to be the oldest known ophiolite complex in the Central Asian Orogenic Belt (CAOB) and is key to understanding the geodynamics of the CAOB's early stages of formation and evolution.



Professor Fenglin Niu (*pictured left*, Department of Earth Science, Rice University, Houston, USA) visited Dr Yingjie Yang to begin collaboration on a project entitled *"Using H/Z ratio from ambient noise to map shallow surface structures"*.

Professor Fiona Darbyshire (*pictured right with Juan Carlos*) from the Université du Québec à Montréal, visited MQ in June 2014 to work with Drs Juan Carlos Afonso and Yingjie Yang on the application of **LitMod** codes (http://eps.mq.edu.au/~jafonso/Software1.htm) to study the lithospheric structure of Canada.

Six representatives from the Guangxi Bureau of Geology & Mineral Prospecting & Exploitation visited CCFS in January 2014 and toured the GAU (MQ). The delegates were interested in setting up research collaborations and reciprocal visits with the centre.



CCFS'S INTERNATIONAL COLLABORATIVE NETWORK

Representatives from the Guangxi Bureau of Geology & Mineral Prospecting & Exploitation. Bottom row (L-R); Bill Griffin, Mr Han Fuli (Chief, No.307 Nuclear Geological Team), Sue O'Reilly, Mr Zhang Mingguo (Deputy Director General), Elena Belousova and the MQ and Guangxi delegation.

On March 31 2014, a delegation of six academics from Tsinghua University of China (*pictured below*) visited CCFS (MQ). The leader of the delegation was the former Executive Vice President of Tsinghua University (currently Director of the Universities Institute of Low Carbon Economy). The delegates aimed to develop future research collaborations, in the direction of resources sustainability, with the departments of Earth and Planetary Sciences and Environmental Sciences. CCFS representatives, including Jin-Xang Huang, Jun Xie, Jianggu Lu, and visitor Zhen Guo (Peking University of China) accompanied the delegation for a campus tour after official meetings.

Photo (from left): Dr Feng Yin, Professor Xiliang Zhang, Professor Qiang Yao, Professor Yongda Yu, Ms Jianggu Lu, Professor Jiankun He, Mr Zhen Guo, Mr Chengxin Jiang, Mr Jun Xie, Dr Siping Luo and Ms Kristin Fan (manager of Academic Relations and Global Programs Office, MQ).

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:

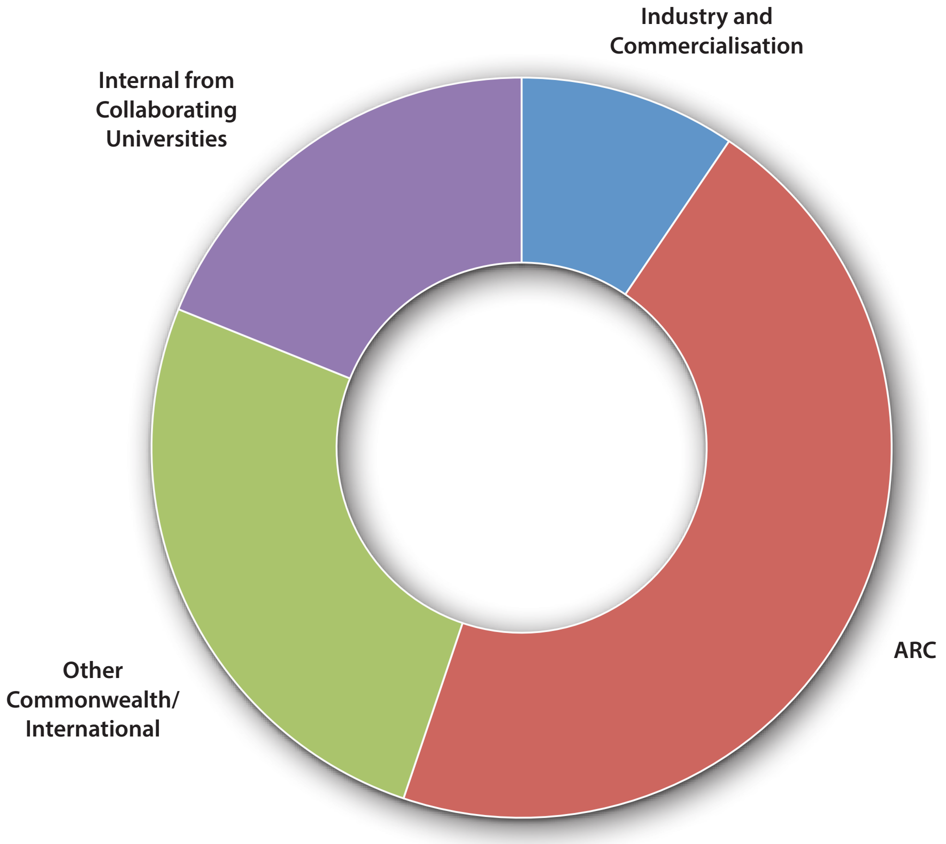
- Collaborative project building with industry partners
- Applications to funding schemes for matching funds for new infrastructure purchases and partner co-investment
- Technology development to deliver new and improved methodologies and tools for enhanced research collaboration and for the exploration 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 2014 income and expenditure. A full, audited statement of detailed expenditure and income is prepared by Macquarie University. No in-kind support is included here.

CCFS Income & Expenditure Statement 2011-2014

Source	2011	2012	2013	2014	2015 Forecast
Income					
ARC	$1,828,350	$2,004,179	$1,971,746	$2,031,333	$1,969,500
MQ	$626,705	$1,032,004	$1,822,748	$1,464,360	$968,500
UWA	$133,500	$763,500	$415,000	$415,000	$415,000
Curtin	$727,725	$608,055	$851,244	$611,290	$530,000
GSWA	$150,000	$150,000	$150,000	$150,000	$150,000
SLF Income	$500,000				
SLF interest	$13,744	$12,530	$5,790	$1,811	
ECR Income from ARC	$1,250,000				
ECR Interest		$24,734	$16,118	$6,566	$1,500
TOTAL INCOME	**$5,230,024**	**$4,595,003**	**$5,232,646**	**$4,680,360**	**$4,034,500**
ACCUMULATED FUNDS FROM PREVIOUS YEAR		$3,702,071	$4,960,194	$5,181,390	$4,802,525
Expenditure					
Salary	$783,390	$1,608,470	$2,263,183	$2,402,327	$3,035,845
Equipment	$90,128	$220,548	$785,851	$512,413	$257,431
Travel	$91,305	$280,795	$388,431	$404,572	$515,379
Maintenance/Consumables	$42,433	$459,530	$487,255	$494,580	$656,207
Scholarship	$520,697	$767,538	$1,086,730	$1,245,333	$608,000
TOTAL EXPENDITURE	**$1,527,952**	**$3,336,880**	**$5,011,450**	**$5,059,225**	**$5,072,862**
ACCUMULATED FUNDS TO NEXT YEAR	$3,702,071	$4,960,194	$5,181,390	$4,802,525	$3,764,163

INCOME SOURCES 2014



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 Programs 2011-2014 summaries and outcomes

1. THE TARDIS PROGRAM: 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 main goals of the TARDIS program are (1) 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; (2) to understand the origins of ophiolitic chromitites; (3) to understand the osmium isotope heterogeneity observed in samples from the convective mantle, and how this heterogeneity may reflect major events in Earth's evolution; and (4) to evaluate the evidence for the preservation of large volumes of ancient continental mantle within the ocean basins.

FINAL REPORT 2011-2014:

A synthesis of existing and new data on the early crust (U-Pb, Hf, O isotopes) and the cratonic subcontinental lithospheric mantle (SCLM) using primarily Re-Os data, shows that no SCLM can be detected prior to a 3.5 Ga, leading to an entirely new model of SCLM formation (*Griffin et al, 2013*), and hence continent stabilisation, mainly driven by major mantle overturns between 3.3-2.8 Ga.

Extensive studies of Platinum Group minerals (PGM) in ophiolitic chromitites have produced a novel model for chromitite formation. This has been sequentially developed in 14 papers, culminating in two major review papers (see *Outputs*). We demonstrated that most ophiolitic peridotites carry evidence of an original *continental* parentage, and represent *pre-existing lithospheric mantle*, the partial melting residues of *ancient* convecting mantle. This new finding has led to a better understanding of the behaviour of the Re-Os systematics of ophiolites and their chromitites; this in turn allows a more sophisticated interpretation of Os isotope data, which will provide a robust foundation for the second stage of this program.

A major discovery (*Gonzalez-Jimenez et al. 2012*) was the high degree of mobility of the PGEs, including Os and Ir, during high temperature UHP metamorphism, which contrasts with traditional ideas that view Os as immobile, thus changing interpretations of Re-Os data. Another high-impact outcome was the identification of a group of Archean-heritage buoyant continental microcontinents that are the likely reason the Mediterranean basin has not closed (Gonzalez-Jimenez et al. 2013).

An integrated study of the eclogite xenolith suite from the Roberts Victor kimberlite, South Africa (relevant to unravelling potential mantle fingerprints of subduction processes) has overturned an existing paradigm. Two PhD theses demonstrated that the major element, trace element and isotopic (Sr, Nd, Hf, O) compositions of the dominant Group I eclogites (and their diamonds) are the products of extensive, young mantle metasomatism, while the rare Group II eclogites are probably ancient mantle cumulates, and the protoliths to Group I. There is thus no evidence in these rocks that can support an origin as subducted ocean floor. These two PhD projects showed that the '*evidence*' used to demonstrate a subducted origin of the eclogites is not diagnostic.

A series of studies on crust-mantle linkages beneath various parts of China (including several PhD projects) has continued our construction of an overall history for the SCLM beneath eastern China, providing insights pertinent to our growing interest in continental collisions.

Bill Griffin in south-central Tibet.

OUTCOMES AND IMPACT:

We have demonstrated the Archean origin of most SCLM, and its genesis between 3.5-2.7 Ga; the lack of SCLM *'roots'* to stabilise continents before this time explains the rarity of Hadean crust. This has resulted in new geologically realistic parameters for geodynamic models.

We have demonstrated the major control that SCLM structure exerts on fluid pathways and hence the distribution of mineralisation in the crust; this campaign culminated in a recent invited article in *Nature Geoscience.*

Our work has challenged traditional concepts that ophiolites are dominantly formed at ocean floor spreading centres, assembling components derived from the convecting mantle. Instead, the mantle components of many ophiolites have ancient subcontinental lithospheric mantle heritage.

The SuR-UHP (**Su**per-**R**educing-**U**ltra **H**igh **P**ressure) environment has been newly recognised and the requirement for its derivation from the Transition Zone promises to change the framework for understanding subduction regimes, related tectonic processes and geodynamic mechanisms.

Jin-Xiang Huang taking a break with miners in Tibet.

Postgraduate students involved:

Yoann Gréau, Jin-Xiang Huang, Nicole McGowan, Ed Saunders, Qing Xiong, Yao Yu, Romain Tilhac

Published outputs:

CCFS Publications #1, 2, 3, 4, 5, 7, 13, 14, 15, 36, 37, 38, 39, 41, 42, 65, 71, 75, 95, 161, 163, 179, 186, 190, 195, 197, 198, 199, 200, 202, 207, 213, 215, 221, 224, 250, 269, 270, 234, 235, 236, 237, 239, 281, 320, 324, 334, 344, 348, 349, 352, 361, 362, 358, 359, 362, 380, 390

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 program was designed to: (1) provide new knowledge on 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-asthenosphere; and (2) unravel the complex transport and concentration mechanisms of siderophile-chalcophile elements such as Ni, Cu and PGE in the deep lithosphere.

FINAL REPORT 2011-2014:

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. The experiments reveal that most incompatible elements and chalcophile metals become increasingly soluble in H_2O-fluids at high temperatures and pressures, with the attainment of complete miscibility between H_2O-fluids and basanitic melts at 4.0 GPa and 1100° C. Experiments have also been conducted on both dry and H_2O-undersaturated mixes for the purpose of determining the composition of the H_2O-saturated fluids coexisting with basanite melt, as well as the solubility of H_2O in the melt. These experiments are ongoing and are part of a completed study of H_2O partitioning between peridotite minerals and basanite melt. In combination, these studies provide important information about the likely distribution and compositional characteristics of H_2O-rich 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 in the upcoming Flagship Program.

In terms of fieldwork, several field seasons have been successfully completed since the commencement of this program in 2011, with Leon Bagas and Jochen Kolb working closely with the Geological Survey of Denmark and Greenland (GEUS) in Greenland, and Marco Fiorentini, Marek Locmelis, Tracy Rushmer, Steve Reddy and John Adam - together with collaborators in various institutions worldwide - in the Ivrea Zone (IVZ), northwest Italy (Fig. 1). These studies have elucidated the size, geometry and nature of deep Ni-Cu-PGE mineralised intrusions, shedding new light on ore-forming processes at the crucial interface between lithospheric mantle and lower continental crust. These field studies were complemented by a series of targeted analytical programs, which have started to unravel the complex chemical and isotopic evolution of these magmatic systems. These data were subsequently integrated with 3D micro-tomography and EBSD studies (Fig. 2) to constrain the

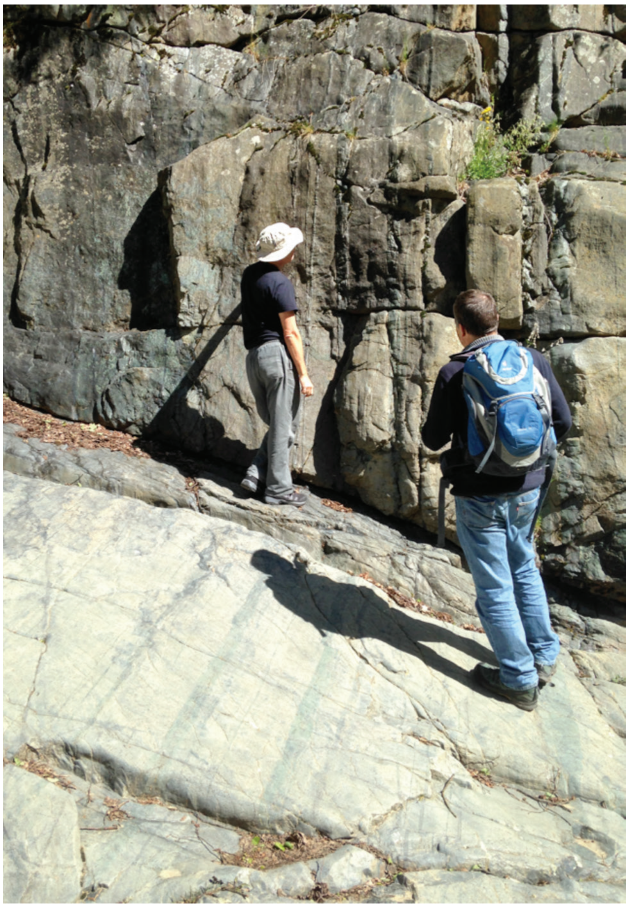


Figure 1. Steve Barnes and Wolf Maier on the mantle peridotite outcrop in Balmuccia (Ivrea Zone, Italy) during a brain storming field trip organised by CI Marco Fiorentini in May 2014. The puzzling question is the link between the pyroxenite veins that cross-cut the outcrop and the occurrence of mineralised intrusions in the overlying mafic underplated stratigraphy.

physical processes that favour the transport and concentration of sulfide liquids in deep lithospheric settings. These results are currently being written up for publication.

OUTCOMES AND IMPACT:

Within the framework of this program, cross-node interaction was extremely fruitful and successful. Researchers from all CCFS nodes carried out joint field activities and collaborated at various levels, as demonstrated from the high number of co-authored publications. Genuine cross-node collaboration was essential because the wide range of expertise that was necessary to attain the challenging goals of the program was not present at any single one of the CCFS nodes but could be gained from a combination of all of them. A measure of the successful interaction is the fact that the same researchers want to keep working together and design ambitious new studies that build on the outcomes of this Foundation Program.

Postgraduate students involved:

Peter Keolleger, Ellen Davies, John Owen, Celia Guergouz, Steve Rennick, Brendan Lally

Published outputs:

CCFS Publications #32, 162, 174, 222, 228, 272, 277, 310, 333, 335, 389, 413, 419, 447, 448

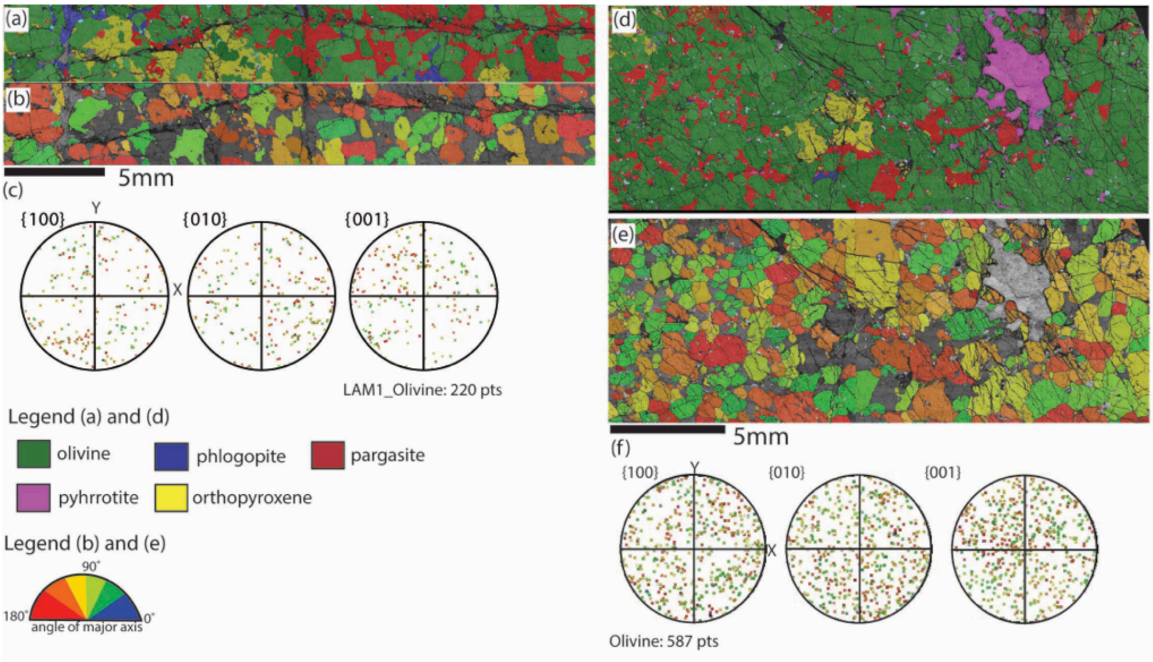


Figure 2. Large area, EBSD maps from samples coming from the centre (a- c) and (d-f) margin of a mineralised ultramafic pipe. Maps a, d show presence and distribution of 5 main phases (see legend). Grain shape EBSD maps show orientation of the long axis of the fitted ellipsoid within the crystal (b and e). Angle of the long axis can be from 0 to 180° (blue to red colour). Pole figure data of olivine crystals (point per grain) is shown on (c) and (f) from the pipe centre and pipe margin respectively. Point colour matches the colour of the olivine crystals from the respective grain shape maps. Data is shown on the equal area projection of the lower hemisphere.

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

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

AIMS:

Understanding mantle dynamics is key to understanding plate tectonics. This program aims to provide new constraints on the nature of mantle deformation in different tectonic environments by exploring the microstructural and geochemical relationships between fluids and/or melts during upper mantle deformation associated with rift initiation, continental margin formation and subduction.

FINAL REPORT 2011-2014:

Mantle deformation has been studied by direct analysis of both peridotite massifs and xenolith samples from a range of different localities. This work has focused on two major aspects of mantle deformation:

1) the role of fluids in controlling the operation of different slip systems, as evidenced by the intragrain microstructures and bulk fabric;
2) the detailed characterisation of mantle deformation associated with melt percolation during rifting and hyper-extensional mantle uplift.

The work has required a detailed analysis of the relationships between intragrain slip systems and bulk fabrics that has provided some fundamental new insights into deformation of mantle materials and the evolution of different fabric types in different tectonic environments. These results are currently being written up for publication and have led to new insights into the role of mantle deformation in controlling supra-subduction zone seismic anisotropy and has led to us questioning the relative roles of mantle and slab in controlling trench-parallel seismic fast directions in forearc environments. Microstructural data of blueschists and high-pressure serpentinites from exhumed slabs confirm the need to consider the slab component of seismic anisotropy in forearc environments. Erin Gray's results also show a relationship amongst crystal plasticity, microcrack development and advective fluid flow in the mantle. Similar approaches have been adopted in the study of mantle extension associated with continental rifting and continental margins. These confirm the activation of the E-type slip-system and provide the first evidence of [001] slip in such an environment. We show that decompression and cooling from high-pressure/high-temperature during rifting is the major factor influencing the localisation of deformation and the change in the dominant slip direction in olivine. Our work on exhumed Alpine peridotites also shows the importance of spatially variable melt percolation in strain localisation in the mantle during hyper-extensional thinning.

OUTCOMES AND IMPACT:

Results of this program on the microstructural state of the mantle in arc environments has led to questioning common models for trench-parallel fast seismic directions. The effect of the slab components in fore-arc environments needs to be considered in more detail. Microstructural studies have identified the mechanism that causes the first slip in rift environments. Melt percolation in the mantle has been shown to cause strong localisation of strain.

Postgraduate students involved:

Erin Gray, Jed Bridges, Tram Do, Mathew van Rensburg

Published outputs:

CCFS Publication #335

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 Foundation Program aimed to understand the genesis and stabilisation of the earliest continental lithosphere and the generation of giant Archean granite blooms, and also to constrain the nature and origin of the oldest preserved crust, as well as the mantle beneath cratonic areas and adjacent Proterozoic terrains. In doing so, it develops and applies new isotopic systems to supplement the use of zircons as tracers of crustal and mantle processes

FINAL REPORT 2011-2014:

The program aimed to understand the genesis of the earliest continental lithosphere, including the processes of fluid/melt extraction that stabilise, and thus preserve, Archean cratonic lithosphere. This involves isotopic studies of zircons from ancient terrains and deep-crustal xenoliths worldwide to further constrain the nature of the oldest preserved crust, and a continued search for the oldest mantle samples beneath cratonic areas. Targeted studies involving a regional characterisation of the 3.1 Ga Mpuluzi batholith (Swaziland/RSA) provide a basis for exploring the processes involved in the formation of stable crustal blocks in the Archean.

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

This program has close linkages with the research of Future Fellow Dr Elena Belousova (*Research Highlight p. 64-65*). This involves 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. The program also studies zircons from deep crustal and mantle xenoliths in basaltic and kimberlitic rocks, and from the ultramafic-mafic Noril'sk-1 intrusion in Polar Siberia (Russia) to look deeper into the lithosphere. This work will be integrated with Os-isotope analysis of sulfides in mantle xenoliths (see *TARDIS program*) to define the origins of the subcontinental lithospheric mantle beneath the old areas where ancient crust is identified, and constrain the role of the mantle lithosphere in stabilising ancient crust.

OUTCOMES AND IMPACT:

The huge volumes of the Mpuluzi batholith were emplaced in a single magmatic episode from 3.17-3.10 Ga. The Mpuluzi magmas show a shift to more mafic compositions over time, suggesting that the compositional variation within the batholith was driven by a change in the degree of partial melting. Sr-Nd-Hf isotopic data demonstrate that the source region included older crust (>3.5 Ga), which constrains the tectonic setting and suggests that the high-degree melts of the lower crust were generated from an older crust, implying the input of enormous amounts of mantle heat, probably related to a mantle overturn. This probably depleted the lower crust in fusible components and established the first subcontinental mantle, leaving this area quiescent for 1.5 Ga.

Studies of material from super-deep drill cores in the Volgo-Uralia region of the East European Craton demonstrated the presence of unexpectedly ancient crust that was later reworked in an analogue to the Swaziland area. Together, these studies give us a picture of processes common to the evolution of the early Archean crust.

A major synthesis of evidence from crust and mantle rocks suggests that most sub-continental lithosphere was generated in a relatively short period around 3-3.5 Ga ago, probably through major mantle overturns. This process stabilised the cratons, providing *'life-rafts'* on which crustal rocks could be protected from destruction.

A study of zircons from kimberlites and crustal xenoliths across the Siberian Craton has mapped both the modification of the Archean crust during the Proterozoic assembly of the craton, and the presence of Archean crust and mantle beneath areas with Proterozoic upper crust. This finding requires a re-evaluation of diamond potential in the eastern Siberian craton.

Techniques have been developed for the analysis of Li isotopes, providing another tracer of magma sources and evolution. This work demonstrated that ^{6}Li and ^{7}Li are fractionated during post-crystallisational uptake of Li into magmatic zircons, and outlined the precautions required for robust interpretation of Li-isotope data.

The processes that disturb U-Pb systematics during metamictisation of U-rich zircons have been defined, producing a '*recipe*' for recognising zircons whose U-Pb systematics cannot be trusted. This should improve the overall quality of detrital zircon datasets.

Postgraduate students involved:

Rosanna Murphy, Yuya Gao, Irina Tretiakova

Published outputs:

CCFS Publications #12, 97, 130, 163, 194, 205, 213, 215, 214, 233, 235, 256, 280, 311, 313, 319, 330, 344, 394, 454, 470, 481, 492, 519, 613

The 3.1 Ga Mpuluzi batholith (Swaziland/RSA).

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 program 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.

FINAL REPORT 2011-2014:

A new smooth particle hydrodynamic code (SPH) to study early planetary evolution and two-component fluid flow problems has been developed. The code has been parallelised in OpenMP, allowing it to be run on traditional supercomputers, in CUDA for GPU processors, and also for Xeon-Phi processors, allowing it to run on the next generation of supercomputing hardware - one of the few modern geodynamics codes with this capability. The code will be hosted at www.ccfs.mq.edu.au/SPH

The next generation of whole-Earth mantle convection simulation tools, based on the community code Aspect, has been developed. Postdoctoral researcher Siqi Zhang has led the development of Aspect modules to handle the next generation of big science problems, including refining physical models for materials under high-pressure conditions (e.g. Peierls-flow mechanisms), developing work-flows to handle the incorporation of gplates plate motion data into global simulations, incorporating melting and multi-component flow, including crustal remixing, into the code. This also incorporates the effects of impacts and re-coding the boundary conditions to handle the problem of core-evolution. This has given CCFS a numerical capacity to handle whole-Earth evolutionary problems not matched anywhere in the world.

The development of a two-phase multi-component reactive flow software platform for mantle processes is completed and benchmarked for the case of viscous rheologies. A two-phase model for micro-textural evolution using non-equilibrium thermodynamics has also been completed and we are using it to study the evolution of trace elements in magmas and of U-series systematics.

Through collaboration with the Institute of Geodesy and Geophysics (Chinese Academy of Sciences), China University of Geoscience (Beijing), we obtained data from the Chinese Seismic Network to construct higher resolution lithospheric structures in northeast and south China using an innovative seismic tomography method including Ambient Noise Tomography and Two-Plane Wave Tomography. Several papers have been published on the lithospheric structures.

Research Assistant, Mr Zhen Guo is working on the origin of intraplate volcanism in NE China and its possible relationship with the subducting Pacific slab by seismically imaging the fine structures of crust and upper mantle in NE China.

OUTCOMES AND IMPACT:

The major legacy outcomes were outlined in the preceding section. The impact of the program can be measured by numerous invited papers and keynote conference presentations. Code development underpinned a major research direction into the dynamics of the Hadean Earth, leading to a series of papers including invited papers in "*Research Frontiers*" (EPSL), *American Journal of Science*, and a *Geological Society of London Special Publication*. Other related invited contributions appeared in *Comparative Climatology of Terrestrial Planets*, the *Australian Journal of Earth Science*, an invited chapter in *Arc-continent collision*, and an invited chapter in the book *Integrated Imaging of the Earth*.

Numerous keynote and invited talks have been presented at international conferences including the *34^{th} International Geological Congress, Brisbane* (2012); the *Australian Space Science Convention*, Sydney; the *Geological Society of America Annual Meeting, Denver*, (2013); the *American Geophysical Union Fall Meeting, San Francisco*; the *Goldschmidt Conference 2013, Florence*; and the *European Geosciences Union 2013, Vienna*.

Yingjie Yang was awarded the prestigious *Anton Hales Medal* by the Australian Academy of Science, 2014, and Juan Carlos Afonso was awarded the *EGU Division Outstanding Young Scientist* in 2013 for integrated studies of the rheology and physical properties of the lithosphere.

PhD student Beñat Oliveira Bravo has been awarded the most prestigious Spanish postgraduate award "*la Caixa*". Grants cover the full cost of matriculation, travel expenses and monthly allowances that can be extended up to 24 months. The award ceremony will take place in Barcelona, the 10^{th} of April 2015, in the presence of the King and Queen of Spain.

Postgraduate students involved:

Beñat Oliveira-Bravo, Chris Grose, Elyse Schinella, Cara Danis, Rajat Taneja, Jonathon Wasiliev, Shahid Ramzan, Samuel Matthews, Chengxin Jiang.

Published output:

CCFS Publications #17, 20, 35, 165, 196, 217, 218, 237, 315, 318, 325, 330, 331, 340, 344, 414, 440, 442, 444, 450, 477, 488, 493, 506, 522, 578, 608

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:

The main aims of this Foundation Program were to define the nature of the first life in the early Archean and links between the early evolution of life and the rise of atmospheric oxygen in the Neoarchean. This will help to understand the evolution of the Earth's oceanic and atmospheric composition during the Archean and Paleoproterozoic, and to evaluate the links between the evolution of the sulfur cycle and the formation of important Archean submarine ore deposits.

FINAL REPORT 2011-2014:

The three main aims were investigated in three research streams: CCFS post-doc David Wacey, and CIs Mark Barley and Martin Van Kranendonk focused on establishing the nature of early life, whereas CI Van Kranendonk was active in documenting the evolution of Earth's oceanic and atmospheric composition together with a host of colleagues. AI Marco Fiorentini and PhD student Carissa Isaac focused on the sulfur cycle and the formation of Archean ore deposit systems. Ongoing investigations are documenting the S-isotope signature of volcanic massive sulfide (VMS) systems in Western Australia.

Highlights from the work on establishing the nature of the first life in the early Archean include the discovery and documentation of ecosystems of bacteria in ~3.5 billion-year-old rocks from Western Australia, and documenting that even this very first foothold of life may have included diverse microbial communities in differing habitats. CCFS researchers also put forward 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 Ga Apex Basalt of Western Australia (*CCFS publication #232*). Additional research identified consortia of 2.3 Ga and 1.9 Ga microfossils from rocks from the Hamersley region of Western Australia, and around Lake Superior, Canada, the former showing evidence for a sulfuretum in deep water conditions and the latter providing the first ever snapshot of organisms eating each other. Both suggest that previously unknown types of microbial metabolisms existed on the ancient Earth.

Figure 1. Chips of microbial mat within 3.5 billion-year-old rocks from Western Australia (front cover of the journal "Astrobiology", December 2013).

Research on the evolution of the Earth's oceanic and atmospheric composition through the Precambrian 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 ever recorded swing in $\delta^{34}S$ isotopic compositions and the rise of seawater sulfate concentrations (*CCFS publication #93*). CI Van Kranendonk and colleagues' 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. These were followed, in turn, by periods of widespread (or even global) glaciation as the supercontinent cycle restarted (*CCFS publication #152*). A climax in the orogenic cycle at c. 1.1 Ga showed that the supercontinent cycle was evolving through time (*CCFS publication #22*). 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 new FP4.

Outcomes from the work on evaluating 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 (*Isaac et al., abst. 2013*) that explains two major heretofore unrelated conundrums about the Archean earth system: (1) why are komatiite-hosted nickel deposits so well endowed?; (2) why did the values of mass-independent S isotopes suddenly expand 200 million years before the Great Oxidation Event? This new discovery 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 (*Kurzweil et al., 2013*).

OUTCOMES AND IMPACT:

The three key aims of Foundation Program 5 (FP5) have been fulfilled, as shown in the extensive publication record from 2011-2014 in a wide range of highly prestigious journals. Investigations into early life led to the discovery that previously unknown types of microbial metabolisms existed on the ancient Earth. Sulfur isotope studies have led to the discovery of the largest known isotope variations, and cycles in these can be linked to the formation and destruction of supercontinents. Studies of komatiite-hosted ore deposits have resulted in a solid hypothesis for the formation of these deposits in the time before the Great Oxidation Event.

Postgraduate students involved:

Carissa Isaac, Tara Djokic

Published outputs:

CCFS Publications #21, 22, 74, 86, 93, 104, 106, 107, 124, 136, 152, 157, 182, 183, 229, 230, 231, 232, 268, 321, 329, 349, 365, 378, 381, 421, 475, 484, 485, 527, 557, 599, 601

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.

In the field - core samples from the Kimberleys.

AIMS:

Through investigation of the age, petrogenesis and palaeomagnetic signature of targeted Australian Paleoproterozoic mafic igneous rocks, we aimed to establish the position(s) of the Australian cratonic blocks in the supercontinent Nuna, and to examine whether the evolution of Nuna was also accompanied by plume/superplume events.

FINAL REPORT 2011-2014:

This Foundation Program has made a number of scientific breakthroughs in the past 3 years. These include publications on the first palaeomagnetically constrained configuration of the pre-Rodinia supercontinent Nuna (*CCFS publications #197, 309*), the recognition of a 40° rotation within the Australian craton during the Neoproterozoic that has fundamental implications in terms of the formation of the Australian continent, the configuration and timing of breakup of Rodinia, and the driving mechanism for Snowball Earth events (*CCFS publications #117, 314*).

A new key pole at age 1.2 Ga for the West Australia craton has been identified, which helps to define the transition between supercontinents Nuna and Rodinia (*CCFS publication #309*), and a new 1.2 Ga Large Igneous Province event in Australia has been documented (*CCFS publication #371*).

A young Hainan plume sourced from an ancient, lower-mantle reservoir has been discovered, the formation of which was likely linked to surrounding subduction zones (*CCFS publications #24, 336*). This mechanism is consistent with that published previously by our group (*Li et al., 2008; Li and Zhong, 2009*).

A new model explaining the collision of South China with northern India after the breakup of Rodinia but during the assembly of Gondwanaland has been conceived and published. This explains early Palaeozoic orogenic and basin record in both northern India and South China (*CCFS publication #366*).

OUTCOMES AND IMPACT:

69 refereed papers and one book have been published, including a large proportion of papers in high-impact journals such as *Geology*, *Earth and Planetary Science Letters*, *Journal of Petrology*, and *Precambrian Research*. The high impact of the research results is also shown by the high numbers of citations the group's work has received, the organisation of conferences on related themes, numerous invited/keynote talks, and the co-editing of three journal special issues/book series by leading researchers Li and Pisarevsky. In addition, we published a series of papers on lithospheric tectonic processes and regional tectonic studies, including work in Tibet (*CCFS publications #223, 496*), NW China and South China.

Postgraduate students involved:

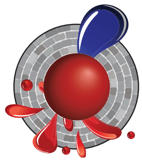
Huiqing Huang, Kongyang Zhu, Weihua Yao, Chong Pang, Ni Tao, Li-Ping Liu, Yingchao Liu, Lifeng Meng

Published outputs:

CCFS Publications #24, 32, 39, 179, 186, 195, 197, 221, 223, 224, 250, 269, 270, 278, 293, 297, 299, 300, 302, 307, 309, 314, 336, 353, 354, 366, 371, 386, 387, 422, 496

Cambrian redbeds

7. FLUID REGIMES AND THE COMPOSITION OF THE EARLY EARTH



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

AIMS:

This two-part program aimed to characterise the earliest crust on Earth and minerals and related fluids phases in extra-terrestrial samples. An objective was to identify new localities where ancient crust may still be preserved by working on both newly-discovered and existing samples of ancient zircon and acquiring full geochemical and isotopic data, so as to compare these with the huge inventory already obtained from Jack Hills and Mt Narryer. The aim was to identify any changes that may have taken place from the formation of the earliest zircons (4.4 Ga) to the time when crust was widely preserved. Conditions on the early Earth were compared with those in the early solar system represented by Martian meteorites, enabling characterisation of any fluid present and identifying primitive mantle deformation mechanisms and processes.

FINAL REPORT 2011-2014:

Areas of preserved ancient crust in Antarctica, Canada, China, Greenland, India, and Western Australia were identified as localities for in-depth study.

Zircon grains from ultra-high temperature rocks of the Napier Complex, Antarctica, were examined using the novel technique of ion imaging by Cameca ims 1280 in Stockholm, using both single collector and multi-collector modes. Patchy distribution of Pb, unrelated to zoning or crystal imperfections, has the potential to affect the $^{207}Pb/^{206}Pb$ age, since spurious Hadean ages can be generated from areas up to 5 nm in diameter. This has led to an explanation of the reverse discordance on concordia diagrams more commonly observed in SIMS analyses than by ICP-MS or TIMS.

Investigations of Ti in Napier Complex zircons also revealed a patchy distribution, which has important implications for Ti-in-zircon thermometry. The redistribution of Pb and Ti was further characterised utilising Raman spectroscopy and the Australian Synchrotron. It is attributed to the combined effects of high-grade metamorphic events at 2.8 and 2.5 Ga that affected the Napier Complex.

The first Atom Probe study of zircon, in association with Prof John Valley and others at Wisconsin-Madison, together with Cameca engineers, has led to the identification of Pb mobilisation on a nano-scale that is attributed to initial alpha recoil damage enhanced by subsequent high-grade metamorphism.

Martian meteorites (Zagami, Nakhla and ALH84001) were investigated in association with the Smithsonian Institute, the Johnson Space Centre Curation Office and the WA Museum. EBSD mapping of minerals showed slip orientations, indicating that clinopyroxene in the Nakhla meteorite has only been mildly shocked with an estimated peak pressure of ~20 GPa, suggesting that the observed deformation pre-dates the shock event. The Zagami meteorite also exhibits shock-related microtextures, including formation of melt pockets and plagioclase converted to maskelynite. This suggests the various systems could be related to both magmatic deformation and a shock event.

Antarctic meteorite sample ALH84001 contains Fe-Mg-Mn-Ca carbonates that are strongly zoned with Mn- and Ca-rich cores, passing outward toward more Fe- and Mg-rich rims. Apatite found in the Zagami sample from the WA museum shows complex microstructures in EBSD related to ductile deformation.

OUTCOMES AND IMPACT:

A re-investigation of ancient zircon in Ordovician volcanics of the North Qinling Orogenic Belt in Central China indicated a range in U-Pb ages from 3909 ± 45 Ma to 4080 ± 9 Ma and Hf crustal model ages up to 4.5 Ga. These Hf model ages are similar to the oldest components recorded from Jack Hills and establish this as another example of the earliest generation of continental crust on Earth, now buried in the basement of the North China Craton.

The first complete traverse across the Jack Hills Belt was completed as part of Qian Wang's doctoral studies at Curtin University. Extensive SHRIMP and MC-ICP-MS zircon data were collected and reveal that only a few units are Proterozoic in age. Importantly, a secular change in Hf results is recorded through the Hadean, documenting extensive re-working of crust throughout the Archaean.

Martian meteorite NWA 7533 contains a zircon with an age of 4430 Ma. This is the first Martian meteorite known to contain zircon and its age establishes the early development of crust on Mars, similar in age to that of the Moon and Earth. The correlation of intra-grain $\delta^{18}O$ variability in the zircon with the degree of radiation damage likely results from interaction of metamict domains with low-temperature fluid. It appears that mass-independent oxygen isotope fractionation in the Martian atmosphere was established as early as ~4.43 Ga.

Postgraduate students involved:

Qian Wang, Rongfeng Ge, Mingdao Sun, Shan Li

Published outputs:

CCFS Publications #278, 282, 301, 403, 404, 405, 406, 407, 408, 409, 412, 420, 426, 427, 428, 429, 430, 431, 432, 542, 548, 555, 608

8. DIAMOND GENESIS: CRACKING THE CODE FOR DEEP-EARTH PROCESSES

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

AIMS:

The LAM-ICP-MS analysis of diamonds, developed at Macquarie, will be combined 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 aim to understand the links between diamond formation and the redox state of the lithospheric and asthenospheric mantle, and to develop a new exploration and evaluation methodologies for kimberlites by defining the trace element signatures of mantle minerals that have been exposed to diamond-bearing fluids.

FINAL REPORT 2011-2014:

A PhD study of polycrystalline diamond rocks (diamondites; K. Rubanova completed 2013) defined the types of carbonatitic-silicic fluids involved, and the isotopic fractionation (C, O) that they undergo during crystallisation. A pioneering EBSD study demonstrated the influence of deformation on diamond recrystallisation, and confirmed that the initial grain-size of the diamondites is much larger than previously thought (*CCFS publication #210*). The present fine-grained aggregates reflect significant recrystallisation under directed stress.

Dan Howell and Craig O'Neill developed software now available in the public domain that makes it possible to produce real maps of FTIR data, allowing the first integrated interpretations of CL, FTIR and chemical data in plates cut from diamonds.

Through a series of detailed studies combining this approach with SIMS analysis of C isotopes (CMCA, Perth), we have gained a better understanding of the growth mechanisms of diamond. A major paper demonstrating the new model is in the final stages of preparation.

We have also become Chief Investigators in studies of the diamonds formed in super-reducing conditions in Tibetan ophiolites (project led by Dr J. Yang, CAGS, Beijing); this will be a major strand of the new integrated TARDIS-II program. There are 3 CCFS CIs on two Chinese projects [led by Prof J. Yang and R. Shi (Tibetan Plateau Research Unit, China Academy of Sciences)] with links to both the TARDIS and Diamond programs.

Dan Howell has played a significant role in the development of N isotopic methodology for SIMS analysis of N isotopes in diamond and development of relevant standards, firstly at Alberta, and later at CMCA (with John Cliff and Laure Martin).

OUTCOMES AND IMPACT:

The demonstration of significant isotopic fractionation of C and O at UHP conditions has opened a new line of research, which will be pursued in the new integrated program. Through a series of studies, we have defined the trace element signature of a '*universal mantle fluid*' (probably a low-volume silico-carbonatite with varying alkali-element content) that is present in many styles of metasomatism, and is involved in the crystallisation of diamond. Differences from this '*universal*' pattern found in the Tibetan diamonds can be correlated with the SuR-UHP conditions. This recognition may be the key to a new approach to identifying '*diamond fingerprints*'; a project is being developed with Russian colleagues and Almazy (the Russian De Beers).

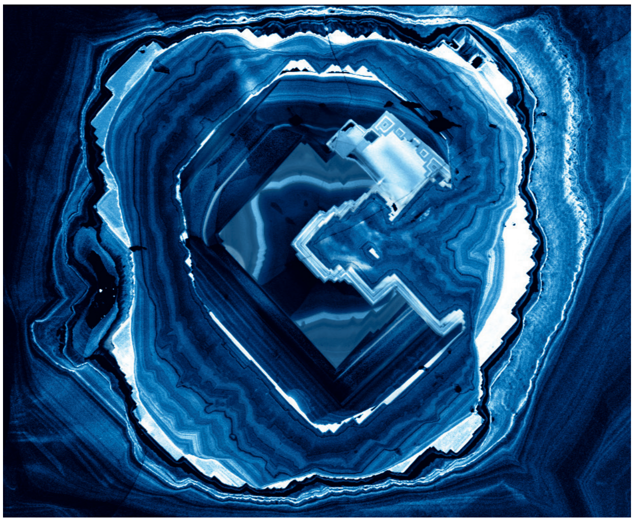
Systematic studies of diamond growth patterns have led to a new model of diamond growth, which differs significantly from the accepted paradigm; a paper is in preparation.

Postgraduate student involved:

Ekaterina Rubanova

Published outputs:

CCFS Publications #2, 6, 11, 52, 135, 168, 178, 180, 210, 211, 212, 236, 320, 332, 328, 372, 385, 502



False colour cathodoluminescence (CL) image of the core of a diamond cube from the Democratic Republic of Congo. While many natural diamond cubes are assumed to be of fibrous growth, detailed study has shown many contain cores of different diamond growth. Sometimes these cores are much older than the fibrous overgrowth. The cause of the blue CL are nitrogen defects within the diamond lattice. Image is approximately 1mm across.

This is one of the samples worked on in collaboration with Dr Masahiko Honda (CCFS AI, ANU RSES).

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:

The program aimed to provide a very well-constrained case study in an Archaean craton outside of the Yilgarn to (1) apply multi-isotopic (U-Pb, Lu-Hf, O) analyses in zircon to map deep lithospheric architecture in space and time, (2) determine if the distribution of mass and energy flow through the lithosphere as mapped by magma products and 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 mineral systems at the craton to terrane scale. The Western Superior Province in Canada was initially selected for comparison due to the detailed geological information base available. This comparative study has since expanded to include Paleoproterozoic terranes of West Africa and the Northern Territory, and Cretaceous to Miocene terranes of Tibet.

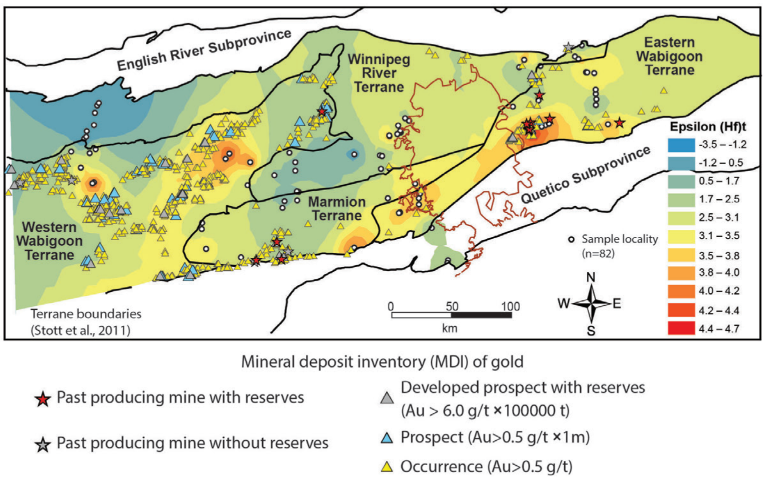
FINAL REPORT 2011-2014:

This program 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. By contrast, we undertook an order of magnitude more analyses in order to effectively map the data spatially. A total of over 400 samples were collected for whole rock geochemical analyses and thin sections. Of these samples, 200 were selected for zircon U-Pb, Lu-Hf, and O isotope analyses, which is the largest and most complete such dataset in Superior Province collected to date. Results from the study have shown (1) that lithospheric architecture and its evolution in space and time can effectively be imaged by multi-isotopic zircon analyses, such that this approach can be used as a form of '*paleogeophysics*', and can detect major ancient lithospheric boundaries NOT imaged in conventional crustal seismic and potential field geophysical surveys, (2) that the first-order whole-lithosphere architecture appears to be established early and reactivated through time, and (3) that the lithospheric architecture imaged by the isotopic maps yield strong control on the location of mineral systems in all terranes studied. This study has resulted in the request by mineral exploration companies to have this research applied in their exploration programs, illustrating the relevance to mineral exploration targeting recognised by industry. This program has initiated successful collaboration and leveraged research funding from China and Canada. The novel approach of this program is now being actively applied in other parts of the world, which places CCFS as the world leader in applying multi-isotopic mapping globally.

OUTCOMES AND IMPACT:

The concept and methodology of this program has subsequently been adopted by other groups in the world, in collaboration with CCFS, to understand the lithospheric architecture. Examples are Tibet and the Uchi/North Caribou terrane in Canada. This program has forged stronger collaborations and leverages with the Chinese Academy of Geological Sciences (CAGS), Lakehead University and the Ontario Geological Survey. The study has attracted significant interest from industry such that several exploration companies are incorporating the results into their exploration strategies (Western Superior, West Africa), the West African mapping will be expanded through an industry-funded research initiative with AMIRA, and a project has now been set up with one of the world's largest gold companies to undertake this isotopic mapping in the Andes.

This interest shows how the program has demonstrated the potential to cause a paradigm shift in exploration strategy within the mineral industry by understanding the spatial and temporal evolution of whole-lithospheric architecture to aid area selection on the large scale. The program also squarely placed CCFS at the forefront of application of this science to mineral exploration globally.



Postgraduate students involved:

Katarina Bjorkman, Luis Parra-Avila, David Stevenson, Linda Iaccheri

Published outputs:

CCFS Publications #23, 32, 100, 162, 167, 170, 185, 206, 222, 243, 253, 255, 257, 258, 259, 260, 273, 346, 350, 382, 383, 452, 456, 457, 467, 494, 503, 517, 521, 530, 582

Zircon Hf-isotope mapping of the Wabigoon Subprovince with 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. See CCFS Research Highlight (2013), Zircon signposts for Gold.

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 program aimed to integrate new and existing data into a 4-dimensional, integrated model of crustal evolution for the western Yilgarn Craton, and to derive a better understanding of the mineralisation processes for this region, how the crust links to underlying lithospheric mantle, and what relationships this piece of lithosphere has with the more highly endowed Eastern Goldfields Superterrane in the eastern part of the craton.

FINAL REPORT 2011-2014:

Significant steps have been taken to address crustal evolution of the western Yilgarn Craton, including the release of the Youanmi and South Carnarvon deep seismic reflection survey results, the planning and deployment of passive seismic arrays, and targeted geological field work.

Three individual seismic lines (YU1, YU2 and YU3) 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 Youanmi and Southern Carnarvon and the 2011 Yilgarn Craton - Officer Basin - Musgrave Province deep seismic reflection surveys add to the existing network of deep-crustal seismic surveys.

The passive source project started in the second half of 2013 with planning of the Capricorn Orogen Passive Array (COPA). COPA is carried in out in collaboration with the Science and Industry Endowment Fund (SIEF) project "*The Distal Footprints of Giant Ore Systems: UNCOVER Australia*". SIEF includes collaborative research between CSIRO, UWA, Curtin University and GSWA that targets the mineral systems in the Capricorn Orogen. COPA has commenced in early 2014 with the deployment of the network.

OUTCOMES AND IMPACT:

The three seismic lines have closed a data gap in the crustal structure of Western Australia, providing a traverse of approximately 1800 km length 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.

A major impact of the passive source project is its contribution to changing the way the Geological Survey of Western Australia approaches the task of understanding the tectonic evolution of Western Australia. There is a growing recognition in Government and Industry that exploring the deep levels of the Solid Earth is a crucial addition to mapping, sampling and imaging the Earth's crust, and this had led to GSWA supporting lithosphere-scale geophysical investigations (Fig 1). The Youanmi seismic reflection survey release workshop on 27 February 2013 attracted more than 90 attendees from the Resources Industry, Academia and Government.

The 2013 CCFS Yilgarn Program Development meeting influenced a number of research proposals, and provided context to projects such as an ARC linkage project granted to the Australian National University and GSWA, which funded a three-year passive array deployment across the south-eastern margin of the Yilgarn.

Published outputs:

CCFS Publications #248, 355, 434, 445

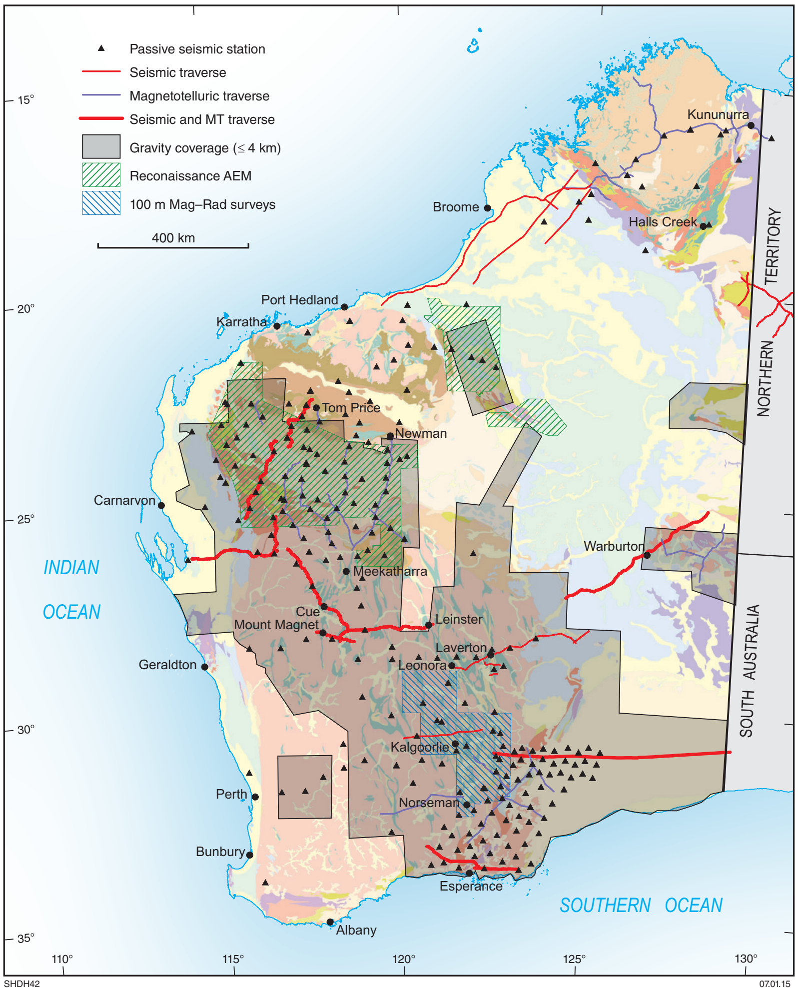


Figure 1. Status of geophysical surveys carried out by GSWA.

10B. ZIRCON LU-HF CONSTRAINTS ON PRECAMBRIAN CRUSTAL EVOLUTION IN WESTERN AUSTRALIA

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

AIMS:

This program aimed to generate Lu-Hf data, and integrate them with geological, geochemical and geophysical information to understand the evolution of continental crust in Western Australia. Efforts were directed at addressing specific geological questions in key areas, particularly along new geophysical transects, as well as in under-explored *'greenfield'* regions, where new information will improve the targeting of mineral exploration.

FINAL REPORT 2011-2014:

This program has made significant progress in integrating zircon Lu-Hf isotope data with other datasets generated by the Geological Survey of Western Australia. More than 10,000 zircon analyses from c. 530 samples have been analysed for Lu-Hf isotopic composition during the 2011-2014 period. Samples have included magmatic zircon from a range of igneous rock types and detrital material, as well as metamorphic zircons. The samples were drawn from the Pilbara and Yilgarn Cratons, Murchison Domain, Kimberley and Amadeus Basins, and the Gascoyne, Musgrave and Rudall Provinces, the Albany-Fraser Orogen and the basement to the Eucla Basin.

OUTCOMES AND IMPACT:

This program has combined time-constrained zircon Lu-Hf isotope data with other datasets to significantly enhance the understanding of crustal evolution in Western Australia. The results continue to further our understanding of several key areas of Western Australia, and feature prominently in new GSWA publications and journal articles. This is the first time in Western Australia that Lu-Hf isotope data obtained on this scale can be integrated with geological, geochemical, and newly acquired gravity, aeromagnetic, seismic and magnetotelluric data.

This program has produced numerous publications to date with the following notable *'snapshot'* highlights. Confirmation that the Biranup and Fraser Zones of the Albany-Fraser Orogen are autochthonous assisted in the delimitation of crustal blocks within the Yilgarn Craton. It also contributed to the understanding of the Mesoproterozoic Giles magmatic system in the Musgrave Province - one of the world's largest super volcanoes, aiding the identification of a suspect terrane within the Capricorn Orogen, radically refining the geological model for the evolution of the Arunta Orogen. It produced evidence for links between the Warumpi and Aileron Provinces, defined a new basement component within the Musgrave Province and

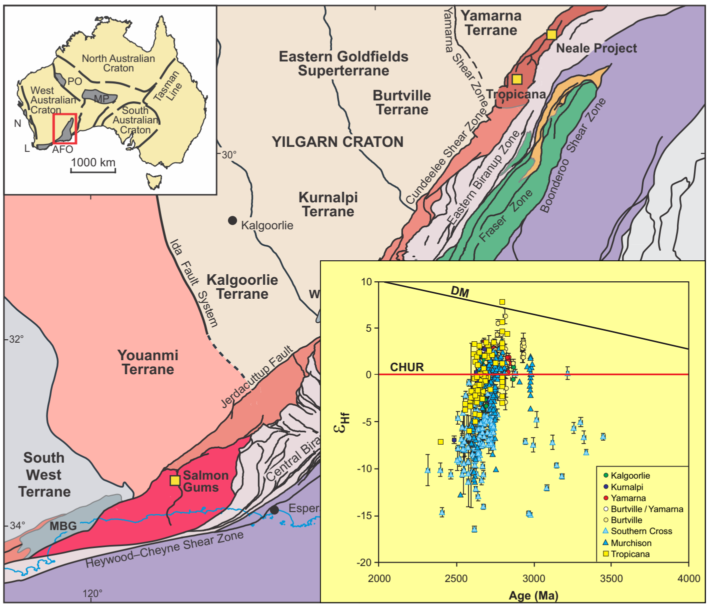


Figure 1. Epsilon Hf evolution plot showing data from the Hercules Gneiss, Tropicana Zone, in comparison to terrains and domains of the Yilgarn Craton. Map is a simplified, pre-Mesozoic interpreted bedrock geology of the east Albany-Fraser Orogen and tectonic subdivisions of the Yilgarn Craton.

demonstrated reworking of Eoarchean crust during Meso-Neoarchean magmatism in the Murchison.

Another focus area was the high-grade Tropicana Zone, a newly defined Archean terrain at the north-eastern margin of the Yilgarn Craton within the Albany-Fraser Orogen (AFO), due to its significant Proterozoic gold endowment. The Hf isotopic signature of the Tropicana Zone zircon shows strong similarities to that from the Eastern Goldfields Superterrane of the Yilgarn Craton. This implies that the Tropicana Zone reflects a deeper crustal level of the Yilgarn Craton, exhumed and thrust northwestwards onto the margin. In addition, we have observed that granulite-facies zircons have a less radiogenic Hf-isotope signature than the preserved pre-metamorphic zircon cores. Based on correlations with alpha dose, U and Th content and $^{176}Hf/^{177}Hf$ we suggest this reflects the preferential destruction and release of unradiogenic Hf from inherited zircon whereas the protolith zircon, with lower U and Th content, was more resistant to mobilisation during high-grade metamorphism. We note this situation may be a more general response of the Hf isotopic system, in which zircon grown in a more mafic melt is less likely to contribute to the metamorphic Hf reservoir than its felsic counterpart.

Postgraduate student involved:

David Mole

Published outputs:

CCFS Publications #61, 68, 78, 185, 209, 247, 256, 264, 265, 266, 267, 274, 275, 337, 346, 436, 441, 456, 497, 518, 547, 609, GSWA Reports 120, 122, GSWA Records 2011/23, 2013/9

Foundation Centre Technology Development programs (Whole-of-Centre programs)

1. CAMECA ION MICROPROBE DEVELOPMENT: MAXIMISING THE QUALITY AND EFFICIENCY OF CCFS ACTIVITIES WITHIN THE UWA ION PROBE FACILITY

AIMS:

This program provided a dedicated Research Associate for the development of CCFS activities utilising the CAMECA Ion Microprobes at the Centre for Microscopy, Characterisation and Analysis (CMCA) 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. 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 CCFS.

FINAL REPORT 2011-2014:

Recent successes in ARC LIEF funding have updated the electron microscopy facilities at CMCA, with the installation of a FEI Titan TEM, a FEI Verios XHR high resolution SEM, and Confocal Raman with AFM in 2014. In 2015-16, a Focused Ion Beam (FIB) platform for the preparation of TEM, NanoSIMS and atom probe samples will be installed.

The CMCA has also received funding for a new Cameca NanoSIMS 50L ion probe through CSIRO's Science and Industry Endowment Fund (SIEF) via the National Resources Science Precinct (NRSP). The new instrument will be part of the tripartite Advanced Resources Characterisation Facility, along with a Cameca LEAP4000 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 multi-collector array and a new oxygen ion source allowing high-resolution isotope measurements on geological samples.

The Ion Probe Facility has continued to contribute to various CCFS programs. These have included a wide range of topics, from the magmatic processes and crustal growth, the origin of ore deposits (O isotopes in zircon, E. Belousova and Y. Lu; S isotopes in sulfides, M. Fiorentini) and the exploration of redox processes in the deep Earth (Si and C isotopes in moissanite; J. Huang and W. Griffin). 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.

OUTCOMES AND IMPACT:

The Ion Probe Facility at CMCA was highly productive, contributing to a number of programs across the whole CCFS. Highlights include zircon analysis, sulfur isotope analysis, isotopic standard development and ultrafine resolution diffusion studies.

The analysis of oxygen isotope in zircon is a powerful tool to identify the magmatic origin of these crystals. E. Belousova and co-authors have conducted an integrated isotopic (U-Pb, Hf and O) study of zircon crystals from upper mantle rocks from the Tumut ophiolite complex. Their study shows that crust-derived zircons can be introduced into mantle rocks even after their obduction onto the continental crust, offering an alternative explanation for the presence of zircon in ultramafic rocks from ophiolite complexes (*CCFS publication #519*).

The ability to measure all 4 stable sulfur isotopes in sulfide minerals *in situ* makes the CAMECA IMS1280 one of the most powerful techniques available for S isotope analysis. The IMS1280 was used to analyse several sets of Precambrian sulfides in order to determine sulfur sources in deep time. A project led by CCFS SAC member James Farquhar (University of Maryland) measured S isotopes in 2.5 billion year old carbonate rocks from Brazil to investigate S sources in the Neoarchean ocean. The data revealed that bacteria were metabolising sulfate even when the ocean contained 1000 times less sulfate than today (*CCFS publication #568*).

Due to the strong '*matrix effect*' inherent in SIMS analysis, each new material requires a chemically and isotopically homogeneous standard of known composition for calibration. 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, C isotopes in SiC, Zr isotopes in zircon crystals from different provenance. O isotope analysis in garnet is in constant development in order to cover the complex chemistry of this mineral. The development of a Cr-rich garnet standard is underway in collaboration with J. Huang, aiming to provide a better characterisation of mantle-derived garnets. The combined development of Li and O isotope measurements in olivine and clinopyroxene is also in progress.

The NanoSIMS proved once again that size does matter as a number of projects utilising the ultra-high spatial resolution and sensitivity to determine diffusion profiles across mineral interfaces. A study by Saunders et al., demonstrated how the ability to acquire high-resolution diffusion profiles could be used to better constrain the timing of volcanic processes on the timescale of days to years. Similarly, experimental studies on Ni and Co revealed that the activity of SiO_2 has a significant effect on the diffusion rates of these elements in olivine from magmas with different compositions *(CCFS publication #600)*.

Published outputs:

CCFS Publications #32, 74, 86, 106, 162, 225, 230, 232, 276, 275, 321, 337, 381, 362, 426, 437, 438, 439, 475, 489, 373, 485, 519, 541, 543, 553, 567, 568, 569, 570, 600, 601

2. FRONTIERS IN INTEGRATED LASER-SAMPLED TRACE-ELEMENT AND ISOTOPIC GEOANALYSIS

AIMS:

The program aims were 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 were based on femtosecond-laser sampling and the coupling of instruments for simultaneous analysis.

FINAL REPORT 2011-2014:

Planned innovations in the Geochemical Analysis Unit (GAU) at Macquarie University in the first term of CCFS were based on new instruments funded by ARC LIEF grants in 2010 (Q-ICP-MS, SF-ICP-MS and Femto-second laser) and 2012 (MC-ICP-MS). This new equipment was necessary for the development of '*split-system*' techniques in which two mass spectrometers (MC-ICP-MS and ICP-MS) are connected to a common laser source for novel simultaneous measurement of geochemical parameters. The current status of this new instrumentation is as follows:

Quadrupole (Q)-ICP-MS: An Agilent 7700cx Q-ICP-MS was installed in June 2010, joining the existing stable of Q-ICPMS (3) and MC-ICPMS (2) instruments. In 2014 a second Agilent 7700cx was installed and co-located with one of the Nu Plasma MC-ICP-MS to establish the laser ablation split-stream infrastructure.

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).

SF-ICP-MS: A Nu AttoM high resolution sector field (SF)-ICP-MS was installed in January 2013. Activity on the Nu AttoM has concentrated on the transfer of *in situ* methodologies from the Q-ICP-MS with an emphasis on U-Pb geochronology of zircon.

MC-ICP-MS: An order was placed for a Nu Plasma II MC-ICP-MS in July 2014 and the instrument is due for delivery and installation in April 2015. This instrument will enable the development of the split-stream methods.

Development of split-stream methods was hampered by instrument performance issues; the main problem was the instability of the magnet on the Nu Plasma 005. Due to these instrumental issues a program was established to evaluate a range of new methods (proof-of-concept) and to refine and improve existing procedures in support of CCFS-funded research programs and to lay the foundations for the split-stream applications. Studies undertaken include:

[1] Evaluation of standard reference materials (zircon, fluorite, garnet, baddelyite, apatite, rutile, perovskite, PGM) for combined measurement using laser ablation ICP-MS and MC-ICP-MS.

[2] An investigation of the fundamental properties of nano- and femtosecond ablation processes in geological materials, focusing on laser-induced U-Pb isotopic fractionation in zircon.

[3] Development of new sample preparation methods for geochemical and isotope analysis in the GAU concentrated on the separation and purification of radiogenic isotopes (Rb-Sr, Sm-Nd and Lu-Hf radiogenic isotope systems) at ultra-low levels and/or small sample volumes and of Li and Mg isotope methodologies for a variety of rocks and minerals.

[4] Revision of GLITTER data reduction software was undertaken to enable the simultaneous treatment of combined trace element and isotope ratio measurements (including refinement of the propagation of uncertainties) and to support output from the Nu AttoM and Nu Plasma mass spectrometers and the Thermo Neptune and Qtegra.

OUTCOMES AND IMPACT:

The activities of the GAU continue to underpin the successful achievement of the goals of the research programs of CCFS and to promote cross-node interaction. The advancement of geochemical methodologies in the GAU plays a significant role in the creation of new research initiatives and to be a major factor in attracting new research collaborators to CCFS. Impact can be measured in terms of the development of innovative new methods and the application of these methods and can be demonstrated by the numbers of researchers and projects supported by the facility, and the communication of results in publications and reports. Access to the GAU facilities has synergised interaction with UWA and Curtin and has enabled researchers to come and undertake their analytical work, as well as spend important '*face-to-face*' time discussing their projects with Macquarie colleagues. Since the commencement of CCFS in July 2011 the GAU has been used by 146 research staff and students, including those from the UWA and Curtin nodes of CCFS, other Australian institutions and international visitors. A total of 111 new collaborative projects utilised the facilities in the period July 2011 to December 2014, 46 of which have involved industry partners undertaking projects using the *TerraneChron®* methodology. The importance of the GAU to CCFS research output is further evidenced by ≥170 peer-reviewed CCFS publications (29% of all CCFS publications; ≥30 with Australian co-authors and ≥120 with overseas collaborators) containing data produced in the GAU. GEMOC also operated as one of the three national geochemical nodes for the NCRIS AuScope program between 2011 and 2014.

Postgraduate students involved:

Yuya Gao, Felix Genske, Nicole McGowan, Qing Xiong

Published output:

CCFS Publication #306

3. OPTIMISING MINERAL PROCESSING PROCEDURES: FROM ROCK TO MICRO-GRAINS

AIMS:

This program aims to optimise the liberation and recovery of the accessory mineral components from any type of rock for geochemical and geochronological analysis. This needed to overcome several major issues with these processes: breakage of grains, potential laboratory contamination, and the concentration and separation of extremely fine-grained phases. These problems are now substantially reduced using electrostatic pulse disaggregation, the use of disposable sieves, and hydroseparation procedures for ultrafine material.

FINAL REPORT 2011-2014:

The first selFrag instrument in Australia, installed in GEMOC in May 2010, uses electrostatic pulse disaggregation 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.

The selFrag is now routinely used for a wide variety of different rock types as the critical first stage in mineral separation procedures, representing a significant advance in method development. Since its installation, the primary application has been the extraction of zircon grains for U-Pb geochronology; in 2013 this accounted for > 90% of the samples processed. It has increased the yield of zircon crystals and the liberated crystals are virtually unbroken with very clean surfaces. 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 new applications include the analysis of grain size and shape of phenocrysts and glass shards in volcanic rocks, the liberation of trace minerals from a range of rocks (e.g. alloys in mantle peridotites, platinum group minerals in chromitites), and archeological.

OUTCOMES AND IMPACT:

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 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.

The 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. Further sample refinement is optimised by sieving using disposable plastic/nylon sieves to prevent contamination; heavy liquid mineral separation; magnetic/paramagnetic separation resulting in three output fractions: magnetic, paramagnetic and non-magnetic; micropanning for further concentration of phases with densities slightly different from their matrix; and hydroseparation of extremely fine-grained water-insoluble particles/grains. The hydroseparator has proved particularly useful to process ultra-fine selFrag material to concentrate rare accessory phases such as alloys in mantle peridotites and platinum group minerals in chromitites.

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, Yongjun Lu in 2013 and Bénédicte Abily in 2014.

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.

Late Cenozoic basalts in southeastern Asia have a unique role in testing whether mantle plumes and subduction are genetically linked because they occur above a seismically detectable mantle plume adjacent to major deeply subducted slabs. This projects aims to examine the petrogenesis of flood basalts located directly above this plume-like mantle structure. It uses a multidisciplinary approach, examining the characteristics of the basalts and their mantle source as well as the temporal-spatial variations in flood basalt geochemistry.

Xuan-Ce in the field in Tibet.

PROGRESS DURING 2014:

The most significant contribution of this project during 2014 was to provide a potential breakthrough hypothesis that links deep-Earth fluid cycling and large-scale intra-continental magmatism (such as continental flood basalts). In this year, we identified low-$\delta^{18}O$ magma from the Late Cenozoic Chifeng continental flood basalts of East Asia. The low $\delta^{18}O$ signatures coincide with clearly-recycled oceanic gabbro-derived signatures. Both of them correlated well with the inferred position of a stagnant Pacific slab within the hydrous mantle transition zone. Our study combines oxygen isotope with conventional geochemistry to provide the first evidence for an origin in the hydrous mantle transition zone. These observations lead us to propose an alternative thermochemical model, whereby slab-triggered wet upwelling produces large volumes of melt that may rise from the hydrous mantle transition zone. This model explains the lack of pre-magmatic lithospheric extension or a hot-spot track and also the arc-like signatures observed in some large-scale intra-continental magmas. Deep-Earth water cycling, linked to cold subduction, slab stagnation, wet mantle upwelling, and assembly-breakup of supercontinents, can account for the chemical diversity of many continental flood basalts.

Another significant contribution of this project during 2014 was to identify the possible disequilibrium-induced initial Os isotopic heterogeneity in a basaltic magma system. The Hainan-Leizhou lavas define good apparent Re-Os isochron correlations, yielding ages significantly older than their formation ages, and display remarkable correlations between the $^{187}Os/^{188}Os$ ratio and the reciprocal of the common Os concentration (i.e., $1/^{192}Os$). This indicates that the initial Os isotopic composition in a basaltic magmatic system was likely heterogeneous. We will further test whether the initial Os isotopic composition was heterogeneous or whether it had reached complete isotopic equilibrium.

Published outputs:

CCFS publications #16, 19, 24, 156, 159, 193, 195, 270, 297, 336, 338, 343, 347, 354, 369, 371, 397, 487, 540, 557

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 Program 1, The TARDIS-E Program: "*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 and electrical conductivity.

This project mainly focuses on the rheology of the uppermost mantle, and investigates the relationship between deformation and fluid-melt-rock interaction 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 in GEMOC has focused on geochemical analysis; this project develops 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.

PROGRESS DURING 2014:

The uppermost mantle in back-arc regions is the site of complex interactions between partial melting, melt percolation, and fluid migration. 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. To constrain melt-fluid-rock interactions, we studied the microstructural development and consequences on the seismic anisotropies in peridotite xenoliths from the uppermost mantle of southwestern (SW) Japan (Fig. 1a).

The seismotectonics and volcanotectonics of SW Japan have been affected by subduction of the old Pacific and the young Philippine Sea slabs. Recent seismic observation reveals the three-dimensional P- and S-wave velocity structures of the uppermost mantle in SW Japan by using a large amount of high-quality arrival-time data recorded by the dense seismograph network on the Japanese Islands. It shows the existence of a large low-velocity anomaly below the Philippine Sea slab at least down to depths of 300km (Fig. 1b).

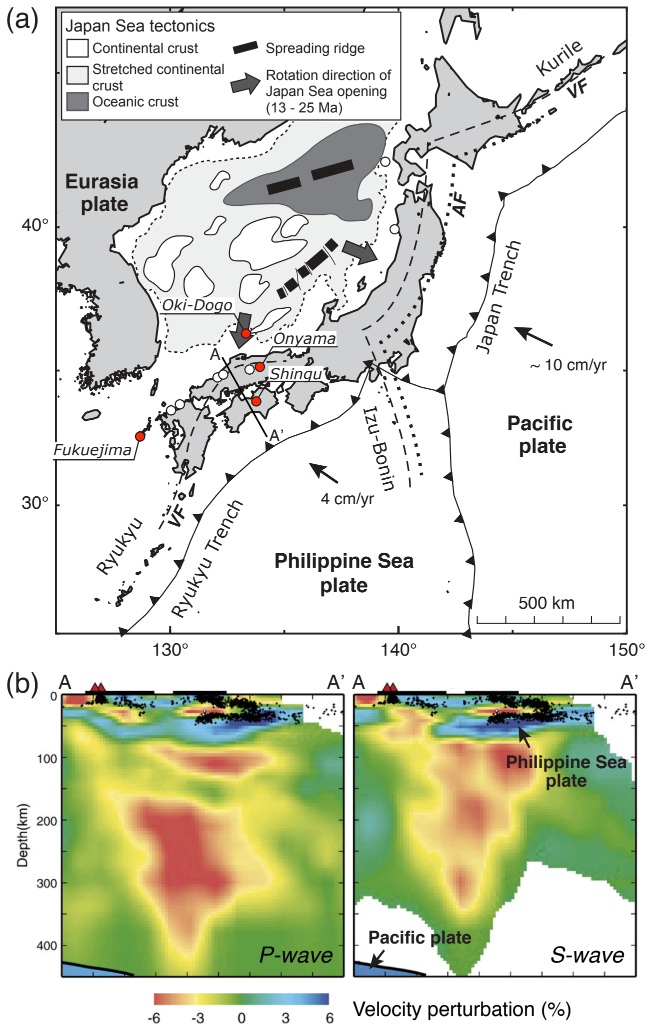


Figure 1. (a) Japanese island arcs and tectonic map of Japan Sea. VF, volcanic front; AF, aseismic front. Movement directions of Pacific and Philippine Sea plates are shown as solid arrows. The Japan Sea adjacent to NE Japan consists of oceanic crust, whereas the Japan Sea adjacent to SW Japan is underlain by continental crust (locally stretched). The peridotite xenoliths are from Oki-Dogo, Onyama, Shingu and Fukuejima, southwest Japan (red circles). Panel is modified after Satsukawa and Michibayashi (2014, Lithos). (b) Across-arc vertical cross section of P-wave and S-wave velocity perturbations (in %) along line A-A' in (a) from Nakajima and Hasegawa (2007, EPSL).

The subduction zone along the Japanese Islands was chosen as a field laboratory to better characterise the deformation processes associated with fluid-melt-rock interaction. Four well-characterised suites of spinel peridotite xenoliths interpreted as sampling the mantle wedge were selected for this study: Fukuejima, Oki-Dogo, Onyama and Shingu are from SW Japan where the Philippine Sea plate is subducting under the Eurasian plate (Fig. 1a). Peridotite xenoliths were erupted (Fukuejima: 1 Ma, Oki-Dogo: 1-4 Ma, Onyama: 5-6 Ma) after the opening of the Japan Sea (13-25 Ma) except for Shingu (18 Ma), which may preserve features of the uppermost mantle prior to back-arc spreading.

Peridotite xenoliths from Fukuejima, Shingu and Oki-Dogo are spinel lherzolite, harzburgite, and wehrlite, whereas all Onyama peridotite xenoliths are spinel lherzolite. Peridotites have equigranular to porphyroclastic textures, with grain boundaries that range from triple junctions to smoothly curving boundaries. Some olivine grains are cut by pyroxenes. In most samples, orthopyroxene crystals have irregular grain boundaries, and fill interstices between the olivine grains.

Variable Cr# (0.1-0.5) of spinels, together with a limited range in olivine compositions (Fo_{90}-Fo_{92}) of Fukuejima peridotite xenoliths, indicate that xenoliths are derived from slightly to highly depleted residual mantle. The equilibrium temperature is relatively high (1070-1200 ºC), which suggests existence of a high geothermal gradient caused by thermal perturbation due

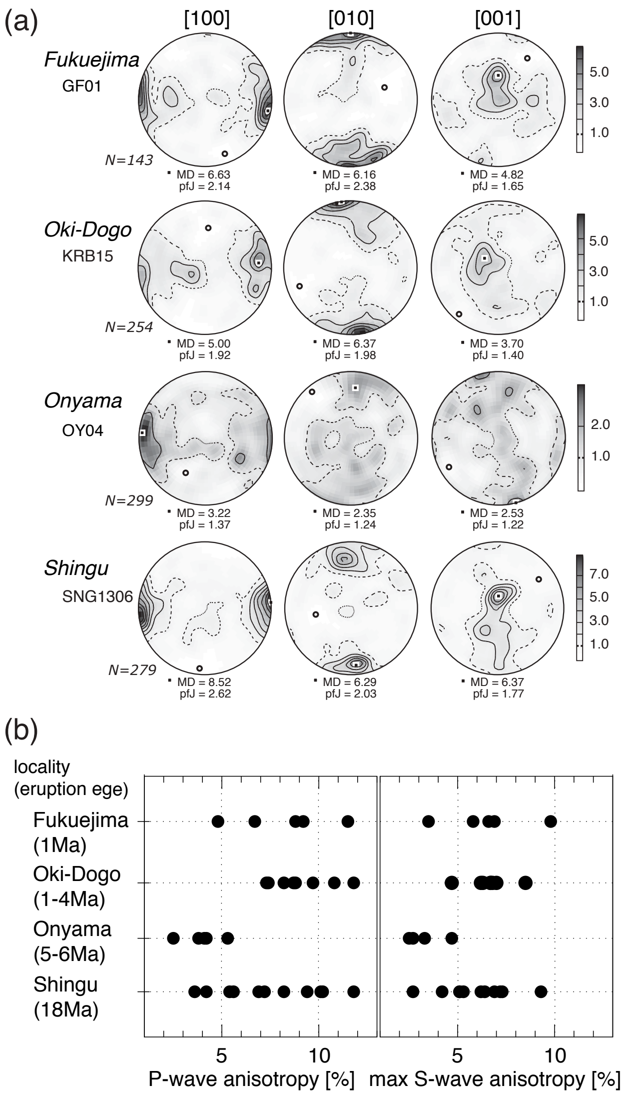


Figure 2. (a) CPO of olivine. Lower hemisphere, equal-area stereographic projections, contours at one multiple of uniform distribution. N is number of measured grains. (b) Variation in P-wave anisotropy and the maximum S-wave anisotropy calculated from CPO and modal composition of peridotite xenoliths.

to the injection of the hot asthenosphere and/or post-rifting uprise of mantle diapirs. Oki-Dogo peridotites have olivines with Mg# 0.86-0.93 and are enriched in LREE (i.e., flat REE pattern of clinopyroxene), interpreted as resulting from high melt-rock ratios. Onyama peridotites show uniform olivine (Fo_{89}-$Fo_9$1) and spinel (Cr# = 0.1) compositions. The mineral chemistry of Shingu is variable. Shingu peridotites preserve a continuum of metasomatic events; (1) partial melting, (2) Fe-enrichment, (3) refertilisation with Ti and Al enrichment, and (4) enrichment in Al and rare earth elements.

Most of the olivine CPOs display a well-developed [100] concentration, and show dominantly (010)[100] and subsequently {0kl}[100] (Fig. 2a). Some of them from Fukuejima and Shingu samples show relatively strong concentration in [010] with a weak [100] girdle, indicating deformation in the presence of melt. Onyama peridotite xenoliths show a weak CPO pattern compare to other localities, which suggests they deformed under low shear strain.

Seismic properties of polycrystalline aggregates were computed by averaging the elastic-constant tensors of individual grains as a function of the CPO and modal composition of the sample (Mainprice, 1997). The P-wave velocity, S-wave velocity, the anisotropy of P-wave, and maximum S-wave anisotropies range from 8.22 to 9.36 km/s, 4.84 to 4.77 km/s, 2.5 to 12.6 %, 2.5 to 10.2 %, respectively (Fig. 2b). Onyama peridotites have significantly lower anisotropy due to their weak CPO.

Combined with petrological and microstructural observations, we argue that a suite of the peridotite xenoliths record a rare snapshot of flow in the uppermost mantle related to the initial stage of back-arc spreading. Geochemical characteristics reveal there was fundamental melt percolation both before and during back-arc spreading. It may indicate that asthenospheric flow and deformation occurred in the presence of small melt fractions. Results indicate the importance of the heterogeneous structure below the Philippine Sea slab with regard to the tectonics of SW Japan, and the preserved deformation during back-arc spreading could affect present-day mantle flow.

Published outputs:

CCFS publications #410, 560

Appendix 2: CCFS workplan 2015

FLAGSHIP PROGRAMS 2014-2017

1. TARDIS II: DEEP-EARTH FLUIDS IN SUBDUCTION ZONES, OPHIOLITES AND CRATONIC ROOTS

This program investigates targeted novel aspects of deep subduction during continental collision, ophiolite fragments that get caught up in the subduction environment, and the role of fluids in deep mantle lithosphere. Recently recognised super-reducing, ultra-high-pressure (SuR-UHP: 400-600 km) mineral assemblages in selected ophiolites carry implications for the evolution of fluid compositions, reactions and redox states in subduction environments from the surface to the Transition Zone, and suggest a new geodynamic collision process that may improve mineral exploration concepts for paleosubduction regimes. We aim to determine the extent of isotopic fractionation in a range of elements caused by redox reactions that produce many oxygen-free phases at UHP conditions. A goal is an experimentally testable model for the generation and preservation of highly reducing conditions, and to quantify constraints on the geochemical and tectonic processes that have produced SuR-UHP assemblages and brought them to the surface in ophiolites, and to produce a geodynamic model for these processes.

UHP rocks and lithospheric diamonds will be used to refine the geochemical signatures of deep fluids and microstructural histories to provide additional insights into deep-mantle fluid types and processes. The isotopic variability of carbon, oxygen, nitrogen and sulfur in diamond-forming fluids will be studied to ascertain whether these are primary signatures, or are produced by isotopic fractionation during diamond growth.

Workplan for 2015

Eight separate but inter-related approaches will be embarked on and progressively integrated. [1] Fluids in diamonds in the ophiolitic material appear, from their nitrogen aggregation states, to have only a relatively short history at low temperatures. Further FTIR will be supported by nitrogen and carbon isotope analyses to test this conclusion. [2] Stable isotope measurements *in situ* of relevant elements in their oxidised and reduced form will test for differences in isotope fractionation. This will require considerable method development across the CCFS instruments. [3] Oxidation-state variations of elements such as Fe, V, Cr and Ti in the SuR-UHP assemblages will be measured with Mössbauer spectroscopy and XANES mapping at the Australian Synchrotron. [4] Characterisation of new, rare high-pressure minerals in the Tibetan chromitites will be carried out, including their microstructures by EBSD. [5] Minor sulfide phases in the chromitites will be analysed for the isotopes of Cu, S, Fe and Pb. [6] Noble gases (He, Ne, Xe) of the SuR-UHP assemblages will be used to ascertain the degree of input from the deep Earth relative to that from the subducted material. [7] Dynamic modelling has already implicated rollback of deeply penetrating slabs. These geodynamic mechanisms will be investigated in detail. [8] Experimental studies at high pressures will enter the planning stages. These will be designed to test the stability fields of new and rare minerals of the SuR-UHP assemblage, and to address other questions that crop up during the course of the program.

2. MULTI-SCALE FOUR-DIMENSIONAL GENESIS, TRANSFER AND FOCUS OF FLUIDS AND METALS

This program aims to address the critical link between metal source fertility and four-dimensional evolution of multi-scale fluid pathways that ensure efficient mass and fluid flux transfer between the mantle and the upper crust.

The ability to discover new mineral resources has become very challenging partly due to the limited predictive capability of the traditional analogue deposit model approach. Recently, new conceptual frameworks such as the mineral systems approach have been proposed, which provide more powerful predictive capability for mineral exploration. This program tests the hypothesis that the genesis of sizeable mineral deposits is the end product of self-organised critical systems operating from the scale of the planet all the way to the very focused environment where ore deposits can form. The mineral systems approach represents a step change in the way we investigate ore-forming processes, and considers the evolving relationship between the localised setting of anomalous metal resources and processes operating at the scale of the planet. Prior to the advent of the mineral systems concept, single deposits were documented in detail as unique occurrences, but this approach failed to focus on the commonalities among various occurrences and, more importantly, ignored the larger scale architectural framework that hosts them. The new rationale takes a more holistic approach, acknowledging that the genesis of mineral occurrences required the conjunction in time and space of three main independent parameters; fertility, lithosphere-scale architecture, and favourable transient geodynamics. This conceptual framework forms a key pillar for the CCFS research goals.

Workplan for 2015

This frontier study is designed to contribute to the goal of creating a step-change in exploration targeting. First it will be necessary to assemble and critically assess the great wealth of already available data. At the same time, a series of pilot studies is starting (e.g. Tibet) and continuing (e.g. Southeast Greenland). These will lay robust foundations for the work program for the following years, in which the researchers will focus on knowledge gaps identified in the pilot studies. More importantly, the program represents the integration and continuation of a series of existing projects.

We will start utilising the new ARC-funded EBSD apparatus housed at Curtin, strengthening our knowledge of the key relationships between deformation at the micro-scale and the transfer of key fluids and metals. This work will tie in nicely with the ongoing work of Sandra Piazolo in her Future Fellowship study. We also endeavour to continue the ongoing work on lithium isotopes and labelled experiments. However, to analyse experimental run products we would need *in situ* techniques that require further development. Hence, we will push the development of *in situ* techniques and also analyse mineral concentrates, glasses, and whole-rock powders at the University of Maryland. Finally, the role of water and other volatiles in the transport and concentration of metals focuses on arc magmas, experiments and Cu-porphyry systems, furthering and expanding the investigation of subduction systems in CCFS.

3. TWO-PHASE REACTIVE FLOW IN MULTI-COMPONENT DEFORMABLE MEDIA

The overarching goal of this program is the development and application of in-house state-of-the-art computational simulation tools to model complex geochemical-geodynamic processes involving two-phase reactive flow in multi-component deformable media. Many aspects of Earth Science, from ore deposits to giant earthquakes, depend critically on the complex interaction of solids and fluids. Numerically simulation of these processes and effective visualisations of the results is critical to understanding how these Earth system components work, but our ability to do this is currently very limited. We are developing the next generation of numerical codes and refining thermodynamic parameters by high-pressure experiments to handle these complex problems. This will lead to important improvements in the quantification and visualisation of Earth processes, and will be applied to a variety of geodynamic situations.

The new experimental group at Macquarie joins this initiative to provide input on physico-chemical parameters of minerals and fluids in the deep mantle, the composition of melts that infiltrate the lithosphere, and their effects on its geodynamics and stability.

Workplan for 2015

A main focus of work for the coming year is the further development of 3D models. High-resolution runs will be performed at Intersect, and the coding of dehydration sequences and melting will be completed.

Development of the FEM methodologies will be continued, the techniques published, and the FEM developments (e.g. chemical advection, multiscale FEM) will be integrated with 3D Aspect models. Further developments will be made to the radial anisotropy code, imaging of the lithosphere, and applications.

The integration of experimental data will begin with collation of existing data, and then we will proceed to planning of further high-pressure experiments on the stability of mantle phases, with the first experiments conducted as the high-pressure equipment is set up. Using a similar approach, high-pressure experimental results relevant to the composition of mantle melts and their interaction with peridotites with varying degrees of depletion in the mantle lithosphere will be assessed and an experimental program planned.

Interacting fluids and solid matrices are extremely important in subduction systems. Recent work has highlighted fluid release during flat subduction, and the geological response to these events may significantly impinge on the over-riding lithosphere. Two modern examples of this are the Farallon slab in western North America, and South China. The western USA is a tectonically active region with extensive magmatism over the past 100 Ma, which is often hypothesised to be related to the flat subduction of the ancient oceanic Farallon Plate. South China has one of the most complete records of hypothesised flat-slab subduction and subsequent slab foundering, causing major regional tectono-thermal events, magmatism, basin formation, large-scale continental vertical tectonic movements, and mineralisation. These areas will be assessed with Ambient Noise Tomography (ANT) and Multiple Plane Wave Tomography (MPWT) in seismic imaging to construct 3D seismic models using data from the extensive broadband Transportable Array component of EarthScope/USArray, which are archived in IRIS/DMC and open for public download. They will be integrated with application runs on the flat subduction scenarios, which will be well advanced in 2015.

4. A PLANETARY DRIVER OF ATMOSPHERIC, ENVIRONMENTAL AND BIOLOGICAL EVOLUTION THROUGH TIME

We investigate how the evolution of life and ore deposits were linked to the changing whole-Earth System, focusing on planetary driving forces that affected all of the different shells of the planet, to develop a 4-dimensional conceptual framework of Earth evolution. Given the broadly comparable petrological evolution of Earth and Mars, we also aim to put forward new working hypotheses on how life and mineral systems may have formed and evolved on the red planet.

This program will test the hypothesis that the evolution of life and the genesis of sizeable mineral deposits are the end products of systems operating at the scale of the planet all the way down to the specific environments where life flourished and mineral deposits formed. A component of the program will focus on Mars to investigate whether the evolution of life and the genesis of mineral systems on the red planet operated in a broadly similar fashion. We evaluate the relative importance of (1) the threshold barriers that form in specific environments creating strong chemical and energy gradients in the crust, and the self-organised behaviour of mineral systems and life; (2) the evolving nature of '*traps*' at the lithosphere-hydrosphere boundary, where life and ore deposits developed through time; (3) the global scale cycle of key elements and heat transfer essential for the evolution of life and formation of ore deposits; and (4) the 4-D evolution of the pathways that connect different geochemical reservoirs through time, linked to the changing tectonic style of the planet, as a guide to understanding biological and ore deposit evolution through time.

Workplan for 2015

Module 1: Vital pathways investigates the role of mantle melts in providing heat and elements to the lithosphere on both Earth and Mars. Multiple sulfur-isotope and trace-element data on a selected series of Martian meteorites will be compared with analogous Proterozoic ferropicrites from Pechenga, Russia. Our aim is to determine if and how such Fe-rich magmas became capable of forming discrete mineralisation. Parallel studies will investigate the changing composition of volcanic belts, ore deposit fluids and S-isotopic compositions through time, focusing on Archean-Proterozoic greenstone belts and a suite of VMS deposits in Western Australia that span the period of supposed onset of modern-style subduction in the Mesoarchean.

Module 2: Critical interfaces will investigate changes to lithosphere/exosphere interaction in two exceptionally well-preserved Precambrian areas. Large-scale hydrothermal alteration systems that harbour the earliest traces of life on Earth in the Paleoarchean rocks of the Pilbara Craton will be analysed in detail by CCFS members and international colleagues. Changes in the composition of carbonaceous matter and the redistribution of metal ions in hydrothermal veins will be ascertained using oxygen isotopes. We will also investigate carbonate minerals as a means to identify microbial processes and the composition of the exosphere on early Earth. Low-grade metamorphic grade rocks of the Paleoproterozoic Turee Creek Group, Western Australia, will be analysed for trace element geochemistry, C and Mo and Sr isotopes, in order to track the changing biosphere as it adapted to rising oxygen levels and the change from a dominantly chemical to a dominantly mechanical weathering regime. This work ties into the SIEF initiative in the Capricorn Orogen, where Proterozoic VMS systems can be compared and contrasted with their Archean equivalents.

Module 3: Global cycles of elements will continue to investigate changes in life-essential elements (C, S, Fe, N) through time, in order to better constrain global changes in the biosphere through time. A major focus will be on both the Mesoarchean onset of modern-style subduction and the rise in atmospheric oxygen. Iron-formation units will be analysed for their S and Fe isotopic compositions, and a set of three diamond-drill cores from the Paleoproterozoic Turee Creek Group of Western Australia will be analysed for their S, Fe, Mo and Sr isotopic compositions. Organic geochemistry will evaluate the evolution of the biosphere across this interval, and S-MIF signatures will assess whether the atmospheric and biological signatures in sulfides can be decoupled, and perhaps distinguish the differing contributions and/or onset of sulfate-reducing bacteria from sulfur-disproportionating bacteria.

Module 4: Planetary Driver will focus on combining all the information from modules 1-3, and from other studies, into a holistic, 4-dimensional model of Earth evolution throughout the Precambrian. A critical aspect is the changes produced by the onset of modern-style subduction, as this gave rise to the modern Earth geodynamic system and fluid circulation systems. Whole-Earth modelling of the effects of rapid and wholescale subduction during the prelude to supercontinent amalgamation events and their effects on mantle temperatures and tectonics will be conducted using a Lagrangian integration point finite element method (Ellipsis). This model uses a Cartesian geometry with a periodic (wrap-around) side boundary condition, and free-slip isotemperature conditions at the top and bottom.

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

Earth's history is considered to have been dominated by cycles of supercontinent formation and breakup. This program will test this hypothesis and its relevance to Australia's geological evolution and assess its positions during the supercontinent cycles by examining the palaeomagnetic, petrological and detrital provenance record of the Australian continent. By studying primarily Australian rocks and comparing the results with global analogues, we aim to extend our knowledge about supercontinent cycles and the evolution of the Australian continent to the Paleoproterozoic and further back in time. Such knowledge is fundamental for understanding the first-order fluid cycles that controlled the formation and redistribution of Earth resources, and the establishment of a 4D global geodynamic model.

We aim to examine the position of the Australian continent during supercontinent cycles and its record of plume events through a multidisciplinary study of Australian rocks. We will focus on the following scientific questions: (1) Was Australia neighboured by East Asian continental blocks during the assembly of Gondwanaland? If yes, which ones, and what was their collision and breakup history? (2) Was there indeed a 40° rotation between northern and southern Australia during the Neoproterozoic that led to the formation of the Paterson-Peterman intraplate orogen? (3) When and how was the Australia Precambrian basement joined together? (4) What was Australia's role in the configuration and evolution of Pre-Rodinia supercontinent(s)?

Workplan for 2015

Paleomagnetic analyses are being conducted on samples collected from the Mesoproterozoic Morawa Lavas (Western Australia), and a sampling trip to the Kimberley region targeting Paleoproterozoic and Neoproterozoic rocks is planned and will hopefully be carried out in 2015. New PhD students will be recruited to sample and analyse southwest Yilgarn dykes for their age, geochemistry and palaeomagnetism. Sampling and analysis of Cambro-Ordovician clastic rocks from NW Australia and South China will also be carried out.

Our new geochronological and paleomagnetic data from the ~2.4 Ga Erayinia mafic dykes in the southwestern Yilgarn, will be completed and published, and we will continue our international collaborations on a number of offshore targets of Precambrian paleomagnetism and paleogeography.

We will participate in the Nordic Paleomagnetic Workshop in Norway with the aim of further developing the Global Paleomagnetic Database, and we will complete trace element and Nd isotope analyses of samples from the Bangemall Basin collected in 2013.

6. FLUID REGIMES AND THE COMPOSITION OF THE EARLY EARTH

Zircon crystals are currently the only material that records events in the first 500 million years of Earth's history, since no rocks have survived from this period and no other minerals have been dated as Hadean in age. There is growing evidence from the study of these zircon crystals that the Earth stabilised rapidly after accretion and that both solid rock and liquid water were present within 150 million years of its formation. In this program, the geochemical signatures of zircon crystals from all known Hadean and early Archean localities will be utilised, together with geochemistry of the oldest known rocks and the application of geophysical and geochemical modelling, to establish how the first crust evolved, why it was destroyed and the role of fluids in this process. Furthermore, it will evaluate the changes that took place throughout the Archean as crustal processes evolved. In addition, work will continue on Martian meteorites and lunar samples in order to provide further constraints on the early history of the Solar System, especially the role played by fluids.

Workplan for 2015

We are investigating rocks and minerals from locations that have so far not been examined during the first three years of operation of the CCFS. This includes analysis of newly acquired material from Labrador and the North China Craton. In addition, work will continue on the Aker Peak samples from Antarctica.

Further work is planned for both the Tarim and Bundelkhand cratons, the former in association with Nanjing University. Preliminary work indicates that these cratons show a similar sequence of magmatic and metamorphic events to the North China Craton. Ion imaging of zircons from Anshan, and those currently available from Acasta and Greenland, will be completed by the end of 2015, and work will commence on the new samples collected from Labrador during the 2014 field season. Associated work utilising EBSD, TEM and the Synchrotron will be undertaken using both Australian and European connections. The first geoscience-dedicated Cameca Atom Probe will be installed at Curtin in 2015 and, after set-up, extensive work will be undertaken on the ancient zircon inventory held by CCFS members.

It is anticipated that work will commence with CI Craig O'Neill and staff appointed at Curtin to the Perth supercomputer consortium on new modelling studies that will evaluate the transition from a possible stagnant-lid state to a tectonically active early Earth.

With respect to extra-terrestrial investigations, work will continue to focus on Martian meteorites and the role that fluids have played in establishing the current mineralogy. Pb and S isotopic data will be collected in order to evaluate the interaction of Martian mantle melts with the evolving crust. Further work is also being undertaken on Apollo 14 Lunar samples, including development work to enable direct dating of basaltic rocks and to provide a unified model for the Pb isotope evolution of the Moon.

7. 3D ARCHITECTURE AND PRECAMBRIAN CRUSTAL EVOLUTION IN THE WESTERN YILGARN, AUSTRALIA

Iron, Gold and Nickel deposits are of global economic significance, and the Neoarchean Yilgarn Craton and the Proterozoic orogens around its margins constitute one of Earth's greatest mineral treasure troves. Whereas the Yilgarn is one of the best-studied Archean cratons, its enormous size and limited outcrop are detrimental to a deep understanding of what controls the distribution of resources and which geodynamic processes were involved in the tectonic assembly of the Australian continent. The principal aim of this program is to combine geological, geochemical and geophysical techniques to propose a 3D structural model of the lithosphere of the Yilgarn Craton and its margins.

The Yilgarn Craton is a large and highly complex piece of Archean crust with a long history extending from 4.4-2.6 Ga. Amalgamation of terranes is thought to have occurred around 2.65 Ga. Recent work by GSWA in the northwestern part of the craton has identified a long-lived, autochthonous history of crustal development there, including episodes of volcanism, granitic magmatism, shearing and gold mineralisation that are similar in composition and temporal development to those further east in the Eastern Goldfields Superterrane, which has been interpreted as the accreted, younger part of the craton. This implies that there are significant problems with current models of crustal development through arc-accretion tectonics.

There is a growing realisation that understanding how mineralised crustal provinces form requires structural and chemical information on the entire lithosphere. This is addressed in the multi-disciplinary SIEF project "*The Distal Footprints of Giant Ore Systems: UNCOVER Australia*", which involves collaborative research between CSIRO, UWA, Curtin and GSWA, and targets the Capricorn Orogen at the northern boundary of the Yilgarn.

It includes the Capricorn Orogen Passive Array (COPA), a passive source experiment that will study the deep crustal and shallow lithosphere structure using earthquake seismology. The data from this experiment will be the main source for the local ambient noise inversion, the receiver function common convection point (CCP) stacking techniques, and possibly a body-wave tomography study. Given the fact that the passive source site coverage in Western Australia is sparse and that the available permanent sites in the region provide nearly 10 years of data at isolated locations, several techniques that focus on crust and upper mantle structure beneath single stations will also be applied. This approach has the potential to provide quick access to the crustal and lithospheric structure from these representative sites.

Workplan for 2015

The Capricorn Orogen Passive Array was deployed in collaboration with the GSWA and CET in 2014. Two field teams worked in the field for three weeks deploying the first 36 sets of broadband instruments. Data processing related to the ambient noise imaging and the receiver function CCP imaging can now proceed. During the intervals between the Capricorn field preparation, test-deployment, field deployment, as well as station servicing, the following activities will be conducted simultaneously throughout the year: individual station structural imaging for the permanent sites, travel-time residual preparation for finite frequency body wave tomography, cross-correlation computation and dispersion measurements for ambient noise, receiver function common-conversion-point stacking, and data preparation for continental scale shear wave tomographic inversion.

WHOLE OF CENTRE TECHNOLOGY DEVELOPMENT

1. CAMECA ION MICROPROBE DEVELOPMENT: MAXIMISING QUALITY AND EFFICIENCY OF CCFS ACTIVITIES WITHIN THE UWA ION PROBE FACILITY

The Ion Probe Facility within the 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. This program provides a dedicated Research Associate to facilitate CCFS activities and lead the development of standards and analytical protocols at the CMCA. This will greatly benefit the CCFS by increasing the capacity of the Facility, enabling a higher degree of interaction and participation on research projects, facilitating standards and protocols development, and allowing greater synergy with other CCFS node facilities.

Workplan for 2015

Short-term goals in the development of standards and analytical protocols will enable new types of analyses to become routine shortly. These include multiple sulfur isotope analyses in a range of sulfide minerals (Fiorentini, Wacey, Martin, Kilburn), oxygen isotope analysis in garnet following development of a multi-element matrix correction (Martin), oxygen and hydrogen analysis in lawsonite (Martin, Cliff), oxygen isotope analysis in chromium-rich garnet (Martin and Huang), zirconium and silicon isotopes in zircon (Martin, Griffin), silicon and carbon isotopes in moissanite, diffusion profile studies using the NanoSIMS (Kilburn), and quantification of Au in sulfide minerals (Kilburn).

In addition, the first results from the new pilot projects should become available. Many of these innovative new projects include developmental work, in particular those that involve NanoSIMS analysis.

2. FRONTIERS IN INTEGRATED LASER-SAMPLED TRACE ELEMENT AND ISOTOPIC GEOANALYSIS

The overall aim of this program is to develop new analytical methods for *in situ* measurement of trace elements and isotope ratios to enable CCFS research programs and provide new directions of research. Specific objectives are [1] combined trace element and isotope analysis - '*split-stream*' analysis, [2] development of analytical routines for '*non-traditional*' stable isotopes, [3] characterisation of reference materials for elemental and isotope ratio measurement, and [4] development of data reduction software for combined trace element and isotope analysis

Workplan for 2015

Work will extend developments relevant to existing activities and projects. Priorities for aspects of this program and work in the coming years will be set following a consultation workshop involving all interested researchers. Anticipated developments include: [1] Installation and commissioning of high resolution MC-ICP-MS. [2] an experimental program to investigate the fundamental properties of femtosecond ablation processes in geological materials, focusing on laser-induced elemental and isotopic fractionation. This will incorporate the examination of the laser pits using the SEM-FIB instrumentation at the University of Adelaide. [3] Continuation of the transfer of *in situ* methodologies for trace element analysis and U-Pb isotope measurements from Q-ICP-MS to the Nu Attom. [4] Development of split-stream laser ablation analysis by Q-ICP-MS (U-Pb isotopes) and MC-ICP-MS (Hf isotopes). [5] Development of split-stream laser ablation analysis for the combined measurement of trace elements (Q-ICP-MS) and radiogenic/stable metal isotopes (MC-ICP-MS). [6] Refinement of Li isotope methodologies in ultramafic rocks. [7] Development of calibration standards and reference materials for Li isotopes in minerals from mantle-derived rocks (e.g. olivine, cpx, phlogopite). [8] On-going development of the procedures for the measurement of the Mg isotope composition of minerals from mantle-derived rocks (e.g. olivine, garnet, cpx, chromite). [9] Parallel development of methods for the determination of Fe isotopes in minerals from mantle-derived rocks (e.g. olivine, garnet, cpx, chromite). [10] Characterisation of calibration standards and reference materials for Si isotopes in Si metal, carbide, oxide and silicates. [11} Alignment with ongoing relevant method developments for the CAMECA IMS 1280, including setting up of critical new standards especially to fulfil the goals of Flagship Programs 1 and 2.

Pilot projects

PILOT PROJECTS 2014-2015: A NEW INTITATIVE

In addition to the Flagship Programs, CCFS has provided 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 Flagship Program. The pilot projects were awarded in a competitive proposal round with a view either to folding them into Flagship Programs 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, Cliff, 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. 82.*

Timescales of mixing and volatile transfer leading to volcanic eruptions	**H. Handley**, **S. Turner**, M. Reagan, J. Barclay: *Supported by ARC Discovery (commencing 2015)* ***Summary:*** The short-lived lead isotope, ^{210}Pb, has the unique ability to place timescale constraints on volcanic processes, such as the input, mixing and degassing of magma. These processes are believed to be of fundamental importance in the triggering of volcanic eruptions. This project will measure ^{210}Pb isotopic compositions and elemental diffusion profiles in crystals of volcanic rocks that represent the end members of mixed magmas to constrain the volume and timescale of volatile transfer from magmatic recharge and also the time between magma mixing events and eruptions. The project aims to test the paradigm that magma recharge triggers volcanic eruptions and aims to yield significant outcomes for understanding eruption triggers at hazardous volcanoes.
Migmatites, charnockites and crustal fluid flux during orogenesis	**I. Fitzsimons**, M. Holness, **C. Clark**: *Supported by ARC Discovery (commencing 2015)* ***Summary:*** Migration of volatile fluid and molten rock controls many Earth processes including rock deformation and the formation of mineral and energy deposits. Deep crustal fluids are hard to study directly, and their characteristics are usually inferred from lower crustal rock brought to the surface by erosion. For over 30 years one such rock called charnockite has been used to argue that lower crust is dehydrated by influx of carbon dioxide -rich fluid, while other evidence supports dehydration by water extraction in silicate melt. This project aims to use the shape, distribution and chemistry of mineral grains to trace the passage of volatiles and melt through charnockite, constrain the nature of lower crustal fluids and resolve a long-standing controversy.
The global consequences of subduction zone congestion	**L. Moresi**, P. Betts, J. Whittaker, M. Miller: *Supported by ARC Discovery (commencing 2015)* ***Summary:*** This project will use a combination of 3D geodynamic modelling, plate kinematic reconstruction and geological and geophysical synthesis to determine how congested subduction zones influence plate kinematics, subduction dynamics and tectonic evolution at orogen and global scales. The project aims to deliver a transformation change in understanding the links between congested subduction, mantle flow, trench migration, crustal growth, transitions between stable convergent margin configurations and deformation in the overriding plates of subduction zones. Determining these relationships is significant because it will provide dynamic context to interpret the geological record of ancient convergent margins, which host a large percentage of Earth's metal resources.
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.

Bromine isotopic evolution of the Earth and solar system	**B. Schaefer**: *Supported by ARC Discovery (commenced 2013)* ***Summary:*** A world first capability of innovative isotopic tracing within the earth and solar system materials will be developed. Insights into how planets are formed and the transport of materials and heat within them will be tracked through the application of the naturally occurring isotopes of Bromine.
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.
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.

Down under down under: using multi-scale seismic tomography to image beneath Australia's Great Artesian Basin	*N. Rawlinson,* **Y. Yang**: *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.
New insights into the origin and evolution of life on Earth	**D. Wacey**: *Supported by ARC Future Fellowship and MQ (commenced 2014)* ***Summary:*** This project aims to provide new insights into the origin of life on Earth, life's diversification through the Precambrian, and the co-evolution of life and early Earth environments. It will be discipline-leading in that it will take the study of early life to the sub-micrometre and hence sub-cellular level. This will facilitate new opportunities for identifying the types of life present during early Earth history, their metabolisms, cellular chemistry and interactions with their environment. This project aims to also provide new search engines and more robust assessment criteria for life on other planets, and help to resolve specific scientific controversies, for example, the validity of claims for cellular life from 3.5 billion-year-old rocks.
Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	**X.C. Wang**: *Supported by ARC Future Fellowship and MQ (commenced 2014)* ***Summary:*** This project aims to test a provocative and potentially ground-breaking hypothesis that fluid released from subducted oceanic slabs and stored in the mantle transition zone, may trigger or control some major intra-plate geotectonic phenomena. It aims to provide a self-consistent model that links geological processes occurring at plate boundaries with those far-field effects well away from plate boundaries via deep-Earth fluid cycling. The outcomes of this project aim to help to better understand links between plume and plate tectonic processes in the first-order dynamic system of Earth, and identify ways to improve success in future mineral exploration.
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.
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.
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.

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.
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.
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.
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.
A new approach to revealing melting processes in the hidden deep Earth	**A. Giuliani**: *Supported by ARC DECRA (commencing 2015)* ***Summary:*** Kimberlite magmas are very rich in volatiles (for example carbon dioxide and water); they are the major host of diamonds and provide the deepest samples from Earth's mantle. The primary compositions of these melts can provide unique information on the nature of the deep mantle. However, kimberlite melts mix and react with wall rocks on the way up, obscuring their primary composition. To see through these secondary processes, the project aims to use a novel approach integrating the study of melt inclusions in magmatic minerals with analysis of radiogenic and stable isotopes, and investigating reactions between kimberlite magmas and wall-rock fragments. The project aims to provide new understanding of the constraints on melting processes and recycling of crustal material in the deep mantle.
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.

Laser ablation multiple split streaming	A. Kemp, M. McCulloch, **M. Fiorentini**, **T. McCuaig**, A. Rate, **C. Clark**, B. Rasmussen, N. Evans, **S. Reddy**, P. Bland, T. Raimondo, **N. Pearson**, **E. Belousova**, **D. Jacob**, D. Rubatto, C. Spandler, S. Barnes: *Supported by ARC LIEF (commencing 2015)* ***Summary:*** This geochemical facility with an innovative, world-leading micro-analytical capability intends to support research of fundamental and strategic problems at the frontiers of the Earth and Environmental Sciences. The facility aims to allow new insight into the age, composition, thermal history and structure of the Australian continent, as necessary for delineating mineral endowment and for tracing the sources of ore metals. It will provide a higher resolution record of climate and environmental change which will better inform assessment of the impacts, both locally and regionally. It is intended that the facility will amplify national and international scientific collaboration and create unique research opportunities for Australian-based scientists.
A fully automated, fully shielded palaeomagnetic system	**Z.X. Li**, E. Tohver, A. Roberts, G. Rosenbaum, **C. O'Neill**, **S. Pisarevsky**, **C. Clark**, C. Elders, P. Bland, **S. Wilde**: *Supported by ARC LIEF (commencing 2015)* ***Summary:*** This project aims to establish the first fully automated and magnetically fully shielded superconducting palaeomagnetic data acquisition system in Australia. Palaeomagnetism is a key research field that has applications to a broad range of pure and applied geoscience disciplines. Australia has been a world leader in this field, including the application of palaeomagnetism to both global and regional tectonic studies. Palaeomagnetic studies demand a labour-intensive process of treating and measuring a large number of samples. The system will significantly enhance the efficiency and accuracy of palaeomagnetic analysis, and thus enhance Australia's research capacity in this and related research fields.
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 (commenced 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.
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 (commenced 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.

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.
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.
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 will 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

Chief Investigators

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Professor Simon Wilde (Node Director, CU)
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Professor Stephen Foley (MQ)
Professor William Griffin (MQ)
Professor Matthew Kilburn (CMCA, UWA)
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Dr Craig O'Neill (MQ)
Associate Professor Norman Pearson (MQ)
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Professor Simon George (MQ)
Dr Richard Glen (NSW Geological Survey)
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Associate Professor Dorrit Jacob (MQ)
Dr Christopher Kirkland (GSWA)
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Associate Professor Sandra Piazolo (MQ)
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Associate Professor Tracy Rushmer (MQ)
Dr Bruce Schaefer (MQ)
Professor Paul Smith (MQ)
Professor Simon Turner (MQ)
Dr Michael Wingate (GSWA)
Dr Yingjie Yang (MQ) - *CI from 2015*
Professor Shijie Zhong (University of Colorado at Boulder, USA)

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Professor Michael Brown (University of Maryland, USA)
Dr Klaus Gessner (Geological Survey of Western Australia)
Professor David Mainprice (Université de Montpellier, France)
Professor Catherine McCammon (Bayreuth University, Germany)
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ECSTARs (ARC Early Career Start-up Award for Researchers)

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Ms Sally-Ann Hodgekiss, Business & Development Officer (MQ)
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Ms Anne Micallef, Centre Administrator (MQ)
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Dr Marion Grange (CU)	Dr Laure Martin (UWA)	Dr Zoja Vikmanovic (CU)
Dr Yoann Gréau (MQ)	Dr Ruth Merdie (GSWA)	Dr David Wacey (UWA)
Dr Heather Handley (MQ)	Dr David Mole (CU)	Dr Weihua Yao (CU)
Dr Daniel Howell (MQ)	Dr Lev Natapov (MQ)	Dr Huaiyu Yuan (MQ)
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Dr Mike Etheridge	Dr Jon Hronsky	Dr John Vann
Professor Jim Everett	Dr Louisa Lawrance	Mr Peter Kym Williams
Dr Richard Glen	Dr David Leach	Dr Peter Williams
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Dr Debora Araujo	Dr Michel Grégoire	Dr Yvette Poudjom Djomani
Dr Jaques Batumike Mwandulo	Dr Jeff Harris	Dr Peter Robinson
Dr Graham Begg	Dr Daniel Howell	Dr Simon Shee
Dr Christoph Beier	Dr Bram Janse	Mr Huayun Tang
Dr Phillip L. Blevin	Dr Felix Kaminsky	Ms Nancy van Wagoner
Dr Christoph Beier	Dr Hans-Rudolf Kuhn	Dr Kuo-Lung Wang
Professor Hannes Brueckner	Mr Qingyong Luo	Professor Xiang Wang
Dr Mei-Fe Chu	Dr Viktor Makhlin	Dr Jin-Hui Yang
Dr Beverly Coldwell	Dr Kreshimir Malitch	Dr Chunmei Yu
Professor Massimo Coltorti	Dr Vlad Malkovets	Professor Jin-Hai Yu
Professor Kent Condie	Dr Claudio Marchesi	Dr Ming Zhang

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Mr David Child (MQ)	Ms Margaux Le Vaillant (UWA)	Mr David Stevenson (UWA)
Mr David Clark (MQ)	Mr Erwann Lebrun (UWA)	Ms Catherine Stuart (MQ)
Mr Bruno Colas (MQ)	Mr Ben Li (UWA)	Mr Rajat Taneja (MQ)
Mr Stephen Craven (MQ)	Mr Yingchao Liu (CU)	Ms Ni Tao (CU)
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Mr Raphael Doutre (UWA)	Ms Jianggu Lu (MQ)	Mr Mehdi Tork Qashqai (MQ)
Ms Eileen Dunkley (MQ)	Mr Volodymyr Lysytsyn (UWA)	Ms Irina Tretiakova (MQ)
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Mr Denis Fougourouse (UWA)	Mr Samuel Matthews (MQ)	Mr Yu Wang (MQ)
Ms Yuya Gao (MQ)	Ms Nicole McGowan (MQ)	Mr James Warren (UWA)
Ms Robyn Gardner (MQ)	Ms Vicky Meier (CU)	Mr Jonathon Wasiliev (MQ)
Mr Rongfeng Ge (CU)	Ms Aileen Mirasol-Robert (UWA)	Mr Jun Xie (MQ)
Mr Christopher Gonzalez (UWA)	Ms Rosanna Murphy (MQ)	Mr Qing Xiong (MQ)
Ms Louise Goode (MQ)	Mr Jiawen Niu (CU)	Mr Bo Xu (MQ)
Ms Erin Grey (CU)	Mr Beñat Oliveira Bravo (MQ)	Ms Weihua Yao (CU)
Mr Christopher Grose (MQ)	Mr Chongjin Pang (CU)	Miss Yao Yu (MQ)
Mr Matthew Hill (UWA)	Mr Luis Parra Avila (UWA)	Mr Kongyang Zhu (CU)
Ms Linda Iaccheri (UWA)	Mr Shahid Ramzan (MQ)	
Ms Carissa Isaac (UWA)	Mr Farshad Salajegheh (MQ)	

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Mr Cameron Piper (MQ)	Ms Josephine Moore (MQ)	Mr Antoine Neaud (UWA)
Mr Alastair Williams (MQ)	Ms Celia Guergouz (UWA)	Ms Tara Djokic (UNSW)
Anthony Lanati (MQ)	Ms Anne Johannesen (UWA/GEUS)	

Appendix 5: 2014 Publications

A FULL LIST OF CCFS PUBLICATIONS IS UPDATED AT: http://www.ccfs.mq.edu.au/

193. **Yao, W.-H.**, **Li, Z.-X.**, Li, W.-X., **Wang, X.-C.**, Li, X.-H. and Yang, J.-H. 2014. Corrigendum to "Post-kinematic lithospheric delamination of the Wuyi-Yunkai orogen in South China: Evidence from ca. 435 Ma high-Mg basalts". *Lithos, 208, 484-485.*

205. Shaw, S.E., Todd, V.R., Kimbrough, D.L. and **Pearson, N.J.** 2014. A west-to-east geologic transect across the Peninsular Ranges batholith, San Diego County, California: Zircon $^{176}Hf/^{177}Hf$ evidence for the mixing of crustal and mantle-derived magmas, and comparisons with the Sierra Nevada batholith. *Peninsular Ranges Batholith, Baja California and Southern California, Geological Society of America, GSA Memoir 211, 499-536.*

236. **Griffin, W.L.**, **Pearson, N.J.**, Andersen, T., Jackson, S.E., **O'Reilly, S.Y.** and Zhang, M. 2014. Sources of cratonic metasomatic fluids: *In situ* LA-MC-ICPMS analysis of Sr, Nd, Hf and Pb isotopes in LIMA from the Jagersfontein kimberlite. *American Journal of Science, 314, 435-461.*

244. **Bagas, L.**, Boucher, R., **Li, B.**, Miller, J., Hill, P., Depauw, G., Pascoe, J. and Eggers, B. 2014. Paleoproterozoic stratigraphy and gold mineralisation in the Granites-Tanami Orogen, North Australian Craton. *Australian Journal of Earth Sciences, 61, 89-111.*

246. Jiang, S.H., Liang, Q.-L. and **Bagas, L.** 2014. Re-Os ages for molybdenum mineralization in the Fengning region of northern Hebei Province, China: new constraints to the timing of mineralization and geodynamic settings. *Journal of Asian Earth Sciences, 79, 873-883.*

249. **Le Vaillant, M.**, Barnes, S.J., Fisher, L., **Fiorentini, M.L.** and Caruso, S. 2014. Use and calibration of portable X-Ray fluorescence analysers: Application to lithogeochemical exploration for komatiite-hosted nickel sulphide deposits. *Geochemistry: Exploration, Environment, Analysis, 14, 199-209.*

252. **Van Kranendonk, M.J.** 2014. Ch 12: Earth's early atmosphere and environments: A review. *Geological Society of America Special Paper 504, 105-130.*

280. Kröner, A., Kovach V., **Belousova, E.**, Hegner, E., Armstrong, R., Dolgopolova, A., Seltmann, R., Alexeiev, D.V., Hoffmann, J.E., Wong, J., Sun, M., Cai, K., Wang, T., Tong, Y., **Wilde, S.A.**, Degtyarev, K.E. and Rytsk, E. 2014. Reassessment of continental growth during the accretionary history of the Central Asian Orogenic Belt. *Gondwana Research, 25, 103-125.*

309. **Pisarevsky, S.A.**, Elming, S.-A., Pesonen, L.J. and **Li, Z.-X.** 2014. Mesoproterozoic paleogeography: Supercontinent and beyond. *Precambrian Research, 244, 207-225.*

323. **Piazolo, S.** and Jaconneli, P. 2014. Sillimanite deformation mechanisms within a Grt-Sill-Bt gneiss: Effect of pre-deformation grain orientations and characteristics on mechanism, slip system activation and rheology. *Geological Society of London Special Publication, 394, 189-213.*

326. Jones, A.G., **Afonso, J.C.**, Fullea, J. and Salajegheh, F. 2014. The lithosphere-asthenosphere system beneath Ireland from integrated geophysical-petrological modeling I: Observations, 1D and 2D hypothesis testing and modeling. *Lithos, 189, 28-48.*

327. Fullea, J., Muller, M.R., Jones, A.G. and **Afonso, J.C.** 2014. The lithosphere-asthenosphere system beneath Ireland from integrated geophysical-petrological modeling II: 3D thermal and compositional structure. *Lithos, 189, 49-64.*

334. **González-Jiménez, J.M.**, **Griffin, W.L.**, Gervilla, F., Proenza, J.A., **O'Reilly, S.Y.** and **Pearson, N.J.** 2014. Chromitites in ophiolites: how, where, when, why? Part I. A review and new ideas on the origin and significance of platinum-group minerals. *Lithos, 189, 127-139.*

338. Li, J., Jiang, X.Y., Xu, J.F., Zhong, L.F., **Wang, X.-C.**, Wang, G.Q. and Zhao, P.P. 2014. Determination of Platinum-Group Elements and Re-Os Isotopes using ID-ICP-MS and N-TIMS from a Single Digestion after Two-Stage Column Separation. *Geostandards and Geoanalytical Research, 38, 37-50.*

341. Borthwick, V.E., **Piazolo, S.**, Evans, L., Griera, A. and Bons, P.D. 2014. What happens to deformed rocks after deformation? A refined model for recovery based on numerical simulations. *Geological Society of London Special Publications, 394, 215-234.*

343. Dan, W., Li, X.H., Wang, Q., **Wang, X.-C.** and Liu, Y. 2014. Neoproterozoic S-type granites in the Alxa Block, westernmost North China and tectonic implications: *In situ* zircon U-Pb-Hf-O isotopic and geochemical constraints. *American Journal of Science, 314, 110-153.*

344. **Griffin, W.L.**, **Belousova, E.A.**, **O'Neill, C.**, **O'Reilly, S.Y.**, Malkovets, V., **Pearson, N.J.**, Spetsius, S.A. and **Wilde, S.A.** 2014. The World Turns Over: Hadean - Archean crust-mantle evolution. *Lithos, 189, 2-15.*

345. Elming, S.-A, **Pisarevsky, S.A.**, Layer, P. and Bylund, G. 2014. A palaeomagnetic and $^{40}Ar/^{39}Ar$ study of mafic dykes in southern Sweden: A new Early Neoproterozoic key-pole for the Baltic Shield and implications for Sveconorwegian and Grenville loops. *Precambrian Research, 244, 192-206.*

347. Li, J., **Wang, X.C.**, Ren, Z.Y., Xu., J.F., He, B. and Xu, Y.G. 2014. Chemical heterogeneity of the Emeishan mantle plume: evidence from highly siderophile element abundances in picrites. *Journal of Asian Earth Sciences, 79, 191-205A.*

349. **González-Jiménez, J.M.**, **Griffin, W.L.**, Proenza, J.A., Gervilla, F., **O'Reilly, S.Y.**, Akbulut, M., **Pearson, N.J.** and Arai, S. 2014. Chromitites in ophiolites: How, where, when, why? Part II. The crystallization of chromitites. *Lithos, 189, 140-158.*

351. Zaccarini, F., Garuti, G., **Fiorentini, M.L.**, **Locmelis, M.**, Kollegger, P. and Thalhammer, O.A.R. 2014. Mineralogical hosts of platinum group elements (PGE) and rhenium in the magmatic Ni-Fe-Cu sulfide deposits of the Ivrea Verbano Zone (Italy): An electron microprobe study. *Journal of Mineralogy and Geochemistry, 191/2, 169-187.*

355. Zibra, I., **Gessner, K.**, Smithies, R.H. and Peternell, M. 2014. On shearing, magmatism and regional deformation in Neoarchean granite-greenstone systems: insights from the Yilgarn Craton. *Journal of Structural Geology, 67, 253-267.*

357. **Clark, C.**, **Kirkland, C.L.**, Spaggiari, C.V., Oorschota, C., **Wingate, M.T.D**. and Taylor, R.J. 2014. Proterozoic granulite formation driven by mafic magmatism: An example from the Fraser Range Metamorphics, Western Australia. *Precambrian Research, 240, 1-21.*

358. Li, X.-Y., Zheng, J.-P., Ma, Q., **Xiong, Q.**, **Griffin, W.L.** and Lu, J.-G. 2014. From enriched to depleted mantle: Evidence from Cretaceous lamprophyres and Paleogene basaltic rocks in eastern and central Guangxi Province, western Cathaysia block of South China. *Lithos, 184-187, 300-313.*

359. Karmalkar, N.R, Duraiswami, R.A., Mallika, K., Jonnalagadda, M.K. and **Griffin, W.L.** 2014. Mid-Cretaceous Lamproite from the Kutch region, Gujarat, India: Tectonic implications. *Gondwana Research, 26, 942-956.*

362. **Huang, J.-X.**, **Griffin, W.L.**, **Gréau, Y.**, **Pearson, N.J.**, **O'Reilly, S.Y.**, **Cliff, J.** and **Martin, L.** 2014. Unmasking xenolithic eclogites: progressive metasomatism of a key Roberts Victor sample. *Chemical Geology, 364, 56-65.*

363. **Zhu, K.-Y.**, **Li, Z.-X.**, **Xu, X.-S.** and **Wilde, S.A.** 2014. A Mesozoic Andean-type orogenic cycle in southeastern China as recorded by granitoid evolution. *American Journal of Science, 314, 187-234.*

364. Godinho, J., **Piazolo, S.** and Balic-Zunic, T. 2014. Importance of surface structure on dissolution of fluorite: implications for surface dynamics and dissolution rates. *Geochimica et Cosmochimica Acta, 126, 398-410.*

366. **Yao, W.-H.**, **Li, Z.-X.**, Li, W.-X., Li, X.-H. and Yang, J.-H. 2014. From Rodinia to Gondwanaland: A tale of detrital zircon provenance analyses from the Southern Nanhua Basin, South China. *American Journal of Science, 314, 278-313.*

369. Li, J., Liang, X.-R., Zhong, L.-F., **Wang, X.-C.**, Ren, Z.-Y., Sun, S.-L., Zhang, Z.-F. and Xu, J.-F. 2014. Measurement of the Isotopic Composition of Molybdenum in Geological Samples by MC-ICP-MS using a Novel Chromatographic Extraction Technique. *Geostandards and Geoanalytical Research, 38, 345-354.*

371. **Wang, X.C.**, **Li, Z.X.**, Li, J., **Pisarevsky, S.A.** and **Wingate, M.T.D.** 2014. Genesis of the 1.21 Ga Marnda Moorn large igneous province by plume-lithosphere interaction. *Precambrian Research, 241, 85-103.*

372. Mikhail, S., Verchovsky, A.B., **Howell, D.**, Hutchison, M.T., Southworth, R., Thomson, A.R., Warburton, P., Jones, A.P. and Milledge, H.J. 2014. Constraining the internal variability of the stable isotopes of carbon and nitrogen within mantle diamonds. *Chemical Geology, 366, 14-23.*

373. **Vukmanovic, Z.**, **Reddy, S.M.**, Godel, B., Barnes, S.J., **Fiorentini, M.L.**, Barnes, S.-J. and **Kilburn, M.R.** 2014. Relationship between microstructures and grain-scale trace element distribution in komatiite-hosted magmatic sulphide ores. *Lithos, 184-187, 42-61.*

375. Tetley, M.G. and **Daczko, N.R.** 2014. Virtual Petrographic Microscope: A multi-platform education and research software tool to analyse rock thin sections. *Australian Journal of Earth Sciences, 61, 631-637.*

376. Godinho, J.R.A., Putnis, C.V. and **Piazolo, S.** 2014. Direct Observations of the Dissolution of Fluorite Surfaces with Different Orientations. *Crystal Growth and Design, 14, 69-77.*

377. **Murphy, M.J.**, Stirling, C.H., Kaltenbach, A., **Turner, S.P.** and **Schaefer, B.F.** 2014. Fractionation of $^{238}U/^{235}U$ by reduction during low temperature uranium mineralisation processes. *Earth and Planetary Science Letters, 388, 306-317.*

378. **Wacey, D.**, McLoughlin, N., Saunders, M. and Kong, C. 2014. The nano-scale anatomy of a complex carbon-lined microtube in volcanic glass from the ~92 Ma Troodos Ophiolite, Cyprus. *Chemical Geology, 363, 1-12.*

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Appendix 6: 2014 Abstract titles

A FULL LIST OF CCFS ABSTRACTS FOR CONFERENCE PRESENTATIONS IS AVAILABLE AT: http://www.ccfs.mq.edu.au/

UHNAI-Nordic Winter School "Water and the Evolution of Life in the Universe", Hawaii, 1-14 January 2014	Diverse life in a volcanic-hydrothermal environment at the c. 3.5 Ga North Pole Dome, Pilbara Craton, Western Australia **T. Djokic** and **M.J. Van Kranendonk**
IGG-CAS 2014 Annual Meeting,16-17 January 2014	Seismic images of craton margins and adjacent orogens and tectonic implications **H. Yuan** **Invited** Upper mantle structure of Northeastern North America using full waveform inversion **H. Yuan**
Biennial Meeting of the Specialist Group in Tectonics and Structural Geology (SGTSG), Thredbo, NSW, Australia, 2-8 February 2014	Tectonic evolution of the Early Mesoproterozoic Mount Painter Province, South Australia **R. Armit**, P. Betts, **B. Schaefer**, M. Pankhurst and D. Giles Pump up the Volume… and the Grade: Fault valving behaviour and the development of Au-Cu mineralisation in the Telfer resource, Paterson Orogen, WA G. Batt, J. Miller and **C. McCuaig** Magma dynamics and metamorphic reaction history of lower-crustal plutons, Western Fiordland Orthogneiss, NZ T. Chapman, G. Clarke, **N. Daczko** and **S. Piazolo** The influence of phase distribution and grain size on the localization of strain in polyphase rocks **D. Czaplinska** and **S. Piazolo** Rheological contrast controlling the development of paired shear zones, Fiordland, New Zealand **N. Daczko**, J. Smith, **S. Piazolo** and L. Evans A crustal section through Archean gneiss dome-greenstone architecture: example from the Southern Cross Domain, Yilgarn Craton M. Doublier, **N. Thébaud**, **K. Gessner**, **M. Wingate**, **D. Mole**, S. Romano and **C. Kirkland** The effect of viscosity on the formation of boudins: comparison of simulation results with field data from Fiordland, New Zealand **R. Gardner** Interpretation of magnetic and gravity data along seismic reflection surveys in the Southern Carnarvon Basin and Northwest Yilgarn Craton, Western Australia **K. Gessner**, T. Jones, J. Goodwin, L. Gallardo, P. Milligan, J. Brett and R. Murdie The opening of the South China Sea: was it driven by Pacific subduction or by India-Eurasia collision? **Z.-X. Li** A Neoproterozoic big twist within Australia: Rodinia, snowball Earth, and mineral deposits **Z.-X. Li** and D. Evans Deformation in an Open System: Fluid assisted brittle-viscous deformation coupled with volume change in a greenschist facies shear zone (Wyangala, Australia) **L. Spruzeniece**, **S. Piazolo** and **N. Daczko** How does melt move through the lower crust? New insight from diffuse porous melt flow resulting in metasomatism and hydration of a two-pyroxene-hornblende granite **C. Stuart**, **S. Piazolo** and **N. Daczko**
Workshop on Advanced Development on *In Situ* and WR High-Precision Elemental and Isotopic Analyses, Taipei, Taiwan, 10-12 March 2014	Back to basics: quantitative elemental and isotope ratio analysis by laser ablation ICP-MS **N. Pearson** **Keynote**

45th Lunar and Planetary Science Conference, The Woodlands, TX, USA, 17-21 March 2014	A unique differentiation history of Mars preserved in Martian meteorite NWA7533 J.J. Bellucci, **A.A. Nemchin**, and M.J. Whitehouse Delayed onset of plate tectonics on Earth and implications for the Martian mantle V. Debaille, **C. O'Neill**, A.D. Brandon, P. Haenecour, Q.-Z. Yin, N. Mattielli and A.H. Treiman Oxygen isotope compositions and Ti and REE concentrations of zircon from Martian meteorite NWA 7533 **A.A. Nemchin**, M. Humayun, M.J. Whitehouse, R.H. Hewins, J.-P. Lorand, A. Kennedy, **M.L. Grange**, B. Zanda, C. Fieni, S. Pont and D. Deldicque
UNCOVER Summit 2014 Adelaide Convention Centre, SA, Australia, 31 March - 2 April 2014	*TerraneChron®*: remote sensing with detrital samples **E. Belousova**, **W. Griffin**, **N. Pearson**, **S. O'Reilly** and **Y. Gréau** Archean SCLM: what do we (think we) know? **W.L. Griffin** Isotope geology through space and time: a tool for understanding crustal evolution. Case studies from the Yilgarn Craton and its margin **C.L. Kirkland** **Keynote** Greenfield identification: big picture matters **Z.-X. Li** A national trajectory for geoscience research in Australia and some historical perspectives towards UNCOVER **S.Y. O'Reilly** **Keynote**
European Geosciences Union General Assembly 2014, Vienna, Austria, 27 April - 02 May 2014	Inward stepping intraplate activity: An example from the Capricorn Orogen, Western Australia A. Aitken, S. Johnson, F. Korhonen, M. Dentith, A. Joly, **I. Tyler**, and **T.C. McCuaig** Osmium isotope systematics of Os-rich alloys and Ru-Os sulfides from oceanic mantle: evidence from Proterozoic and Paleozoic ophiolite-type complexes I.Y. Badanina, K.N. Malitch, **E.A. Belousova**, R.A. Lord, T.C. Meisel, V.V. Murzin and **N.J. Pearson** What does the deep crustal structure of the Yilgarn Craton tell us about Mesoarchean Dynamics? **K. Gessner**, **C. Kirkland** and I. Zibra Cross-gradient joint inversion of gravity and aeromagnetic data in mineralized northern Menderes Massif, Turkey **K. Gessner**, L. Gallardo, F. Wedin and K. Sener Cenozoic denudation of the Menderes Massif and its geodynamic framework: slab tear or not? **K. Gessner**, L. Gallardo, V. Markwitz, U. Ring and S.N. Thomson Ancient Pb and Ti mobilization revealed by Scanning Ion Imaging **M.A. Kusiak**, M.J. Whitehouse and **S.A. Wilde** Radiogenic and stable isotope study of the Dyumptaley and Binyuda ultramafic-mafic intrusions and associated Ni-Cu-PGE sulfide ores (Russian Arctic) K. Malich, I. Badanina, **E. Belousova**, **N. Pearson**, A. Romanov and S. Sluzhenikin Is there really carbon in the detrital zircons from Jack Hills, Western Australia? M. Menneken, T. Geisler, **A.A. Nemchin**, K. Pollok, M. Whitehouse, **R. Pidgeon** and **S. Wilde** 3D Fault Network of the Murchison Domain, Yilgarn Craton R. Murdie and **K. Gessner** Long hard road from Nuna to Rodinia **S.A. Pisarevsky** **Invited** New insights into the late Paleozoic evolution of the New England Orogen (eastern Australia) in view of the recent paleomagnetic data **S.A. Pisarevsky**, G. Rosenbaum, U. Shaanan and D. Hoy Experimental studies on TTGs the Nuvvuagittuq Complex, Quebec, Canada: Implications for early crustal recycling and Archaean granitoids **T. Rushmer** and **J. Adam** Three-dimensional crustal structure of a craton rim: Preliminary results from passive seismic imaging of the eastern Albany-Fraser Orogen, Western Australia C. Sippl, H. Tkalcic, B.L.N. Kennett, C.V. Spaggiari and **K. Gessner** Heading down early on? Start of subduction on Earth **S. Turner**, **T. Rushmer**, M. Reagan and J.-F. Moyen

European Geosciences Union General Assembly 2014, Vienna Austria, 27 April - 02 May 2014 cont...	Micro-continents offshore Western Australia: implications for East Gondwana reconstructions J. Whittaker, S. Williams, J. Halpin, **N. Daczko** and **R. Gardner** Integrated exploration platform: An interactive multi-data interpretation tool J.C. Wong, P. Kovesi, E.J. Holden, **K. Gessner** and R. Murdie
International Workshop on: Ophiolites, Mantle Processes and Related Ore Deposits, Beijing, China, 14-15 April 2014	Transition-Zone mineral assemblages in peridotite massifs, Tibet: Implications for collision-zone dynamics and orogenic peridotites **W.L. Griffin** **Invited**
6th Orogenic Lherzolite Conference, Morocco, 4-15 May 2014	Major and trace element geochemistry, origin and timing of sulfide formation in ultramafic xenoliths from the Nógrád-Gömör Volcanic Field (northern Hungary - southern Slovakia) L.E. Aradi, C. Szabó, **J.-M. González-Jiménez**, **S.Y. O'Reilly** and **W.L. Griffin** Transition-Zone mineral assemblages in peridotite massifs, Tibet: Implications for collision-zone dynamics and orogenic peridotites **W.L. Griffin**, **N.M. McGowan**, **D. Howell**, **J.M. Gonzalez-Jimenez**, **E. Belousova**, **J.C. Afonso**, J.S. Yang, R. Shi, **S.Y. O'Reilly** and **N.J. Pearson** Updating metasomatism concepts: Stealth, densification, and geophysical consequences **S.Y. O'Reilly**, **W.L. Griffin** and **N.J. Pearson** Fluid-induced deformation in chromite during metamorphism **T. Satsukawa**, **J.-M. González-Jiménez**, **V. Colás**, **W.L. Griffin**, **S. Piazolo**, **S.Y. O'Reilly**, F. Gervilla and I. Fanlo History of the subcontinental lithospheric mantle beneath the Carpathian-Pannonian region C. Szabó, L.E. Aradi, **J.M. González-Jiménez**, **W.L. Griffin**, **S.Y. O'Reilly** and K. Hattori Diamonds and highly reduced minerals from chromitite of the Ray-Iz ophiolite of the Polar Urals: deep origin of podiform chromitites and ophiolitic diamonds J.S. Yang, F.C. Meng, S.Y. Chen, W.J. Bai, X.Z. Xu, Z.M. Zhang, P. T. Robinson, Y. Dilek, **W.L. Griffin**, A.B. Makeeyev, and N.I. Bryanchaninova Transition between two supercontinents in late Mesoproterozoic: paleomagnetic approach **S.A. Pisarevsky**
Biosignatures Across Space and Time. Joint Meeting - Nordic Network of Astrobiology and the Centre of Geobiology, Bergen, Norway, 20-22 May 2014	Early life on Earth: Possible metabolic pathways in the c. 3.5Ga Dresser Formation, North Pole Dome, Pilbara Craton, Western Australia **T. Djokic** and **M.J. Van Kranendonk**
GAC-MAC Annual Meeting, Fredericton, Canada, 21-23 May 2014	Formation of mantle plumes and superplumes: Driven by subduction? **Z.X. Li**, **S. Zhong** and **X.C. Wang** SS25. Mineral systems: beyond source, transport and trap D. Huston, **C. McCuaig** and R. Blewett
XIX Geological Congress of Argentina, Córdoba, Argentina, 2-6 June 2014	U-Pb age of detrital zircon from Candon Williams, northeast Chubut Province, Patagonia: implication for the provenance of the Chubut Group sedimentary sequences L.E. Navarro, **E. Belousova**, M.V. Guler and R. Astini
Goldschmidt 2014 Conference, Sacramento, USA, 8-13 June 2014	Ediacaran granites in the Tuareg Shield, West Africa: Alkalinity and end-Gondwanan assembly P. Bowden, J.-Y. Cottin, **E. Belousova**, **Y. Gréau**, **W. Griffin**, **S. O'Reilly**, A. Azzouni-Sekkal, N. Remaci-Benouda and F. Bechiri-Benmerzoug Taking fingerprints of metamorphism in chromite using minor and trace elements **V. Colás**, **J.M. González-Jiménez**, I. Fanlo, **W.L. Griffin**, F. Gervilla, **S.Y. O'Reilly**, **N.J. Pearson** and T. Kerestedjian Is there a secular change in supercontinent assemblies? K.C. Condie, **S.A. Pisarevsky** and J. Korenaga

Goldschmidt 2014 Conference, Sacramento, USA, 8-13 June 2014 cont...	Biogeochemical influences on uranium speciation in the Mulga Rock Sedimentary Uranium Ore Deposit, Western Australia S. Cumberland, C. Jaraula, K. Grice, G. Douglas, K. Evans, **C. McCuaig**, L. Schwark, R. Curtain, S. Rubanov, M. de Jonge, D. Howard and J. Moreau New evidence for ~4.45 Ga terrestrial crust from zircon xenocrysts in Ordovician ignimbrite in the North Qinling Orogenic Belt, China C. Diwu, Y. Sun and **S.A. Wilde** Sediment-eclogite fluid exchanges during subduction in the Tavsanli zone, Turkey L. Gauthiez-Putallaz, D. Rubatto, J. Hermann, **L. Martin**, K.F. Fornash and D.L. Whitney PGE remobilisation during metamorphism of chromitites in Central Chile **J.M. González-Jiménez**, F. Barra, M. Reich, E. Hernandez, F. Gervilla, **W.L. Griffin**, **S.Y. O'Reilly** and **N.J. Pearson** Re-Os isotopic constraints on the evolution of Bangong-Nujiang Tethyan oceanic mantle Q.-S. Huang, R.-D. Shi, **W.L. Griffin**, **S.Y. O'Reilly** and D.-L. Liu Radiolytic alteration of biopolymers in the Mulga Rock Uranium Deposit C.M. Jaraula, L. Schwark, X. Moreau, W. Pickel, **L. Bagas** and K. Grice Ru-Os-Ir alloys and Ru-Os sulfides from oceanic mantle: Evidence for robustness of Os-Isotope system K. Malich, I. Badanina, **E. Belousova**, R. Lord, T. Meisel, V. Murzin and **N. Pearson** Tibetan chromitites: Digging in the slab graveyard **N. McGowan**, **W. Griffin**, **J.-M. González-Jiménez**, **E. Belousova**, **J.C. Afonso**, R. Shi, **C. McCammon**, **N. Pearson** and **S.Y. O'Reilly** The Neoarchaean Skjoldungen Orogeny - A continent-continent collision orogeny? T. Næraa, T.F. Kokfelt, **L. Bagas** and K. Thrane Global magmatism and changing tectonics at the Archean-Proterozoic boundary: Insights from O isotopes in zircon J. Payne, K. Barovich, **N. Pearson** and M. Hand Laser ablation of zircon and implications for U-Pb geochronology **N. Pearson**, **W. Powell**, J. Payne, **R. Murphy**, **E. Belousova**, **W. Griffin** and **S. O'Reilly** Organics in orogenic gold systems: Characterisation of organic matter associated with gold (Au) deposits **A. Robert**, H. Grotheer, R. Lockhart, P. Greenwood, **C. McCuaig**, C. Jaraula, K. Grice, **L. Bagas** and L. Schwark 100 Ma magmatism in the Jiamusi Block, NE China: An indication for lithospheric extension driven by Paleo-Pacific roll-back M. Sun, H. Chen and **S. Wilde** Time-Space relationships of ore-related igneous activity: Lishui Basin, middle and lower Yangtze River L. Wang, J. Huang and **W.L. Griffin** Proterozoic Mantle Lithosphere beneath the Khanka Massif in Far East Russia: *In situ* Re-Os Evidence K.-L. Wang, V. Prikhodko, **S.Y. O'Reilly**, **W.L. Griffin**, **N. Pearson**, V. Kovach, Y. Iizuka and Y.-H. Chien Long link of Cathaysia Block of South China with East Gondwana J.-H. Yu, L. Wang, **S.Y. O'Reilly**, **W.L. Griffin** and Q. Liu
Sydney Space Society, Australia, 16 June, 2014	The tectonics of exoplanets **C. O'Neill** **Invited**
AESC Australian Earth Sciences Convention, Sustainable Australia, Newcastle, NSW, Australia, 7-10 July 2014	Accretion of andesitic crust along a high-temperature oceanic detachment fault in the Oman Ophiolite (Bahla Massif) **B. Abily**, G. Ceuleneer, M. Python, M. Grégoire, M. Benoit and D. Baratoux Archean andesites in the East Yilgarn Large Igneous Province, Australia: The case for their origin by plume/crust interaction S. Barnes, **M.J. Van Kranendonk**, **D. Mole** and **C. Isaac** The enigma of crustal zircons in upper mantle rocks: Insights from U-Pb ages, Hf-O-isotopes and trace-element signatures (Tumut Region, SE Australia) **E. Belousova**, **J.M. González Jiménez**, I. Graham, **W.L. Griffin**, **S.Y. O'Reilly** and **N.J. Pearson** Exploration of Miocene biomarkers in cored sedimentary rocks from IODP expedition 317, Canterbury Basin, New Zealand S. Bratenkov and **S.C. George** A Mesoarchean terrane boundary in the Southern Pilbara Craton? A. Coates and **M.V. Kranendonk**

AESC Australian Earth Sciences Convention, Sustainable Australia, Newcastle, NSW, Australia, 7-10 July 2014 cont...

K-Ar dating of fault gouge and slickensides to resolve the precise ages of low-grade basin inversion and coaxial events deforming Proterozoic metasedimentary rocks
H. Cutten, H. Zwingmann, **M. Wingate** and S. Johnson

Geochemistry and source of ash layers in Bering Sea sediment at IODP site 323-U1341
K. Dadd

The rise and fall of life in the ca 3.5Ga Dresser Formation, North Pole Dome, Pilbara Craton, Western Australia
T. Djokic, **M.J. Van Kranendonk** and M.R. Walter

Metal sources and transport mechanisms at crust-mantle boundary conditions: new search space for deep-seated magmatic mineral systems
M.L. Fiorentini, **M. Locmelis**, **T. Rushmer**, **J. Adam** and **S. Turner** **Keynote**

Subduction refertilisation of orogenic lithosphere detected by trace elements in olivine
S.F. Foley, D. Prelevic and **D.E. Jacob**

Using synchrotron X-ray microtomography to image structure and porosity in sheared Neoarchean granite, Yilgarn Craton, Western Australia
K. Gessner, I. Zibra, J. Liu, M. Paesold, V. Toy, X. Xiao, K. Regenauer-Lieb and L. Menegon

Innovation in Australian geochronology and thermochronology
A. Gleadow, B. McInnes and **N. Pearson** **Keynote**

Diamond fluids at work - nanoscale insights from polycrystalline diamond aggregates
W.L. Griffin, **D.E. Jacob**, **D. Howell**, **S. Piazolo**, **M. Kilburn** and R. Wirth

Zircon U-Pb-Hf-O isotope evidence suggests that Mesoarchean crust formation dominated early growth of the North Australian Craton
J.A Hollis, J.A Whelan, L.M. Glass, C.J. Carson, N. Kositcin, R.A. Armstrong, G.M. Yaxley, J.D. Woodhead and **J. Cliff**

Basin formation by orogenic collapse: zircon U-Pb-Hf isotope evidence from the Kimberley and Speewah Groups, Northern Australia
J.A Hollis, A.I Kemp, **I.M Tyler**, **C.L. Kirkland**, **M.T.D Wingate**, C. Phillips, S. Sheppard, **E. Belousova** and **Y. Gréau**

Rapid advance from hydrous to biotite-dehydration melting of a metasedimentary source in the formation of the Jiufeng Pluton, Southern China: A result of basaltic underplating during slab foundering?
H.-Q. Huang, X.-H. Li, **Z.-X. Li** and W.-X. Li

Geochemical characterisation of granitic rocks in the Granites-Tanami Orogen
L.M Iaccheri and **L. Bagas**

3D crustal structure in North Tibet from ambient noise tomography: Implications for the growth of the Tibetan Plateau
C. Jiang, **Y. Yang** and Y. Zheng

Growing ancient Australia: Hafnium and neodymium isotope constraints from the Yilgarn and Pilbara Cratons
A. Kemp, J. Vervoort, A. Hickman, H. Smithies, S. Wyche, **M.T.D. Wingate** and **C. Kirkland**

What does the deep crustal structure of the Yilgarn Craton tell us about Mesoarchean geodynamics?
K. Gessner, **C. Kirkland** and I. Zibra

Geochronology and lithostratigraphy of a major Birimian sedimentary basin: insight into the tectonostratigraphic evolution and gold mineralisation controls of the Siguiri Basin, Guinea (West Africa)
E. Lebrun, **N. Thébaud**, J. Miller and **T.C. McCuaig**

Zircon multi-isotopic mapping - a potentially robust pathfinder to large-scale targeting for gold mineral systems
Y.-J. Lu, **T.C. McCuaig**, A.I.S. Kemp, **K. Bjorkman**, **J. Cliff** and P. Hollings

Tectono-stratigraphic evolution of the Sadiola Gold Camp, Mali, West Africa: Defining the framework of a world-class gold province
Q. Masurel, **N. Thébaud**, J. Miller and **T.C. McCuaig**

Tracking of CO_2 geosequestration using downhole gravity gradiometry, Otway Basin, Vic
S. Matthews, **C. O'Neill**, **M. Lackie** and N. Fraser

Paleoproterozoic sedimentation and contemporary basin tectonics in the Lower Wyloo Group, Western Australia
R. Mazumder and **M.J. Van Kranendonk**

Tibetan chromitites: to the transition zone and back?
N. McGowan, **W. Griffin**, **J.-M. González-Jiménez**, **E. Belousova**, **J.C. Afonso**, **N. Pearson**, **S. O'Reilly**, **C. McCammon** and R. Shi

Organic matter in orogenic gold (Au) systems
A. Mirasol-Robert, C. Jaraula, **C. McCuaig**, **L. Bagas**, H. Grotheer, P. Greenwood, L. Schwark and K. Grice

AESC Australian Earth Sciences Convention, Sustainable Australia, Newcastle, NSW, Australia, 7-10 July 2014
cont...

Is there a window for plate tectonics in terrestrial planet evolution?
C. O'Neill, A. Lenardic, **S. Zhang** and **J. Wasiliev**

Was the early Earth stagnant?
C. O'Neill and V. Debaille **Invited**

Modelling planetary interiors in aspect: Viscosity, volatiles and varying mass
C. O'Neill, **S. Zhang** and **J. Wasiliev**

Archean lithospheric mantle: The fount of all ores?
S.Y. O'Reilly, **W.L. Griffin**, G. Begg, **N.J. Pearson** and J.M.A. Hronsky

Changes in global magmatism and the limitations of Hf-O isotope data in zircon
J. Payne, **N.J. Pearson**, K.M. Barovich and M. Hand

Building national infrastructure using *TerraneChron®* and lithosphere mapping
N.J. Pearson, **S.Y. O'Reilly**, **W.L. Griffin**, **E. Belousova** and **G. Begg**

Filling the gap: The tectonic significance of the Ayr Conglomerate in the New England Orogen
B. Phu and **M.J. Van Kranendonk**

Towards a better understanding of the rheology of seprentine bearing rocks in subducting slabs
S. Ramzan, **T. Rushmer**, **S. Piazolo** and **C. O'Neill**

How to make subduction zones weak: Understanding the rheology of serpentine in subducting slabs
S. Ramzan, **T. Rushmer**, **S. Piazolo** and **C. O'Neill**

3D crustal architecture of the East Albany-Fraser Orogen in Western Australia from passive seismic data
C. Sippl, H. Tkalčić, B.L.N. Kennett, C.V. Spaggiari and **K. Gessner**

Tectonic links between Proterozoic sedimentary cycles, basin formation and magmatism in the Albany- Fraser Orogen, Western Australia
C.V. Spaggiari, **C.L. Kirkland**, H. Smithies, **M.T.D. Wingate** and **I.M Tyler**

How deformation affects reaction rates: new insights from phase transformation experiments in the KBR-KCL-H_2O system
L. Spruzeniece, **S. Piazolo** and S. Joyce

The Granites-Tanami Orogen subsurface geometry as revealed by an integrated potential field geophysical and geological study
D. Stevenson, **L. Bagas** and A. Aitken

How melt moves through the crust: evidence for reactive diffuse porous melt flow under static conditions in the hot lower continental crust
C. Stuart, **S. Piazolo** and **N. Daczko**

Formation and alteration history of detrital chromites from Jack Hills sediments, Western Australia
S. Tessalina, I. Puchtel, **W. Griffin**, **A. Nemchin** and V. Kamenetsky

How mantle heterogeneities control supra-subduction metasomatism: constraints from the Cabo Ortegal Complex, Spain
R. Tilhac, **S.Y. O'Reilly**, **W.L. Griffin**, **N.J. Pearson**, M. Grégoire, D. Guillaume and G. Ceuleneer

Zircons from Yakutian kimberlites reveal Archean crust under the Eastern Siberian Craton
I. Tretiakova, **E. Belousova**, V. Malkovets and **W.L. Griffin**

An event horizon in the Sydney Basin: Passage of a forebulge?
M.J. Van Kranendonk, D. Flannery and R. Mazumder

A thriving Proterozoic biosphere at the rise of atmospheric oxygen: Evidence from the c. 2.3 Ga Turee Creek Group, Western Australia
M.J. Van Kranendonk, E. Barlow, M.R. Walter and J.W. Schopf

Formation of horizontally layered Archean crust: examples from the Pilbara, Kaapvaal, and Yilgarn Cratons
M.J. Van Kranendonk **Keynote**

Lawsonite acts as a trace element sponge in subduction zones of the Alpine-Himalayan Orogenic Belt: Evidence from Tavşanlı Blueschist (Turkey)
Y. Wang, D. Prelević and **S. Foley**

Sulfur dioxide degassing during Archean komatiite volcanism
B. Wing, **C. Isaac**, E. Griffiths and **M. Fiorentini**

The evolution of early Mars: Does mobile-lid exist in its early age?
S. Zhang and **C. O'Neill**

XXXIV Reunión de la Sociedad Española de Mineralogía, Granada, 2 July 2014	Inherited mantle and crustal zircons in mantle chromitites (E Cuba): Implications for the evolution of oceanic lithosphere J.A. Proenza, **J.M. González-Jiménez**, A. García-Casco, **E. Belousova**, **W.L Griffin**, F. Gervilla, Y. Rojas- Agramonte, D. Navarro-Ciruana, **S.Y. O'Reilly**, C. Talavera and **D. Jacob**
Gondwana 15, Madrid, Spain, 14-18 July 2014	What drives the formation of mantle plumes and superplumes? **Z.X. Li**, **S. Zhong** and **X.C. Wang** New paleomagnetic data from the Late Paleozoic New England Orogen (East Australia) and developed kinematic model of its evolution **S.A. Pisarevsky**, G. Rosenbaum, U. Shaanan and D. Hoy Post-collisional Early Ordovician magmatism in the Central Iberian Zone: evidence from zircon Hf isotopes in metagranitic orthogneisses from the Spanish Central System C. Villaseca, E. Merino Martínez, D. Orejana, T. Andersen and **E. Belousova** The collision of South China with NW India to join Gondwanaland in the Cambrian: results of foreland basin sedimentology and provenance analyses W. Yao, **Z.X. Li**, W.X. Li, X.H. Li and J.H. Yang
AOGS 11th Annual Meeting, Royton Sapporo Hotel, Japan, 28 July - 1 August, 2014	The 3D crustal structure in north Tibet revealed by ambient noise tomography: implications for the growth of the Tibetan Plateau **Y. Yang**, C. Jiang and Y. Zheng Application of long period surface waves from ambient noise in regional surface wave tomography: Verification and a case study in W. USA **Y. Yang**
Australian Institute of Geoscientists Minerals Systems Workshop, Perth, 11 August 2014	The mineral system concept: the key to exploration targeting **T.C. McCuaig** and J.M.A. Hronsky
12th International Platinum Symposium, Yekaterinburg, Urals, Russia, 11-14 August 2014	Mineral chemistry and isotopic composition of ophiolitic Os-rich alloys and Ru-Os sulfides: Synthesis of new data I.Y. Badanina, K.N. Malitch, R.A. Lord, **E.A. Belousova**, **W.L. Griffin**, T.C. Meisel, V.V. Murzin, **N.J. Pearson** and **S.Y. O'Reilly** Insights into ore genesis of zoned Uralian-type massifs using Osmium isotopes: Evidence from laurite and Os-rich alloys from the Nizhniy Tagil Massif, Middle Urals, Russia I.Y. Badanina, K.N. Malitch, **E.A. Belousova** and V.V. Khiller Crust-mantle interaction in the Tumut region of the Lachlan Fold Belt, southeastern Australia: A synthesis of new isotopic information (Re-Os, U-Pb, Lu-Hf and O) **E. Belousova**, **J.M. Gonzáles-Jiménez**, I. Graham, **W.L. Griffin**, **S.Y. O'Reilly**, and **N.J. Pearson** Tranzition-zone mineral assemblages in '*ophiolitic*' chromitites: implications for collision-zone dynamics and orogenic peridotites **W.L. Griffin**, **N.M. McGowan**, **J.M. Gonzalez-Jimenez**, **E.A. Belousova**, **D. Howell**, **J.C. Afonso**, J.S. Yang, R. Shi, **S.Y. O'Reilly** and **N.J. Pearson** Platinum group minerals in ophiolitic chromitites of Timor Lester A. Lay, I. Graham, D. Cohen, J.M. Gonzáles-Jiménez, K. Privat, **E. Belousova** and S.-J. Barnes Closed-system behaviour of the Re-Os isotope system in primary and secondary PGM assemblages: Evidence from the Nurali Ultramafic Complex (Southern Urals, Russia) K.N. Malitch, E.V. Anikina, I.Yu Badanina, **E.A. Belousova**, **W.L. Griffin**, V.V. Khiller, **N.J. Pearson**, E.V. Pushkarev and **S.Y. O'Reilly** Nd-Sr-Hf-S-Cu isotope systematics of ore-bearing ultramafic-mafic intrusions from Polar Siberia (Russia): Genetic constraints and implications for exploration K.N. Malitch, I.Y. Badanina, **E.A. Belousova**, **W.L. Griffin**, R.M. Latypov, A.P. Romanov and S.F. Sluzhenikin Source of platinum-group minerals (PGM) from pyrope-garnet rich placer deposit, Bohemian Massif: Results from mineralogical and Re-Os geochronological studies J. Pašava, J. Malec, **W.L. Griffin** and **J.-M. Gonzáles-Jiménez** Mineralogy, geochemistry and *in situ* Re -Os dating of sulfides from megacrystalline pyrope peridotites from the Udachnaya Pipe, Siberian Craton **I.G. Tretiakova** and V.G. Malkovets, **W.L. Griffin**, **N.J. Pearson**, L.N. Pokhilenko, N.P. Pokhilenko, S.I. Kostrovitsky and V.S. Sobolev

12th International Platinum Symposium, Yekaterinburg, Urals, Russia, 11-14 August 2014 cont...	Diamonds and highly reduced minerals in ophiolitic mantle rocks and chromitites J.S. Yang, X.X. Zhang, X.Z. Xu, Z.M. Zhang, Z. Huang, P.T. Robinson, Y. Dilek, and **W.L. Griffin**
Gordon Research Conference: Rock Deformation, Andover, New Haven, USA 17-22 Aug, 2014	The effect of second phases on the rheology of polycrystalline material: experiments with pure and '*dirty*' D_2O ice **D. Czaplinska** Numerical simulation of pinch and swell structures: Lessons for field interpretation **R. Gardner** Strain heterogeneities and dynamic recrystallization in anisotropic materials: Insights from ice and ice mixture deformation experiments and modeling **S. Piazolo** **Keynote**
Ninth International Mining Geology Conference, Adelaide, SA, 18-20 August 2014	Mines versus mineralisation - Deposit quality, mineral exploration strategy and the role of '*Boundary Spanners*' **T.C. McCuaig** J.E. Vann and J.P. Sykes **Keynote**
21st General Meeting of the International Mineralogical Association 2014, Gauteng, South Africa, 1-5 September 2014	Insights into the mantle structure beneath the Lunda Norte kimberlitic province (NE Angola): petrography and palaeothermobarometry of fresh mantle xenoliths **M. Castillo-Oliver**, S. Galí, J.C. Melgarejo, V. Pervov and **W. Griffin** *In situ* trace-element geochemistry and U-Pb dating on perovskite from kimberlites of the Lundas Norte province (NE Angola): petrogenetic and tectonic implications **M. Castillo-Oliver**, S. Galí, J.C. Melgarejo, V. Zinchenko, **E. Belousova** and **W.L. Griffin** Pink colour in Type I diamonds: is deformation twinning the cause? **D. Howell**, D. Fisher, **S. Piazolo**, **W. Griffin** and S. Sibley Water contents of Roberts Victor eclogites: primary vs metasomatic controls **J. Huang**, **W. Griffin**, Q. Xia, P. Li, **Y. Gréau**, **N. Pearson** and **S. O'Reilly** Mineralogy and geochemistry of megacrystalline pyrope peridotites from the Udachnaya pipe, Siberian Craton V. Malkovets, L. Pokhilenko, N. Pokhilenko, T. Ota, E. Nakamura and **W. Griffin** Understanding $\delta^{15}N$ variations in the mantle using internal variabilities in natural diamonds R. Southworth, S. Mikhail, **D. Howell**, A. Verchovsky, F. Brenker and A. Jones Metasomatic diamonds in eclogite xenoliths from Yakutian kimberlites: implications for diamond-grade estimation Z. Spetsius, **W. Griffin**, **S.Y. O'Reilly** and I. Bogush Morphology and microstructures of chromite crystals from the Merensky Reef: implications for inclusion entrapment **Z. Vukmanovic**, S. Barnes, **S. Reddy**, B. Godel and **M. Fiorentini**
14th International Conference on Thermochronology, Chamonix, 8-14 September 2014	Constraining the vertical tectonic movements in southern South China by multi-system geo-/thermochronology **N. Tao**, **Z.X. Li**, M. Danišík, N.J. Evans, G.E. Batt, W. Li, C. Pang, F. Jourdan and Y. Xu Earthquake seismology: Exploring the cratonic crust in Western Australia **H. Yuan** **Invited**
77th Annual Meeting of the Meteoritical Society, Casablanca, Morocco, 8-12 September 2014	A complex thermal history of the Southern Highlands preserved in Martian meteorite NWA7533 and its pairs J.J. Bellucci, **A. Nemchin** and M.J. Whitehouse A new perspective on the Pb isotopic composition of Mars R.B. Kielman, **A.A. Nemchin**, M.J. Whitehouse, J.J., Bellucci, J.F. Snape and F. Thiessen Pyrite tracks late hydrothermal alteration in Martian regolith breccia NWA 7533 J.-P. Lorand, R.H. Hewins, L. Remusat, B. Zanda, S. Pont, M. Humayun, **A. Nemchin**, **M. Grange**, A. Kennedy and C. Göpel Do lunar impact breccias date basin forming events? F. Thiessen, **A.A. Nemchin**, M.J. Whitehouse, J.J. Bellucci, J.F. Snape, R.B. Kielman and R.E. Merle Decomposition of zircon in Mistastin Lake impact melt glass: an integrated SIMS, Hyperspectral-CL, Raman and EPMA study M. Zanetti, A. Wittmann, **A. Nemchin**, P. Carpenter, E. P. Vicenzi and B. Jolliff

Kimberley diamond symposium and trade show, The Big Hole, Kimberley, South Africa, 11-14 September 2014	Xenolithic eclogites from Roberts Victor, South Africa: A metasomatic model **J. Huang**, **Y. Gréau**, **W.L. Griffin**, **N. Pearson** and **S.Y. O'Reilly**
2014 Annual Meeting of Japan Association of Mineralogical Sciences, Kumamoto, Japan, 17-18 September 2014	Chemical homogenization by fluid-induced deformation in chromitites during metamorphism **T. Satsukawa**, **S. Piazolo**, **V. Colás**, J.M. González-Jiménez, **W.L. Griffin**, **S.Y. O'Reilly**, F. Gervilla and I. Fanlo Terminal events in the eastern segment of the Central Asian Orogenic Belt **S.A. Wilde**
2014 EMAS regional Workshop, Leoben, Austria, 21-24 September 2014	*In situ* quantitative determination of PGE concentrations in komatiitic chromites: application to nickel-sulphide targeting **M.L. Fiorentini** **Invited**
SEG 2014: Building Exploration Capability for the 21st Century, Keystone, CO, USA, 27-30 September 2014	Gravity and magnetic investigation of 3D basement structure within Siguiri Basin (Guinea, West Africa): Implications for gold deposit distribution **J. Markov**, Aitken A., Dentith, M., Jessell, M. and Miller, J. The mineral system concept: Key to exploration targeting under cover **T.C. McCuaig** and J.M.A. Hronsky **Invited** The Granites-Tanami Orogen subsurface geometry as revealed by an integrated potential field geophysical and geological study **D. Stevenson**, **L. Bagas** and A. Aitken
SEISMIX 2014, 16th Int. Symposium on Multi-scale Seismic Imaging of the Earth's crust and Upper Mantle, Castelldefels, Spain, 12-17 October 2014	Seismic interpretation of the Cue-Weld range area, Yilgarn Craton, Western Australia O. Ahmadi, H. Koyi, C. Juhlin and **K. Gessner**
Nordic Supercontinent Workshop, Haraldvangen, Norway, 13-19 October 2014	Precambrian Continents and Terranes for GPLATES **S.A. Pisarevsky** IAGA Global Paleomagnetic Database **S.A. Pisarevsky** Rodinia: Status and Challenges **S.A. Pisarevsky**
Dating Origin of Life: Present-Day Molecules and First Fossil Record, Göttingen, Germany, 16-18 October 2014	Biogeochemical characterization of Paleoarchaean Rocks from the Pilbara Craton (Western Australia) J.-P. Duda, J. Reitner, M. Blumenberg, D. Ionescu, N. Schäfer, V. Thiel and **M. Van Kranendonk** Early Archean carbonates on early Earth - microbial biosignature versus hydrothermal origin J. Reitner, J.-P. Duda, F. Wilsky, N. Schäfer, **M.J. Van Kranendonk**, M. Hoppert, F. Wilsky and B. Bent A planetary driver of environmental, atmospheric and biological change through the Precambrian **M.J. Van Kranendonk**
GSA 2014, Vancouver, British Columbia, Canada, 19-22 October 2014	Reidite and shock-twinned zircon in polymict breccia from the Ordovician Rock Elm Impact Structure, USA A. Avosie, **T.M. Erockson**, and N. Timms Rheological contrast controlling the development of paired shear zones, Fiordland, New Zealand **N.R. Daczko**, J. Smith, **S. Piazolo** and L. Evans
Symposium on International Safeguards, IAEA, Vienna, 20-24 October 2014	Novel mass spectrometric techniques for the rapid characterization and fingerprinting of nuclear fuel materials **J. Cliff**, J. Denman, **L. Martin**, and **M. Kilburn**

24e Réunion des Sciences de la Terre (24th Earth Sciences Meeting), Pau, France, 27-31 October 2014	Petrology and geochemistry of mantle xenoliths of the Neogene-Quaternary Middle Atlas Volcanic Field (Morocco) B. Arnoux, **B. Abily**, M. Benoit, N. Youbi, F. Ait-Hamouh, M. Grégoire, A. Idris and M.A. Boumehdi Les roches crustales profondes de l'Archipel de Kerguelen (Sud de l'Océan Indien) J. Chevet, M. Grégoire, **S.Y. O'Reilly**, M.-C. Gerbe, G. Delpech, B. Moine, D. Guillaume, **W. Griffin** and J.Y. Cottin Upper mantle structure of Northeastern North America using full waveform inversion **H. Yuan** Petrology and geochemistry of mantle xenoliths of the Neogene-Quaternary Middle Atlas Volcanic Field (Morocco) B. Arnoux, **B. Abily**, M. Benoit, N. Youbi, F. Ait-Hamouh, M. Grégoire, A. Idris and M.A. Boumehdi
2014 GSWA Kimberley Workshp, Perth, 21 November 2014	The geochemical architecture of the Hart Dolerite at Speewah Dome, Western Australia **M.L. Fiorentini** **Invited**
Archean Tectonics debate and symposium "Plumes or plates in the late Archaean: how far does uniformitarianism apply in Archaean tectonics?" CSIRO, Kensington, WA, 27-28 November 2014	No plate tectonics in the Archaean? **C. O'Neill** **Invited** Archean tectonics and the tyranny of "*too few constraints*" **M.J. Van Kranendonk** Internal seismic structure of the cratonic lithosphere **H. Yuan** **Invited**
1st Australian Workshop for EMC Geoscientists, Macquarie University, NSW, Australia, 1-2 December 2014	Present and future of UNCOVER and the Geosciences in the context of the Australian Academy of Sciences **S.Y. O'Reilly**
AGU Fall meeting, San Francisco, CA, USA, 15-19 December 2014	Multi-observable probabilistic tomography reveals the thermochemical structure of Central-Western US **J.C. Afonso**, **Y. Yang**, N. Rawlinson, D. Schutt, A. Jones and J. Fullea Trace elements in olivine in Italian potassic volcanic rocks distinguish between mantle metasomatism by carbonatitic and silicate melts E. Ammannati, **D.E. Jacob**, R. Avanzinelli, **S.F. Foley** and S. Conticelli Magmatic controls on the genesis of Ni-Cu-PGE sulphide mineralisation on Mars **R.J. Baumgartner**, **M. Fiorentini**, D. Baratoux, S. Micklethwaite, K. Sener and **C. McCuaig** The genesis of the Dunite Transition Zone in the Oman Ophiolite: new insights from Major and Rare Earth Elements M. Benoit, M. Theveny, M. Claverie, M. Rospabé, **B. Abily** and G. Ceuleneer Looking up from the base of a thickened arc - Evaluating eclogite fractionation depths T. Chapman, G.L. Clarke, and **N.R Daczko** Thermochemical structure and stratification of the Hudson Bay lithosphere, Northern Canada: Evidence from multi-observable probabilistic inversion F.A. Darbyshire and **J.C. Afonso** **Invited** Magmatic processes and systems deduced from single crystals J. Davidson, **R.C. Bezard**, D.J. Morgan and C. Ginibre The complex history of Alarcon Rise Mid-Ocean Ridge rhyolite revealed through mineral chemistry B.M. Dreyer, R.A. Portner, D.A. Clague, **N.R. Daczko**, P. Castillo and I.N. Bindeman Temporal distribution of mantle-derived potassic rocks and carbonatites linked to stabilization of mantle lithosphere and redox states during subduction **S.F. Foley** Towards coupled modeling of grain-scale non-equilibrium thermodynamics and mantle-scale geodynamics **C.J. Grose** and **J.C. Afonso** Crustal and uppermantle structure of Northeast China from ambient noise and teleseismic earthquake rayleigh wave tomography Z. Guo, Y.J. Chen, **Y. Yang**, and **J.C. Afonso**

AGU Fall meeting, San Francisco, CA, USA, 15-19 December 2014 cont...

The importance of redox reactions in fluid transport systems in the Earth's deep mantle: Evidence from nano-inclusions
D.E. Jacob, R. Wirth and L. Dobrzhinetskaya

On the formation of the Dabashan Orocline, Central China: Evidence from seismic ambient noise tomography
C. Jiang, **Y. Yang** and Y. Zheng

Life with and life without plate tectonics
A. Lenardic, T. Hoeink, M. Jellinek, C.L. Johnson, N.B. Cowan, R. Pierrehumbert, V. Stamenkovic, **C. O'Neill** and R. Dasgupta

Supercontinent break-up: Causes and consequences
Z.-X. Li

On the limitations of interstation distances in ambient noise tomography
Y. Luo and **Y. Yang**

Accounting for propagation outside of the model boundaries in regional full waveform inversion based on adjoint methods
Y. Masson, C. Pierre, B.A. Romanowicz, S.W. French and **H. Yuan**

Water in the cratonic mantle: Insights from FTIR Data on Lac de Gras Xenoliths (Slave Craton, Canada)
A.H. Peslier, A.D. Brandon, L.A. Schaffer, **S.Y. O'Reilly**, **W.L. Griffin**, R.V. Morris, T.G. Graff and D.G. Agresti

Stress heterogeneities in anisotropic materials - their effect on dislocation fields and post-deformational recrystallization: Insights from combined experiments and numerical simulations of polycrystalline ice
S. Piazolo, M. Montagnat, V. Borthwick, L. Evans, A. Griera, F. Grennerat, H. Moulinec and J. Wheeler

Lessons from Dynamic Heds: Diagonite microstructures suggest solid-state deformation, annealing and incipient differentiation
S. Piazolo, **T. Rushmer** and V. Luzin

Anisotropic shear velocity models of the North American upper mantle based on waveform inversion and numerical wavefield computations
C. Pierre, Y. Masson, B.A. Romanowicz, S.W. French and **H. Yuan**

Deformation of the deep crust: Insights from physiochemical characteristics of deformation microstructures of plagioclase and quartz in gneiss from the Salt Mylonite Zone, Western Gneiss Region, Norway
R.N. Renedo, **S. Piazolo**, D.L. Whitney and C.P. Teyssier

High pressure experimental study of eclogite with varying H_2O contents
A. Rosenthal, D.J. Frost, S. Petitgirard, G.M. Yaxley, A. Berry, A.B. Woodland, Z. Pinter, P. Vasilyev, D.A. Ionov, **D.E. Jacob**, G.D. Pearson, I. Kovacs and A. Padron-Navarta

Chemical homogenization by fluid-present deformation in chromitites: An example from Golyamo Kamenyane chromitites, SE Bulgaria
T. Satsukawa, **S. Piazolo**, J.-M. González-Jiménez, **V. Colás**, **W.L. Griffin**, **S.Y. O'Reilly**, F. Gervilla and I. Fanlo

Feg-EPMA and nanosims profiles of zoned crystals for diffusion chronometry
K. Saunders, B. Buse, **M. Kilburn**, S. Kearns and J.D. Blundy

A Br isotopic study of Australian Arid Playa Lakes and halophyte vegetation as a monitor of Br transport
B.F. Schaefer

Crustal and lithospheric structure of the Albany-Fraser Orogen, Western Australia, from passive-source seismology
C. Sippl, H. Tkalcic, B.L.N. Kennett, C.V. Spaggiari and **K. Gessner**

Fluid-induced transition from Kyanite- to bimineralic Eclogite: A petrological, geochemical and mass balance approach to mantle eclogites
H. Sommer, **D.E. Jacob**, G.D. Pearson and R.A. Stern

Fluid-controlled fabric development across a brittle-ductile shear zone: an example from a Wyangala Batholith, Australia
L. Spruzeniece and **S. Piazolo**

Sink or Swim? The role of intracrustal differentiation in the generation of compositional diversity and crustal delamination in the Archean
J.A. VanTongeren, C.T. Herzberg, B. Kaus, T.E. Johnson and **M. Brown**

Lawsonite blueschists in recycled mélange involved in K-rich orogenic magmatism
Y. Wang, D. Prelevic, **S.F. Foley**, S. Buhre and S.J.G. Galer

High-resolution ambient noise adjoint tomography of the crust and upper mantle beneath the eastern margin of the Tibetan plateau
G. Xing, F. Niu, M. Chen and **Y. Yang**

AGU Fall meeting, San Francisco, CA, USA, 15-19 December 2014 cont...	Genesis of diamond-bearing and diamond-free podiform chromitites in the Luobusa Ophiolite, Tibet J. Yang, F. Xiong, X. Xu, T. Robinson, Y. Dilek and **W.L. Griffin** Imaging upper mantle structures in regional, continental and global scales using long-period surface waves (50-300 sec) from ambient noise **Y. Yang** and **J. Xie** Crustal composition of the Western Australian craton and implications for craton formation tectonics **H. Yuan** Rayleigh wave and shear wave tomography of Northeastern China: Results coconstrained by multiple datasets T. Zhou, J. Chen, J. Han, Y. Tian, M. Wu, **Y. Yang** and J. Ning

Appendix 7: CCFS visitors

CCFS VISITORS 2014 (Excluding participants in conferences and workshops)

VISITOR	ORGANISATION	COUNTRY
Dr Chris Adams	Lower Hutt	New Zealand
Dr Olivier Alard	Universite Montpellier	France
Dr Sarmad Ali	University of Wollongong	Australia
Dr Hooshang Asadi Haroni	Isfahan University of Technology	Iran
Dr Steve Barnes	CSIRO	Australia
Dr Graham Begg	Minerals Targeting International	Australia
Ms Robin-Mary Bell	GEUS	Denmark
Professor Mike Brown	University of Maryland	USA
Dr Sascha Brune	School of Geosciences, University of Sydney	Australia
Ms Rachelle Caldwell	Newcastle Institute for Energy and Resources	Australia
Ms Montgarri Castillo Oliver	University of Barcelona	Spain
Dr Mauro Cesar Geraldes	Rio de Janeiro State University	Brazil
Mr Henry Chalk	University of Adelaide	Australia
Mr Tim Chapman	School of Geosciences, University of Sydney	Australia
Ms Sarah Chapman	School of Geosciences, University of Sydney	Australia
Mr Mathieu Chasse	Sorbonne	France
Professor John Cottle	UCSB	USA
Mr Thomas Czertowicz	University of Otago	New Zealand
Associate Professor Fiona Darbyshire	Université du Québec à Montréal	Canada
Professor Huw Davies	Cardiff University	UK
Professor Jun Deng	China University of Geosciences, Beijing	China
Dr Nathaniel Dixon	MIT	USA
Dr Zoe Doubleday	The University of Adelaide	Australia
Mr Mark Eastlake	Geological Survey of NSW	Australia

VISITOR	ORGANISATION	COUNTRY
Dr Steve Eggins	Australian National University	Australia
Dr Aurélien Eglinger	Universite de Lorraine, Nancy	France
Professor Bruce Foukes	University of Illinois-Champagne-Urbana	USA
Dr Mayoko Fukuyama	Akita University	Japan
Mr Han Fuli	No.307 Nuclear Geological Team of Guangxi	China
Dr Andrea Giuliani	The University of Melbourne	Australia
Mr Zhen Guo	Peking University	China
Dr Jacqueline Halpin	University of Tasmania	Australia
Dr Derek Hasterok	The University of Adelaide	Australia
Professor Graham Heinson	The University of Adelaide	Australia
Dr Phillip Hellman	H&S Consultants	Australia
Mr Huang Hengjie	Guangxi Bureau of Geology & Mineral Prospecting & Exploitation	China
Professor Kaj Hoernle	University of Kiel	Germany
Professor Greg Houseman	University of Leeds	UK
Ms Ping Ji	China Earthquake Administration	China
Professor Alan Jones	Dublin Institute for Advanced Studies	Ireland
Dr Zhiqiang Kang	College of Earth Sciences, Guilin University of Technology	China
Professor Shun Karato	Yale University	USA
Dr Penny King	Australian National University	Australia
Dr Viktor Kovach	Russian Academy of Sciences	Russia
Dr Andrew Kylander-Clark	UCSB	USA
Mr Xi-yao Li	China University of Geosciences, Wuhan	China
Mr Guoliang Li	China University of Petroleum, Beijing	China
Mr Lei Liu	Nanjing University	China
Mr Guangxu Liu	Zhenjiang University	China
Professor Xiao-Ping Long	Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou	China
Dr Robert Loucks	Geoscience Research Consultant	USA
Professor Yinhe Luo	China University of Geosciences, Wuhan	China
Mr Pan Luozhong	Guangxi Regional Geological Survey Research Institute, Guilin	China
Mr Qiang Ma	China University of Geosciences, Wuhan	China
Dr Ian Madsen	CSIRO, Monash	Australia
Professor Wolfgang Maier	Cardiff University	UK
Professor Vladimir Malkovets	Institute for Study of the Earth's Interior Okayama University, Misasa	Japan
Dr Helen Maynard-Casely	Bragg Institute, ANSTO	Australia
Dr Lucy McGee	Universidad de Chile	Chile
Mr Zhang Mingguo	Guangxi Bureau of Geology & Mineral Prospecting & Exploitation	China
Dr Maurine Montagnat	Grenoble	France
Dr Nick Mortimer	GNS Science	New Zealand
Mr Jacob Mulder	University of Tasmania	Australia
Professor Guy Narbonne	Queens University	Canada
Dr Lutz Nasdala	Vienna University	Austria
Professor Fenglin Niu	Rice University	USA
Dr Allen Nutman	School of Earth and Environmental Sciences, University of Wollongong	Australia

VISITOR	ORGANISATION	COUNTRY
Dr Hugh O'Brien	Geological Survey of Finland	Finland
Dr Masatsugu Ogasawara	Geological Survey of Japan	Japan
Dr Gerrit Olivier	Institute of Mine Seismology	Australia
Dr Muriel Pacton	University of Lyon	France
Dr Matt Pankhurst	School of Earth and Environment, University of Leeds	UK
Dr Justin Payne	The University of Adelaide	Australia
Professor Emeritus Julian Pearce	School of Earth & Ocean Sciences, Cardiff University	UK
Pascal Phillippot	IPGP	France
Mr Leandre Ponthus	Universite Paul Sabatier	France
Dr Ryan Portner	Monterey Bay Aquarium Research Institute & Brown University	USA
Professor Andrew Putnis	University of Muenster	Germany
Ms Adrianna Rajkumar	University of Sydney	Australia
Professor Mark Reagan	University of Iowa	USA
Professor Carmen Sanchez-Valle	Swiss Federal Institute of Technolog (ETH), Zurich	Switzerland
Dr Joyce Schmatz	RWTH Aachen University	Germany
Associate Professor Shuqing Sha	China University of Geosciences, Beijing	China
Mr Luo Shouwen	Guangxi Bureau of Geology & Mineral Prospecting & Exploitation	China
Associate Professor Ken Sims	University of Wyoming	USA
Dr Zdislav Spetsius	ALROSA Co. Ltd	Russia
Dr (Mr) Huayun (Tom) Tang	China University of Geoscience	China
Dr Stephan Thiel	The University of Adelaide	Australia
Dr Ulrike Troitszch	Research School of Earth Sciences, Australian National University, ACT	Australia
Dr Kathryn Waltenberg	Geoscience Australia	Australia
Dr Kuo-Lung Wang	Institute of Earth Sciences, Academica Sinica	Taiwan
Mr Kai Wang	China University of Geosciences, Wuhan	China
Professor Qinyan Wang	China University of Geosciences, Wuhan	China
Associate Professor Changming Wang	China University of Geosciences, Beijing	China
Dr Wuyi Wang	Gemological Institute of America	USA
Ms Laurène-Marie Wavrant	Université du Québec, Chicoutimi	Canada
Mr Gordon Webb	The University of Melbourne	Australia
Professor John Wheeler	Liverpool University	UK
Dr Joanne Whittaker	Marine Geoscientist, UTAS	Australia
Mrs Hasini Wijayaratne	University of Auckland	New Zealand
Dr Boswell Wing	McGill University	Canada
Dr Richard Wirth	GFZ Postdam, Germany	Germany
Professor Yixian Xu	China University of Geosciences, Wuhan	China
Associate Professor Zhiming Yang	Chinese Academy of Geological Sciences	China
Mr Ou Yecheng	Guangxi Beihai Institute of Hydrogeology Engineering Geology and Mineral Resources Prospecting	China
Professor Shouting Zhang	China University of Geosciences, Beijing	China
Professor Chuanheng Zhang	China University of Geosciences, Beijing	China
Mr Kaifeng Zhao	China University of Geosciences, Wuhan	China
Professor Jianping Zheng	China University of Geosciences, Wuhan	China
Ms Xueyao Zhou	Nanjing University	China

Appendix 8: Research funding

GRANTS AND OTHER INCOME FOR 2014

Investigators	2014 Funding Source	Project Title	Amount
O'Reilly	ARC Centre of Excellence	Core to Crust Fluid Systems	$2,031,333
Wilde	ARC CoE (Curtin contribution)	Core to Crust Fluid Systems	$280,000
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	$259,059
Afonso, Yang, Rawlinson, Jones, Connolly, Lebedev	ARC Discovery Project (DP120102372)	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 (DP120104004)	Supercells and the supercontinent cycle	$80,000
Nemchin, Grange	ARC Discovery Project (DP120102457)	Investigation of the early history of the Moon	$70,000
Piazolo, Daczko, Putnis, Jessell	ARC Discovery Project (DP120102060)	Investigating the fundamental link between deformation, fluids and the rates of reactions in minerals	$70,000
Rawlinson, Yang	ARC Discovery Project (DP120103673)	Down under down under: using multi-scale seismic tomography to image beneath Australia's Great Artesian Basin	$130,000
Rosenbaum, Pisarevsky, Fielding, Speranza	ARC Discovery Project (DP130100130)	Unravelling the geodynamics of eastern Australia during the Permian: the link between plate boundary bending and basin formation	$130,000
Schaefer	ARC Discovery Project (DP130102366)	Bromine isotopic evolution of the Earth and solar system	$50,000
Walter, Neilan, George, Summons, Schopf	ARC Discovery Project (DP1093106)	Oxygenating the Earth: using innovative techniques to resolve the timing of the origin of oxygen-producing photosynthesis in cyanobacteria	$100,000
Jacob	ARC Future Fellowship	A new approach to quantitative interpretation of paleoclimate archives	$205,359
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	$160,208
O'Neill	ARC Future Fellowship	Strength and resistance along oceanic megathrust faults: implications for subduction initiation	$70,844

Investigators	2014 Funding Source	Project Title	Amount
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	$187,585
Wang	ARC Future Fellowship	Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	$96,463
Wacey	ARC Future Fellowship	New insights into the origin and evolution of life on Earth	$95,788
Clark (C)	ARC 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 et.al.	ARC LIEF (LE140100047)	Australian membership of the International Ocean Discovery Program	$1,800,000
Arculus, Rohling, Roberts, Exon, Yeats, O'Reilly, George, Muller, Aitchison, Webster, Coffin, Vasconcelos, Welsh, McCuaig et.al.	ARC LIEF (MQ contribution)	Australian membership of the International Ocean Discovery Program	$60,000
Hand, Kamenetsky, Gillanders, Foden, Kennedy, Clark, Raimondo, Payne, Reid, Dutch	ARC LIEF (LE140100141)	High sensitivity and precision mass spectrometry for tracing Australia's ancient evolution and securing our future groundwater resources	$360,000
McInnes, van Riessen, Bland, Iglauer, Eksteen, Kemp, Muhling, Fiorentini, Thébaud, Wingate, Kirkland, Senanayake, Nikoloski	ARC LIEF (LE140100150)	A digital mineralogy and materials characterisation hub for petrology, mineralogy, exploration, metallurgy and reservoir characterisation research	$700,000
Tkalcic, Kennett, Spaggiari, Gessner	ARC Linkage Project (LP130100413)	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
Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate	ARC Linkage Project (LP130100922)	Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	$170,000
Jessell, Holden, Baddeley, Kovesi, Ailleres, Wedge, Lindsay, Gessner, Hronsky	ARC Linkage Project (LP140100267)	Reducing 3D geological uncertainty via Improved data interpretation methods	$60,000
McCuaig, Barley, Fiorentini, Kemp, Miller, Belousova, Jessell, Hein, Begg, Tunjic, Angerer, Said, Bagas	ARC Linkage Project (industry contrib.)	Four dimensional lithospheric evolution and controls on mineral system distribution in Neoarchean to Paleoproterozoic terranes	$432,844
Aitken, Dentith, Lindsay, McCuait	Geological Survey of Western Australia	Second generation regional targeting products	$245,833
McCuaig, Miller, Ulrich	Societe d'Exploitation des Mines d'Or de Sadiola SA	Controls on the genesis, geometry and location of the Sadola - Yatela Gold deposit	$250,000
McCuaig, Miller, Ulrich	AngloGold Ashanti	Controls on the genesis, geometry and location of the Siguiri gold deposit, Guinea	$190,000

Investigators	2014 Funding Source	Project Title	Amount
McCuaig, Miller, Ulrich	AngloGold Ashanti	Controls on the genesis, geometry and location of the Obuasi - gold deposit, Ghana	$205,000
Hough, Reddy, McCuaig, Tyler	SIEF	The distal footprints of giant ore systems: UNCOVER Australia	$250,000
Grice, McCuaig, Evans and others	CSIRO Cluster	CSIRO cluster in organic-inorganic interactions in mineral systems	$1,000,000
Dadd	ANZIC IODP	Analysis of volcanic ash collected from cores on IODP exp 349	$20,000
Piazolo, Griffins, Venter, Luzin	Braggs Institute, ANSTO	A new view on diamonds: Deformation textures of polycrystalline diamond	$53,600
Van Kranendonk, Keleman	Alfred P Sloan Foundation	Integrative field studies for the deep carbon observatory	$46,250
González-Jiménez, Satsukawa, Abily	Contrib to Post-award	Core to Crust Fluid Systems	$75,000
Wang	Contrib to Post-award	Core to Crust Fluid Systems	$30,000
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	Geological Survey of Western Australia	Mapping sulfur sources in selected Precambrian terranes of Western Australia to enhance predictive targeting for gold and base metal mineralization	$30,000
McCuaig, Greenwood, McCulloch	CSIRO Flagship Collaboration Fund	Mineral Systems Flagship Cluster	$272,688
Rushmer	ANSTO	ANSTO/MQ funding for a 5 year academic position	$84,916
Fiorentini, Barnes, Miller	MERIWA M413	Hydrothermal footprints of magmatic nickel sulphide deposits	$130,000
Houh, McCuaig, Reddy, Clark	MERIWA	Distal Footprints of Giant Ore Systems: Capricorn WA case study	$867,000
O'Reilly	NCRIS AuScope	Earth composition and evolution	$139,000
Piazolo	AINSE	Neutron activation analysis of natural polycrystalline diamond aggregates	$1,360
Fiorentini	Iluka Resources Limited	A mineral system approach to the geology of *"hard-rock"* Ti and Zr deposits	$35,000
Fiorentini	Rio Tinto	The applicability of Ru-chromite signatures in the exploration for picrite-hosted Ni-Cu-PGE sulfide deposits	$100,000
Fiorentini	CNRS France	Systèmes de minéralisation Ni-Cu-PGE associés au magmatisme martien	$15,000
Rushmer, Zellmer	National Geographic Society	Dynamics of magma ascent beneath New Zealand's subduction zone volcanoes: implications for hazard mitigation strategies	$24,292

Investigators	2014 Funding Source	Project Title	Amount
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (Minerals Targeting International Pty Ltd)	Lithospheric architecture mapping in Phanerozoic orogens	$60,000
Foley	MQSIS Research Infrastructure Special Reserve Fund	High pressure experimental equipment: cbic multi-anvil apparatus	$150,000
Clark, Afonso, O'Neill, Jacob, Pearson, Rushmer, Foley, Griffin, O'Reilly, Turner	MQSIS Research Infrastructure Special Reserve Fund	High spectral resolution confocal raman micro-spectrometer	$150,000
O'Neill, Lackie	MQ FSE Learning & Teaching Grants	Teaching module for GEOS306 based on the development of Arduino geophysical loggers	$2,500
George, Goodwin, Armand, Jacob, Westaway, Leefmann	RIBG	Facility for large lipid analysis of geological and environmental samples, including new ability to derive important palaeothermometers	$100,000
Jacob	RIBG	Core to crust experiments: establishment of a high-pressure, high-temperature diamond anvil cell facility	$67,000
McGowan	PGRF	Messages from the Mantle: geochemical Investigations of Ophiolitic Chromitites	$5,000
Firth, Jessop, McGowan	MQ Scholarships	APA	$58,177
Gardner, Matthews, Murphy, Stuart, Wasiliev	MQ Scholarships	MQRES	$104,253
Brens, Colas, Czaplinska, Goode, Grose, Hoshino, Jiang, Oliveira Bravo, Peters, Ramzan, Spruzeniece, Tork Qashqai, Tretiakova	MQ Scholarships	IMQRES	$247,129
Bezard, Castillo Oliver, Gao, Lu, Tihac, Wang, Xie, Xiong	MQ Scholarships	IMQRES Cotutelle	$121,756
Lanati, Miller, Moore, Murhll-Grifith, Nguyen, Piper, Williams	MQ Scholarships	MRES	$68,975
Bjorkman, Davis, Parraavila, Markov, Stevenson, Iaccheri	UWA Scholarships	SIRF/IPRS	$155,941
Tao, Wang, Liu, Ge, Liu, Niu, Pang, Yao, Zhu, Erickson, Meier, Stark, Huang, Sun	Curtin Scholarships	APRA, student support	$331,290
Macquarie University	GLITTER software	Core to Crust Fluid Systems	$46,228
Macquarie University	Access MQ	Core to Crust Fluid Systems	$233,211
Macquarie University	Interest	Post Award and SLF interest	$8,377

GRANTS AND OTHER INDICATIVE INCOME FOR 2015

Investigators	2015 Funding Source	Project Title	Amount
O'Reilly	ARC Centre of Excellence	Core to Crust Fluid Systems	$1,969,500
Wilde	ARC CoE (Curtin contribution)	Core to Crust Fluid Systems	$280,000
GSWA	ARC CoE (GSWA)	Core to Crust Fluid Systems	$150,000

Investigators	2015 Funding Source	Project Title	Amount
O'Reilly	ARC CoE (MQ contribution)	Core to Crust Fluid Systems	$450,000
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
Rosenbaum, Pisarevsky, Fielding, Speranza	ARC Discovery Project (DP130100130)	Unravelling the geodynamics of eastern Australia during the Permian: the link between plate boundary bending and basin formation	$117,507
Moresi, Betts, Whittaker, Miller	ARC Discovery Project (DP150102887)	The global consequences of subduction zone congestion	$150,000
Handley, Turner, Reagan, Barclay	ARC Discovery Project (DP150100328)	Timescales of mixing and volatile transfer leading to volcanic eruptions	$125,000
Fitzsimons, Holness, Clark	ARC Discovery Project (DP150102773)	Migmatites, charnockites and crustal fluid flux during orogenesis	$65,000
Jacob	ARC Future Fellowship	A new approach to quantitative interpretation of paleoclimate archives	$205,617
Belousova	ARC Future Fellowship	Dating down under: resolving Earth's crust - mantle relationships	$89,081
Fiorentini	ARC Future Fellowship	From Core to Ore: emplacement dynamics of deep-seated nickel sulphide systems	$88,816
Handley	ARC Future Fellowship	The timescales of Earth-system processes: extending the frontiers of uranium-series research	$153,015
Piazolo	ARC Future Fellowship	Flow characteristics of lower crustal rocks: developing a toolbox to improve geodynamic models	$101,787
Yang	ARC Future Fellowship	How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	$185,609
Wang	ARC Future Fellowship	Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	$192,926
Wacey	ARC Future Fellowship	New insights into the origin and evolution of life on Earth	$191,766
Giuliani	ARC DECRA (DE150100510)	A new approach to revealing melting processes in the hidden deep Earth	$124,000
Arculus, Rohling, Roberts, Exon, Yeats, O'Reilly, George, Muller, Aitchison, Webster, Coffin, Vasconcelos, Welsh, McCuaig et al.	ARC LIEF (LE140100047)	Australian membership of the International Ocean Discovery Program	$1,800,000
Kemp, McCulloch, Fiorentini, McCuaig, Rate, Clark, Rasmussen, Evans, Reddy, Bland, Raimondo, Pearson, Belousova, Jacob, Runatto, Spandler, Barnes	ARC LIEF (LE150100013)	Laser ablation multiple split streaming.	$860,000
Kemp, McCulloch, Fiorentini, et al.	ARC LIEF (LE150100013) (MQ contribution)	Laser ablation multiple split streaming.	$40,000

Investigators	2015 Funding Source	Project Title	Amount
Li, Tohver, Roberts, Rosenbaum, O'Neill, Pisarevsky, Clark, Elders, Bland, Wilde	ARC LIEF (LE150100065)	A fully automated, fully shielded palaeomagnetic system	$560,000
Tkalcic, Kennett, Spaggiari, Gessner	ARC Linkage Project (LP130100413)	Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	$100,000
Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate	ARC Linkage Project (LP130100922)	Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	$170,000
Jessell, Holden, Baddeley, Kovesi, Ailleres, Wedge, Lindsay, Gessner, Hronsky	ARC Linkage Project (LP140100267)	Reducing 3D geological uncertainty via Improved data interpretation methods	$120,000
Aitken, Dentith, Lindsay, McCuait	Geological Survey of Western Australia	Second generation regional targeting products	$245,833
McCuaig, Miller, Ulrich	Societe d'Exploitation des Mines d'Or de Sadiola SA	Controls on the genesis, geometry and location of the Sadola - Yatela Gold deposit	$205,000
Hough, Reddy, McCuaig, Tyler	SIEF	The distal footprints of giant ore systems: UNCOVER Australia	$250,000
Hough, Reddy, McCuaig, Tyler	SIEF	The distal footprints of giant ore systems: UNCOVER Australia	$1,000,000
Dadd	ANZIC IODP	Analysis of volcanic ash collected from cores on IODP exp 349	$20,000
Piazolo, Griffins, Venter, Luzin	Braggs Institute, ANSTO	A new view on diamonds: Deformation textures of polycrystalline diamond	$53,600
Van Kranendonk, Keleman	Alfred P Sloan Foundation	Integrative field studies for the deep carbon observatory	$46,250
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	Geological Survey of Western Australia	Mapping sulfur sources in selected Precambrian terranes of Western Australia to enhance predictive targeting for gold and base metal mineralization	$30,000
McCuaig, Greenwood, McCulloch	CSIRO Flagship Collaboration Fund	Mineral Systems Flagship Cluster	$272,688
Rushmer	ANSTO	ANSTO/MQ funding for a 5 year academic position	$84,916
Fiorentini, Barnes, Miller	MERIWA M413	Hydrothermal footprints of magmatic nickel sulphide deposits	$130,000
Houh, McCuaig, Reddy, Clark	MERIWA	Distal Footprints of Giant Ore Systems: Capricorn WA case study	$867,000
O'Reilly	NCRIS AuScope	Earth composition and evolution	$211,000
Piazolo	AINSE	Neutron activation analysis of natural polycrystalline diamond aggregates	$1,360

Investigators	2015 Funding Source	Project Title	Amount
Fiorentini	Rio Tinto	The applicability of Ru-chromite signatures in the exploration for picrite-hosted Ni-Cu-PGE sulfide deposits	$100,000
Rushmer, Zellmer	National Geographic Society	Dynamics of magma ascent beneath New Zealand's subduction zone volcanoes: implications for hazard mitigation strategies	$24,292
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (Minerals Targeting International Pty Ltd)	Lithospheric architecture mapping in Phanerozoic orogens	$60,000
Pisarevsky	UWA-UQ Bilateral Research Collaboration award	Orogenic bending and the sedimentary record	$5,540
O'Reilly	DVCR Discretionary Fund	EOI for CoE 2017 round	$12,500
Clark	MQRIBG	*In-situ* study of materials under deep Earth conditions: building on synergies between current Raman and Diamond Anvil capabilities	$64,877
Afonso	MQRIBG	Cluster Computing for Large-Scale Geophysical Simulations: Towards an Integrated Multidisciplinary Framework	$98,500
Gardner	MQPGRF	What can asymmetry tell us? Investigation of asymmetric versus symmetric pinch and swell structures in nature and simulation	$4,623
Stuart	MQPGRF	Flow characteristics of lower crustal rocks: characterising melt migration in the lower crust	$4,858

Appendix 9: Standard performance indicators

All values maximised at double target

Area	Category	Code	Indicator		Value	Note
RESEARCH	Number & quality of publications	R1	Research outputs	Actual	146	
				Target	40	
		R2(a)	Journals with Impact Factor >2.5	Actual	83%	
				Target	70%	
		R2(b)	Journals with impact Factor >3 Note: (20%>6)	Actual	78%	
				Target	50%	
		R2(c)	Journals with specific target audiences	Actual	17%	
				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	225	
				Target	30	
		R3(b)	Number of invited or keynotes given at major international meetings	Actual	17	
				Target	8	
		R4	Number & nature of commentaries on Centre's achievements in general/specialist publications	Actual	29	
				Target	8	
		R5(a)	Citation data for publications: at least 4 CI's in top 200 Geoscientists	Actual	4	
				Target	4	
		R5(a)	Citations for all CCFS publications (2014)	Actual		3675 (Thomson Reuters - Web of Science)
	Research training and professional education	R6	Number of attended professional training courses for staff and postgraduate students	Actual	23	
				Target	10	
		R7	Number of Centre attendees at all professional training courses	Actual	43	
				Target	20	
		R8	Number of new postgraduates working on core Centre research, supervised by CoE staff (PhD, MRes)	Actual	16	
				Target	8	
		R9	Number of new postdoctoral researchers recruited to the CoE working on core Centre research	Actual	3	
				Target	4	
		R10	Number of new Honours students working on core Centre research & supervised by CoE staff	Actual	0	Now MRes at MQ - Target to be reviewed
				Target	6	
		R11(a)	Number of postgraduate completions working on core Centre research and supervised by CoE staff	Actual	14	
				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	13	
				Target	6	
		R13	Number of students mentored	Actual	87	
				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	79	
				Target	20	
		R16	Number of national and international workshops held / organised by Centre	Actual	9	
				Target	3	
		R17	Number of visits to overseas laboratories and facilities	Actual	41	
				Target	20	
		R18	Examples of relevant interdisciplinary research supported by the Centre	Actual	93%	
				Target	50%	

Area	Objective	No.	Indicator		Value
RESEARCH	Build end-user links	R19	*Number of government, industry & business community briefings*	*Actual*	6
				Target	6
		R20	*Number and nature of public awareness programs*	*Actual*	5
				Target	5
		R21	*Currency of information on the Centre's website*	*Actual*	6
				Target	4
		R22	*Number of website hits*	*Actual*	13,837
				Target	8,000
		R23	*Number of public talks given by centre staff*	*Actual*	11
				Target	6
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*	2,561,580
				Target	1,790,000
		O2	*Annual in-kind contributions from collaborating organisations*	*Actual*	13,358,018
				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*	1,340,795
				Target	1,229,300
		O5	*Other research income secured by Centre staff*	*Actual*	11,235,256
				Target	140,000
		O6	*Number of new organisations collaborating with, or involved in, the Centre*	*Actual*	43
				Target	5
		O7	*Level and quality of infrastructure provided to the Centre*	Documented *p.73*	
GOVERNANCE	Intersect the right set of expertise to guide the Centre	G1	*Breadth, balance and experience of the members of the Advisory Board*	The Advisory Board includes senior representatives from industry and other end users such as Geoscience Australia (documented p.8), and was endorsed by the Mid-term Review Panel.	
		G2	*Frequency, attendance and value added by Advisory Committee meetings*	Two very productive Advisory Board meetings were held in April and July, 2014. Attendance at the meetings was over 90%. Frequency of Board meetings exceeded target. Board input has been invaluable, including providing a different perspective of Centre activities, and has been very engaged in workshopping key aspects of Centre business and in realigning the CCFS Vision. *"During the site visit the Panel spoke with members of the Advisory Board and found there was effective engagement between the Centre and the Board and that the Board was pleased with the Centre's scientific achievements and interdisciplinary work across the country."* (Extract, CCFS Review Panel Report, Sept. 2014)	
		G3	*Vision and usefulness of the Centre strategic plan*	Strategic plan was reviewed mid 2014 and endorsed by the CCFS Board and executive.	
		G4	*Adequacy of the Centre's performance measure targets*	Centre's performance measure targets are discussed with the board annually. CCFS has consistently performed well against the current measures. As a result of feedback and reassessment post review, they continue to be revised on a regular basis.	
		G5	*Effectiveness of the Centre in bringing researchers together to form an interactive and effective research team*	*"The Centre, now half way through its seven year term, has quickly evolved into an integrated entity that is addressing fundamental problems around water and mineral resources, and is offering Australian researchers opportunities to work on large-scale problems over longer time periods."* (Extract, CCFS Review Panel Report, Sept. 2014)	

GOV	Intercest expertise cont…	G6	*Capacity building of the Centre through scale and outcomes*	*"The Centre is building Australia's capacity in Earth science research and is attracting personnel to the Centre from within Australia and abroad."* *"Through its personnel and partnerships the Centre is serving as a point of interaction, particularly amongst the international research community and industry sector. Senior researchers described the Centre as "leading the national conversation in mineral exploration science". The researchers viewed the Centre as bringing the geoscience community together, and that the Centre's seven (7) year program is just the start of this effort."* (Extract, CCFS Review Panel Report, Sept. 2014)

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		20	
		N2	*Postgraduate units established by end year 3*	*Actual*	6	
				Target	2	
			Number of honours and Postgraduate students		87	

CCFS KPI	Outcomes	C1	*Linkage of geochemical / petrologic / geological data with geophysical datasets / modelling* *2014 - Convene international conference on integration of geophysics / geology*	*Actual*	Complete	
				Target	Complete	*Brisbane IGC, 2013*
		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*	Complete	
				Target	Complete	
	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.
- **International Postgraduate Research Scholarships (E-IPRS Endeavour Scholarships):** available to overseas students to cover tuition fees with a closing date in late August annually (http://www.innovation.gov.au/InternationalEducation/EndeavourAwards/Pages/default.aspx).
- **Macquarie University 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).
- **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)
- **China Scholarship Council - Post-graduate Study Abroad Program** is a national scholarship program financing outstanding Chinese students (Chinese citizens) to study at top universities around the world. Curtin, Macquarie and UWA are partner universities in this program (http://www.csc.edu.cn/).

CCFS also provides research funding through competitive internal schemes; 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 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
(i)MQRES	(International) Macquarie University Research Excellence Scholarships
MQSIS	Macquarie University Strategic Infrastructure Scheme
MOU	Memoranda of Understanding
NASA	National Aeronautics and Space Administration
NCRIS	National Collaborative Research Infrastructure Scheme
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
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MACQUARIE University

Curtin University

THE UNIVERSITY OF WESTERN AUSTRALIA

GEOLOGICAL SURVEY WESTERN AUSTRALIA

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