2018

Annual Report

CCFS

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/

- Contact CCFS via email at:

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: These balls and dendrites of native vanadium are enclosed in crystals of hibonite ($CaAl_{12}O_{19}$) ejected from Cretaceous volcanoes on Mt Carmel in northern Israel. The balls nucleated as droplets on the faces of growing hibonite crystals, when a vanadium melt became immiscible with the Ca-Al silicate melt that was crystallising hibonite, grossite ($CaAl_4O_7$) and spinel, in a magma chamber near the crust-mantle boundary. The dendrites grew out into the silicate melt, and were overgrown by the hibonite. The presence of vanadium melts testifies to the most reduced conditions yet recognised on Earth, equivalent to the oxygen fugacity of the early solar nebula, where the atmosphere was dominated by hydrogen. See Research highlight pp. 57-59.

QR code to view 3D images

Cover and Report design 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 2018 (formally 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: GEMOC from Macquarie University (Administering Institution), Curtin University (TiGeR) and CET at the University of Western Australia (Collaborating Institutions). The Geological Survey of Western Australia is a Partner Institution and researchers from Monash University, the University of Melbourne and the University of New South Wales are formally affiliated.

The 7-year allocated funding from the ARC ceased at the end of 2018, but ARC formally granted continuation of the status of CCFS as an ARC Centre of Excellence for three years, contingent on demonstration of a relevant, funded continuing research program and retention of key researchers. The latter was easy to fulfil, as CCFS attracted awards for eleven ARC Future Fellows and two Laureate Fellowships. Eight of the Future Fellows (including four women) have become, or are transitioning to, full-time academic staff positions, providing a powerhouse of outstanding mid-career (and gender-balanced) intellectual depth across the collaborating institutions. CCFS thus has forged a dynamic researcher cohort, now forming the next generation of leading researchers who are part of the Australian and global geoscience fabric. Those in CCFS nodes now lead research programs, have initiated new strategic directions, and some have initiated new University Centres, springboarding from CCFS in new directions.

73 PhD students undertook research aligned with CCFS in 2018. CCFS postgraduates are producing world-class research with authorship of 42 publications (29 first-authored) in high-impact journals in 2018 and 75 presentations at peak international workshops and conferences. 163 PhD students and 43 early-career researchers have participated in CCFS until now.

CCFS created a world-leading, enduring and uniquely interdisciplinary geoscience framework that seamlessly incorporates information across geoscience datasets including those from geophysics, geochemistry, tectonics, geology, numerical modelling, Bayesian mathematics and the imaging of minerals, rocks and Earth domains from nano- to global-scales. This was built on the visionary goals and breakthroughs achieved in the preceding GEMOC National Key Centre (www.GEMOC.mq.edu.au) and has taken that holistic approach to

understanding Earth processes to a new level. A few eclectic examples include:

- Presenting element and isotopic data as contoured images on regional scales, making geochemical data (traditionally presented as multi-element diagrams and plots) as accessible as geophysical tomography images
- Driving the resurgence of experimental simulations of high-pressure and temperature conditions at varying depths within the Earth (including creation of a distributed national infrastructure network)
- Refining palaeomagnetic reconstructions and methodologies to better understand Earth's tectonic evolution, and especially the assembly, breakup and relative positions of continents over Earth's 4.65 billion year history
- Recognising domains of ultra-high pressure rocks excavated from depths of the mantle transition zone (>400 km) and defining, for the first time, unique microstructural characteristics to refine seismic interpretations, and to screen other ultramafic rocks for possible deep-Earth origins
- Developing new cutting-edge *in situ* geochemical analytical methods with new instrumentation including imaging of atomic environments in minerals, multi-split streaming for laser-sampled analyses, and continuing the quest for higher resolution analysis of lower and lower element and isotopic abundances
- Forming alliances with instrument manufacturers to revolutionise hardware design of e.g. detectors, to enable analysis of critical light elements (e.g. C, O, H, N)
- Discovering new extreme conditions (e.g. ultra-reduced) within regions of the mantle from at least ~400 km to shallow volcanic systems, revealing conditions within the Earth equivalent to those in the solar nebula and in some

meteorites and providing new knowledge of the carbon, nitrogen and hydrogen cycles from the deep mantle to the surface
- Innovative geodynamic modelling to probe the nature of the early Earth and huge advances towards the holy grail of theoretical multi-observable probabilistic prediction of the composition of the lithospheric mantle and beyond (with evolving open-access software)
- Ground-breaking development of adjoint methodologies for processing seismic data; collaborations with Chinese colleagues to gain unprecedented geophysical data and images of many regions in western and eastern Australia and analogue terranes globally
- Using leading-edge microstructural imaging and analysis to better understand geophysical signals, mantle deformation and mineral characteristics

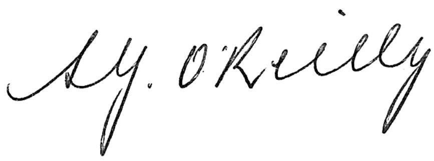
The interdisciplinary environment within CCFS has inspired teams to work across the boundaries of geophysics, geochemistry, petrology and geodynamic modelling to develop new holistic understandings of core to crust fluid systems. One of the most exciting outcomes (from 2 early-career researchers) will be presented to the 2019 Goldschmidt Conference: *A unified model for mantle magmatism* (see *Research highlight, p. 45 for a preview*). The Research Highlights (collated version downloadable from http://ccfs.mq.edu.au/Research Highlights/), presented in the Annual Report for each year of CCFS are an impressive record of the rich tapestry of new Earth knowledge that has been created - and the individual research components that contributed. The eclectic items listed here only skim the surface.

The CCFS Vision *"Delivering the fundamental science needed to sustain Australia's resource base"* has been more than fulfilled over the last seven years. CCFS has continued to be a significant thought-leader in global geoscience research, and has become influential in shaping the national research and geoscience agenda. Such contributions include:

- CCFS participants made significant contributions to the AMIRA *"Undercover Roadmap"* (http://www.amirainternational.com/WEB/site.asp?section=activities&page=ExplorationUnderCover-STAGE2-RegistrationForm)
- CCFS Chief and Associate Investigators, collaborating researchers and Board members have continued assisting the advance of UNCOVER Australia (https://www.uncoveraustralia.org.au/), including fruitful discussions with senior Department of Industry Innovation and Science (DIIS) representatives and with the Office of the Shadow Minister for Science. These discussions are helping shape government resource policies.
- CCFS CIs and Board representatives were members (and Chair) of the Australian Academy of Science National Committee for Earth Science (NCES) in 2018. In that capacity, they played a key role in producing the Decadal Plan for Australian Geoscience *"Our Planet, Australia's Future: A decade of transition in Geoscience"* which was launched in October 2018. See *p. 22*.
- CCFS representatives have contributed numerous submissions to the Chief Scientist on geoscience infrastructure and its role in Australia's sustainable energy future.
- CCFS representatives have been active in contributing to Workshops planning the future strategy and vision for NCRIS AuScope
- Australian Honours awarded to CCFS Board members Jon Hronsky and Phil McFadden, in 2018, and Sue O'Reilly's previous award, all for services to national geoscience, demonstrate the national recognition of CCFS influence

CCFS' huge and rapidly growing international network has forged collaborations that bring complementary expertise, funded resource leverage, access to an unsurpassed virtual laboratory for geochemical analysis and imaging, experimental capabilities, geophysical instruments and techniques, and global natural laboratories that provide analogues to understand the Australian continent where its geological clues are hidden beneath cover.

CCFS has exceeded its original goals: it has delivered transformational new geoscience knowledge relevant to Earth's composition, evolution, geodynamics and structure, has transferred fundamental new research results to mineral exploration entities, has mentored and delivered a substantial new generation of outstanding mid- and early-career researchers, and has become an influential voice in Geoscience strategy and policy. We are proud of these enduring legacies.



Professor S.Y. O'Reilly

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

Vision

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

GOALS - THE MISSION

- **to reach a new level of understanding of Earth's internal dynamics and fluid cycles, and how these have evolved to generate the hydrosphere, continents and atmosphere**
- **to provide a world-leading interdisciplinary research environment for the development of the next generation of Australia's geoscientists**
- **to deliver new concepts about the spatial and temporal distribution of Earth resources to the minerals and energy industries**
- **to develop new educational approaches that can renew and revitalise Australian research in the Earth Sciences**

CONTEXT

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

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

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

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

CENTRE RESEARCH

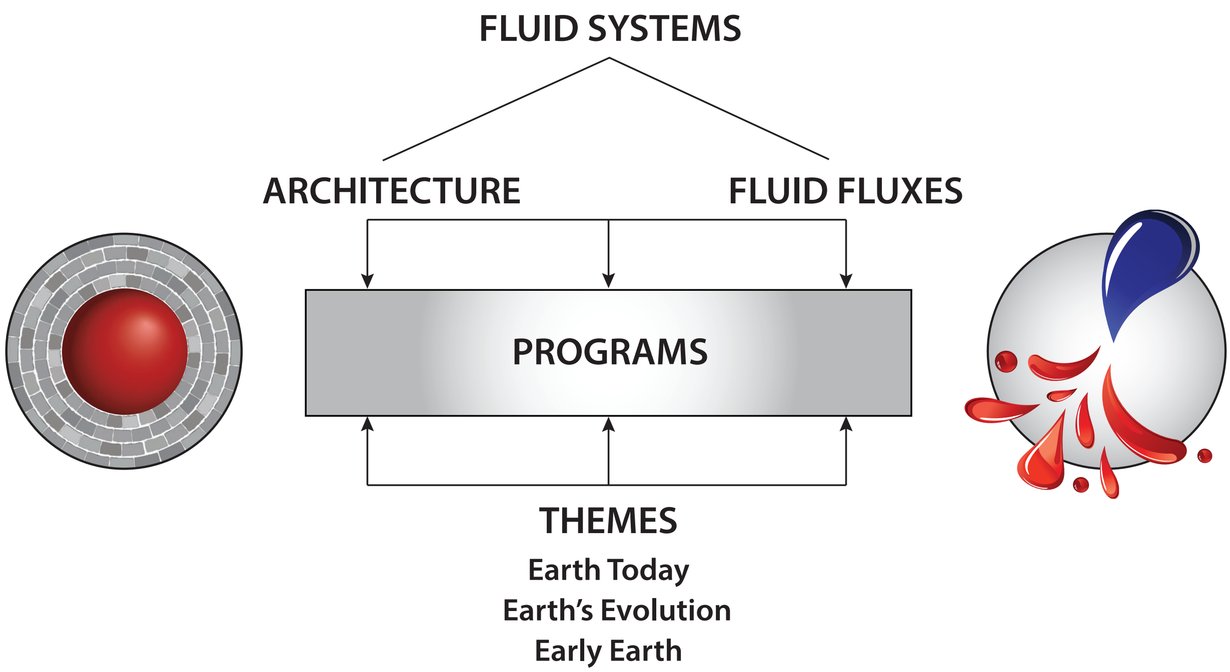
Research programs within the Centre are focused to provide maximum synergy for the scope enabled by the resource base. As it is not possible to encompass the full range of research about the Earth's fluid cycle and deep Earth dynamics, all applied and mature strategic research is carried out in parallel, 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. 16*) were put in place as cross-node streams contributing to the three global Themes (Early Earth, Earth's 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:



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

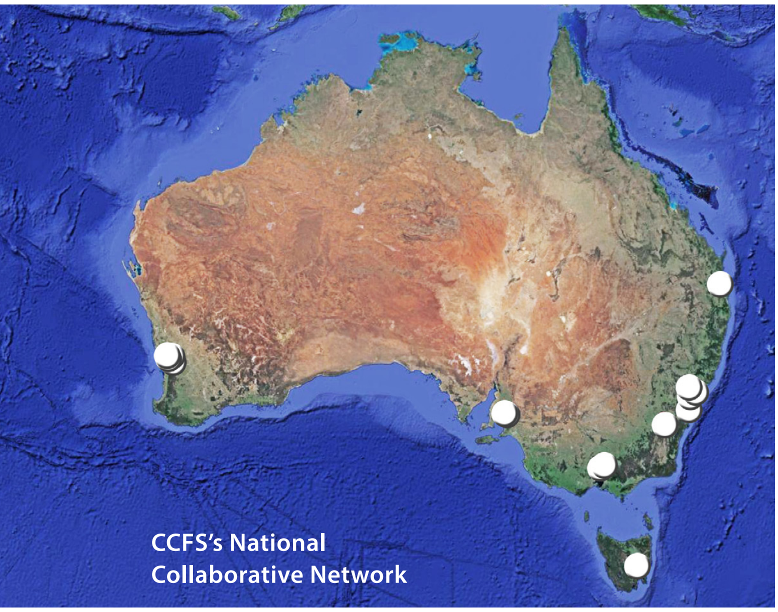
Earth Today - Dynamics, decoding geophysical imaging, and Earth resources. Geophysical imagery gives us a snapshot of the current status of the deep Earth but also carries the imprints of past processes. Realistic interpretation of these data will give us new insights into Earth's internal dynamics and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

A glimpse back into the Archean - Single-celled living fossils, thrombolites, at Lake Clifton south of Mandurah, WA (photo: Zheng-Xiang Li).

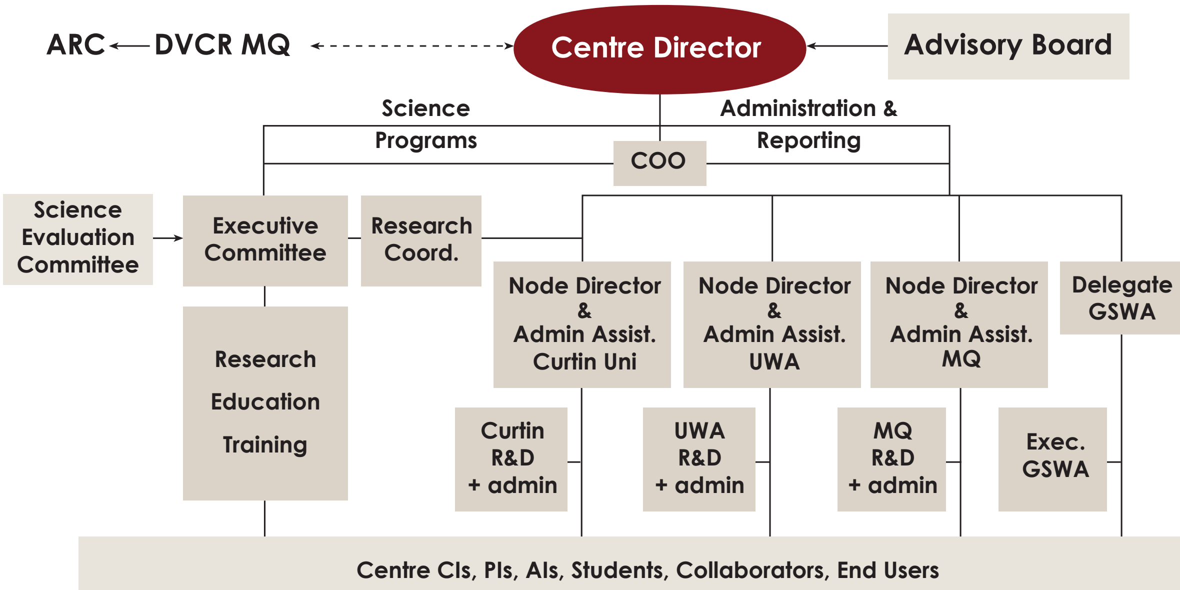
Structure

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 six additional global institutions with leading reputations in the field. CCFS also has formal Cotutelle MOU with a further fourteen global institutions (see *p. 96*). 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*).



Governance & management

Centre Director Professor Suzanne O'Reilly is supported by a Chief Operating Officer and a Reporting and Communications Manager. 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 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

Associate Professor 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

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

Associate Professor Matthew Kilburn
Deputy Director, CMCA
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
Former 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
Treasurer and Executive Committee,
Fellow, Australian Academy of Science;
driver of the UNCOVER initiative

Dr Roric Smith
Consulting Geologist
Evolution Mining

(Ex Officio)
Dr Campbell McCuaig
Principal Geoscientist
Geoscience Centre of Excellence
BHP Billiton

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

Associate Professor Elena Belousova - MQ

Professor Simon Clark - MQ

Associate Professor Marco Fiorentini,
Node Leader - UWA

Professor Stephen Foley, Research Coordinator - MQ

Professor William Griffin - MQ

Associate Professor Matthew Kilburn - CMCA/UWA

Professor Zheng-Xiang Li - CU

Associate Professor Alexander Nemchin - CU

Associate Professor Craig O'Neill - MQ

Professor Suzanne Y. O'Reilly, Director - MQ

Professor Martin Van Kranendonk - UNSW

Professor Simon Wilde, Node Leader - CU

Associate Professor Yingjie Yang - MQ

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

Partner Investigators

Australian Partner Investigator

Dr Klaus Gessner - GSWA

Dr T. Campbell McCuaig - BHP Billiton

International Lead Partner Investigators

Professor Michael Brown - University of Maryland

Dr David Mainprice - Université de Montpellier

Professor Catherine McCammon - Bayreuth University

Professor Fuyuan Wu - CAS Beijing

Associate Investigators

Professor Juan Carlos Afonso - MQ

Dr Olivier Alard - MQ

Associate Professor Nathan Daczko - MQ

Professor Simon George - MQ

Dr Richard Glen - MQ Adjunct Professor

Dr Masahiko Honda - Australian National University

Professor Dorrit Jacob - MQ

Associate Professor Mary-Alix Kaczmarek - University Paul Sabatier Toulouse III

Associate Professor Christopher Kirkland - CU

Professor Jochen Kolb - GEUS

Dr Yongjun Lu - GSWA

Professor Louis-Noel Moresi - University of Melbourne

Professor Steven Reddy - CU

Associate Professor Tracy Rushmer - MQ

Associate Professor Bruce Schaefer - MQ

Professor Paul Smith - MQ

Professor Simon Turner - MQ

Dr Michael Wingate - GSWA

Professor Shijie Zhong - University of Colorado, Boulder, USA

Early Career Researchers

Dr Raphael Baumgartner - UWA

Dr Montgarri Castillo-Oliver - MQ

Dr Denis Fougerouse - CU

Dr Rongfeng Ge - CU

Dr Andrea Giuliani - DECRA - MQ at UM

Dr Christopher Gonzalez - UWA

Dr Johannes Hammerli - UWA

Dr Hadrien Henry - MQ

Dr Uwe Kirscher - CU

Early Career Researchers

Dr Crystal LaFlamme - UWA
Dr Nora Liptai - MQ
Dr Jianggu Lu - MQ
Dr Ross Mitchell - CU
Dr Hugo Olierook - CU
Dr Beñat Oliveira Bravo - MQ
Dr Luis Parra-Avila - UWA
Dr Romain Tilhac - MQ
Dr Lei Wu - CU
Dr Weihua Yao - CU

NEW STAFF

Dr Luc-Serge Doucet joined CCFS as part of Prof Zheng-Xiang Li's ARC Laureate team at Curtin University to work on data mining and the field-based Oceanic-LIP project.

Luc-Serge completed a PhD at the Université Jean Monnet. His research focused on studies of the formation and evolution of the lithosphere using major, minor and trace elements and isotopic data (Re/Os, Lu/Hf, Zn, Fe, Cu, etc.) as well as petrographic and petrophysic observations.

ECRs *(featured on pp. 9-14 of our ECR section)*

Dr Hadrien Henry - MQ
Dr Nora Liptai - MQ
Dr Jianggu Lu - MQ
Dr Lei Wu - CU

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. Eleven Future Fellows; Associate Professor Elena Belousova, Associate Professor Marco Fiorentini, Dr Heather Handley, Professor Dorrit Jacob, Associate Professor Craig O'Neill, Professor Sandra Piazolo, Associate Professor Yingjie Yang, Dr Xuan-Ce Wang, Dr David Wacey, Dr Olivier Alard and Dr Kate Selway have completed or are working on projects relevant to CCFS goals. The CCFS Future Fellows all continue to make significant contributions to CCFS, either directly or as external collaborators and Associates. Their profiles can be accessed from the "*Participants*" section of our previous reports (http://www.ccfs.mq.edu.au/AnnualReport/Index.html).

Those of this outstanding cohort who have completed their Fellowship, have now transitioned to permanent high-level positions and become international research leaders in roles both nationally and abroad. Those in CCFS nodes now lead research programs, have initiated new strategic directions, some with new University Centres, springboarding from CCFS in new directions.

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*".

These CCFS ECRs have all achieved high positions, both nationally and abroad, and are having significant impact across many countries including Japan, Spain, Chile, USA, Europe and Asia. They are contributing in diverse areas that include: the nuclear science and environmental sector, CSIRO, Geological Surveys, international Research Centres, Government instrumentalities, the exploration industry and in consultancies in the private sector.

The following profiles present 2018 ECRs and summarise their expertise and research areas.

NEW 2018

Dr Hadrien Henry is a Research Associate at CCFS, Macquarie University. He completed his BSc and MSc at the Université Paul Sabatier Toulouse III. In 2015, he commenced a cotutelle PhD degree between Macquarie University and Université Paul Sabatier, Toulouse III. Hadrien's thesis focused on the microstructure and petrophysics of pyroxenites and mantle using samples from the Cabo Ortegal Complex, Spain and the Trinity ophiolite, California, USA. In 2018, he graduated from Université Paul Sabatier Toulouse III, and will graduate from Macquarie University in early 2019. As a Research Associate in CCFS at Macquarie University, Hadrien works on the microstructure of olivine megacrysts from Åheim peridotite body in western Norway and takes part in multiple collaborations involving Electron BackScattered Diffraction (EBSD) and the study of microstructures. Hadrien is also part of the *TerraneChron*® team at CCFS. This research contributes to CCFS Flagship Program 1. See *Research highlight pp. 54-55.*

Dr Nora Liptai joined CCFS as a cotutelle student with Eötvös Loránd University in Budapest, Hungary after completing her undergraduate degree there. Nora commenced her PhD studies with CCFS at Macquarie University on *"The Geochemical and physical properties and evolution of the lithospheric mantle beneath the Nógrád-Gömör Volcanic Field (Northern Pannonian Basin, Central Europe)"* in 2015.

This study derived and interprets an extensive integrated set of analytical and imaging results for upper mantle peridotite xenoliths from the northern Pannonian Basin, Central Europe, including mineral, whole-rock and melt-inclusion petrography and geochemistry, crystal preferred orientation and *'water'* contents. A sequence of geochemical, deformation and tectonic processes is reconstructed, tracing the geodynamic evolution of the region. Multiple metasomatic events by a variety of different infiltrating mafic melts at different times prior to entrainment by the host alkali basalt are identified, as well as deformation due to recent tectonism.

On completion of her PhD, Nora became part of the *TerraneChron®* team at CCFS until September 2018. She then commenced a postdoctoral research position at the Geodetic and Geophysical Institute, Hungarian Academy of Sciences, Budapest, Hungary, continuing her studies of mantle geochemistry and physical properties. This research contributes to CCFS Flagship Program 1. See *Research highlight pp. 43-44*.

Dr Jianggu Lu was awarded a cotutelle PhD by China University of Geosciences and CCFS at Macquarie University. Her project examined mantle xenoliths from southeast China and southeast Australia, *"Investigating the Nature and Evolution of the Lithospheric mantle"*.

Studies of peridotite xenoliths from SE China show how the residual refractory lithospheric mantle has become more fertile through multi-stage melt infiltration related to paleo-Pacific subduction. Garnet pyroxenite xenoliths from southeastern Australia record partial melting of the convective mantle wedge above an analogous subduction zone; they crystallised from the earliest recognised mafic melts to infiltrate the lithospheric mantle, and imprint a geochemical record of subsequent tectonic uplift. Decoding these complex records allowed reconstruction of lithospheric evolution and the nature and origins of volatile fluxes from the deep Earth through time.

In September 2018, Jianggu commenced a Research Associate position at the Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou China. This research contributes to CCFS Flagship Program 1.

Dr Lei Wu received his PhD in 2017 from the University of Alberta, Canada where he reconstructed the amalgamation history of East Asia using paleomagnetic and seismological data. After his PhD, Dr Wu conducted a nine-month postdoc applying the shear wave splitting and receiver functions methods to determine the upper lithospheric mantle / crustal anisotropy in the Western Canada Sedimentary Basin. In 2018, Dr Wu commenced a two-year postdoc position with CCFS at Curtin University, working with Zheng-Xiang Li to build a new global full-plate paleogeographic model. His research interests involve geophysics, paleogeographic reconstruction, seismology and paleomagnetism. This research contributes to CCFS Flagship Program 5.

CONTINUING

Dr Raphael Baumgartner received his MSc in Economic Geology from the University of Leoben (Austria). He joined CCFS/CET at UWA in June 2013, as a PhD candidate, seeking to unravel the potential of martian igneous systems to host precious metal-enriched sulfide mineralisation. His work provided important insights into the behaviours of (highly) siderophile and chalcophile elements in martian mantle reservoirs and derived igneous systems through mineral-scale analytical experiments on sulfide and oxide phases from shergottite and chassignite meteorites - a rare group of meteorites that are thought to represent samples of the volcanic martian crust.

At the completion of his PhD, Raphael was employed as a Research Associate at CET. His research focused on the 3.5 Ga old stromatolites at North Pole Dome, Dresser Formation, Pilbara (WA) and their link to hydrothermal fluids.

He examined whether such fluids delivered transition metals such

as Zn, Mo and Ni, known to be key ingredients for bacterial metabolism and thus likely catalysts for the origin of life on Earth. For this research, Raphael examined the micron- to nano-scale textural and trace metal characterisation of associated Fe- and Zn-sulfide laminate using systematic *in situ* multiple sulfur-isotope analyses to unveil the potential microbial component of sulfide precipitation.

In 2018 Raphael took up a postdoctoral position at UNSW to continue his work with Martin Van Kranendonk's group. Raphael's research contributes to CCFS Flagship Program 4.

Dr Montgarri Castillo-Oliver completed her Bachelor and Master degrees in Geology at Universitat de Barcelona. In November 2014, she joined CCFS as a cotutelle PhD student, carrying out her research both at Universitat de Barcelona and Macquarie University. During her PhD, Montgarri characterised several Angolan kimberlites of the Las Lundas province, as well as their diamond indicator minerals (mainly ilmenite and garnet). She also studied their mantle xenoliths to better understand the structure and metasomatic evolution of the subcontinental lithospheric mantle in NE Angola. In 2016, she graduated with a PhD from both universities

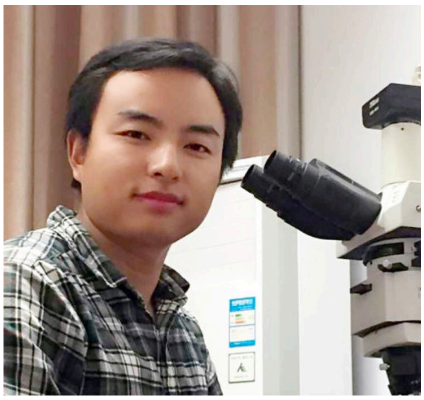
Since then, Montgarri has been employed as a Research Associate by CCFS at Macquarie University. Her postdoctoral research is based on the use of *in situ* techniques [(MC)-LA-ICP-MS and SIMS] to characterise primary and secondary carbonates in kimberlites worldwide, combining textural information with *in situ* compositional and isotopic (C, O and Sr) analysis. This integrated approach provides new insights into the isotopic composition of the parental kimberlite melt, and thus that of the Earth's mantle. It also allows discrimination between the different processes that led to carbonate formation in kimberlites (i.e. magmatic and deuteric crystallisation, degassing, weathering, etc.). By studying the C isotope variation of the deep mantle with space and time, Montgarri aims to contribute to the current understanding of the deep Earth's carbon cycle in cratonic roots. This research contributes to CCFS Flagship Program 1. See *Research highlight pp. 38-39.*

Dr Denis Fougerouse completed his BSc at the university of Saint-Etienne (France). His MSc, at the University of Nancy (France), focused on the timing of mineralisation events in the West Africa Craton using Re-Os dating. In 2012, Denis commenced his PhD at the University of Western Australia in the Centre for Exploration Targeting (CET). Completed in 2015, his PhD focused on the mineralisation processes occurring in the giant Obuasi gold deposit.

Denis is currently a Postdoctoral Research Associate at Curtin University in the Geoscience Atom Probe group. He has worked on developing the geological applications of atom probe microscopy to a wide range of minerals including zircon, monazite, titanite, plagioclase and sulfides. In particular, Denis is investigating the mobility of trace elements and their implications for geochemistry and geochronology. His research contributes to CCFS Flagship Program 2.

Dr Rongfeng Ge completed his undergraduate and MSc studies at Nanjing University (China) and joined CCFS in 2012 as a cotutelle PhD candidate. He received his PhD degrees from Nanjing University in December 2014 and from Curtin University in August 2015 and became a Research Associate at Curtin University. Rongfeng's study interests included the origin and evolution of continental crust, the reconstruction of Precambrian supercontinents, and the tectonic evolution of orogenic belts. His primary focus was on the Tarim Craton, NW China, and the Central Asian Orogenic Belt. Through multiple laboratory techniques and field-based work, his study revealed the oldest rocks and crustal components from the Tarim Craton, a Tarim - North China connection in the Columbia/Nuna supercontinent, and a long-lived subduction - accretionary orogenic system at the circum-Rodinia subduction zone.

Rongfeng's research then focused on the Hadean detrital zircons from Jack Hills. Using cutting-edge techniques, including ion imaging and the atom probe, Rongfeng re-examined isotopic and elemental distributions and compositions of these ancient and complex zircon grains. This study provided new insights into the origin of continental crust and the geodynamic setting in the early Earth.



In May 2018, Rongfeng left CCFS to take up the position of Associate Professor at Nanjing University where his research focuses on the Precambrian geological evolution of the Tarim Craton. This research contributes to CCFS Flagship Program 6.

Dr Andrea Giuliani joined CCFS in June 2015 as an ARC DECRA (Discovery Early Career Research Award) Fellow. Andrea completed his PhD in mantle geochemistry at the University of Melbourne in 2013 where he then undertook a year of post-doctoral research in 2014 before becoming a lecturer in Igneous Petrology in January 2015.

Andrea's research focuses on the composition and sources of deep Earth fluids and melts - including kimberlites, which are the primary source of terrestrial diamonds. Kimberlites represent the deepest melts that reach the Earth's surface and therefore provide a unique probe into the deepest realms of our planet.

At CCFS, Andrea is working closely with Professors Sue O'Reilly, Bill Griffin and Steve Foley to improve current understanding of the evolution of the Earth's interior and the melting processes affecting it, with particular attention to the role of volatiles and recycled crustal and surface material that trigger deep melting events. His research contributes to CCFS Flagship Program 1. See *Research highlights pp. 38-39, 42-43*.

Dr Christopher Gonzalez joined the CET and CCFS team, first as a PhD student in 2012, and then as a Research Associate. Chris graduated from the University of Minnesota, Twin Cities with Bachelor of Science degrees in Geology and Geophysics (2011). Chris undertook PhD studies at CET as part of an Arc Linkage project *"Multiscale Dynamics of Ore Body Formation"*.

His research included numerical modelling of geodynamic processes with a focus on H_2O-CO_2 fluids. Using a thermomechanical numerical modelling code (I2VIS), new (de) carbonation routines and carbonated lithologies were coded into I2VIS during his thesis to gain a better understanding of the two most abundant recycled volatiles on Earth (H_2O and CO_2).

As a Research Associate, he applied this code to quantitatively assess metasomatism and melting processes ongoing during continental collision using the Ivrea-Verbano zone as a natural laboratory. Specifically, sulfur-rich carbonate bearing 'pods' have been observed and are thought to be a direct consequence of slab derived carbonic fluids interacting with the mantle wedge. To examine this hypothesis, Chris used his code to numerically constrain the sequence of events that led to the formation of the sulfur-rich carbonate pods. This research aligned with CCFS Flagship Program 2.

In Feb 2018, Chris moved to the School of Earth Atmosphere & Environment at Monash University to take up the position of Assistant Lecturer.

Dr Johannes Hammerli completed his MSc in Earth Sciences at the University of Bern, Switzerland, before moving to Townsville, Australia. He received his PhD from James Cook University in 2014, where he studied element mobility during metamorphism and the identification of hydrothermal fluids by microanalysis. In late 2014 Johannes joined CET on a Swiss National Science Foundation Fellowship. During this time, he focused on studying crustal differentiation and evolution. In May 2016, Johannes joined the CCFS research group where he used the microanalysis of accessory minerals, in particular apatite from magmatic systems, to unravel processes which lead to the fertile systems feeding ore deposits.

In mid 2019, Johannes will return to the University of Bern, where he will commence an Ambizione fellowship. His research contributes to CCFS Flagship Program 2.

Dr Uwe Kirscher completed his PhD in geophysics at the Ludwig-Maximilians University in Munich in 2015 working on the Paleozoic paleogeography of the Central Asian Orogenic Belt using paleomagnetism. In early 2016, he joined Curtin University as a CCFS funded Research Associate as part of Professor Zheng-Xiang Li's Laureate team. His research interests are focused on Proterozoic paleomagnetic constraints of the Australian Precambrian blocks. He aims to use several paleomagnetic approaches to constrain and more precisely understand the supercontinent cycle and its geodynamic features. His research contributes to CCFS Flagship Program 5.

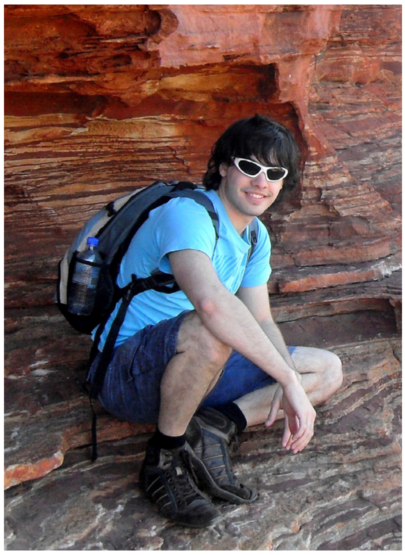
Dr Crystal LaFlamme attended Acadia University for her BSc and completed her MSc at Memorial University of Newfoundland studying the tectonostratigraphy and formation of volcanic rocks of the Makkovik Province in northern Labrador. Her PhD at the University of New Brunswick investigated the formation and geodynamic evolution of a reworked Archean high-grade terrane in the Western Churchill Province in the Canadian Arctic.

In February 2015 Crystal joined CCFS/CET as a Postdoctoral Research Associate to study the sulfur isotope record of craton margins. Her research focuses on tracing anomalous sulfur isotope signatures preserved in the Archean-Proterozoic rock record to better understand large-scale crust formation processes and small-scale thermochemical processes leading to metal occurrences. This knowledge base is building to ultimately better understand the link between fluid-driving tectonic processes and ore genesis.

Crystal was awarded a tier II Canada Research Chair in sulfur isotope geochemistry at Carleton University, Canada. See *Research highlight p. 35.*

Dr Ross Mitchell is a Research Fellow in the Earth Dynamics Research Group at Curtin University. He completed his PhD in geology and geophysics at Yale University in 2013 on *"Supercontinents, the true polar wander, and the paleogeography of the Slave Craton".*

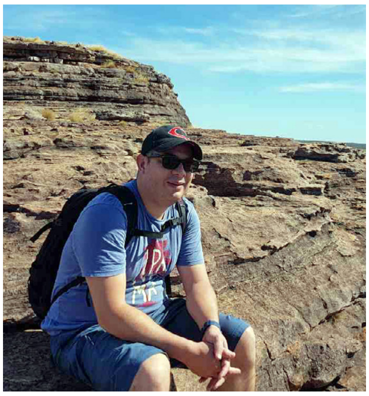
His interests centre on the supercontinent cycle, which describes not only the suturing and rifting of continents via plate tectonics but also the wholesale organisation of mantle convection patterns, which has consequences for true polar wander. Prior to Pangea, paleomagnetism is the only quantitative method for reconstructing continents. Ross conducts extended paleomagnetic sampling campaigns grounded in field geology. Synthesising newly acquired data with the global paleomagnetic database, he aims to both generate paleogeographic maps for 3 billion years of Earth history and to evaluate how such empirical constraints shape plate tectonic and true polar wander theory. He pairs these studies of ancient supercontinents with detailed magnetostratigraphic profiles of Phanerozoic time and electron-probe analyses of magnetic mineralogy in order to test the limits of paleomagnetism as a paleogeographic method. His research contributes to CCFS Flagship Program 5.



Dr Hugo Olierook completed his undergraduate studies at Curtin University in 2011. He continued at Curtin with a PhD examining the tectonic and stratigraphic evolution of the Western Australian margin. After completing his PhD in 2015, he moved to the University of Liverpool as an NERC postdoctoral associate studying reservoir quality in the United Kingdom and adjacent petroleum domains. In November 2016, Hugo returned to Curtin University and joined CCFS to take up a two-year postdoctoral fellowship as part of the SIEF Distal Footprints project in the Capricorn Orogen of Western Australia. Hugo used his expertise in geochronology, geochemistry, tectonics and geodynamics to understand the 3 billion year history of the Capricorn Orogen and its mineral endowment. In 2019 Hugo will continue at Curtin University as the manager of geochronology and geochemistry projects for the mining and mineral exploration industry, liaising with geological surveys around the globe.

Dr Beñat Oliveira completed his Bachelor and Master degrees in Civil Engineering at Universitat Politecnica de Catalunya. In February 2013, he joined CCFS-MG3 as a PhD student, where he developed an internally-consistent numerical platform for multiphase reactive transport modelling. The numerical model is based on two main ingredients: 1) a general and scalable multi-phase approach, coupled with 2) a sound chemical thermodynamic framework for the reactive and chemical transport phenomena. He continues with his research as a Research Associate in CCFS. In his current role, he has expanded his code

to quantitatively assess the origin and evolution of transcrustal magmatic systems, including both disequilibrium trace-element and isotopic modelling. This research contributes to CCFS Flagship Program 3. See *Research highlight p. 45*.



Dr Luis Parra-Avila, from Caracas, Venezuela, earned his PhD as part of CCFS at CET UWA, in 2016. His PhD project focused on establishing the crustal tectonic history of the Paleoproterozoic Domain of the West African Craton across Burkina Faso, Ghana, Mali, Ivory Coast and Guinea and its links to mineral deposits. The project was funded through the ARC linkage program and was part of the AMIRA West Africa Exploration Program (P934A).

In October of 2015, Luis became a Post-Doctoral Research Associate with a research focus on evaluating zircon characteristics and the link to porphyry Cu deposits. The project sought to develop new pathfinders to assist with the exploration of porphyry Cu deposits and to understand the difference between fertile and unfertile tectonic environments for such deposits.

Luis' research aims to unravel the geologic history of Northern Thailand. This project focuses on the tectonic history (collision and amalgamation) of continental and arc terranes, including closure of ocean basins across the Sukhothai (arc) terrane, Nan Suture zone and western Indochina terrane. It follows and expands on existing work in the Loei-Phetchabun Foldbelt and mid-Triassic intrusive magmatism associated with subduction of Paleotethys seafloor beneath western Indochina. The results of this study will provide a geologically *'young'* example of continental crustal evolution to compare with Archean and Proterozoic examples in Australia and other ancient cratonic regions elsewhere, as well as a context for understanding the formation of particular mineral deposits. His research contributes to CCFS Flagship Program 2.

Dr Romain Tilhac completed his BSc and MSc in Earth and Planetary Sciences at Paul Sabatier University in Toulouse, France. He joined CCFS in 2013 as a cotutelle PhD student between Macquarie University and Paul Sabatier University. Romain's thesis focused on the petrology, geochemistry and isotope geochemistry (Sr, Nd, Hf and Os) of arc-related mantle pyroxenites exposed in the Cabo Ortegal Complex, Spain. After graduating from both universities in 2016 and 2017, he took up a Research Associate position in CCFS at Macquarie University. His current research relates to the compositional evolution of the Earth's mantle and the genesis of mantle-derived magmas, and associated tectonics and geodynamics. He uses petrology, *in situ* and solution geochemistry and geochronology of mafic and ultramafic terranes to understand the sources and differentiation processes of arc magmatism with the aim to better understand elemental mobility and isotopic fractionation associated with pyroxenite petrogenesis and the role of fluid-melt-rock interaction in subduction zones. This research contributes to CCFS Flagship Program 1 (TARDIS II).

Romain also works in collaboration with Beñat Oliveira on the numerical modelling of reactive transport associated with melt generation, migration and differentiation, melt-rock interaction and metamorphic reactions as part of the Flagship Program 3.

In October 2017, he became the manager of the *TerraneChron*® team at CCFS. *TerraneChron*® integrates *in situ* analysis of U-Pb ages, Hf-isotopes, and trace-element concentrations of zircons and fosters collaboration with industry and geological survey partners. See *Research highlight p. 45*.

Dr Weihua Yao completed her undergraduate study at China University of Geosciences (Wuhan), and graduated with a PhD degree from Curtin University (August 2014). After her graduation, Weihua joined CCFS as a Postdoctoral Research Associate working with CCFS, TIGeR, ACTER and IGCP648 at Curtin University. Her research focused on sedimentary, stratigraphic and provenance correlations between the Indian-Australian Gondwana and Asian continents (including South China and Indochina blocks), and also the Precambrian paleogeography of Hainan Island in the supercontinents Nuna and Rodinia.

In April 2018 Weihua took up the position of Associate Professor at Guangdong Provincial Key Lab of Geodynamics and Geohazards, School of Earth Sciences and Engineering, Sun Yat-sen University, Guangzhou, China.

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 research programs, are determined by the funding base allocated by ARC with strategic leverage planned to expand available resources.

FLAGSHIP RESEARCH PROGRAMS

The original Foundation Programs for 2011-2014 were funded from the ARC Centre funds allocation, and included components from the Universities' funding support. Programs were 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. The Programs were designed to be interdisciplinary, cross-nodal and to foster participation of early-career/postgraduate researchers. Research directions 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 included three integrated projects targeted at Technology Development.

In 2014 the Flagship Programs were restructured 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 seven Flagship Programs (see *p. 16*) 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 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.

Aims and progress are detailed in *Appendix 1*.

***Appendix 2* presents the 2019 workplan.**

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

FLAGSHIP PROGRAMS (FROM 2014)

Program / Theme / Framework	Coordinator and main Centre personnel
1. Deep Earth fluids in collision zones and cratonic roots (TARDIS II) Themes 1, 2, 3 Earth's Architecture and Fluid Fluxes	**O'Reilly, Griffin**, Kilburn, Martin, Alard, Shafaii Moghadam, Huang, Gréau, Lu Giuliani, Castillo-Oliver, Tilhac (ECRs) Henry, Liptai (PhDs/ECRs) Greene (PhD)
2. Genesis, transfer and focus of fluids and metals Themes 2 and 3 Fluid Fluxes	**Fiorentini**, McCuaig, Foley, O'Reilly, Griffin, Reddy, Rushmer, Lu, Bagas, Kilburn, Loucks, Clarke Fougerouse, Gonzalez, Hammerli, LaFlamme, Parra-Avila (ECRs) Bennett, Dering, Jara, Lampinen, Poole (PhDs)
3. Modelling fluid and melt flow in mantle and crust Themes 2 and 3 Earth's Architecture and Fluid Fluxes	**O'Neill**, Afonso, Yang, Li, Foley, Clark, S. Zhang, Smith, O'Reilly, Griffin Jiang, Oliveira Bravo (ECRs) Förster, Lanati, Manassero, Pinter, Wasilev, Wang, Wu, Zhang (PhDs)
4. Atmospheric, environmental and biological evolution Theme 1 Earth's Architecture and Fluid Fluxes	**Van Kranendonk**, Fiorentini, Foley, Kirkland, Kilburn, Alard, LaFlamme, Baumgartner (ECRs) Barlow, Caruso, Djokic, Nomchong, Soares, Teece (PhDs) Tadbiri (MPhil)
5. Australia's Proterozoic record in a global context Themes 2 and 3 Earth's Architecture	**Li**, Pisarevsky, Wang, Wingate, O'Reilly, Griffin, Belousova, McCuaig, Mitchell Kirscher, Yao (ECRs) Stark, Y. Liu, Martin, Nordsvan, Volante (PhDs)
6. Fluid regimes and composition of early Earth Themes 1 and 3 Earth's Architecture and Fluid Fluxes	**Wilde**, Nemchin, Martin, O'Neill Ge (ECR) Liu, K (PhD)
7. Precambrian architecture and crustal evolution in WA Themes 1, 2 and 3 Earth's Architecture	**Gessner**, Kirkland, Belousova, Gréau, Yuan, Wingate, Tyler, Lu Wu (ECR) Dering (PhD)
TECHNOLOGY DEVELOPMENT	
Cameca Ion microprobe development Themes 1, 2 and 3 Earth's Architecture and Fluid Fluxes	**Kilburn**, Martin, Fiorentini, McCuaig, Griffin, LaFlamme, Reddy 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's Architecture and Fluid Fluxes	**Alard**, Griffin, O'Reilly, Gréau, Kilburn, Martin, Huang Henry, Liptai (PhD/ECRs)

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 the Moon, Mars and Venus.

Pre-conference field trip, South Lanzo peridotites, EMW 2018 (photo: Romain Tilhac).

Shennongjia, central China-IGCP 648 field symposium (photo: Zheng-Xiang Li).

WHERE IN THE WORLD IS CCFS?

View across the Central Cordillera south of Medellin, Colombia (photo: Simon Wilde).

This way to Mongolia! Simon Wilde in Inner Mongolia, close to the Mongolian border, collecting ophiolite samples.

Eastern Desert field region, Egypt (photos: Zheng-Xiang Li).

Communications 2018

CCFS web resources (http://ccfs.mq.edu.au/) 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 2018 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 2018 are given in Appendix 5.

The 199 CCFS publications that were published in 2018 are dominantly in high-impact international journals (Thomson ISI); the remainder are in outlets targeted to specific stakeholders (e.g. Australian Journal of Earth Sciences, Economic Geology).

CCFS now has a LinkedIn Group - Join the conversation at http://www.linkedin.com/groups/6969996

PARTICIPATION IN WORKSHOPS, CONFERENCES AND INTERNATIONAL MEETINGS IN 2018

CCFS Investigators, associated staff, early-career researchers and postgraduates had a high profile at 30 peak geophysical, metallogenic, geodynamic and geochemical conferences as convenors, invited speakers, or presenters, with 189 presentations including:

- Origins of Life, Gordon Research Conference, Galveston, Texas USA, 14-19 January 2018
- International Diamond School, Bressanone, Italy, 28 January - 3 February 2018
- 49th Lunar and Planetary Science Conference, The Woodlands, Texas, USA, 19-23 March 2018
- EGU General Assembly 2018, Vienna, Austria, 8-13 April 2018
- The Royal Society, Earth dynamics and the development of plate tectonics, London, UK, 19-20 March 2018
- International Workshop of Deep Earth Dynamics, Nanjing, China, 24 April 2018
- 12th General Assembly of the Asian Seismological Commission (ASC), Chengdu, China, 12-14 May 2018
- 15th AOGS Annual Meeting, Honolulu, 3-8 June 2018
- RFG 2018 Resources for Future Generations 2018, Vancouver, Canada, 16-22 June 2018
- Joint 5th Central European Mineralogical Conference (CEMC) - 7th Mineral Sciences in the Carpathians Conference (MSCC), Banská Štiavnica, Slovakia, 26-30 June 2018
- Astrobiology Australasia Meeting (AAM), Rotorua, New Zealand, 25-26 June 2018 (*pictured p. 19*)
- 3rd EMAW, European Mantle Workshop, Pavia, Italy, 26-28 June 2018 (*some of the CCFS attendees pictured below*)

- Geoanalysis 2018, Sydney, Australia, 8-13 July 2018
- 10th International Conference on Analysis of Geological and Environmental Materials, Sydney, Australia, 8-13 July 2018
- Landscapes, Seascapes & Biota: Unique WA - Past, Present and Future, Royal Society of WA, Perth, Australia, 27-28 July 2018
- 24th EM Induction Workshop, Helsingor, Denmark, 12-19 August 2018
- Goldschmidt 2018, Boston, USA, 12-17 August 2018
- XXII Meeting of the International Mineralogical Association, Melbourne, Australia, 13-17 August 2018
- European Microbeam Analysis Society (EMAS 2018), Bristol, UK, 4-7 September 2018

- IMC19, 19th International Microscopy Congress, Sydney, Australia, 9-14 September 2018
- 9th International SHRIMP Meeting, Ochang, South Korea, 10-15 September 2018 *Pictured below: Attendees following the announcement that China will build future SHRIMPs.*

- First Workshop of Project IGCP-662 Orogenic architecture and crustal growth from accretion to collision, Beijing, China, 20-22 September 2018
- SEG 2018-Metals, Minerals, and Society, Keystone, Colorado, USA, 22-25 September 2018
- Tethys Dynamics Workshop, Beijing, China, 8-9 October 2018
- AGCC Australian Geoscience Council Convention - Big issues and ideas in geoscience, Adelaide, Australia, 14-18 October 2018
- Fourth landing site workshop for the Mars 2020 rover mission, Glendale CA, USA, 16-18 October 2018
- Annual Meeting of Chinese Geoscience Union, Beijing, China, 19-23 October 2018
- GSA Earth Sciences Student Symposium, Western Australia (GESSS-WA), Australia, 29 November 2018
- American Geophysical Union (AGU) Fall Meeting, Washington DC, USA, 10-14 December 2018
- National MT workshop and AusLAMP SA Release Day, Adelaide, Australia, 5 December 2018

INVITED TALKS AT MAJOR CONFERENCES IN 2018

Origins of life, Gordon Research Conference, Galveston, Texas USA, 14-19 January 2018	Insights for origins of life from the earliest convincing record of life on Earth **T. Djokic, M.J. Van Kranendonk,** M.R. Walter, K.A. Campbell and C.A. Ward **Invited**
The Royal Society, Earth dynamics and the development of plate tectonics, London, UK, 19-20 March 2018	The inception of plate tectonics on terrestrial planets **C. O'Neill** **Keynote**
EGU General Assembly 2018, Vienna, Austria, 8-13 April 2018	Have mantle get crust--consequences of fluid-peridotite interaction for continental crust composition **A. Beinlich**, H. Austrheim, V. Mavromatis, B. Grguric, C. Putnis and A. Putnis **Invited** Multi-scale magnetic mapping of serpentinite carbonation and its future application for deep submergence magnetometry M. Tominaga, **A. Beinlich**, N. Vento, E. Ortiz, J. Greene, J. Einsle, E. Lima and B. Weiss **Invited**
15th AOGS Annual Meeting, Honolulu, 3-8 June 2018	Refined seismic structure of Southern California by ambient noise adjoint tomography **Y. Yang**, **K. Wang**, P. Basini, P. Tong, Q. Liu and C. Tape **Invited**

Field trip to Waimangu, Rotorua - Astrobiology Australasia Meeting 2018 (photo: Martin Van Kranendonk).

INVITED TALKS AT MAJOR CONFERENCES IN 2018 *cont...*

RFG 2018 Resources for Future Generations 2018, Vancouver, Canada, 16-22 June 2018	Distinctive chemical characteristics, geodynamic settings and petrogenesis of gold-ore-forming arc magmas **R.R. Loucks** **Invited**
3rd EMAW, European Mantle Workshop, Pavia, Italy, 26-28 June 2018	Water and its distribution in the upper mantle beneath the Pannonian-Basin: Geodynamical and geophysical implications I.J. Kovács, V. Wesztergom, L. Patkó, L. Aradi, **N. Liptai**, G. Falus, C. Szabó, L. Lenkey **Keynote**
Landscapes, Seascapes and Biota: Unique WA - Past, Present and Future, Royal Society of WA, Perth, Australia, 27-28 July 2018	The Archean of WA: from the earliest crust to the onset of life on Earth **S.A. Wilde** and A.H. Hickman **Keynote**
European Microbeam Analysis Society (EMAS 2018), Bristol, UK, 4-7 September 2018	Isotopic imaging of minerals with NanoSIMS **M.R. Kilburn** **Invited**
First Workshop of Project IGCP-662 Orogenic Architecture and Crustal Growth from Accretion to Collision, Beijing, China, 20-22 September 2018	UHP versus super-reducing parageneses in Tethyan ophiolites **W. Griffin**, **J.-X. Huang**, **Q. Xiong**, X.-H. Gong and **S.Y. O'Reilly** **Invited** Geodynamic processes during heroic collisions: Integration of geochemical, microstructural and geodynamic information **S.Y. O'Reilly**, **W.L. Griffin**, **Q. Xiong**, **J-C. Afonso** and T. Satsukawa **Invited**
SEG 2018-Metals, Minerals and Society, Keystone, Colorado, USA, 22-25 September 2018	Integrating petroleum and minerals systems approaches to sedimentary basins R. Chuchla and **T.C. McCuaig** **Plenary** The power of a systems approach to minerals and petroleum exploration in sedimentary basins **C. McCuaig** **Invited**
Tethys Dynamics Workshop, Beijing, China, 8-9 October 2018	Crustal structural beneath coastal NW Australia: seismic signature from paleo-collision to modern rifting **H. Yuan** and the CWAS Team **Invited**
AGCC Australian Geoscience Council Convention - Big Issues and Ideas in Geoscience, Adelaide, Australia, 14-18 October 2018	From geosystem to mineral system: Contextualising ore deposits G. Begg, **W. Griffin**, **S. O'Reilly** and J.M.A. Hronsky **Keynote** GSA Ringwood Medal Lecture: Illuminating Mantle Metasomatism **S. Foley** **Keynote** Decadal Plan for Geoscience: Our planet, Australia's future - A decade of transition in Geoscience **S.Y. O'Reilly** **Keynote**
Annual Meeting of Chinese Geoscience Union, Beijing, China, 19-23 October 2018	Joint inversion of surface waves and teleseismic body waves for sedimentary structures **Y. Yang**, G. Li and F. Niu **Invited**
National MT Workshop and AusLAMP SA Release Day, Adelaide, Australia, 5 December 2018	Developing meaningful interpretations for MT models: Current state of play **K. Selway** **Invited**

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

OTHER CONFERENCE ROLES

RFG 2018 Resources for future generations 2018, Vancouver, Canada, 16-22 June 2018

Course Convenor: Juan Carlos Afonso
"Joint inversion of multiple datasets"

Session Co-Chair: Crystal LaFlamme
"Isotope geochemistry in a mineral systems framework: Analytical and application advances"

Session Co-Organiser / Co-Chair: Zheng-Xiang Li
Session: EA11 *"Supercontinent cyclicity with a focus on contributions from Circum-Pacific regions (I, II)"*

AOGS 15th Annual Meeting, Honolulu, USA, 18 June 2018

Lead Convenor: Huaiyu Yuan
Session: SE19 *"Characterizing Precambrian crust and lithosphere"*

Geoanalysis 2018, Macquarie University, Sydney, Australia, 8-13 July 2018

Organiser / Chair: Dorrit Jacob See *p. 100* for more info.
Scientific Program: Dorrit Jacob, Elena Belousova
Website coordinator: Sally-Ann Hodgekiss

CCFS *Sponsored*

XXII Meeting of the International Mineralogical Association, Melbourne, Australia, 13-17 August 2018

Session Co-Convenor: Simon Clark
Session: *"Water in minerals and its effect on physical properties"*

Session Co-Convenor: Andrea Giuliani
Session: *"Mantle xenoliths, kimberlites and related magmas: The Diamond Trilogy"*

24th EM Induction Workshop, Helsingor, Denmark, 13-20 August 2018

Program Committee / Session Convenor: Kate Selway
Session: *"Tectonics"*

AGCC Australian Geoscience Council Convention - Big Issues and Ideas in Geoscience, Adelaide, Australia, 14-18 October 2018

Session Chair: Yongjun Lu
Session: 3.1.3
"Understanding mineral systems for exploration - from craton to micron-scale"

OTHER CONFERENCE ROLES *cont...*

AGCC Australian Geoscience Council Convention - Big Issues and Ideas in Geoscience, Adelaide, Australia, 14-18 October 2018 *cont...*	*Session Champion:* Zheng-Xiang Li Session: 1.1.1 *"Decoding Earth's supercycles: from the core to the crust"* *Session Chair:* Sue O'Reilly Session: 5.5 *"Planning the future of geoscience: Decadal Plan Q&A" (see below)*
GSA Earth Sciences Student Symposium, Western Australia (GESSS-WA), Australia, 29 November 2018	*Vice Chair:* Julian Chard *Treasurer:* Enjoo Choi *Secretary:* Erin Martin *Program/abstracts:* Adam Nordsvan *Sponsorship:* Gonzolo Henriquez CCFS *Sponsored*
American Geophysical Union (AGU) Fall Meeting, Washington DC, USA,10-14 December 2018	*Primary Convenor:* Klaus Gessner *Co-Convenor:* Huaiyu Yuan Sessions: T41A (De)Cratonization Dynamics I (Talks), T42A (De)Cratonization Dynamics II (Talks) *Primary Convenor:* Klaus Gessner *Co-Convenor / Chair:* Huaiyu Yuan Session: T33C (De)Cratonization Dynamics III (Posters)

Members of the Australian Academy of Science National Committee for Earth Science (NCES) at the Decadal Plan launch, October 2018: L to R: Bill Shaw (President Australian Geoscience Council (AGC)) Tim Rawling (CEO, NCRIS AuScope), Sue O'Reilly (Chair NCES), Phil McFadden (UNCOVER, NCES), Craig O'Neill (NCES). (photo: B. Charlton)

Geoscience in the coming decade must be underpinned by:

- **Scientific excellence in geoscience research**
- **A better understanding of our continent in 4D using transformational imaging (nano to global), and analytical, computational and communication resources**
- **Education at all levels to develop skills to work in a digitalised context**
- **Advocacy by geoscientists to ensure awareness and understanding of geoscience**

The story told by our planet is extraordinary - from its birth 4.56 billion years ago to its current state of solid outer shell of continents and liquid ocean on which we live. Geoscientists are uniquely placed to interrogate Earth's records and engage the community about our society's use of Earth's finite resources.

The coming decade will be a critical period in human history. It will see humanity continue to put the planet under increasing pressure, ultimately calling for a new understanding of sustainability, and innovative approaches to sustainability.

Use the search engine: "Decadal Plan for Australian Geoscience: Our Planet, Australia's Future" to download copies of the Decadal Plan and the extensive companion report.

SELECTED WORKSHOP ROLES

Activity	Details & Participant/s	Date
International Workshop of Deep Earth Dynamics, Nanjing, China	Invited speakers, Sue O'Reilly, Bill Griffin and Yingjie Yang	24 April 2018

Activity	Details & Participant/s	Date
National Virtual Core Library for Advancing Exploration Through Cover and Ore Body Knowledge	Workshop Co organiser - Nathan Daczko	8 May 2018
EPS HDR Conference Day	Organised by the MQ EPS and CCFS PhD students, featuring presentations and posters from EPS and CCFS MQ PhD students	15 June 2018
Pre-conference workshops: Geoanalysis 2018, Macquarie University, Sydney, Australia	Workshop Co-Convenors - Will Powell, Elena Belousova, Romain Tilhac and Steve Craven: *"Workshop II - Application of LA-ICP-MS/MC-ICP-MS to exploration needs"*	8-13 July 2018
2018 ACTER Field Symposium, Gansu Province, China	Co-Director - Zheng-Xiang Li *"Tectonic evolution of the North Qilian Mountain"*	25 August - 3 September 2018
First Workshop - Project IGCP-662 Orogenic architecture and crustal growth from accretion to collision, Beijing, China	Co-Chair - Bill Griffin, Session: *"Tethys"* Co-Chair - Sue O'Reilly, Session: *"Other Regions"* Organiser - Sue O'Reilly: *"Tracing crustal evolution and crust-mantle linkages with zircon Hf isotopes"* Organiser - Bill Griffin: *"Os-isotopes and the subcrustal mantle lithosphere"*	20-22 September 2018

Activity	Details & Participant/s	Date
Western Australian Geophysics Planning Workshop, Perth, Australia	Organiser - Klaus Gessner	13-14 November 2018

SELECTED WORKSHOP ROLES *cont...*

Activity	Details & Participant/s	Date
Multiple Sulfur Isotope Workshop UWA, Perth, Australia	Organiser - Marco Fiorentini, Crystal LaFlamme	28 November 2018
IGCP 648 2018 Field Symposium - From Rodinia to Pangea: Geodynamics, Life and Climate	Two-day IGCP 648 workshop and field trip, Zheng-Xiang Li - Keynote Presentation See *International Links p. 99.*	1-9 November 2018
Western Australian Geophysics Planning Workshop	Organiser - Klaus Gessner	13-14 November 2018
EPS HDR Conference Day, MQ	Organised by the MQ EPS and CCFS PhD students, featuring presentations and posters from EPS and CCFS MQ PhD students	15 November 2018
CET-UWA 2018 Member's Day	Presenter - Marco Fiorentini	27 November 2018

ESTEEM

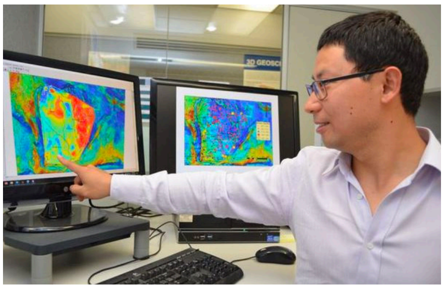
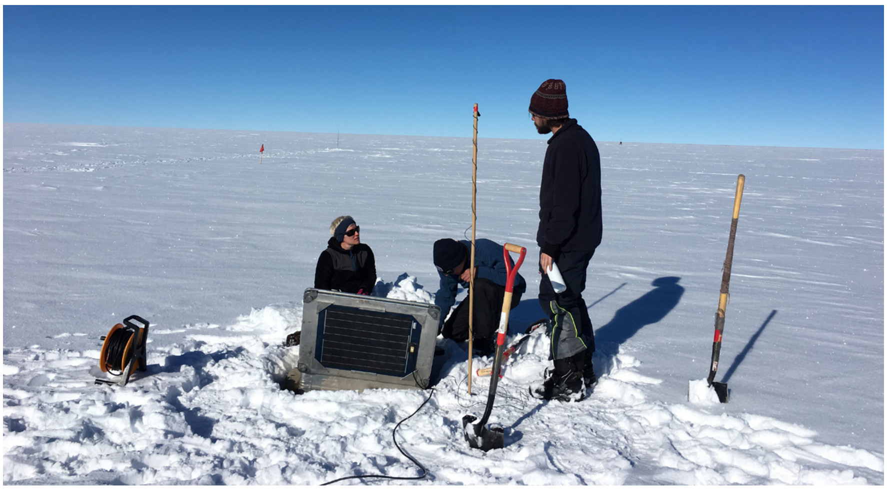
AWARDS

Participant	Activity
Juan Carlos Afonso	Awarded a 2019 Early Career Scientist Award by the International Union of Geodesy and Geophysics. The award will be presented at the XXVII General Assembly of the IUGG, Montreal, Canada, July 2019 Awarded an MQ Faculty of Science and Engineering Award - Excellence in Research Leadership
Elena Belousova	Awarded an MQ Faculty of Science and Engineering Award - Excellence in Research
Nathan Dazcko	Awarded an MQ Earth and Planetary Sciences Award - HDR Supervision Awarded an MQ Earth and Planetary Sciences Award - Academic Service
Steve Foley	Awarded an ARC Australia Laureate Fellowship: The project aims to understand the roles of carbon, water and nitrogen in the development of plate tectonics as drivers of mantle evolution.

Australian Laureate Fellowships pin ceremony: Steve was awarded a commemorative pin by Professor Sue Thomas, ARC Chief Executive Officer and Mr Andrew Laming MP, representing Minister for Education and Training, Senator the Hon Simon Birmingham.

Participant	Activity
Steve Foley	Received the A.E. Ringwood Medal, Geological Society of Australia
Richard Glen, Bill Griffin	Dick Glenn (with co-authors Ian Fitzsimons, Bill Griffin and Ayesha Saeed) received The Stillwell Award - The best paper of the year as judged by the editorial board of the Geological Society of Australia.

AWARDS *cont...*

Participant	Activity
Johannes Hammerli	Awarded the Paul Niggli medal for 2018, Switzerland's most prestigious '*young scientist award*' in the Earth Sciences.
Yongjun Lu	Was the SEG Waldemar Lindgren Award recipient for 2018: "The Waldemar Lindgren Award is offered annually to a young scientist whose published research represents an outstanding contribution to economic geology"  (https://www.segweb.org/SEG/Membership/Medals_and_Awards/SEG/_Membership/_Medals_and_Awards/Waldemar_Lindgren_Award.aspx)
Sue O'Reilly	Recognised in the Web of Science's Highly Cited Researchers 2018: https://hcr.clarivate.com/
Sue O'Reilly, Bill Griffin 	The 11th IKC Volume, *"Cratons, Kimberlites and Diamonds Part 2"* (Mineralogy and Petrology, 2018, 112) was dedicated to Sue O'Reilly and Bill Griffin. Extract from the dedication: …a formidable scientific team was born. [Sue and Bill] have made transformative contributions to the study of the lithospheric mantle through the development of *"4-dimensional geochemical tomography"* … [integrating] geochemical-petrologic tools with geophysical observables and numerical models for a holistic view of the continents through time. Sue and Bill's contribution to our understanding of Earth's crust and mantle is profound and it is most worthy that a volume on the 11th Kimberlite Conference is named after them. *Sue and Bill in 2007, during fieldwork on eclogites in Brittany (photo: Norman Pearson).*
Kate Selway *Kate Selway, Bernd Kulessa (U. Swansea) and Sinan Özaydin collecting magnetotelluric data on the Greenland ice sheet.*	Named in 2019's list of the superstars of STEM, announced 11 December 2018 by Science & Technology Australia (STA) https://scienceandtechnologyaustralia.org.au/list/2019-superstars/ 

For Postgraduate awards see p. 73.

2018 NEW APPOINTMENTS AND POSITIONS

Klaus Gessner	Guest Editor - "*Characterization of ore-forming systems - Advances and challenges*" (Geological Society, London, Special Publication 2018)
Matt Kilburn	Appointed Director - Centre for Microscopy Characterisation and Analysis, UWA UWA Node Director - Microscopy Australia (NCRIS), National Imaging Facility (NCRIS)
Zheng-Xiang Li	Principal Project Leader - IGCP 648: Supercontinent Cycles and Global Geodynamics Member of the Overseas Advisory Committee, China State Council
Anthony Lanati	Chair of the Geological Society of Australia NSW Division, Geological Society of Australia Governing Councillor - NSW Division, Geological Society of Australia Honorary Treasurer, Geological Society of Australia Member of the Executive Committee, Geological Society of Australia Chair of the Finance and Risk Committee, Geological Society of Australia
Yongjun Lu	Appointed Councillor for Society for Geology Applied to Mineral Deposits (SGA) in 2016-2019 Secretary of the 6th International Archean Symposium (6IAS), Perth 2020 Treasurer, Specialist Group in Geochemistry, Mineralogy & Petrology (SGGMP), Geological Society of Australia Mentor, Society of Economic Geologists (SEG)
Craig O'Neill	Member of the Australian Academy of Science National Committee for Earth Sciences Guest Editor - "*Lid tectonics*" (Edited volume, Geoscience Frontiers 2018)
Sue O'Reilly	Member Executive Committee, UNCOVER national initiative (Auspices of the Australian Academy of Science) Chair, Academy of Science National Committee for Earth Sciences, and Decadal Plan preparation Member of Council, Australian Academy of Science Elected Member of Executive Committee, Australian Academy of Sciences from 2018 Co-Chair inaugural Australian Academy of Science Task Force for "*Equity and Diversity*" Invited Member, Scientific Committee for 3rd European Mantle Workshop (EMAW), Pavia, 2018 Australian Member, IUGG Nominations Committee Project Leader - IGCP 622: "*Orogenic architecture and crustal growth from accretion to collision*" Chair, Equity and Diversity Reference Group, Australian Academy of Science Member, Expert Working Group for the Women in STEM Decadal Plan (and the Decadal Plan launch speaker for the Australian Academy of Science in April 2019
Kate Selway	Guest Editor - "*Earth, Planets and Space*" (24th EM Induction workshop special issue)
Martin Van Kranendonk	Mars2020 Sample Return team member Co-Editor with Vickie Bennett & Elis Hoffmann of "*Earth's Oldest Rocks (2nd Edition)*", a book published by Elsevier in 2018
Huaiyu Yuan	Guest Editor - "*Lithospheric Discontinuities*" volume (AGU Geophysical Monograph Series, V239)

EDITORIAL APPOINTMENTS	
Acta Geologica Sinica	Li
American Journal of Science	Wilde
American Mineralogist	Handley
Cogent Geosciences	O'Neill, Moresi
Earth and Planetary Physics (EPP)	Yang
Exploration Geophysics	Selway, Yang
Geodynamics & Tectonophysics	Pisarevsky
Geology	Li
Geol. Society of America Bulletin	Griffin, Kirkland, Li
Geophysical Journal International	Afonso
Geosphere	Yuan
Journal of Earth Sciences	Li, Wang
Lithos	C. Clark, Foley, Griffin
Mineralium Deposita	Fiorentini
Nature Scientific Reports	Jacob
Physics & Chemistry of Minerals	McCammon
Precambrian Research	Pisarevsky
Russian Geology and Geophysics	Pisarevsky
Science China	Yuan
Solid Earth Sciences	Griffin
Tectonophysics	Li

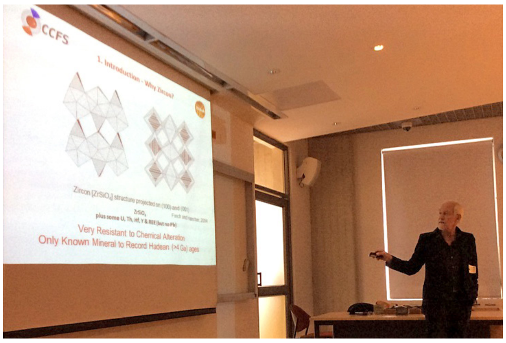
OUTREACH

Forum	Participant/s	Date
Numerous (daily) **Government / Industry briefings**	Chris Kirkland	2018
CCFS China Mission to enhance collaborations and cotutelle relationships (For details see *International Links p. 96*)	Sue O'Reilly, Steve Foley, Bill Griffin, Yingjie Yang	April 2018
Review of Geology Course at the University of Botswana	Simon Wilde	12-20 May 2018
General Science Article - Australasian Science - *"A piece of North America is now in Queensland"*	Adam Nordsvan, Zheng-Xiang Li, Bill Collins	May 2018
Public lecture - *"What was it like on the Early Earth: The Zircon Story"*, University of Botswana	Simon Wilde	16 May 2018
Primary School Visit - Year 4, Epping West Public School	Nathan Dazcko	13 June 2018
National Youth Science Forum workshops: *"Meteorites and Mars"* *"Unveiling the deep workings of volcanoes and planetary interiors with earthquakes"*	Craig O'Neill, Bruce Schaefer, Steve Hansen, Juan Carlos Afonso	16 July 2018
Public lecture - Royal Society of Western Australia: Landscapes, Seascapes & Biota: Unique WA - Past, Present & Future, Invited Keynote *"The Archean of WA: From the Earliest Crust to the Onset of Life on Earth"*	Simon Wilde	27 July 2018
Sydney Science Festival Science Expo hosted by the Australian Museum - Primary School Children - Microscopic Earth interactive and hands-on experience in geology and petrographic microscopy	Nathan Dazcko, Louise Good, Lucy McGee	7 August 2018

National Science Week - High schools - Booth	Nathan Dazcko	7-15 August 2018

OUTREACH *cont...*

Forum	Participant/s	Date
Department of Physics & Astronomy Colloquium's seminar: *"Alternate Earths: A spectrum of Earth-like planets over the course of galactic evolution"*	Craig O'Neill	4 September 2018
Faculty Mission to China - Participants visited multiple institutions to establish new collaborations, cotutelle agreements and staff and student exchange programs	Juan Carlos Afonso, Yingjie Yang	October 2018
Public lecture - University of Sydney	Kate Selway	1 October 2018
Public lecture -The fourth and final landing site workshop for the Mars 2020 rover mission *"A Mars2020 mission to Columbia Hills: Risk minimisation through ground truth"*	Martin Van Kranendonk	1 October 2018
Public lecture - *"Teasing apart the cassiterite multi-tool"*, Mineralogical Society of Western Australia	Jason Bennett	14 November 2018
Public lecture - *"High-Resolution Seismic Survey of the Eastern Goldfields in Western Australia"*, to 100+ Exploration and Mining Professionals in Kalgoorlie, WA	Klaus Gessner	15 November 2018
Public lecture - *"Ancient Crystals from Jack Hills: An Alphabet to the Early History of the Earth"*, University of the Andes, Bogota, Colombia	Simon Wilde	19 November 2018
Public lecture - *"The Global Hadean Zircon Record: Implications for the Earth's Oldest Crust"*, Geological Society of Colombia, Bogota, Colombia	Simon Wilde	21 November 2018
School visits - High school and Primary school Nathan is part of the **MyScience @MQ mentor program**	Nathan Dazcko	14, 21, 23 November 2018



MEDIA

Activity	Participant/s	Date, Forum	Web address
Behind the Scenes with Prof Martin Van Kranendonk	Martin Van Kranendonk	11/2/2018, YouTube	https://www.youtube.com/watch?v=vF3xOwuqyMo
University study sheds light on exploration potential for Shefa Yamim in Israel *(See picture p. 29)*	Bill Griffin	19/2/2018, proactiveinvestors, Google News, Bing News, Stock TUBE, Mining Capital	https://www.proactiveinvestors.co.uk/companies/stocktube/8762/university-study-sheds-light-on-exploration-potential-for-shefa-yamim-in-israel-8762.html

MEDIA *cont...*

Activity	Participant/s	Date, Forum	Web address
There is liquid water on Mars	Bruce Schaefer et al.	26/7/2018, Gizmodo	https://www.gizmodo.com.au/2018/07/theres-liquid-water-on-mars/
What would life in the Mars lake look like?	Bruce Schaefer	29/7/2018, The Sydney Morning Herald	https://www.smh.com.au/national/what-would-life-in-the-mars-lake-look-like-20180728-p4zu6p.html
How minerals will help shift Australia to renewable energy	Stephen Foley	20/9/2018, The Lighthouse	https://lighthouse.mq.edu.au/article/august/building-a-model-of-the-deep-earth
The Australian's 2018 Lifetime Achievement Leaderboard	Zheng-Xiang Li	26/9/2018, The Australian	https://specialreports.theaustralian.com.au/1163512/lifetime-achievement-leaderboard/
Downward-looking telescope will unlock Australia's mineral wealth	Sue O'Reilly	15/10/2018, Adelaide Advertiser	Print
The Australian online - Science Academy proposes powerful *'downward-looking telescope'*	Sue O'Reilly	15/10/2018, The Australian Online	https://www.theaustralian.com.au/higher-education/higher-ed-daily-brief/science-academy-proposes-powerful-downwardlooking-telescope/news-story/b6afbe8193c6011e666e598d4022d9a0
Downward-looking telescope will unlock Australia's mineral wealth	Sue O'Reilly	15/10/2018, 720 ABC Perth	ABC Radio Perth Breakfast program (syndicated through Western Australia via regional ABC Radio stations)
Tech targets taking exploration 300km underground	Sue O'Reilly	15/10/2018, Australian Mining	https://www.australianmining.com.au/news/tech-targets-taking-exploration-300km-underground/
Exploration finance, deeper exploration and water considered at AGC conference first day	Sue O'Reilly	15/10/2018, International Mining	https://im-mining.com/2018/10/15/exploration-finance-deeper-exploration-water-considered-agc-conference-first-day/
Downward-looking telescope will unlock Australia's mineral wealth	Sue O'Reilly	15/10/2018, Oil Voice	https://oilvoice.com/Press/23768/DownwardLooking-Telescope-Will-Unlock-Australias-Mineral-Wealth
Scientists take long view on Australia's mineral future	Sue O'Reilly	15/10/2018, Industry Queensland	https://www.i-q.net.au/main/scientists-take-long-view-on-mineral-future
"Downward-looking telescope" could *'transform'* Australian mining industry: experts	Sue O'Reilly	15/10/2018, China Xinhua News (English) - (syndicated three times on other sites)	http://www.xinhuanet.com/english/2018-10/15/c_137533365.htm http://en.ce.cn/World/Asia-Pacific/201810/15/t20181015_30523337.shtml
Aussie *"Downward-looking telescope"* could transform mineral exploration	Sue O'Reilly	15/10/2018, STOCKHEAD	https://stockhead.com.au/resources/aussie-downward-facing-telescope-could-transform-mineral-exploration/
Downward-looking telescope to unlock Australia's mineral wealth	Sue O'Reilly	16/10/2018, Mining Magazine	https://www.miningmagazine.com/exploration/news/1348834/downward-looking-telescope-to-unlock-australia%E2%80%99s-mineral-wealth
POLICY - Looking Down	Sue O'Reilly	17/10/2018, Nature News	https://www.nature.com/articles/d41586-018-07035-3

MEDIA *cont...*

Activity	Participant/s	Date, Forum	Web address
Downward-looking telescope could unlock Australia's mineral wealth	Sue O'Reilly	17/10/2018, National Resources Review	https://www.nationalresourcesreview.com.au/news_article/scientists-propose-downward-looking-telescope-to-unlock-australias-mineral-wealth/
Earliest evidence of life on Earth in Greenland rocks disputed by new study	Craig O'Neill	18/10/2018, ABC News	https://www.abc.net.au/news/science/2018-10-18/earliest-evidence-of-life-on-earth-in-greenland-rocks-challenged/10378214
Downward telescope planned by Australian Academy of Science	Sue O'Reilly	22/10/2018, The Land	https://www.theland.com.au/story/5713965/australia-digs-deeper-into-the-earths-surface/
Macquarie's STEM Superstars named, Smashing gender assumptions about scientists	Kate Selway	11/12/2018, Macquarie University Newsroom	https://www.mq.edu.au/newsroom/2018/12/11/macquaries-stem-superstars-named-smashing-gender-assumptions-about-scientists/
GSWA scientist wins prestigious international award	Yongjun Lu	20/12/2018, DMP WA News	http://www.dmp.wa.gov.au/News/GSWA-scientist-wins-prestigious-24876.aspx

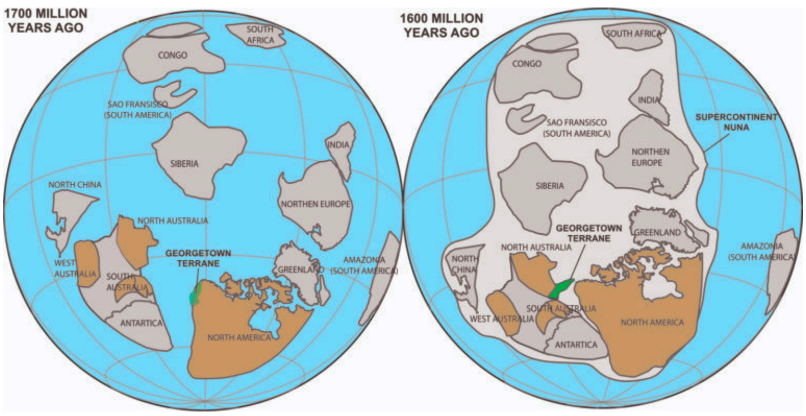
MEDIA - FEATURED PAPERS

1043. **Nordsvan, A.**, Collins, W.J., **Li, Z.-X.**, Spencer, C.J., **Pourteau, A.**, Withnall, I.W., Betts, P.G. and **Volante, S.** 2018. Laurentian Crust in Northeast Australia: Implications for the assembly of the supercontinent Nuna. *Geology, 46, 251-254*.

Activity	Date, Forum	Web address
Georgetown in northern Queensland once part of North America - geologists	19/1/2018, The Guardian	https://www.theguardian.com/science/2018/jan/19/georgetown-in-northern-queensland-once-part-of-north-america-geologists
Part of Queensland used to be in Canada	21/1/2018, Newshub	https://www.newshub.co.nz/home/world/2018/01/part-of-queensland-used-to-be-in-canada.html
Mounting evidence suggests a remote Australian region was once part of North America	22/1/2018, ScienceAlert	https://www.sciencealert.com/canadian-shield-australia-rocks-nuna-columbia-supercontinent
Australia once part of North America: Curtin University	22/1/2018 Canning Times	https://www.communitynews.com.au/canning-times/news/australia-once-part-of-north-america-curtin-university/
Researchers discover a piece of America in northern Australia	22/1/208, Tdnews	http://www.tunisiesoir.com/science/scientists-discover-a-piece-of-america-in-northern-australia-2041-2018/
Bizarrely, a tiny town in Australia Is actually sitting on a part of ancient North America	22/1/2018, IFLScience	https://www.iflscience.com/environment/tiny-town-australia-actually-sitting-part-ancient-north-america/
Small town in Australia was once part of North America in Prehistoric times	23/1/2018, The Inquisitr	https://www.inquisitr.com/4749101/small-town-in-australia-was-once-part-of-north-america-in-prehistoric-times/
Australia was part of North America supercontinent over 1 billion years ago, new study shows	22/1/2018, Outer Places	https://www.outerplaces.com/science/item/17589-australia-part-north-america-supercontinent-new-study
1.7-Billion-Year-Old Chunk of North America Found Sticking to Australia	22/1/2018, Live Science	https://www.livescience.com/61490-chunk-of-north-america-in-australia.html
Evidence suggests that part of Australia used to be connected to Canada	22/1/2018, New York Daily News	https://www.nydailynews.com/life-style/evidence-suggests-part-australia-connected-canada-article-1.3772011
Researchers believe Australia was part of North America 1.7B years ago	22/1/2018, MLive.com	https://www.mlive.com/news/us-world/2018/01/researchers_believe_australia.html
A piece of North America found in Australia bolsters theory of two-billion-year-old supercontinent	22/1/2018, Newsweek	https://www.newsweek.com/piece-north-america-found-australia-bolsters-theory-two-billion-year-old-787387
Australia, Canada were once connected as part of supercontinent Nuna	22/1/2018, ValueWalk	https://www.valuewalk.com/2018/01/australia-canada-supercontinent-nuna/
Geologists say part of northern Australia was once stuck to North America	22/1/2018, ZME Science	https://www.zmescience.com/science/geology/australia-joined-north-america-0432432/

MEDIA - FEATURED PAPERS *cont..*

Activity	Date, Forum	Web address
Telltale rocks suggest that part of Australia was once part of North America	23/1/2018, New Atlas	https://newatlas.com/australia-canada-rocks-nuna/53072/
Georgetown was once part of Canada	22/1/2018, The North West Star	https://www.northweststar.com.au/story/5183067/georgetown-was-once-part-of-canada/
New evidence suggests Australia was once part of Canada	22/1/2018, Digital Journal	http://www.digitaljournal.com/tech-and-science/science/new-evidence-suggests-australia-was-once-part-of-canada/article/512818
New research suggests Australia and North America were once neighbours	23/1/2018, The Sydney Morning Herald	https://www.smh.com.au/technology/new-research-suggests-australia-and-north-america-were-once-neighbours-20180119-h0lbbm.html
Ancient rocks reveal part of Australia was once connected to Canada to form the giant supercontinent 'Nuna' that broke up 1.6 billion years ago	24/1/2018, Daily Mail	https://www.dailymail.co.uk/sciencetech/article-5301529/Australian-town-sitting-ancient-North-America.html
G'day mate: 1.7-billion-year-old chunk of North America found in Australia	23/1/2018, USA Today	https://www.usatoday.com/story/tech/science/2018/01/23/australia-north-america-supercontinent-nuna/1058577001/
There's still a piece of Canada stuck to Australia	24/1/2018, Popular Science	https://www.popsci.com/nuna-canada-crashed-into-australia
Discovery changing everything we thought we know about Australia	25/1/2018, News.com.au	https://www.news.com.au/travel/australian-holidays/queensland/discovery-changing-everything-we-thought-we-know-about-australia/news-story/ce494c21ddb5c7b3500becaf29e38baa
This Australian town is technically sitting on parts of Canada	24/1/2018, National Geographic	https://www.nationalgeographic.com.au/australia/this-australian-town-is-technically-sitting-on-parts-of-canada.aspx
Northern Australia was once smushed up against North America	26/1/2018, Atlas Obscura	https://www.atlasobscura.com/articles/northern-australia-smushed-up-against-north-america-supercontinents
Australia and North America were once part of a supercontinent	24/1/2018, Earth.com	https://www.earth.com/news/australia-north-america-supercontinent/#.XJhMAhMzbUI
Researchers discover a piece of America in northern Australia	24/1/2018, Phys.org	https://phys.org/news/2018-01-piece-america-northern-australia.html
Canada and Australia were once connected, study suggests	24/01/2018, CTV News	https://www.ctvnews.ca/sci-tech/canada-and-australia-were-once-connected-study-suggests-1.3774026
Australia once part of North America:	24/01/2018, BBC Radio 5	https://www.bbc.co.uk/programmes/b09nvp8j
HomeGrown - Professor Li - North America found in Australia	25/02/2018, 6PR 882	https://www.6pr.com.au/podcast/homegrown-professor-li-north-america-found-in-australia-february-25th-2018/
Curtin University researchers discover part of North America in northern Australia	5/2/2018, Curtin News & Events	https://news.curtin.edu.au/stories/curtin-university-researchers-discover-part-north-america-northern-australia/



Cartoon illustrating that the Georgetown terrane of present-day northern Queensland was originally part of North America some 1700 million years ago. It then joined Australia at around 1600 million years ago during the formation of the supercontinent Nuna, and has remained part of Australia since.

MEDIA - FEATURED PAPERS *cont...*

1208. **LaFlamme, C.**, **Fiorentini, M.**, Lindsay, M. and Bui, T.H. 2018. Atmospheric sulfur is recycled to the crystalline continental crust during supercontinent formation. *Nature Communications, 9, 4380.*

Activity	Date, Forum	Web address
Life cycle of sulphur predicts location of valuable minerals	23/10/2018, Geology	http://www.geologyin.com/2018/10/life-cycle-of-sulphur-predicts-location.html
Life cycle of sulphur predicts location of valuable minerals	23/10/2018, Phys Org	https://phys.org/news/2018-10-life-sulphur-valuable-minerals.html
Life cycle of sulphur predicts location of valuable minerals	23/10/2018, UWA Science Matters	http://www.news.uwa.edu.au/2018102311057/international/life-cycle-sulphur-predicts-location-valuable-minerals
Life cycle of sulphur predicts location of valuable minerals	24/10/2018, ENN Environmental News Network	https://www.enn.com/articles/55834-life-cycle-of-sulphur-predicts-location-of-valuable-minerals
How to find mineral deposits at the edges of ancient continents	MINING.com	http://www.mining.com/find-mineral-deposits-edges-ancient-continents/

See *Research highlight p. 35.*

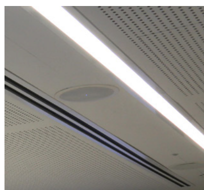
VISITORS

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.

Australian and international visitors are listed in Appendix 7. They have participated in collaborative research, technology exchange, seminars, discussions and joint publications and collaboration in postgraduate programs. For More information see the section on *International Links*.

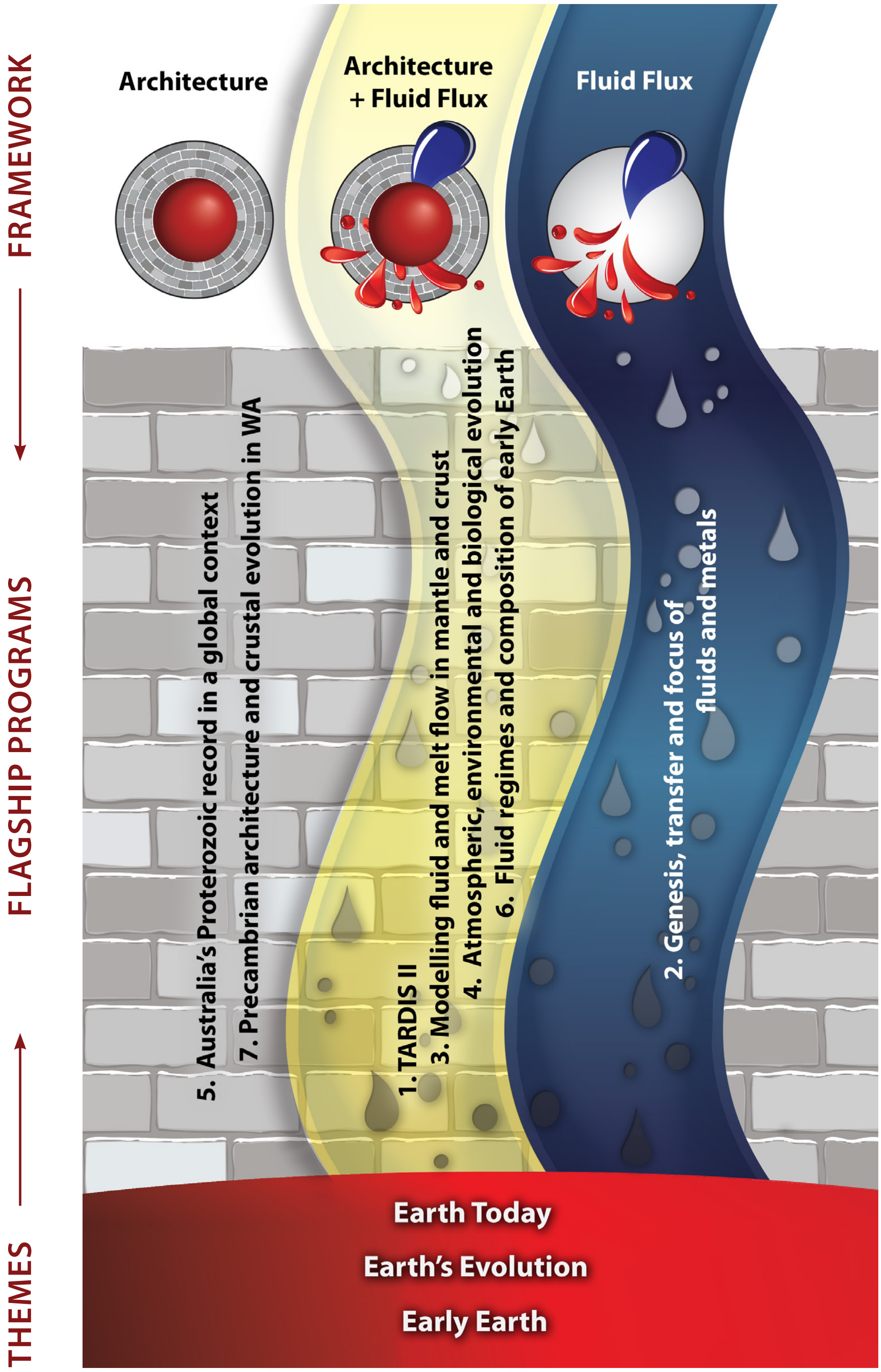
CCFS Visitor Vlad Malkovets from the Russian Academy of Sciences catching up with Bill Griffin.

Craig O'Neill and visitor Julian Lowman, University of Toronto. Professor Lowman's research focuses on the Interior Structure and Dynamics of Terrestrial Planets.



Research highlights 2018

Following the conceptual framework outlined on *page 4*, these Research highlights are identified as contributing to understanding Earth's Architecture (the '*roadmap*' for fluids) and/or Fluid Fluxes (the '*traffic report*'), with logos for easy attribution.
For a full description of the Flagship Programs, see *Appendix 1*.



At the end of the rainbow - Where is the pot of gold?

The nobility of gold, along with its high conductivity, ductility and especially its rarity have made it one of the most desired commodities in the history of humanity. Despite seven millennia of mining, the processes that locally enrich Au in the Earth are still enigmatic. Understanding these processes is becoming increasingly important as fewer new large gold deposits are being discovered, leading to claims that *'peak gold'* production has been reached. Most previous geological studies on Au have investigated crustal processes related to the formation of Au deposits. However, the ultimate source of the gold remains poorly constrained. Gold has been one of the least studied elements in the mantle. There are several reasons for this, including the fact that Au occurs in low levels in the mantle, making analysis difficult, and the mono-isotopic nature of Au makes isotope dilution, the technique commonly used to analyse the geochemically similar platinum group elements (PGE), impossible.

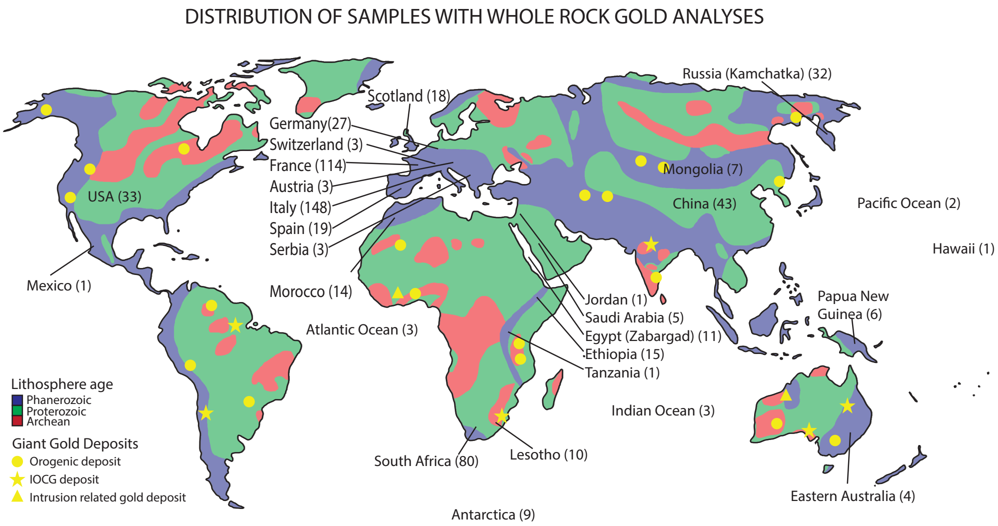


Figure 1. Global map showing distribution of upper mantle samples included in this study. Lithospheric ages simplified from the data in Artemieva (2006). Note: Location of giant gold deposits (classified as containing >500 t Au) from Groves et al. (2016).

We have compiled whole-rock analyses in mantle rocks (*CCFS publication #1206*) to investigate the abundance of gold in the lithospheric mantle, and how this distribution can be modified. This is the first time such an extensive database has been compiled for Au in mantle rocks, and several surprising results have emerged, including:

1. Modern lithospheric mantle has similar gold concentrations to the primitive upper mantle and the average continental crust, indicating that the lithospheric mantle has not been significantly depleted in Au over the course of Earth's history. This contrasts with previous suggestions that the primitive mantle was enriched in Au, making it a more fertile source for Au mineralisation in the Archean.

2. The lithospheric mantle has a relatively homogenous Au distribution, with the exception of the North China Craton, which appears to be anomalously enriched in Au. This enrichment is likely the result of the unique *'decratonisation'* event that the region underwent in the Mesozoic.

3. Au shows no systematic relationship with the LILE, and does not appear to be enriched by hydrous fluids in the mantle, which strongly contrasts with its behaviour in the crust. There is likewise no evidence that Au is enriched by carbonatitic metasomatism in the mantle. It may, however, be enriched by silicate melts in the mantle.

4. Au content of pyroxenites is commonly elevated relative to that of peridotites in the lithospheric mantle (median Au-in-pyroxenite = 2.0 ppb; median Au-in-peridotite = 1.2 ppb). The data indicate that the melts from which these pyroxenites have crystallised may be effective metasomatic agents within the lithospheric mantle. Such gold-rich pyroxenites and related magmas may play an important role in crustal mineralisation processes.

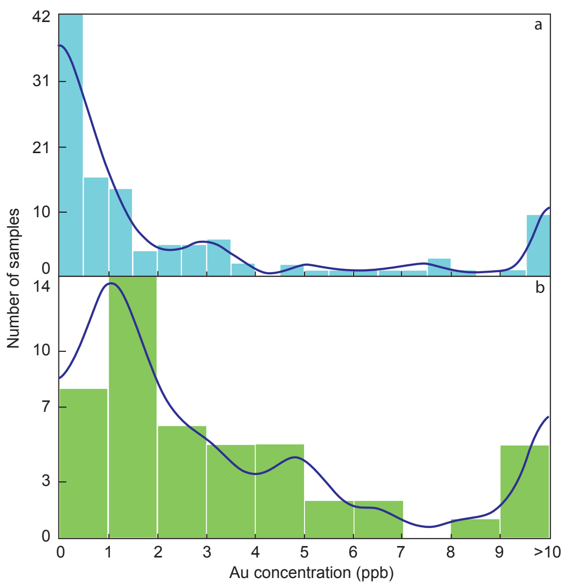


Figure 2. Histograms for Au concentrations in different lithologies: (a) dunite and harzburgite samples (n = 116); (b) pyroxenite samples (n = 48). All analyses >10 ppb have been included together on far right of histogram.

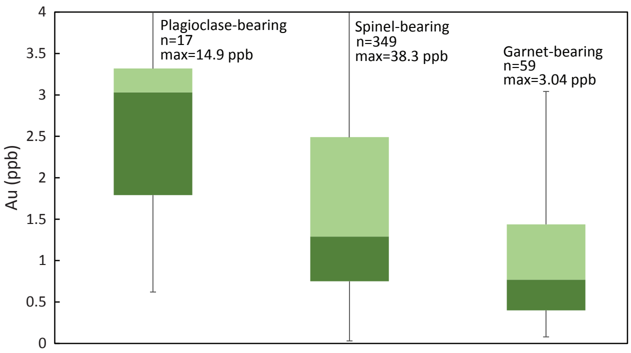


Figure 3. Box-and-whisker plots showing the decrease in Au with depth (from shallow, plagioclase-bearing peridotites on the left to deep, garnet-bearing peridotites on the right) in the lithospheric mantle.

In summary:

- Au contents in the subcontinental lithospheric mantle (SCLM), primitive upper mantle and crust are comparable, likely indicating efficient recycling through Earth history at least post-Archean
- The median Au contents in metasomatised, refertilised SCLM are higher than those in depleted and primitive SCLM
- Au is not sourced from subducted oceanic lithosphere but from asthenosphere
- Au is transported in silicate melts (evidenced by mantle pyroxenites), and not by *"fluids"*
- Shallow SCLM is most Au-enriched (indicating Au is upwardly mobile via silicate melt movement) in the lithospheric mantle

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

Contacts: Ed Saunders, Sue O'Reilly, Bill Griffin
Funded by: TARDIS Flagship Program

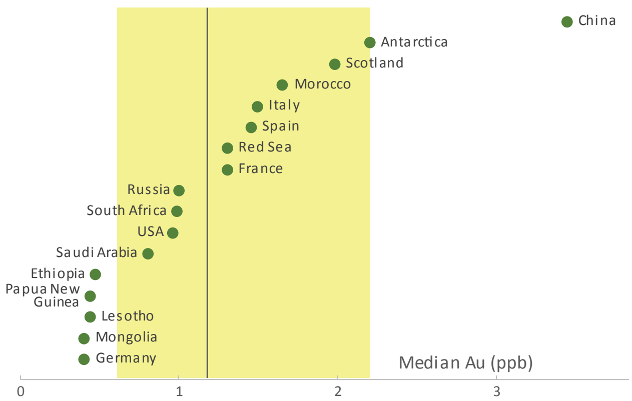


Figure 4. Median Au concentration in countries with five or more samples in the compiled database. Yellow box represents the 25-75th percentiles for upper mantle peridotites globally, dark grey line is median gold concentration for Au in upper mantle peridotites globally.

Atmospheric sulfur is recycled into the continental crust during supercontinent formation

The sulfur cycle across the lithosphere and the role of this volatile element in the metasomatism of the mantle at ancient cratonic boundaries are poorly constrained. We address these knowledge gaps by tracking the journey of sulfur in the assembly of a Proterozoic supercontinent using mass independent isotope fractionation (MIF-S) as an indelible tracer. MIF-S is a signature that was imparted to supracrustal sulfur reservoirs before the ~2.4 Ga Great Oxidation Event. The spatial representation of multiple sulfur isotope data indicates that successive Proterozoic granitoid suites preserve $\Delta^{33}S$ up to +0.8‰ in areas adjacent to Archean cratons. These results indicate that suturing of cratons began with devolatilisation of slab-derived sediments deep in the lithosphere. This process transferred atmospheric sulfur to a mantle source reservoir, which was tapped intermittently for over 300 million years of magmatism. Our work tracks pathways and storage of sulfur in the lithosphere at craton margins.

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

Crystal LaFlamme and Marco Fiorentini (UWA) try to unravel the cryptic link between the global sulfur cycle and the genesis of world-class mineral deposits.

Contacts: Marco Fiorentini, Crystal LaFlamme
Funded by: SIEF, MRIWA, CCFS Flagship Program 2

The curious story of the uniqueness of Archean lithospheric mantle in the Earth:

Lithospheric mantle comes of age - dominant, persistent and widespread

Continental crust on the modern Earth is underlain by a subcontinental lithospheric mantle (SCLM), consisting dominantly of variably depleted ultramafic rocks. It ranges from a few tens of kilometres thick beneath active rift zones, to >250 km beneath some Archean cratons, and is represented as dismembered buoyant blobs in ocean basins following intracratonic rifting (*CCFS publication #37*). Archean SCLM is both more depleted, and much more widespread, than previously understood. Its generation led to the formation of buoyant (and hence unsubductable) continental nuclei, which influenced the preservation of early crust and the nature of early plate tectonics. Its persistence has provided important constraints on the mechanisms and extent of growth of SCLM, including precluding growth by subcretion of subducted oceanic crust (e.g. *GEMOC publication #461*). The composition of the SCLM has changed through time (*CCFS publication #1183, Fig. 1*): SCLM thick enough to permit the formation of diamonds may only have formed uniquely in Archean time, lurking beneath some cratons ever since.

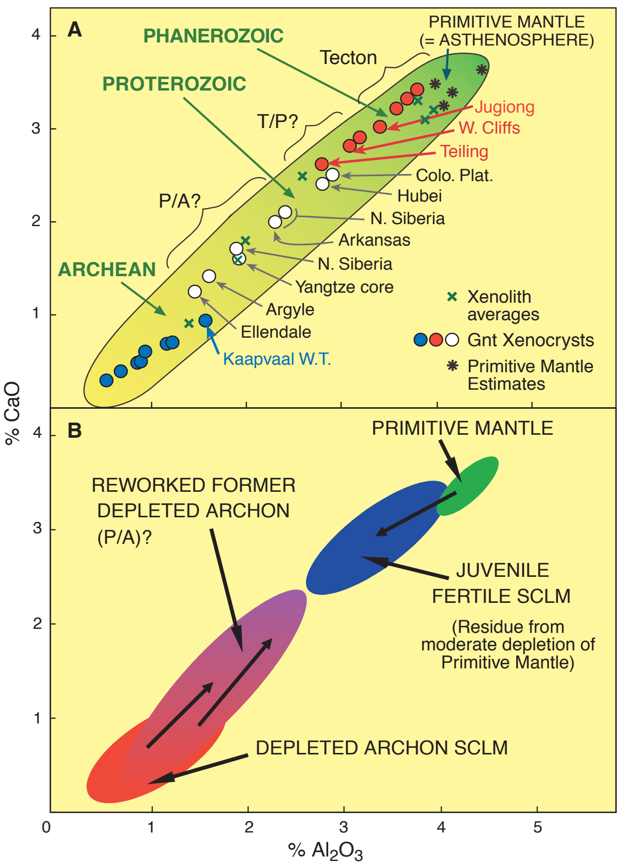


Figure 1. A. Estimates of the mean CaO and Al_2O_3 contents in subcontinental lithospheric mantle (SCLM) sections of different tectonothermal age based on the compositions of garnet xenocryst populations (circles) and xenolith populations (crosses) in volcanic rocks. B. Interpretation of the data in (A) in terms of depletion - refertilisation processes.

Archean SCLM is unique

The composition of the SCLM can be estimated from exposed orogenic massifs and from xenolith and xenocryst suites; each has its advantages and disadvantages. Most massifs represent relatively shallow SCLM sections, and have been strongly deformed during their emplacement, but exceptions may be found in some ultra-high-pressure zones, such as western Norway and in some orogenic domains in Tibet (*CCFS publication #704*). Xenolith suites sample larger vertical sections of the SCLM, but the relationships between different rock types are seldom obvious, and sampling (either by the volcano or by the geologist) may not be representative. Garnet xenocrysts in volcanic rocks can be used to estimate the composition of the SCLM, and this technique has provided a broader basis for mapping rock-type sections of the SCLM (*CCFS publications #1, 299, 303*).

How old is it?

The most robust isotopic system available for measuring the ages of SCLM peridotites is provided by the decay of ^{187}Re to ^{187}Os. During partial melting of the mantle, Re is extracted into the fluid phase, while Os remains concentrated in the residue; the removal of the melts from the system tends to freeze in the isotopic composition of the residual Os. The ^{187}Os/^{188}Os of the rock, or constituent minerals, can then be referred to a model for the evolution of Earth's Re-Os system to derive a model age that approximates the timing of the melt-extraction event. Detailed sulfide Re-Os data show a general overall decrease in model ages with depth beneath at least the Kaapvaal craton, but old sulfides and younger ones coexist in single hand specimens, reflecting the injection of multiple generations of sulfide.

Although the *in situ* sulfide dating method has been applied to a large range of lithospheric samples from different Archean cratonic regions, very few reliable model ages older than 3.6 Ga have been found (*CCFS publication #1183, Fig. 2.*); and the same is true for whole-rock data. While we do not have xenoliths of the SCLM from beneath areas that contain Hadean crustal rocks, the apparent lack of Hadean model ages beneath the oldest cratons seems to indicate that there was no Hadean SCLM. If the SCLM that we see today came into being only in Archean time, what does this tell us about the evolution of the early Earth?

How did it form?

A common model used to explain the formation of Archean SCLM is by the accumulation of subducted slices of oceanic mantle (*'lithospheric stacking'*). However, detailed seismic tomographic images of modern subducting slabs show that most descend steeply into the Earth, down to at least the 660 km discontinuity, rather than accumulating at shallow depths beneath the continents. In areas where shallow subduction is

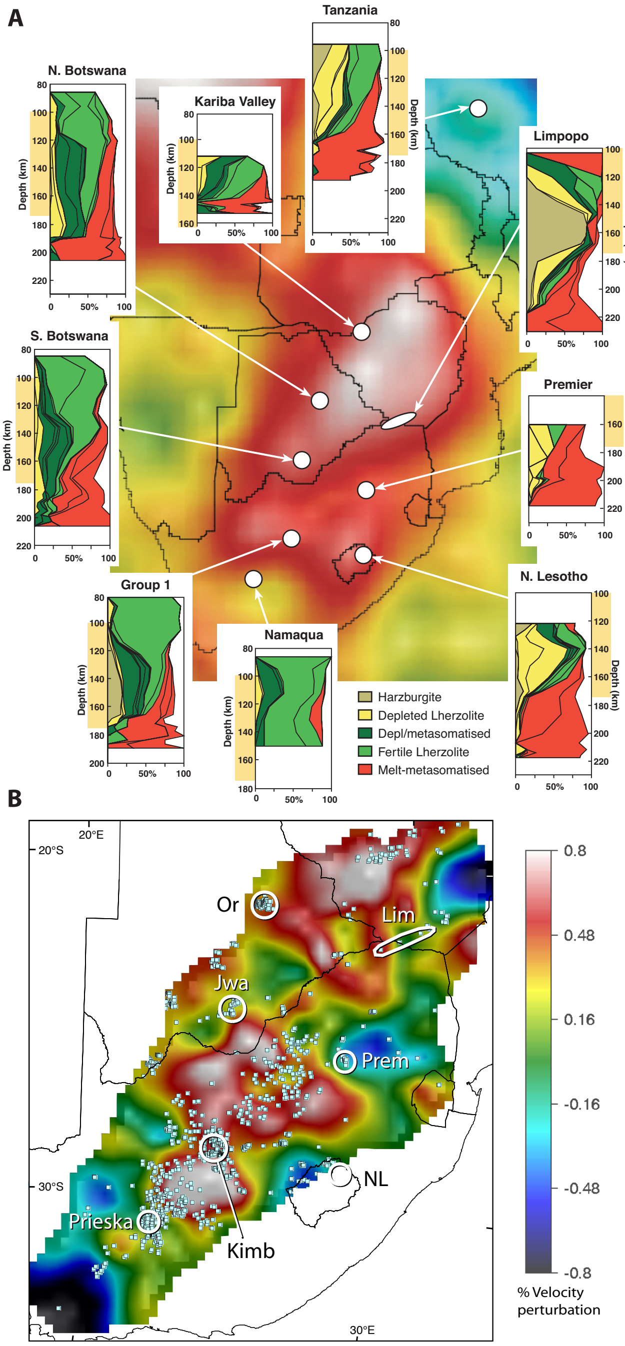


Figure 2. A. Seismic tomography image (100-175 km) of southern Africa, with location of well-documented xenolith suites and chemical tomography sections. White-pink colours indicate high seismic velocities, related to strong depletion and low geotherms; yellow-green colours indicate low velocities related to fertile compositions and higher geotherms. B. Detailed Vs tomography at 200 ± 50 km showing locations of known kimberlites. This emphasises that kimberlites tend to avoid blocks of best-preserved Archean subcontinental lithospheric mantle (white areas), instead following (and sampling) their more metasomatised, and hence lower-Vs, marginal zones. (Kimb, Kimberley area; NL, Northern Lesotho; Prem, Premier mine, Lim, Limpopo Belt; Jwa, Jwaneng; NB, Northern Botswana; Or, Orapa) (A) After Deen, T. et al., 2006, (B) After Fouch, M.J. et al., 2004.

observed, the slab rarely extends far under the continents, and does not produce thick SCLM.

The composition of Archean SCLM as defined by xenolith suites is unique; the *'pristine'* Archean SCLM is even more highly depleted than previous estimates and new values for the major oxides have been calculated (*CCFS publication #1183*). Thus, the formation of these highly depleted volumes appears to be related to specifically Archean processes, and are inferred to include megaplumes or massive mantle overturns (*CCFS# 330; references therein*). It is also unlikely to be coincidental that the production of highly depleted Archean SCLM coincides in time with the large-scale production of komatiitic magmas, which probably reflect high degrees of partial melting, requiring rapid decompression and leaving a highly depleted residue. Cogent evidence for the contribution of plumes to the ancient SCLM is provided by mineral inclusions in diamonds of minerals that are stable only under ultradeep lower-mantle conditions (e.g. ferropericlase, CaSi- and MgSi-perovskites).

How extensive is Archean SCLM?

The Global Lithospheric Architecture Mapping (GLAM) project (*GEMOC publication #547, CCFS publication #75*) had produced maps of the rock types and ages of upper-lithosphere domains. These are blocks of crust and lithosphere generated or reworked at different times, and delineated by integrating regional tectonics and geochronology with all available geophysical data (magnetic, gravity, seismic) and geochemical datasets in a multi-dimensional database in a GIS environment (Fig. 3) The origins and evolution of the underlying lower-lithosphere domains are interpreted from a high-resolution global shear-wave tomographic model (*CCFS publication #75*), using thermal/compositional modelling (*CCFS publications #217, 218*) and xenolith/xenocryst data (compositions and ages) from volcanic rocks. This work has shown that most continents are assembled from Archean cratons and smaller cratonic fragments, stitched together and flanked by younger fold belts (e.g. *GEMOC publication #547; CCFS publications #75, 1183*). The larger cratons are underlain by geochemically depleted, buoyant and mechanically robust SCLM; these cratonic roots have steep sides, extending in some cases to more than 300 km.

The SCLM is not only widespread *geographically* beneath existing continents, but it also shows great *vertical* extent in at least some regions. High-resolution global seismic tomography (Vs) models reveal high-velocity domains beneath cratonic crust in Africa that extend to depths of 300-400 km (*GEMOC publication #576*). These high-velocity domains show a distinct contrast with the characteristics of *'normal'* asthenosphere and are interpreted as depleted, buoyant roots that formed in the Archean and have remained attached to the overlying ancient crust. Archean lithospheric mantle has also been inferred beneath the Atlantic oceanic crust from tomographic models and the world magnetic-anomaly map (GEMOC #575; *Korhonen et al., 2007*) confirms that continental roots, overlain by thinned continental crust, locally extend well out under the deep Atlantic Ocean basin. However, such high-velocity domains are not confined to the Atlantic basin margins, but are scattered randomly through other basins. These high-velocity domains are interpreted to be remnant buoyant ancient lithospheric fragments isolated by

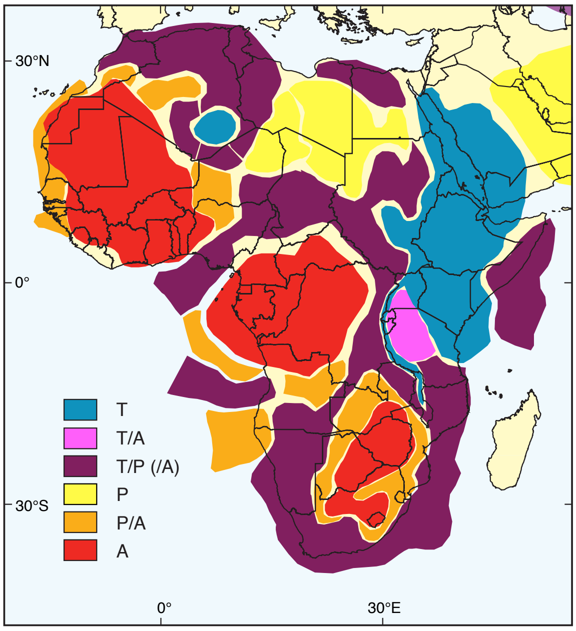


Figure 3. A Global Lithospheric Architecture Mapping interpretation of the subcontinental lithospheric mantle structure of Africa. A, Archon; P, Proton; T, Tecton (After Begg, et.al., 2009).

disruption of continental cratonic regions during rifting. This interpretation is supported by the old Os depletion ages of mantle peridotites from mid-ocean ridges and oceanic islands. (e.g. *GEMOC publication #576; CCFS publication #1183*).

This view of the secular evolution process emphasises the importance and uniqueness of the Archean SCLM. The formation of the Archean SCLM was one of the major events in Earth history, and the Paleoarchean-Mesoarchean period may have been a remarkable interregnum between the Hadean and a more modern Earth.

Implications for crustal evolution

If much of the present continental crust is underlain by SCLM produced in Archean time, then Archean crust may also be much more extensive than suggested by current outcrop patterns. Detailed studies of crustal xenoliths in basalts and kimberlites are now providing abundant evidence that ancient lower crust can be preserved while younger igneous rocks *'resurfaced'* it to form the upper crust. Such areas include localities in the North China Craton (*CCFS publication #95*), the Mediterranean region (*CCFS publication #234*), Spitsbergen (*CCFS publication #37*) and the Yangtze Craton (*CCFS publication #396*).

Our estimates based on the GLAM methodology indicate that more than 70% of SCLM has Archean heritage: it underlies most younger continental crust, and even some oceanic crust.

These advances in understanding the timing and mechanisms of SCLM formation have implications for models of crustal growth and recycling through time, which remain to be explored.

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

Contacts: Bill Griffin, Sue O'Reilly

Building the house from the basement: *in situ* isotopes in kimberlitic carbonates

Kimberlites are volcanic rocks, rich in volatiles (H_2O and CO_2), derived from a deep (>200 km) mantle source. As a consequence, they are often regarded as probes of the lithospheric mantle, providing unique insights of its structure, composition and evolution.

This project is focused on the study of *primary* kimberlitic carbonates, since they are considered good traps for the original CO_2 in kimberlite magmas and thus the best minerals to constrain the C and O isotope composition of the kimberlite parental melts. However, initial petrographic and compositional studies of kimberlites worldwide emphasised the complex petrogenesis of kimberlitic carbonates, involving both syn- and post-emplacement processes (i.e. magma crystallisation, hydrothermal alteration, crustal contamination, degassing or weathering). This heterogeneous nature explains why C-O isotope analysis of bulk carbonates in kimberlites yield inconclusive results about their origin. It clearly was necessary to develop a new approach that could correctly identify the origins of the different generations of carbonates described in the kimberlites. For the first time, textural and compositional studies were combined with *in situ* isotopic techniques (SIMS) to accurately measure the Sr, C and O isotope compositions of both primary and secondary carbonates.

A good example of the potential of this integrated methodology can be seen in our recent characterisation of the Benfontein kimberlite sills (South Africa). These three sills are well-known for their enrichment in carbonates, which show a variety of textures and compositions (e.g. laths, interstitial groundmass, veins) (Fig. 1 a-c). Another characteristic feature of the Benfontein kimberlite is the presence of calcite blobs or *'diapirs'* intruding the uppermost layers of the lowest of the three sills (Fig. 1 d-f). The origin of carbonate-rich sills associated with kimberlites has been a matter of debate since their discovery, and there is still no consensus about the origin of the *'diapirs'* at Benfontein. They have been related to carbonate-rich melt segregations from an evolved kimberlite magma; infilling of early gas cavities with a residual kimberlitic fluid; or crystallisation from hydrothermal, crustal-contaminated fluids.

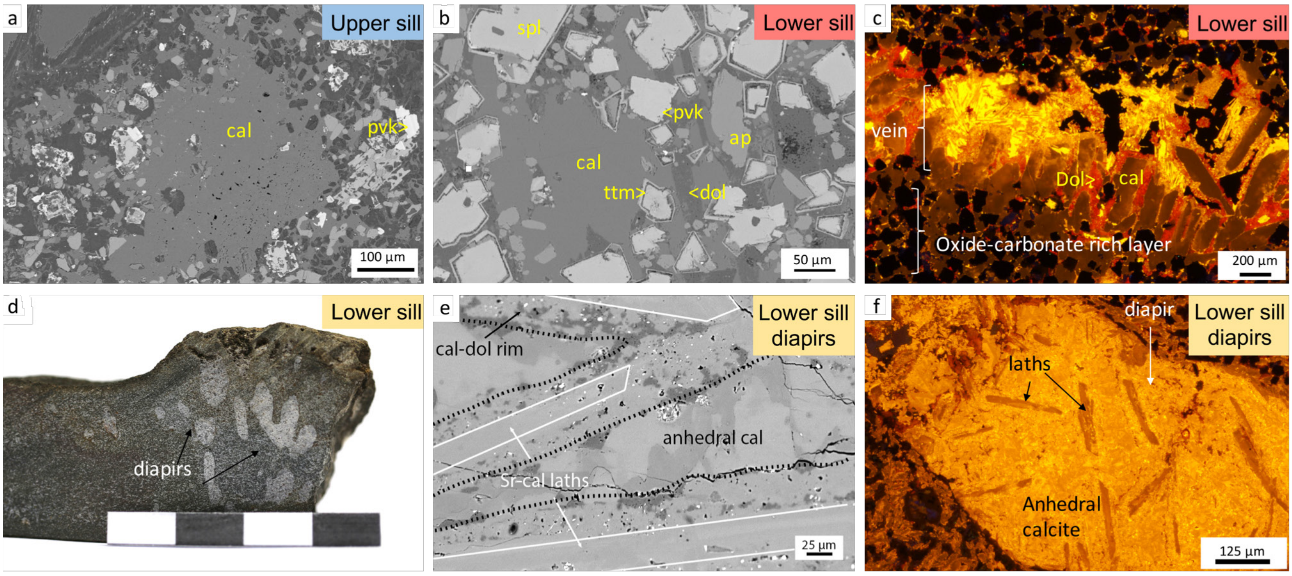


Figure 1. Carbonate petrography of the upper and lower sills in Benfontein. A) BSE-SEM image of the groundmass calcite (cal), interstitial to serpentinised olivine, with groundmass spinel and perovskite (pvk). B) BSE-SEM image of the oxide-rich layer, with abundant atoll spinel (spl) with a titanomagnetite rim (ttm), apatite (ap) and perovskite, with interstitial calcite and dolomite (dol). C) Cathodoluminescence (CL) image of the oxide-rich layer of the lower sill, crosscut by a carbonate-rich vein. (D-F) Hand sample, BSE-SEM and CL images of the diapirs of the lower sill. Note the different generations of carbonates: Sr-rich calcite laths, pure anhedral calcite of most of the diapir and a calcite-dolomite reaction rim.

Our multidisciplinary approach not only revealed the petrographic and geochemical complexity of carbonates in kimberlites in unprecedented detail, but also allowed confident identification of the processes that led to their formation. As shown in Figure 2, *in situ* C-O isotope studies, combined with Sr isotope analysis, have identified carbonates derived from: i. magmatic crystallisation of Sr-rich calcite laths and groundmass; ii. crystallisation of late groundmass calcite from hydrothermal fluids; and iii. variable degrees of crustal contamination in carbonate-rich diapirs and secondary veins. These diapirs most likely resulted from a residual C-O-H fluid or carbonate melt that had interacted with the local Dwyka shales, leading to higher $^{87}Sr/^{86}Sr$ and $\delta^{18}O$, but lower $\delta^{13}C$, than pristine magmatic calcite. Before coalescing into the diapiric segregations, they also variably entrained early-formed calcite laths and groundmass phases.

Comparison between *in situ* and bulk carbonate analyses (Fig. 2) confirms that C-O isotopic analyses of bulk carbonates from kimberlite rocks are not representative of the original C-O isotopic signature of the kimberlite magma. In contrast, calcite laths and most groundmass grains at Benfontein preserve isotopic values ($\delta^{18}O$ = 6 to 8‰ and $\delta^{13}C$ = -4 to -6 ‰), similar to those of pristine carbonatites, which therefore probably correspond to those of their parental melts. This narrow range suggests that the "*mantle carbonate*" box in Figure 2 could be more restricted than previously proposed.

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

Contacts: Montgarri Castillo-Oliver, Andrea Giuliani, Bill Griffin, Sue O'Reilly, Russell Drysdale, Adam Abersteiner, Emilie Thomassot, Xian-Hua Li

Funded by: CCFS Flagship Program 1, ARC DECRA to Andrea Giuliani (grant DE-150100009, European Science Foundation: Europlanet 2020 Consortium (project n. 16-EPN2-017)

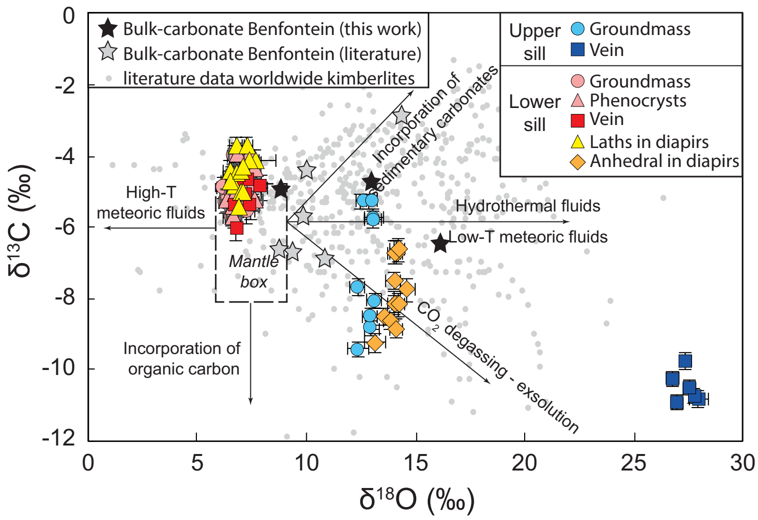


Figure 2. Plot of $\delta^{13}C$ (relative to VPDB) versus $\delta^{18}O$ (relative to VSMOW) showing the isotopic composition of different textural types of calcite from the Benfontein kimberlite analysed in situ by SIMS. Note that calcite in the groundmass, veins and diapirs (laths only) from the Lower sill plot in the "mantle box". Qualitative trends show how syn- and post-magmatic processes would modify the C-O isotope composition of magmatic carbonates.

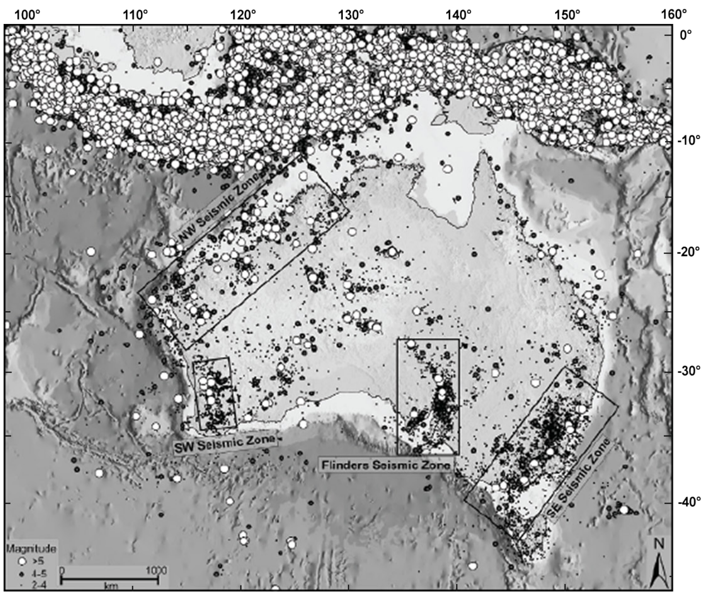
The physics of recent earthquakes in southwest WA

On September 16, 2018, a magnitude 5.7 earthquake occurred near Lake Muir in southwestern Western Australia. The epicentre of the earthquake is located at the southwest corner of the SW Seismic Zone (Geoscience Australia 2018), where no quakes over magnitude 5 have ever been recorded before. After the mainshock, a sequence of aftershocks were recorded by the sparse regional seismic network. Obtaining reliable moment tensor solutions is important for revealing the seismogenic zones of the Lake Muir earthquake cluster, and to better understand the regional stress field that is important in regional hazard assessment.

In this study, we used a time-domain linear least-squares inversion method (*Lin et al. Tectonics 2018; CCFS contribution #1109*) to analyse the moment tensors of Lake Muir earthquakes and earlier regional earthquakes. Compared with other methods, this wave-form-based technique has a better control on the source parameters. We used long-period waveforms between 20 and 50 seconds, in the moment tensor inversion. For the smaller earthquakes or the noise waveforms, we also considered the long-period waveforms between 14.3 and 25 seconds or 10 and 25 seconds.

An important aspect in source-mechanism inversions is to have robust P- and S-wave velocity models. Taking advantage of the location of the Muir Earthquake being close to a permanent seismic station (RKGY), we constructed the S-wave velocity models by applying a transdimensional tomographic inversion technique (*Yuan and Bodin, Tectonics 2018; CCFS Contribution 1181*) to the dispersion datasets measured from station pairs between RKGY and other permanent stations. The P-wave model is approximated by using an active source reflection profile *(Dentith, Tectonophysics 2000).*

The solutions of the M5.7 Lake Muir earthquake and its M5.4 aftershock are shown in Figure 2 below. It is interesting is that the M5.7 main shock on Sept 16 (Fig. 2 left) shows mainly a thrust mechanism, but the two aftershocks, each occurring nearly a month apart on Oct 12 (M4.6) and Nov 08 (M5.4; righthand side in Fig. 2), show a gradual change in the solution towards strike-slip. We also inverted for source mechanisms for several recent earthquakes in southwestern WA. Some solutions were compared with that by the USGS (Fig. 1) which show consistent results.



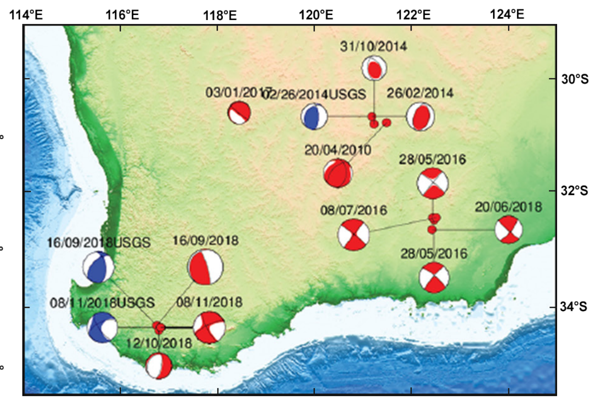


Figure 1. Seismic Zones of Australia (left; Rajabi et al., Earth-Science Reviews 2017) and Moment tensor solutions of earthquakes in SW Western Australia (right) obtained from this study (red beachballs). The M5.7 Lake Muir Earthquake occurred on Sept 16, 2017. Three solutions from the USGS (blue) are plotted for comparison.

The *regional stress field* indicates an east-west compression *(Rajabi et al., Earth-Science Reviews 2017)*, which explains the thrust-type mechanism of the M5.7 main shock, as well as of those earthquakes within the Yilgarn craton in the Kalgoorlie region. The change of the source mechanisms in the Lake Muir aftershocks may be attributed to a combined effect of complex stress release of the main shock in the complex local fault systems and triggering of new faults due to stress release of the main shock. Similar strike-slip solutions are found further east along the NE-SW trending craton margin in the east Albany-Fraser zone.

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

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Funded by: CCFS Flagship Program 7

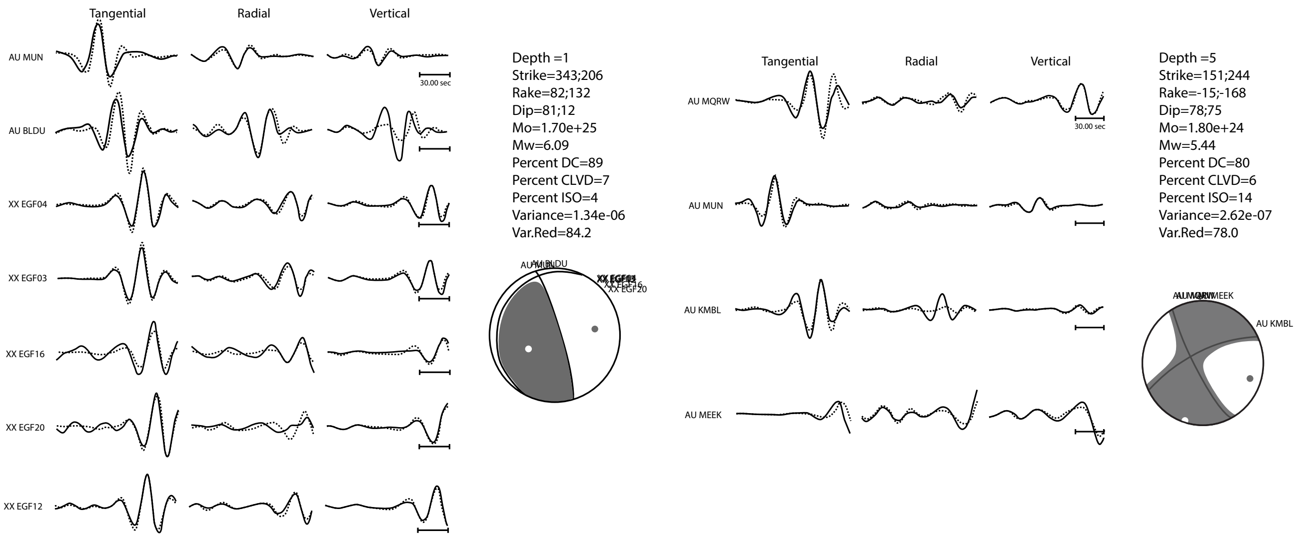

Figure 2. Source mechanism inversions for the M5.7 main shock (left) and the M5.4 aftershock (right) of the Lake Muir earthquake sequence.

CO_2 degassing - a new model approach to melting of mantle lithosphere

Reactivation of metasomatised mantle lithosphere may occur during continental extension, which is an important component of plate tectonics. The lower-most part of the metasomatised domains in the subcontinental mantle lithosphere can be locally enriched in CO_2. Therefore, partial melting of these metasomatised domains may play a crucial role in the global carbon cycle. However, little is known about this process and up until now few numerical constraints are available. Here we address this knowledge gap and use a 2-D high resolution petrological-thermomechanical model to assess lithospheric rifting, CO_2 degassing and melting. The numerical models fit well into natural rifting zones of the European Cenozoic Rift System for young (shallow) and of the North Atlantic Rift for old (thick) lithosphere.

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

Contacts: Weronika Gorczyk, Christopher Gonzalez
Funded by: CCFS Flagship 2

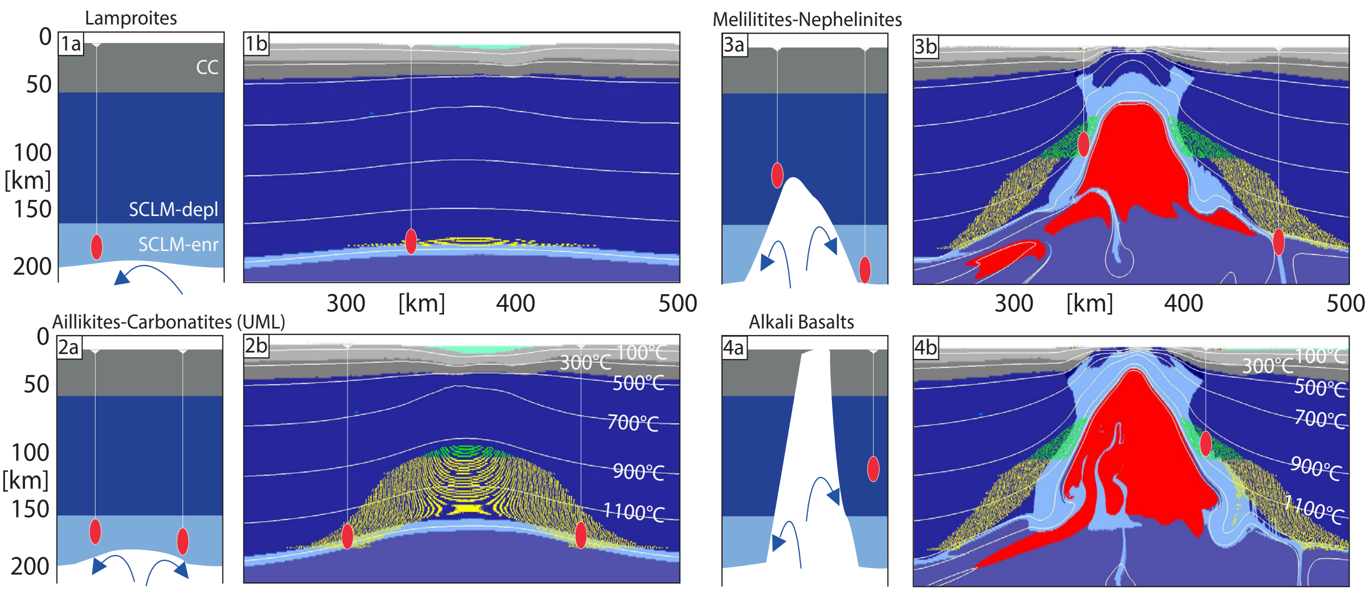

Figure 1. Comparison of tectonomagmatic model (plates [a]) of a segment of North Atlantic Craton close to the southern craton margin modified after Tappe et al. (2007), to numeral model 200 (plates [b]). Abbreviations: cc - continental crust, SCLM-depl - subcontinental lithospheric mantle - depleted, SCLM-enr - subcontinental lithospheric mantle - enriched in CO_2.

Olivine grains - new clues to the origin of diamondiferous kimberlites

Kimberlites are small-volume igneous rocks that have a unique role in the Earth sciences because they represent the primary host of diamond deposits; and derive from the deepest melts that occur at the surface of our planet. Despite decades of dedicated studies, the petrogenesis of kimberlites remains not fully understood. This is largely due to the complex hybrid nature of these rocks, including magmatic as well as abundant xenocrystic and alteration components. Olivine can provide unique insights into kimberlite origin and evolution, because it is the most abundant xenocrystic phase and a stable magmatic product over most of the crystallisation history of these magmas. Most olivine grains in kimberlites are compositionally zoned regardless of size and shape (Fig. 1). The zonation typically includes a core of variable composition that is overgrown by a rim characterised by relatively restricted Mg contents (Fig. 3), lower Ni and Cr, and higher Mn, Ca and Ti contents. One or more internal zones of variable composition may occur between core and rim of some grains (Fig. 1). The internal zones may be euhedral, diffuse or partially resorbed (embayments).

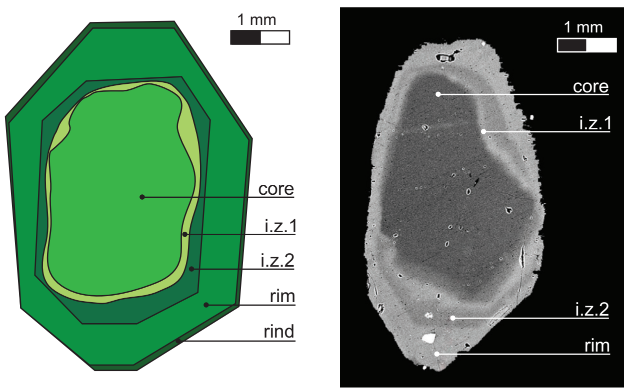

Figure 1. Cartoon showing the compositional zoning of an idealised olivine phenocryst, compared to a SEM back-scattered electron (BSE) image of a complexly zoned phenocryst from the Udachnaya-East kimberlite (Siberia).

A comparison between the compositions of olivine cores and olivine from mantle xenoliths (including megacrysts) entrained in kimberlites (Fig. 2), demonstrates that olivine cores are xenocrysts derived from disaggregation of mantle wall-rocks. This interpretation is consistent with the occurrence of mantle phases (i.e. orthopyroxene, clinopyroxene, garnet and Cr-spinel) as inclusions in olivine cores, and evidence of resorption (embayments) and abrasion (rounded shapes) of these cores. A variable proportion of olivine cores is sourced from mantle wall-rocks previously metasomatised kimberlitic magmas at mantle depths (including sheared peridotites and megacrysts), implying variable degrees of kimberlitic magma activity in the mantle before current kimberlite emplacement at surface.

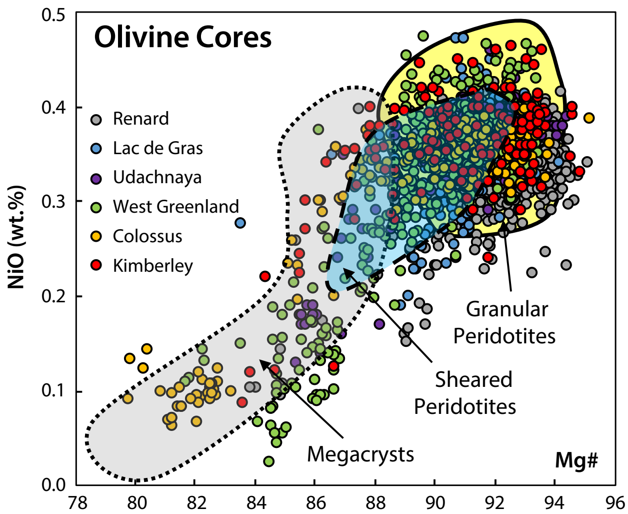

Figure 2. Mg#-NiO covariation diagram comparing the compositions of olivine cores in kimberlites with those of olivine in mantle lithologies sampled by kimberlite magmas, including megacrysts and peridotite xenoliths.

Olivine rims host inclusions of groundmass minerals (e.g. spinel, Mg-ilmenite, rutile), requiring a magmatic origin for the rims. There is a direct correlation between olivine rim and groundmass composition: high Mg/Fe rims are associated with carbonate-rich kimberlites, and lower Mg/Fe rims are correlated with increased phlogopite and Fe-bearing oxide modes (Fig. 4). With few exceptions, the compositions of olivine rims in each kimberlite locality, cluster (e.g. Kimberley) or form a compositional trend (e.g. Lac de Gras) within a restricted Mg# range (Fig. 3). This suggests that kimberlites within the same cluster derive from similar parental melts (and therefore sources), consistent with available radiogenic isotope results. Olivine rims in kimberlites from Lac de Gras, are compositionally indistinguishable from those occurring in rocks in hypabyssal root-zones, dykes and volcaniclastic units, thus indicating that such olivine crystallised during ascent, before different emplacement processes modified magma compositions. It can thus be inferred that the composition of (near-primitive) melt parental to olivine has

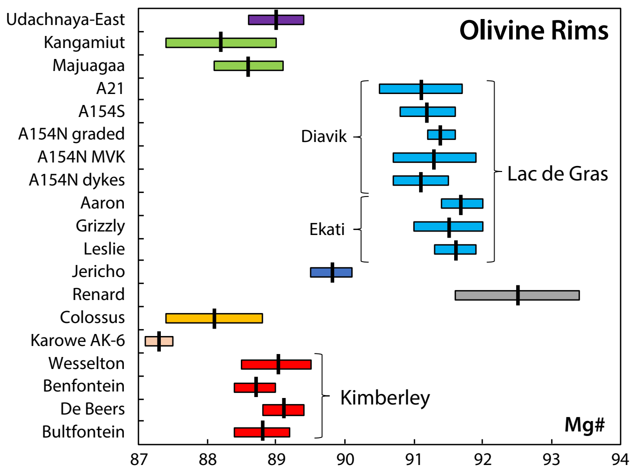

Figure 3. Average Mg# (± 2 s.d.) values of olivine rims in kimberlites worldwide. Note the similar compositions of rims within the same kimberlite cluster (i.e. Kimberley) and field (i.e. Lac de Gras).

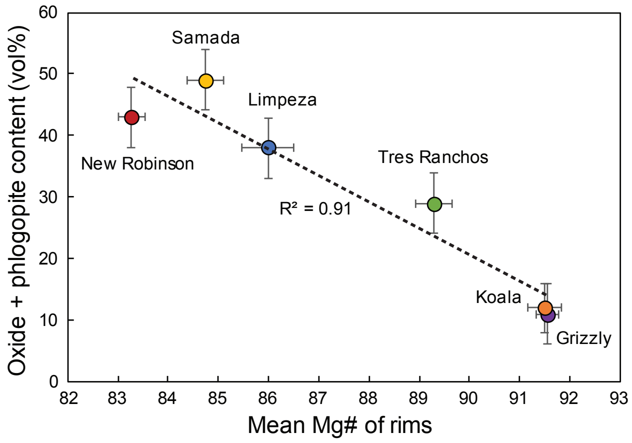

Figure 4. Comparison of mean Mg# value of olivine rims with the estimated abundance of phlogopite plus oxide minerals (spinel + Mg-ilmenite + perovskite) in the groundmass of kimberlites examined in this study. Note the statistical robustness of the inverse correlation between the two parameters (after Lim et al., 2018 Mineral Petrol).

minimal influence on kimberlite emplacement mechanism. Variations in the compositions of olivine rims in kimberlites from different areas relate to different parental melt compositions and contributions from a range of local processes (e.g. including olivine and spinel fractionation, assimilation of mantle material, CO_2 loss, melt oxidation) rather than variations in tectonic setting or emplacement mechanism.

Based on their compositional and textural features, three types of internal zones can be distinguished: 1) euhedral early liquidus olivine with higher Mg# and Ni than rims and hosting inclusions of magmatic chromite; 2) diffusional zones with compositions intermediate between those of cores and rims; 3) zones exhibiting resorption features that may be products of earlier kimberlite metasomatism at mantle depths.

In summary, olivine exhibits broadly analogous zoning in kimberlites worldwide. Olivine grains represent unique capsules that provide a potentially complete record of the evolution of kimberlite systems. Olivine cores store information on material entrained by kimberlites from the traversed mantle column, including evidence for early kimberlite metasomatism. Internal zones can show the effects of mantle metasomatism and/or record early kimberlite crystallisation at mantle depths. Rim compositions testify to the complex interplay of different processes during ascent and emplacement of kimberlite magmas. Ongoing research is exploring potential links between mantle-xenocrystic core and magmatic rim compositions to understand the effect of assimilation of mantle material on kimberlite melt composition; the oxygen isotopic composition of olivine to constrain the potential occurrence of recycled crustal material in the source of kimberlites; and the variability of olivine composition with time within kimberlite provinces to decipher the sources and evolution of different kimberlitic magma batches during protracted (10-30 Myr) magmatic episodes.

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

Contact: Andrea Giuliani
Funded by: ARC DECRA

Micro to global: microstructures reveal mantle secrets beneath the Pannonian Basin, Central Europe

Microstructures of mantle xenoliths can reveal the nature and behaviour of the upper mantle during tectonic processes. The characteristics of mantle-rock deformation are imprinted on the silicate minerals of the xenoliths, potentially identifying the tectonic history, as well as variables such as temperature, pressure, H ("*water*") content, and/or the interaction with melts/fluids. Physical properties of olivine, the most abundant upper mantle mineral, can be a proxy for the deformation processes that affected the xenolith-sampled mantle domain. Such parameters include orientation patterns of crystal axes, the strength of fabric expressed by the J-index (a dimensionless value that is a measure of the fabric strength, ranging from 1 (random orientation distribution) to infinity), and the grain orientation spread (a measure of the average amount of intragranular deformation).

The Pannonian Basin is a young back-arc basin located in Central Europe, surrounded by the Alps, Carpathians and Dinarides (Fig. 1). It has undergone significant extension during the Miocene then a compressional phase from ~8 Ma to recent times, resulting from the convergence of Adria and the European platform. Mantle-derived xenoliths were brought to the surface by late Miocene-Pleistocene alkali basalts in five areas (Fig. 1).

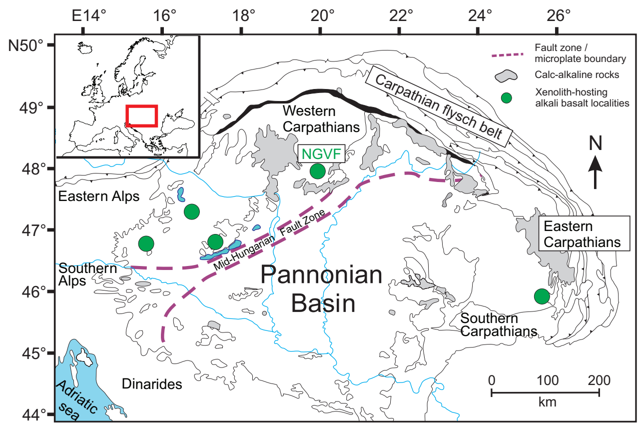

Figure 1. Locations of mantle xenolith-hosting alkali basalt outcrops within the Carpathian-Pannonian region. NGVF - Nógrád-Gömör Volcanic Field.

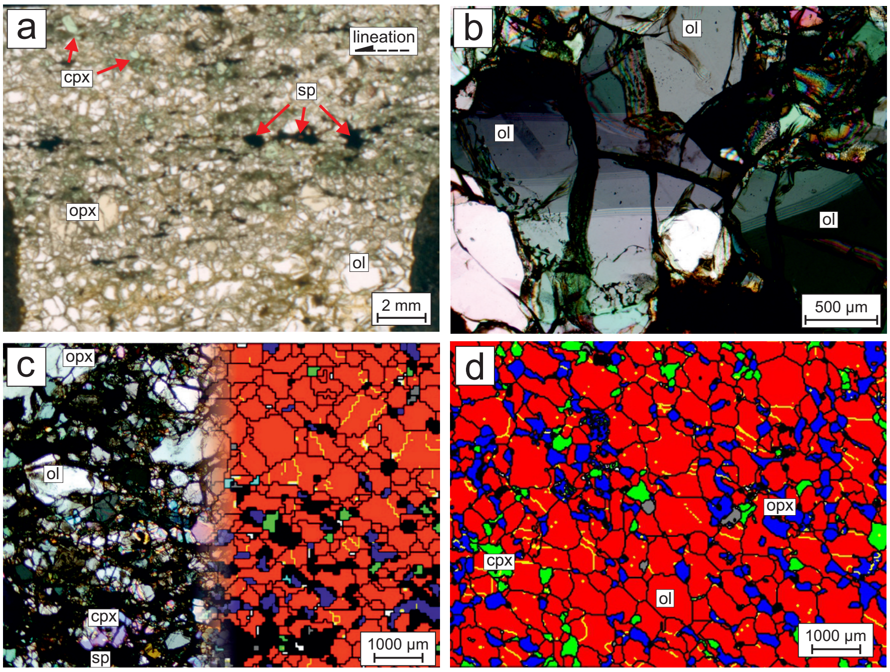

Figure 2. Characteristic microstructures in the studied Nógrád-Gömör xenoliths. a - lineation indicated by the distribution of spinel grains; b - subgrain boundaries in olivine; c - different olivine grain sizes in pyroxene-rich and pyroxene-poor domains; microphotograph (left) and electron backscattered diffraction (EBSD) phase map (right); d - EBSD map of equilibrated texture (straight grain boundaries, 120° triple junctions). Photomicrographs are transmitted light, plane-polarised in a, and cross-polarised in b and c. Colours on EBSD phase maps: red - olivine, dark blue - orthopyroxene, green - clinopyroxene, grey - spinel, light blue - amphibole. Abbreviations: ol - olivine, opx - orthopyroxene, cpx - clinopyroxene, sp - spinel.

The focus of this study is the xenoliths from the northernmost locality, the Nógrád-Gömör Volcanic Field, where crystal preferred orientations have not previously been described.

The xenoliths were analysed with a polarisation microscope and electron backscatter diffraction technique. Microstructural features indicating deformation include lineation outlined by spinel distribution (Fig. 2a) and elongated grain shapes, as well as common subgrain boundaries (seen as undulose extinction (Fig. 2b)). These deformation markers are commonly overprinted by annealing (static recrystallisation) resulting in grain growth of olivine (where olivine is not pinned by pyroxenes (Fig. 2c)), and straight grain boundaries with 120° triple junctions (Fig. 2d). Crystal preferred orientations of olivine reveal that most orientation patterns indicate deformation in a transpressional regime. This is consistent with the stress field generated by the convergent tectonics between the Adria microplate and the European platform.

Based on the positive correlation between the J-index and the equilibration temperatures (Fig. 3a) calculated from mineral compositions (*Liptai et al., 2017, J. Pet.; CCFS publication #1004*), the extent of deformation varies with depth. In addition, the extent of intragranular deformation is more dependent on the location, as it decreases from the northern part of the volcanic field towards the south (Fig. 3b). Post-kinematic annealing is linked to percolation of metasomatic mafic melts in the upper mantle of the NGVF before eruption of the host alkali basalt. Elevated equilibration temperatures in xenoliths from the central part of the volcanic field (Fig. 3b) are interpreted to derive from the youngest metasomatic event, which only shortly preceded the ascent of the host magma.

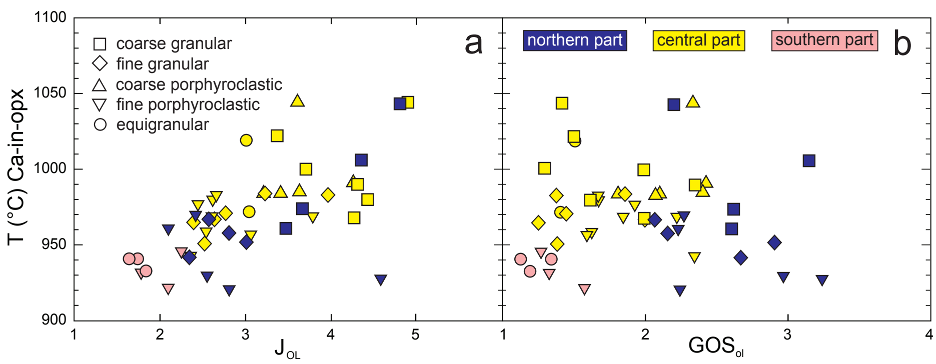

Figure 3. Olivine deformation features compared to calculated equilibration temperature (Ca-in-opx thermometer after Nimis & Grütter, 2010, CMP).

Crystal preferred orientation data also allow the calculation of seismic properties; combining that with measured shear wave splitting times in the area, the thickness of the anisotropic layer was estimated. The anisotropic thickness depends on the orientation of the foliation and lineation. The preferred model, on the available data, is horizontal lineation and vertical foliation. This is consistent with the recent tectonic regime, and also gives a minimum value for the thickness of the anisotropic layer. Some asthenospheric contribution may be needed to produce the observed shear wave splitting.

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

Contacts: Nora Liptai, Sue O'Reilly, Bill Griffin, Csaba Szabó (Eötvös University, Hungary), Károly Hidas (University of Granada, Spain), Andréa Tommasi (University of Montpellier II, France)

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A giant step towards a unified model for mantle magmatism

Mantle magmatism is a consequence of thermal discontinuities in, and one of the main mechanisms for the thermal evolution of, the Earth and other terrestrial planets. Encompassing partial melting, melt migration and mixing, melt-rock interaction and crystallisation, mantle magmatism can be modelled as a combination of phase changes (e.g. from solid to liquid), differential flow (e.g. of a fluid through a rigid matrix) and chemical reactions (exchange of chemical components). It can be described as a Multi-Phase, Multi-Component, Reactive Transport system (MPMCRT) that can, in principle, be constrained experimentally and numerically modelled.

Over the past four decades specific aspects of MPMCRT, in the context of mantle magmatism, have been independently addressed by different communities (including petrologists, geochemists, geophysicists, computational geodynamicists). A new conceptual and numerical approach, integrating petrological, geochemical and geophysical considerations into a fully quantitative and comprehensive approach to mantle magmatism, bridges these traditional research silos.

This approach combines (1) a microstructural model for diffusion-controlled trace-element transport and (2) disequilibrium extensions of the multi-phase reactive transport model developed by *Oliveira et al.* (2018) (*CCFS Publication #1012*). In particular, chemical disequilibrium is accounted for by the novel thermodynamic formalism Dynamic Disequilibrium Melting (DDM, Fig. 1). DDM provides a versatile platform, not only able to study the dynamics and feedback of many magmatic systems over multiple scales but also rendering possible realistic comparisons between geophysical and geochemical datasets.

For example, the results of our MPMCRT model of mid-ocean ridges suggest that the modal, major- and trace-element compositions of abyssal peridotites could solely be accounted for by melt-extraction processes if disequilibria arising from transport, phase changes and diffusion (Fig. 2) are accounted for. Similarly, local and global trends in MORB compositions could be reproduced using self-consistent tectonic scenarios. Application to lithospheric refertilisation processes is also particularly promising by introducing the properties for radiogenic isotope systems (currently under development).

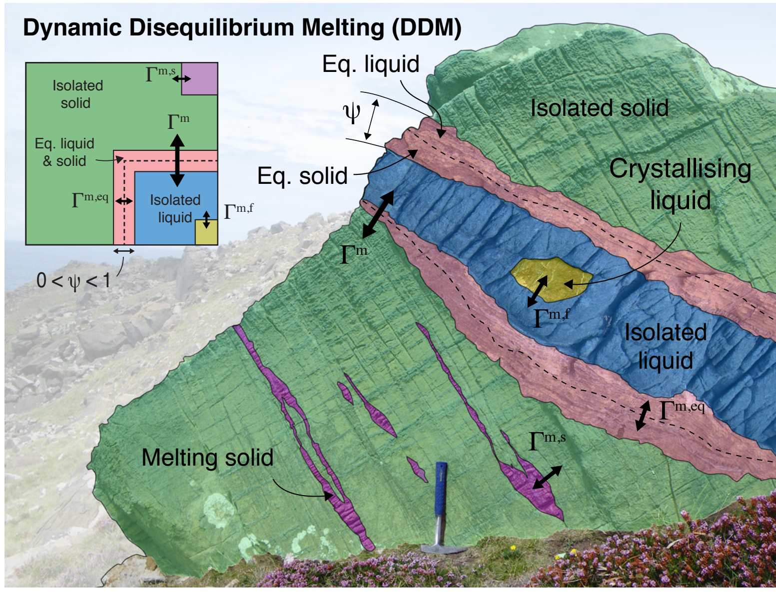

Figure 1. Schematic illustration (a) and projection (b) of the Dynamic Disequilibrium Melting model on a virtual outcrop of mantle rocks. Pink areas refer to fully equilibrated regions (e.g. dunitic reaction zone) and green and blue refer to chemically isolated solid (e.g. harzburgite) and liquid (e.g. basaltic melt), respectively. Each of the three regions has its own set of P-T-c^b conditions, and thus individual Gibbs free-energy minimisations are possible, allowing for independent crystallisation (yellow areas) and/or melting (purple areas) in the liquid and solid regions, respectively.

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

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Funded by: CCFS Flagship Program 4, European Space Agency, La Caixa scholarship, iMQRES scholarships

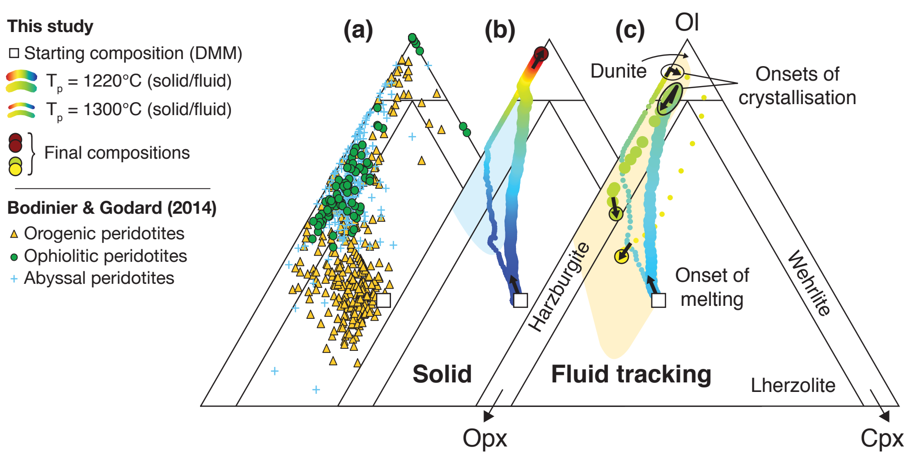
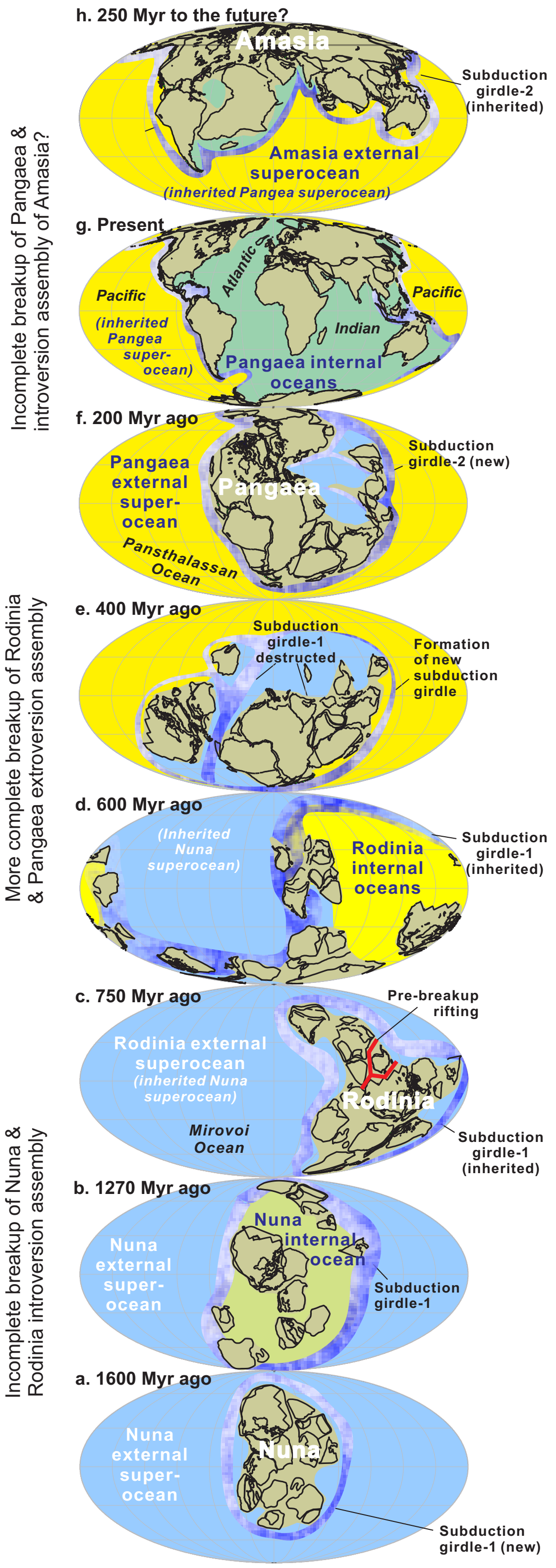


Figure 2. Comparison between modelled peridotites and the modal compositions of abyssal, ophiolitic and orogenic peridotites (a). Results were obtained while tracking either (b) an ascending mantle domain (solid tracking) or (c) a melt parcel (fluid tracking). Two scenarios are shown corresponding to a relatively cold (1220 ºC, bold lines) and hot (1300 ºC, bold lines) mantle potential temperature. Note that crystallisation occurs as the melts enter the thermal lithosphere (c), resulting in metasomatised peridotite compositions that overlap the field of orogenic peridotites. Colour code along the paths represent the evolution in time for each scenario.

Decoding Earth's supercycles

Repeated, and possibly cyclic, events of supercontinent assembly and breakup have been increasingly recognised over the past two decades. The latest of such events was the supercontinent Pangaea (ca 320-170 Ma), preceded by Rodinia (ca 900-700 Ma), and by Nuna (ca 1600-1400 Ma), implying a cyclicity of ~600 ± 100 Myr. A similar cyclicity, with a 50-100 Myr time lag, is found in global mantle plume intensity, leading to a geodynamic model of a coupled supercontinent-superplume cycle in Earth history. However, variations in global zircon Hf isotopic signatures and seawater Sr isotope ratios are both characterised by a longer-term variation trend with ca twice the wavelength of a typical supercontinent cycle. This billion-year variation trend (or supercycle) is also exhibited in global juvenile crust generation, and by the distribution of ages of certain global-scale mineral deposits (such as lead and zinc deposits and orogenic gold deposits), but why?



Li et al. (*CCFS publication #242*) suggested that the answer lies in the evolution of Earth's ocean basins. According to the model, supercontinents appear to assemble through two alternating pathways. One is extroversion (e.g. the assembly of Pangaea) where the previous supercontinent (Rodinia) was turned inside-out to form the new supercontinent, and in the process the superocean surrounding Rodinia was consumed (see Figs. 1c to 1f). The other is introversion (e.g. the assembly of Rodinia), where the previous superocean surrounding Nuna survived the supercontinent cycle. In the latter case, the assembly of the new supercontinent occurred through the collapse of the internal oceans formed during the break-up of the previous supercontinent Nuna (Figs. 1a to 1c).

More intriguingly, these two alternating methods of supercontinent assembly determine not only whether the superocean survives, but also whether the circum-superocean magmatism (e.g. the present-day Pacific Ring of Fire, which is scientifically referred to as the subduction girdle) survives. If this ring of fire survives along with the superocean, then the mantle structure maintains its pattern from the previous supercontinent cycle (the so-called degree-2 mantle structure; Fig. 2a). If not (in the case of extroversion supercontinent assembly), then the Earth's mantle structure is completely reorganised from a degree-2 pattern into a so-called degree-1 pattern (Fig. 2b), with the new supercontinent formed over a giant mantle downwelling (shown in blue). We speculate that such alternating pathways of supercontinent assembly (along with the survival or regeneration of the superocean and ring of fire) have produced an Earth cycle which is twice as long as the ca 600 Myr supercontinent cycle, influencing the formation of some of Earth's resources.

Figure 1. Survival of an external superocean over two supercontinent cycles as evidenced by global palaeogeography over the past 2000 Myr (a-h), and speculated corresponding mantle structures. Each major internal or external ocean system is colour-coded throughout the series of reconstructions. The assembly of Rodinia at 900 Ma (also future Amasia) is shown to be predominantly achieved through the closure of the internal ocean system formed as Nuna at 1400 Ma (or Pangaea at 170 Ma) fragmented (i.e. introversion), whereas the assembly of Pangaea was predominantly accomplished through the closure of the external ocean that surrounded Rodinia (i.e. extroversion).

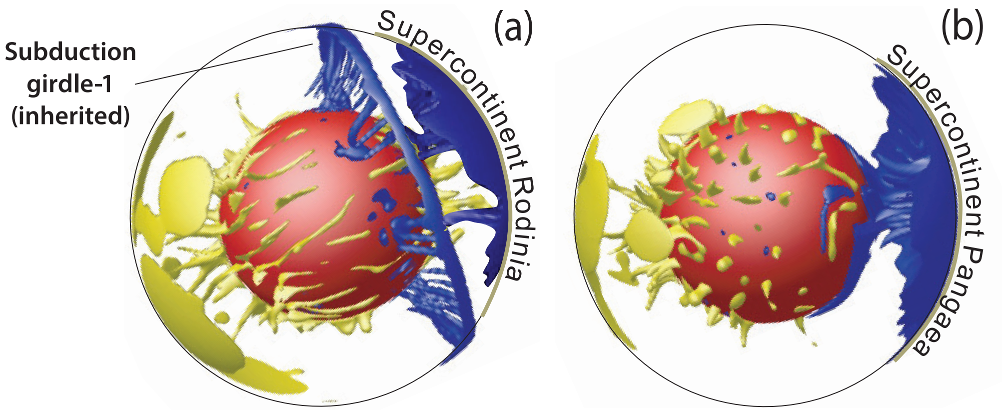


Figure 2. Different mantle structures related to the two different ways of supercontinent assembly. (a) A dominantly introverted supercontinent assembly inherits the pre-existing subduction girdle and degree-two mantle structure, along with the external superocean outside the subduction girdle. (b) A dominantly extroverted supercontinent assembly is accompanied by the destruction of the subduction girdle and the previous external superocean, where the new supercontinent forms above.

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

Contact: Zheng-Xiang Li

Funded by: ARC Laureate Fellowship (ZX Li)

Volatile elements and metasomatism: how to move things around in the lithosphere

Volatile elements (C-H-N-S) are the chemical backbone for all essential organic molecules. They are also key to the planet's habitability and its geodynamic activity, including ore forming processes. Exchanges between Earth's interior and its exospheres (crust, hydrosphere, atmosphere) and biosphere occur during subduction and volcanism, but to what extent? What are the mechanisms and rates by which volatiles moves between deep and shallow reservoirs? What is the impact of mantle degassing on the secular evolution of the mantle and on the exospheres? As noted by the Deep Carbon Observatory (https://deepcarbon.net/) the inventory, cycles and behaviour of these key elements in the deep Earth are far from being constrained.

Because volatile elements have variable speciation they can be stored in the mantle in various ways: (i) as dissolved trace elements in the main silicate minerals (such as H in nominally anhydrous minerals: ol, opx, cpx); (ii) being a major element of specific/metasomatic phases, such as H in amphibole or C in carbonate, graphite and diamond; (iii) stored in melt/fluid inclusions; (iv) entering grain-boundary components. Therefore, their study requires a new approach integrating geochemical and mineralogical investigations at both whole-rock and mineral scales.

As a first step toward this aim, we have used an elemental analyser to determine whole-rock C, H, N and S contents in a series of alkali basalt-hosted peridotite xenoliths. Volatile contents vary widely (70-8000 ppm C; 50-485 ppm N, 90-1200 ppm H, 10-1500 ppm S). Eight well-characterised peridotite xenolith suites from alkali basalts were investigated, representing various degrees of melting and metasomatism. Correlations between C,H,N,S and melt-depletion criteria (e.g. Fo%, Al_2O_3WR) or metasomatic indicators (La/Sm) suggest that the variability in CHNS is not related to weathering or alteration but was mostly established during mantle processes. However, these relationships vary between suites. For example, the Ray Pic (RP) and Bullenmerri (BM) peridotites both contain amphibole. However RP xenoliths show H enrichment (up to ≈600 ppm), but low C contents (≈120±30 ppm) consistent with H_2O contents of

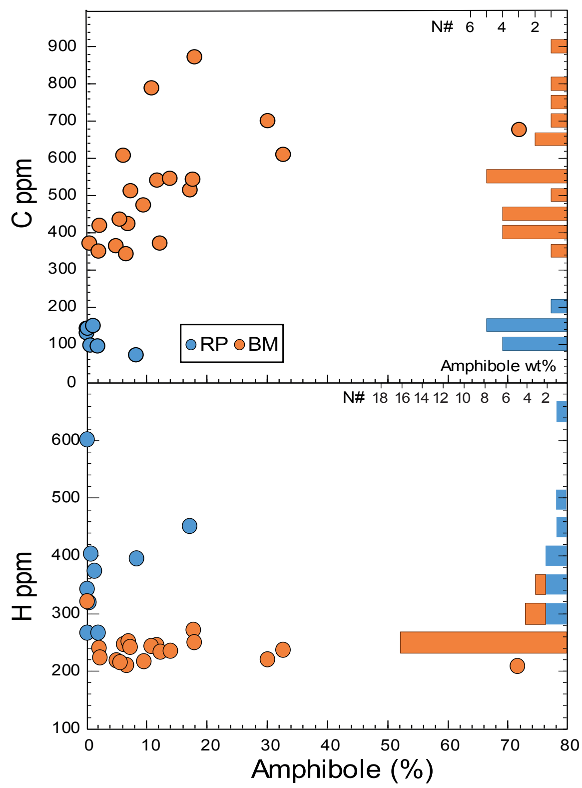


Figure 1. Whole rock C and H concentration (ppm) in amphibole bearing peridotite xenoliths from Ray-Pic (RP, Massif Central, France) and Bullenmerri (BM, Newer Volcanic Province, Australia).

ca 1.4 wt% in the RP amphibole. BM xenoliths have, in contrast, low H contents (≈220 ppm) but clear enrichment in C (up to ≈700 ppm), well correlated with modal amphibole abundances (Fig. 1). This difference in C and H behaviour is related to the distinctive trace-element patterns and amphibole compositions in each suite. In contrast, Borée peridotites, which contain no metasomatic amphibole, show high C and H contents (up to 1200 and 8000 ppm, respectively). Low H_2O contents in ol, opx and cpx obtained by FTIR (in collaboration with S. Demouchy, Géoscience Montellier, France) indicate that C and H enrichments in BO xenoliths are not related to the main silicate minerals. Spitsbergen xenoliths show both high C and S contents in agreement with their well-documented occurrence of sulfide and carbonate-bearing metasomatic pockets.

Volatile elements have always been considered to be a key component of most metasomatic melts/fluids invoked for modal, cryptic and stealth metasomatism. While mantle petrologists and geochemists have defined various metasomatic agents (including carbonatitic, carbonated, hydrous) with specific geochemical fingerprints, the nature of, and ratios between, the various volatile elements in these melts/fluids are still highly debated. Our preliminary results suggest that it may be possible to more closely constrain the relative abundance and behaviour of volatiles during these metasomatic processes and investigate their effects on the transport and fractionation of trace elements including chalcophile elements.

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

Contacts: Ananuer Halimulati, Olivier Alard, Sue O'Reilly
Funded by: Olivier Alard ARC Future Fellowship, CCFS

The power of a systems approach to mineral and petroleum exploration in sedimentary basins

Petroleum systems and hydrothermal sedimentary rock-hosted copper, lead-zinc (clastic-dominated and Mississippi Valley-type), and uranium systems can be described in a common system framework comprising the critical processes of:

(1) establishing the fertility of source(s) of the commodity of interest and the transporting fluid,
(2) geodynamic triggers for commodity movement and accumulation,
(3) establishing an architecture for fluid movement,
(4) accumulation by deposition of the commodity, and
(5) preservation.

Consideration of these commodity systems in the context of the Earth's evolving atmosphere-hydrosphere-biosphere-lithosphere highlights the power of paleotectonic, paleogeographic, and paleoenvironmental reconstructions in the critical step of basin selection. Such consideration also highlights common gaps in understanding the commodity systems. These knowledge gaps constitute high-value research paths that would provide greatest leverage in area selection at the basin and play scales. These include improved knowledge of paleogeographic and paleoenvironmental reconstructions, basin hydrodynamics, and timelines of mass and energy flow through basins. For metal systems, better understanding is required of how metal extraction efficiency, solubility, mineral precipitation, permeability, and pressure and temperature gradients dynamically interact along flow paths during the evolution of basins. See *CCFS publication #1186*.

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

Contact: Cam McCuaig
Funded by: BHP

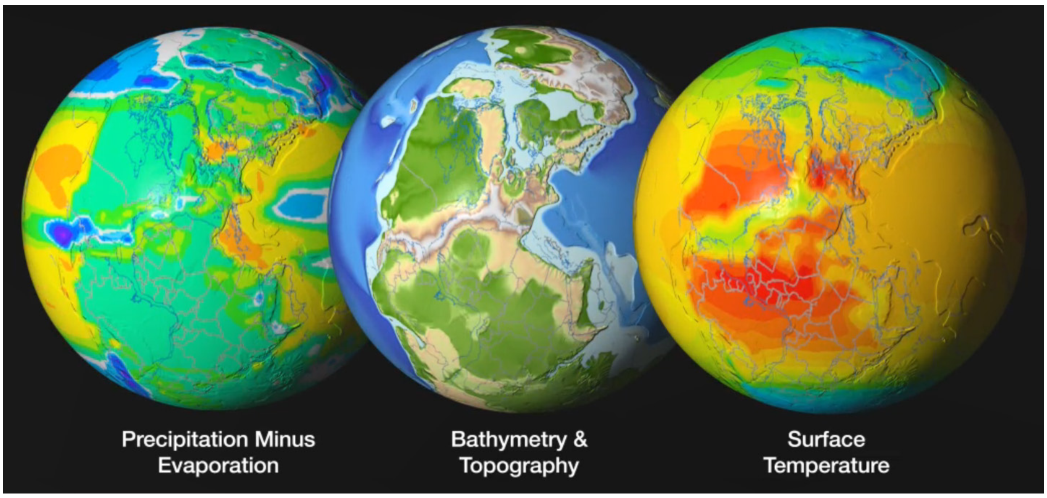


Figure 1. Getech (unpub. commercial software, 2015) paleogeographic reconstruction at 257 Ma. The figure illustrates how paleogeographic and paleotectonic reconstruction has the power to screen basins for fertility. The Late Permian, one of the world's great periods of deposition for petroleum source rocks, was also the time when the fertility for sedimentary rock-hosted copper and lead-zinc was established.

Can olivine's temperature diagnose the diamond potential of a kimberlite?

Kimberlite is the main volcanic host for transporting diamonds to the Earth's surface. Kimberlites also entrain fragments of rock (xenoliths) and disaggregated single grains from the lithospheric mantle (xenocrysts) which can provide valuable windows into the region from about 40 to 250 km beneath the surface.

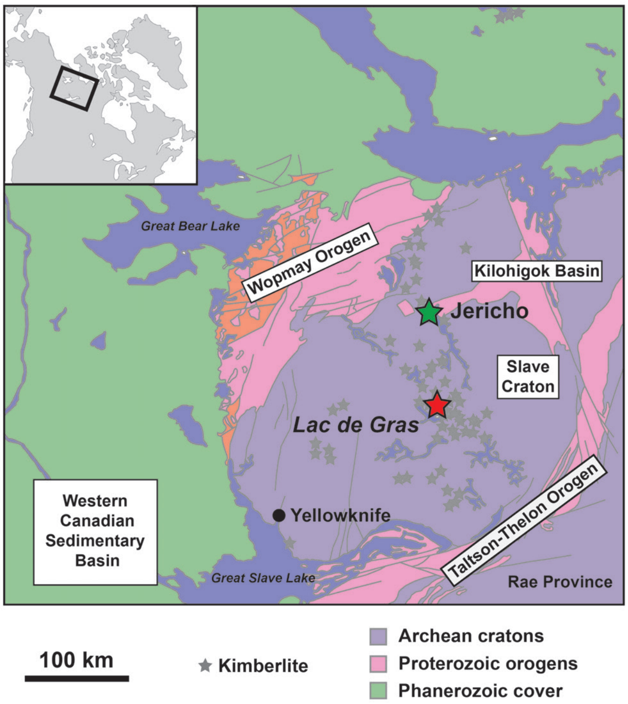


Figure 1. Map of the Slave Craton in northern Canada.

This study uses such xenoliths and xenocrysts from several kimberlite occurrences in the Cenozoic Lac de Gras kimberlite field in the Slave Craton, and the Jurassic (173 million years old) from northern Canada (Fig. 1). Geochemical data for abundant olivine xenocrysts in these two kimberlites are integrated to constrain their source depths. Olivine xenocrysts constitute about half the volume of these host rocks, and therefore their temperature profile may assist the identification of potential diamond occurrence, as diamond stability is limited to depths greater than ~140 km, equivalent to a temperature of 1000 °C. If the temperature of equilibration of at least some olivine xenocrysts indicate derivation from more than 140 km, diamond would be stable, and would have formed if there was sufficient carbon available.

Approximately 85% of the olivine xenocrysts studied here have compositions consistent with their derivation from mantle peridotites and pyroxenites. A new approach to single-grain olivine thermobarometry is being explored, based on the correlation between equilibration temperature, pressure and composition of olivine composition for the xenoliths from these localities.

A correlation between xenolithic olivine Mg# and pressure for most of these peridotitic and pyroxenitic bodies in the Jericho and Lac de Gras xenolith suites was observed. The relationship between xenolithic olivine Mg# and pressure thus may allow inferred estimates of the pressure (and by reference to the ambient geotherm, to the temperature) of xenocrysts assuming they derived from disaggregation of these source xenoliths.

Preliminary results suggest good agreement of the relative abundance of xenoliths and xenocrysts in the Lac de Gras pipes: both appear to be sourced predominantly from the deep lithospheric mantle (140-220 km; Fig. 2). At Jericho, xenoliths are sourced from as deep as 165 km, but xenocrysts appear to be exclusively above 140 km (Fig. 2).

The dominance of shallow material in the Jericho kimberlite may explain why the Jericho pipe has a lower concentration of diamonds than do the Lac de Gras mines

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

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Funded by: CCFS

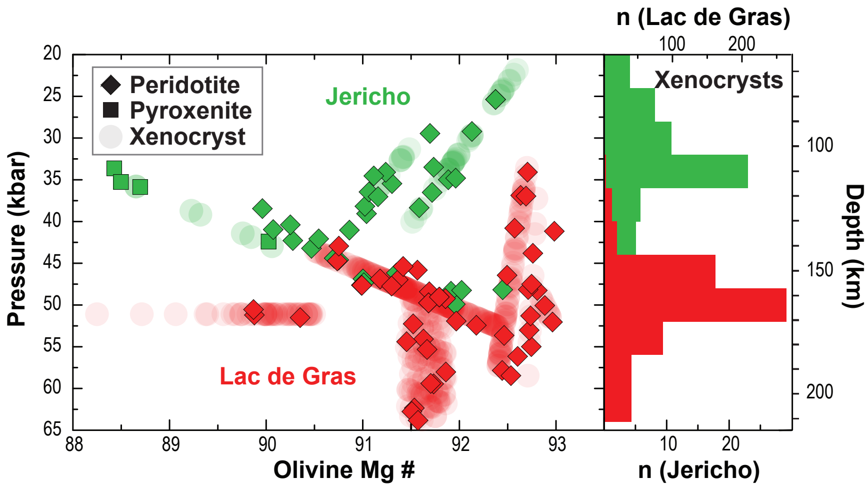


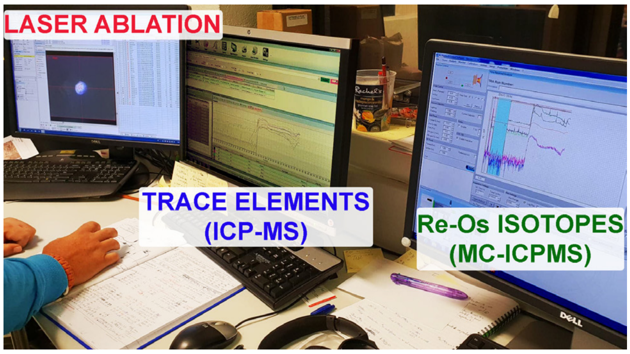
Figure 2. Pressure results for Jericho and Lac de Gras xenoliths compared to Mg# of olivine from xenoliths. Xenocrysts are projected onto the xenolith arrays and the depth profiles are expressed as a histogram.

In situ laser ablation split-stream (LASS-) MC-ICP-MS for simultaneous determination of Re-Os isotopes and siderophile-chalcophile elements in sulfides: Ablating away a Cornelian dilemma

In 1999, in an important World's first, GEMOC/GAU developed the techniques for *in situ* measurement of Re-Os isotopes in sulfides by LA-MC-ICPMS. It was then possible to date single *in situ* sulfide grains to infer the timing of melt-extraction events in the upper mantle. Since then the pioneering work of GEMOC/GAU demonstrated that elemental (e.g. PGEs) and isotopic *in situ* characterisations of (mantle) sulfides are powerful tools to unveil and date magmatic processes. Unfortunately, due to analytical and sample limitations (mantle sulfides Ø<100µm), investigators were left with the dilemma of choosing between trace elements or Re-Os isotopes.

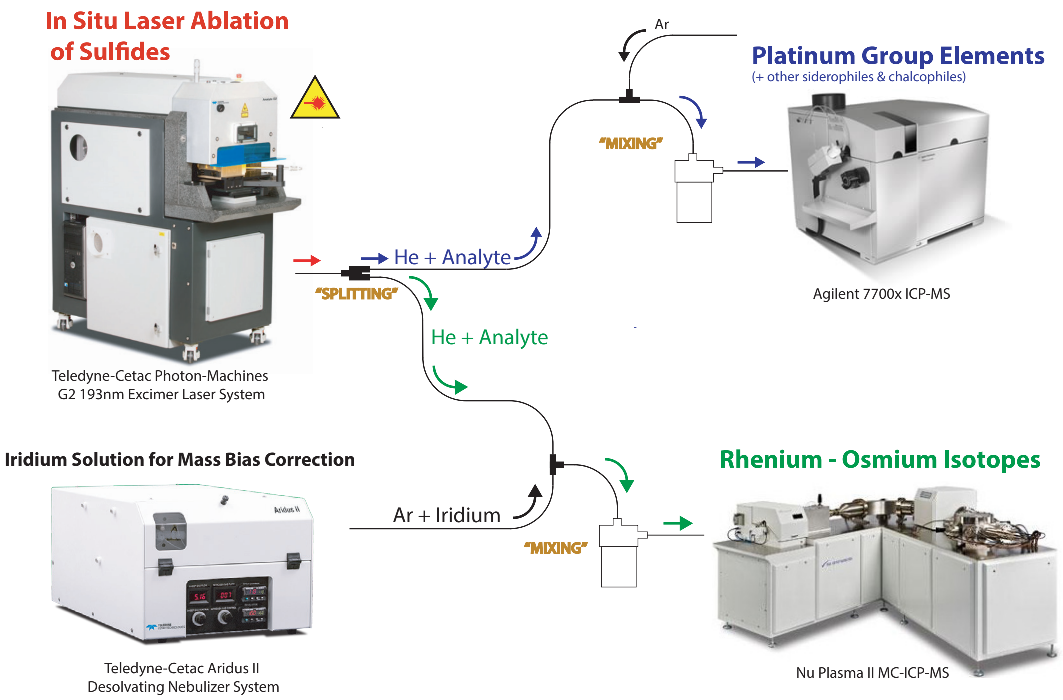
20 years later, we report a 2nd World's first: we have now developed the capability to simultaneously measure *in situ* Re-Os isotopes and the concentrations of Platinum Group Elements (PGEs) in sulfides using laser ablation split stream (LASS) between a Nu Plasma II MC-ICPMS (Re-Os) and an Agilent 7700x Q-ICPMS (PGEs).

Owing to the considerable increase in sensitivity of the newer generations of Nu Instruments, and due to the ion counter inherent limitation, the amount of analyte sent to the Nu Plasma could be restricted, thus allowing us to divert the excess towards the ICP-MS for analysis of PGE and chalcophile trace element abundances. While the trace-element signal has been lowered by ≈50%, in contrast the implementation of the LASS was done without any loss of sensitivity (and thus precision) for the MC-ICP-MS. Although counting statistics are significantly lower (≈50%) for the ICP-MS, the accuracy and reproducibility for trace elements in reference materials (e.g. Po62, Ai3-W, FeS1) are satisfactory. For instance, Os content in Po62 is ca 1.67±0.06 ppm, while the Se content of AI3-W was found to be 168±1 ppm.



This technological breakthrough provides a significant increase in time efficiency as both measurements are now acquired in a single session. However the real advance resides in the ability to not have to choose between one or the other type of measurement. Therefore, this new methodology will enable us to build more comprehensive datasets offering better constraints on the systematics between the isotopic signatures and the trace-elements patterns of the sulfides, which will allow more accurate petro-geochemical understanding of the nature and timing of the processes occurring in the upper mantle.

Contacts: Olivier Alard,
Yoann Gréau
Funded by: CCFS



Holy hibonite! - *'meteoritic'* mineral assemblages in volcanic rocks

Hibonite ($CaAl_{12}O_{19}$) is a constituent of some refractory Calcium-Aluminum Inclusions (CAIs) in carbonaceous meteorites, commonly accompanied by grossite ($CaAl_4O_7$) and spinel. These phases are usually interpreted as having condensed, or crystallised from silicate melts, early in the evolution of the solar nebula. Both Ca-Al oxides are commonly found on Earth, but as products of high-temperature metamorphism of pelitic carbonate rocks. However, our ongoing studies of the ultra-reduced mineral assemblages in the ejecta from Cretaceous pyroclastic deposits on Mt Carmel, N. Israel have identified unique magmatic hibonite-grossite-spinel assemblages, crystallised from Ca-Al-rich silicate melts under conditions (high temperature, very low oxygen fugacity (fO_2)) comparable to those of their meteoritic counterparts.

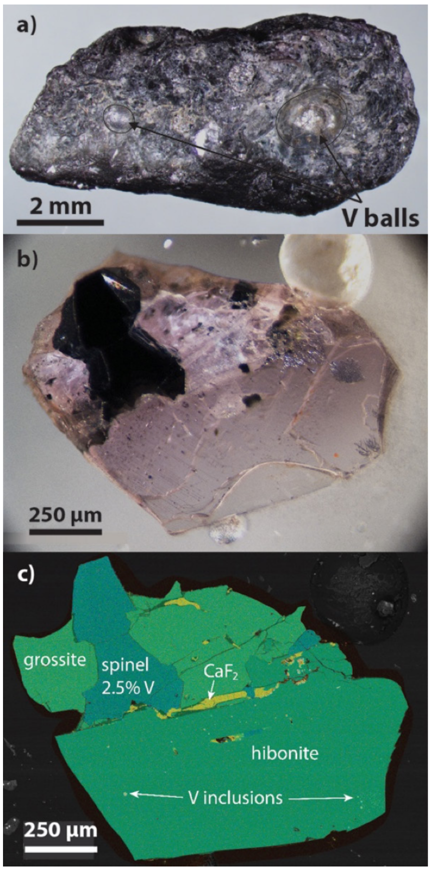


Figure 1. Hibonite-grossite aggregates. (a) large grain of hibonite-grossite aggregate with mm-size spheres of native V (V^0); (b) transmitted-light photo of transparent specimen, enclosing black spinel grain and rods of V^0; (c) phase map of (b) showing paragenesis of aggregates. Comparison of (b) and (c) shows that each tiny V^0 inclusion represents the end of a long rod or dendrite branch.

The Mt Carmel material includes aggregates of hopper/skeletal Ti-rich corundum, which have trapped melts that crystallised at fO_2 extending from 7 log units below the Iron-Wustite buffer (ΔIW= -7; SiC, Ti_2O_3, Fe-Ti silicide melts) to $\Delta IW \leq -9$ (native V, TiC, TiN). The assemblage hibonite + grossite + spinel + TiN first crystallised late in the evolution of the melt pockets; this hibonite contains % levels of Zr, Ti and REE, reflecting the concentration of incompatible elements in the residual melts as corundum continued to crystallise.

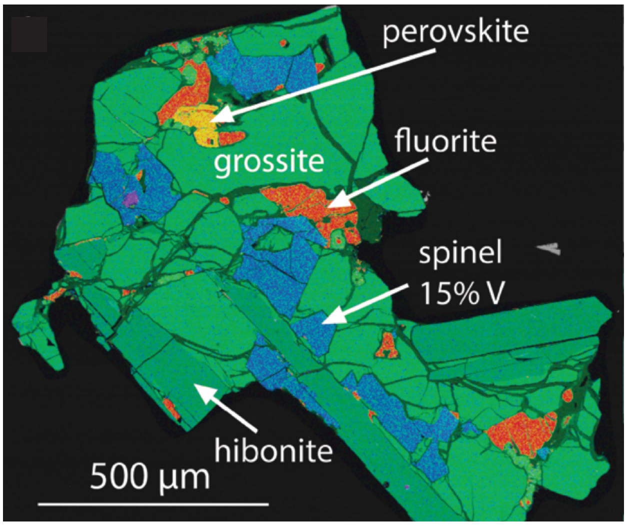


Figure 2. Hibonite-grossite aggregate illustrating crystallisation sequence. Resorbed corundum in hibonite reflects peritectic reaction L + Cor → Hib, followed by grossite + spinel ± krotite; fluorite and $Ca_4Al_6F_2O_{12}$ crystallise last.

A still later stage appears to be represented by coarse-grained (cm-size crystals) ejecta that show the crystallisation sequence: corundum + Liq → (low-REE) hibonite → grossite + spinel ± krotite ($CaAlO_4$) → $Ca_4Al_6F_2O_{12}$ + fluorite ± perovskite ($CaTiO_3$). This is the first reported terrestrial occurrence of krotite, which is otherwise found in CAIs. $Ca_4Al_6F_2O_{12}$ has been produced

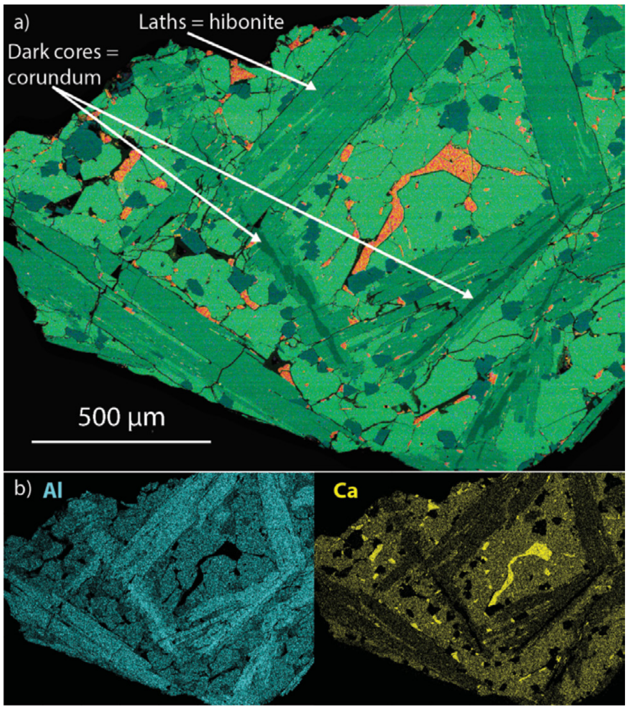


Figure 3. (a) Phase map of aggregate showing randomly-oriented hibonite plates, with narrow resorbed corundum cores, and hibonite + grossite intergrowths at edges of plates. Grossite (light green) is euhedral against CaF_2 (orange), the last phase to crystallise. Spinels (blue-green) are euhedral.

synthetically, but not previously found in nature; it is important because it is unstable below 1150 °C and constrains the temperature range of the assemblages. V^0 appears as spheroidal droplets, balls up to mm size, and spectacular dendritic growths, included in hibonite, grossite and spinel (see *Research highlight p. 57-59*). Spinels contain 10-16 wt% V in V^0-free samples, and <0.5 wt% V in samples with abundant V^0.

Ongoing paragenetic studies (see CCFS *Annual Report 2017*) suggest that the fO_2 evolution of the Mt Carmel magmatic system reflects interaction between OIB-type mafic magmas and mantle-derived $CH_4 + H_2$ fluids near the crust-mantle boundary. Temperatures estimated by comparison with 1-atm. phase-equilibrium studies range from ca 1500 °C down to 1200-1150 °C. When fO_2 reached ca ΔIW = -7, the immiscible segregation of Fe,Ti-silicide melts and the crystallisation of SiC and TiC effectively desilicated the magma, leading to supersaturation in Al_2O_3 and the rapid crystallisation of corundum, leading finally to the development of the hibonite-bearing assemblages.

The analogies to the mineralogy of CAIs suggest that this work is also relevant to studies of processes in the early Solar system. See *CCFS publication #1209*.

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

Contact: Bill Griffin

Funded by: CCFS Flagship program 1

Early cratonisation of the Yangtze Craton

The Earth is unique among terrestrial planets for its extensive regions of felsic crust, making up the continents. The felsic continental crust was largely generated during Archean time (>2.5 billion years ago), through tonalite-trondhjemite-granodiorite (TTG) magmatism, but exactly when and how such TTG-dominated crust formed and evolved into mature granitic compositions similar to modern upper crust is contentious.

The Yangtze Craton, southern China (Fig. 1) is one of the oldest blocks of continental East Asia, although the exact timing and evolution of, and the spatiotemporal relationships between these crustal provinces are not well understood.

Recent work has contributed to the recognition of several Archean crustal provinces (i.e. the Kongling Complex, the Yudongzi Complex, the Douling Complex, and the Zhongxiang Complex) in this Craton. The newly discovered Zhongxiang Complex in the northern Yangtze Craton (Fig. 1b) is among the known Archean crustal provinces and documents both sodic TTG and potassic granitic magmatism, providing a critical record of the evolving continental crust. An integrated study of petrology, zircon U-Pb geochronology and Hf-isotopes, and whole-rock geochemistry was conducted on the Zhongxiang Complex to better understand the crustal history. Our results revealed three major periods of Archean felsic magmatism in the Zhongxiang Complex: late Mesoarchean (2.90-2.87 Ga), early Neoarchean (2.77 Ga), and late Neoarchean (2.70-2.62 Ga). The 2.90-2.87 Ga magmatism is represented by monzogranites from the southern Zhongxiang Complex, which were derived from mixing of ancient and juvenile crustal components at relatively shallow crustal depths. This was followed by the emplacement of 2.77

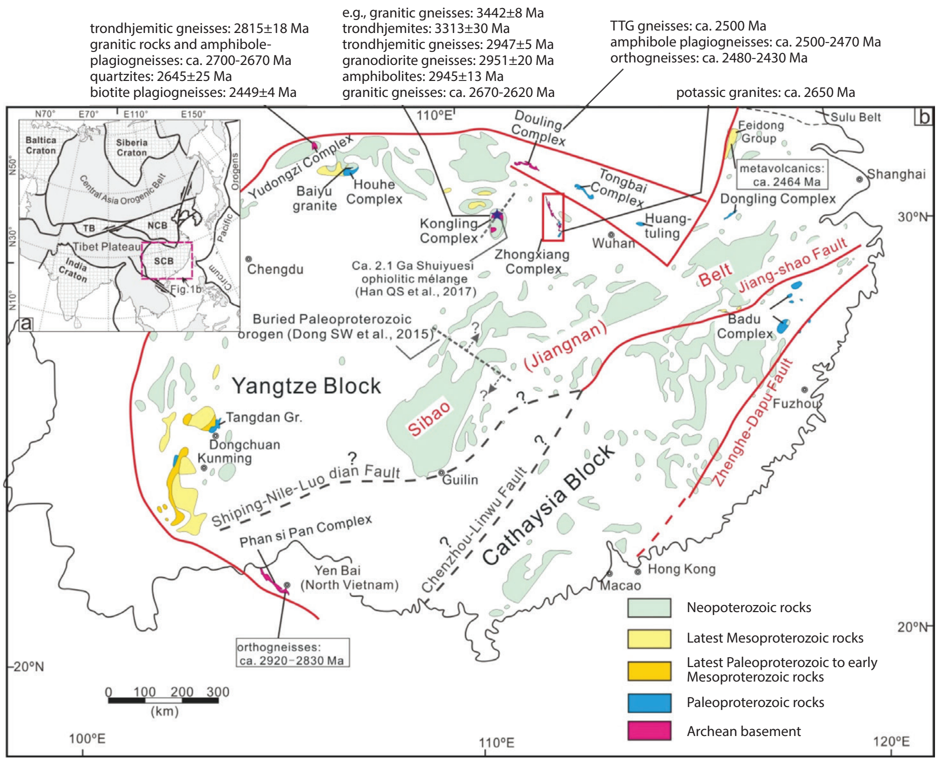


Figure 1. (a) Simplified tectonic map of Eurasia showing the major tectonic units and the location of SCB - South China Block, TB - Tarim Block, and NCB - North China Block. (b) A simplified geological map highlighting the Precambrian geological units of south China. Note the distribution of the Archean magmatic rocks along the northern and southern Yangtze margins.

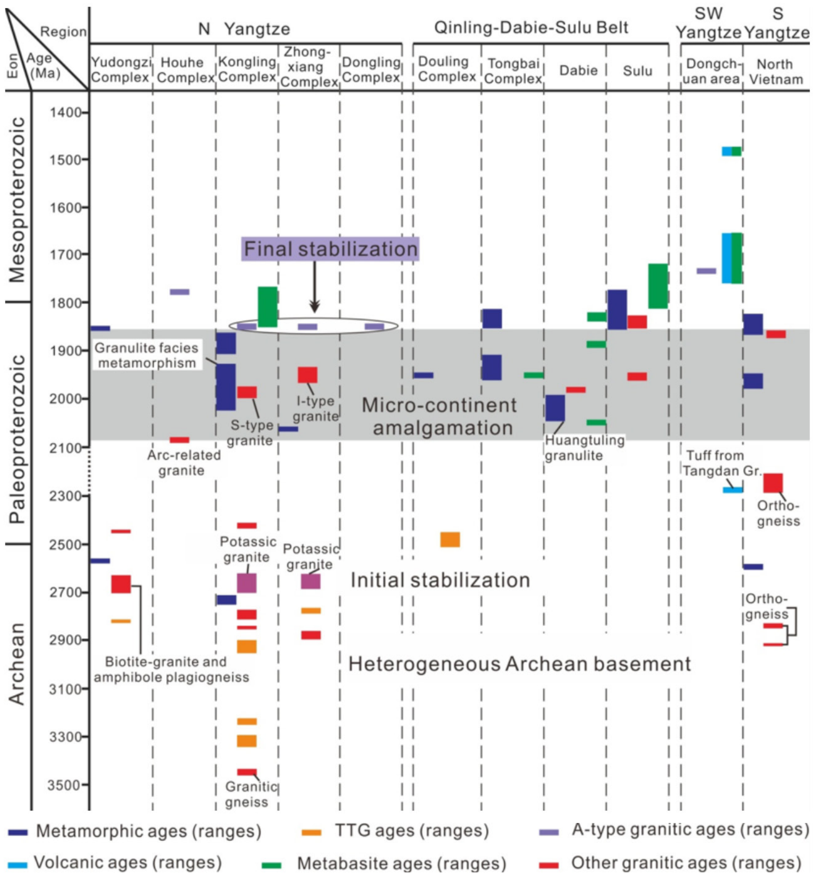


Figure 2. Time-space correlation chart of the Yangtze Craton illustrating the age ranges of principal Archean to early Proterozoic (>1.4 Ga) tectono-thermal events recorded in different parts of the Yangtze Craton. The compositionally variable Archean continental crust among different crustal domains of the Yangtze Craton, and their similar orogenic-related magmatic and metamorphic overprint during the late Paleoproterozoic point to the formation of a uniform Yangtze Craton by accretion of several crustal domains or terranes during the late Archean to Paleoproterozoic time. The concurrent emplacement of ca. 1.85 Ga A-type granites at different localities likely marked the final stabilisation of a coherent Yangtze Craton.

Ga trondhjemitic gneisses in nearby regions of the southern Zhongxiang Complex, which represent the only potential TTG with ages of 2.80-2.70 Ga in the Yangtze Craton. The trondhjemitic gneisses are typical of a medium-pressure TTG component and are interpreted as the products of partial melting of a basaltic source with appreciable involvement of pre-existing crustal components (i.e. tonalites). In contrast, the 2.67-2.62 Ga magmatism, represented by potassic granites from the northern Zhongxiang Complex, corresponds to high-temperature melting of meta-sedimentary source rocks in a within-plate extensional setting.

The transition of the felsic magma from Na-rich (2.77 Ga) toward K-rich (2.67-2.62 Ga) in the Zhongxiang Complex would have led to extensive removal of heat-producing elements from the lower crust, enabling the thermal stabilisation of the continental crust. This transition is broadly coeval with global TTG-granite and tectonic transitions related to thermo-mechanical and geodynamic changes of the continental crust at the end of the Archean, but appears to slightly postdate the TTG-granite transition in the nearby Kongling Complex (2.90-2.80 Ga) and to predate those in the Yudongzi Complex (2.70 Ga) and the Douling Complex (2.50 Ga), all of which are documented from the Yangtze Craton. Age and isotopic comparisons among the known Archean provinces further indicate a compositionally heterogeneous Archean Yangtze Craton, which likely comprises several Archean terranes that accreted to form the craton during the late Archean or even early Paleoproterozoic (Fig. 2).

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

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Funded by: ARC Laureate Fellowship (ZX Li)

Sulfide aggregation in ophiolitic dunite channels amplifies Os-isotope mismatch between oceanic crust and mantle

Re-Os isotopic compositions of oceanic crust represented by fresh basaltic glasses from the mid-ocean ridges and primitive gabbroic cumulates in the ridge system are systematically more radiogenic than the normal values for Os isotopes [quartiles of $\gamma Os(t)$ with Q1= -4.1 and Q3= -0.6] of oceanic mantle, represented by abyssal peridotites and Os-Ir alloys from global ophiolites which are below the values for chondrites - i.e. '*sub-chondritic*'. Os isotopic decoupling between oceanic crust and mantle has been explained by radiogenic Os contributions from metasomatic sulfides and/or recycled pyroxenites in the convective mantle. However, the possible role of melt channels that regulate the flow of magmas feeding the oceanic crust at the crust-mantle boundary, have so far not been considered.

In situ Re-Os isotopic compositions of nearly 200 base-metal sulfide grains have been analysed from the ophiolitic low-Cr#

chromitites from Zedang (South Tibet) (*CCFS Publication #965*). These chromitites occur within dunite lenses, interpreted as interaction products between MORB-like melts and harzburgites. Thirty-eight analyses (mainly sulfide inclusions in chromite) show a wide range of $^{187}Os/^{188}Os$ (calculated at 130 Ma) from 0.1191 to 0.1702 with γOs(t) from -6.4 to +33.8. These values are similar to those of the oceanic crust and the Os-rich sulfides from the Oman low-Cr# chromitites. The initial $^{187}Os/^{188}Os$ ratios (0.1281-0.1296) of chromites from the Zedang chromitites are close to those for the Primitive Upper Mantle, but higher than those of the Zedang and other ophiolitic peridotites along the Yarlung Zangbo suture (South Tibet). This suggests that radiogenic Os components from asthenospheric or lithospheric mantle have been added to the dunite melt channels. The significant Os isotopic heterogeneity observed in the Zedang and Oman chromitites indicates that the Os-bearing phases were not well mixed, but aggregated together during the precipitation of chromite and monosulfide solid solution grains, when the dunite melt channels were produced in the oceanic crust-mantle transition zone. Such melt channels will affect the Os isotopic compositions of the migrating melts that ultimately generate the oceanic crust: and this process can explain the Os isotopic mismatch between oceanic crust and mantle (Fig. 1).

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

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Funded by: NSFC (41520104003 and 41873032), CCFS Flagship Program 1

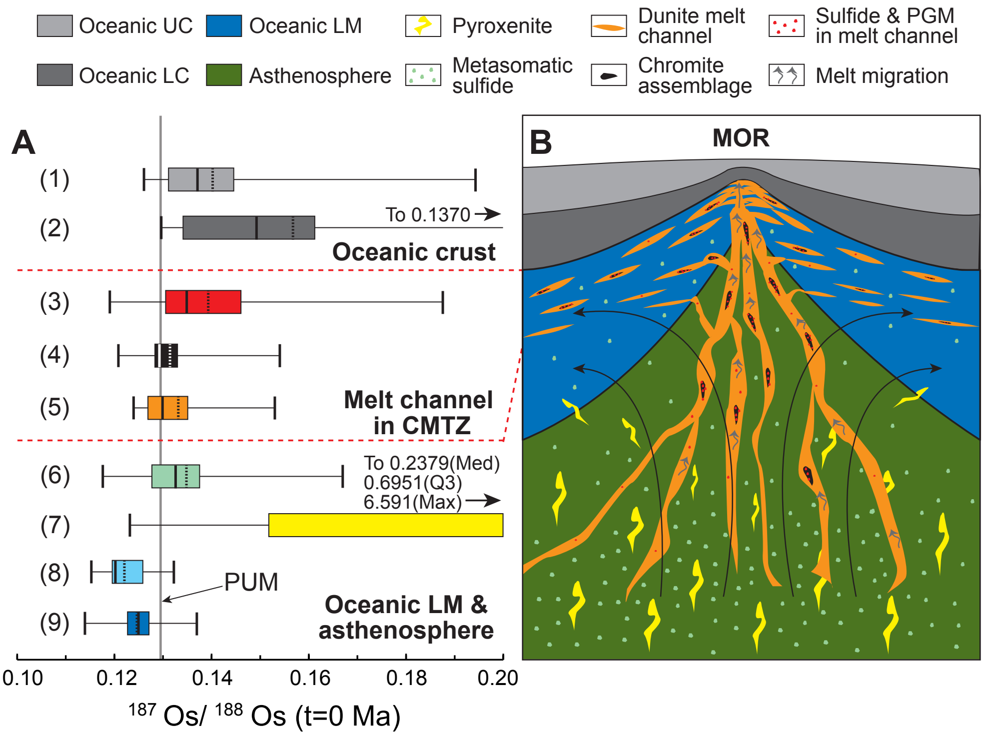

Figure 1. Comparison of box-whisker plots (A) for $^{187}Os/^{188}Os$ (t=0 Ma) ratios of oceanic crust, dunite melt channels and mantle. A schematic cartoon (B) shows the formation and distribution of dunite melt channels and relevant chromite assemblages beneath a mid-ocean ridge (MOR). Discrete Os components with heterogeneous Os isotopic compositions from the asthenosphere or lithospheric mantle were aggregated in the dunite melt channels, which regulate and contribute the Os isotopes of oceanic crust. Abbreviations: UC, upper crust; LC, lower crust; CMTZ, crust-mantle transition zone; LM, lithospheric mantle.

Pyroxenite microstructures help unlock deep Earth secrets

Seismic waves and their response to the mediums they travel through provide most of our knowledge of the structures and discontinuities of the deep Earth. Most minerals in Earth's mantle have strongly directional elastic properties, and thus the seismic waves passing through them will be slightly accelerated or decelerated depending on the incidence direction. Therefore, to improve the characterisation of the architecture of Earth's mantle, we need to be able to accurately interpret the geological significance of seismic dataset.

Olivine is the dominant mineral in Earth's upper mantle, but pyroxenes can be volumetrically dominant in specific geological contexts. A previous Research Highlight (*CCFS 2016 Annual Report, p. 55*) and *CCFS publication #969* examined the microstructure of deformed pyroxenites from the exhumed mantle terrane at Cabo Ortegal (Spain). In order to fully characterise the nature of deformation in pyroxenites, we also studied pyroxenites from the Trinity Ophiolite (USA), an undeformed analogue of the Cabo Ortegal pyroxenites.

Within the Trinity ophiolite, California, USA, the fossil magma chamber of Bear Creek contains abundant pyroxene-rich facies showing no evidence for plastic deformation. Down-section, the pyroxenite cumulates commonly alternate between

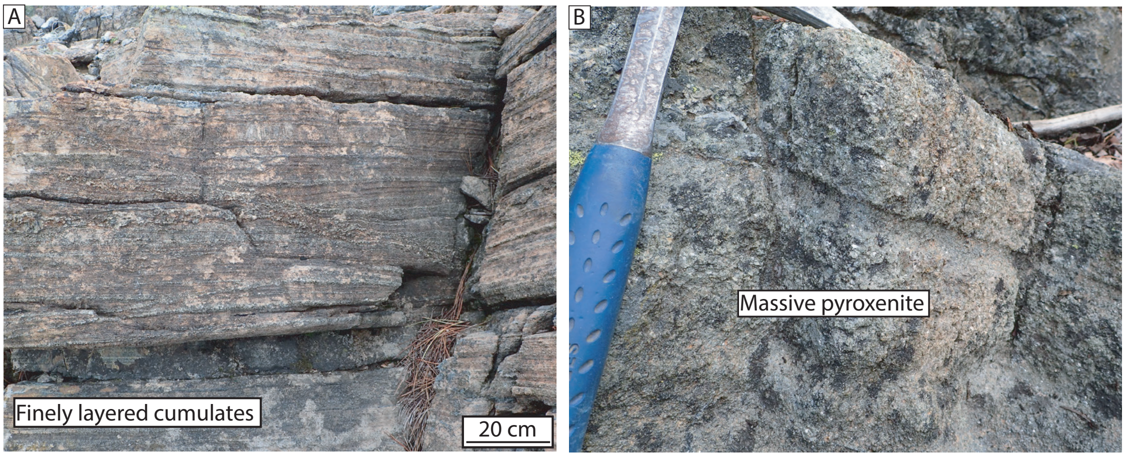

Figure 1. Field pictures of (A) the finely layered cumulates displaying the characteristic high-frequency layering and (B) Massive clinopyroxenites with significantly less olivine-rich layers.

olivine-rich and pyroxene-rich layers (Fig. 1B). Up-section, the frequency of olivine-rich layers decreases gradually until massive clinopyroxenites outcrop (Fig. 1B).

Spatial orientations of the pyroxene and olivine grains in this cumulate suite were determined using the Electron Back-Scattered Diffraction (EBSD) technique. Our data demonstrate that magmatic processes in a magma chamber can cause strong preferred crystal orientation of the mineral grains. This preferred orientation is strongly planar, as observed in the field, but the grains have a cryptic preferred orientation within that plane (Fig. 2). We interpret this to be the result of the grains settling to the base of the magma chamber, oriented in a preferred crystallographic plane and/or as the result of compaction.

From a seismic perspective, fabrics from the Bear Creek cumulates show a distinctive anisotropy unique to such pyroxenite fabrics, and thus making them potentially seismically distinguishable from *'average'* lherzolitic upper mantle.

Our results further suggest that the pre-existing magmatic fabric could influence the behaviour of cumulate rocks during later deformation, because the pre-existing fabric will result in a favourably oriented set of slip systems that could be easily activated. This emphasises the caution required when interpreting deformation conditions based on slip system activation.

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

Contact: Hadrien Henry

Funded by: CCFS, Centre National de la Recherche Scientifique (CNRS), France

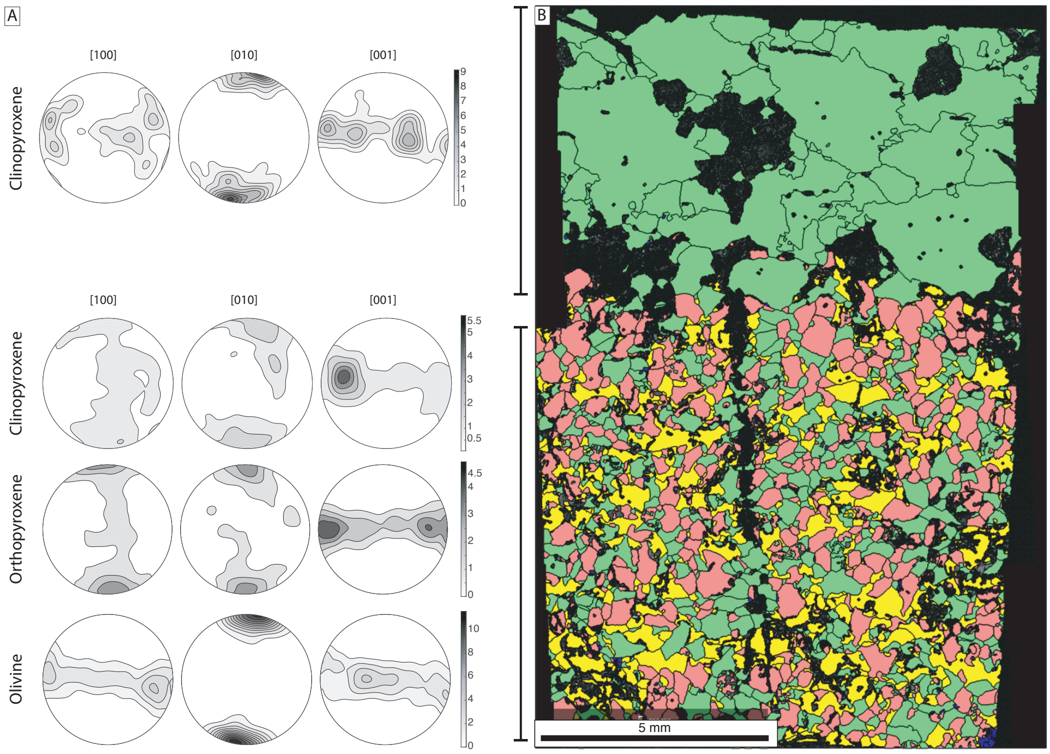

Figure 2. (A) Crystallographic preferred orientation of the rock-forming minerals along a sample where finely layered cumulates (bottom) and massive pyroxenites (top) are in contact. The strong planar feature is highlighted by the girdles formed by the [001] axis for all minerals. (B) Colour-coded map representing the distribution of the phases in the sample. Yellow codes for olivine, green for clinopyroxene and red for orthopyroxene. Black denotes non-indexed data.

Persistent ancient oceanic slab hovers in the upper mantle of western China?

Ancient oceanic slabs generally cannot be preserved in continental lithosphere for significant periods of time. Ancient subduction zones, which can provide important clues to the past tectonics, have rarely been imaged by geophysical techniques. However, the Junggar terrain (Fig. 1) appears to be an exception where a fossil oceanic slab has been well preserved since the late Paleozoic. The unique evolution history and the lack of subsequent thermal events in this region provide an undisturbed environment allowing the slab to remain until the present. Imaging the detailed geometry of the fossil subduction system in this region helps us to investigate the past tectonic process.

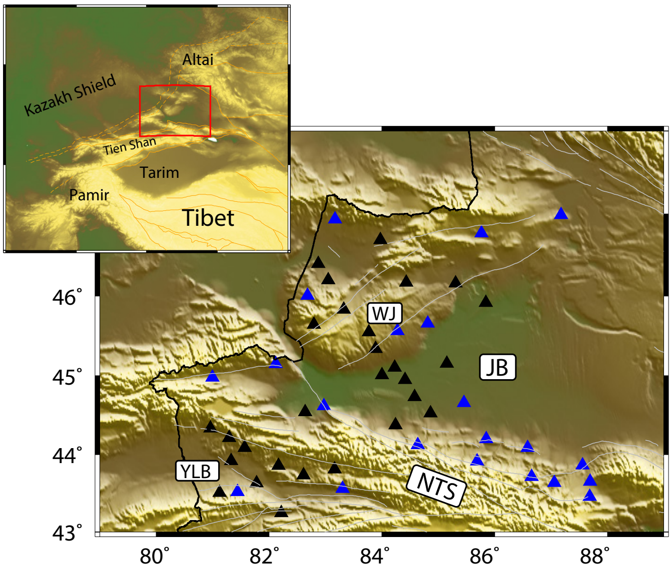

Figure 1. Location of the study region (red rectangle) and the broadband seismic stations. Blue triangles represent the 21 fixed stations from CEA and black triangles indicate the 28 deployed stations. Tectonic blocks around study region are outlined by orange lines, grey solid lines are the location of major faults, and the black solid line is the Chinese national border. WJ: West Junggar (or the Zaire mountains); YLB: Yili Block; JB: Junggar Basin or Dzungarian Basin; NTS: Chinese northern Tien Shan (or the Borohoro Mountains).

We deployed a seismic array occupying a larger spatial region across the Junggar Terrane (Fig. 1), in order to generate a high-resolution velocity model for the crust and upper mantle. This array consisted of 28 newly deployed broadband seismic stations from July 2016 to September 2017 along with 21 permanent stations from the China Earthquake Administration (CEA) Array. Based on data from this array, shear-wave velocity (Vs) models of the crust and upper mantle in the Junggar terrane are constructed using ambient noise and teleseismic surface-wave tomography techniques. According to our Vs model (Fig. 2), the patterns of velocity anomalies in the shallow crust agree well with the geological features in the surface. A large triangular-shaped low velocity zone dominates the entire Junggar Basin, corresponding to the thick sedimentary layer within the basin (~8-9 km in the north and over 10 km in the south). For the deeper structures, inverse velocity features compared to those observed for the shallow crust, characterise the study region with high velocities occupying the entire Junggar Basin.

One vertical profile (AA') is plotted in Figure 3 to illustrate the vertical variations of velocity structures. This profile starts at the northern foothill of Northern Tien Shan and runs northwestward through the entire Junggar Basin and to the West Junggar. This ~400 km cross-section shows several interesting features. In the upper crust, the Junggar Basin is imaged as a prominent low Vs zone, with shear velocities much lower than 3.0 km/s. The thickest part of this low velocity body occurs beneath the southern margin of the Junggar Basin. At the depths of middle to lower crust, the Vs beneath Junggar Basin increases significantly, reaching ~3.9 km/s to ~4.0 km/s in the lowermost crust. The mid/lower crust high velocities extend into the NTS in the south, and dip toward northwest with depth underneath the

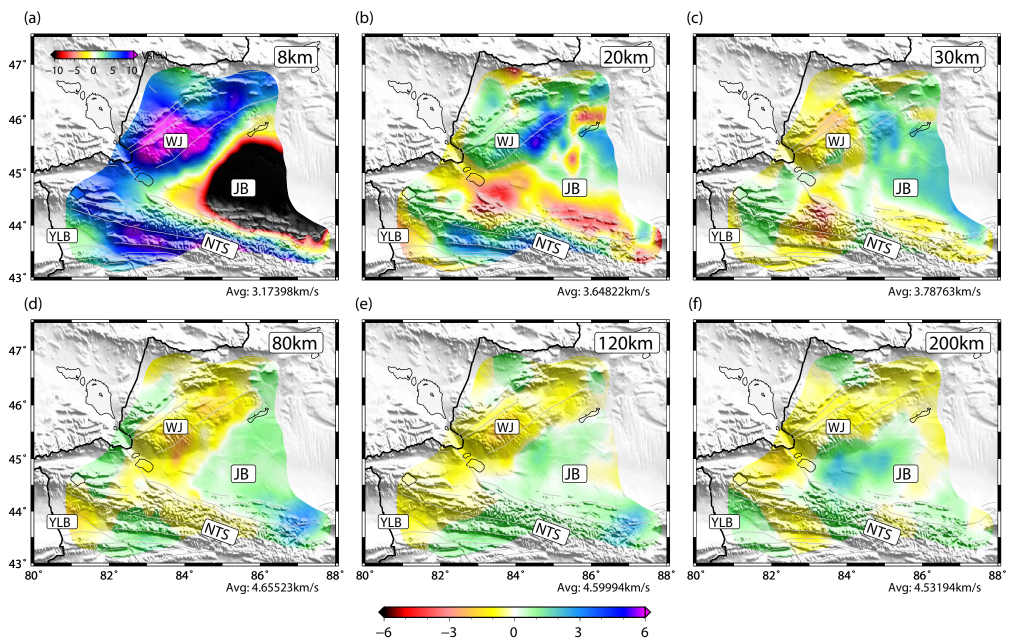

Figure 2. Vs perturbation maps at six different depths ranging from 8 km to 200 km. Colour pattern for the depth of 8 km is different from others and plotted in the top of (a). The average Vs is labelled at the bottom right of each subfigure.

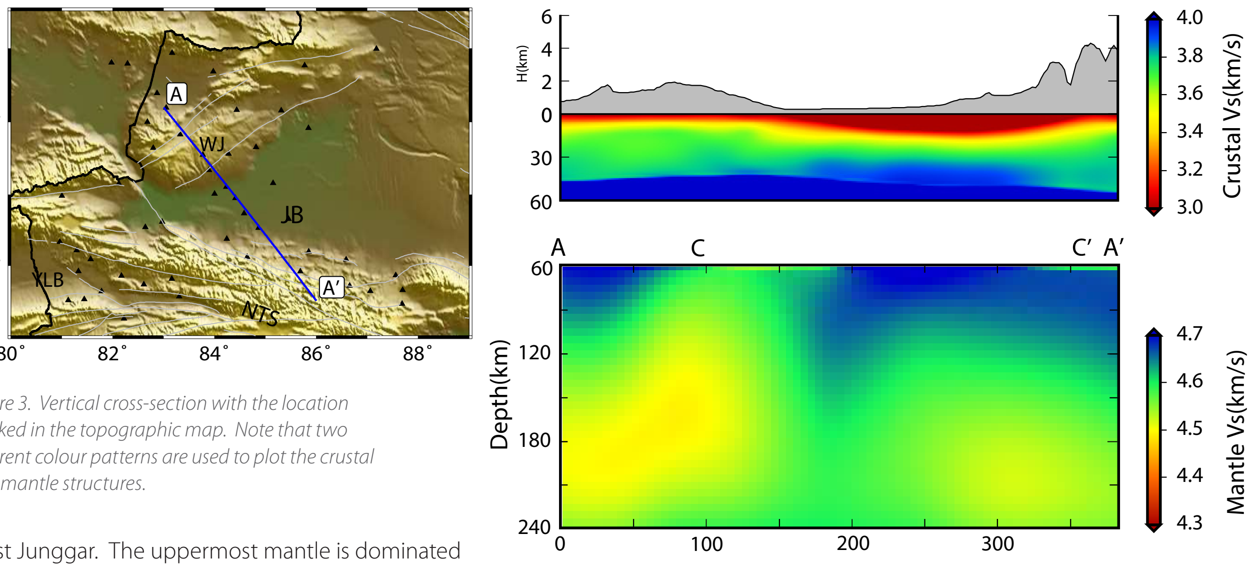

Figure 3. Vertical cross-section with the location marked in the topographic map. Note that two different colour patterns are used to plot the crustal and mantle structures.

West Junggar. The uppermost mantle is dominated by a high velocity body beneath Junggar Basin and Northern Tien Shan. The thickness of this high velocity layer is ~60 km with Vs higher than 4.65 km/s. In the margin between Junggar Basin and West Junggar, this high velocity domain slightly dips northwest, reaching a depth around 150 km. High velocity domains are also observed to the west part of West Junggar with a thickness of only ~30 km, thinner than the high velocity layer beneath the WJ and Northern Tien Shan. The uppermost mantle of West Junggar is dominated by a relatively low velocity anomaly extending to a depth of ~240 km.

Integration with previous magnetotelluric, geochemical, geochronological and geomagnetic studies in the Junggar Basin as the remnant of the ancient oceanic lithosphere beneath the ancient Junggar Ocean. In the AA' profile beneath West Junggar, the upper mantle high velocity body slightly dips northwestward and then terminates at a depth of around 150 km. According to the geometry of the high velocity body, it is reasonable to deduce the polarity of the late Paleozoic subduction in the West Junggar is northwest. We then compare the current geothermal model in the Junggar region with the predicted oceanic slab half-space cooling model. The perfect match between them supports the hypothesis that the high velocity beneath the Junggar Basin at the lower crust and upper mantle depths, reflects the trapped Late Paleozoic oceanic slab. This finding is significant since very few ancient oceanic slabs can be preserved and imaged in continental collision zones worldwide. Also, the imaged, well-preserved subduction system in the Junggar terrane provides vital constraints for the past tectonics in this region.

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

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Funded by: CCFS Flagship Program 3, NSFC 41530319, iMQRES 44659946

Vanadium melts reflect Earth's most reducing conditions

The pyroclastic ejecta of Cretaceous intraplate basaltic volcanoes exposed on Mt Carmel, in northern Israel, provide snapshots of unusual melt-fluid systems, sampled at different stages of their evolution. Now they have provided evidence of the most reducing conditions ever found on Earth, reflecting a hydrogen-dominated fluid phase.

Aggregates of skeletal corundum crystals found in the ejecta and secondary alluvial deposits contain melt pockets requiring high T (>1450-1200 °C), moderate P (ca 1 GPa) and extremely low oxygen fugacity (fO_2). Paragenetic studies (*Griffin et al., 2018, 2019a; Xiong et al., 2017*) suggest that the crystallisation of skeletal corundum and low fO_2 reflect the interaction of originally mafic magmas with $CH_4 + H_2$ at high fluid/melt ratios.

As the magmas were progressively reduced, the original silicate melts were depleted in Fe and Si by the exsolution of immiscible Fe-Ti-C-silicide melts that crystallised moissanite (SiC) and khamrabaevite (TiC). Still lower fO_2 is witnessed by inclusions of Ti^{2+}-bearing phases (TiB_2, TiN, TiC, TiO). The silicide melts efficiently scavenged Fe and heavier transition elements; no Fe-Ni-Co-bearing oxides or silicates are found in the melt pockets. The assemblages described here thus formed from residual melts, enriched in Ca, Al and minor elements (REE, Zr, Ti, V, Mn, Sc).

Hibonite ($CaAl_{12}O_{19}$) first appears together with corundum, Mg-Al spinel, TiN, Fe-Ti silicides, TiC and glass (see *Research highlight pp. 51-52*). Coarser-grained (to cm-sized crystals) intergrowths of hibonite, grossite and spinel also occur as grains up to 2.5 cm across in placers of the Kishon and Yoqneam Rivers that drain Mt

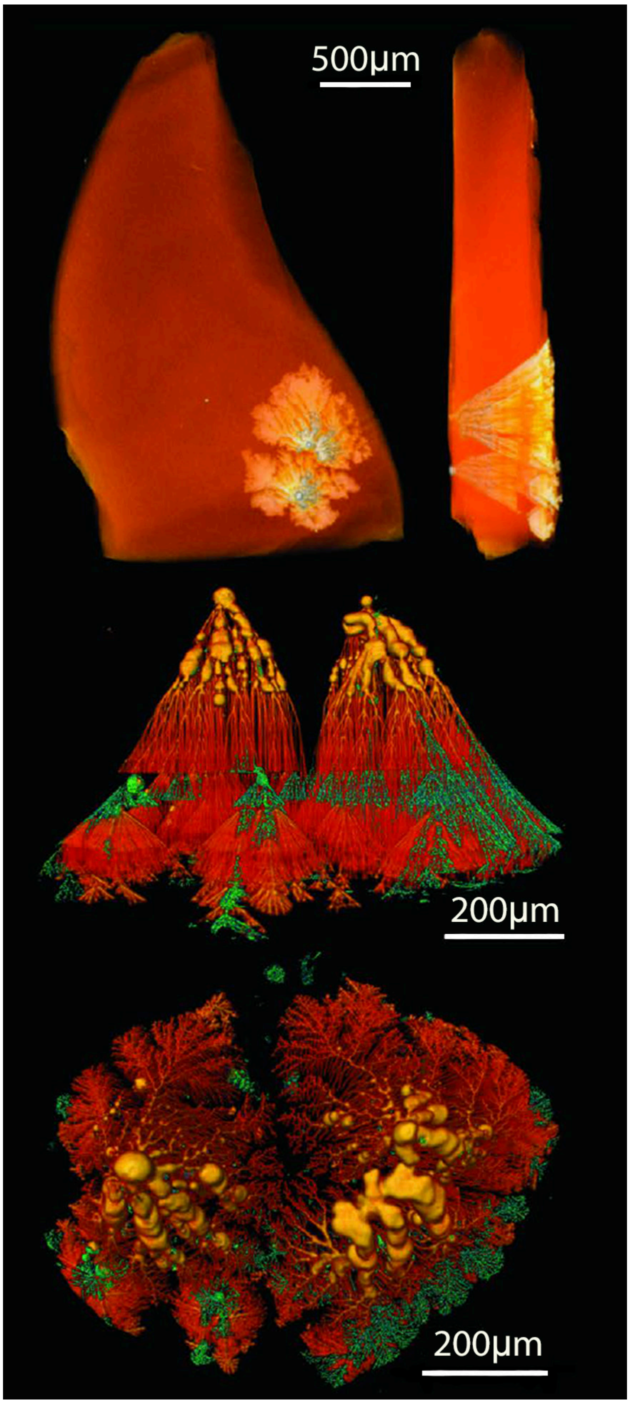


Figure 1. 3D-µCT images of dendritic native V in hibonite. a) low-resolution image of two dendrite clusters in a hibonite grain. b) magnified view, looking parallel to (0001) face; red to orange, vanadium; green, open cavities; (c) view from starting point, toward crystal face along c axis. Tendrils radiate off irregular clumps of V^0. Some consist of a series of joined balls that extend toward the crystal surface, then sprout into 3-D dendritic networks with clear breaks and restarts at intermediate crystal planes. The patterns suggest nucleation of V melts on the surface of growing crystals. Cover image.

Carmel. They suggest that hibonite-bearing melts like those trapped in the corundum aggregates evolved even further beneath some volcanic centres.

In these xenoliths, native vanadium (V^0) and V-Al alloys occur mainly as spheroidal to amoeboid balls up to mm size in hibonite crystals. More commonly, V^0 forms droplets on (0001) planes, or rods normal to (0001) that commonly are necked down to produce linear trains of droplets. The inclusions are zonally distributed in some crystals.

Rare V^0 inclusions develop (Fig. 1) into *'dense branching structures'* (*Goldenfeld, 1989*). These grow roughly parallel with the c-axis of the host hibonite crystal, and each filament terminates in a single dendritic crystal. Clusters of fine branches terminate at planes parallel to (0001), suggesting a pause in the growth of the hibonite crystal. Some branches continued to grow when crystal growth resumed, but new droplets of V^0 also nucleated on the new crystal plane and grew independently of the older branches. In the example shown in Figure 1, this stop-start process occurred at least four times. 3D-µCT images (scan QR code, inside cover) show that the outer parts of many filaments are *'empty'*, even where they terminate well below the present crystal face.

The structures shown in Figures 1 and 2 are best explained by the nucleation of drops of molten vanadium on the faces of oxide crystals exposed to the silicate melt. These drops attracted more V^0 as the crystal grew, producing larger and elongated (sometimes hollow) inclusions. The formation of dense branching structures reflects diffusion-controlled interface motion, such as the growth of a crystal into a fluid, under conditions of mild to strong supercooling.

The melting point of vanadium is >1900 °C - so how could V^0 melts be present in this relatively low-T system? The answer lies in the reducing conditions. The fO_2 required for the presence of V^0 ($\leq\Delta$IW -9) implies a hydrogen-dominated environment, equivalent to the early solar nebula (*Grossman et al., 2008*). Analyses of hibonite grains have revealed hydrogen concentrations up to 0.5 wt%, suggesting that the '*voids*' are filled with H_2, and grains of VH_2 (the first natural metal hydride) occur among the V^0 balls (*Bindi et al., 2019*). In a hydrogen atmosphere, the melting point of vanadium can be lowered by >1000°C as H_2 dissolves in the melt, only to be expelled during solidification. We suggest that these hollow tubes and voids reflect the exsolution of H_2 from the solidifying V^0 melts in the inner parts of the structures, leading to the remelting and expulsion of V^0 in the outer parts, before the next layer of hibonite nucleated, and perhaps to production of the observed VH_2 phase.

The assemblages from Mt Carmel are interpreted to have crystallised late in the pre-eruption evolution of fO_2 in magma-fluid systems, ultimately leading to the most reducing conditions found on Earth, with free hydrogen as a volatile phase. The observed abundance of carbon in the assemblages suggests an important role for CH_4 in this process, and high fluid/rock ratios (Fig. 2). At Mt Carmel, such conditions existed for at least 10 m.y. and over an area of ca 150 km^2, in the uppermost part of a thin mantle lithosphere. This suggests the derivation of abundant $CH_4 \pm H_2$ fluids from the deeper mantle. We suggest that the sublithospheric mantle beneath this area was metal-saturated (i.e. fO_2 = IW), such that any C-O-H fluid issuing from it was dominated by $CH_4 \pm H_2$. This conclusion has implications for understanding melting and metasomatic processes in the mantle. See *CCFS publications #1209 and 1160.*

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

Contact: Bill Griffin
Funded by: CCFS Flagship program 1

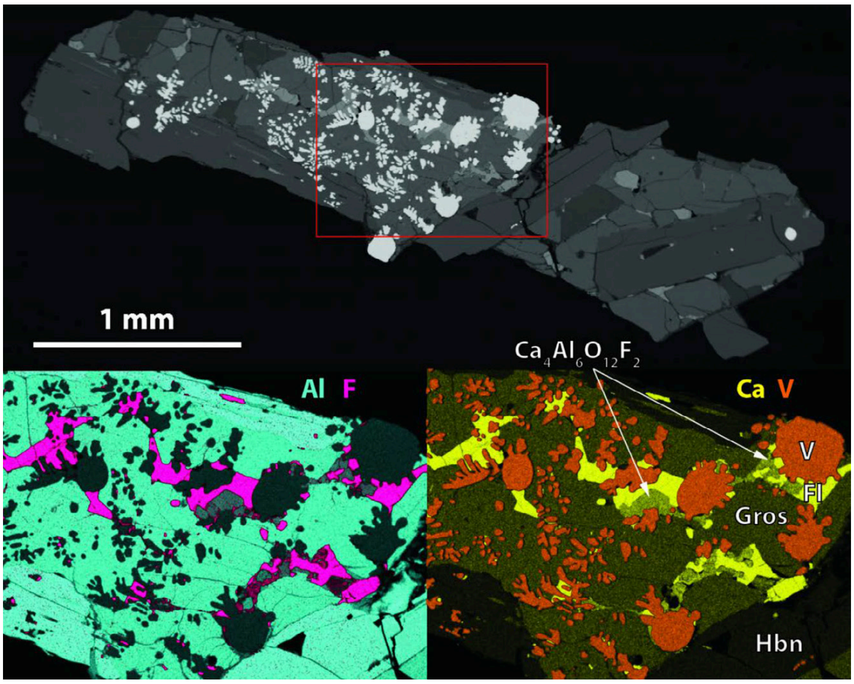


Figure 2. High-Al (mean 15 wt%) V balls in nest of grossulite between hibonite laths, with outlines suggesting they were fluid when trapped.

Revealing Gold Pathways in El Indio Belt, Chile-Argentina

This project to understand the structural architecture in one of the most highly Au-endowed provinces of the Andes Cordillera: the young Miocene El Indio Belt, is undertaken in collaboration with (and supported by) Barrick Exploration.

The El Indio Belt is a 150 km^2 metallogenic camp located in the Chilean-Argentinean Andes Cordillera. It hosts a resource of >45 Moz Au mostly in world-class Miocene Au-Ag epithermal deposits (Pascua-Lama, Veladero, El Indio-Tambo District and the most recent discovery Alturas). It provides a natural laboratory to study the trans-lithospheric architecture that acts as the pathway for magma/fluids/gold, and also the geodynamic evolution of the structural domains related to metallogenic events.

The project includes the reinterpretation of geophysical datasets (mainly aeromagnetometry, gravity and seismics) integrated with petrophysical data acquisition, as well as six months of surface structural mapping, all aimed to reveal the architecture of the El Indio Belt. This is coupled with cutting-edge techniques for zircon isotopic analyses, which have revealed the ancient nature of the El Indio Belt (see *CCFS Annual Report, 2017 pp. 49-50*) and the magmatic evolution associated with the metallogenic processes.

Recent re-interpretation of the geophysical datasets has confirmed that the El Indio Belt is affected by a series of NW-SE- and NE-SW -ending structures that cross-cut the main

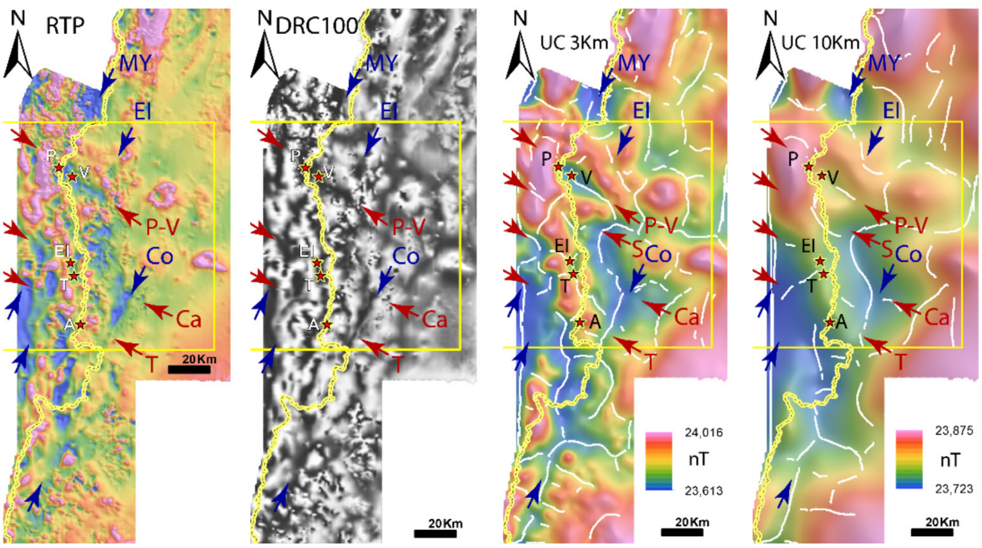
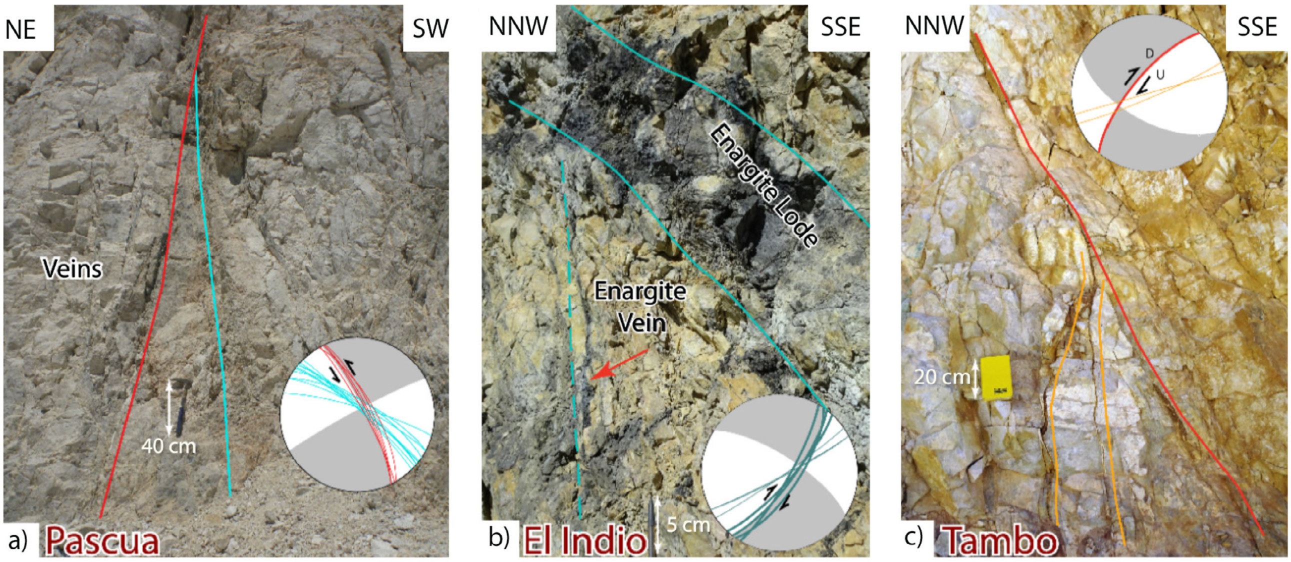


Figure 1. Different processing and enhancements on the EIB aeromagnetic surveys. RTP: Reduced to the pole. DRC: Dynamic Range Compression. UC: Upward continuation. Arrows show aeromagnetic lineaments, red correspond to NW-SE (P-V: Pascua-Veladero, S: Sancarron, Ca: Campana, T: Trapiche) and blue to NE-SW (MY: Molino Yaco, El: El Indio, Co: Colangüil). Yellow box indicates EIB working area. Stars correspond to Au-Ag HS epithermal deposits within the belt (P: Pascua, V: Veladero, El: El Indio, T: Tambo, A: Alturas). Yellow line is the international Chile-Argentina border.



Faults with associated Qz veins (125) En lodes with associated En veins (105) Fault with associated Al-Jar veins (114)

Figure 2. Altered and mineralised structures with kinematic indicators (tension veins and fractures) within the Miocene El Indio Belt (EIB), main Au-Ag deposits and minor prospects: a) Pascua fault with quartz (Qz) veins, b) El Indio enargite (En) lodes and veinlets, c) Tambo fault with alunite-jarosite (Al-Jar) veins. Numbers in parenthesis indicate station number.

N-S Andean trend. The Au-Ag deposits are located along the magmatic axis at the intersection of these structures, some of which penetrate at least 10 km into the crust (Fig. 1).

This deep-seated architecture has been corroborated in the field, where the NW-SE and NE-SW structures dominate in the areas within and around the deposits. These structures are '*old*', traceable in the pre-Cenozoic basement, and may have originated during the Upper Triassic when they focused the intrusion of mafic dyke swarms trending in the same orientations. They have indeed persisted from the basement to the overlying Miocene magmatic arc which produced the epithermal Au-Ag deposits. The structural orientations obtained for the mineralising events recorded around the El Indio Belt indicate that these deposits follow those trends. Furthermore, they originated mainly in a strike-slip regime, with dextral movement occurring along the NE-SW and sinistral movement in the NW-SE structures (Fig. 2). The magmatic signature of the ore-bearing magmas, however, denotes they were originated in a compressive setting, carrying high La/Yb in whole rock (previously found by *Bissig et al., 2001, IGR, 43: 4,312-340*) as well as low εHf ('*crustal-type*' signature) associated with '*mantle-like*' $\delta^{18}O$ signatures in zircon (this project, Fig. 3). This confirms that the main metallogenic period in the El Indio Belt took place in a change from a highly compressive tectonic setting to a more strike-slip environment, as previously reported by Giambiagi et al. (*2017, Tectonics, 36, 2714-2735*).

The combination of a favourable architecture (NW-SE and NE-SW cross-arc structures), with a proper geodynamic trigger (transition from compression to strike-slip), and Au-fertile magmatic suites (possibly generated during the compression event), have all been found in the El Indio Belt. They confirm the mineral systems hypothesis in the area, and provide a valuable insight into one of the most important Au-mineralisation events within the Andes.

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

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Funded by: Barrick Exploration, CCFS Flagship Program 2

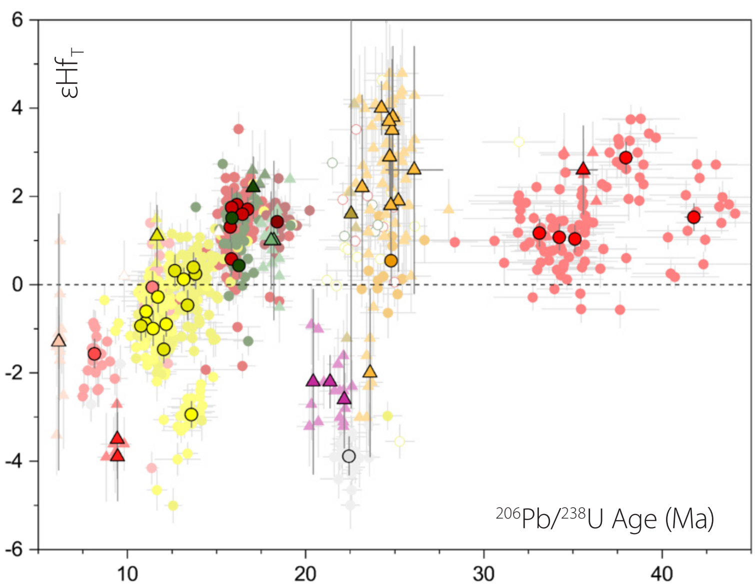

Figure 3. Age-εHf_T *signature for Cenozoic magmas of the EIB. Between Eocene and Oligocene, the* εHf_T *is relatively constant. Since ~20 Ma there is a sustained decrease in* εHf_T *values towards lower values in the syn-mineralisation magmas (red stars), during the Upper Miocene compression.*

Oblique crustal structural grain in the crust beneath the Phanerozoic Perth Basin

The Perth Basin is a nearly 1300 km long north-northwest trending basin, located along the south-western margin of the Australian continent, formed during the breakup of Australia and Greater India in the Permian to Early Cretaceous. Extension and trans-tension deformations during the rifting processes led to the formation of deep (up to 15 km) rift basins and structurally complex crustal structure.

A 40-station 250 km long passive source linear array was deployed in 2017, to better define whole-crustal structural elements. The array is centred on the Perth Metropolitan region and is sub-parallel to the major structural boundary, the Darling fault, that separates the Yilgarn craton in the east. The array employed both 20-s and 120-s Trillium Compact sensors, operating variously from 6 months to a year to provide continuous recordings suitable for crustal receiver function and ambient noise analyses.

Here we present the crustal shear wave velocity model which was derived by applying a transdimensional inversion technique (*Bodin et al., JGR 2012*) to the dispersion group velocity dataset extracted using ambient noise (e.g. *Yang et al., JGR 2008*).

The technique treats the number of velocity layers as a free parameter (i.e. transdimensional), and therefore can recover high-resolution layered velocity variations in the crust (e.g. see *Yuan and Boding, Tectonics 2018, CCFS Contribution #1181*).

In the modelling area, the first 10-km of the crust is mostly covered by the thick Phanerozoic basin. This is consistent with previous active source reflection profiles that show 10-12 km basin thickness south of Perth. At 15 km depth, however, two relatively high-velocity crustal structures may be recognised, separated by a NW-SE trending slow velocity zone. This trend is at a high angle to the NS-striking Darling Fault that separates the Yilgarn Craton (east) and the Perth Basin (west). The deep structural trend seems to continue further into the mid- to lower-crust, where our dataset (<28 s) quickly loses depth sensitivity.

Our results illustrate that passive-source seismology provides powerful means (in this case crustal tomographic imaging) to delineate deep crustal domains. An important finding of this study is the NW-SE trending crustal structure under cover. Intriguingly the trend is parallel to the large-scale NW-SE trending fault systems at the southwestern corner within the Yilgarn Craton. The results may shed light on the complex local tectonics and help us better understand the craton evolution along its southwest margin.

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

Contacts: Dr Xiangdong Lin (Beijing Earthquake Agency - visit sponsored by CCFS (2017-2018)), Huaiyu Yuan, Mike Dentith (GSWA), Simon Johnson (GSWA), Ruth Murdie (GSWA), and Klaus Gessner

Funded by: Perth Basin Seismic (PBS) project (UWA-GSWA)

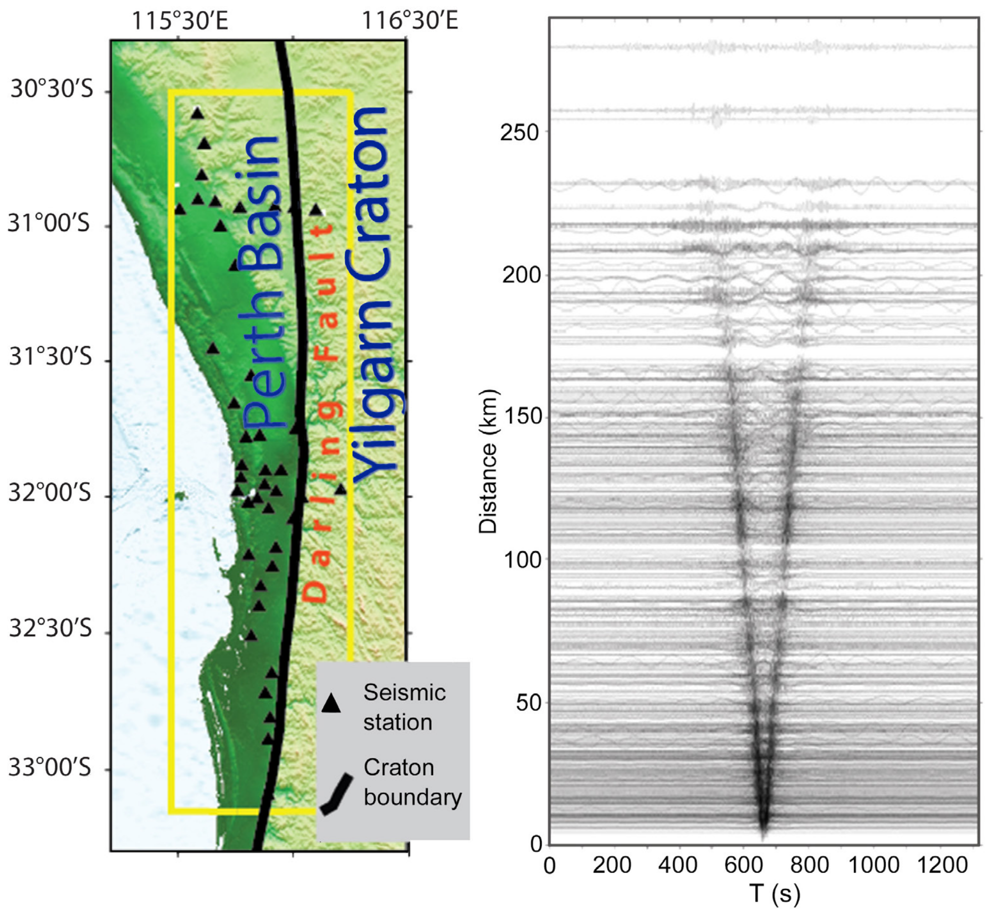

Figure 1. Perth Basin Seismic (PBS) array stations (left) and stacked cross-correlation functions (right) from ambient noise. Each trace shows equivalent surface wave signal traveling between a station pair. Craton boundary in the map is the Darling Fault separating at the surface the Yilgarn Craton (right) from the Perth Basin (left).

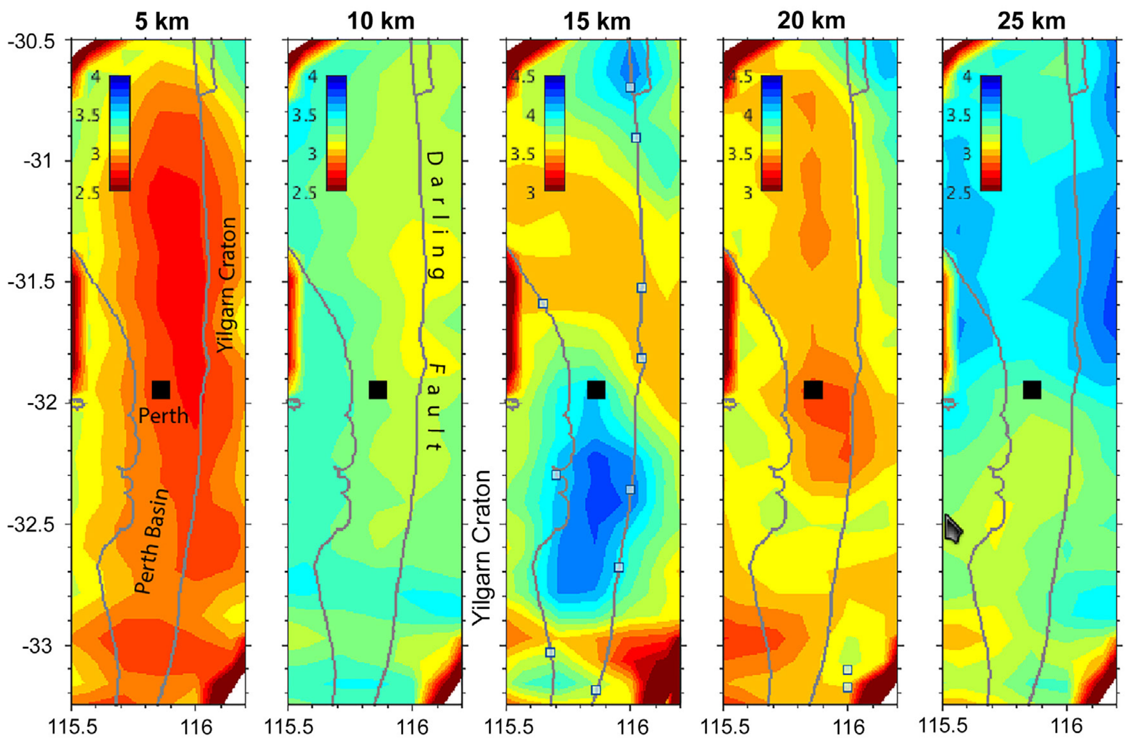

Figure 2. Map views of the shear-wave tomographic velocity model at various depths. Black square: Perth City.

A bigger tent for CAMP

New high-precision geochemical and isotopic data show that magmas related to the Central Atlantic Magmatic Province (CAMP) were emplaced at the base of the continental crust in the Ivrea Zone of northwest Italy (Fig. 1). These results significantly extend the known footprint of one of the largest examples of a large igneous province (LIP) on the planet. The La Balma-Monte Capio intrusion ranges from dunitic at the base to plagioclase-bearing pyroxenitic at the top. Zircons were extracted from two samples at different levels and dated using the chemical abrasion-isotope dilution-thermal ionisation mass spectrometry (CA-ID-TIMS) U-Pb method. The two weighted-mean $^{206}Pb/^{238}U$ ages at 200.5 ± 0.3 Ma and 200.1 ± 0.5 Ma indicate a short-lived magmatic system that fractionated in place. The timing of emplacement is different from that of all other mafic-ultramafic intrusions in the Ivrea Zone and is consistent with magmatism associated with the CAMP. We suggest that exposure in the Ivrea Zone provides a unique glimpse into the presently unknown character of LIP magmas at the base of the continental crust, where the emplacement of this intrusion was facilitated by its location at a lithospheric suture. See *CCFS publication #1188*.

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

Contacts: Marco Fiorentini, Steve Denyszyn
Funded by: CCFS Flagship Program 2

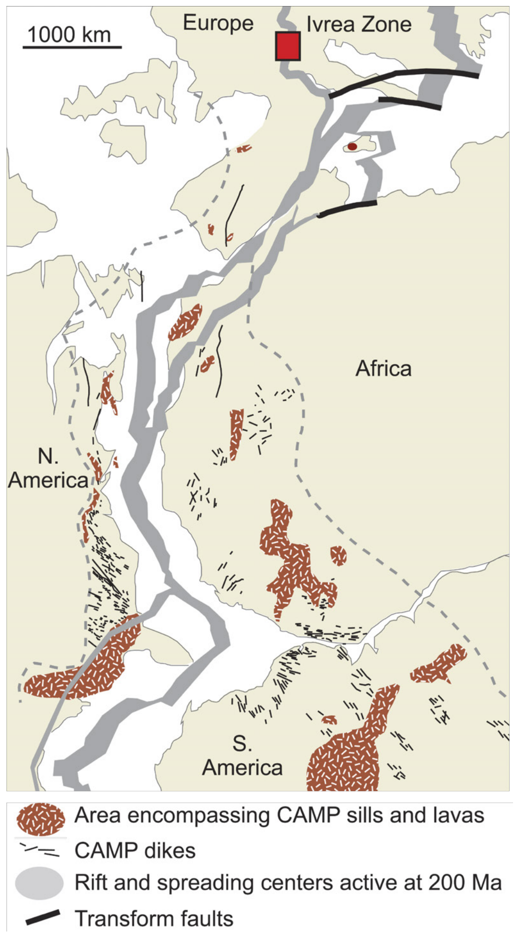

Figure 1. Reconstruction at ca. 200 Ma, with extent of intrusive and extrusive rocks of Central Atlantic Magmatic Province (CAMP) large igneous province (LIP). Star denotes location of La Balma-Monte Capio (LBMC) intrusion.

Langshan basalts record recycled Paleo-Asian oceanic materials beneath the northwest North China Craton

Crustal recycling is an important cause of mantle heterogeneity and can have significant control on basalt compositions. Recycled components from the subducted (Paleo-) Pacific slab have frequently been recognised in Cenozoic basalts from the eastern North China Craton (NCC). However, it still remains unclear if the subducted Paleo-Asian oceanic slab contributed to intraplate basalts in this Craton.

In a search of evidence for the recycled components from this slab, we have studied the Ar-Ar age, elemental and Sr-Nd-Pb isotope compositions of newly-discovered basalts from Langshan area and compiled a regional synthesis of Cenozoic alkali basalts from the northwest NCC (Fig. 1). This region is far from the Pacific domain but near the suture zone of the Paleo-Asian Ocean. With a Late Cretaceous eruption age (~89 Ma), Langshan basalts (Fig. 2) have low silica and high FeO, MgO and alkali contents, high incompatible elemental concentrations, positive Sr, Eu, Ba, Zr, Hf, Nb, Ta and negative Pb and Ti anomalies with subducted oceanic crust-like Ce/Pb, Nb/U, Rb/Sr and Ba/Rb ratios, superchondritic Zr/Hf ratios, and uniform radiogenic isotopes (εNd(t) = 2.32~2.64, $^{87}Sr/^{86}Sr_i$ = 0.703796~0.704340, $^{206}Pb/^{204}Pb_i$ = 18.601~18.828, $^{207}Pb/^{204}Pb_i$ = 15.489~15.536, $^{208}Pb/^{204}Pb_i$ = 38.527~39.000). These compositional characteristics are shared by the compiled Cenozoic alkali basalts from northwest NCC.

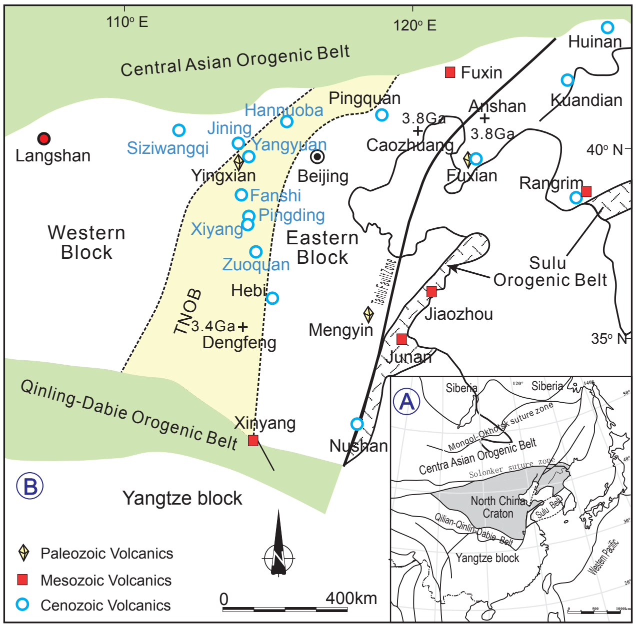

Figure 1. A) Simplified tectonic map of the North China Craton (Li et al., 2016). B) Tectonic sketch map of the NCC (Zhao et al., 2001, 2005; Kwon et al., 2009) with localities of mantle xenolith-bearing volcanics (Zheng et al., 2007; Yang et al., 2010; Xu et al., 2017; Dai et al., 2018). This craton is divided into eastern and western blocks with the Trans-North Orogenic belt in between according to Zhao et al. (2001). The compiled Cenozoic basalts in this study are from Siziwangqi and Jining in the western NCC, and Hannuoba, Yangyuan, Fanshi, Pingding, Xiyang, and Zuoquan in the TNOB. The term "northwest NCC" in this study refers to these localities and Langshan.

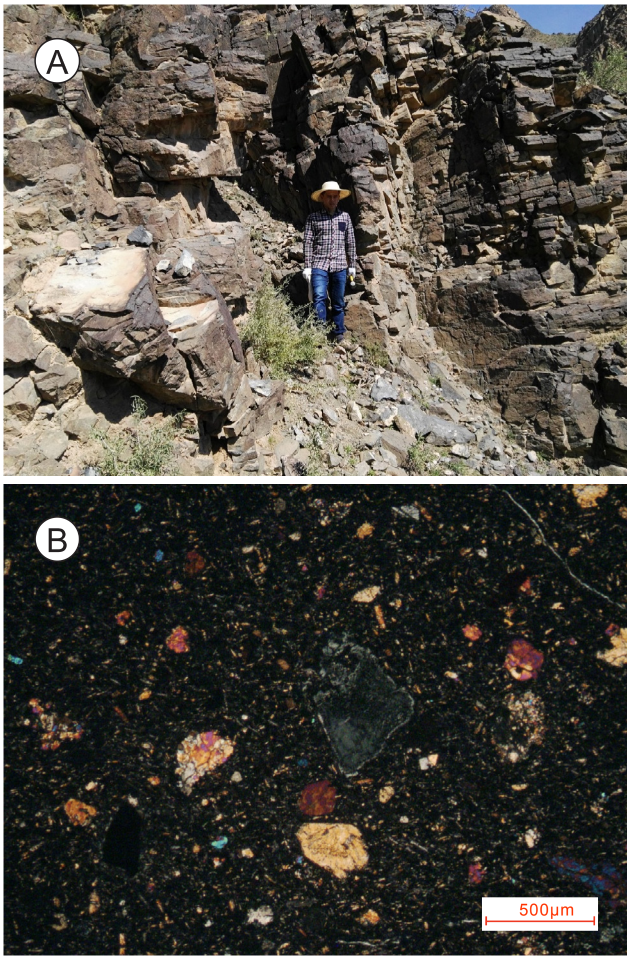

Figure 2. Field outcrop A) and microphotograph B) of the Langshan basalts. The man in A) is ~ 1.7 metres tall.

The low silica and high MgO, FeO and alkali contents together with the positive Zr, Hf, Nb, Ta and negative Ti anomalies probably reflect silica-deficient garnet pyroxenites in their mantle source. The high Nb/U and Ce/Pb ratios and unradiogenic isotopes together with P-T estimates (P = ~2.5 GPa, T_p = 1300~1450 °C) collectively suggest an asthenosphere origin. The positive Sr, Eu, Ba, Zr, Hf, Nb, Ta anomalies and the canonical indices (high Ce/Pb, Nb/U and low Rb/Sr and Ba/Rb ratios) indicate the involvement of a subducted oceanic igneous slab. Considering 1) the particular tectonic setting of the study region (Fig. 1), 2) the inferred northward increase of silica-deficient pyroxenite in the mantle source of Cenozoic alkali basalts, 3) the evidence for strong lithospheric modification beneath the northwest NCC induced by slab-derived components, and 4) the longevity of subducted slab in convection mantle, the subducted Paleo-Asian oceanic materials could have introduced ubiquitous mantle heterogeneity beneath the northwest NCC and have played a significant role in generation of the Late Cretaceous to Cenozoic intraplate alkali basalts there.

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

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Funded by: National Key R&D Program of China (2016YFC0600403), NSFC (41520104003), CSC (201706415070), iMQRES, Outstanding Doctoral Dissertation of CUG, IGCP 622

Carmeltazite - The latest Mt Carmel sensation

One of the most common exotic phases in the ultra-reduced assemblages from Mt Carmel (see *Research Highlights pp. 51-52, 57-59, 71*) has now been recognised as a new mineral by the International Mineralogical Association. *Carmeltazite* has the idealised chemical formula $ZrAl_2Ti_4O_{11}$ and is named after the locality (Mt Carmel) and its dominant elements (Titanium, Aluminium and Zirconium).

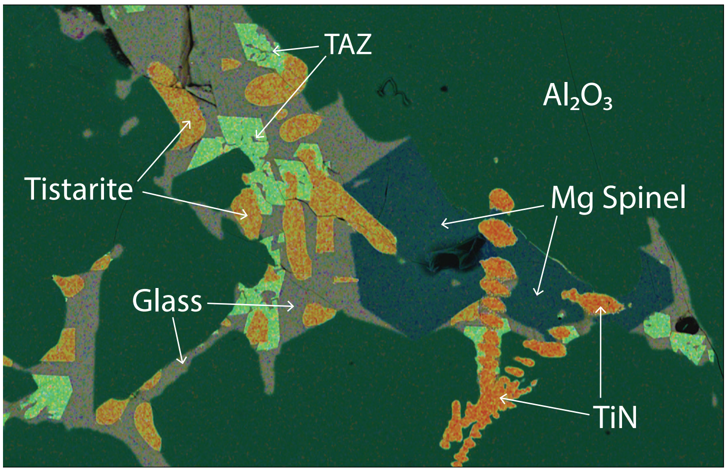


Figure 1. A typical melt pocket trapped in skeletal crystals of corundum (Al_2O_3). Euhedral crystals of carmeltazite (TAZ) surround locally resorbed crystals of tistarite (Ti_2O_3), set in a CaO-Al_2O_3-MgO glass. Image is 400 microns wide.

These unique mineral assemblages crystallised in melt pockets trapped in aggregates of corundum crystals (Carmel Sapphire™) found among the ejecta of small Cretaceous pyroclastic volcanoes on Mt Carmel. They are believed to have been crystallising in magma pockets trapped near the crust-mantle boundary, when they were entrained in basalts erupting from much deeper levels.

Carmeltazite typically crystallises after the earliest phases, tistarite (Ti_2O_3), TiN and spinel ($(Mg,Ti)(Al,Ti)_2O_3$) (Fig. 1). The assemblage is unusual on Earth, because Ti is present as Ti^{3+} instead of the common valence, Ti^{4+}, reflecting conditions in which oxygen fugacity lies 6 log units below the Iron-Wustite buffer ($fO_2 = \Delta IW$ -6) (see *Research Highlights pp. 51-52, 71*). Carmeltazite appears to crystallise at the expense of tistarite, but since both phases contain Ti^{3+}, there is no obvious change in fO_2 driving the crystallisation sequence. It is more likely that the crystallisation of tistarite and spinel served to further concentrate Zr to a critical level, leading to precipitation of carmeltazite.

Single-crystal X-ray diffraction studies were performed at Universita degli studi di Firenze, Italy, on fragments extracted from polished sections. The structure (Fig. 2) is orthorhombic, with space group Pnma. The refined X-ray formula can be written as $(Ti^{3+}_{3.75}\ Al_{1.94}\ Zr_{0.85}\ Mg_{0.22}\ Si_{0.14}\ Sc_{0.04}\ Ca_{0.03}\ Y_{0.02}\ Hf_{0.01})_{\Sigma=7.00}\ O_{11}$, in excellent agreement with that obtained from electron microprobe: $(Ti^{3+}_{3.60}\ Al_{1.89}\ Zr_{1.04}\ Mg_{0.24}\ Si_{0.13}\ Sc_{0.06}\ Ca_{0.05}\ Y_{0.02}\ Hf_{0.01})_{\Sigma=7.04}\ O_{11}$.

Over 130 different phases have thus far been recognised in the Carmel Sapphire™ provided by Shefa Yamim Ltd for this research. Most of these have not been found previously in Nature, and they will continue to provide insights into the evolution of this remarkable mineral system. See *CCFS publications #830 and 1229.*

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

Contacts: Bill Griffin, Luca Bind (University of Florence), Fernando Camara (University of Milan)
Funded by: CCFS

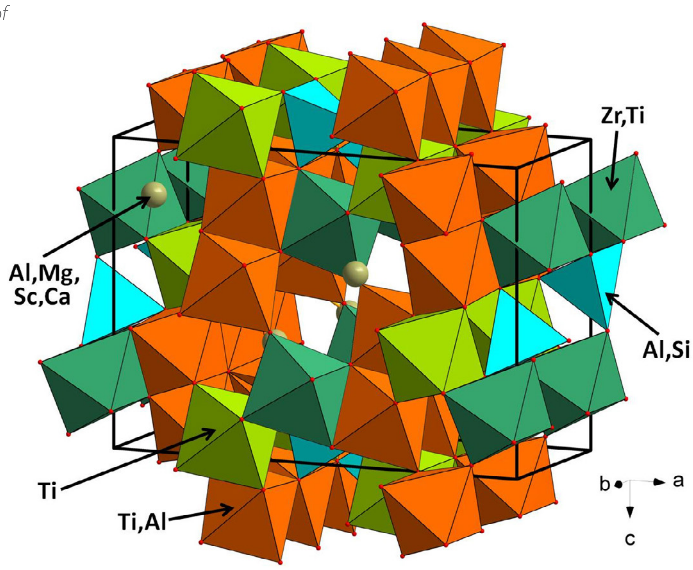


Figure 2. Structure of carmeltazite.

Putting the spin on Australia: First Precambrian palaeomagnetic data from the Mawson Craton (East Antarctica)

East Antarctica has been a key piece in Precambrian palaeogeographic reconstructions. As one of the most effective methods used to reconstruct supercontinents, palaeomagnetic studies have encountered great difficulties in East Antarctica due to inaccessibility, limited outcrops, and difficulties in conducting fieldwork in the Antarctic. There are only two Precambrian palaeomagnetic poles available from East Antarctica: the ca. 1130 Ma "BM" pole from the Borgmassif intrusions in Dronning Maud Land and the ca. 1100 Ma "CL" pole from Coats Land (Fig. 1). However, it is likely that neither the Dronning Maud Land nor Coats Land terranes joined the Mawson Craton until the final assembly of Gondwana at ca 520 Ma. Therefore, the BM and CL poles cannot be used to constrain the location of the Mawson Craton in pre-530 Ma palaeogeographic reconstructions. Additionally, for much of Precambrian time, the Mawson Craton is thought to have been a part of Australia, connected to the Gawler Craton, which also lacks reliable pre-800 Ma palaeomagnetic constraints. We conducted a pilot palaeomagnetic study on the ca 1134 Ma Bunger Hills dykes of the Mawson Craton. Of the six dykes sampled, three gave meaningful results providing the first well-dated Precambrian palaeopole at 40.5°S, 150.1°E (A95 = 20°) for the Mawson Craton.

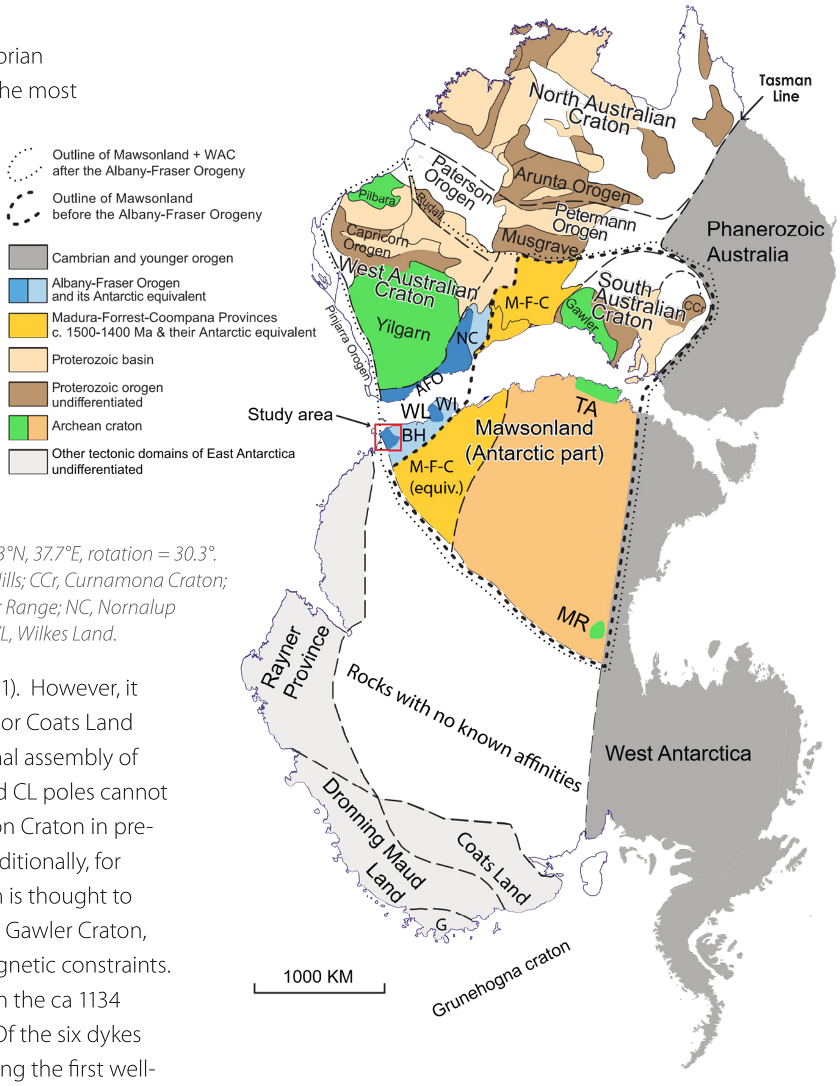


Figure 1. Tectonic map of Australia and Antarctica in a Gondwana configuration. Antarctica is rotated to Australia coordinates using a Euler pole7 at 1.3°N, 37.7°E, rotation = 30.3°. Abbreviations: AFO, Albany-Fraser Orogen; BH, Bunger Hills; CCr, Curnamona Craton; M-F-C, Madura-Forrest-Coompana Provinces; MR, Miller Range; NC, Nornalup Complex; TA, Terre Adélie craton; WI, Windmill Islands; WL, Wilkes Land.

Although it is generally agreed that Precambrian Australia (west of the Tasman line; Fig. 1) is composed of three Archaean to Palaeoproterozoic cratons (the West, North, and South Australian cratons - WAC, NAC and SAC respectively), when and how the present-day configuration took form is still a matter of debate. In an effort to reconcile some mismatching coeval poles of

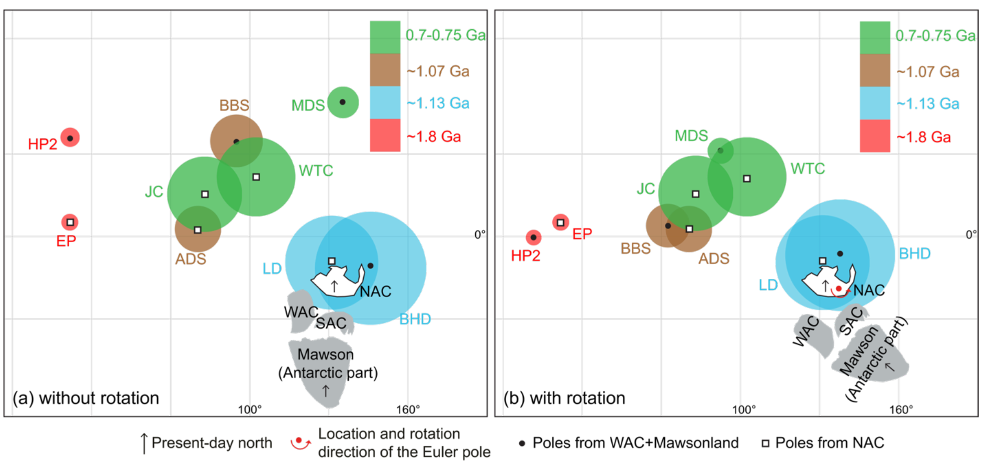


Figure 2. Four groups of coeval poles from the WAC + Mawson and NAC plotted in Mercator projection. Mawson (Antarctic Part) rotated to SAC in its Gondwana configuration using a Euler pole at 1.3°N, 37.7°E, rotation = 30.3°. (a) Australia in its present-day configuration; (b) WAC + SAC + Mawson rotated to NAC about a Euler pole at 20°S, 135°E, rotation = 40°. Poles from the NAC: EP - Elgee-Pentecost Formations; LD - Lakeview dolerite; ADS - Alcurra dykes and sills; JC - Johnny's Creek Member (Bitter Springs Formation); WTC - Walsh Tillite Cap Dolomite. Poles from WAC + SAC + Mawson: HP2 - Hamersley Overprint 2; BHD - Bunger Hills dykes; BBS - Bangemall Basin sills; MDS - Mundine Well dyke.

Australia, Li & Evans (2011, Geology) proposed that WAC + SAC (with Mawson) rotated ~40° relative to the NAC at ca 650-550 Ma to form the Precambrian part of Australia as we know it today (Fig. 1). Our new pole and the coeval Lakeview Dolerite pole make up another group of coeval poles from the NAC and WAC + SAC + Mawson, respectively, with which the intraplate rotation may be further tested. With the rotation applied, the area of overlap of the 95% confidence circles of the BHD and LD poles increases (Fig. 2), which constitutes a positive test for the relative rotation between WAC + SAC (+ Mawson) and NAC. The vast intracratonic rotation hypothesis not only reconciles discrepant coeval palaeopoles, but also provides a mechanism for the enigmatic Paterson and Petermann orogenies that account for significant mineralisation such as the massive Telfer Au deposit.

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

Contacts: Yebo Liu, Zheng-Xiang Li, Earth Dynamic Research Group, Curtin University
Funded by: ARC Laureate Fellowship (ZX Li), Australian Antarctic Science Project 4191

Sorting the wheat from the chaff in the source of Australian lamproites

Olivine is the main mineral in the Earth's upper mantle, but because of its very simple composition, it has been considered historically as being of little use as a tracer of mantle and magmatic processes. This has changed with recent advances in the analysis of minor and trace elements, which have made the low amounts of trace elements accessible by high-precision electron microprobe and Laser ablation-ICP-MS.

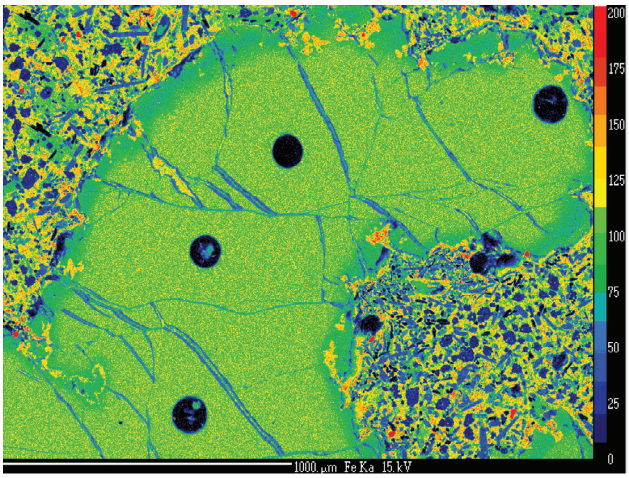


Figure 1. Main petrographic features of West Kimberley lamproite olivines. X-ray map (Fe Ka at 15 kV) of olivine xenocryst showing narrow reversely zoned rim.

As a result, minor and trace elements in olivine are used increasingly to identify the rocks present in the source, namely whether these are dominantly peridotite or contain significant amounts of other rocks, including material recycled into the mantle at subduction zones. Kimberlites are magmatic rocks with the deepest known origins (200-250 km), and a healthy debate has arisen recently as to how much of the olivine carried by them crystallised from the kimberlite melt and how much is entrained mantle material that may be related to part of the source.

The next deepest magmatic rocks are diamond-bearing lamproites, of which those of the Kimberley region of Western Australia (the name match is merely coincidental) are prime examples. We have investigated olivines from these lamproites and find many to have homogeneous cores with rims that crystallised at a late stage from the rising melt (Fig. 1). Phenocrysts - crystals that form directly from the melt - commonly show increasing Ca and Mn and decreasing Cr and Ni towards the rims. Xenocrysts - the entrained mantle material - are overgrown by rims of similar composition to all other rims. These rims are magnesium-rich (Mg# 91-92) and have compositions that show they formed from melts with 22-24 wt% MgO.

The xenocrysts are pieces of garnet peridotites from 115-190 km depth and show consistent variations in minor and trace element abundances with temperature and pressure of origin. The olivines from the deepest levels of the lithosphere have more Na, Al, P, Ti and Zr than shallower ones. This indicates that the mantle is more strongly depleted at shallower depths by previous melt loss, presumably in the first half of Earth history. However, this does not mean that this has always been the case: it is more likely that these shallower upper mantle levels escaped re-enrichment by later melts from below because the rising melts get stuck in the lower lithosphere.

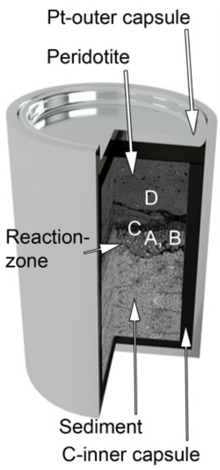
Previous Pb isotope studies have shown that subducted sedimentary material was probably involved in the source of the West Kimberley lamproites. Our earlier studies of Mediterranean magmatic rocks showed that the presence of crustal material in the source is often flagged by the enrichment of lithium in olivines. However, we found that olivines in the West Kimberley lamproites are not enriched in lithium, which is thought to be due to its later loss in fluids or by diffusion during the long time period (around 2 billion years) between subduction and production of the lamproites in the relatively recent past. See *CCFS publications #1248.*

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

Contact: Stephen Foley
Funded by: CCFS Flagship Program 1

Reaction of subducted marine sediment with peridotite produces saline fluid inclusions in diamonds

Diamonds form in Earth's mantle at depths of greater than 150 km and are carried to the surface by volatile-rich magmas, the so-called kimberlites. Most of the non-gem quality and some gem-quality diamonds carry inclusions of other minerals or fluid phases. Commonly, the fluid inclusions are highly saline and carbonate-rich. They were previously explained as a proof of the recycling of sea-water to Earth's mantle within marine sediments and oceanic crust. However, the mechanism of their transport into the mantle remained unresolved.



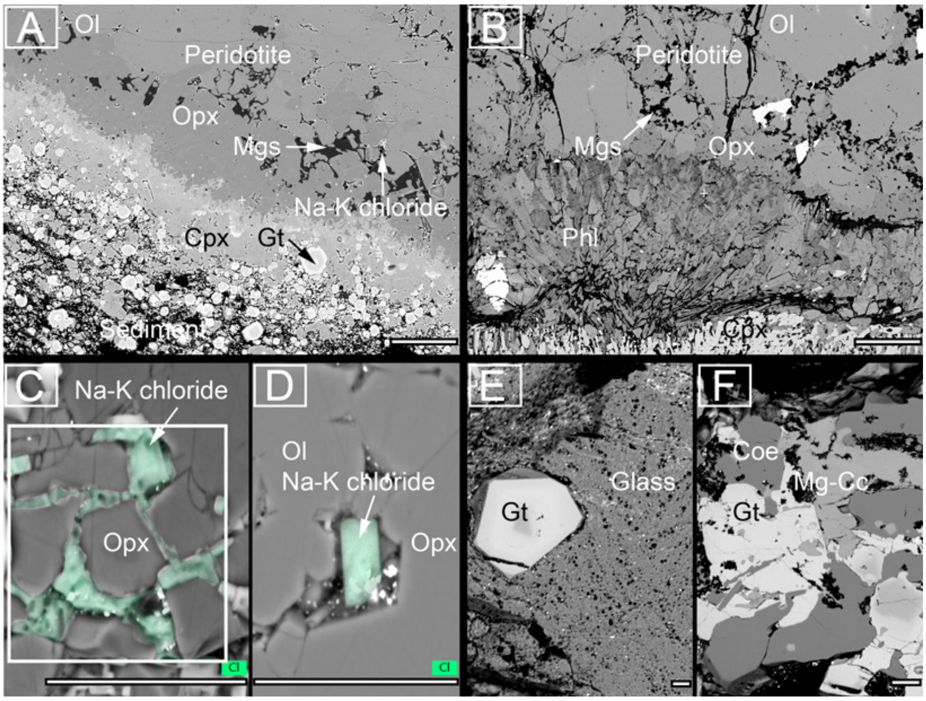


Figure 1. Backscattered electron images of experimental charges. Locations of images A-D from sediment-peridotite reaction experiments are schematically shown in capsule on left. A, C, D: reaction experiments at 5 GPa/1000 ºC with superimposed EDX maps of chlorine (green in C, D). The sediment half of two-layer experiments recrystallised to garnet and clinopyroxene, whereas orthopyroxene, magnesite (Mgs) and Na-K chlorides formed at the leading edge of the reaction zone against the peridotite. B: Peridotite layer in reaction experiment at 3 GPa/900 °C contained phlogopite behind the magnesite + orthopyroxene zone, and Na-K chlorides were absent. E, F: sediment melting experiment (no peridotite included) at 4 GPa/1000 °C showing silicate melt (E) in equilibrium with garnet, coesite, and mg-calcite shown in (F). Scale-bar in A, B = 100 µm and C, D, E, F = 20 µm.

In this study, we melted oceanic sediment and reacted it with dunite in a 2-layer arrangement (Fig. 1) at pressures corresponding to depths of 90-180 km, where the sediment layer recrystallised to garnet and clinopyroxene (Fig. 1, A and B). The experiments also produced a reaction zone between the two rock types; in experiments at pressures at and above 4 GPa these reaction zones contain Na-K chlorides (Fig. 1, A, C, and D, Fig. 2). Most of the analysed chlorides contain 5-15 wt% Na and 30-45 wt% K, with K/Na ratios between 2 and 9 (Fig. 3).

In contrast, all reaction experiments at 3 GPa and the higher-temperature experiment at 4 GPa/1100 °C, as well as a sediment-melting experiment at 4 GPa/1000 °C are devoid of chlorides. In these experiments, potassium and sodium are contained in phengite, Mg-rich mica (phlogopite), and melt (Fig. 1, B, E, and F).

The crystallisation of Na-K chlorides is induced by the reducing conditions in the inner graphite capsule and a shift in fluid species which consumes H_2O following the reactions:

(1) $CH_4 + H_2O = 3H_2 + CO$ and (2) $2CO = C + CO_2$ (the CCO buffer).

Any oxygen fugacity (fO_2) equal to or below CCO will lead to chloride precipitation from an oversaturated solution: $Na/K^+(aq) + Cl^-(aq) = (Na,K)Cl$. Since the dehydration of the fluid (reaction (1)) is only observed in reaction experiments at >3 GPa, the sequence leading to chloride precipitation has to be as follows: (1) melting of the sediment and reaction with dunite, (2) total consumption of the melt phase by anhydrous phases (garnet and pyroxene) which drives all H_2O into a fluid phase, and (3) dehydration of the fluid by reaction

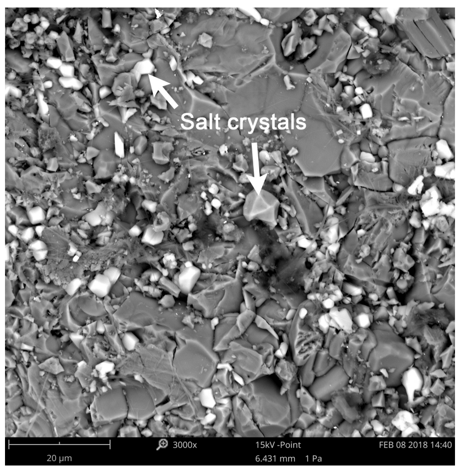


Figure 2. Secondary electron image of unpolished capsule showing idiomorphic salt crystals embedded in garnet and clinopyroxene.

(1) and precipitation of chloride from a fluid saturated in K, Na and Cl, and precipitation of carbon as graphite or diamond by reaction (2). If fO_2 is above CCO, Na-K chlorides will not precipitate, but instead be dissolved in highly saline hydrous fluids. The absence of hydrous crystalline phases such as mica in all chloride-bearing experiments is probably a direct result of the depletion of the fluid in H_2O.

Our results show that salt is a stable solid phase in the mantle below 110 km. The composition of the salts that form during the experiments are identical to the saline fluid inclusions in diamonds. We demonstrate that the processes that lead to the growth of salt and diamond crystals are driven by the recycling of oceanic sediments at subduction zones. The reaction products of our experiments also contain Mg-rich carbonates such as magnesite, which are necessary ingredients for the formation of kimberlite magmas that transport diamonds to Earth's surface.

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

Contacts: Michael Förster, Stephen Foley, Horst Marschall, Olivier Alard, Stephan Buhre
Funded by: ARC grant FL180100134

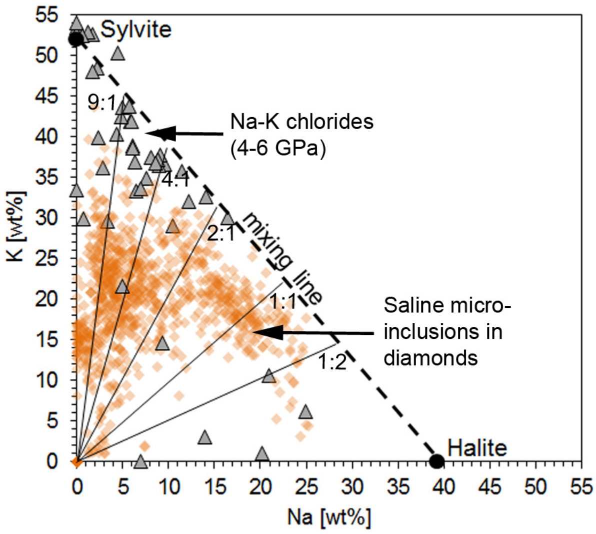


Figure 3. K/Na ratios of experimental chlorides and saline micro-inclusions in diamonds. Most saline micro-inclusions (orange diamonds) have a K/Na ratio between 1 and 9, similar to the ratios found in the experimental Na-K chlorides of this study (grey diamonds).

Pitfalls in the dating game: A cautionary tale

So when is a date not an age? This is an ongoing dilemma in U-Pb zircon geochronology and has led to a series of protocols being developed to potentially address this vexed question. But what if, even after doing all the '*correct*' things, you find that your date does not record the age of crystallisation? This is something that has been brought into clear focus in a recent paper published by our group (*Ge et al., Geology, 46, 303-306, 2018*).

But let us step back for a moment and briefly review the background to this problem; one that we have been working on since the inception of the CCFS. It had long been known that zircons in certain rocks can show reverse discordance, i.e. the result of either Pb gain or U loss (see *CCFS publication #738, Kusiak et al., PNAS, 112, 4958-4963, 2015* for a recent summary of this phenomenon). This appeared to be more prevalent when using secondary ion mass spectrometry (SIMS) techniques than either thermal ionisation mass spectrometry (TIMS) or laser ablation inductively-coupled mass spectrometry (LA-ICP-MS). During our re-investigation of high-grade gneisses from the Napier Complex in Antarctica it was evident, utilising the scanning ion-imaging capacity of a CAMECA IMS 1280, that radiogenic Pb had been locally mobilised and concentrated into micron- and nano-scale clusters. Further work using transmitted electron microscopy (TEM) established that, for the Napier Complex zircons, the Pb was concentrated into nanospheres of metallic Pb. The small size of these clusters, also established in related studies utilising atom probe tomography (APT), explains why this phenomenon was largely only detected by SIMS analyses, since the analysed volume is considerably smaller using this technique.

Mobility of Pb within zircon thus has the potential to affect the veracity of dates obtained from crystals showing this feature. However, it was generally considered that, owing to the small size of the clusters, their low concentration in areas showing this phenomenon, and their overall irregular distribution within the zircon crystals, that they were unlikely to have a major effect on the U-Pb ages obtained from such grains. It also appeared to be a feature affecting mainly high-grade gneisses that had undergone intense metamorphism and was therefore not a *'mainstream'* issue. Notwithstanding this view, since a large proportion of the oldest rocks on Earth are high-grade gneisses, it was evident that this needed to be carefully investigated.

The largest known inventory of Hadean zircons in the world resides in a conglomerate unit in the Jack Hills belt of Western Australia. Hence, this was the obvious place to see if Pb mobility was present and, if found, to test its nature and significance on the oldest ages recorded from Earth. A total of ~2500 detrital zircon grains were extracted from a sample collected at the original W74 discovery site and a large proportion of these was analysed rapidly by SIMS in order to identify Hadean crystals. From 215 identified Hadean crystals, a suite of 51 grains was finally selected as representing the most pristine grains based on multiple U-Pb SIMS dating, their lack of

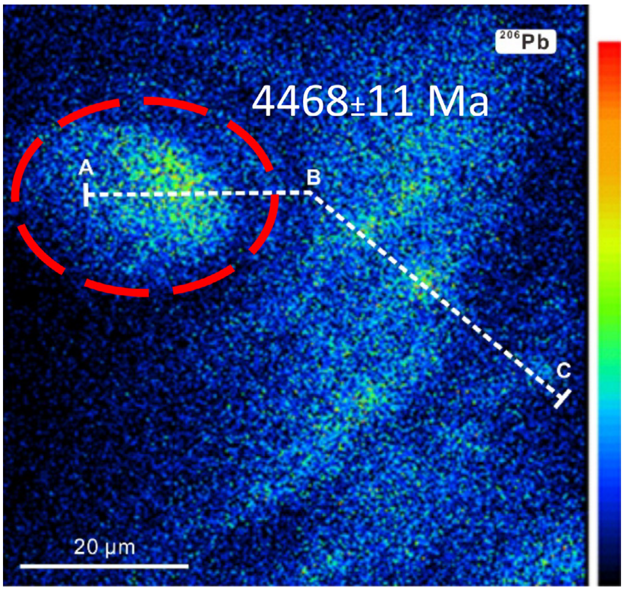


Figure 1. Site of SIMS analysis with date of 4468±11 Ma (2s), obtained on surface 2, projected onto scanning ion image of ^{206}Pb obtained on surface 5. The line A-B-C is a profile along which individual U and Pb isotopes were counted (see Ge et al., 2018 for details). The lighter areas in the figure indicate an increased Pb content.

imperfections and inclusions, and magmatic features evident in cathodoluminescence (CL) imaging.

One crystal (grain 14041) proved to be a stand-out. It recorded a concordia $^{207}Pb/^{206}Pb$ date of 4463 ± 17 Ma (2σ), the oldest zircon *'age'* ever recorded from Earth. This was established using multiple analyses and by re-polishing and re-analysing the same site. Indeed, a total of six dates revealed a range from 4486 ± 17 to 4425 ± 55 Ma (1σ): it met all the criteria for being an acceptable age for crystallisation of that zircon. However, knowing the potential for Pb mobilisation, it was imperative to test if this had affected grain 14041. Scanning ion imaging revealed a highly-significant phenomenon not previously recorded from zircon; an approximately 20-micron concentration of radiogenic Pb (Fig. 1). Fortuitously, the SIMS site had been placed exactly over this circular zone of Pb-enrichment. Additional analyses and modelling established that the actual age of zircon grain 14041 was significantly younger at between 4.32 and 4.27 Ga, consistent with the 4277 ± 16 Ma (2σ) concordia age recorded by the majority of SIMS analyses in that crystal.

So what are the salutary lessons to be taken from this study? Firstly, it highlights that even concordant U-Pb ages can be spurious and up to 200 Ma older than the actual crystallisation age. This is an important finding, because dating the oldest zircons has major implications for crustal evolution on Earth, other terrestrial planets and the Moon. Secondly, it indicates the need to not only take multiple ages from the same zircon domain identified in CL images, but to also test this further by undertaking either scanning ion imaging or atom probe tomography to validate the findings. Finally, although Pb mobility has now been established in zircon in several parts of the world and in a variety of host rocks, the mechanism(s) remains elusive and is the subject of our ongoing investigations.

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

Contact: Simon Wilde

Funded by: CCFS Flagship Program 6

A new mechanism for the formation of diamond-bearing eclogites?

The base of the cratonic lithosphere varies in its lithology: it consists mostly of highly depleted harzburgite as well as progressively modified metasomatised lherzolite, related to melt metasomatism. Melts rich in C, H and O originate from the underlying convecting mantle; they can infiltrate the cratonic lithosphere, where they are important in diamond formation and refertilisation (~150-200 km depth). These low-volume incipient melts can exist over a large temperature range (~300°C) in the upper mantle before major melting begins. They can form in reduced conditions dominated by $CH_4 + H_2O$ volatiles, or in oxidised conditions with hydrous carbonatitic affinity ($CO_2 + H_2O$).

Our experiments focused on the redox freezing of oxidised incipient melts as they encounter reduced depleted harzburgite at the bottom of the cratonic lithosphere. As oxidised incipient melts (predominantly CO_2 - H_2O) are unstable in the reduced cratonic lithosphere, reaction with surrounding mantle is inevitable and will result in the reduction of carbonate. The result is precipitation of diamond by a process known as *'redox freezing'*. Redox freezing deposits diamond in a reaction ($CO_2 = C + O_2$) that forms clinopyroxene-rich (omphacitic clinopyroxene, grossular-rich garnet) reaction zones (Fig. 1), in which mineral compositions are similar to those in eclogitic mantle xenoliths (Fig. 2).

The remaining reactive, hydrous and low-silica melt migrates further into the depleted reduced craton and consumes pyroxenes, precipitating olivine that is richer in Fe than in surrounding peridotites. The melt progressively increases its silica content by this process, becomes more 'oxidised', and finally precipitates hybrid, alkali-rich wehrlite veins with omphacitic clinopyroxenes and pyrope-rich (grospyditic) garnets similar to *'type A'* eclogites (Fig. 1, 2). The formation of such eclogites has previously been explained by high-pressure metamorphic transformation of subducted oceanic crust, or by recrystallisation of high-pressure cumulates from mantle-derived melts.

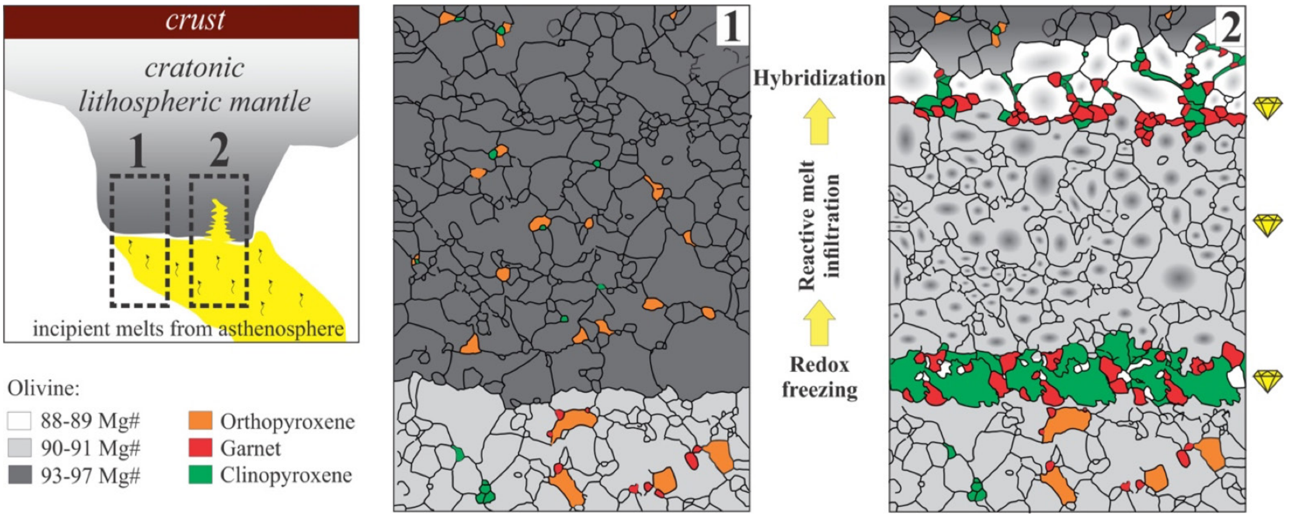


Figure 1. Hidden processes caused by redox freezing. The bottom of the depleted, reduced cratonic lithosphere is exposed to the infiltration of oxidised (CO_2-H_2O) silica-poor incipient melts (like ultramafic lamprophyre). Redox freezing forms a diamond-bearing eclogitic assembly. Remaining reactive hydrous melt infiltrates further into the cratonic lithosphere, forming dunites by consuming pyroxenes and precipitating Fe-richer olivines. The hybridisation reaction finally deposits the remaining melt as garnet-bearing wehrlite veins with adjacent Fe-rich olivines.

In contrast, the redox freezing of alkaline, silica-undersaturated ultramafic lamprophyre-like incipient melts forms a diamond-bearing *'type C'* eclogitic assembly (also classically explained as subduction-related eclogites). Further hybridisation reactions precipitate the enigmatic *'type A'* wehrlite veins, usually linked to the crystallisation of more mafic (Mg-rich) melts in cratons. The redox reactions between reduced depleted cratonic rocks and infiltrating oxidised melts is more complex than previously assumed, and results not only in different types of bimineralic eclogitic rocks, but also in dunitic rocks (olivine with very minor pyroxenes) without high-degree melting of the cratonic lithosphere.

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

Contact: Zsanett Pintér

Funded by: Flagship program 3

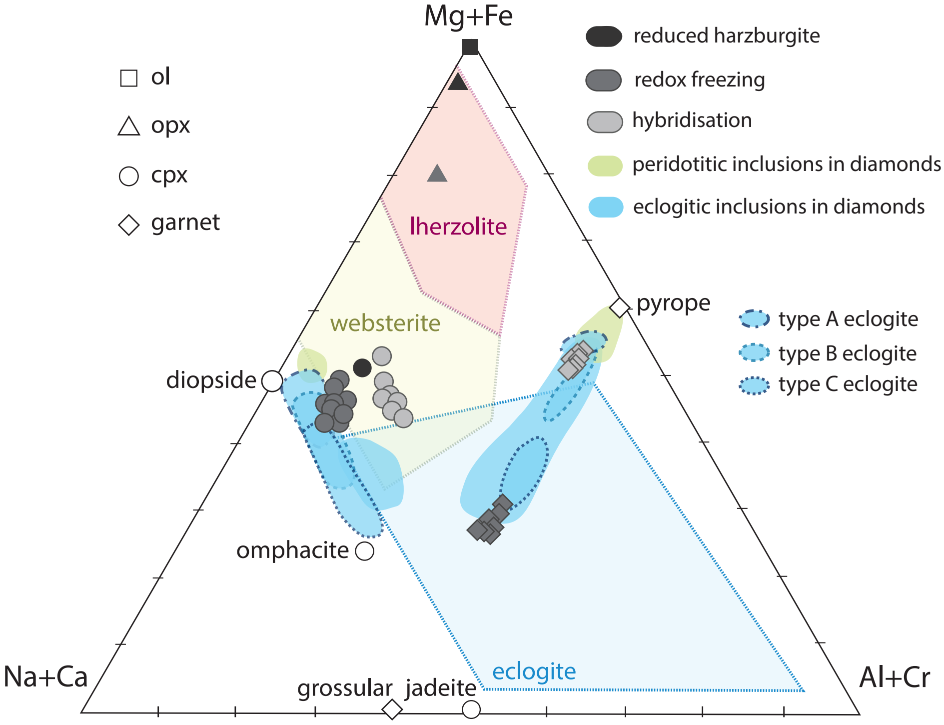


Figure 2. Ternary plot of mineral and rock compositions (defined by Mg + Fe, Ca + Na and Al + Cr) showing the complex nature of the redox freezing. Mineral end members for clinopyroxene and garnet are shown (diopside-omphacite, grossular-pyrope). Depleted, reduced harzburgite minerals are shown in black symbols. The reaction first precipitates grossular-rich garnets and omphacitic clinopyroxenes, proceeding to pyrope-rich garnets and Mg-rich omphacitic clinopyroxenes. Type A-B-C eclogites from Jacob 2004, Lithos 77, 295-316, diamond inclusions from Kiseeva et al., 2013, Geology 41 (8): 883-886.

Moissanite in the lithospheric mantle: Crystallisation from metallic melts

The redox state of Earth's mantle is a critical parameter in Earth processes, controlling the speciation of fluid and solid phases. The occurrence of moissanite (SiC) as xenocrysts in mantle-derived basaltic and kimberlitic rocks is a paradox in terms of the redox conditions of the mantle, since SiC can crystallise and remain stable only at fO_2 <ΔIW-6 (6 log units below the Iron-Wustite buffer) while the fO_2 of the lithospheric mantle is commonly considered to be much more oxidised (fO_2 ≥ΔIW-0).

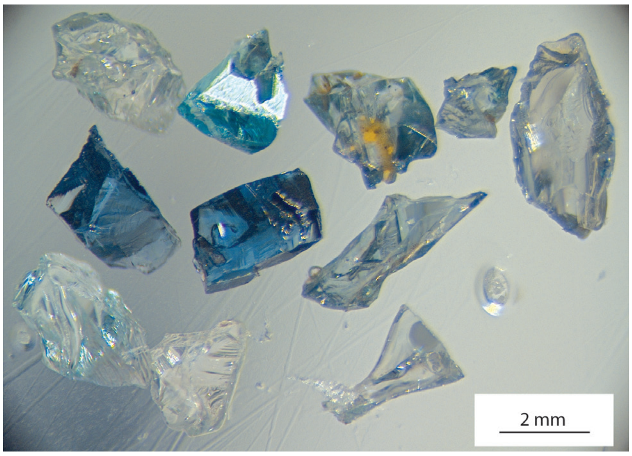


Figure 1. Moissanite grains from Mt Carmel, Israel.

Moissanite grains (Fig. 1) have been recovered from alkali basalts and related alluvial deposits at Mt Carmel, northern Israel, and from the Udachanaya and Aikhal kimberlites in Siberia. Most grains are fractured, but some partly preserve crystal faces. Grains from Mt Carmel are generally 0.5-2.0 mm in diameter, and range from black, blue, bluish-green to colourless. The Siberian samples are typically 0.4-1.0 mm in diameter; most are colourless, and some are bluish-green. 3D-CT scans of SiC grains reveal solid inclusions and elongated cavities; both tend to be aligned parallel to the c axis of the host crystal. Some cavities are associated with inclusions, but others are not. The inclusions in SiC (Fig. 2) typically have round to oval shapes, but some have straight boundaries, constrained by the crystal structure of the host grain, suggesting they were entrapped as melts. Each inclusion contains two or more phases with or without cavities.

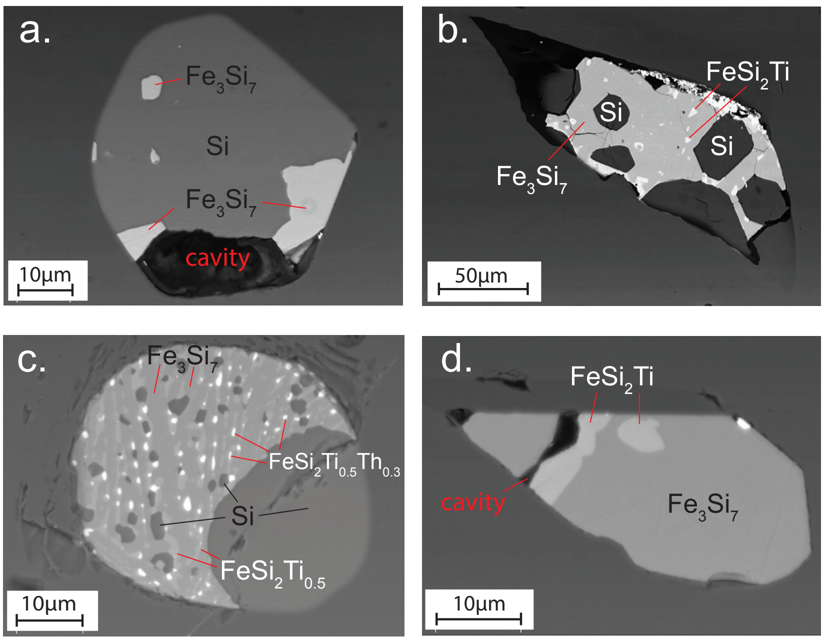


Figure 2. Back-scattered electron (BSE) images of inclusions in moissanite grains from Mount Carmel basalts and Yakutian kimberlites. a-b are Mt Carmel samples and c-d are Siberian samples.

Native Si (Si^0) is usually the main phase and is always associated with one or more silicide phases, Si + Fe_3Si_7 ± $FeSi_2Ti$ ± $CaSi_2Al_2$ ± $FeSi_2Al_3$ ± $CaSi_2$. The existence of cavities suggests the former presence of a volatile phase during SiC crystallisation. These observations suggest that SiC crystallised in the lithospheric mantle from metallic melts (Si-Fe-Ti-C ± Al ± Ca), with dissolved carbon and H_2 derived from the sublithospheric mantle, which may be closely related to mantle plumes. SiC has been found in a melt pocket in corundum from Mt Carmel (see *Research Highlight, 2017*), suggesting genetic connections between SiC, corundum and their melt inclusions. Paragenetic studies of trapped melts in the associated corundum aggregates indicate that these silicide melts separated immiscibly from silicate melts following extended reduction of mafic magmas by $CH_4 + H_2$ fluids. When mafic/ultramafic magmas formed in the lithospheric mantle are fluxed with $CH_4 + H_2$ from depth, they can be progressively reduced, to a point where silicide melts become immiscible, and crystallise phases such as SiC.

The widespread occurrence of SiC in explosive volcanic rocks from different tectonic settings indicates that the delivery of $CH_4 + H_2$ from depth may commonly accompany explosive volcanism; this in turn implies that much of the sublithospheric mantle is metal-saturated, more than previously thought. The heterogeneity of redox states in the lithospheric mantle further influences geochemical reactions such as melting and geophysical properties such as seismic velocity and the viscosity of mantle rocks. The gases involved in SiC formation provide extra information on the degassing of the deep Earth.

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

Contacts: Jin-Xiang Huang, Bill Griffin
Funded by: CCFS Flagship Program 1

CCFS postgraduates

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.

SUBMITTED 2018

Michael Alderson: Spatially resolved Micro-XRF data for geochemical exploration strategies

Benjamin Alsop: Microstructural evidence of melt-present deformation and its effect on zircon modification

Stephanie Hawkins: Investigating an igneous dyke swarm using Applied Field Magnetics

Angela Mabee: Plume volcanism controls site1172 sediment provenance and deposition pre-Antarctic Circumpolar Current

Joshua Shea: Identifying a Source Assemblage for Buckland Volcanic Province

Peter Targett: Direct evidence for hydrothermal fluid mineralisation in the Velkerri Formation, Northern Australia

Alice Van Tilburg: Exploring Lithospheric Scale Structure in the Southern Yilgarn Craton with 3D Magnetotellurics

AWARDED 2018

Thomas Connell: Approximate Bayesian Tomography

Joyjit Dey: Recognition of quartz grown from a melt during static and dynamic conditions

Omar Elkhaligi: Olivine trace element geochemistry of volcanics from central and southern Africa

Victoria Elliott: Zircon growth and modification during deep melt flux through a magmatic arc

Anthony Finn: Tracing shallow lateral preferential pathways of fluid movement using electrical geophysics

Jean-Antoine Gazi: Evolution of small planetary bodies: A view from carbonaceous chondrites

Tasman Gillfeather-Clark: The electrical properties of the Woodroffe thrust: A resistive shear zone

Joshua Shea, picture above at the EMP, presented his work at the November 2018 GSA NSW Division Monthly Meeting - Honours and Masters Night.

Harrison Jones: Geophysical signatures of small-scale base metal occurrences in southeastern NSW

Carla Raymond: Mummification unwrapped: investigating an Egyptian votive mummy using novel, non-invasive archaeometric techniques

Luke Smith: Precision positioning in unmanned aerial geophysics

Alexander Tunnadine: Fingerprinting the source of mineralising fluids in IOCG Systems, Mount Woods Inlier

John Wardell: Mineralogical and geochemical constraints on magmatic evolution at Tengger Caldera, Indonesia

Harry West: Metal-silicate-sulphide segregation within the Yaringie Hill Meteorite

Haoming Wu: Constraining crustal and sedimentary structure of Southeast Australia with Rayleigh wave ellipticity

MRes graduation: Luke Smith, Stephanie Kovacs and Carla Raymond.

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 2012-2018. 42 papers with CCFS postgraduates as authors were published in high-profile international journals in 2018 including *Nature Geoscience, Gondwana Research, Geology, Geochimica et Cosmochimica Acta, Journal of Metamorphic Geology, Geobiology, Precambrian Research, Lithos, Tectonics, Chemical Geology* and *Journal of Geophysical Research*. 75 presentations were also given at international conferences (see *Appendix 6*).

2018 HIGHLIGHTS

Michael Förster received an MQ Faculty of Science and Engineering Award for Higher Degree Research. Michael was also awarded the 2018 *"Bernd Rendel Preis"* from the German Research Foundation (DFG) for his outstanding achievements in geochemistry. The jury said, *"Even at this relatively early stage, Förster has a number of impressive scientific achievements to his credit, demonstrating an exceptional ability and degree of scientific independence."* The prize included ~€1500 to assist with travel to international conferences. Michael also completed the Future STEMM Leaders Critical Skills Development Program.

Eunjoo Choi was a GESSS-WA 2018 Presentation Winner at the meeting held on the 29th November. Eunjoo was also the GESSS-WA meeting treasurer.

Maria Manassero (pictured right with Kate Selway at the National MT workshop and AusLAMP SA Release Day, Adelaide, Australia, 5th December 2018) was awarded the EPS HDR Best HDR presentation at the 11th November EPS HDR presentation day.

Jonathon Wasiliev won the best talk and MRes student **Alice Van Tilburg** the best poster at the MQ EPS HDR presentation day held in June.

Zsanett Pintér was awarded Best Student Poster Presentation at *"Geoanalysis - 10th International Conference on the Analysis of Geological and Environmental Materials"* held at Macquarie University on the 18-13 July 2018.

Anthony Lanati was extremely active in the Geological Society of Australia, taking on the roles of: Chair of the Geological Society of Australia NSW Division, Governing Councillor of the NSW Division, Honorary Treasurer, Member of the Executive Committee, Chair of the Finance and Risk Committee.

Tarra Djokic was a guest speaker at the NSW Division Monthly Meeting held on the 10th May 2018. Her presentation was titled *"Life in Archean hot springs and implications for astrobiology"*.

COMPLETED

Sonia Armandola (PhD): Detrital accessory phase geochemistry and geochronology of Capricorn basins and implications for the evolution of the Capricorn Orogen (WA) (CU 2018)

Bataa Baatar (MSc): Fertility of the Lock Lilly Belt for porphyry Cu-Au mineralisation - constraints from whole-rock chemistry and zircon studies (UWA 2017)

Raphael Baumgartner (PhD): Ore deposits of the future; magmatic Ni-Cu-PGE sulfide mineral systems on Mars (UWA 2017).

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

Katarina Bjorkman (PhD): 4D lithospheric evolution and controls on mineral system distribution: Insights from Marmion Terrane, Western Superior Province, Canada (UWA, 2017)

Eleanore Blereau (PhD): Petrochronology of the Ultrahigh-Temperature (UHT) Metamorphic Rogland-Vest Agder Sector, Southwestern Norway (CU 2017)

Raul Brens Jr (PhD): Constraints on petrogenesis and elemental recycling of the Tonga-Kermadec Island Arc System and the associated Lau and North Fiji Basins (MQ 2018)

Lauren Burley (MSc): The geology of the Fisher East komatiite-hosted nickel sulfide deposit (UWA 2015)

Montgarri Castillo-Oliver (PhD): Compositional evolution of indicator minerals: Application to diamond exploration (MQ 2016) See *Research highlight p. 38-39.*

Mathieu Chassé (PhD): Mechanisms of enrichment of rare earth elements in supergene conditions (MQ, 2018)

David Child (PhD): Characterisation of actinide particles in the environment for nuclear safeguards using mass spectrometric techniques (MQ 2016)

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)

Bruno Colas and Beñat Oliveira Bravo.

Bruno Colas (PhD): Structural constraints on the crystallisation of Amorphous Calcium Carbonate (MQ 2017)

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)

Stephen Craven (PhD): The evolution of the Wongwibinda Metamorphic Complex, New England Orogen, NSW, Australia (MQ 2016)

Daria Cyprych (PhD): Deformation behaviour of polymineralic rocks: implications for rheology and seismic properties of the middle to lower crust (MQ 2017)

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

Tara Djokic (MPhil): Assessing the link between Earth's earliest convincing evidence of life and hydrothermal fluids: The c. 3.5 Ga Dresser Formation of the North Pole Dome, Pilbara Craton, Western Australia (UNSW 2015)

Raphael Doutre (PhD): Spatial periodicity, self-organisation and controls on large ore deposits (UWA 2018)

Timmons Erickson (PhD): Deformation microstructures in zircon and monazite: implications for shock, tectonic and geochronological studies (CU 2017)

Christopher Firth (PhD): Elucidating magmatic drivers and eruptive behaviours of persistently active volcanoes (MQ 2016)

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

Denis Fougerouse (PhD): 4D geometry and genesis of the Obuasi gold deposit, Mali (UWA 2016)

Yuya Gao (PhD): Origin of A-type granites in East China: Evidence from Hf-O-Li isotopes (MQ 2015)

Robyn Gardner (PhD): Flow behaviour of the middle and lower crust: Insights from field observations and numerical modelling (MQ 2017)

Rongfeng Ge (PhD): Precambrian to Paleozoic tectono-thermal evolution in the Korla area, northern Tarim Craton, NW China (CU 2015)

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

Markus Gogouvitis (MSc): Distinguishing hydration in Shear Zones by Aqueous Fluid versus Silicate Melt (UNSW 2017)

Christopher Gonzalez (PhD): CO_2 devolatilisation and its influence on partial melting, subduction, and metasomatism in the mantle lithosphere (UWA 2016) See *Research highlight p. 41.*

Louise Rebecca Goode (PhD): Investigating the magmatic drivers behind temporal variations in eruption frequency and style at Kelut volcano, Indonesia (MQ 2018)

Erin Gray (PhD): Deformation of Earth's upper mantle: insights from naturally occurring fabric types (UWA 2014)

Christopher Grose (PhD): Thermochemical models of oceanic upper mantle (MQ 2015)

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

Hadrien Henry (PhD): Mantle pyroxenites: Deformation and seismic properties (MQ 2018) See *Research highlight p. 54-55.*

Matthew Hill (PhD): 4D structural, magmatic and hydrothermal evolution of the Au-Cu-Bi system in the Tennant Creek Mineral Field, NT, Australia (UWA 2015)

Yosuke Hoshino (PhD): Investigation of hydrocarbon biomarkers preserved in the Fortescue Group in the Pilbara Craton, Western Australia (MQ 2015)

Jin-Xiang Huang (PhD): Origin of eclogite and pyroxenite xenoliths in kimberlites and basalts (MQ 2012) See *Research highlight p. 71.*

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

Linda Iaccheri (PhD): Petrogenesis of granitic rocks in the Granites-Tanami Orogen (UWA 2017)

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 (UWA 2015)

Inalee Jahn (PhD): Crustal evolution of the Capricorn Orogen, Western Australia (CU 2017)

Kim Jessop (PhD): The role of aqueous fluids in the formation of regional-style high-temperature low-pressure (HTLP) metamorphic complexes (MQ 2018)

Chengxin Jiang (PhD): Combining seismic tomography and sedimentology to understand the deep structure and evolution of the northern edge of Tibetan Plateau (MQ 2016)

Heta Lampinen (PhD): Defining a base metal mineral systems footprint in the Edmund Basin of the Capricorn Orogen, Western Australia (UWA 2018)

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 (UWA 2015)

Margaux Le Vaillant (PhD): Characterisation of the nature, geometry and size of hydrothermal remobilisation of base metals and platinum group elements in magmatic nickel sulfide deposit systems. Implications for exploration targeting (UWA 2015)

Ben Li (PhD): Evolution of fluid associated with gold mineralisation in the Paleoproterozoic Granites-Tanami Orogen (UWA 2015)

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

Nora Liptai (PhD): Geochemical and physical properties and evolution of the lithospheric mantle beneath the Nógrád-Gömör Volcanic Field (Northern Pannonian Basin, Central Europe) (MQ 2018) See *Research highlight p. 43-44.* *Pictured below, right.*

Cait Stuart and Nora Liptai.

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 (CU 2015)

Yingchao (Leo) Liu (PhD): Recognising gold mineralisation zones using GIS-Based modelling of multiple ground and airborne datasets (CU 2015)

Jianggu Lu (PhD): Mantle xenoliths from SE China and SE Australia: Nature and evolution of the lithospheric mantle (MQ, 2018) *Pictured right.*

Yongjun Lu (PhD): Controls on porphyry emplacement and Porphyry Au-Cu mineralisation along the Red River Fault, Hunan Province, China (UWA 2012)

Volodymyr Lysytsyn (PhD): Mineral prospectivity analysis and quantitative resource assessments for exploration targeting-development of effective data integration models and practical applications (UWA 2015)

Jelena Markov (PhD): 3D geophysical interpretation of the Archean-Paleoproterozoic boundary, Leo-Man Shield, West Africa (UWA 2015)

Quentin Masurel (PhD): Controls on the genesis, geometry and location of the Sadiola-Yatela Gold Deposit, Republic of Mali (UWA 2016)

Nicole McGowan (PhD): Messages from the mantle: Geochemical investigations of ophiolitic chromites (MQ 2017)

Holly Meadows (PhD): Mineral geochemistry, deformation and ore-fluid evolution in the Capricorn Orogen, WA (CU 2018)

Vicky Meier (PhD): Metamorphic evolution of the Kerala Khondalite belt, India (CU 2017)

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

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

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

Rosanna Murphy (PhD): Stabilising a craton: The origin and emplacement of the 3.1 Ga Mpuluzi Batholith (MQ 2015)

Antoine Neaud (MSc): The geology of the Savannah nickel sulfide deposit, Western Australia (UWA 2016)

Jiawen Niu (MPhil): Neoproterozoic paleomagnetism of South China and implications for global geodynamics (CU 2016)

Beñat Oliveira Bravo (PhD): Multicomponent and multiphase reactive flows in the Earth's mantle (MQ 2017) See *Research highlight p. 45*. *Pictured p. 74*.

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)

Luis Parra-Avila (PhD): 4D evolution of felsic magmatic suites and lithospheric architecture of the Paleoproterozoic Birimian terranes, West Africa (UWA 2016)

Carl Peters (PhD): Deep time biomarkers - A study of organic matter and fluid inclusions in Precambrian rocks (MQ 2017)

Jonathon Poh (MSc): Numerical investigation of the driving forces of Archean fluid and heat transfer flows (UWA 2015)

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 *Research highlight p. 34-35.*

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)

Vikram Selvaraja (PhD): Multiple sulfur isotopes as a tracer of geological processes (UWA 2017)

Liene Spruzeniece (PhD): Fundamental link between deformation, fluids and the rates of reactions in minerals (MQ 2017)

Camilla Stark (PhD): Decoding Mafic Dykes in the Southern Yilgarn Craton: Significance to Australia's Positions in the Supercontinent-Superplume Cycle (CU 2018)

Jack Stirling (MSc): Geochronology of lower crustal cumulate complexes in the Kohistan Terrane, North-East Pakistan (UWA 2017)

Catherine Stuart (PhD): Melt migration in the lower crust by porous melt flow (MQ 2018) *Pictured p. 75.*

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

Rajat Taneja (PhD): The origin of seamount volcanism in the Northeast Indian Ocean (MQ 2015)

Ni Tao (PhD): Thermochronological record of tectonic events in central and southeastern South China since the Mesozoic (CU 2015)

Romain Tilhac (PhD): Petrology and geochemistry of pyroxenites from the Cabo Ortegal Complex, Spain (MQ 2017) See *Research highlight p. 45.*

Mehdi Tork Qashqai (PhD): Multi-observable probabilistic inversion for the thermochemical structure of the lithosphere (MQ 2017)

Irina Tretiakova (PhD): The nature, extent and age of the lower crust and underlying subcontinental lithospheric mantle (SCLM) beneath the Siberian Craton (Russia) (MQ 2017)

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

Kai Wang (PhD): Adjoint Tomography of Surface Wave Observables from Ambient Seismic Noise (MQ 2018) See *Research highlight p. 52-53.*

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 (CU 2015)

Yu Wang (PhD): Melting process in recycled continental crust (MQ 2015)

James Warren (PhD): 4D evolution of the Ora Banda and Coolgardie Domains (UWA 2016)

Jun Xie (PhD): Verification and applications of surface waves extracted from ambient noise (MQ 2017)

Qing Xiong (PhD): Shenglikou and Zedang peridotite massifs, Tibet (China): Upper mantle processes and geodynamic significance (MQ 2015) See *Research highlight p. 53-54, 63-64.*

Weihua Yao (PhD): Lower Paleozoic basin record in southern South China: Nature of the Cathaysia basement and evolution of the Wuyi-Yunkai Orogeny (CU 2014)

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

Arash Amirian (PhD): Quantitative determination of the amount and location of water in the Earth; *iRTP* (MQ, commenced 2017)

Halimulati Ananuer (PhD): Elemental and isotopic fractionation of chalcophile elements during mantle processes; IMRTPS (MQ, commenced 2017)

David Barbosa da Silva (PhD): The microchemical and microstructural evolution of fluid and melt transfer in deep crustal shear zones; *iMQRES* (MQ, commenced 2016)

Erica Barlow (PhD): Microfossils of the Paleoproterozoic Turee Creek Group: Biological evolution resulting from atmospheric change?; *RTP* (UNSW, commenced 2015)

Hugh Bannister (MPhil): Adaptive response of the biosphere to Paleoproterozoic glaciations at the Great Oxygenation Event; *FP4* (UNSW, commenced 2016)

Jason Bennett (PhD): The *in situ* microanalysis of cassiterite to constrain the genesis, evolution and geochronology of tin bearing mineralised systems; *RTP* (UWA, commenced 2015)

Richard Blake (MPhil): Determining recent organic contamination in ancient rocks; *FP4* (UNSW, submitted 2018)

Stefano Caruso (PhD): Geological controls on the fractionation of multiple sulfur isotopes in Archean mineral systems; *SIRF & MRIWA Postgraduate Scholarship* (UWA, submitted 2018)

Julian Chard (PhD): Petrochronology of accessory minerals related to metamorphism and fluid-flow events in the Albany-Fraser Orogen and Eucla basement, Western Australia; *CIPRS* (CU, commenced 2016)

Eunjoo Choi (PhD): Alkaline magmatism as a probe into the lithospheric mantle; *IRPT, MRIWA* (UWA, commenced 2016)

Hongkun Dai (PhD): Nature and evolution of the lithospheric mantle beneath the western North China Craton; CTIMRTPS (MQ, commenced 2018) See *Research highlight p. 63-64*.

Benedikt Demmert (PhD): Modelling the effect of minority components in biominerals via biomimetic mineralisation; CTIMRTPS (MQ, commenced 2018)

Gregory Dering (PhD): Dynamics and emplacement mechanisms of mafic magma networks with implications for intrusion-hosted magmatic Ni-Cu-PGE sulfide deposits; *APA, IPRS* (UWA, submitted 2018)

Tara Djokic (PhD): A reconstructed subaerial hot spring field in the ~3.5 billion-year-old Dresser Formation, Pilbara Craton, Western Australia; *APA* (UNSW, commenced 2016)

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; *RTP* (MQ, part time, commenced 2014)

Michael Förster (PhD): Experimental melting of rocks of ultramafic and sedimentary origin in accretionary orogens; *IPRS* (MQ, commenced 2016) See *Research highlight p. 67-68*.

Hamed Gamal El Dien (PhD): Neoproterozoic Oceanic Large Igneous Province (O-LIP) record and crustal growth of the Arabian-Nubian Shield; *CIPRS* (CU, commenced 2017) *Pictured right with Neoproterozoic pillow basalts in East Desert, Egypt.*

Hindol Ghatak (PhD): Role of fluids in facilitating the intracontinental Alice Springs Orogeny; *iMQRTP* (MQ, commenced 2017)

Stephanie Greene (PhD): Origin and evolution of eclogite xenoliths from the Jericho Kimberlite pipe; IMRTPS (MQ, commenced 2017) See *Research highlight p. 49*.

Kui Han (PhD): Modelling the physical properties of multiphase rock assemblages; *IRPT* (MQ, commenced 2017)

Michael Hartnady (PhD): Crustal evolution of the Albany-Fraser Orogen; *CIPRS* (CU, commenced 2016)

Gonzalo Henriquez (PhD): Improving zircon morphology and chemistry as a tool for assessing and ranking the prospectivity for Cu porphyry deposits in greenfield terranes; *Industry - BHP Billiton* (UWA, commenced 2017)

Raham Jalil (PhD): Mineralogy, geochemistry and genesis of ophiolite associated economic minerals (PGEs, gold, silver, base metals and REEs) in Waziristan area, North-West Pakistan; CFIMRTPT (MQ, commenced 2018)

Constanza Jara Barra (PhD): Gold pathways: in the El Indio Belt, Chile-Argentina; *Barrick Exploration* (UWA, commenced 2015) See *Research highlight p. 59-60*.

Anthony Lanati (PhD): Petrology, geochemistry and origin of the shoshonites; APA1 (MQ, commenced 2018)

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; *iMRTPS* (MQ, part time, commenced 2010)

Guoliang Li (PhD): Joint inversion of multiple seismic data for Basin structures; *iMRTP* (MQ, commenced 2017)

Jiangyu Li (PhD): Proterozoic thermal history of NE Australia: New Insights into Nuna assembly and breakup; *CIPRS, CSC* (CU, commenced 2016)

Shaijie Li (PhD): Isotopic dating oil generation and charge events in Canning (Australia) and Sichuan (China); *CIPRS* (CU, commenced 2015)

Kai Liu (PhD): The tectonic evolution of the paleo-Pacific Ocean in the Eastern Central Asian Orogenic Belt during the Mesozoic: Constraints during magmatism and detrital zircons; *CSC CIPRS* (CU, commenced 2016)

Yebo Liu (PhD): Paleomagnetism of Proterozoic igneous rocks in Australia and East Antarctica: implications for pre-Pangea supercontinents and supercontinent cycle; *CIPRS* (CU, commenced 2015) See *Research highlight p. 65-66.*

Zairong Liu (PhD): Identifying source rocks and oxidation states in southern Australian volcanic rocks; *CTiMRTP* (MQ, commenced 2017)

Maria Constanza Manassero (PhD): Multi-observable probabilistic inversions for the physical state and water content of the continental lithosphere; *iMQRES* (MQ, commenced 2016)

Erin Martin (PhD): Understanding Neoproterozoic geodynamics through H isotopes in zircon; *APA* (CU, commenced 2016)

Samuel Matthews (PhD): Novel Applications of gravity gradiometry for the detection and monitoring of sequestered CO_2; *CO_2CRC Scholarship* (MQ, submitted 2018)

Shiladitya Mazumdar (PhD): Biomineralization pathways and element partitioning in calcium carbonate; IMRTPS (MQ, commenced 2017)

Keith McKenzie (PhD): Magnetic and gravity gradient tensors and the application to the analysis of remanence; *RTP* (MQ, commenced 2015)

Uvana Meek (PhD): Melt metasomatism within the lower crust; *RTP* (MQ, commenced 2016)

Stephanie Montalvo Delgado (PhD): Compositional modification of zircon at the nanoscale; *CIPRS* (CU, commenced 2016)

Jonathan Munnikhuis (PhD): Microchemical and microstructural evolution of fluid and melt transfer in deep crustal shear zones; *iRTP* (MQ, commenced 2017)

Thusitha Nimalsiri (PhD): Gravity and magnetic response of the Marulan Supersuite, focusing around the Yerranderie Area; *iMRTPS* (MQ, commenced 2016)

Brendan Nomchong (PhD): The origin of clotty-textured (thrombolitic) microbialites at the rise of atmospheric oxygen: The c. 2.4 Ga Turee Creek Group, Western Australia; RTP (UNSW, commenced 2017)

Adam Nordsvan (PhD): Sedimentology and provenance of the NE Australian Proterozoic basins to understand the supercontinent Nuna; *APA* (CU, commenced 2016)

Sinan Özaydin (PhD): Measuring the mantle hydrogen content of cratons by implementing the magnetotelluric method; IMRTPS (MQ, commenced 2018)

Zsanett Pintér (PhD): The composition of melts in the incipient melting regime; *IMRTPS* (MQ, commenced 2016) See *Research highlight p. 49, 70.*

Greg Poole (PhD): Permian magmatism in an early Andean metallogenic belt, Cordillera Frontal, Argentina; *APA* (UWA, commenced 2015)

Carla Raymond (PhD): Archaeometric Investigations of Egyptian Artefacts Using Novel Techniques; MRTPS (MQ, commenced 2018)

Valerie Roy (MSc): Hydrogeological and hydrogeochemical study of the Peak Hill-Horseshoe Deposit, Capricorn Orogen to identify mineral system footprints; *RTP* (UWA, commenced 2015)

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

Sarath Patabendigedara (PhD): Quantifying the effects of surface and bulk proton transport in mantle materials; *IMRTPS* (MQ, commenced 2016)

Georgia Soares (PhD): A moment in time; the exploration of life that flourished after the Great Oxidation event 2.4Ga; *RTP* (UNSW, commenced 2017)

Dennis Sugiono (PhD): Multiple sulfur Isotope analysis in Kanowna Belle Deposit; *SIRF, Northern Star (Kanowna) Pty Ltd* (UWA, commenced 2017) *Pictured below: Dr Gleb Pokrovski (CNRS, France), Prof Georges Beaudoin (Université Laval, Canada), CET PhD candidate Dennis Sugiono studying core.*

Sahand Tadbiri (MSc): The geometry and kinematics of hydrothermal veins in the c. 3.5 Ga Dresser Formation, North Pole Dome, Western Australia; *FP4* (UNSW, commenced 2015)

Bronwyn Teece (PhD): Organic geochemistry of complex life at the rise of atmospheric oxygen; *RTP* (UNSW, commenced 2018)

Rick Verberne (PhD): Trace element distribution and mass transfer processes in Rutile; *CIPRS* (CU, commenced 2016)

Marina Veter (PhD): Calibration of geochemical *"scouts"* for mantle processes; *IRTPS* (MQ, commenced 2017)

Silvia Volante (PhD): Palaeo- to Mesoproterozoic structural and metamorphic evolution of NE Australia and implications for the assembly of the supercontinent Nuna: Multi-scale analytical approach to decrypt ancient signatures; *CIPRS* (CU, commenced 2016)

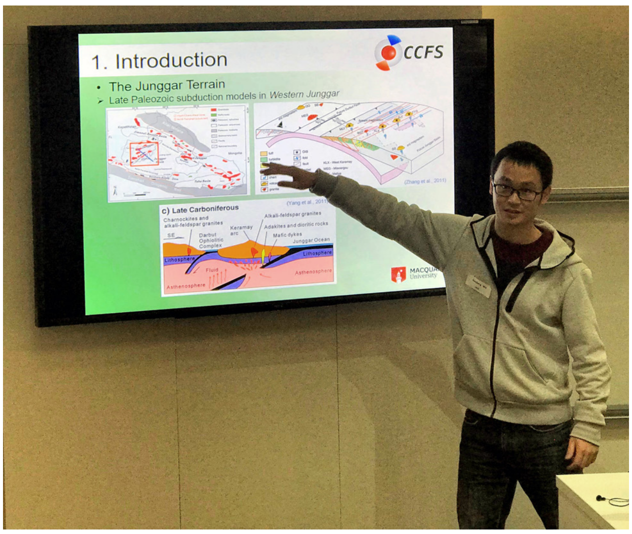
Alexander Walker (PhD): Trace elements and sulfur isotope signatures from sulfides in mineralised and unmineralised environments within the Albany-Fraser Orogen, Western Australia; *CIPRS* (CU, commenced 2016)

Chong Wang (PhD): Paleomagnetism of mafic dykes from eastern North China Craton, and implications for Proterozoic paleogeography; *CIPRS* (CU, commenced 2017)

Chengyuan Wang (PhD): Modification of mantle lithosphere: reaction between recycled carbonate melt and mantle peridotite; *CTIMRTPS* (MQ, commenced 2018)

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

Shucheng Wu (PhD): The geodynamic setting of the Western Junggar region during the Late Paleozoic: evidence from seismic tomography; *IMRTPS* (MQ, submitted 2018) See *Research highlight p. 56-57. Pictured below: June 2018 MQ HDR Presentation Day.*



Bo Xu (PhD): Mantle-Derived Igneous Rocks from Southern Tibet: Nature and Evolution of the Lithospheric Mantle and Implications for Mineralization from Subduction to Collision; *CFIMRTPS* (MQ, submitted 2018)

Anqi Zhang (PhD): Joint inversion of multiple geophysical data sets to constrain the evolution of the lithosphere beneath the Junggar and Tianshan, NW China; *CTIMRTPS* (MQ, commenced 2018)

Infrastructure and technology development

CCFS links three internationally recognised concentrations of analytical geochemistry infrastructure: GEMOC's Geochemical Analysis Unit (Macquarie University, reorganised in 2016 as MQGA) 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 GeoAnalytical facilities contain:

- a Cameca SX-100 electron microprobe
- a Zeiss EVO MA15 Scanning electron microscope (with Oxford Instruments Aztec Synergy EDS/EBSD and Horiba HCLUE spectral cathodoluminescence detector)
- Scanning X-ray spectrometer M4 Tornado from Bruecker
- three Agilent quadrupole ICPMS (industry collaboration; one 7500cs; two 7700cx)
- two Nu Plasma multi-collector ICPMS (one decommissioned in June 2015)
- a triple quad (Q3) ICP-MS 8900 (installed December 2017)
- a Nu Plasma II multi-collector ICPMS (installed in June 2015)
- a Nu Attom high resolution single-collector sector field ICPMS
- a Thermo Finnigan Triton TIMS
- a Photon Analyte LSX213nm laser ablation system (installed December 2017)
- two Photon Machines Excite Excimer laser ablation systems
- a Photon Machines Analyte G2 Excimer laser ablation system
- a Photon Machines Analyte198 Femtosecond laser ablation system
- a PANalytical Axios 1kW XRF with rocker-furnace sample preparation equipment
- a Vario El Cube CHNS elemental analyser
- an Ortec Alpha Particle counter
- a New Wave MicroMill micro-sampling apparatus
- a ThermoFisher iN10 FTIR microscope
- a Horiba LABRAM HR Evolution confocal laser Raman microscope
- a 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.

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

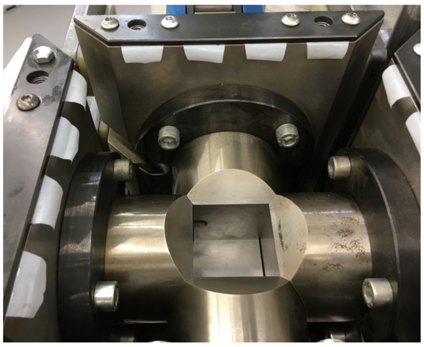
This facility was built up to fulfil the vision of providing spatially controlled high-resolution analysis and imaging of trace elements and isotopic abundances *in situ*, analogous to the then routine capabilities of the mature technology of the electron microprobe for major elements in geological materials. This unique vision and approach enabled benchmark technology and *in situ* analytical methodology milestones in GEMOC starting with trace elements in mantle minerals from the mid-1990s, Hf isotopes in zircon from 2000, and Re-Os in mantle sulfides and alloys also from 2000. This distinctive *in situ* approach sparked research into new ways of understanding earth processes and identified GEMOC, then CCFS, as the leading geochemical facility for such applications, and distinguished it from outstanding analytical laboratories that continued to undertake bulk analytical approaches. The new Decadal Plan for Earth Sciences prepared by the Australian Academy of Science National Committee of Earth Sciences has identified the continuation of *in situ* analysis as the preferred direction for geochemical analytical applications for industry and academia over the next 10 years.

This facility is based on *in situ* imaging and microanalysis of trace elements and isotopic ratios in minerals, rocks and fluids. The Facility for Integrated Microanalysis 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*').

The FIM has been in operation since mid-1999. Major instruments were replaced or upgraded in 2002-2004 through the $5.125 million DEST Infrastructure grant awarded to GEMOC, Macquarie University with the Universities of Newcastle, Sydney, Western Sydney and Wollongong as partners. Further enhancement of the facility took place following the award of an ARC LIEF grant in 2010 to integrate the two existing multi-collector inductively-coupled-plasma mass spectrometers (MC-ICPMS) with three new instruments: a femtosecond laser-ablation microprobe (LAM; installed in June 2012); a high-sensitivity magnetic-sector Nu Attom ICPMS (installed in January 2013); an Agilent 7700 quadrupole ICPMS (installed in 2010). In 2012 GEMOC was awarded ARC LIEF funding for a second-generation MC-ICPMS, and a Nu Plasma II was installed in June 2015.

EQUIPMENT FOR HIGH-PRESSURE EXPERIMENTATION

The experimental laboratory was closed in February 2018 for renovation and expansion. In April 2019, two multi-anvil presses were lowered into position through a removable roof. The larger MAX2003 is a cubic anvil set-up (*pictured below*), and is complemented by a Walker module in the smaller 1000 ton-press (*pictured below*). The laboratory is expected to reopen mid 2019.



Cubic anvils MAX2003.

The FP3 870 LP1000 being manoeuvred into position.

The extended laboratory now includes three multi-anvil apparatuses, one diamond-anvil cell and two piston-cylinder apparatuses. Two additional rapid-quench piston-cylinder apparatuses are due for delivery in August 2019. There are also two Griggs apparatuses, and one-atmosphere quench furnaces.

Experimental projects include partial melting of peridotites in controlled volatile-present conditions at mantle pressures, electrical conductivity measurements on mantle minerals and rocks, reaction experiments that juxtapose subducted sedimentary materials with mantle peridotite to study melting behaviour, and the stability of nitrogen-bearing phases at high pressures, including the partitioning behaviour of nitrogen between minerals and melts.

PROGRESS IN 2018:

1. Facility for Integrated Microanalysis

a. Electron Microprobe: Dr Timothy Murphy, appointed in 2017, oversees the electron microprobe. The SX100 was fully refurbished by Cameca engineers (thanks to Nicolas Boutron and Pierre-Yves Corre) in November 2017 and now performs extremely well on a day to day basis. High-quality mapping of amazing microstructures in corundum from Israel (*Griffin et al., CCFS publication #830*) were published in the CAMECA user guide and marketing booklet. The EPMA is being updated with "*Probe*" software developed by John Donovan.

CCFS and AuScope have provided significant funding support and scientific expertise to purchase a Scanning X-ray spectrometer to enable fast scanning and mapping of thin sections and blocks, thus providing a wider and more complete spatial framework for *in situ* analysis. The acquisition and running of this instrument is a joint venture with Professor Damien Gore (Dept. Environmental Sciences). The versatility of this instrument has attracted significant interest from most faculties across Macquarie University, including Arts, and is heavily used by MRes and PhD students. Dr Timothy Murphy is leading a group developing new approaches with this instrument.

b. Laser-ablation ICPMS microprobe (LAM): Dr Yi-Jen Lai manages the extensive LA-ICP-MS and MC-ICP-MS instrument park available at Macquarie. CCFS Research Associate Yoann Gréau provided invaluable technical help and expertise, with CCFS technical and research staff Romain Tilhac and Hadrien Henry providing generous assistance for users.

The Photon Machines Excite/G2 laser system and Agilent 7700 ICPMS are used for *in situ* trace element analyses and U-Pb geochronology. The facility was used by 10 Macquarie PhD thesis projects, 6 international visitors, 4 Masters Research students and several in-house funded research projects and industry collaborations. Projects included the analysis of minerals from mantle-derived peridotites, pyroxenites and chromitites, meteorites, unusual types of ultra-reduced phases from volcanic sources and ultra-high pressure terranes, high-grade metamorphic rocks and biominerals.

With the addition of trace gases such as N_2 and H_2 in the ablation gas, Olivier Alard and collaborators have obtained a significant increase in terms of sensitivity (counts per ppb multiplied by 2) and a noticeable decrease in detection limit. This breakthrough allows researchers to investigate: (i) olivine trace element abundances (i.e. higher sensitivity means complete REE patterns can now be obtained), (ii) ultratrace element concentrations and distributions between silicates, sulfides and oxides of rarely investigated elements such as metalloids form the d- and p-blocks elements (e.g. Sn, Sb, Cd , Mo, W …). This technique is now being applied by Marina Vetter (Ph.D.) S. Foley and S. Demouchy (CNRS, Géoscience Montpellier) who visited this year.

The new Q3-ICP-MS (Agilent 8900) was installed in December 2017 and is co-located with the upgraded Nu-Plasma HR. The development of *in situ* Rb-Sr analysis is well underway. Preliminary results will be presented by Lauren Gorojovsky and Olivier Alard at the Goldschmidt conference in August

Fred Fryer (Agilent) demonstrating the ins and outs of the new Agilent Triple Quad ICPMS to the 2018 Geoanalysis delegates.

2019 (Barcelona, Spain). In-house reference materials have been characterised to extend the range of material (matrix) analysed. The team lead by Olivier Alard is also working on other developments for the precise (interference-free) measurement of chalcophile and siderophile elements for precise S-Se and Te analyses by LA-ICP-MS in submarine glasses (L. Gorojovsky MRes).

c. MC-ICPMS: A Nu Plasma II MC-ICPMS was installed in June 2015 and followed the decommissioning of the Nu Plasma 005 after 16 years of service. Although the Nu Plasma II represents a significant advance in its electronics and engineering, much of the fundamental design is adapted from the Nu Plasma I. This enabled a relatively seamless transition of existing methods developed over the past 15 years on the Nu Plasma I. The combination of the expanded collector array (16 Faraday cups and 5 ion counters) and enhanced sensitivity compared to the first-generation Nu Plasma instruments has enabled the refinement of several *in situ* techniques pioneered at GEMOC, Macquarie.

Montgarri Castillo-Oliver and Yoann Gréau have refined the measurement of *in situ* Sr isotopes in carbonate and clinopyroxene by LA-MC-ICP-MS. New results are under review.

The *in situ* measurement of U-Pb isotopes in zircon using the combination of the femtosecond laser system and the Nu Plasma II was a world first, with preliminary results reported at the Goldschmidt Conference in Prague, August 2015 (*N.J. Pearson, W.J. Powell, Y. Gréau, R.C. Murphy, J.L. Payne, E. Belousova, W.L. Griffin and S. Y. O'Reilly 2015. U-Pb geochronology of zircon by femtosecond laser ablation, Goldschmidt Abstracts, 2015, 2437*). The development of standard operating procedures for *in situ* U-Pb, Re-Os and Rb-Sr isotope measurements is on-going. At the time of the installation of the new Nu Plasma II, the Nu Plasma HR 034 underwent an upgrade with an enhanced interface.

The upgrade increased sensitivity between 1.5 and 2 times, and this contributed to an overall improvement in signal stability, as well as in the precision of single measurements and long-term reproducibility. In 2015 a third Photon Machines excimer laser microprobe was installed and co-located with the Nu Plasma HR 034. After successful installation and commissioning had been achieved and the first experiments with the Femtosecond laser microprobe were completed (and presented at the 2015 Goldschmidt conference), key staff to develop the integrated system and applications were no longer available in 2016.

In addition, CCFS has funded a technology development program employing a Research Associate with a high level of instrument expertise (Dr Yoann Gréau) who, with Dr Olivier Alard (Future Fellow who brought the relevant expertise), has been recently making good progress with the envisaged developments. A novel split-stream approach has been established, involving the simultaneous measurement of Re-Os isotopes on the Nu plasma II and siderophile and chalcophile trace elements on the Agillent 7700. Preliminary results for this world first will be presented at the Goldschmidt conference in Barcelona (see *Research highlight p. 50*). The technique will be used by several of our Chinese, Japanese and European collaborators visiting the laboratories in the first half of 2019. Planned applications are (i) combined U-Pb and Lu-Hf characterisation of zircons and (ii) simultaneous measurements of Sr isotopes and trace elements in silicates and carbonates. New technique strategies involving splitting with the Q3-ICP-MS are also being investigated.

CCFS/GEMOC remains one of the few facilities with the capability to perform *in situ* Re-Os dating of single grains of Fe-Ni sulfides and alloys in mantle-derived rocks. CCFS is translating the full methodology to the Taiwan Academia Sinica laboratories under the auspices of Dr Kuo-Lung Wang, a former GEMOC Research Fellow and CCFS Associate Researcher, to ensure preservation of the associated intellectual property and approach. CCFS Future Fellow Olivier Alard is undertaking studies of mantle sulfides worldwide, integrating *in situ* Re-Os and S isotopes obtained using the LA-MC-ICP-MS (Macquarie University) and ion probe (CAMECA 1280, CMCA Perth), respectively, in collaboration with CCFS Research Associate Laure Martin. This activity was also made possible by the expertise of CCFS Research Associate Yoann Gréau.

The LAM MC-ICPMS is the vehicle to deliver *in situ* high-precision ratio measurements including the analysis of Lu-Hf isotopes in zircon as a major part of *TerraneChron®* (see *http://www.gemoc.mq.edu.au/TerraneChron.html*). *TerraneChron®* applications continued and have been recently up-scaled with the involvement of Dr Romain Tilhac, Nora Liptai and Hadrien Henry to meet the increasing demand for this powerful tool for understanding the evolution of Earth's crust, for isotopic mapping and paleogeophysics, and geochemical remote sensing for the exploration industry.

d. Laboratory development: The clean-room facility established in 2005 continued to be used primarily for isotope separations for analysis on the Triton TIMS and the Nu Plasma MC-ICPMS. Routine procedures continued for Rb-Sr, Nd-Sm, Lu-Hf and Pb isotopes, as well as U-series methods (U, Th and Ra). Isotope dilution routines are being implemented by Peter Weiland and will soon be available.

e. Software: GLITTER (GEMOC Laser ICPMS Total Trace Element Reduction) software is our online 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 AccessMQ and GEMOC provides customer service and technical backup. During 2018 a further 4 full licences of GLITTER were sold, bringing the total number in use to more than 300 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 2018 on a consultancy basis, following his resignation and relocation to Rio Tinto (Melbourne) in early 2016. The current GLITTER release is version 4.4.5 and is currently available without charge to existing customers.

2. X-Ray Fluorescence Analysis

2.1. In November 2012, a PANalytical Axios 1 kW X-ray Fluorescence (XRF) Spectrometer was installed and 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. The major element calibration was modified in 2015 to extend the spectrum of rock types that could be analysed to include Fe-rich samples such as iron ores and laterites. This year the PANalytical was refurbished to maintain high accuracy and precision. Recent round robin tests (GeoPT) show that the PANalytical Axios is performing very well.

2.2. The high performance CHNS elemental analyser from Elementar (Vario El Cube) fitted with an extra IR-detector for low-level sulfur analysis is now in operation and is providing high quality S analyses for projects involving Re-Os isotopic analysis but also the distribution and abundance of volatile elements in the Earth's mantle (PhD students Halimulati Ananuer, Michael Förster). A large suite of reference materials (n≈36), with variable matrix and composition, has been measured and the results have been presented at the Geoanalysis Conference (held at Macquarie University in July 2018). This facility enables us to better estimate whole-rock sulfur contents and thus sulfide abundance crucial to interpreting whole-rock and *in situ* Re-Os isotopic analysis. The reproducibility and low detection limit of the El Cube Elementar analyser yields remarkably accurate measurement of C, H and N at low levels for relatively small samples (i.e. ≈20 mg). See *Research highlight pp. 47-48*)

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. We are testing the performance of the Nu Attom for ultratrace element measurements. 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*).

4. 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.

Steve Craven discussing the applications of the selFrag at the 2018 Geoanalysis Pre Conference workshop.

At the end of 2018 Dr Steve Craven retired. Steve helped building up the selFrag and was of immense value to numerous users in supporting them to get the best possible results for their sample preparation and consecutive analytical sessions at MQGA. This year the selFrag lab is supported by Miss Lauren Robinson, supported by Dr Timothy Murphy and Dr Sean Murray. Dr Steve Craven drops by from time to time to keep his guidance accessible.

5. Spectroscopy

The spectroscopy infrastructure includes an FTIR microscope (ThermoFisher iN10 FTIR microscope; 2008). 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. 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. A Horiba H-CLUE CL monochromator was installed on the Zeiss EVO SEM in January 2016. The monochromator system provides spatially resolved quantitative cathodoluminescence spectra, which allow identification of emitters (e.g. REE in zircons), crystal lattice vacancies (e.g. in diamond) and crystallographic information on how specific elements are incorporated in the mineral crystal lattices (e.g. Mn in aragonite). The new instrumentation is acquiring a growing group of users and is currently part of projects in biomineralisation (HDR student Laura Otter/Prof Dorrit Jacob), diamond growth (Professor Dorrit Jacob) and zircon characterisation (Honorary Associate Dr Christoph Lenz/Dr Elena Belousova).

6. Raman spectrometry

A confocal laser Raman microscope (co-funded by the Macquarie University Strategic Infrastructure Scheme (MQSIS), 2014 and Future Fellowship funding to Professor Dorrit Jacob) delivers information for non-destructive phase-identification and -characterisation at one micrometre spatial resolution. The Raman spectrometer continues to serve the CCFS, the Department and the Faculty. In 2018 the system's capabilities were extended with the purchase of two new laser wavelengths (785 and 432 nm; MQSIS 2017). The instrument continued to grow its user base across the Faculty of Science and Engineering at Macquarie University with users from Chemistry, Physics, Biology, Environmental Sciences as well as users from the Faculty of Arts, Department of Ancient History and the Museum of Ancient Cultures.

In 2019 we plan to extend the applications of Raman Spectrometry towards other areas of scientific research.

These include:

- Earth and Planetary Science, analysis of sulfate speciation in glasses (Dr Oliver Alard and Lauren Gorojovsky)
- Forensics applications, namely ink characterisation on Egyptian papyrus (with Prof Damian Gore and Assoc Prof Malcolm Choat)
- Chemistry, surface enhanced Raman spectroscopy (SERS) of nano particle interactions in serum (Dr Alfonso Garcia-Bennett and Inga Kuschnerus)
- Molecular Science, plasmonic nanostructures for surface-enhanced Raman spectroscopy
- Physics, analysis and mapping of element distribution in wave guides (Prof Simon Gross, Dr Toney Fernandez and Thomas Gretzinger)
- Archaeology, oxide and corrosion analysis of ancient lead scrolls (Prof Simon Clark and Carla Raymond)
- Archaeology, identification of pigments used in Egyptian Mummy Carapace (Dr Karin Sowada and Dr Ronika Powers)
- Archaeology, pigment analysis of Amarna Blue used in Egyptian pottery (Prof Martin Bommas and Penelope Edwell)

7. Computer cluster

Computational geodynamics has been supported throughout this project through a number of in-house machines (Enki and Toto), as well as a Macquarie partnership with NCI, that has enabled large project-based allocations on the national machines. The former resources have enabled the development and testing of in-house computational tools, including Aspect modules (led by Craig O'Neill and former postdoc Siqi Zhang) to model crustal production, impact melting and magmatic melt emplacement, and also Litmod in modelling crustal and lithospheric structure. Our access to the large-scale facilities has enabled production-level simulations and has supported > 5 PhD projects, postdocs and numerous Masters projects.

CMCA TECHNOLOGY DEVELOPMENT AND INSTRUMENTATION

The University of Western Australia's Centre for Microscopy, Characterisation and Analysis (CMCA) is a $50M 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 and NanoSIMS 50L)
- Electron probe microanalysis (JEOL JXA 8530F)
- Focused ion beam (FEI Helios)
- 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 IMS1280 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 IMS1280 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). UWA's Ion Probe Facility can currently lay claim to being the best-equipped SIMS lab in the world, as no other facility has two NanoSIMS alongside an IMS1280.

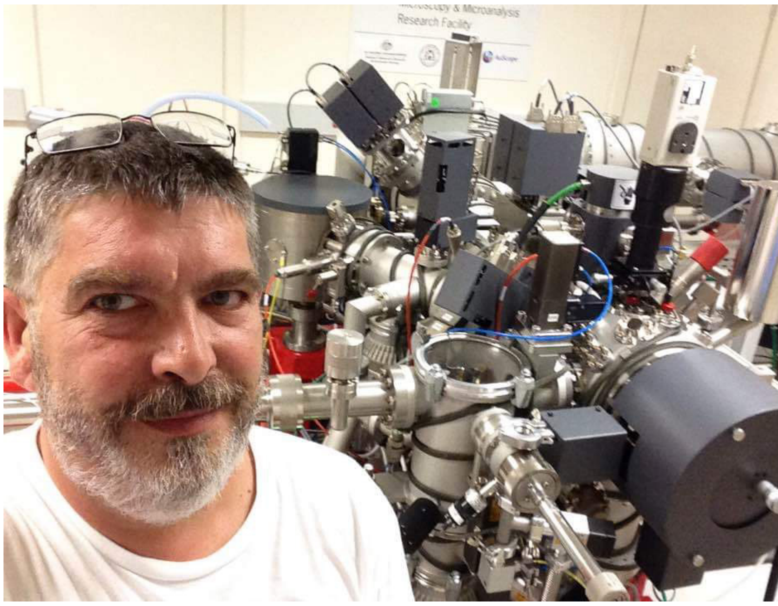
The Ion Probe Facility is a key characterisation component within the ARC Centre of Excellence for Core to Crust Fluid Systems. To ensure the highest levels of quality and throughput, CCFS has provided funding for a Research Associate position within the Ion Probe Facility, to facilitate direct scientific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

PROGRESS IN 2018:

The Ion Probe Facility has continued to contribute to various projects in the context of CCFS. Both 1280 and NanoSIMS laboratories contributed to ~40 individual projects in Earth Sciences, originating from CCFS partners, other Australian research institutes and overseas. 34 journal articles were published in 2018 featuring data acquired using the IMS1280, the nanoSIMS 50 and 50L at UWA, of which 10 were directly related to CCFS projects.

CMCA was successful in winning an ARC LIEF grant for a new EPMA to support the characterisation of minerals and materials for researchers in Western Australia. It is anticipated that the new instrument will be installed in early 2019.

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



Olivier Alard visiting CMCA to use the CAMECA SIMS 1280.

JOHN DE LAETER CENTRE

The John de Laeter Centre (JdLC) is based at Curtin University and forms one of the university's core research centres. The centre houses advanced instrumentation for high-quality chemical, mineralogical and microstructural analysis, and high-resolution imaging. 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.

The JDLC website (http://www.jdlc.edu.au) provides detailed information on the multiple facilities, instruments and research staff that make up the centre.

The components of the JDLC are organised into fourteen major facilities including:

(GAP) Geoscience Atom Probe Facility:
GAP is a node of the Advanced Resources Characterisation Facility (ARCF) funded by a $12,400,000 Science and Industry Endowment Fund grant to Curtin, UWA and CSIRO. The GAP hosts a Cameca LEAP 4000X HR microscope capable of carrying out atom probe tomography (APT), a recent development in the geosciences, that provides high spatial resolution with time-of-flight mass spectrometry to provide 3-dimensional chemical information at the atomic scale. More commonly used to study semiconductors and metal alloys, the GAP is the first atom probe facility in the world to be dedicated to the study of geological materials (http://www.geoscienceatomprobe.org). The ARCF also commissioned a Tescan Lyra focused-ion-beam scanning electron microscope (FIB-SEM), with a Ga+ gun capable of micro-milling out a 100 nm wide needle of a mineral sample prior to APT analysis. The Lyra system is a highly advanced platform for 2D and 3D microanalysis with time of flight mass spectrometry

(TOF-SIMS) and electron backscattered diffraction (EBSD) detectors. By correlating the analytical outputs of both the LEAP and the Lyra instruments, the ARCF provides an unprecedented capability of characterising highly complex materials at the nanoscale.

(DMH) Digital Mineralogy Hub Facility:

The Facility hosts a Tescan Integrated Mineral Analyzer (TIMA GM) - a fully automated, high throughput, analytical Field Emission Gun Scanning Electron Microscope (FEGSEM) for automated analysis of sample composition. TIMA measures mineral abundance, liberation properties, mineral association and grain size automatically on multiple samples of grain mounts, thin sections or polished sections. Applications include ore characterisation, process optimisation, remediation and the search for precious metals and strategic elements. The facility is being used by a broad spectrum of researchers: geologists and archaeologists are using the facility in petrological characterisation, sample classification and lithofacies studies; while geochemists and geochronologists are using the mineral classification outputs as targeting maps for further ion, electron or laser microprobe analysis.

(CEG) Curtin Experimental Geochemistry Facility:

CEG provides a facility for experimental petrology, geochemistry and hydrogeochemistry at pressures and temperatures that range from those at the Earth's surface to those at the base of the Earth's crust. The Facility contains:

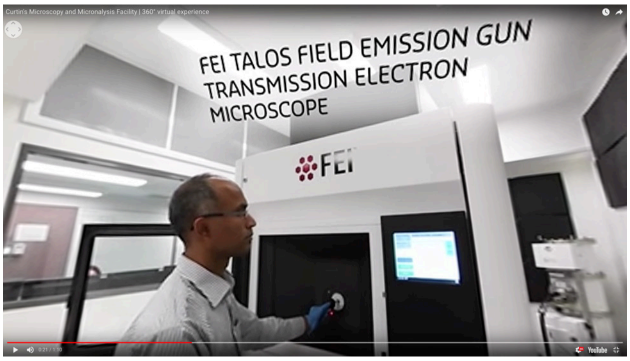
- 2 x 150 ton end loaded piston cylinder presses
- Coretest hydrothermal apparatus
- Assorted furnaces to 1400 degrees C
- Assorted titanium and Teflon-lined bombs

(GHF) GeoHistory Facility:

The GHF houses state-of-the-art laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) equipment, in addition to a low temperature thermochronology laboratory. The LA-ICPMS comprises a Resonetics S-155-LR 193nm excimer laser ablation system coupled to an Agilent 7700x quadrupole ICPMS. The Excimer laser is also coupled to a RESOchron helium analysis line for *in situ* (U-Th-Sm)/He, U-Pb and trace element analysis of single crystals. The facility also has a separate Alphachron helium line with a diode laser and furnace in order to facilitate conventional (U-Th)/He dating on single mineral crystals and larger samples. A Nu Plasma II multi-collector was integrated into the facility to facilitate split stream analysis.

(MMF) Microscopy and Microanalysis Facility:

The MMF houses a broad range of advanced microanalysis instrumentation providing high quality chemical, mineralogical and microstructural information, and high resolution images for research and technical publications. The facility staff have expertise in Materials and Earth Science research which is used to support both academic research and applied projects for the



Take a 360° virtual tour of Curtin's Microscopy and Microanalysis Facility at https://www.youtube.com/watch?time_continue=21&v=mEtg_citH_w.

Western Australian minerals and energy sector. Techniques and instrumentation available include:

- High resolution imaging is available through a FEI Talos F200X transmission electron microscope (TEM), which was commissioned in early 2017 to complement ongoing research at the nanoscale. The system combines high resolution S/TEM and TEM imaging with EDS and 3D chemical characterisation. The instrument is capable of elemental and microstructural analysis at extremely high magnifications.
- Spatially resolved elemental analysis (EDS) and phase and orientation analysis (EBSD) on a Tescan MIRA3 platform - a variable pressure field emission scanning electron microscope (VP-FESEM) that features sensitive EDS and Oxford Symmetry EBSD detectors and integrated software for high quality microstructural analysis of crystalline samples. In 2019 this instrument will be complemented by a new state-of-the-art FESEM with a second Symmetry EBSD system, which will allow EBSD analysis at up to 3000 Hz.
- Quantitative mineral analysis (Q-XRD) - The D8A is an X-ray Diffractometer (XRD) with a copper X-ray source and an automated 45 position sample changer. It features a LynxEye position sensitive detector that is 200 times faster than a conventional scintillator detector, allowing collection of superior data in a short time-frame.
- Ion beam sample manipulation including TEM & TKD lamella preparation (FIB) - 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, allowing for site specific analysis of the surface and subsurface of samples in 2D or 3D.

The MMF also houses a suite of equipment that includes light microscopy, vacuum mount impregnation, manual and automated polishers, mills and coaters that are used to prepare samples for electron microscopy and X-ray diffraction.

(SAXS) Small Angle X-Ray Scattering Facility:
Small angle X-ray scattering can be used to characterise the size, shape and distribution of objects between 1 and 100 nm. In 2016, LIEF funding was used to upgrade the instrumentation in the facility. The WA SAXS facility houses a Bruker NANOSTAR SAXS instrument comprising an Excillum MetalJet high-intensity X-ray source, in-vacuum specimen chamber, and a two-dimensional photon counting detector, capable of covering a q-range of 0.008 - 1.25 Å-1.

(SHRIMP) Sensitive High Resolution Ion Micro Probe Facility:
The SHRIMP are large mass spectrometers that allow *in situ* isotopic and trace element micro-analysis of complexly zoned minerals in grain mounts and thin section plugs, with a spatial resolution of 5-20 microns. 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 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. SHRIMP II is fitted with a Cs source, electron gun and 5 channel M/C.

(SMS) SelFrag & Mineral Separation Facility:
A SelFrag facility, supported by an ARC LIEF grant, has been installed within the Department of Applied Geology at Curtin University. High voltage electrodynamic disaggregation of materials in gram- to kilo-scale batches, along with downstream mineral separation processing, to deliver mineral concentrates, separates, mounts for SHRIMP and LA-ICPMS analysis. 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.

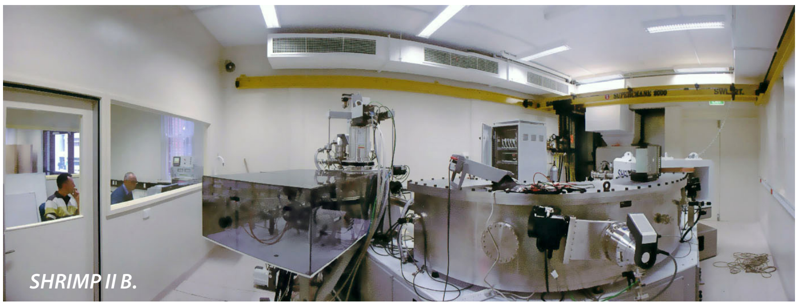
(TIMS) Thermal Ionisation Mass Spectrometry Facility:
The TIMS Facility provides highly accurate and precise measurements of the isotopic composition of elements using TIMS TritonTM instrument, including sample preparation in a clean, contamination-free environment. The Triton is equipped with a 21-sample 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. The facility has recently installed a Thermo Scientific Triton™ mass spectrometer, facilitating a new range of geochemical, geological and environmental research applications.

(TRACE) TRACE Research Advanced Clean Environment Facility:
This consists of a ~400 m^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.

(WAAIF) Western Australian Argon Isotope Facility:
This is located at Curtin and is equipped with A MAP215-50 mass spectrometer and an Argus VI Multi-Collector Noble Gas Mass Spectrometer with a low-blank automated extraction system coupled with a New Wave Nd-YAG dual IR (1064 nm) and UV (216 nm) lasers, electromultiplier detectors and Niers sources. The ultra-violet laser is capable of high-resolution (up to 10 µm beam size) ablation of any mineral, allowing detailed analysis of individual mineral grains. The $^{40}Ar/^{39}Ar$ method is used to date a myriad of geological events such as volcanism, tectonic plate movements, mountain building rates, sediment formation, weathering and erosion, hydrothermal fluid movements, and alteration and diagenesis of minerals.

(WA-OIG) WA Organic and Isotope Geochemistry Facility:
WA-OIG is an internationally-recognised group contributing to world-class research in the fields of organic and stable isotope geochemistry, paleogenomics and geomicrobiology. Available techniques are listed here: http://jdlc.edu.au/wa-organic-and-isotope-geochemistry-facility-wa-oig/.

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


SHRIMP II B.

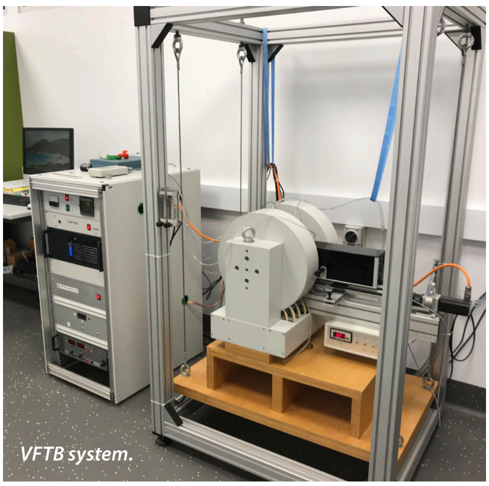
WESTERN AUSTRALIA PALEOMAGNETIC AND ROCK-MAGNETIC FACILITY

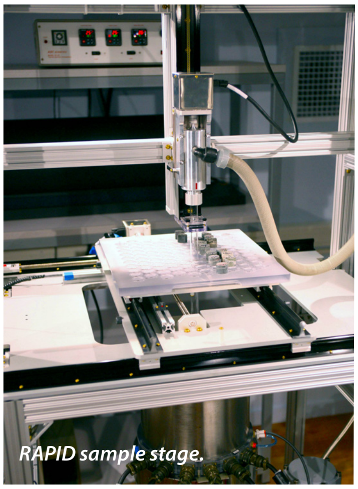
The Western Australia Paleomagnetic and Rock-magnetic Facility is a national research infrastructure supported by the Australian Research Council and collaborating institutions including Curtin University, the University of Western Australia (UWA), the Australian National University, Macquarie University and University of Queensland. The facility was established at UWA in 1990 by CCFS CI Z.X. Li, and has been progressively upgraded over the years. The facility is now completely housed in purpose-built laboratories on Curtin University's Bentley campus.


Inside the Shielded Room.

A significant component of the facility is the magnetically shielded room (constructed in mid-2015 by Dr Gary Scott's team) which provides a 20m^2 laboratory space with ambient magnetic fields less than 0.5% of the local geomagnetic field. Within this shielded room are: a 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system), an AGICO JR-6A spinner magnetometer, and ASC TD-48SC and MAGNETIC MEASUREMENTS thermal demagnetisers. An earlier model 2G 755 cryogenic magnetometer, which underwent repair and upgrade during 2017-18, will be installed within the shielded room during the first half of 2019.

Other apparatus are housed in the renovated laboratory spaces surrounding the shielded room and include: a MAGNETIC MEASUREMENTS MMPM5 pulse magnetiser, an AGICO MFK-1FA Kappabridge, and the Petersen Instruments Variable Field Translation Balance (VFTB). In mid-2018 both the Kappabridge and VFTB were upgraded to bring them up to the current state-of-the-art. A temperature-susceptibility (K-T) module was added to the Kappabridge and a full electronics upgrade was performed on the VFTB system, improving the sensitivity and response time, as well as providing additional functionality (First Order Reversal Curve measurement). An additional module has also been recently installed on the RAPID system to enable acquisition, and subsequent measurement, of Isothermal Remanent Magnetisation (IRM).


VFTB system.


RAPID sample stage.

The recent purchases, upgrades and co-location of all instruments represent a major enhancement to the productivity and capabilities of the facility. Apparatus in the facility include:

- a 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system) and other accessories (including; AF coils, susceptibility meter, ARM and IRM modules)
- an earlier model 2G 755 cryogenic magnetometer upgraded to a 4K DC SQUID system (plus a recent upgrade carried out by 2G enterprises, including the repair of the lightning-damaged cold head)
- an AGICO JR-6A spinner magnetometer
- 1x MMTD80, 2x MMTD18 and a TD-48-SC thermal demagnetiser
- a Petersen Instruments Variable Field Translation Balance (VFTB)
- an AGICO MFK-1FA Kappabridge with K-T capacity
- a MAGNETIC MEASUREMENTS MMPM5 pulse magnetiser

The facility supports a wide range of research topics, including reconstruction of global paleogeography (the configuration and drifting history of continents) through Earth's history, reconstructing the evolving geomagnetic field (e.g. paleointensity) through time, analyses of regional and local structures and tectonic histories, dating sedimentary rocks and thermal/chemical (e.g. mineralisation) events, studying past climate changes, and orienting rock cores from drill-holes.

A national workshop on paleomagnetism, rock magnetism and their applications to tectonics, paleoclimate research, and Earth resource exploration will be conducted in February 2020. It will include a tour of the facilities along with training on the operation of all instruments for potential users of the laboratory.

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 "*Infrastructure and 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.uncoverminerals.org.au/

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 2018

- *TerraneChron*® studies (see *p. 91* 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 32,000 zircon U-Pb and Hf-isotope analyses) in the Macquarie laboratory allows unparalleled contextual information in the interpretations and reports provided to industry.

  In 2018, MQ Faculty of Science highlighted *TerraneChron*® in the *ERA Engagement and Impact exercises.*
- The Distal Footprints of Giant Ore Systems: UNCOVER Australia (supported by CSIRO ex Science & Industry Endowment Fund (SIEF), MRIWA 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 CCFS collaboration with Shefa Yamim (A.T.M.) Ltd. (Akko, Israel) continued and expanded in 2017. Bill Griffin and Sue O'Reilly visited Israel in January to give talks at the annual congress of the Israeli Geological Society (IGS) in Eilat. There was also a very active and vibrant poster session. Following the meeting they returned to the Mt Carmel area to examine and sample several localities of the Cretaceous volcanic rocks, and to visit the alluvial exploration sites under the guidance of Dr John Ward, an expert on alluvial mining. Laboratory work on the remarkable super-reduced mineral associations continued, including collaboration with Prof Martin Saunders in the TEM lab at CMCA in Perth.
- CET held their annual "*Corporate Members Day*" on the 27th of November 2018, to showcase its research to its Corporate Members. The day provided an audience of over 70 representatives from CET Member companies with the opportunity to discuss the innovative work of the CET, including its involvement in CCFS, and gave CCFS ECR and postgraduate students a chance to interact with industry. Posters and poster presentations by CET staff and students showcased the width and breadth of research activities. CCFS CI, Marco Fiorentini, presented a talk on *"The metallogenic DNA of the continental lithosphere"*.
- 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-licensing agreement with Minerals Targeting International accommodates Dr Graham Begg's role and access to GLAM IP (in relationship to Macquarie, BHP Billiton and the GLAM project) as Director of this company. Dr Begg spent significant research time at GEMOC through 2018 as part of the close collaborative working pattern for this project.

  In 2018 Matthew Smith, an MQ undergraduate internship student supervised by Elena Belousova, participated in a project in collaboration with Minerals Targeting to date the Donkerhuk Granite, Damara Orogen, Namibia. Matthew was mentored by Elena and Romain Tilhac from the *TerraneChron*® team. Matthew prepared a detailed report on the age and possible emplacement mechanisms of the granite.
- The Linkage Project "*Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia*" continued between CCFS Associate Investigator Elena Belousova, the University of Tasmania, ANU, the Geological Survey of NSW, Geoscience Australia, Rio Tinto Limited, Alkane Resources Ltd, Sandfire Resources Nl, IMEX Consulting, Evolution Mining Limited, Heron Resources Limited and the Department of State Growth. The project aims to look at ore deposits and the tectonic evolution of the Lachlan Orogen in SE Australia.

  The outcomes of this project will be used to identify areas of high potential for economically valuable ore deposits, enabling more efficient prioritisation of mineral exploration efforts in South-Eastern Australia.
- 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. It played a significant role in Montgarri Castillo-Oliver's PhD study of Angolan kimberlites, carried out in collaboration with the mineral exploration industry in Angola.
- Industry partners provided mentoring and both logistical and financial support for CCFS postgraduate research projects in 2018. Participating organisations include: BHP Billiton (BHP Chile Inc.), Barrick Exploration (Compania Minera Barrick Chile Ltd.), Northern Star (Kanowna) Pty ltd., Teck Resources Ltd, CSIRO, ANSTO and MRIWA. See *CCFS Postgraduates* (*p. 72*) for a full list of postgraduate projects.
- Industry visitors spent varying periods at Macquarie, Curtin and UWA (CET) in 2018 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.
- CCFS publications, preprints and non-proprietary reports are available on request for industry libraries.
- CCFS participants were prominent in delivering keynote and invited talks and workshop modules, and convening sessions relevant to mineral exploration at national and international industry peak conferences in 2018 (see Abstracts, *Appendix 6*).

A full list of previous CCFS publications is available at http://ccfs.mq.edu.au/Publications/Publications.html


TerraneChron®
A new tool for regional exploration for minerals and petroleum
GEMOC
CCFS
Based on zircon analyses
Efficient and cost-effective
Identifies regional tectonic events
Dates magmatic episodes
Fingerprints crust reworking and mantle input (fertility)
Contact: Elena Belousova, Bill Griffin or Suzanne O'Reilly
ARC CoE CCFS & GEMOC National Key Centre
Department of Earth and Planetary Sciences
Macquarie University,
NSW 2109, Australia
MACQUARIE University
www.gemoc.mq.edu.au/ www.ccfs.mq.edu.au/
What is TerraneChron®?
The methodology was developed by GEMOC to provide rapid, cost-effective characterisation of crustal history on regional (10-1000 km²) scales. It is based on U-Pb, Hf-isotope and trace-element analysis of single zircon grains by laser-ablation ICPMS (single- and multi-collector) methods.
• U-Pb ages, with precision equivalent to SHRIMP
• Hf isotopes trace magma sources (crustal vs juvenile mantle input)
• Trace elements identify parental rock types of detrital zircons
What kind of samples?
• Regional heavy-mineral sampling (modern drainages: terrane analysis)
• Sedimentary rocks (basin analysis)
• Igneous rocks (dating, specialised genetic studies)
Applications to mineral exploration
• Rapid assessment of the geology in difficult or poorly mapped terrains
• "Event Signatures" for comparison of crustal histories from different areas
• Identify presence/absence of key rock types (eg Cu/Au porphyries, A-type granites….)
• Prioritisation of target areas
Applications to oil and gas exploration
In provenance studies, the information from Hf isotopes and trace elements provides a more detailed source signature than U-Pb ages alone.
• TerraneChron® defines the crustal history of the source region of the sediment
• Changes in direction of basin filling track regional tilting, subsidence
• Stratigraphic markers in thick non-fossiliferous sediment packages
• Proven applications in the North Sea

CURRENT INDUSTRY-FUNDED COLLABORATIVE RESEARCH PROJECTS

These are brief descriptions of 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. AccessMQ Limited, at Macquarie).

CCFS industry collaborative projects are designed to develop the strategic aspects and applications stemming from the fundamental research programs; 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. The basic research strands that have given rise 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*®) have been developed as regional isotopic mapping tools for integration with geophysical modelling.

This integrated approach, has been widely adopted by a significant proportion of the mineral exploration industry and has resulted in granting of licence to use methodologies developed. CCFS Chief and Associate Investigators, collaborating researchers and Board members have been instrumental in shaping UNCOVER Australia (https://www.uncoveraustralia.org.au/) and in shaping the 2017 AMIRA "*Undercover Roadmap*" (ROADMAP). Indeed the 4-D Lithosphere Mapping approach, established by GEMOC and CCFS with industry partners, forms the robust conceptual basis for UNCOVER, contributed significantly to the AMIRA Roadmap process, and has become part of the vernacular in smart exploration strategies.

CCFS PROJECTS FUNDED BY INDUSTRY (INCLUDING ARC LINKAGE)

Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia	***Linkage Project (LP160100483)*** ***Industry Collaborators: Rio Tinto Limited; Alkane Resources Ltd; Sandfire Resources Nl; IMEX Consulting; Evolution Mining Limited; Geoscience Australia; Geological Survey of NSW; Heron Resources Limited; Department of State Growth*** ***CIs: Meffre, Whittaker, Norman, Cracknell, Belousova, Collins, Arundall, Cooke, Maas, Huston, Musgrave, Greenfield*** ***Summary:*** This project aims to develop and test models to evaluate past tectonic processes and configurations in South-East Australia, using both new and existing geological, geophysical and isotopic data. Over the past 550 million years, plate tectonic processes have formed metal-rich mineral deposits in South-East Australia. The project will identify areas of high potential for economically valuable ore deposits, enabling more efficient prioritisation of mineral exploration efforts. This is expected to increase the probability of significant ore deposit discoveries leading to national economic benefit.
Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP)	***Linkage Project (LP170100233)*** ***Industry Collaborators: CSIRO, Geological Survey of NSW Geological Survey of South Australia, Geoscience Australia, Northern Territory Geological Survey*** ***CIs: Regenauer-Lieb, Afonso, Clark, Thiel, Czarnota, Poulet, Jones, Walsh*** ***Summary:*** This project aims to provide a newly developed science approach to the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP). AusLAMP provides unparalleled geophysical information aimed at unravelling the tectonic history of the Australian continent and its mineral potential. The project will use thermodynamically based geodynamic simulators to jointly analyse and quantify intraplate deformation. This will illuminate the cause of driving fluid flow thorough the lithosphere, mineralisation phenomena, their datasets and geometries, and dynamic aspects of the processes driving mineral systems.

Enabling 3D stochastic geological modelling	***Linkage Project (LP170100985)*** ***Industry Collaborators: AUSCOPE, British Geological Survey, Department of Planning and Environment, Geological Survey of Canada, Geological Survey of South Australia, GSWA, Geoscience Australia, Northern Territory Geological Survey, Research for Integrative Numerical Geology, Georessources - Université de Lorraine, RWTH Aachen University of Technology, Germany*** ***CIs: Ailleres, Jessell, de Kemp, Caumon, Wellmann, Armit, Droniou, Lindsay, Cui, Betts, Cruden, Kemp, Gessner, Spampinato, Harrison, Kessler*** ***Summary:*** The project aims to develop technologies to mitigate 3D geological risk in resources management. The project is expected to create new knowledge and methods in the field of 3D geological modelling through the innovative application of mathematical methods, structural geology concepts and cutting-edge probabilistic programming. The expected outcomes are an enhanced capability to model the subsurface, characterise model uncertainty and test multiple geological scenarios. This enhanced capability is extremely important for the future of Australia's subsurface management; including urban geology and our continuously growing sustainable resources industry (including water).
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.
Multiple sulfur isotope systematics of the Kanowna Belle Gold deposit	***Industry Collaborator: Northern Star Resources Ltd*** ***CIs: LaFlamme, Thébaud, Fiorentini*** ***Summary:*** This study aims to 1) resolve the paragenetic sequence of veins in relation to the mineralisation, intrusions and structural episodes of the Kanowna Belle deposit, Western Australia, 2) apply the quadruple sulfur isotope techniques in conjunction to the vein paragenesis and structural events to understand the evolution, possible source changes of hydrothermal fluids and their relationship to the tectonic framework changes in Archean orogenic gold deposits, and 3) carry out in-depth mineral scale quadruple sulfur isotope analysis incorporated with other geochemical analyses to interpret how gold is transported and precipitated in Archean orogenic gold systems.
Geochemical appraisal of mafic and ultramafic rocks from a series of IGO prospects along the Albany-Fraser Belt of Western Australia	***Industry Collaborators: IGO Independence Group*** ***CI: Fiorentini*** ***Summary:*** This study will carry out a comprehensive geochemical appraisal of mafic and ultramafic rocks from a series of IGO prospects along the Albany-Fraser Belt of Western Australia. A selected number of CA-IDTIMS high-precision analyses will be done to unravel the timing of emplacement and crystallisation of mafic magmas that display geochemical features that reflect fertility for orthomagmatic mineral systems.
Predictive genetic study of the Nova-Bollinger deposit and host-rocks	***Industry Collaborators: IGO Independence Group*** ***CIs: Barnes, Fiorentini*** ***Summary:*** This study aims to determine the multiple sulfur isotope architecture of the Nova-Bollinger deposit in the Albany-Fraser Belt of Western Australia by spatially mapping tracer S isotopes across the orebody as well as country rocks.

Improving zircon morphology and chemistry as a tool for assessing and ranking the relative prospectivity for Cu porphyry deposits in "*greenfield*" terrains	***Industry Collaborator: BHP Billiton*** ***CIs: Fiorentini, Loucks*** ***Summary:*** A substantial exploration and research problem remains outstanding: although all porphyry copper ore-forming magmas are adakites (distinguished from ordinary calc-alkalic arc magmas by high Sr/Y ratio and spoon-profile rare-earth-element patterns), many adakites are apparently unmineralised or have weak, subeconomic copper mineralisation. Then, how to distinguish a hydrothermally altered adakitic igneous complex that is weakly mineralised or barren from a hydrothermally altered adakitic igneous complex that is likely to contain a major copper deposit? This study is set to address this very question.
The role of whole-lithosphere architecture on the genesis of giant gold systems in the El-Indio region, Chile-Argentina	***Industry Collaborator: Barrick Gold Corporation*** ***CIs: McCuaig, Fiorentini*** ***Summary:*** The overall aim of the project is to establish and link the near-surface, basement and sub-continental lithospheric structures in an integrated structural architecture and geodynamic model for the El Indio-Pascua belt to identify the fundamental controls of the location and formation of giant HS gold deposits. The research will focus on two main objectives: 1. Define the structural framework that acts as the magma/hydrothermal fluids pathway from the deep fertile source region to the shallow-crustal location of the major HS deposits. Specifically, the concept is to build a multi-scale interpretation of the fundamental structural framework and how the conduit structures are linked from surface through the lithosphere. 2. Link the Miocene metallogenic events to the geodynamic evolution of this segment of the Andean subduction system. The aim here is to document the proposed transient nature of the geodynamic evolution and its linkages to metallogenic / mineralisation pulses.
CA-IDTIMS high-precision geochronology	***Supported by Department of Industry Innovation and Science - AusIndustry: Innovation Connections*** ***Industry Collaborator: Panoramic Resources*** ***CI: Fiorentini*** ***Summary:*** This project aims to determine the precise timing of the Ni-Cu-Co-PGE ore-forming process(-es) at Savannah and along the Central Zone of the Halls Creek Orogen, Western Australia. The study builds on the outcomes of the recent MRIWA M459 and M484 projects, which established not only the petrological and geochemical architecture of the Savannah Ni-Cu deposit, but also resolved the ca. 1 Ma difference in the timing of emplacement of the mineralised intrusions through use of the high-precision CA-IDTIMS U-Pb method for geochronology.
Distal footprints of giant ore systems: UNCOVER Australia	***Supported by CSIRO ex Science & Industry Endowment Fund (SIEF)*** ***Industry Collaborators: CSIRO, UWA, CU, 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.
Geology and ore genesis of the Nova-Bollinger Ni deposit, WA	***Industry Collaborator: IGO Independence Group*** ***CIs: Barnes, Fiorentini*** ***Summary:*** This study focuses on unravelling the multiple sulfur isotope architecture of the Nova-Bollinger deposit. Expected outcomes from this work will help to define the ore genesis of the most significant Australian nickel sulfide discovery in decades as well as provide a new framework for the exploration of mafic-hosted systems along the margins of Archean cratons.

Distal footprints of giant ore systems: Capricorn WA case study	***Supported by MRIWA M436*** ***Industry Collaborators: CSIRO, MRIWA, Northern Star Resources Ltd, Thundelarra, Sandfire Resources NL, MMG, Golden Phoenix Resources LTD, Marindi Metals Pty Ltd, Independence Group NL, RNI*** ***CIs: Hough, McCuaig, Reddy, Clark, Fiorentini, Gray, Miller*** ***Summary:*** This study investigates the distal footprint of mineral systems by examining the indelible nature of the mass-independent fractionation of sulfur (MIF-S), which was imparted to different sulfur-bearing reservoirs prior to 2.4 billion years ago, in the Archean eon. This fractionation process led to the unique preservation of this anomalous sulfur isotope signature (as $\Delta^{33}S$) in the Archean sedimentary rock record (*Farquhar et al., 2000*). Subsequently, as this signature was recycled through different geological processes operating at various scales in space and time, we are now in the privileged position to be able to use it as an indelible tracer and marker of different geological processes.
Yilgarn 2020	***Supported by MRIWA M530*** ***Industry Collaborators: Gold Road Resources, BHP Billiton Nickel West, Newmont, Northern Star Resources Limited, Saracen, Evolution Mining*** ***CI: Thebaud, Aitken, Jessell, Occhipinti, Dentith, Hagemann, Kemp, Fiorentini, Smithies, Lu, Gessner*** ***Summary:*** Yilgarn 2020 is a 3-year research-intensive program that integrates priority research and technology activities with complementary data compilation and targeted data acquisition. The research project is articulated into three modules ranging from regional- to camp- and deposit-scale studies applied to both well-mineralised, and less well-endowed areas. The combination of studies conducted on both mineralised and less mineralised areas is critical to evaluate and test the robustness of perceived mineralisation controls derived from the study of well mineralised domains.

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 MEMORANDUM 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:

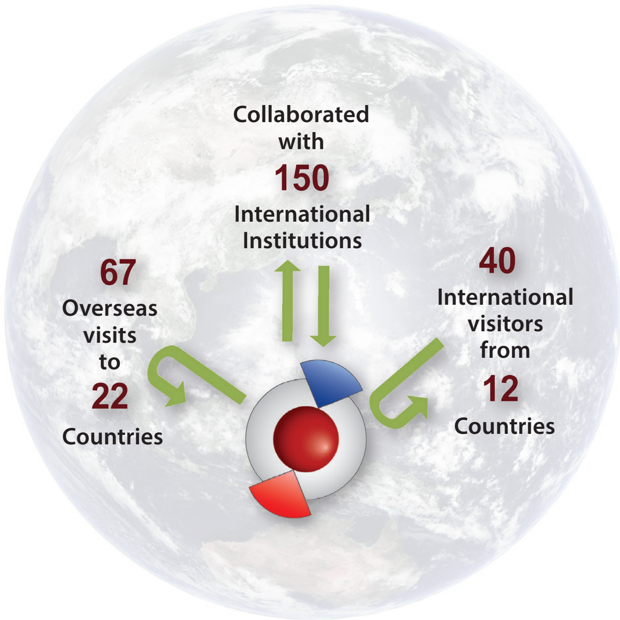
- China University of Geosciences (Wuhan) - 2011 (& Cotutelle)
- Constitution of the International University Consortium in Earth Science - 2012
- University of Science and Technology of China, Hefei - 2012 (& Cotutelle)
- Institute of Geology and Geophysics, China University of Geosciences (IGGCAS, Beijing) - 2014 (& Cotutelle)
- Institute of Tibetan Plateau Research, CAS (Beijing) - 2014
- Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Germany - 2015

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
- Nanjing University, China
- Pierre and Marie Curie University, PARIS VI
- Peking University, China
- São Paulo University, Brazil
- University of Barcelona, Catalonia, Spain
- Universidad de la Republica, Uruguay
- Université Montpellier 2, France
- Université Paul Sabatier, France
- Université Jean Monnet, France
- University of Zaragoza, Spain

2018 COLLABORATIVE ACTIVITY

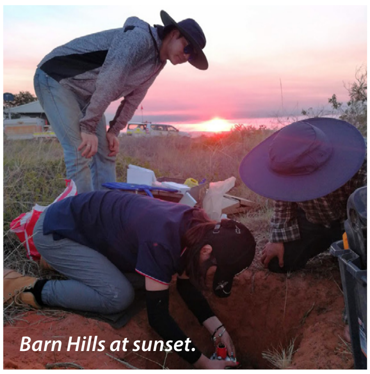


INTERNATIONAL LINKS - 2018 SELECTED HIGHLIGHTS

- A collaborative project between the Institute of Geology and Geophysics, China Academy of Science, Beijing (IGG CAS), CCFS, Geoscience Australia, and ANSIR (Australian facilities for Earth sounding) resulted in a 4-year passive seismological deployment (China-Western Australia Seismic survey - CWAS) along a 900 km profile across Western Australia from Port Hedland to the southwestern border of the Kimberly Craton. The station spacing is 10-15 km, using 80 broadband seismic stations and extends beyond the continent margin in the Canning Basin using ocean-bottom seismometers (CANPASS).

  The Phase 2 installation of the CWAS project was completed successfully in September 2018. Colleagues and students from the Geological Survey of Western Australia, the Institute of Geology and Geophysics, Chinese Academy of Sciences and CCFS Macquarie University put 38 broadband portable seismic stations in the field. These "*in-filled*" the Phase 1 deployment which started recording late 2017. Combining stations from the Ocean-Bottom-Seismic array (CANPASS),

IGG CAS students Chao Lu, Liz Li and visitor Xiangdong Lin installing a temporary seismic station near Pardoo Roadhouse.



Barn Hills at sunset.

early portable deployments by ANU and permanent networks of Geoscience Australia and the German GEOFON program, the CWAS project provides an exciting opportunity to seismically map the crust and lithosphere architecture beneath both onshore and offshore regions of the Canning. This will help us better understand the regional tectonics through time, including, shaping up the continent in the first place, subsequent intracratonic rifting and basin forming in the Paleozoic, late Jurassic sea-floor spreading of the Neotethys Ocean, and the present-day transition from passive margin to active subduction along the continent's northern boundary.

- Delegates from a range of international institutions visited CCFS in 2018 to discuss programs including the exchange of staff, joint research activities and the exchange of students.
- A collaborative research agreement continued with the China University of Geosciences (Wuhan) with funding by the Chinese Scholarship Council (CSC). This grant provides a living allowance and travel between China and Australia for students and visiting scholars. Students and researchers funded by this project will study and work under the project's aims, integrating geological, geochemical, geophysical and experimental techniques to study the structure, composition, geodynamics and metallogeny of the deep lithosphere and beyond.
- Prof Zheng-Xiang Li continued as Co-director of the Australia-China Joint Research Centre for Tectonics and Earth Resources (ACTER). ACTER is a joint research centre led by the Institute for Geoscience Research at Curtin University, and the Institute of Geology and Geophysics of the Chinese Academy of Sciences, with participants from collaborating institutions from the two countries. CET, TIGeR and GEMOC are all Key Australian Partner Institutions (http://tectonics.curtin.edu.au/).

ACTER aims to facilitate: collaborative research and research training in geotectonics and mineral and hydrocarbon resources, the exchange of staff and joint supervision of research students, shared access to analytical facilities, the organisation of joint conferences and annual focused field-based workshops and the exchange of academic materials and information.

ACTER Field Symposium to the Qilian Mountains.

The 2018 ACTER annual field symposium *"Tectonic evolution of the North Qilian Mountains: From Paleozoic oceanic subduction to Cenozoic plateau expansion"* was held in Gansu province, China from the 25th August to the 2nd September 2018. The field trip focused on (1) the Early Paleozoic North Qilian Orogen featuring oceanic subduction and

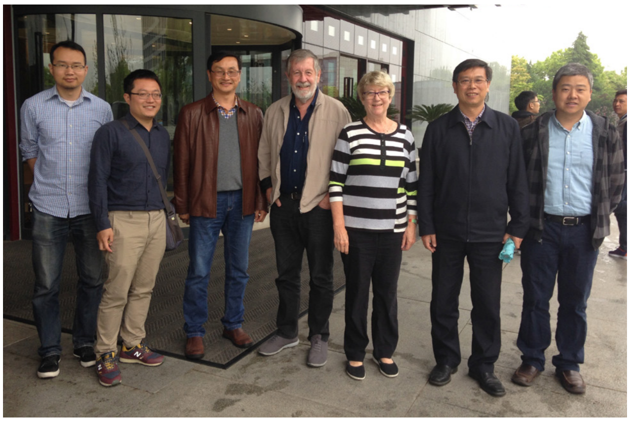
CCFS INTERNATIONAL COLLABORATIVE NETWORK

arc-continent collision, and (2) the Cenozoic fold-and-thrust belt in relation to the uplift and expansion of the Tibetan Plateau. For more information see http://tectonics.curtin.edu.au/acter-2018-field-symposium/.

- In April 2018, Sue O'Reilly, Steve Foley, Bill Griffin and Yingjie Yang travelled to China on a CCFS mission to enhance collaborations and cotutelle relationships. They visited China Academy of Science Guangzhou, China University of Geoscience Wuhan, Institute of Geology and Geophysics, China Academy of Science Beijing, and Nanjing University. Sue O'Reilly also met with Professor Zengqian Hou (Vice-President National Science Foundation of China (NSFC), and in charge of Department of Earth Sciences and Department of Management Sciences under the Ministry of Science and Technology).

  At Guangzhou Institute of Geochemistry (GIG), Steve Foley discussed future collaboration with Eiichi Takahashi, the leader of a new experimental laboratory.

  While in Wuhan Steve met with Yongsheng Liu, co-supervisor of MQ cotutelle student Chengyuan Wang and visiting 2019 PhD student, Mingdi Gao. Another post-doc from Wuhan, Chunfei Chen, will join CCFS in May 2019.



April 2018 visit by CCFS researchers with collaborators from Nanjing University including longstanding CCFS Honoraries Professors Xisheng Xu (DVC Research, Nanjing) and Jinhai Yu.

Formal dinner at China University of Geoscience, Wuhan during CCFS visit for research collaboration in April 2018. Recent CCFS postdoctoral fellow Qing Xiong at lower right.

The Multi-anvil press in Guangzhou Institute of Geochemistry: Stephen Foley and Eiichi Takahashi.

Stephen Foley and Yongsheng Liu in Wuhan.

Professor Hou, Leader of China National Science Foundation delegation to discuss Australia-China Earth Science research collaboration with key government and opposition resource leaders, Geoscience Australia, and ARC administrators and AuScope with Australian Academy of Science representatives (and CCFS participants, Sue O'Reilly and Phil McFadden).

The April 2018 meeting with Professor Hou resulted in very successful high-level meetings with the Secretary and two Deputy Secretaries from the Department of Industry, Innovation, Science (DIIS), Senator Kim Carr (Shadow Minister for Science in 2019), Geoscience Australia, ARC, AuScope and Australian Academy of Science representatives.

- CCFS Director, Professor Sue O'Reilly, is a group leader of one of seven new UNESCO-IUGS IGCP projects, announced on the 21 February 2018, aimed at providing insights on current global issues and supported by the International Geoscience Programme (IGCP) (https://en.unesco.org/news/new-projects-will-explore-geological-record-support-sustainable-development). *"IGCP 662: Orogenic architecture and crustal growth from accretion to collision"* aims to conduct comparative studies of several types of orogens (accretionary and collisional) to better understand the dynamics of Earth's crust, and the genesis and distribution of mineral deposits (metallogenesis). It will include a comparative study of the Central Asian Orogenic Belt (CAOB); one of the world's largest accretionary orogens spanning six nations and evolving over some 800 million years, the Tethyan orogenic belt; the world's youngest extensive collisional and metallogenic belt, and other composite orogens. The project included participants from more than 143 countries with diverse socio-economic and political contexts.

  The First IGCP-662 workshop was held successfully on the 23rd of September 2018. It included a five-day pre-conference field excursion to Dunhuang and Liuyuan in Gansu province, NW China. A two-day workshop and a one-day post-workshop training course in Beijing followed. Sue O'Reilly and Bill Griffin each delivered invited talks and Short Course lectures on Lithosphere Mapping and *TerraneChron*®.

  IGCP-662 project information and upcoming events are available from http://igcp662.org.cn/.

First IGCP-662 workshop.

- The UNESCO-IUGS IGCP Project 648, Supercontinent cycles and global geodynamics continued in 2018. The project brings together a diverse range of geoscience expertise from around the world, including three CCFS CIs, to explore the occurrence and evolution history of supercontinents through time and construct global databases of geotectonics, mineral deposits and the occurrences of past mantle plume events.

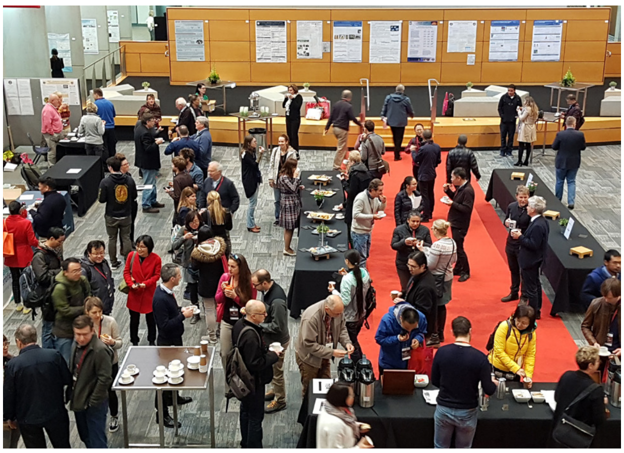
  The 2018 IGCP 648 Field Symposium *"From Rodinia to Pangea: Geodynamics, Life and Climate"* visited the Yichang, Three Gorges Region, China on the 1-9 November 2018. For more information visit http://geodynamics.curtin.edu.au/igcp-648-2018-field-symposium/.

2018 IGCP 648 Field Symposium.

IGCP 648 field symposium, Yichang (photos: Zheng-Xiang Li).

- In July 2018, Macquarie University hosted Geoanalysis 2018. The conference is one of the major international conferences on analytical research in the Earth Sciences and showcased the MQ Geoanalytical facilities and the research in this field at Macquarie University, including the newly installed Thermo Hub and the new Agilent QQQ instrument as its state-of-art instrumentation.

  Besides the sizable number of company exhibits, the conference attracted a large number of international visitors, mostly geologists or chemists specialising in the analysis of geological and environmental materials. The meeting provided an excellent opportunity for CCFS postgraduates to present their research to an international audience. See *Abstracts p. 135*.



International visitors are listed in Appendix 7.

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

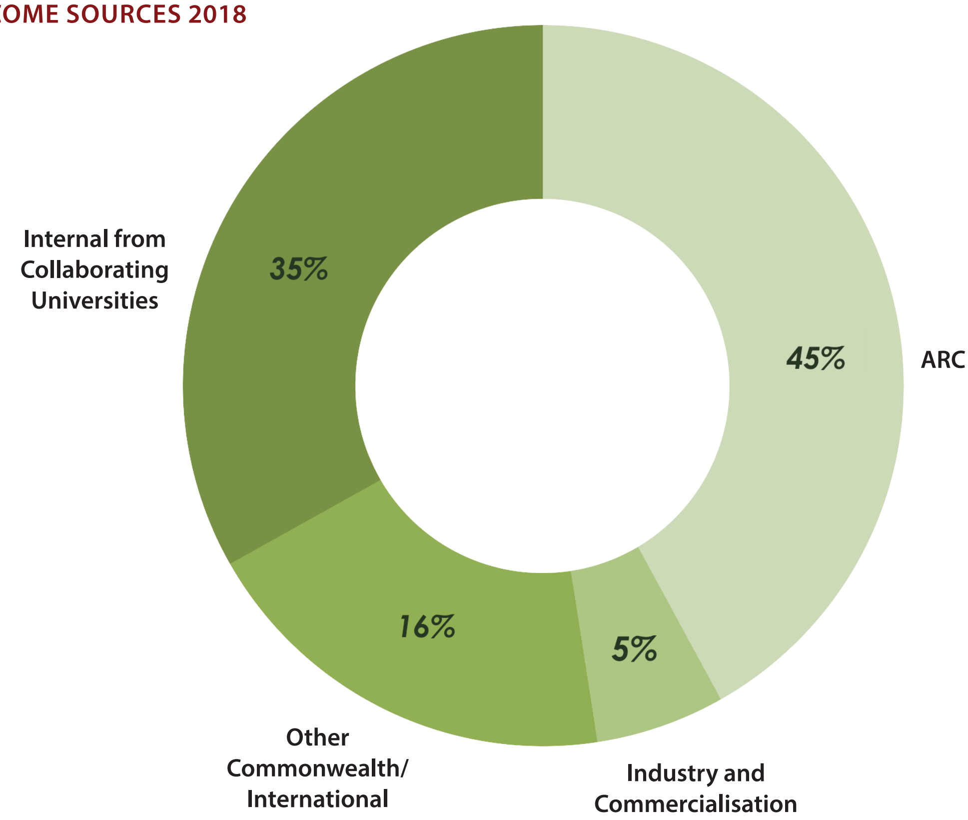
This is an unaudited summary of 2011-2018 income and expenditure. A full, audited statement of detailed expenditure and income is prepared by Macquarie University. No in-kind support is included here.

CCFS Income & Expenditure Statement 2011-2018

Source	2011	2012	2013	2014	2015	2016	2017	2018
INCOME								
ARC	$1,828,350	$2,004,179	$1,971,746	$2,031,333	$1,952,842	$1,986,040	$2,015,831	$0
MQ	$626,705	$1,032,004	$1,822,748	$1,464,360	$1,925,076	$1,621,113	$1,845,829	$1,639,628
UWA	$133,500	$763,500	$415,000	$415,000	$453,539	$415,000	$931,756	$611,873
Curtin	$727,725	$608,055	$851,244	$611,290	$523,292	$1,027,772	$1,133,376	$983,180
GSWA	$150,000	$150,000	$150,000	$150,000	$150,000	$150,000	$185,000	
SLF Income	$500,000							
SLF Interest	$13,744	$12,530	$5,790	$1,811	$336	$405		
ECR Income - ARC	$1,250,000							
ECR Interest		$24,734	$16,118	$6,566	$1,841			
TOTAL	**$5,230,024**	**$4,595,003**	**$5,232,646**	**$4,680,360**	**$5,006,926**	**$5,200,330**	**$6,111,792**	**$3,234,681**
ACCUMULATED FUNDS		$3,702,071	$4,960,194	$5,181,390	$4,776,770	$4,378,094	$4,020,390	$3,042,701
EXPENDITURE								
Salary	$783,390	$1,608,470	$2,263,183	$2,402,327	$2,423,825	$2,828,977	$3,299,846	$1,932,114
Equipment	$90,128	$220,548	$785,851	$512,413	$93,008	$86,061	$44,275	$40,989
Travel	$91,305	$280,795	$388,431	$404,572	$440,158	$398,178	$585,554	$258,999
Maint./Consum.	$42,433	$459,530	$487,255	$494,580	$640,889	$461,139	$383,845	$318,128
Scholarships	$520,697	$767,538	$1,086,730	$1,271,088	$1,807,722	$1,783,678	$2,775,961	$3,011,933
TOTAL	**$1,527,952**	**$3,336,880**	**$5,011,450**	**$5,084,980**	**$5,405,602**	**$5,558,034**	**$7,089,482**	**$5,562,163**
ACCUMULATED FUNDS	$3,702,071	$4,960,194	$5,181,390	$4,776,770	$4,378,094	$4,020,390	$3,042,701	*$715,219

** $715, 219 Institution funds, $0 ARC funds*

INCOME SOURCES 2018



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; https://www.science.org.au/supporting-science/science-sector-analysis/reports-and-publications/searching-deep-earth-vision). CCFS addresses initiatives (ii) - (iii): investigating Australia's lithospheric architecture, 4D geodynamic and metallogenic evolution, and distal footprints of ore deposits.

Appendix 1: Flagship Programs aims and progress for 2018

1. DEEP-EARTH FLUIDS IN COLLISION ZONES AND CRATONIC ROOTS (TARDIS II)

Themes 1, 2 and 3, Early Earth, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

This program investigates the role of fluids in the deep mantle and lithosphere, using studies of kimberlites and other volcanic rocks, xenoliths of mantle and crustal rocks in volcanic rocks, ophiolites, and UHP terrains related to subduction zones. Super-reducing, ultra-high-pressure (SuR-UHP: 400-600 km) mineral assemblages in some 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. The recent discovery of similar ultra-reduced mineral assemblages in ejecta from Cretaceous volcanoes in Israel suggests a previously unrecognised process of interaction between highly reducing deep-mantle fluids and ascending basaltic magmas. We aim to produce an experimentally testable model for the generation of such fluid conditions in the mantle, to quantify constraints on the geochemical and tectonic processes that have produced SuR-UHP assemblages, and to produce a geodynamic model for these processes.

2018 Report

A comprehensive investigation of microstructures and mineralogy in Tibetan ophiolites has defined their evolution, including formation in ancient SCLM within subduction-zone settings, followed by subduction into the upper transition zone and exhumation to the seafloor prior to final emplacement by thrusting during continental collision. Studies of ophiolites in Mexico have revealed similar recycling processes, though not extending all the way to the transition zone. A UHP phase described by us in 2016 from the Luobusa peridotites was successfully synthesised by Prof Luca Bindi (Univ. Firenze) and proved to be an inverse ringwoodite stable only in the Mantle Transition Zone, supporting the subduction-exhumation model for the Yarlung-Zhangbo *'ophiolites'*. Studies on chromitites in ophiolites expanded to Chile, Cuba and Mexico.

Dr Hadi Shafaii Moghadam and his students continued their investigations into the portion of the Tethyan Belt that lies in Iran, integrating field studies, petrology and isotopic geochemistry of granitoid rocks (as probes of the deep crust), volcanic rocks and ophiolites. The evolution of this *'soft collision zone'* can then be compared and contrasted with the *'hard collision'* between India and Asia, exposed in Tibet. The project has established a geochemical and geochronological framework, shown the existence of buried Archean-Paleoproterozoic crust in the Georesources - Université de Lorraine east-central part of the orogeny and defined major magmatic flare-ups (Neoproterozoic and Cenozoic) related to major collisions and subduction.

Studies of the suite of highly reduced minerals in the ejecta from Cretaceous volcanoes in Israel (industrial collaboration with Shefa Yamin Ltd., Akko) led to the development of a model involving the interaction of mantle-derived methane and hydrogen with basaltic magmas in conduits or magma chambers near the crust-mantle boundary. Detailed mineralogical studies included further TEM analysis, in collaboration with Prof Martin Saunders (CMCA, UWA), and single-crystal XRD analysis in collaboration with Italian crystallographers (see *below*). Analyses of microstructures and mineralogy have demonstrated that moissanite in the Israeli ejecta and in Siberian kimberlites has grown from carbon-rich Fe-silicide melts, immiscibly separated from silicate melts. There are clear linkages between the silicide melts that have crystallised SiC and those found within the corundum aggregates found in the Israeli volcanics. This model offers a possible explanation for the wide range of Si isotopes in SiC analysed by SIMS (Perth and Beijing (courtesy of collaborator Prof Li Xian-Hua)). Preliminary noble-gas measurements show that the corundum aggregates contain mantle He, while measurements of gasses included in hibonite aggregates have shown percent levels of hydrogen, consistent with the discovery of the first natural metal hydride (VH_2) coexisting with native vanadium in the hibonite aggregates. The hibonite aggregates were the subject of the first detailed description of one of the important parageneses found at Mt Carmel and included similar material from a still undocumented locality in Argentina (collaboration with Prof Fernando Camara (Univ. of Milan) and Prof Luca Bindi).

The work on other mantle rocks continued, with studies of pyroxenites from SE Australia, the Pannonian Basin in Hungary, Cabo Ortegal (Spain) and the Trinity ophiolite (California). Work continued on kimberlites and diamonds in Angola, Siberia and South Africa, including studies of conventional (S, C, O, N) and unconventional (Mg, Fe) isotopes. A major study on the petrography and Sr-C-O isotopes of carbonates in kimberlites worldwide produced consistent criteria for the identification of primary magmatic carbonates and elucidated their role in kimberlite petrology. In collaboration with Prof A. Perchuk (State Univ. of Moscow) we analysed trace element transport across synthetic basalt-peridotite contacts at high P and T to study melt-rock reaction in open systems. Work on the deep crust and its reworking continued in China, with petrological studies of xenoliths and adakites, and geophysical imaging.

See *Research highlights pp. 34-35, 36-38, 38-39, 42-43, 43-44, 51-52, 53-54, 54-55, 57-59, 63-64, 64, 66, 71.*

Published outputs for 2018

CCFS publications: #958, 974, 978, 992, 993, 1030, 1034, 1054, 1055, 1101, 1106, 1107, 1108, 1124, 1126, 1150, 1156, 1160, 1174, 1179, 1183, 1184, 1192, 1195, 1196, 1197, 1201, 1202, 1205, 1206, 1211, 1212, 1216, 1229, 1244

>25 Conference Abstracts

2. GENESIS, TRANSFER AND FOCUS OF FLUIDS AND METALS

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

AIMS

This program embodies a holistic approach to ore deposit research, acknowledging that the genesis of mineral occurrences requires the conjunction in time and space of three main independent parameters: fertility, lithosphere-scale architecture, and favourable transient geodynamics. In this context, the integrated studies in this Flagship program 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. Our studies test 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 environments where ore deposits can form. This Flagship Program is not commodity-focused but rather looks at the basic commonalities among various mineral systems to unravel the main constraints in the formation of ore systems.

2018 Report

In 2018, the ongoing projects reached some important milestones. Module 1 (Fertility) focused on unravelling the global cycle of metals. Outcomes include the calibration of a new oxybarometer that can be used to evaluate the copper fertility of porphyry belts and to track the evolution of Earth's oxygen fugacity from the Hadean through the Eoarchean. We also defined new fertility indicators for porphyry copper mineralisation based on the trace-element composition of zircon. This work is integrated with a series of industry-funded projects on mineralisation in arc environments, mainly the Philippines, Indonesia and Chile-Argentina.

In the Ivrea Zone of Italy, mafic and ultramafic pipes that intrude into the lower crust illustrate how the lower continental crust can be fertilised with mantle-derived metals and volatiles, which then can be remobilised into upper-crustal ore systems. World-class mineral deposits along the margins of lithospheric blocks may thus be the result of both favourable crustal architecture (focusing of magmas and fluids) and localised volatile and metal enrichment of the lower crust related to mantle-derived hydrous metasomatism.

Module 2 (Architecture) continued on the premises that ore deposits are loci on Earth where energy and mass flux are greatly enhanced and focused. They act as magnifying lenses into the mechanisms of metal transport, fractionation and concentration through the continental lithosphere, providing new constraints on its poorly known metallogenic architecture. Studies of the geochemical signatures of metasomatised mantle rocks and magmatic-hydrothermal mineral systems located at varying crustal depths reveal that anomalously gold (Au)- and tellurium (Te)-rich magmatic sulfides are associated with alkali-enriched magmas emplaced in the lower crust. These sulfides share a common Au-Te-rich *"metallogenic DNA"* with ores associated with upper crustal porphyry and epithermal systems. They define a trans-lithospheric metallogenic continuum with the underlying metasomatised lithospheric mantle.

Module 3 was, for the first time, able to couple recently produced solidii for carbonated basalts and sediments at pressures and temperatures relevant to upper mantle conditions with geodynamic modelling. This was accomplished through a robust modelling framework previously applied to decarbonation of subducting slabs and decarbonation within intracratonic settings. In the Ivrea Zone a section of the lower crust and lithospheric mantle was deformed during the Variscan Orogeny, and carbonated alkaline pipes were emplaced over a time span of ca 40 Ma, following a crustal underplating event at ca 288 Ma. We used a coupled 2D petrological-thermomechanical approach to geodynamically model the processes that led to the Variscan continental collision and subsequent emplacement of the alkaline pipes. The generic model involved: 1) closure of the Rheic Ocean through subduction of oceanic crust and related metasomatism of the lithospheric mantle, 2) high-temperature metamorphism of the lower crust associated with continental collision, preceding 3) a crustal underplating event, and 4) subsequent partial melting of metasomatised lithospheric mantle domains during gravitational collapse of the orogen to source the alkaline pipes. We varied the thermal ages of the intervening oceanic crust (40, 60, and 80 Ma) and the rheological strength of the lower crust: wet quartzite, plagioclase An75, and mafic granulite. Our results show three scenarios, controlled by the rheology of the lower crust. 1: the wet quartzite model features widespread H_2O and CO_2 metasomatism of the lithospheric mantle, but little melt productivity due to the presence of an overthickened crust. 2: the 40 Ma plagioclase An75 model generates high-temperature metamorphism of the lower crust, the metasomatism of the lithospheric mantle, and the crustal underplating event, but the relative timings are wrong. 3: the 80 Ma mafic granulite model is the only one that reproduces the timing relationships between high-temperature metamorphism, the magmatic underplating event, and localised melting of metasomatised domains of the lithospheric mantle. However, scenarios 1 and 2 may provide information about tectono-magmatic processes at craton margins, including metasomatism and fertilisation of the lithospheric mantle with implications for the localisation of mineralised camps at the regional scale.

See *Research highlights pp. 35, 38-39, 41, 45, 47-48, 48, 49, 59-60, 62.*

Published outputs for 2018

CCFS Publications: #976, 987, 1024, 1025, 1026, 1028, 1040, 1045, 1059, 1066, 1125, 1161, 1162, 1169, 1175, 1176a, 1187, 1188, 1189, 1191, 1198, 1208, 1210, 1214, 1223, 1243, 1316

24 Conference Abstracts

3. MODELLING FLUID AND MELT FLOW IN MANTLE AND CRUST

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

AIMS

Many aspects of Earth Science, from ore deposits to giant earthquakes, depend critically on the complex interaction of solids and fluids. Numerical 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. Flagship Program 3 is developing the next generation of numerical codes and aims to refine the thermodynamic parameters involved by integrating 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 high-pressure experimental group at Macquarie joins this initiative to provide input on physico-chemical parameters of minerals, melts and fluids in the deep mantle, the composition of melts that infiltrate the lithosphere and their effects on its geodynamics and stability.

2018 Report

The seismic imaging of the Chinese crust and lithosphere continued with contributions published on the Balikun Basin, Northern Ordos, western Junggar (Northwest China) and intraplate Northeast China. The program also contributed to constraining the crustal and uppermost mantle structure of both southern California (using ambient noise tomography) and the Western-Central United States (using probabilistic inversion), as well as the mantle transition zone beneath NE Asia.

Postdoc Siqi Zhang, who drove the technical innovation of the numerical codes, moved on in late 2018. Advances in the numerical stream include new functionality to simulate melt migration through the mantle and crust using statistical approaches, simulating the interaction of impactors and tectonics throughout the Archaean, understanding the initiation of tectonics in Earth's history and constraining the tectonic evolution of terrestrial exoplanets with different compositions to the Earth. The latter was the subject of a keynote at the 2018 ISSI (International Space Science Institute) in Bern, Switzerland, on Isotopes in Solar System evolution; and the initiation of plate tectonics was an invited keynote at Royal Society Meeting on plate tectonic evolution in London, March 2018, as well as an invited paper contribution to Proceedings of the Royal Society.

High-pressure experimental projects are being conducted to investigate the reaction of mantle peridotite with melts of very different materials, including sedimentary rocks and mica-rich assemblages in the mantle. Two rocks are juxtaposed in the same capsule and heated to a temperature above the melting point of one rock but below the other. The result is a layered reaction zone in which some elements (major and trace) are concentrated in specific zones because of their distinctive

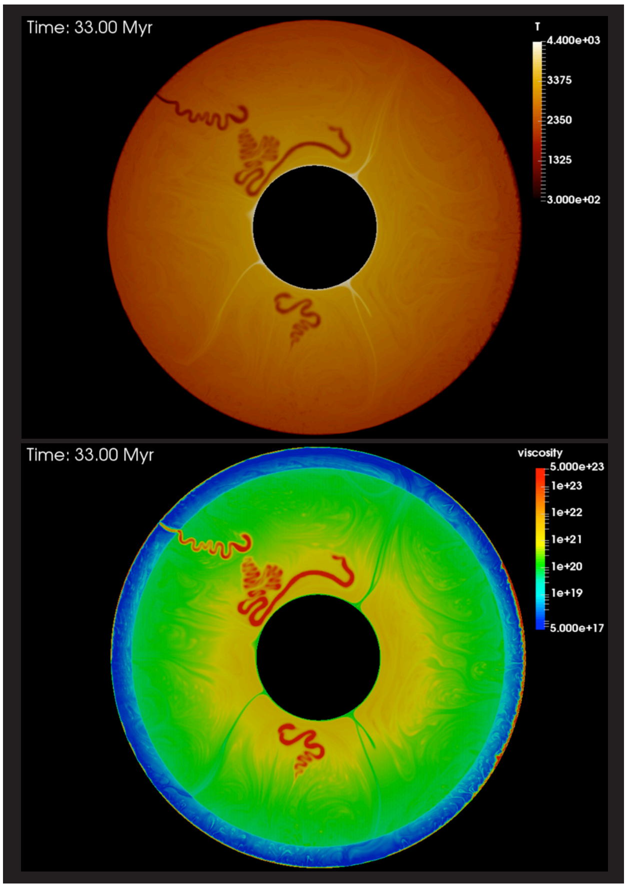


Figure 1. Snapshot of temperature (top) and Viscosity (bottom) of a terrestrial exoplanet with a composition expected for early galactic history. Lower total iron in the interstellar media leads to a lower core, and the planet has a higher concentration of heat-producing elements. Tectonic activity is extremely high on such planets.

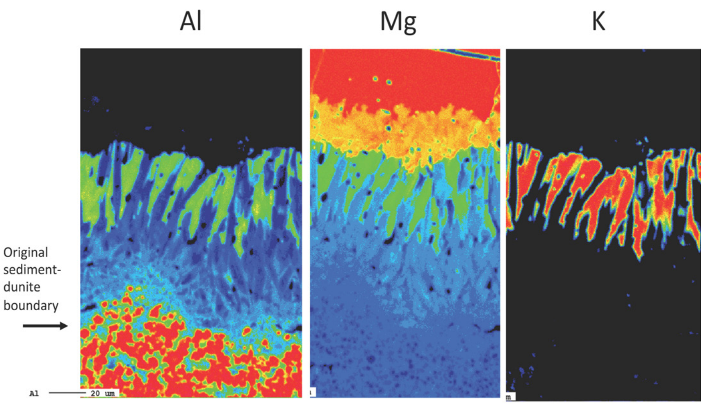


Figure 2. Element maps of experimental reaction zones between peridotite (top) and melts of subducted sediment (bottom). Potassium (right) is concentrated in a central zone that was originally in the K-free peridotite. The orange zone (centre) is orthopyroxene formed from reacted olivine.

mineralogy. An example is the restriction of potassium to a single zone containing mica (Fig. 2) even though it started the experiment in the lower zone where potassium is essentially absent after the experiment. These reaction zones are very effective in fractionating elements and could improve our understanding of the origin of unusual melt types such as those seen in cratonic alkaline rocks and post-collisional volcanoes.

The renovation and expansion of the high-pressure experimental laboratory made great advances in April 2019 with the installation of two multi-anvil presses, which were lowered into position through a removable roof. The larger MAX2003 is a cubic anvil set-up, and is complemented by a Walker module in the smaller 1000 ton-press. See phots *p. 81*.

See *Research highlights pp. 45, 56-57, 67-68, 69-70.*

Published outputs for 2018

CCFS Publications: #984, 1012, 1029, 1032, 1102, 1118, 1119, 1157, 1163, 1164, 1170, 1190, 1193, 1203, 1248, 1264, 1270, 1274, 1309, 1311, 1314, 1348, 1349, 1350, 1351

27 Conference Abstracts

4. ATMOSPHERIC, ENVIRONMENTAL AND BIOLOGICAL EVOLUTION

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

AIMS

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 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 and are involved in NASA's Mars2020 landing site selection process.

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 cycles 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.

2018 REPORT

In 2018, CCFS Flagship Program 4 was engaged in a wide range of research activities, from continuing investigations of the habitats and biogenicity of the earliest evidence of life on Earth

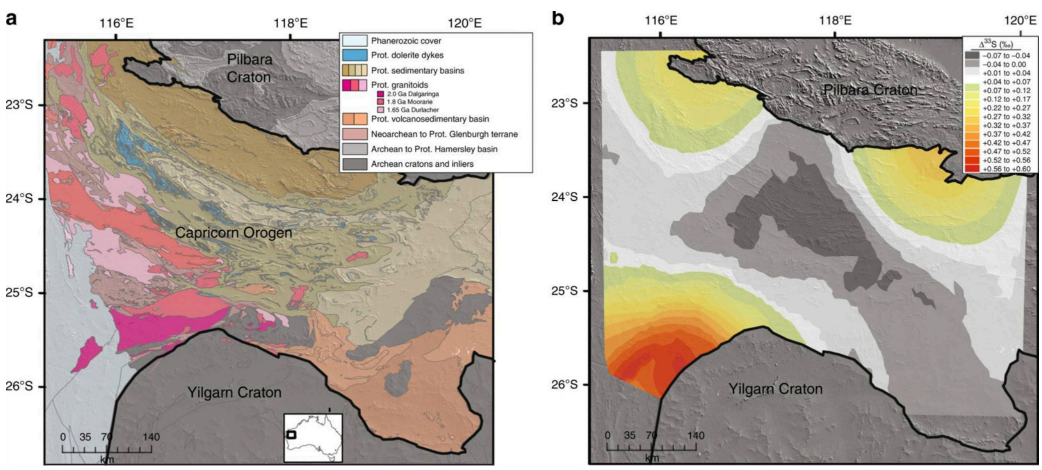
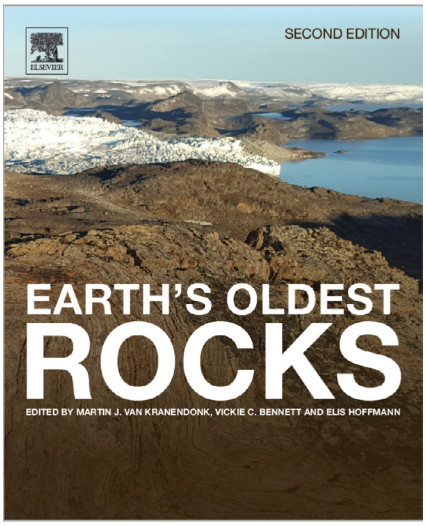


Figure 1. Interpolated model of MIF-S within Capricorn Orogen. a. Location and geology of the Proterozoic Capricorn Orogen between the Archean Pilbara and Yilgarn cratons in Western Australia. b. Interpolated model of $\Delta^{33}S$ for Proterozoic samples of the Capricorn Orogen by ordinary kriging to show that MIF-S occurs in Proterozoic rocks located along the margins of the Archean Pilbara and Yilgarn cratons.

to the adaptation of life across the Great Oxygenation Event, sulfur isotopes in the crust, and the changing nature of tectonics over time.

One of the highlights of the group has been a much more thorough understanding of how sulfur is produced and cycled through the crust and preserved in ore deposits. It turns out it is a complex process that can be tied to the supercontinent cycle, as described by Crystal LaFlamme and others in a series of papers published in 2018 (*CCFS publication #1208*, Fig. 1). A highlight of the year was that Crystal LaFlamme was awarded a Tier II Canada Research Chair in Sulfur isotope geochemistry at Carleton University, Canada.



Another publishing highlight in 2018 was the second edition of Earth's Oldest Rocks, edited by M. Van Kranendonk, V. Bennett, and J. Elis Hoffmann, published by Elsevier (*left*). With over 40 chapters by more than 120 authors, key features of the book are:

- Advances in early Earth research since 2007 based primarily on evidence gleaned directly from the rock record
- More than 50% of the chapters in this edition are new, and the rest of the chapters are revised from the first edition, with more than 700 pages of new material
- Comprehensive reviews of areas of ancient lithosphere from all over the world, and of crust-forming processes
- New chapters on early solar system materials, composition of the ancient atmosphere-hydrosphere, and overviews of the oldest evidence of life on Earth, and modelling of early Earth tectonics.

Dr Raphael Baumgartner's (post-doc at UNSW) work on tiny samples of drillcore material from Dresser Formation stromatolites continued to shine. Through nitric acid etching of heavily sulfidised stromatolites, he has discovered trapped organic material - including strands of microbial Extrapolymeric substance (EPS) and probable microfossils - as well as biomineralised microbarite spheroids and a very distinctive *'spongy'* pyrite that is also associated with microbial activity.

The work has been difficult to get published because of the high bar set by the null hypothesis for early life studies, but there are now four papers resubmitted and will soon be published.

Other FP4 activities included the fourth Astrobiology Australasia Meeting held in Rotorua, New Zealand (June 25-29), followed by the *"Grand Tour"* field trip across Western Australia consisting of a 10-day outback camping experience on a transect back through time from the living stromatolites at Shark Bay to the 3.5 billion-year-old stromatolites of the Dresser Formation in the Pilbara Craton. Growing in popularity, the 2018 version of the trip had 45 paying participants and a support crew of 5. It is doubtful we will do such a large trip again, as there was some concern about the amount of time people had on some of the smaller, more detailed outcrops. Nevertheless, it was a fun-filled excursion with much delight for many newcomers to Australia, including a ride on the back of tray-back utes through a burning spinifex fire!

In October, four members of FP4 travelled to Glendale, California, to participate and vote in the last of NASA's Mars2020 landing site workshops to select the final landing site of the top three remaining sites. Van Kranendonk presented a talk to the assembled crowd on *"A Mars2020 mission to Columbia Hills: Risk minimisation through ground truth"* in which he outlined the benefits of returning to the Columbia Hills site previously visited by the Spirit Rover, and the higher risk of venturing to a new locality, as related to finding signs of life. In the end, the argument was not persuasive, and NASA decided to send Mars2020 to the delta in Jezero Crater.

Finally, Stefano Caruso (UWA) is to be congratulated on completing his PhD on *"Geological controls on the fractionation of multiple sulphur isotopes in Archaean mineral systems"*.

Published outputs for 2018

CCFS Publications: #980, 1017, 1022, 1024, 1025, 1026, 1028, 1125, 1191, 1208, 1240, 1255, 1322, 1323, 1324, 1328, 1345, 1346, 1347

8 Conference Abstracts

Group photo of Australian Centre for Astrobiology team - UNSW - Astrobiology tour, Pilbara, WA (Martin Van Kranendonk).

5. AUSTRALIA'S PROTEROZOIC RECORD IN A GLOBAL CONTEXT

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

AIMS

Earth's history is considered to have been dominated by cycles of supercontinent formation and breakup. This program tests this hypothesis and its relevance to Australia's geological evolution, assessing Australia's positions during the supercontinent cycles by examining the paleomagnetic, petrological and detrital provenance record of the Australian and adjacent continents.

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 or even 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 covered in other Flagship Programs.

2018 Report

Research on the Yilgarn dyke swarms by two PhD students, Camilla Stark and Yebo Liu, has made breakthrough discoveries, and the results are being published. Geochronological and geochemical work on the newly discovered 2.62 Ga, 1.89 Ga and 1.39 Ga mafic dyke swarms are all published (see papers by *Stark et al., 2018, CCFS publications #1068, 1246, 1285*). Of the palaeomagnetic results, one paper (*CCFS publication #1123*) is in press, and papers on high-quality 2.62 Ga and 1.39 Ga poles will be submitted in 2019. Two papers on the Bunger Hills dykes of the East Antarctic craton report the first Precambrian palaeomagnetic pole for the East Antarctica (and Mawson) Craton. The new results confirm the putative ~40° late Neoproterozoic intraplate rotation within the proto-Australian continent (*Li & Evans, 2011 Geology, CCFS publication # 117*). These latter results were published in *Scientific Reports* (*CCFS publication #1247*).

PhD student Hamed Gamaleldien resting during field work in Egypt's Eastern Desert.

Palaeomagnetic results from the 1.8 Ga Hart Dolerite of the Kimberley craton led to a new conceptual model, in which the Proterozoic supercontinent Nuna was formed in two-stages (*CCFS publication #1238*).

Numerous exciting new findings, supported by Li's ARC Laureate Fellow project, have been published in 2018-2019. The northern Queensland team had two papers published in Geology documenting, for the first time, the 1.6 Ga final Nuna suture in Australia (*CCFS publications #1143 and #1207*). In a 2019 publication (*CCFS publication #1242*), we produced a model showing the superposition of a 1.2 Ga superocean cycle with a 600 Myr supercontinent cycle. Both articles have generated a huge global publicity, including radio and TV interviews (see *pp. 31-32*).

Writing up of palaeomagnetic results from the Yilgarn and Kimberley cratons will continue in 2019.

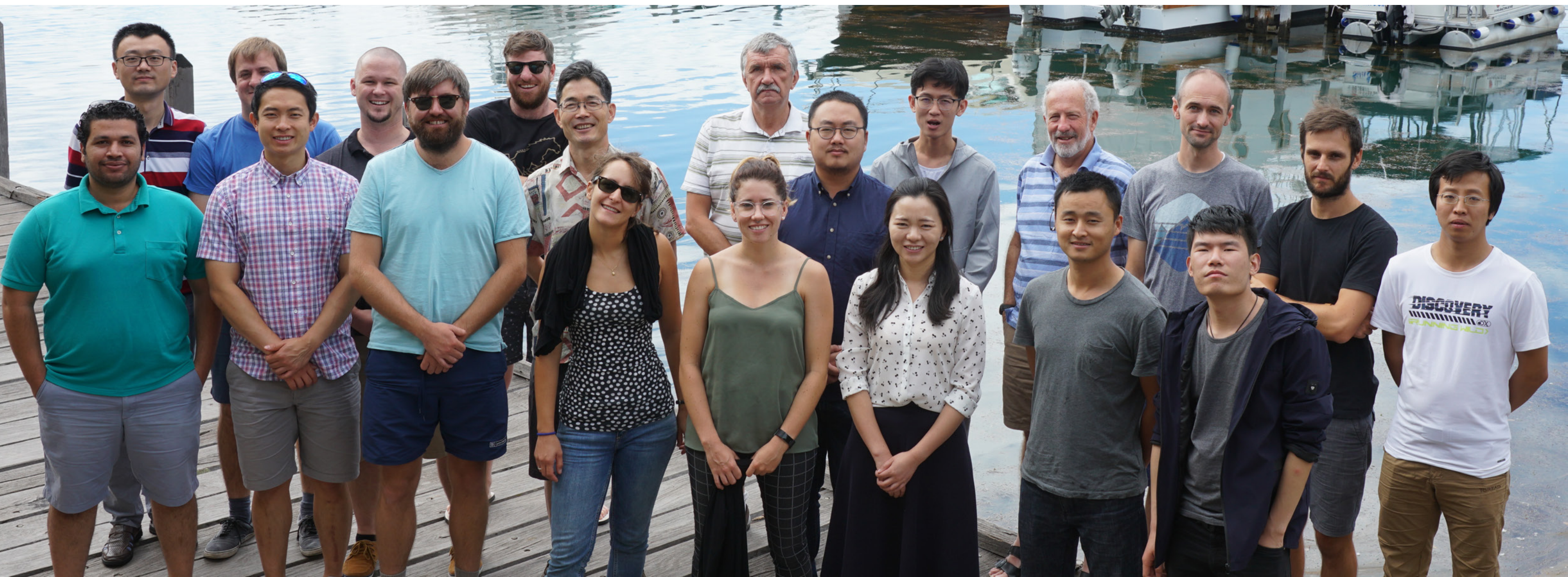
See *Research highlights pp. 46-47, 52-53, 65-66.*

Published outputs for 2018

CCFS Publications: #1033, 1039, 1043, 1068, 1069, 1121, 1167, 1207, 1241, 1246, 1247, 1260, 1263, 1265, 1275, 1282, 1283, 1285, 1286, 1288, 1294, 1304, In Press #1123, 1182, 1238, 1242, 1306

20 Conference Abstracts

Li's Laureate team at their annual science retreat, Mandurah, March 2018.



6. FLUID REGIMES AND THE COMPOSITION OF EARLY EARTH

Themes 1 and 3, Early Earth and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

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 established 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. This program uses the geochemical signatures of zircon crystals from all known Hadean and early Archean localities, together with geochemistry of the oldest known rocks and the application of geophysical and geochemical modelling, to establish how the first crust formed, why it was destroyed and the role fluids played in this process. The changes that took place throughout the Archean are being evaluated as crustal processes evolved and plate tectonics became the dominant regime. A key component is determining the interaction between the mantle and the evolving crust. In addition, work undertaken on Martian meteorites and lunar samples is providing further constraints on the early history of the Solar System, especially the role played by fluids.

2018 Report

CCFS post-doctoral fellow Dr Rongfeng Ge was appointed an Associate Professor at Nanjing University and returned to China in March. His re-evaluation of the Jack Hills detrital zircon suite, continued, focusing on the recognition of radiogenic lead (Pb*) mobility on a nanometre to micron scale using ion imaging techniques. This led to the discovery of a concordant grain recording the oldest age known on Earth (4481 ± 17 Ma), which proved to be spurious due to Pb* mobilisation: the results were published in *Geology* early this year: a second paper is under consideration for *Earth & Planetary Science Letters*. This work will be continued by a new post-doctoral fellow who will take up the appointment in March 2019. Further investigation of the Hadean and Eoarchean zircons from Jack Hills has commenced with a number of local and international collaborators.

Overviews of the ancient rocks and zircons at Jack Hills, in the Narryer Terrane, and in the various cratons in China were prepared and published in the 2nd edition of the Elsevier book *"Earth's Oldest Rocks"*, edited by Martin van Kranendonk, Vickie Bennett and Elis Hoffmann. Further investigations of the distribution of Hadean zircon continued and a new study commenced on the potential for the presence of ancient material in the Guyana Craton in Colombia, in association with the Geological Survey of Colombia.

Lu-Hf analyses were conducted on ancient zircon crystals from Jack Hills and from Aker Peaks in Kemp Land, Antarctica, in order to better characterise their age and provenance: this work is being prepared for publication. Metallic lead nanospheres identified in ancient zircons from the Napier Complex, Antarctica, have also been investigated by both NanoSIMS and atom probe; the former has been submitted for publication and the latter is currently being finalised. Investigation of the radiogenic Pb distribution in the Jack Hills Hadean zircons will commence shortly.

Sample preparation and zircon separation commenced on the samples collected in 2017 from the Saglek Bay area of Labrador, Canada, to further investigate the ancient gneisses where vestiges of life at 3.9 Ga have been reported by Japanese scientists. Several papers prepared in association with scientists at the Polish Academy of Sciences, based on this and earlier work, were published or submitted for publication.

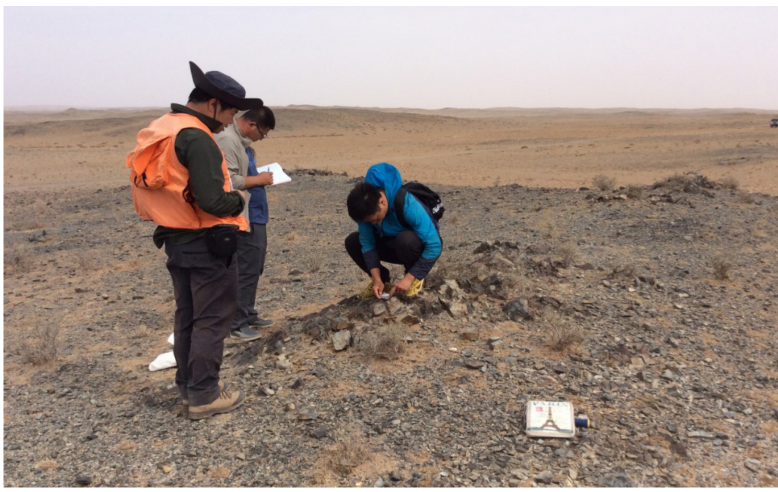
The highlight of the Lunar work in 2018 was the identification that the lunar surface may possibly contain fragments ejected when an asteroid struck the Earth. This was published in *Earth & Planetary Science Letters* in March 2019 and is based on the ongoing study of material collected some 50 years ago from the Apollo 14 site. The sample contained quartz (extremely rare on the Moon) and zircon crystals unlike any previously described from the moon with respect to their geochemical signature. Two new hypotheses are possible for interpreting this clast: it either indicated that the moon went through a period when oxidising conditions briefly prevailed, or else the sample was derived from the Earth's crust - both intriguing scenarios.

See *Research highlights pp. 47-48, 68-69*.

Published outputs for 2018

CCFS Publications: #950, 1036, 1041, 1250, 1252, 1254, 1256, 1258, 1260, 1262, 1265, 1266, 1268, 1271, 1273, 1276, 1280, 1281, 1285, 1290, 1291, 1292, 1295, 1296, 1298, 1300, 1335, 1336, 1337, 1338, 1339, 1340

5 Conference Abstracts



Collecting ophiolite samples in northern Inner Mongolia with doctoral students from the Chinese Academy of Geological Sciences. Prof Tong Ying on left (photo: Simon Wilde).

7. PRECAMBRIAN ARCHITECTURE AND CRUSTAL EVOLUTION IN WA

Themes 1, 2 and 3, Early Earth, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture.

AIMS

The enormous size and limited outcrop of the Neoarchean Yilgarn Craton and the Proterozoic orogens around its margins are detrimental to a deep understanding of what controls the distribution of mineral 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. This aim is predominantly addressed through passive source seismic experiments and integrated analysis of Hf-isotope data.

2018 Report

In 2018, several passive-source array deployments (~70 sites) were finished, including in the Perth Basin, Phase 1 of the China-Western Australia Seismic Experiment (CWAS), and the Ocean Bottom Seismometer deployment (CANPASS) in the Canning Basin. Two new field deployments (~60 sites) started in the Eastern Goldfields and in Phase 2 of CWAS. Preparations are also underway for the acquisition of six high-resolution seismic reflection lines by the Geological Survey of Western Australia in February and March 2019. This seismic survey has been funded through the Western Australian Government's Exploration Incentive Scheme (EIS Phase 4).

Seismic models utilising data from field deployments under Flagship 7 program started to come out as publications. The first finished field project resulted in 3 peer-reviewed journal articles this year. Various seismic models, including the Capricorn and the Perth Basin projects are currently in preparation for publication in 2019. New research activities include the source-mechanism inversion for the September 16, 2018 magnitude-5.4 earthquake at Lake Muir also commenced by CCFS visitor Dr Xiangdong Lin, Beijing Earthquake Agency.

See *Research highlights pp. 40-41, 61-62.*

Published outputs for 2018

CCFS Publications: #1037, 1109, 1110, 1181, 1219, 1293, 1307, 1321

10 Conference Abstracts

Figure 1. The CWAS Phase 2 installation team from IGG-CAS, GSWA and MQ line up before packed vehicles at Marble Bar, WA before heading out for the 38-site deployment on 21 August 2018.

Figure 2. Recovery of an Ocean Bottom Seismometer from Australia's North West Shelf after a 9-month deployment on the seafloor.

WHOLE OF CENTRE TECHNOLOGY DEVELOPMENT

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

Themes 1, 2 and 3, Early Earth, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

The Ion Probe Facility within the CMCA at UWA is one of the best-equipped Secondary Ion Mass Spectrometry (SIMS) labs in the world. It houses a CAMECA IMS 1280 large-radius ion microprobe, for the high-precision analysis of stable isotopes in minerals, and two CAMECA NanoSIMS 50s 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 greatly benefits 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.

For progress in 2018 and plans for 2019, please see pp. 80-84 in Technology Development.

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

Themes 1, 2 and 3, Early Earth, Earth's Evolution and Earth Today, contributing to understanding Earth's Architecture and Fluid Fluxes.

AIMS

The overall aim is to develop new analytical methods for *in situ* measurement of trace elements and isotope ratios to support and enable CCFS research programs and to provide new directions of research. Specific objectives include:

(1) combined trace element and isotope analysis - '*split-stream*' analysis

(2) development of '*non-traditional*' stable isotopes

(3) characterisation of reference materials for elemental and isotope ratio measurement

(4) development of data reduction software for combined trace element and isotope analysis

For progress in 2018 and plans for 2019, please see pp. 84-85 in Technology Development.

Appendix 2: CCFS workplan 2019

1. DEEP-EARTH FLUIDS IN COLLISION ZONES AND CRATONIC ROOTS (TARDIS II)

Activities planned include:

- completing and publishing the remaining studies on the Iranian Tethys
- continuing the detailed analytical work on the Mt Carmel magmatic system
- carrying out analytical work on an analogue from Devonian kimberlites from the Azov area, Ukraine
- publishing work on the Mt Carmel system in at least three papers
- continuing work on kimberlitic carbonates, and publishing at least one paper

2. GENESIS, TRANSFER AND FOCUS OF FLUIDS AND METALS

Writing up of results of the various projects that are still in progress in the three modules will continue. In Module 1, focus will continue on unravelling the genesis of adakites by looking at the natural laboratory provided by Patagonia. In order to provide the necessary constraints to the working hypotheses that are being developed as part of the continuing PhD project of Gonzalo Javier Henriquez, a modelling project will be carried out in parallel in Module 3. The study will examine the style of emplacement of magmas in the crust under a compressive regime and model the evolution of the subducting Nazca plate during the opening of the slab window. In Module 2, we anticipate that further high-precision TIMS dating, as well as the completion of pending trace element analyses on apatite and zircon crystals from selected porphyry copper systems globally, will elucidate the key constraints on ore genesis in magmatic arcs. It is expected that the work carried out in 2018 will have laid the foundations for new collaborations into the future.

3. MODELLING FLUID AND MELT FLOW IN MANTLE AND CRUST

During 2019 the foundation project will see the maturation of many of its numerical approaches and the application to a wide range of CCFS projects. In addition, we will continue to expand the capabilities of the current numerical platform. We foresee immediate applications to a multitude of problems through collaborations across CCFS nodes.

The development of a statistical approach to modelling the transport of melt and crustal production in global mantle convection models will continue to extend into simulations on the interaction of mantle melts, eclogitisation and lithosphere recycling.

Further seismic imaging combining surface waves and body waves continues in NE China to investigate the origin of intraplate volcanism in NE China. This work is carried out in collaboration with China University of Geosciences (Wuhan) and Southern University of Science and Technology of China.

The experimental laboratory at MQ is closed until mid 2019 for renovations. Some experiments will be carried out in the laboratories of partner institutions (e.g. Australian National University, University of Mainz, China University of Geosciences, Wuhan), whereas other projects will concentrate on data collection and analysis from experiments already run. Current projects include volatile-induced melting of mantle peridotite, carbonate/silicate rock reactions in subduction zones, the deep Earth nitrogen cycle, trace elements in mantle orthopyroxenes, and trace elements in olivine phenocrysts from eastern Australian volcanic rocks.

4. ATMOSPHERIC, ENVIRONMENTAL AND BIOLOGICAL EVOLUTION

In 2019, Research will continue on established CCFS FP4 projects, including:

Evidence of early life in the Dresser Formation of the North Pole Dome, funded by two new major grants, one by the ARC Discovery Program (to CIs Van Kranendonk and Fiorentini "*A terrestrial hot spring setting for the origin of life? Darwin's Warm Little Pond revisited*") and a nearly $1M NZD Marsden Fund grant to Prof Kathy Campbell (U Auckland) and CI Van Kranendonk, which includes a significant component for a new diamond drilling program through the 3.5 Ga Dresser Formation.

Stefano Caruso joins the UNSW team as a 2-year ARC funded post-doctoral fellow, where he will join another UWA alumnus, Raphael Baumgartner, to continue work on unravelling the Dresser volcanic caldera system and its microbial inhabitants. New PhD candidate Luke Steller will join the Dresser team, tasked with unravelling the processes that help to concentrate prebiotically important elements.

Writing up and further research will continue on the evolution of complex life in the immediate aftermath of the Great Oxygenation Event, with contributions from PhD candidates Erica Barlow, Georgia Soares, Brendan Nomchong, and Bonnie Teece, who came to UNSW from Macquarie University, to undertake organic geochemical studies of these complex life-bearing rocks. Late in 2019, Prof Clark Johnson from the University of Wisconsin-Madison, will spend a month at UNSW to write up a major paper on global changes that are tied to the supercontinent cycle and link the geosphere with the exosphere, including the biosphere, over the Precambrian history of the Earth.

At UWA, Marco's team continues to investigate the role of sulfur in magmatic and life systems through detailed understanding of sulfur isotope systematics, as well as the continued study of a variety of ore deposits.

5. AUSTRALIA'S PROTEROZOIC RECORD IN A GLOBAL CONTEXT

Numerous exciting new findings, supported by Li's ARC Laureate Fellow project, are due to be published in 2019. Writing up of palaeomagnetic results from the Yilgarn and Kimberley cratons will continue in 2019.

6. FLUID REGIMES AND THE COMPOSITION OF EARLY EARTH

Work in Australia will remain focused on Jack Hills. The characterisation of the oldest zircons from the W74 site and other locations along the traverse of former PhD student Qian Wang will continue with the aim of placing tighter constraints on the nature of Earth's oldest crust. Further work on Pb mobility in these grains will be undertaken using the Atom Probe.

The atom probe investigation of lead (Pb) nanospheres in ancient zircons from the Napier Complex, Antarctica, will continue in order to precisely determine their distribution and isotopic composition.

Another field trip to Labrador will be undertaken in mid-2019 to focus on the distribution of the most ancient gneissic components identified in the 2017 field season. In addition, fieldwork will commence in several locations in West Greenland.

Work will continue on both lunar rocks and Martian meteorite samples with the aim of constraining the age of the oldest crust and the precise timing of events in the early solar system.

7. PRECAMBRIAN ARCHITECTURE AND CRUSTAL EVOLUTION IN WA

Preparations are also underway for the acquisition of six high-resolution seismic reflection lines by the Geological Survey of Western Australia in February and March 2019. This seismic survey has been funded through the Western Australian Government's Exploration Incentive Scheme (EIS Phase 4).

Seismic models utilising data from field deployments under Flagship 7 program will continue to be published. Various seismic models, including the Capricorn and the Perth Basin projects are currently in preparation for publication in 2019.

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 pp. 89-95.*

Mantle dynamics and ore deposits	A. Cruden, **M. Fiorentini**, S. Barnes, A. Bunger, C. Jackson: *Support by ARC DP (commencing 2019)* ***Summary:*** This project aims to investigate where, how and why narrow finger-like conduits form in lithosphere-scale magma plumbing systems by a novel integration of field surveys, three-dimensional reflection seismic data, laboratory experiments and rock fracture mechanics. The project expects to generate new knowledge on the formation and location of highly valuable ore deposits of nickel, copper, cobalt and platinum group elements, which are preferentially trapped in poorly understood finger-like magma conduits.
Unveiling the fine structure of the Australian continent using ocean waves	**Y. Yang**, **J.C. Afonso**, N. Rawling, M. Ritzwoller, F. Niu: *Support by ARC DP (commencing 2019)* ***Summary:*** This project aims to develop new methods to better image lithospheric and upper-mantle structures by using noise from ubiquitous ocean waves, and then use these methods to illuminate fine-scale lithospheric-asthenospheric structures in Australia, from the surface to the upper mantle. Imaging the Earth's structure using seismic tomography is one of the most fundamental tasks of geoscience. Conventional earthquake-based seismic tomography has difficulties in deciphering fine-scale lithospheric structures. The images from this project will provide a better understanding of the nature of intraplate earthquakes and volcanoes, and improve the assessment of intraplate seismic and volcanic hazards in Australia.
A terrestrial hot spring setting for the origin of life? Darwin's Warm Little Pond revisited	**M. Van Kranendonk**, **M. Fiorentini**, K.A. Campbell, D. Deamer: *Support by ARC DP (commenced 2018)* ***Summary:*** This Project aims to test the proposal that a terrestrial hot spring field could have been the setting for the origin of life, in preference to the currently favoured site at deep sea vents. This will be achieved by: 1) detailed characterisation of the only known, truly ancient, inhabited terrestrial hot spring analogue in the geological record - the 3.5 billion-year-old Dresser Formation, Western Australia; 2) comparison of this ancient analogue with active hot spring fields in New Zealand; and 3) experimental research on prebiotic organic chemistry using Dresser materials and active hot spring fluid chemistries. Results will be used to develop a terrestrial origin of life setting and assist in the search for life on Mars.
Establishing the critical physical-chemical factors in the early surface environment and tectonic regime that supported early life and continuing habitability	A. Nutman, V. Bennett, **M. Van Kranendonk**: *Support by ARC DP (commenced 2017)* ***Summary:*** Engineering planetary habitability: Earth's first billion years. This project aims to establish the critical physical-chemical factors in the early surface environment and tectonic regime that supported early life and continuing habitability. Life was established on Earth within the first billion years of its 4.56-billion-year history. This project's integrated geological and geochemical study will investigate this period's rare sedimentary and volcanic record, including the oldest fossiliferous sequences discovered recently, to show how the early Earth's chemistry supported life and evolution. The project expects to enhance understanding of why life prospers on some habitable zone planets but not on others

Rehydration of the lower crust, fluid sources and geophysical expression	M. Hand, **C. Clark**, D. Hasterok, **T. Rushmer**, **S. Reddy**, B. Hacker: *Support by ARC DP (commenced 2016)* ***Summary:*** This project aims to explore a long-standing mystery: the origin of deep crustal electrical conductors detected by magnetotelluric imaging of tectonically stable crust. These features occur in cratons of all ages, and commonly cross-cut structures and lithologies. This project aims to investigate the hypothesis that such features are the record of ancient deep crustal fluid flow, which modified the rocks' electrical properties. Using an exceptionally exposed natural laboratory preserving large-scale rehydration of anhydrous lower crust, the project plans to determine the source of fluids and the compositional changes they induced. It then plans to experimentally determine changes in resistivity induced by fluid flow and use that data to model the magnetotelluric response at crustal scale.
To develop a geophysically relevant proton conduction model for the Earth's upper mantle	**S. Clark**, **J.C. Afonso**, A. Jones: *Support by ARC DP (commenced 2016)* ***Summary:*** The aim of this project is to develop a geophysically relevant proton conduction model for the Earth's upper mantle. This will allow the robust interpretation of conductivity maps of the interior of the Earth and the discovery of major new mineral deposits. This advance will be achieved through four major initiatives based on recently developed experimental and computational facilities. This project will develop new methods for determining rock conductivities and subsurface mapping from combined datasets. We will obtain new insights into the structure and dynamics of the upper mantle as well as providing key data necessary for a national effort aimed at reestablishing Australia as a primary target for mineral exploration.
Just add water: a recipe for the deformation of continental interiors	**A. Putnis**, T. Raimondo, **N. Daczko**: *Support by ARC DP (commenced 2016)* ***Summary:*** By integrating geochemical, geochronological and microstructural datasets, this project aims to provide a novel framework for fluid-rock systems in the lithosphere. Plate tectonics argues that continental interiors are usually stable, rigid and undeformable, yet mountain belts have formed in these locations. Their existence suggests that strong crust can be weakened to allow the accommodation of deforming forces, but the underlying causes for this change in behaviour are not clear. This project aims to investigate the largely unexplored impact of fluid flow on the characteristics of intraplate deformation. This would improve our understanding of what modulates the strength of continental crust, including its susceptibility to seismic activity, and the ways in which fluids interact with the deep crust, including their mineralisation potential.
Mechanisms of proxy uptake in biominerals	**D. Jacob**, S. Eggins, R. Wirth: *Support by ARC DP (commenced 2016)* ***Summary:*** This project plans to combine nano-analytical and aquaculture methods to develop new models that improve the reliability of paleoclimate reconstructions. The compositions of shells and skeletal materials of marine invertebrates are essential archives for quantifying temperatures and environmental conditions before modern climate records began. However, their reliability relies on understanding their formation. Emerging knowledge from material sciences indicates that these biocarbonates form via transient precursors rather than direct precipitation from seawater, profoundly affecting their interpretation. This project plans to transfer this new understanding to the earth sciences using nanoscale analytical methods including in vitro geochemical partitioning experiments. This would enable realistic models for geochemical proxy behaviour to be developed, significantly improving paleoclimate interpretations and assessments of ocean acidification effects on marine calcifiers.

The global consequences of subduction zone congestion	**L. Moresi**, P. Betts, J. Whittaker, M. Miller: *Supported by ARC DP (commenced 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.
The roles of carbon, water and nitrogen in the development of plate tectonics as drivers of mantle evolution	**S. Foley**: *Supported by ARC Laureate Fellowship (commencing 2019)* ***Summary:*** This project aims to understand the roles of carbon, water and nitrogen in the development of plate tectonics as drivers of mantle evolution. Through improved understanding of the impact of melting on the deep earth cycles of carbon, water and nitrogen, this project intends to better understand how key elements are enriched towards economically viable concentrations. This project will generate knowledge of long-term benefit for decision-making in the minerals exploration industry and key government agencies. The project will establish a new generation of Australian scientists with a deep interdisciplinary understanding of earth sciences, and pave the way for eventual unification of plate tectonic with climate systems.
How the Earth works-toward building a new tectonic paradigm	**Z.X. Li**: *Supported by ARC Laureate Fellowship (commenced 2015)* ***Summary:*** This fellowship project aims to build on the latest technological and conceptual advances to establish the patterns of Earth evolution, and use this information to examine a ground-breaking geodynamic hypothesis which links cyclic plate aggregation and dispersion to deep Earth processes. Half a century after the inception of plate tectonics theory, we are still unsure how the Earth '*engine*' works, particularly the forces that drive plate tectonics. The project involves extensive national and international collaboration to potentially create a paradigm shift in our understanding of global tectonics, and hopes to contribute to an understanding of the formation and distribution of Earth resources to provide a conceptual framework for their exploration.
Measuring mantle hydrogen to map ore fluids and model plate tectonics	**K. Selway**: *Supported by ARC Future Fellowship (commenced 2016)* ***Summary:*** The goal of this project is to use magnetotellurics to measure mantle hydrogen contents to aid in the discovery of new mineral deposits. Hydrogen controls the strength of Earth's mantle and is a vital component of the systems that form giant ore deposits. However, mantle hydrogen content is unconstrained. Ore-forming fluids hydrate the mantle pathways on which they travel. The first aim of this project is to image these fluid pathways to improve mineral exploration techniques. Plate tectonic models assume that the lithospheric mantle is dehydrated but existing data from magnetotellurics and mantle rocks show high hydrogen contents. The second aim of this project is to create a map of the hydrogen content of the plates, which may lead to new models for continental evolution and mantle dynamics.
Earth's origin and evolution: a sulphurous approach	**O. Alard**: *Supported by ARC Future Fellowship (commenced 2015)* ***Summary:*** This project aims to shed new light on global element cycles in the deep Earth and how they connect to the evolution of the exospheres - one of the hottest topics in geosciences. It also aims to produce key knowledge on the extraction and transport of elements from the deep Earth to the surface, which may provide valuable information for resource exploration. Using novel integrated elemental and isotopic approaches, this program aims to track the origin and fate of sulfur, selenium and tellurium during accretion and subsequent redistribution in fluids to Earth's surface. This new knowledge is critical to understanding how these and other elements of strategic and economic importance, such as the Platinum Group Elements, are extracted from the deep Earth and transported to the surface.

A new approach to revealing melting processes in the hidden deep Earth	**A. Giuliani**: *Supported by ARC DECRA (commenced 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.
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.
The Western Australia ThermoChronology Hub	M. Danisik, N. Evans, B. McInnes, **C. Kirkland**, **Z.X. Li**, **M. Fiorentini**, **M. Wingate**: *Support by ARC LIEF (commencing 2019)* ***Summary:*** This project aims to facilitate novel geochronological research in diverse areas of Earth and planetary science by providing a world-first triple-dating instrument facility. Combining three independent radiometric dating methods, the facility will undertake research to advance our understanding of the origin and evolution of the Earth and other planets, and provide tools to enhance exploration for Earth's resources. Expected outcomes include the formation of a strong collaborative facility for academic, government and industry research and a further strengthening of Australia's position as an international research and education leader in the field of geochronology. It will lead to an improved understanding of the evolution of Earth's surface, and the formation and distribution of mineral and petroleum resources.
A novel ToF-SIMS facility for organic and inorganic analyses in WA	K. Grice, W. Rickard, G. Benedix, S.-P. Jiang, **S. Reddy**, **M. Kilburn**, P. Clode, D. Peyrot, D. Wacey, P. Lavery, P. Masque, R. Trengove, F. Xia, A. Deditius, G. Maker: *Support by ARC LIEF (commencing 2019)* ***Summary:*** Time-of-flight secondary ion mass spectrometry is a surface sensitive analytical technique that provides detailed elemental, isotopic and molecular information on surfaces, interfaces and thin layers with detection limits reaching in the parts-per-billion-range. The proposed facility is a next generation time-of-flight secondary ion mass spectrometer that allows parallel detection of organic and inorganic species in a given sample. Most importantly it will provide structural information of organic molecules intimately associated with minerals, meteorites, fossils, petroleum source-rocks to biochemical samples bolstering Western Australia's Earth and planetary sciences, energy, materials sciences, life science and metabolomics research.

Cutting-edge electron probe microanalysis driving Western Australia's resource geosciences	D. Sampson, S. Barnes, **M. Fiorentini**, I. Fitzsimons, S. Johnson, A. Kemp, **M. Kilburn**, M. Martyniuk, A. Putnis, **S. Reddy**, R. Smithies, Y. Uvarova: *Support by ARC LIEF (commenced 2018)* ***Summary:*** The overwhelming demand for electron probe microanalysis from outstanding research groups in Western Australia requires renewal of over-subscribed, aging facilities to drive innovation and alleviate bottlenecks in advanced geosciences multi-capability workflows. A new generation electron microprobe, with advances in trace element mapping and cathodoluminescence analysis, will enable superior characterisation of a wide range of materials. The electron probe will drive underpinning geoscience, resources science and economic geology, as well as support a broad range of disciplines and diverse fields, such as nanotechnology, microelectronics and aquatic sciences.
Femtosecond-laser, micropyrolysis gas-chromatographmass spectrometer	S. George, J. Paterson, **M. Van Kranendonk**, J. Brocks, N. Sherwood, **D. Jacob**, A. Fuerbach, G. Brock, S. Löhr, S. Sestak: *Support by ARC LIEF (commenced 2018)* ***Summary:*** This project aims to build a femtosecond-laser, micropyrolysis gas-chromatographmass spectrometer. The facility will have the capability to selectively analyse very small petrographically-recognisable organic components, hence bridging the analytical gap between organic petrography and organic geochemistry. The project aims to understand the early evolution of life, the response of the biosphere to mass extinction, the migration of fluids in petroleum reservoirs, the heterogeneity of organic matter in shale gas reservoirs, and the composition of macromolecules in biominerals and macerals. The facility will contribute to a broad range of Australia's theoretical and applied problems in geoscience and geobiology.
Australian membership of the International Ocean Discovery Program	R. Arculus, D. Cohen, S. Gallagher, P. Vasconcelos, C. Elders, J. Foden, M. Coffin, O. Nebel, H. McGregor, M. Clennell, C. Sloss, A. Heap, A. Webster, A. Kemp, **S. George**: *Supported by ARC LIEF (commenced 2016)* ***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.
Magmatic oxidation state, water content, and volatile nature: New insights into genesis of porphyry copper mineralisation at Zhunuo in the Gangdese belt, southern Tibet	X. Sun, **Y. Lu**: *Supported by the National Natural Science Foundation of China (commenced 2017)* ***Summary:*** The Zhunuo porphyry Cu deposit in the western part of the Gangdese copper belt is characterised by the occurrence of many Miocene igneous rocks rarely present in the porphyry copper deposits in the eastern Gangdese. Thus the Zhunuo deposit offers a new window into the genesis of porphyry Cu mineralisation in continental collision zones. This project is aimed at analysing compositions of some minerals such as zircon, apatite, amphibole, and plagioclase by Electron microprobe analysis (EMPA) and LA-ICP-MS, and *in situ* sulfur isotopes of sulfides, studying magmatic oxidation state, water content and volatile (e.g. S, F, Cl) and their evolution during magma mixing, and constraining the source of magmatic water and contribution of different magmas for porphyry copper mineralisation. The results will not only be helpful for further understanding porphyry copper mineralisation and evaluate the fertility of igneous rocks in the Gangdese belt but also provide new insights into improving porphyry copper metallogenic theory in collisional zones.

Genesis of comb quartz layers: case studies from porphyry Cu deposits at Qulong, Tibet and Now Chun, Iran	Z. Yang, **Y. Lu**: *Support by the National Natural Science Foundation of China (commenced 2015)* ***Summary:*** Two hypotheses have been proposed to account for formation of Comb quartz layers (also unidirectional solidification textures, UST). One concept proposes that these textures have grown from pockets of exsolved magmatic fluid located between the magma and its crystallised border, but the other proposes that they have precipitated directly from a crystallising silicate melt. To test these hypotheses, as well as to investigate nature and source of primitive ore-forming fluids in porphyry Cu systems, comb-layered quartz from Qulong and Now Chun porphyry Cu deposits have been selected for the following studies. Features to be studied include: (1) their distribution, occurrence and petrographic characteristics; (2) their spatial and genetic relationships with Cu mineralisation; (3) characteristics of melt/fluid inclusions (e.g. composition, formation temperature, Cu content) in comb-layered quartz; and (4) their elemental and oxygen isotopic geochemistry. The aims of this study are to: (1) document nature and variation of initial ore-forming fluids in the two deposits; (2) clarify genesis of comb quartz layers; and (3) identify source of ore-forming fluids for porphyry Cu system.
3D Earth	**J.C. Afonso**, J. Ebbing: *Supported by European Space Agency and MQ University (commenced 2017)* ***Summary:*** The goal of this project is to establish a global 3D reference model of the crust and upper mantle based on the analysis of satellite gravity and (electro-)magnetic data in combination with seismological models and analyse the feedback between processes in Earth's deep mantle and the lithosphere. Selected case examples will provide the possibility to test these approaches on a global and regional scale. This will result in a framework for consistent models that will be used to link the crust and upper mantle to the dynamic mantle.
CWAS: China-Western Australia Seismic Survey	L. Zhao, **H. Yuan**, **GSWA**: *Supported by the Institute of Geology & Geophysics, Chinese Academy of Sciences, Beijing (commenced 2016)* ***Summary:*** Western Australia is an ideal natural laboratory for understanding the evolution of the Australian craton. To better understanding how and where the cratonic nuclei merged in the Precambrian requires high-resolution probing of the crustal and mantle structure beneath Western Australia. IGGCAS, CCFS and GWSA will install a 900-km-long dense (station spacing of 10 to 15 km) seismic profile across the Western Australia from the Port Hedland to the southwestern border of Kimberly Craton, in order to: - image the crustal structure of the north edge of Pilbara craton, the Canning basin and south edge of Kimberly craton with a high-resolution, and address the following issues: 1) deep geometry of the craton boundaries, 2) deep geometry of craton collisional belt; 3) differences of crustal structures between two cratons - image the mantle structure of the north edge of Pilbara craton, the Canning basin and south edge of Kimberly craton and address the following questions: 1) geometry of the convergence beneath the craton boundaries, 2) characteristic difference of the upper mantle of the two cratons.

Appendix 4: Participants list

Chief Investigators

- Professor Suzanne Y. O'Reilly (Centre Director, MQ)
- Professor Simon Wilde (Node Director, CU)
- Associate Professor Marco Fiorentini (Node Director, UWA)
- Associate Professor Elena Belousova (MQ)
- Professor Simon Clark (MQ)
- Professor Stephen Foley (MQ)
- Professor William Griffin (MQ)
- Associate Professor Matthew Kilburn (CMCA, UWA)
- Professor Zheng-Xiang Li (CU)
- Associate Professor Alexander Nemchin (CU)
- Associate Professor Craig O'Neill (MQ)
- Professor Martin Van Kranendonk (UNSW)
- Associate Professor Yingjie Yang (MQ)

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- Dr Olivier Alard (MQ)
- Associate Professor Nathan Daczko (MQ)
- Professor Simon George (MQ)
- Dr Richard Glen (Adjunct Professor)
- Dr Masahiko Honda (Australian National University)
- Professor Dorrit Jacob (MQ)
- Associate Professor Mary-Alix Kaczmarek (University Paul Sabatier Toulouse III)
- Associate Professor Christopher Kirkland (CU)
- Professor Jochen Kolb (GEUS and KIT, Germany)
- Dr Yongjun Lu (GSWA at UWA)
- Dr Louis-Noel Moresi (University of Melbourne)
- Professor Steven Reddy (CU)
- Associate Professor Tracy Rushmer (MQ)
- Associate Professor Bruce Schaefer (MQ)
- Professor Paul Smith (MQ)
- Professor Simon Turner (MQ)
- Dr Michael Wingate (GSWA)
- Professor Shijie Zhong (University of Colorado at Boulder, USA)

Partner Investigators

- Dr Ian Tyler (CCFS Leader, GSWA)
- 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)
- Dr T. Campbell McCuaig (BHP Billiton)
- Professor Fuyuan Wu (Chinese Academy of Science, China)

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- Ms Sally-Ann Hodgekiss, Reporting & Comms. Manager (MQ)
- Ms Summer Luo, Centre Finance & Admin Officer (MQ) *until Sept. 2018*
- Ms Anna Wan, Centre Admin Officer (MQ)
- Mr Yacoob Padia, Business Manager (CU)
- Keng Chai Ng, Finance Officer (CET, UWA)
- Mr Sean Webb, Business Manager (CMCA, UWA)
- Ms Hava Zhang, Finance Officer (CMCA, UWA)

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- Mr Steven Craven (MQ)
- Ms Sarah Gain (MQ) *until Nov. 2018*
- Dr Oliver Gaul (MQ)
- Mr Anthony Lanati (MQ) *until Feb. 2018*
- Dr Will Powell (MQ)
- Mr Farshad Salajegheh (MQ) *until July 2018*
- Mr Peter Wieland (MQ)

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	Dr Hadrien Henry (MQ)	Adjunct Professor Robert Pigeon (CU)
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Dr Luc-Serge Doucet (CU)	Dr Uwe Kirscher (CU)	Dr Amaury Pourteau (CU)
Assistant Professor Steven Denyszyn (UWA)	Dr Mark Lackie (MQ)	Dr Kate Selway (MQ)
Dr Richard Flood (MQ)	Dr Crystal LaFlamme (UWA) *until May 2018*	Dr Nicholas Thébaud (UWA)
Dr Denis Fougerouse (CU)		Dr Romain Tilhac (MQ)
Dr Nicholas Gardiner (CU) *until Sept. 2018*	Dr Zhen Li (CU) *until Sept. 2018*	Dr Xuan-Ce Wang (CU)
Dr Rongfeng Ge (CU) *until May 2018*	Dr Nora Liptai (MQ) *until Sept. 2018*	Dr Lei Wu (CU)
Dr Andrea Giuliani (MQ at UM)	Dr Jianggu Lu (MQ) *until June 2018*	Dr Weihua Yao (CU) *until April 2017*
Dr Christopher Gonzalez (UWA)	Dr Laure Martin (CMCA, UWA)	Dr Huaiyu Yuan (MQ at UWA)
Dr Weronika Gorczyk (UWA)	Dr Ross Mitchell (CU)	Dr Nan Zhang (CU)
Dr Yoann Gréau (MQ)	Dr Hugo Olierook (CU) *until Oct. 2018*	Dr Siqi Zhang (MQ) *until Nov. 2018*
Dr Johannes Hammerli (UWA)	Dr Beñat Oliveira Bravo (MQ)	

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Dr Mike Etheridge	Dr Jon Hronsky	Dr John Vann
Professor Jim Everett	Professor Alan Jones	Dr Peter Williams
Dr Richard Glen	Dr Robert Loucks	Professor Xisheng Xu
Dr Richard Goldfard	Dr Franco Pirajno	

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Dr Mehmet Akbulut	Dr Jeff Harris	Dr William Powell
Dr Debora Araujo	Dr Daniel Howell	Dr Takako Satsukawa
Dr Jacques Batumike Mwandulo	Dr Felix Kaminsky	Dr Ed Saunders
Dr Graham Begg	Dr Christoph Lenz	Dr Hadi Shafaeimoghaddam
Dr Christoph Beier	Dr Kreshimir Malitch	Dr Thomas Stachel
Professor Hannes Brueckner	Dr Vlad Malkovets	Dr Kuo-Lung Wang
Dr Mei-Fe Chu	Dr Claudio Marchesi	Professor Xiang Wang
Dr Beverly Coldwell	Dr Bertrand Moine	Dr Xiao-Lei Wang
Professor Massimo Coltorti	Ms Ria Mukherjee	Dr Qing Xiong
Professor Kent Condie	Dr Rosanna Murphy	Dr Jin-Hui Yang
Professor Jean-Yves Cottin	Dr Lev Natapov	Professor Jin-Hai Yu
Dr Cara Donnelly	Dr Oded Navon	Professor Jianping Zheng
Professor Manel Fernandez	Professor Sandra Piazolo	
Dr José María Gonzaléz-Jiménez	Dr Ryan Portner	

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Ms Halimulati Ananuer (MQ)	Mr Raham Jalil (MQ)	Mr Sinan Özaydin (MQ)
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Mr Jason Bennett (UWA)	Mr Anthony Lanati (MQ)	Mr Sarath Patabendigedara (MQ)
Mr Raul Brens Jr (MQ)	Mr Pablo Lara (MQ)	Mr Farshad Salajegheh (MQ)
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Mr Julian Chard (CU)	Mr Shaojie Li (CU)	Ms Jutta Camilla Stark (CU)
Miss Eunjoo Choi (UWA)	Mr Guoliang Li (MQ)	Miss Catherine Stuart (MQ)
Mr Hongkun Dai (MQ)	Miss Nora Liptai (MQ)	Mr Dennis Sugiono (UWA)
Mr Benedikt Demmert (MQ)	Mr Yebo Liu (CU)	Ms Bronwyn Teece (UNSW)
Mr Gregory Dering (UWA)	Mr Kai Liu (CU)	Mr Rick Verberne (CU)
Ms Tara Djokic (UNSW)	Miss Zairong Liu (MQ)	Ms Marina Veter (MQ)
Ms Katherine Farrow (MQ)	Ms Jianggu Lu (MQ)	Mrs Silvia Volante (CU)
Mr Michael Förster (MQ)	Miss Maria Manassero (MQ)	Mr Alexander Walker (CU)
Mr Hamed Gamal El Die (CU)	Ms Erin Martin (CU)	Mr Chengyuan Wang (MQ)
Mr Hindol Ghatak (MQ)	Mr Shiladitya Mazumdar (MQ)	Mr Chong Wang (CU)
Miss Louise Rebecca Goode (MQ)	Mr Keith McKenzie (MQ)	Mr Kai Wang (MQ)
Mrs Stephanie Greene (MQ)	Miss Uvana Meek (MQ)	Mr Jonathon Michael Wasiliev (MQ)
Mr Kui Han (MQ)	Ms Stephanie Montalvo Delgado (CU)	Mr Shucheng Wu (MQ)
Mr Michael Hartnady (CU)	Mr Jonathan Munnikhuis (MQ)	Mr Bo Xu (MQ)
Mr Gonzalo Henriquez (UWA)	Mr Thusitha Nimalsiri (MQ)	Miss Anqi Zhang (MQ)
Mr Hadrien Henry (MQ)	Mr Brendan Nomchong (UNSW)	

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Mr Benjamin Alsop (MQ)	Mr Jean-Antoine Gazi (MQ)	Mr Sahand Tadbiri (UNSW)
Mr Hugh Bannister (UNSW)	Ms Stephanie Hawkins (MQ)	Mr Peter Targett (MQ)
Mr Richard Blake (UNSW)	Mr Tasman Gillfeather-Clark (MQ)	Ms Alice Van Tilburg (MQ)
Mr Thomas Connell (MQ)	Mr Harrison Jones (MQ)	Mr Alexander Tunnadine (MQ)
Mr Joyjit Dey (MQ)	Miss Angela Mabee (MQ)	Mr John Wardell (MQ)
Mr Omar Elkhaligi (MQ)	Ms Carla Raymond (MQ)	Mr Harry West (MQ)
Mrs Victoria Elliott (MQ)	Mr Joshua Shea (MQ)	Mr Haoming Wu (MQ)

Appendix 5: 2018 Publications

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

948. Aitken, A.R.A., Occhipinti, S.A., Lindsay, M.D., Joly, A., Howard, H.M., Smithies, R.H., Johnson, S.P., Hollis, J., Spaggiari, C., **Tyler, I.M.**, **McCuaig, T.C.** and Dentith, M.C. 2018. The tectonics and mineral systems of Proterozoic Western Australia; Relationships with supercontinents and global secular change. *Geoscience Frontiers, 9, 295-316.*

950. Zhou, J.B., **Wilde, S.A.**, Zhao, G.C. and Han, J. 2018. Nature and assembly of microcontinental blocks within the Paleo-Asian Ocean. *Earth-Science Reviews, 186, 76-93.*

953. **Gorczyk, W.**, **Mole, D.R.** and Barnes, S.J. 2018. Plume-lithosphere interaction at craton margins throughout Earth history. *Tectonophysics, 746, 678-694.*

958. Malitch, K.N., **Belousova, E.A.**, **Griffin, W.L.**, Badanina, I.Yu., Latypov, R.M. and Sluzhenikin, S.F. 2018. New insights on the origin of ultramafic-mafic intrusions and associated Ni-Cu-PGE sulfide deposits of the Noril'sk and Taimyr provinces, Russia: evidence from radiogenic and stable-isotope data. *S. Mondal, W.L. Griffin (Eds.), Processes and Ore Deposits of Ultramafic-Mafic Magmas Through Space and Time. Elsevier Inc., Chapter 7, 197-238.*

974. Yu, J., Zhang, C., **O'Reilly, S.Y.**, **Griffin, W.L.**, Linga, H., Suna, T. and Zhou, X. 2018. Basement components of the Xiangshan-Yuhuashan area, South China: Defining the boundary between the Yangtze and Cathaysia blocks. *Precambrian Research, 309, 102-122.*

976. **LeVaillant, M.**, **Fiorentini, M.** and Barnes, S. 2018. Review of predictive and detective exploration tools for magmatic Ni-Cu-(PGE) Deposits, with a focus on komatiite-related systems in Western Australia. *In: Mondal, S. and Griffin, W.L. (Eds.), Processes and Ore Deposits of Ultramafic-Mafic Magmas Through Space and Time. Elsevier Inc., Chapter 2, 47-78.*

978. Begg, G.C., **Hronsky, J.M.A.**, **Griffin, W.L.** and **O'Reilly, S.Y.** 2018. Global- to district-scale controls on orthomagmatic Ni-Cu(-PGE) and PGE reef deposits. *In: S. Mondal, W.L. Griffin (Eds.), Processes and Ore Deposits of Ultramafic-Mafic Magmas Through Space and Time. Elsevier Inc., Chapter 2, 1-46.*

980. Duda, J.-P., Thiel, V., Bauersachs, T., Mißbach, H., Reinhardt, M., Schäfer, N., **Van Kranendonk, M.J.** and Reitner, J. 2018. Ideas and perspectives: hydrothermally driven redistribution and sequestration of early Archaean biomass - the "*hydrothermal pump hypothesis*". *Biogeosciences, 15, 1535-1548.*

984. **Foley, S.F.** and **Pintér, Z.** 2018. Primary melt compositions in the Earth's mantle. *In: Y. Kono, C. Sanloup (Eds.), Magmas under pressure: advances in high-pressure experiments on structure and properties of melts, Chapter 1, Elsevier, 3-42.*

990. Sun, X., **Lu, Y.-J.**, **McCuaig, T.C.**, Zheng, Y.-Y., Chang, H-F., Guo, F., Liu, Y. and Xu, L.-J. 2018. Miocene ultrapotassic, high-Mg dioritic, and adakite-like rocks from Zhunuo in Southern Tibet: Implications for metasomatism of the mantle and porphyry copper mineralization in collisional orogens. *Journal of Petrology, 59, 341-386.*

992. Gao, Y.-Y., **Griffin, W.L.**, Chu, M.-F., **O'Reilly, S.Y.**, **Pearson, N.J.**, Li, Q.-L., Liu, Y., Tang, G.-Q. and Li, X.-H. 2018. Constraints from zircon Hf-O-Li isotopic compositions on the genesis of slightly low-$\delta^{18}O$ alkaline granites in the Taohuadao area, Zhejiang Province, SE China. *Journal of Asian Earth Sciences, 167, 197-2018.*

993. **Shafaii Moghadam, H.**, **Griffin, W.L.**, Li, X.-H., Santos, J.F., Karsli, O., Stern, R.J., Ghorbani, G., **Gain, S.**, **Murphy, R.** and **O'Reilly, S.Y.** 2018. Crustal evolution of NW Iran: Cadomian arcs, Archean fragments and the Cenozoic magmatic flare-up. *Journal of Petrology, 58, 2143-2190.*

999. Witt, W.K., Cassidy, K.F., **Lu, Y.-J.** and Hagemann, S.G. 2018. The tectonic setting and evolution of the 2.7 Ga Kalgoorlie - Kurnalpi Rift: a world-class Archean gold province. *Mineralium Deposita*, *https://doi. org/10.1007/s00126-017-0778-9.*

1006. Witt, W.K., Cassidy, K.F., **Lu, Y-J.** and Hagemann, S.G. 2018. Syenitic Group intrusions of the Archean Kurnalpi Terrane, Yilgarn Craton: hosts to ancient alkali porphyry gold deposits? *Ore Geology Reviews, 96, 262-268.*

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Appendix 6: 2018 Abstract titles

A FULL LIST OF CCFS ABSTRACTS FOR CONFERENCE PRESENTATIONS IS AVAILABLE AT: http://www.ccfs.mq.edu.au/

Origins of life, Gordon Research Conference, Galveston, Texas, USA, 14-19 January 2018	Insights for origins of life from the earliest convincing record of life on Earth **T. Djokic, M.J. Van Kranendonk,** M.R. Walter, K.A. Campbell and C.A. Ward **Invited**
International Diamond School, Bressanone, Italy, 28 January - 3 February 2018	Mystery mineral in Jericho eclogite: A constraint on mantle metasomatism **S. Greene**, **D. Jacob** and L. Heaman
49th Lunar and Planetary Science Conference, Woodlands, Texas, USA, 19-23 March 2018	Atomic scale depth profile of space weathering in an Itokawa olivine grain L. Daly, M.R. Lee, L.J. Hallis, P.A. Bland, **S.M. Reddy**, D.W. Saxey, W.D.A. Rickard, **D. Fougerouse**, N.E. Timms and F. Jourdan U-Pb Chronology of Apollo 17 samples **A.A. Nemchin**, M.J. Whitehouse, J.F. Snape, F. Thiessen and R.T. Pidgeon Apollo 17, Station 2, Boulder 1: Revisiting Consortium Indomitabile D.A. Kring, D.H. Needham, R.J. Walker, **A.A. Nemchin** and H.H. Schmitt Deformation microstructures preserved in zircon and monazite from the Yarrabubba impact structure, Western Australia **T.M. Erickson**, **C.L. Kirkland** and N.E. Timms Terrestrial hot springs and the origin of life: Implications for the search for life beyond Earth **M. Van Kranendonk**, **R. Baumgartner**, E. Boyd, S. Cady, K. Campbell, A. Czaja, B. Damer, D. Deamer, **T. Djokic**, **M. Fiorentini**, A. Gangidine, J. Havig, A. Mulkidjnian, S. Ruff and P. Thordarson
The Royal Society, Earth dynamics and the development of plate tectonics, London, UK, 19-20 March 2018	The inception of plate tectonics on terrestrial planets **C. O'Neill** **Keynote**
EGU General Assembly 2018, Vienna, Austria, 8-13 April 2018	Contributions of microstructure and crystallographic preferred orientation to seismic anisotropy in the lower continental crust B. Almqvist, **D. Cyprych, S. Piazolo** and M. Bazargan Have mantle get crust - Consequences of fluid-peridotite interaction for continental crust composition **A. Beinlich**, H. Austrheim, V. Mavromatis, B. Grguric, C. Putnis and A. Putnis **Invited** The "*hidden*" craton in the Adria plate: evidence from geochemistry and Re-Os of mantle xenoliths from Veneto Volcanic Province (North-East Italy) V. Brombin, C. Bonadiman, M. Coltorti, **O. Alard**, **Y. Gréau**, **S.Y. O'Reilly**, **W.L. Griffin** and A. Marzoli Hydrating the Earth's deep, dry crust **C. Clark**, M. Hand, **T. Erickson** and **S. Reddy** Monitoring the evolution and mineralization of porphyry systems by using the geochemical inventory of apatite **J. Hammerli**, A. Kemp, **M. Fiorentini** and P. Blevin A new melt contamination model for the generation of "I-type" granitic rocks by melting heterogeneous lower crust **J. Hammerli**, A. Kemp and T. Shimura LLSVP survival from an early Earth mantle: analysing stability beneath a stagnant-lid P. Heron, **C. O'Neill**, **S. Zhang** and J. van Hunen

EGU General Assembly 2018, Vienna, Austria, 8-13 April 2018 *cont.*	'*Water*' poor rock forming constituents in upper mantle xenoliths and their possible implications from the Nógrád-Gömör Volcanic Field (Northern Pannonian Basin) **N. Liptai**, L. Patkó, I. Kovács, L. Aradi, **W. Griffin**, **S. O'Reilly**, V. Wesztergom and C. Szabó Including magnetotelluric data into multi-observable probabilistic inversion: implications for the physical state and water content of the continental lithosphere **M.C. Manassero, J.C. Afonso**, F.I. Zyserman, S, Zlotnik, M. Rosas-Carbajal and **S. Thiel** Deformation-induced metasomatism of the lower crust: The importance of brittle mechanisms for fluid infiltration revealed by microstructures at a hydration interface J. Moore, H. Austrheim, **A. Beinlich** and A. Putnis Nano-correlative microscopy (TEM/APT) constrains the nature and timing of nanoclusters formation in monazite crystals A.-M. Seydoux-Guillaume, **D. Fougerouse**, A. Laurent, **S. Reddy** and D. Saxey Multi-scale magnetic mapping of serpentinite carbonation and its future application for deep submergence magnetometry M. Tominaga, **A. Beinlich**, N. Vento, E. Ortiz, J. Greene, J. Einsle, E. Lima and B. Weiss **Invited** Geochemical characteristics of mantle xenoliths from the Khamar Daban Ridge, south Russian Siberia **K.-L. Wang**, S. D'ril, **S. O'Reilly**, M.Kuzmin, **W. Griffin** and **N. Pearson**
International Workshop of Deep Earth Dynamics, Nanjing, China, 24 April 2018	Geodynamic processes during heroic collisions: integration of geochemical, microstructural and geodynamic information **S.Y. O'Reilly**, **W.L. Griffin**, **Q. Xiong**, **J.C. Afonso** and T. Satsukawa Imaging lithosphere structures using broadband surface waves from ambient noise **Y. Yang** Super reducing conditions in ancient and modern volcanic systems: implications for the carbon budget of the deep lithosphere **W.L. Griffin**, **J-X. Huang**, E. Thomassot, **S.E.M. Gain**, V. Toledo and **S.Y. O'Reilly**
12th General Assembly of the Asian Seismological Commission (ASC), Chengdu, China, 12-14 May 2018	Sensitivity kernels for multi-component ambient noise cross correlation functions: Love wave adjoint tomography in southern California **Y. Yang**, **K. Wang** and Q. Liu
15th AOGS Annual Meeting, Honolulu, 3-8 June 2018	3-D crustal and upper mantle velocity structure beneath the Cenozoic Intraplate Volcanic Belt in Northeast China **A. Guo**, **K. Wang**, **Y. Yang** and J. Chen Crustal structure of the Canning Basin, NW Australia: Preliminary results R. Murdie, **H. Yuan**, **K. Gessner**, K. Wang, T. Li and X. Xu Lithospheric structure underneath the Ordos Block of the North China Craton, revisited using transdimensional inversion of ambient noise and surface wave dispersion K. Wang, T. Li, L. Yuan, X. Xu, L. Zhao, **H. Yuan** and T. Bodin Finite-frequency P Wave tomography of the upper mantle beneath Capricorn Orogen and adjacent areas X. Xu, L. Zhao, **H. Yuan**, S. Johnson, M. Dentith, R. Murdie, **K. Gessner**, F. Korhonen and P. Varas Refined seismic structure of Southern California by ambient noise adjoint tomography **Y. Yang**, **K. Wang**, P. Basini, P. Tong, Q. Liu and C. Tape **Invited** Crustal velocity structure of the Paleoproterozoic Capricorn Orogen in the West Australian Craton **H. Yuan**, M. Dentith, P. Varas, S. Johnson, R. Murdie, **K. Gessner** and F. Korhonen
RFG 2018 Resources for Future Generations 2018, Vancouver, Canada, 16-22 June 2018	New instrumentation for high throughput carbon and oxygen isotope analysis of carbonate minerals S. Barker, B. Andrew, J. Mering, P. Jarman, G. Dipple and **A. Beinlich** Mapping the whole lithosphere: Uncovering metallogenic truths G. Begg, **W. Griffin**, **S. O'Reilly**, J. Hronsky and **L. Natapov** A heterogeneous, ancient lithosphere - Constraints for more robust models G. Begg, **W. Griffin**, **S. O'Reilly** and **L. Natapov** Defining the carbonate alteration footprint of the Cortez Hills Carlin-Type gold deposit, Nevada Using ^{13}C and ^{18}O stable isotopes and geochemistry C. Herron, G. Dipple, K. Hickey and **A. Beinlich**

RFG 2018 Resources for Future Generations 2018, Vancouver, Canada, 16-22 June 2018 *cont.*	Spatially-constrained sulfur isotopes highlight processes controlling sulfur cycling in the near surface of the Iheya North hydrothermal system **C. LaFlamme** Decoding Earth's rhythms: Modulation of supercontinent cycles by longer superocean cycles **Z.-X. Li**, **R. Mitchell**, C. Spencer, R. Ernst, **S. Pisarevsky** and **U. Kirscher** and **B. Murphy** Distinctive chemical characteristics, geodynamic settings and petrogenesis of gold-ore-forming arc magmas **R.R. Loucks** **Invited** CO_2 availability controls whether hydrotalcites or hydrated Mg-carbonates act as carbon sinks in serpentinite mineral wastes from the Woodsreef Chrysotile Mine, NSW, Australia C. Turvey, S. Wilson, J. Hamilton, A. Tait, J. McCutcheon, **A. Beinlich**, S. Fallon, G. Dipple and G. Southam Th/U ratios in high-temperature metamorphic zircon C. Yakymchuk, **C. Kirkland** and **C. Clark**
Joint 5th Central European Mineralogical Conference (CEMC) - 7th Mineral Sciences in the Carpathians Conference (MSCC), Banská Štiavnica, Slovakia, 26-30 June 2018	Neogene evolution of the lithospheric mantle beneath the Nógrád-Gömör Volcanic Field **N. Liptai**, L. Patkó, L.E. Aradi, I.J. Kovács, K. Hidas, **S.Y. O'Reilly**, **W.L. Griffin** and C. Szabo
Astrobiology Australasia Meeting (AAM), Rotorua, New Zealand, 25-26 June 2018	Records of early life: Context and preservation are key **E.V. Barlow** and **M.J. Van Kranendonk** The power of textural biosignatures in the search for life on Mars **T. Djokic**, **M.J. Van Kranendonk** and K.A. Campbell Links between phosphorus, evolution and astrobiology **G.G. Soares**, **M.J. Van Kranendonk**, **E. Belousova** and S. Thomson
3rd EMAW, European Mantle Workshop, Pavia, Italy, 26-28 June 2018	*In-Situ* Re-Os analyses of sulfides in mantle xenoliths: New constraints on the cratonic signature of the Veneto Volcanic Province (North-East Italy) V. Brombin, C. Bonadiman, M. Coltorti, **O. Alard**, **Y. Gréau**, **S.Y. O'Reilly**, **W.L. Griffin** and A. Marzoli Kimberlite carbonate petrogenesis from combined compositional and C-O-Sr isotope analysis: The Benfontein case **M. Castillo-Oliver**, **A. Giuliani**, **W.L. Griffin**, **S.Y. O'Reilly**, R. Drysdale, E. Thomassot, X. Ling and X. Li Camping in the Ivrea Zone, Italy **M. Fiorentini**, **S. Denyszyn, G. Dering** and R. Maas Olivine, kimberlites and the modification of carbonated melts in the deep Earth **A. Giuliani**, A. Soltys, E. Lim, H. Farr, D. Phillips, **S.F. Foley** and **W.L. Griffin** Sources and behaviour of carbon-rich fluids in the lithospheric mantle: Insights from off-craton **W.L. Griffin**, **J. Huang**, **S. Gain**, V. Toledo and **S.Y. O'Reilly** Microstructure of layered ultramafic cumulates: case study of the Bear Creek intrusion, Trinity ophiolite, California, USA **H. Henry**, G. Ceuleneer, **S.Y. O'Reilly**, **W.L. Griffin**, **M.A. Kaczmarek**, M. Gregoire and **R. Tilhac** Localization of deformation: The role of metasomatism and mineral mode in an ocean-continent transition **M.A. Kaczmarek**, P. Vonlanthen and **S. Reddy** Water and its distribution in the upper mantle beneath the Pannonian-Basin: Geodynamical and geophysical implications I.J. Kovács, V. Wesztergom, L. Patkó, L. Aradi, **N. Liptai**, G. Falus, C. Szabó and L. Lenkey **Keynote** Reconstructing geochemical and deformation events in mantle xenoliths from the Northern Pannonian Basin **N. Liptai,** Patkó L., **O'Reilly S.Y.**, **Griffin W.L.** and Szabó C. Tracking the sources of metasomatic melts in the Finero Mafic Complex, Ivrea-Verbano zone **J.K. Munnikhuis**, **N. Daczko**, A. Langone and S. Piazolo Geochemical, microstructural and tectonic evidence for geodynamic processes during heroic collision events **S.Y. O'Reilly**, **W.L. Griffin**, **Q. Xiong**, **J. Afonso** and T. Satsukawa

3rd EMAW, European Mantle Workshop, Pavia, Italy, 26-28 June 2018 *cont.*	A diffusion-controlled trace-element disequilibrium model for two-phase reactive transport in mafic-ultramafic systems **B. Oliveira**, **R. Tilhac** and **J.C. Afonso** Low water content in upper mantle xenoliths from the Nógrád-Gömör Volcanic Field (Northern Pannonian Basin): Geodynamic implications and the role of post-eruptive water loss L. Patkó, **N. Liptai**, I.J. Kovács, L. Aradi, Q. Xia, J. Ingrin, J. Mihály, **S.Y. O'Reilly**, **W.L. Griffin**, V. Wesztergom and C. Szabó Amphibole as window on the Archean mantle composition G. Sessa, M. Tiepolo, **M.L. Fiorentini**, M. Moroni and A. Langone Evidence of Nb/Ta heterogeneity in the Earth's mantle M. Tiepolo, **M. Fiorentini**, G. Sessa, M. Moroni and A. Langone Hafnium-neodymium isotopic decoupling during the formation of arc pyroxenites (Cabo Ortegal Complex, Spain) **R. Tilhac**, **W.L. Griffin**, **S.Y. O'Reilly**, **B.F. Schaefer**, Ceuleneer G. and Grégoire M.
Geoanalysis 2018, Sydney, Australia, 8-13 July 2018	Exploring the range of U-containing minerals for geochronological applications **E. Belousova** Li abundances of magmatic zircons in Eocene-Oligocene porphyry Cu mineral systems of Yunnan, China M.-F. Chu, Y.-Y. Gao, Q.-L. Li, Y.-J. Lu, X.-H. Li and **S.Y. O'Reilly** The effect of laserprobe optical path design on laser ablation of minerals with low melting points L. Danyushevsky, S. Gilbert, J. Thompson, P. Olin and **O. Alard** Determination of nitrogen in experimental and natural samples using EPMA and CHNS analyser **M.W. Förster**, S. Buhre, **O. Alard** and **S.F. Foley** Assessment of trace-element homogeneity in gem quality zircons from Mud Tank, NT **S.E.M. Gain**, **E.A. Belousova**, **N.J. Pearson**, I. Dainis and **W.L. Griffin** Isotopic heterogeneity of the Pre-Ordovician Earth's crust of the western part of the Central Asian Fold Belt (CAFB) based on LA-ICP-MS study of detrital zircons N.B. Kuznetsov, T.V. Romanjuk, **E.A. Belousova**, K.E. Degtyarev, V.S. Sheshukov, A.S. Dubenskiy, N.A. Kanygina and S.M. Lyapunov Struggle with inhomogeneously quenched melts **Z. Pintér**, **S.F. Foley**, G.M. Yaxley and **T. Rushmer** LA-ICP-MS analysis routine for trace elements in olivine **M. Veter**, **S.F. Foley** and **D.E. Jacob**
10th International Conference on Analysis of Geological and Environmental Materials, Sydney, Australia, 8-13 July 2018	Struggle with inhomogenously quenched melts - An approach to standardize their major element measurements **Z. Pintér**, **S.F. Foley**, G.M. Yaxley and **T. Rushmer**
Landscapes, Seascapes and Biota: Unique WA - Past, Present and Future, Royal Society of WA, Perth, Australia, 27-28 July 2018	The Archean of WA: from the earliest crust to the onset of life on Earth **S.A. Wilde** and A.H. Hickman **Keynote**
24th EM Induction Workshop, Helsingor, Denmark, August 2018	Measuring the hydrogen content variations in Southern African mantle S. Ozaydin and **K. Selway** Using MT to constrain Greenland's glacial isostatic adjustment and ice loss **K. Selway** and C. Conrad Unextractable partial melt in the asthenosphere: Evidence from new geophysical constraints **K. Selway** and J.P. O'Donnel

Goldschmidt 2018, Boston, USA, 12-17 August 2018	Heavy $\delta^{30}Si$ in Archean granitoids as evidence for supracrustal components in their sources A. Andre, K. Abraham, **S.F. Foley** and A. Hofmann
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	Olivine, kimberlites and the modification of carbonated melts in the deep Earth **A. Giuliani**, A. Soltys, E. Lim, H. Farr, D. Phillips, **S.F. Foley** and **W.L. Griffin**
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	The OCT-Type ophiolite recognized from the Bangong-Nujiang Suture Zone, Central Tibet R. Shi, X. Huang, **W. Griffin**, **S. O'Reilly**, Q. Huang and S. Chen
	Phosphogenesis in the wake of the Great Oxidation Event: Evidence from the Turee Creek Group, W.A **G.G. Soares**, **M.J. Van Kranendonk**, **E. Belousova** and S. Thomson
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	An EPMA, LA-ICPMS and fluid inclusion study on the growth of a single cassiterite crystal from Blue Tier, Tasmania **J. Bennett**
	Hybrid lithologies in the source of diamonds from Copeton and Bingara, NSW, Australia A. Burnham, **B. Griffin** and H. O'Neill
	The origin of carbonates in the Benfontein kimberlite sills: An *in situ* C-O-Sr approach **M. Castillo-Oliver**, **A. Giuliani, W.L. Griffin, S.Y. O'Reilly**, R.M. Drysdale, X. Ling and X.H. Li
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	Nanoscale behaviour of platinum group elements A. Deditius, F. Barra, J.-M. Gonzalez-Jimenez, M. Reich, S. Sperring, A. Suvorova, **M. Kilburn** and M. Roberts
	Melt evolution of the Finsch orangeite, South Africa H. Farr, **A. Giuliani** and D. Phillips
	Sr-Nd-Hf-Pb isotope compositions of MARID and PIC minerals: progressive metasomatism of the mantle by kimberlitic melts processes and diamond prospecting A. Fitzpayne, **A. Giuliani**, R. Maas, J. Hergt, D. Phillips and P. Janney
	The relationship between alkaline magma generation and the stability of continental lithosphere **S. Foley**
	Nitrogen partitioning in subduction zone processes **M.W. Förster**, D. Prelević, S. Buhre and **S.F. Foley**
	Unusual alluvial sapphires from Orosmayo, Argentina: A multi-analytical approach to decipher their origin and evolution I. Graham, S. Harris, **L. Martin**, A. Lay, **W. Powell**, **E. Belousova** and E. Zappettini
	Super-reducing conditions in a modern volcanic system: Implications for the carbon budget of cratonic lithosphere **W. Griffin**, **S. Gain**, **J. Huang**, V. Toledo and **S.Y. O'Reilly**
	Modeling the physical properties of multiphase rock assemblage **K. Han** and **S. Clark**
	Hydrous melting of labradorite: An electrical conductivity investigation **A. Lanati**, **G. Amulele** and **S. Clark**

XXII Meeting of the International Mineralogical Association, Melbourne, Australia, 13-17 August 2018 *cont...*	Evolution of the Manuka Mississippi Valley type deposit through its smoky quartz crystals A. Lay, S. Harris, I. Graham, D. Colchester, **L. Martin**, K. Privat, J. Bennett, A. Stopic, **N. McGowan** and **L. Spruzeniece** The effect of C-O-H fluids on partial melting of eclogite and lherzolite under reducing conditions **Z. Liu**, A. Rohrbach, S. Klemme, **S. Foley** and J. Berndt Neutron computed tomography: A new approach to measure grain-boundary proton diffusion in polycrystalline forsterite matrix **S. Patabendigedara**, **S. Clark** and F. Salvemini The composition of the melts in the incipient melt regime **Z. Pintér**, **S.F. Foley**, G.M. Yaxley and **T. Rushmer** Determination of the oxidation state of iron in natural peridotitic and eclogitic garnets by synchrotron Mössbauer spectroscopy A. Rosenthal, **C. McCammon**, W. Crichton, V. Cerantola, A. Chumakov, P. Vasilyev, M. Laubier, D. Andrault, **D. Jacob**, G. Yaxley, A. Woodland, **S. Foley**, G. Pearson, D. Laporte, R. Njul and H. Schulze Apatite from southern African kimberlites: Petrography and mineral chemistry A. Soltys, **A. Giuliani** and D. Phillips Distinguishing coherent kimberlite units of the Ekati Diamond Mine - Implications for emplacement processes and diamond prospecting M. Tovey, **A. Giuliani** and D. Phillips The signature of cratonic lithosphere root formation modes in olivine and orthopyroxene trace element compositions **M. Veter** and **S.F. Foley** Geographic typing of gem corundum taken a step further via *in-situ* oxygen isotope and trace element analysis: the example of Paranesti, Greece K. Wang, I. Graham, **L. Martin**, P. Voudouris, A. Lay, S. Harris, **E. Belousova**, G. Giuliani and A. Fallick
European Microbeam Analysis Society (EMAS 2018), Bristol, UK, 4-7 September 2018	Isotopic imaging of minerals with NanoSIMS **M.R. Kilburn** **Invited**
IMC19, 19th International Microscopy Congress, Sydney, Australia, 9-14 September 2018	A showcase of analytical techniques: V metal in hibonite **S.E.M. Gain**, **W.L. Griffin**, V. Toledo, M. Saunders, J.A. Shaw and **S.Y. O'Reilly** Elemental and isotopic imaging using NanoSIMS P. Guagliardo, H. Jiang, J. Bougoure, **L. Martin** and **M. Kilburn** Stable isotope labelling and imaging mass spectrometry as a tool to investigate mineral-fluid interaction **M. Kilburn**, **M. Fiorentini**, **S. Piazolo** and **T. Rushmer**
9th International SHRIMP Meeting, Ochang, South Korea, 10-15 September 2018	Did the Albany-Fraser Province go west? **S. Wilde**
First Workshop of Project IGCP-662 Orogenic Architecture and Crustal Growth from Accretion to Collision, Beijing, China, 20-22 September 2018	Crust-mantle interaction in the formation of the Kalmakyr and Muruntau ore giants, Uzbekistan A. Dolgopolova, R. Seltmann, R. Armstrong, **E. Belousova** and D. Konopelko Paleoproterozoic crustal growth of the Siberian craton T.V. Donskaya, D.P. Gladkochub, A.M. Mazukabzov and **S.A. Pisarevsky** UHP versus Super-Reducing parageneses in Tethyan ophiolites **W. Griffin**, **J.-X. Huang**, **Q. Xiong**, X.-H. Gong and **S.Y. O'Reilly** **Invited** Tracing the final collision of accretionary orogens: New magmatic constraints from the southern Central Asian Orogenic Belt S. Li, T. Wang, W.-J. Xiao, S.-L. Chung and **S.A. Wilde** Geodynamic processes during heroic collisions: Integration of geochemical, microstructural and geodynamic information **S.Y. O'Reilly**, **W.L. Griffin**, **Q. Xiong**, **J-C. Afonso** and T. Satsukawa **Invited**

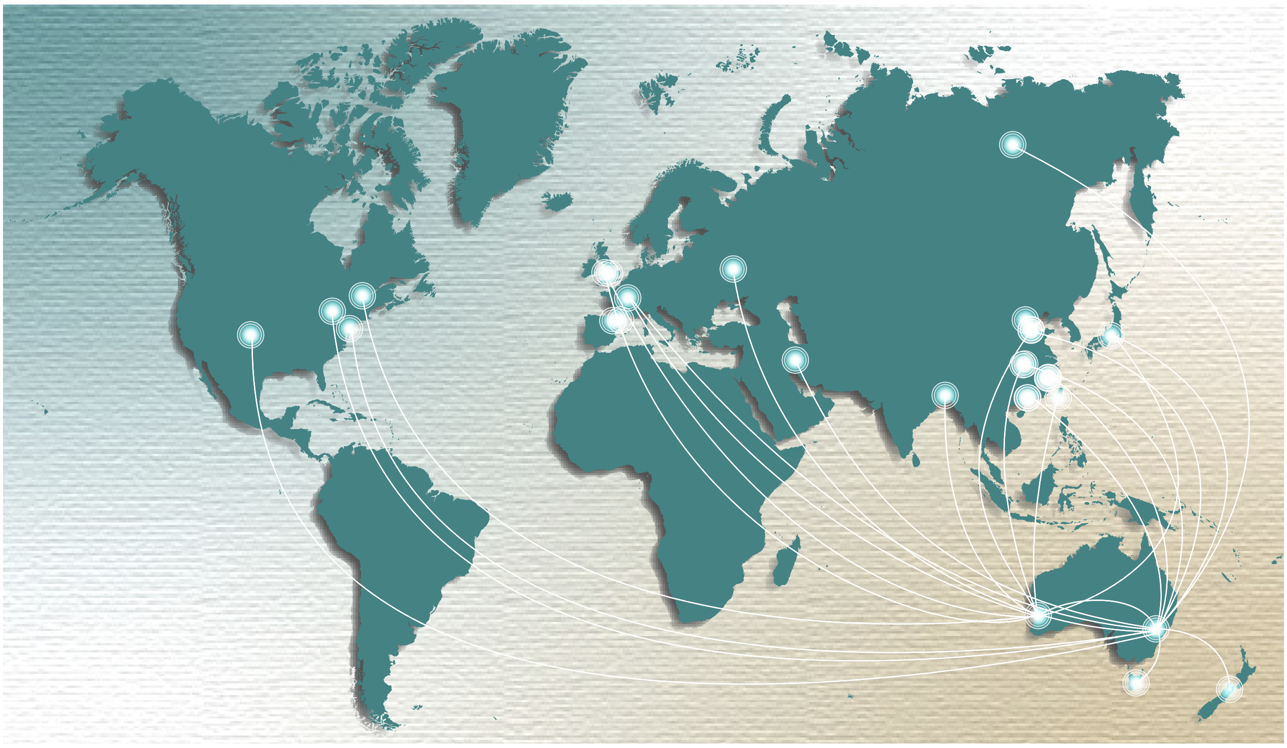
SEG 2018-Metals, Minerals and Society, Keystone, Colorado, USA, 22-25 September 2018	PGE-Au signature of alkaline magmas from the Yilgarn Craton: Insights into the metallogenic architecture of the lithospheric mantle **E. Choi**, **M. Fiorentini**, **A. Giuliani** and **S.F. Foley** Integrating petroleum and minerals systems approaches to sedimentary basins R. Chuchla and **T.C. McCuaig** **Plenary** The implication of Early Architecture for gold endowment in a low strain environment: The Yaouré Gold Deposit C. d'Ivoire, N. Mériaud, **N. Thébaud** and Q. Masurel New insights into zircon fertility indicators for porphyry copper deposits: Deciphering the adakitic signatures in Patagonia **G.J. Henriquez**, **R.R. Loucks**, **M.L. Fiorentini** and C.M. Allen Structural evolution of the El Indio Belt (Chile-Argentina): from Zircons to Gold **C. Jara**, **M. Fiorentini**, **H. Jeon**, M. Fanning, J. Miller and D. Winocur 3D mineral footprints of an undercover sediment-hosted polymetallic Abra Ore System, Western Australia **H.M. Lampinen**, C. Laukamp, S.A. Occhipinti and L. Hardy Basement architecture controls for sediment-hosted base-metal mineral systems in the Mesoproterozoic Edmund Basin, Western Australia **H.M. Lampinen**, S.A. Occhipinti, M.D. Lindsay and **M. Fiorentini** Distinctive chemical characteristics, geodynamic settings, and petrogenesis of gold ore-forming arc magmas **R.R. Loucks** Whole-rock and zircon fertility indicator of Archean granites **Y.-J. Lu**, R.H. Smithies, **M.T.D. Wingate**, N. Evans, D. Champion and **T.C. McCuaig** The power of a systems approach to minerals and petroleum exploration in sedimentary basins **C. McCuaig** **Invited** Permian magmatism in an early Andean metallogenic belt, Cordillera Frontal, Argentina **G.H. Poole**, S.G. Hagemann, A.I. Kemp, **M.L. Fiorentini** and E.O. Zappettini Origin of collision-related porphyry copper deposit at Zhunuo in western Gangdese belt of southern Tibet A. Sun and **Y.-J. Lu**
Tethys Dynamics Workshop, Beijing, China, 8-9 October 2018	Crustal structure beneath coastal NW Australia: seismic signature from paleo-collision to modern rifting **H. Yuan** and the CWAS Team **Invited**
AGCC Australian Geoscience Council Convention - Big Issues and Ideas in Geoscience, Adelaide, Australia, 14-18 October 2018	Reappraisal of MORB redox state using both Fe and S speciation **O. Alard**, C. Baudouin, **M. Chassé**, F. Parat and M. Munoz From geosystem to mineral system: Contextualising ore deposits G. Begg, **W. Griffin**, **S. O'Reilly** and J.M.A. Hronsky **Keynote** Multiple sulfur isotopes as indelible tracers of ore-forming processes in magmatic and hydrothermal mineral systems **S. Caruso**, **M. Fiorentini** and **C. LaFlamme** Insights into the magmatic and hydrothermal evolution of the Black Swan Succession: Evidence from microchemical and sulfur isotope investigation **S. Caruso**, **M. Fiorentini**, S. Barnes, **C. LaFlamme** and **L. Martin** Fingerprinting mantle plume activities in the oceanic realm through time **L.S. Doucet** GSA Ringwood Medal Lecture: Illuminating mantle metasomatism **S. Foley** **Keynote** Exploring the potentially early evolution of complex life **G.G. Soares** and **M.J. Van Kranendonk** Deep structures in the Pilbara Craton, WA, and their relationship to overlying deformation, mineralisation and kimberlite emplacement L. Harris and **Y.-J Lu** Detrital zircon age, oxygen and hafnium isotope systematics record rigid continents after 2.5 Ga **L. Iaccheri**, A. Kemp and Edinburgh Ion Microprobe Facility (EIMF)

AGCC Australian Geoscience Council Convention - Big Issues and Ideas in Geoscience, Adelaide, Australia, 14-18 October 2018 *cont...*	Long lived supercontinent Nuna - updated paleomagnetic constraints from Australia **U. Kirscher**, **R.N. Mitchell**, Y. Liu, **Z.X. Li**, G.M. Cox and **S. Pisarevsky** Shallow crustal structure of southeast Australia constrained by Rayleigh wave phase velocity and Z/H ratio **G. Li**, **H. Wu** and **Y. Yang** Decoding Earth's rhythms: Modulation of supercontinent cycles by longer superocean cycles **Z.X. Li**, **R. Mitchell**, C. Spencer, R. Ernst, **S.A. Pisarevsky**, **U. Kircher** and **B. Murphy** Whole crustal structure revealed by the Perth Basin Seismic (PBS) Array X. Lin, **H. Yuan**, M. Dentith, R.E. Murdie and **K. Gessner** First Precambrian palaeomagnetic data from the Mawson Craton (East Antarctica) and tectonic implications **Y. Liu**, **Z.X. Li**, **S.A. Pisarevsky**, **U. Kirscher**, **R. Mitchell**, **J. Stark**, **C. Clark** and M. Hand Zircon composition as a fertility indicator of Archean granites **Y.-J. Lu**, R.H. Smithies, **M.T.D. Wingate**, N. Evans, D. Champion and **T.C. McCuaig** Whole Earth harmonics **R. Mitchel**, **U. Kirscher**, G. Cox, R. Ernst, W. Collins, C. Spencer, **S.A. Pisarevsky**, **L. Doucet** and **Z. Li** Australian space and planetary capabilities: Implications for Earth Sciences **C. O'Neill** Could meteorite bombardment have kick-started the plate tectonic machine? **C. O'Neill** Decadal Plan for Geoscience: Our planet, Australia's future - A decade of transition in Geoscience **S.Y. O'Reilly** **Keynote** Development of the Global Paleomagnetic Database and new global paleogeographic animation for 2000-1600 Ma **S.A. Pisarevsky** Northeast-Australian collisional tectonics during the assembly of Nuna unravelled by multi-method petrochronology **A. Pourteau** Unravelling the structural and metamorphic evolution from MT-MP to LP-HT: A journey through the crust in the Georgetown Inlier (NE Australia) **S. Volante** Long-lived connection between the North China and North Australia cratons (NCC NAC) in the supercontinent Nuna: New palaeomagnetic constraints **C. Wang**, **Z. Li**, P. Peng, **S.A. Pisarevsky** and **Y. Liu** A global full-plate reconstruction model for the last 2.0 Ga **L. Wu**, **Z.X. Li** and **S.A. Pisarevsky** Insights into changes in crust formation processes at the Archean-Proterozoic Transition from receiver functions: Capricorn Orogen, Western Australia **H. Yuan**, **Y.-J. Lu**, R.E. Murdie, M. Dentith, S.P. Johnson and **K. Gessner** The effects of supercontinent size on the global mantle structures **N. Zhang**, **Z. Li** and C. Huang
Fourth landing site workshop for the Mars 2020 rover mission, 16-18 October 2018, Glendale CA, USA	Origin and Significance of Opaline Silica Deposits at Columbia Hills K.A. Campbell, **T. Djokic**, **M.J. Van Kranendonk**, S.W. Ruff, J.D. Farmer, C. Sriaporn, K.M. Handley, M. Millan, **B. Teece** and D.M. Guido From Planetary Evolution to Potential Biosignatures: Achieving Mission Success with the Mars 2020 Rover and Instrument Suite at the Columbia Hills Site S.W. Ruff, V. Hamilton, D. Rogers, C. Edwards, B. Horgan, and **M. Van Kranendonk** A Mars 2020 Mission to Columbia Hills: Risk Minimization through Ground Truth **M.J. Van Kranendonk**, S. Ruff, K.A. Campbell, and **T. Djokic**
Annual Meeting of Chinese Geoscience Union, Beijing, China, 19-23 October 2018	Joint inversion of surface waves and teleseismic body waves for sedimentary structures **Y. Yang**, G. Li and F. Niu **Invited**

GSA Earth Sciences Student Symposium, Western Australia (GESSS-WA), Australia, 29 November 2018	Multiple sulfur isotopes as indelible tracers of ore-forming processes in magmatic and hydrothermal mineral systems **S. Caruso**, **M. Fiorentini** and **C. LaFlamme** Metamorphism and hydrothermal alteration in relation to mineralisation of the Harris Lake Shear Zone, Albany- Fraser orogen, Western Australia **J. Chard**, **C. Clark** and **C. Kirkland** Alkaline magmatism as a probe into the mantle under the Yilgarn Craton, WA **E. Choi**, **M. Fiorentini**, **A. Giuliani** and **S.F. Foley** Self organising maps - a case study of Broken Hill **T. Gillfeather-Clark** and **L. Smith** New insights on porphyry-copper deposit fertility indicators: unfolding the adakitic signature in Patagonia **G.J. Henriquez**, **R.R. Loucks**, **M.L. Fiorentini** and C.M. Allen Hyperspectral detection for zoned mineral footprint around undercover sediment-hosted polymetallic Abra **H. Lampinen**, C. Laukamp, S. Occhipinti and L. Hardy Palaeomagnetism of a ca. 2.62 Ga dyke swarm in the Yilgarn Craton, Western Australia, and palaeogeographic implications **Y. Liu**, **Z.-X. Li**, **S.A. Pisarevsky**, **U. Kirscher** and **R.N. Mitchell** The origin of Cuyania revealed by Hf isotopes of zircon **E.L. Martin**, W. Collins and C.J. Spencer A thermochronological history of Lindås Nappe amphibolites based on combined microstructural and geochemical analysis of rutile J. Moore, **A. Beinlich**, J. Porter, C. Talavera, J. Berndt, **S. Piazolo**, H. Austrheim and A. Putnis Major shoreline retreat in the wake of Snowball Earth **A.R. Nordsvan**, **R.N. Mitchell**, **U. Kirscher** and M. Barham Permian magmatism related to porphyry and epithermal mineralisation in a Permian metallogenic belt, Cordillera Frontal, Argentina **G. Poole**, S. Hagemann, A. Kemp, **M. Fiorentini**, E. Zappettini, **H. Jeon**, I. Williams and N. Rubinstein Deformation and retrogression initiated by hydration along pre-existing fabrics: Using monazite and apatite to track and time geological events A.M. Prent, **A. Beinlich**, T. Raimondo, **C. Kirkland**, N. Evans and A. Putnis Growth of continental crust at island arcs revealed by high-precision geochronology J.E. Stirling, **S.W. Denyszyn**, **R.R. Loucks**, A.I.S. Kemp, **M.L. Fiorentini** and **J. Hammerli** Building the geological framework of the Kanowna Belle deposit for a methodical sulphur isotope application **D. Sugiono**, **N. Thébaud**, **C.K. LaFlamme**, **M.L. Fiorentini** and J. Rogers Trace element composition of sub-micrometre monazite inclusions in ultra-high temperature metamorphic rutile **R. Verberne**, **S.M. Reddy**, D.W. Saxey, **D. Fougerouse**, W.D.A. Rickard and **C. Clark** Unravelling the structural and metamorphic evolution of the Georgetown Inlier (NE Australia) **A. Volante**, W.J. Collins, **A. Pourteau**, **A. Nordsvan**, **E. Blereau**, **Z.-X. Li** and J. Li Sulphur sources and magmatic sulphide mineralisation in the Fraser Zone: Insights from mineral prospects A.T. Walker, K.A. Evans, **C.L. Kirkland**, **L. Martin**, O.C. Kiddie and C.C. Spaggiari
GSA Earth Sciences Student Symposium, Sydney, Australia (GESSS-NSW), 3-4 December 2018	Evolution of the Jericho kimberlite constrained by olivine macrocrysts **S. Greene**
American Geophysical Union (AGU) Fall Meeting, Washington DC, USA,10-14 December 2018	Parallel MCMC multi-algorithm strategies for the thermochemical structure of lithosphere **I. Fomin**, **J.C. Afonso** and M. Sambridge Spatial variations in crustal structure and shear wave velocity across the Canning Basin, NW Australia **K. Gessner**, R. Murdie, **H. Yuan** and L. Zhao Long lived supercontinent Nuna - updated paleomagnetic constraints from Australia **U. Kirscher**, **R.N. Mitchell**, Y. Liu, **Z.X. Li**, G.M. Cox, **A. Nordsvan**, C. Wang and **S. Pisarevsky**

American Geophysical Union (AGU) Fall Meeting, Washington DC, USA,10-14 December 2018 *cont...*	Paleomagnetism of a ca. 2.62 Ga dyke swarm in the Yilgarn Craton, Western Australia, and paleogeographic implications **Y. Liu**, **Z.X. Li**, **S.A. Pisarevsky**, **U. Kirscher** and **R. Mitchell** Sensitivity kernels for multi-component ambient noise empirical Green's functions based on adjoint method Q. Liu, **K. Wang** and **Y. Yang** Did Earth's first supercontinent form the inner core? **R.N. Mitchell**, G.M. Cox, J.G. O'Rourke, **Z.-X. Li**, C.J. Spencer, **U. Kirscher**, **N. Zhang**, **J.B. Murphy**, **A. Nordsvan** and P.D. Asimow Major shoreline retreat following Snowball Earth **A. Nordsvan**, **R. Mitchell**, **U. Kirscher** and M. Barham A multiphase multicomponent reactive transport formalism for disequilibrium melt-rock processes and geochemical geodynamics **A. Oliveira**, **J.C. Afonso** and **R. Tilhac** Global applicability of ultramafic serpentinization and carbonation magnetic mapping P.N. Pruett, M. Tominaga, N. Francis R. Vento, E. Ortiz, J.A. Greene, **A. Beinlich**, E.A. Lima, B.P. Weiss and P.N. Fulton The composition of the melts in the incipient melt regime **Z. Pintér**, **S.F. Foley**, G.M. Yaxley and **T. Rushmer** Development of the Global Paleomagnetic Database and new global paleogeographic animation for the last 2 Gy **S.A. Pisarevsky**, **Z.X. Li** and L. Wu Evidence for a 1.24-1.21 Ga large igneous province in the North China Craton **C. Wang**, **Z. Li**, P. Peng, **S.A. Pisarevsky** and **Y. Liu** Crustal radial anisotropy of Southern California revealed by multi-component ambient noise adjoint tomography **K. Wang**, Q. Liu and **Y. Yang** Insights into changes in crust formation mechanisms across the Archean-Proterozoic Transition: Receiver function observations in the Capricorn Orogen, Western Australia **H. Yuan**, R.E. Murdie, M. Dentith, S.P. Johnson, **K. Gessner** and **Y. Lu** Crustal and uppermost mantle structure of the alpine region unraveled by transdimensional inversion of receiver functions and surface wave dispersion data L. Zhao, **H. Yuan**, M.G. Malusa, G. Lu, A. Paul, **Y. Lu** and T. Bodin
National MT Workshop and AusLAMP SA Release Day, Adelaide, Australia, 5 December 2018	Continental architecture: The geosystem-mineral system connection G. Begg, **W. Griffin** and **S.Y. O'Reilly** Developing meaningful interpretations for MT models: Current state of play **K. Selway** **Invited**

Appendix 7: CCFS visitors



CCFS VISITORS 2018 (Excluding participants in conferences and workshops)

VISITOR	ORGANISATION	COUNTRY
Dr Chris Adams	Lower Hutt	New Zealand
Dr Graham Begg	Minerals Targeting International	Australia
Professor SM Mahbubul Ameen	Jahangirnagar University, Dhaka	Bangladesh
Professor Georges Beaudoin	Université Laval	Canada
Professor Hannes Brueckner	Lamont-Doherty Earth Observatory, Columbia University	USA
Mr Chunfei Chen	Chinese University of Geosciences, Wuhan	China
Mr Chun Chen	Division Chief of Mineral Exploitation Management Division, Tianjin Bureau of Land Resources Administration	China
Mr Qinfeng Chen	Deputy Director general of Dongli branch bureau, Tianjin Bureau of Land Resource Administration	China
Assistant Professor Mei-Fei Chu	National Taiwan University	Taiwan
Mr Hong-Kun Dai	Chinese University of Geosciences, Wuhan	China
Professor Alexander Dubenskiy	Geological Institute, Russian Academy of Sciences, Moscow	Russia
Ms Dong Fu	China University of Geosciences, Wuhan	China
Mr Mingdi Gao	China University of Geosciences, Wuhan	China
Ms Louise Hawkins	University of Liverpool	UK
Dr David Holwell	University of Leicester	UK
Mr Bo Huang	China University of Geosciences, Wuhan	China
Mr Zhenda Kang	Deputy Director, Tianjin Land Consolidation Center	China
Dr Xiangdong Lin	Beijing Seismological Bureau	China
Assistant Professor Xiangdong Lin	Earthquake Administration of Beijing	China
Ms Jing Liu	China Earthquake Administration	China

VISITOR	ORGANISATION	COUNTRY
Prof Julian Lowman	University of Toronto, Scarborough	Canada
Dr Vladimir Malkovets	Russian Academy of Sciences	Russia
Mr Alessandro Maritati	University of Tasmania	Australia
Mr Ramin Movaghari	International Institute of Earthquake Engineering and Seismology	Iran
Professor Gleb Pokrovski	Geosciences Environment Toulouse	France
Miss Julie Salme	Ecole Normale Superieure (ENS)	France
Dr Taichi Sato	Geological Survey of Japan	Japan
Mr Guangyue Shang	Deputy Director, Tianjin Land Consolidation Center	China
Professor Joe Smyth	University of Colorado	USA
Dr Zdislav Spetsius	Chief of Laboratory, Geology of Diamond Deposits, NIGP Alrosa Co Ltd, Mirny, Yakutia	Russia
Dr Andréa Tommasi	Université de Montpellier	France
Professor Yuichiro Ueno	Tokyo Institute of Technology - Earth-Life Science Institute	Japan
Professor Olivier Vanderhaeghe	Geosciences Environment Toulouse, Paul Sabatier University, Toulouse 3	France
Mr Kai Wang	CAGS & Peking University	China
Mr Zhongwei Wang	China University of Geosciences, Wuhan	China
Mr Jinyun Xie	China University of Geosciences, Wuhan	China
Dr Huajun Xu	Zhejiang University of Science and Technology	China
Mr Xiaozhou Yang	China University of Geosciences, Wuhan	China
Mr Yugui Yue	Chief Economic Manager, Tianjin Bureau of Land Resource Administration	China
Mr Hui Zhang	China Earthquake Administration	China
Mr Yang Zhao	Southern University of Science and Technology of China	China
Dr Yuanchuan Zheng	China University of Geosciences, Beijing	China
Dr Irina Zhukova	University of Tasmania	Australia

Appendix 8: Research funding

GRANTS AND OTHER INCOME FOR 2018

Investigators	2018 Funding Source	Project Title	Amount
Wilde	ARC CoE (CU contribution)	Core to Crust Fluid Systems	$20,000
O'Reilly	ARC CoE (MQ contribution)	Core to Crust Fluid Systems	$110,000
Fiorentini	ARC CoE (UWA contribution)	Core to Crust Fluid Systems	$120,000
Moresi, Betts, Whittaker, Miller	ARC Discovery Project (DP150102887)	The global consequences of subduction zone congestion	$150,000
Jacob, Eggins, Wirth	ARC Discovery Project (DP160102081)	Mechanisms of proxy uptake in biominerals	$117,315
Putnis, Raimondo, Daczko	ARC Discovery Project (DP160103449)	Just add water: a recipe for the deformation of continental interiors	$28,500
Clark, Afonso, Jones	ARC Discovery Project (DP160103502)	To develop a geophysically relevant proton conduction model for the Earth's upper mantle	$77,508
Hand, Clark, Hasterok, Rushmer, Reddy, Hacker	ARC Discovery Project (DP160104637)	Rehydration of the lower crust, fluid sources and geophysical expression	$101,862
Nutman, Bennett, Van Kranendonk	ARC Discovery Project (DP170100715)	Establishing the critical physical-chemical factors in the early surface environment and tectonic regime that supported early life and continuing habitability	$100,000
Van Kranendonk, Fiorentini, Campbell, Deamer	ARC Discovery Project (DP180103204)	A terrestrial hot spring setting for the origin of life?	$193,000
Foley	ARC Australian Laureate Fellowship (FL180100134)	Understanding the roles of carbon, water and nitrogen in the development of plate tectonics as drivers of mantle evolution	$297,250
Li	ARC Australian Laureate Fellowship (FL150100133)	How the Earth works - Toward building a new tectonic paradigm	$609,068
Selway	ARC Future Fellowship (FT150100541)	Measuring mantle hydrogen to map ore fluids and model plate tectonics	$169,039
Selway	ARC Future Fellowship (FT150100541)	Measuring mantle hydrogen to map ore fluids and model plate tectonics (MQ contrib.)	$3,000
Alard	ARC Future Fellowship (FT150100115)	Earth's origin and evolution: A sulphurous approach	$260,216
Wang	ARC Future Fellowship (FT140100826)	Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	$91,113
Giuliani	ARC DECRA (DE150100510)	A new approach to revealing melting processes in the hidden deep Earth (MQ contribution)	$25,000
Arculus, Cohen, Gallagher, Vasconcelos, Elders, Foden, Coffin, Nebel, McGregor, Clennell, Sloss, Heap, Webster, Kemp, George	ARC LIEF (LE160100067)	Australian membership of the International Ocean Discovery Program	$2,000,000

Investigators	2018 Funding Source	Project Title	Amount
Sampson, Barnes, Fiorentini, Fitzsimons, Johnson, Kemp, Kilburn, Martyniuk, Putnis, Reddy, Smithies, Uvarova	ARC LIEF (LE180100070)	Cutting-edge electron probe microanalysis driving Western Australia's resource geosciences	$966,283
Sampson, Barnes, Fiorentini, Fitzsimons, Johnson, Kemp, Kilburn, Martyniuk, Putnis, Reddy, Smithies, Uvarova	ARC LIEF (LE180100070) UWA, Curtin, GSWA, CSIRO contributions	Cutting-edge electron probe microanalysis driving Western Australia's resource geosciences	$812,500
George, Paterson, Van Kranendonk, Brocks, Sherwood, Jacob, Fuerbach, Brock, Löhr, Sestak	ARC LIEF (LE180100160)	Femtosecond-laser, micropyrolysis gas-chromatographmass spectrometer	$297,463
George, Paterson, Van Kranendonk, Brocks, Sherwood, Jacob, Fuerbach, Brock, Löhr, Sestak	ARC LIEF (LE180100160) UNSW, ANU, New England contributions	Femtosecond-laser, micropyrolysis gas-chromatographmass spectrometer	$95,000
Meffre, Whittaker, Norman, Cracknell, Belousova, Collins, Arundell, Cooke, Maas, Huston, Musgrave, Greenfield	ARC Linkage Project (LP160100483)	Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia	$20,829 (to MQ)
Ailleres, Jessell, de Kemp, Caumon, Florian Wellmann, Armit, Droniou, Lindsay, Cui, Betts, Cruden, Kemp, Gessner, Spampinato, Harrison, Kessler	ARC Linkage Project (LP170100985)	Mitigating 3D geological risk in resources managements	$120,000
Hough, McCuaig, Reddy, Clark, Fiorentini, Gray, Miller	SIEF/MERIWA M436	Distal Footprints of Giant Ore Systems: Capricon WA Case Study	$193,382
Hough, Reddy, McCuaig, Tyler	SIEF RP	Distal footprints of giant ore systems: UNCOVER Australia	$85,405
Yang, Lu	National Natural Science Foundation of China	Genesis of comb quartz layers: Case studies from porphyry Cu deposits at Qulong, Tibet and Now Chun, Iran	$50,000
Sun, Lu	National Natural Science Foundation of China	Magmatic oxidation sate, water content, and volatile nature: New insights into genesis of porphyry copper mineralization at Zhunuo in the Gangdese belt, southern Tibet	$40,000
Zhao, Yuan	Institute of Geology and Geophysics, Chinese Academy of Sciences	China-Western Australia Seismic Survey	$238,645
Thebaud, Aitken, Jessell, Occhipinti, Dentith, Hagemann, Kemp, Fiorentini, Smithies, Lu, Gessner	MRIWA M530, Industry	Yilgarn 2020	$663,500
LaFlamme, Thebaud, Fiorentini	Northern Star Resources	Multiple sulfur isotope systematics of the Kanowna Belle Gold deposit	$73,774
Fiorentini	Department of Industry Innovation and Science - AusIndustry: Innovation Connections	CA-IDTIMS high precision geochronology	$45,000

Investigators	2018 Funding Source	Project Title	Amount
Fiorentini	Panoramic Resources	CA-IDTIMS high precision geochronology	$35,000
Fiorentini	IGO Independence Group	Geochemical appraisal of mafic and ultramafic rocks from a series of IGO prospects along the Albany-Fraser Belt of Western Australia	$120,350
Barnes, Fiorentini	IGO Independence Group	Predictive genetic study of the Nova-Bollinger deposit and host-rocks	$15,000
Loucks, Fiorentini	BHP Billiton	Improving zircon morphology and chemistry as a tool of assessing and ranking the relative prospectivity for Cu porphyry deposits in *"greenfield"* terrains	$262,982
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (Minerals Targeting International Pty Ltd)	Lithospheric architecture mapping in phanerozoic orogens	$30,000
Fiorentini	Barrick Gold Corporation	The role of whole-lithosphere architecture on the genesis of giant gold systems in the El-Indio region, Chile-Argentina	$44,386
O'Reilly	NCRIS AuScope	AuScope Project Plan 3.53 - Earth composition and evolution	$156,620
O'Reilly	NCRIS AuScope (MQ contribution)	AuScope Project Plan 3.53 - Earth composition and evolution	$50,000
O'Reilly	RAAP	AuScope - Earth composition and evolution	$200,000
Afonso	European space agency	3D Earth	$63,767
Afonso	CSIRO Scholarship	CSIRO Scholarship	$30,000
Daczko and ImageMatrix team	Macquarie University Strategic Priority Grants Scheme, 2018; plus external sponsorship	ImageMatrix - Developing a platform for clustered 2D image management, display and manipulation	$22,420
Belousova	Faculty Science and Engineering	Research Award - Excellence	$1,000
Afonso	Faculty Science and Engineering	Research Award - Leadership	$1,000
Afonso	MQ DVCR	Co-funded fellowship scheme	$28,315
Foley	DVCR and Faculty	Discretionary Grant	$33,000
O'Neill	MQSN	MQ Research Seeding Grant	$5,642
Clark	ANSTO	Scholarship	$27,353
Stefano Caruso	MRIWA scholarship	Geological controls on the fractionation of multiple sulfur isotopes in Archean mineral systems	$15,000
Eunjoo Choi	MRIWA scholarship	Alkaline magmatism as a probe into the lithospheric mantle	$11,515
Barbosa Da Silva	MQPGRF R1	The microchemical and microstructural evolution of fluid and melt transfer in deep crustal shear zones	$2,755
Nimalisiri	MQPGRF R2	Gravity and magnetic response of the Marulan Supersuite, focusing around the Yerranderie Area	$5,074
Patabendigedara	MQPGRF R2	Quantifying the effects of surface and bulk proton transport in mantle materials	$5,000
Munnikhuis	MQPGRF R2	Microchemical and microstructural evolution of fluid and melt transfer in deep crustal shear zones	$4,801

Investigators	2018 Funding Source	Project Title	Amount
Pintér	MQPGRF R2	The composition of melts in the incipient melting regime	$4,943

GRANTS AND OTHER INDICATIVE INCOME FOR 2019

Investigators	2019 Funding Source	Project Title	Amount
Moresi, Betts, Whittaker, Miller	ARC Discovery Project (DP150102887)	The global consequences of subduction zone congestion	$60,000
Jacob, Eggins, Wirth	ARC Discovery Project (DP160102081)	Mechanisms of proxy uptake in biominerals	$30,000
Nutman, Bennett, Van Kranendonk	ARC Discovery Project (DP170100715)	Establishing the critical physical-chemical factors in the early surface environment and tectonic regime that supported early life and continuing habitability	$70,000
Van Kranendonk, Fiorentini, Campbell, Deamer	ARC Discovery Project (DP180103204)	A terrestrial hot spring setting for the origin of life?	$253,098
Yang, Afonso, Rawling, Ritzwoller, Niu	ARC Discovery Project (DP190102940)	Unveiling the fine structure of the Australian continent using ocean waves	$130,000
Cruden, Fiorentini, Barnes, Bunger, Jackson	ARC Discovery Project (DP190102422)	Magma dynamics and ore deposits	$100,000
Foley	ARC Australian Laureate Fellowship (FL180100134)	Understanding the roles of carbon, water and nitrogen in the development of plate tectonics as drivers of mantle evolution	$668,816
Foley	ARC Australian Laureate Fellowship (FL180100134) MQ contribution	Understanding the roles of carbon, water and nitrogen in the development of plate tectonics as drivers of mantle evolution	$190,000
Li	ARC Australian Laureate Fellowship (FL150100133)	How the Earth works - Toward building a new tectonic paradigm	$564,331
Selway	ARC Future Fellowship (FT150100541)	Measuring mantle hydrogen to map ore fluids and model plate tectonics	$76,044
Alard	ARC Future Fellowship (FT150100115)	Earth's origin and evolution: A sulphurous approach	$100,120
Arculus, Cohen, Gallagher, Vasconcelos, Elders, Foden, Coffin, Nebel, McGregor, Clennell, Sloss, Heap, Webster, Kemp, George	ARC LIEF (LE160100067)	Australian membership of the International Ocean Discovery Program	$2,000,000
Danisik, Evans, McInnes, Kirkland; Li, Fiorentini, Wingate	ARC LIEF (LE190100079)	The Western Australia ThermoChronology Hub	$365,380
Grice, Rickard, Benedix, Jiang, Reddy, Kilburn, Clode, Peyrot, Wacey, Lavery, Masque, Trengove, Xia, Deditius, Maker	ARC LIEF (LE190100053)	A novel ToF-SIMS facility for organic and inorganic analyses in WA	$1,267,674
Meffre, Whittaker, Norman, Cracknell, Belousova, Collins, Arundell, Cooke, Maas, Huston, Musgrave, Greenfield	ARC Linkage Project (LP160100483)	Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia	$45,000

Investigators	2019 Funding Source	Project Title	Amount
Regenauer-Lieb, Afonso, Clark, Thiel, Czarnota, Poulet, Jones, Walsh	ARC Linkage Project (LP170100233)	A newly developed science approach to the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP)	$660,000
Ailleres, Jessell, de Kemp, Caumon, Florian Wellmann, Armit, Droniou, Lindsay, Cui, Betts, Cruden, Kemp, Gessner, Spampinato, Harrison, Kessler	ARC Linkage Project (LP170100985)	Mitigating 3D geological risk in resources managements	$240,000
Sun, Lu	National Natural Science Foundation of China	Magmatic oxidation sate, water content, and volatile nature: New insights into genesis of porphyry copper mineralization at Zhunuo in the Gangdese belt, southern Tibet	$40,000
Thebaud, Aitken, Jessell, Occhipinti, Dentith, Hagemann, Kemp, Fiorentini, Smithies, Lu, Gessner	MRIWA M530, Industry	Yilgarn 2020	$663,500
Giuliani	Swiss National Foundation Ambizione Fellowship	A new understanding of kimberlite magmas from deep Earth to diamond mines	CHF 952,334
Conrad, Selway, Steinberger, Tarasov, Kellogg, Nisancioglu	Norwegian Research Council, FRINATEK	Magnetotelluric analysis for Greenland and postglacial isostatic evolution (MAGPIE)	$300,000
LaFlamme, Thebaud, Fiorentini, Sugiono	Northern Star Resources	Multiple sulfur isotope systematics of the Kanowna Belle Gold deposit	$69,518
Barnes, Fiorentini	IGO Independence Group	Predictive genetic study of the Nova-Bollinger deposit and host-rocks	$15,000
Loucks, Fiorentini	BHP Billiton	Improving zircon morphology and chemistry as a tool of assessing and ranking the relative prospectivity for Cu porphyry deposits in "*greenfield*" terrains	$228,444
Huaiyu Yuan	Canning CWAS	China-Western Australia Seismic Survey (CWAS 2nd stage)	$53,330
O'Reilly	NCRIS AuScope	AuScope Project Plan 3.53 - Earth composition and evolution	$200,000
O'Reilly	NCRIS AuScope (MQ contribution)	AuScope Project Plan 3.53 - Earth composition and evolution	$50,000
Selway, Goodwin	Macquarie Research Infrastructure Scheme	Geophysical infrastructure for polar measurements	$75,300

Appendix 9: Standard performance indicators

All values maximised at double target

Area	Category	Code	Indicator		Value
RESEARCH	Number & quality of outputs	R1	*Research outputs*	*Actual*	199
				Target	40
		R2(a)	*Journals with Impact Factor >2.5*	*Actual*	81%
				Target	70%
		R2(b)	*Journals with impact Factor >3*	*Actual*	73%
				Target	50%
		R2(c)	*Journals with specific target audiences*	*Actual*	18%
				Target	20%
		R2(d)	*Book chapters / international conference proceedings*	*Actual*	11%
				Target	10%
		R3(a)	*Number of presentations / talks / papers / lectures given at major international meetings*	*Actual*	189
				Target	40
		R3(b)	*Number of invited or keynotes given at major international meetings*	*Actual*	16
				Target	10
		R4	*Number & nature of commentaries on Centre's achievements in general/specialist publications*	*Actual*	54
				Target	8
		R5	*Citation data for publications: at least 4 CIs in top 200 Geoscientists*	*Actual*	4
				Target	4
	Research training and professional education	R6	*Number of attended professional training courses for staff and postgraduate students*	*Actual*	11
				Target	10
		R7	*Number of Centre attendees at all professional training courses*	*Actual*	79
				Target	20
		R8	*Number of new postgraduates working on core Centre research, supervised by CoE staff (PhD, Mast.)*	*Actual*	9
				Target	8
		R9	*Number of new postdoctoral researchers recruited to the CoE working on core Centre research*	*Actual*	5
				Target	4
		R10	*Number of new MRes students working on core Centre research & supervised by CoE staff*	*Actual*	7
				Target	6
		R11(a)	*Number of postgraduate completions working on core Centre research and supervised by CoE staff*	*Actual*	28
				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*	97
				Target	24
		R14	*Number of mentoring programs*	*Actual*	4
				Target	3
	Build int. national and regional links/networks	R15	*Number of international visitors and visiting fellows*	*Actual*	43
				Target	20
		R16	*Number of national and international workshops held / organised by Centre*	*Actual*	5
				Target	3
		R17	*Number of visits to overseas laboratories and facilities*	*Actual*	26
				Target	20
		R18	*Examples of relevant interdisciplinary research supported by the Centre*	*Actual*	100%
				Target	>50%

RESEARCH	Build end-user links	R19	*Number of government, industry & business community briefings*	*Actual*	>10
				Target	6
		R20	*Number and nature of public awareness programs*	*Actual*	6
				Target	5
		R21	*Currency of information on the Centre's website*	*Actual*	13
				Target	4
		R22	*Number of website sessions*	*Actual*	15,660
				Target	10,000
		R23	*Number of public talks given by centre staff*	*Actual*	7
				Target	6
ORG SUPPORT	Generate cash & in-kind contributions from partners & other sources & build collab. & infrastructure support	O1	*Annual new and existing cash contributions from collaborating organisations*	*Actual*	4,241,384
				Target	1,790,000
		O2	*Annual in-kind contributions from collaborating organisations*	*Actual*	12,913,622
				Target	12,418,100
		O3	*Annual cash contributions from partner organisations*	*Actual*	Complete
				Target	Complete
		O4	*Annual in-kind contributions from partner organisations*	*Actual*	1,944,481
				Target	1,229,300
		O5	*Other research income secured by Centre staff*	*Actual*	7,948,380
				Target	140,000
		O6	*Number of new organisations collaborating with, or involved in, the Centre*	*Actual*	19
				Target	6
		O7	*Level and quality of infrastructure provided to the Centre*	Documented *pp. 80-88*	
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. 7*), and was endorsed by the Mid-term Review Panel.	
		G2	*Frequency, attendance and value added by Advisory Committee meetings*	CCFS has held 9 Advisory Board meetings over seven years. Attendance at the meetings were consistently high. Input from the board has been invaluable, providing a different perspective on Centre activities. The CCFS board has been very engaged in workshopping key aspects of Centre business, in realigning the CCFS Vision and planning for the Centre's post-funding future and Legacy.	
		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*	Jointly authored presentations and publications as well as co-supervised postgraduates (see *Appendices 5, 6 and pp. 72-79*)	
		G6	*Capacity building of the Centre through scale and outcomes*	Recruitment of staff: 5 (see *pp. 9-10*) Recruitment of postgraduate students: 16 (see *pp. 72-79*) International Linkages: 40 visitors (see *pp. 96-100, 142-143*)	

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		14	
		N2	*Postgraduate units established by end year 3*	*Actual*	6	
				Target	2	
			Number of honours and Postgraduate students		97	

CCFS KPI	Outcomes	*C1*	*Linkage of geochemical / petrologic / geological data with geophysical datasets / modelling*	*Actual*	Complete	
			2014 - Convene international conference on integration of geophysics / geology	*Target*	Complete	
		C2	*Technology & method development related to NCRIS infrastructure*	*Actual*	Complete	
			2013 -1st results submitted for publication / conference presentation	*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*	*Actual*	Complete	
			2013 - proceed with projects	*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:

- **Research Training Program (RTP) -** available to both domestic and international students from 2017 (https://www.education.gov.au/research-training-program). The scheme is administered by individual universities on behalf of the Department of Education and Training. Applications for a RTP Scholarships can be made directly to participating universities.
  Each university has its own application and selection process:
  MQ - http://www.mq.edu.au/research/phd-and-research-degrees/scholarships/hdr-main-scholarship-rounds
  Curtin - http://research.curtin.edu.au/postgraduate/rtp-scholarship-policy/
  UWA - http://www.scholarships.uwa.edu.au/
- **China Scholarship Council - Postgraduate 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, Greenland and other locations globally (see the map on *p. 17* of this Report).

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

Examples of broad PhD project areas include (but are not limited to):

- Lithosphere structure and geochemistry: mantle provinciality and tectonism
- Granitoid and mineralised provinces along western Pacific convergent margins
- Fluid-vapour transfer of elements in the crust and mantle
- Heat production and evolution of the crust: crust-mantle interaction
- Paleomagnetism and supercontinent reconstruction
- Geodynamic modelling
- 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

AMIRA	Australian Mineral Industry Research Association
AMMRF	Australian Microscopy and Microanalysis Research Facility
(RSES) ANU	(Research School of Earth Sciences) Australian National University
ANSTO	Australian Nuclear Science and Technology Organisation
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
COPA	Capricorn Orogen Passive-source Array
CSIRO	Commonwealth Scientific Industrial Research Organisation
CU	Curtin University
CWAS	China-Western Australia Seismic Survey
DECRA	Discovery Early Career Researcher Award
DEST	Department of Education, Science and Training
DP	Discovery Project
EBSD	Electron Backscatter Diffraction
ECR	Early Career Researcher
EPS	Earth and Planetary Sciences (Department, Macquarie University)
EMP	Electron Microprobe
FIM	Facility for Integrated Microanalysis
FSE	Faculty of Science and Engineering (MQ)
FTIR	Fourier Transfer Infrared Spectroscopy
GAC-MAC	Geological Association of Canada-Mineralogical Association of Canada
GAU	Geochemical Analysis Unit (EPS, Macquarie University)
GEMOC	Geochemical Evolution and Metallogeny of Continents
GET	Géosciences Environnement Toulouse, France
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
(C)IPRS	(Curtin) International Postgraduate Research Scholarship
KIT	Karlsruhe Institute of Technology, Germany
LAM-ICPMS	Laser Ablation Microprobe - ICPMS
LIEF	Linkage Infrastructure, Equipment and Facilities
ING PAN	Institute of Geological Sciences, Polish Academy of Sciences
MC-ICPMS	Multi-Collector - ICPMS
MQGA	Macquarie University GeoAnalytical (formerly GAU)
MRIWA	Minerals Research Institute of Western Australia
(i)MQRES	(International) Macquarie University Research Excellence Scholarships
MOU	Memoranda of Understanding
NASA	National Aeronautics and Space Administration
NCRIS	National Collaborative Research Infrastructure Scheme
PGE	Platinum Group Element
RAAP	NSW Research Attraction and Acceleration Program
RTPS	Research Training Program Stipend (formerly APA)
SAC	Science Advisory Committee
SEM	Scanning Electron Microscope
SIEF	Science & Industry Endowment Fund
SIRF	UWA Scholarship for International Research Fees
TIGeR	The Institute for Geoscience Research
UM	University of Melbourne
UNSW	University of New South Wales
UWA	University of Western Australia

Australian Government
Australian Research Council

MACQUARIE University

Curtin University

THE UNIVERSITY OF WESTERN AUSTRALIA

GEOLOGICAL SURVEY WESTERN AUSTRALIA

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