2016
Annual Report

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

CCFS information is accessible on WWW at:

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

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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: Transport, power, communications, construction and health are just a few essential aspects of modern life that rely heavily on minerals and metals. CCFS' integrated application of geology, tectonics, experimental and analytical geochemistry, petrophysics, geophysics, and petrophysical and dynamical modelling is delivering the fundamental science needed to ensure our society can continue to thrive in the future.

The cover features Honours student Brendan Nomchong, in the Hamersley Ranges, WA (Photo E. Barlow).

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 2016 (commenced mid 2011). Activities include research, technology development, stakeholder engagement, international links and research training.

The overarching goal of CCFS is to understand Earth's internal dynamics, evolution and fluid cycles from core to crust. CCFS multiplies the capabilities of three national centres of research excellence in Earth and Planetary Sciences: Macquarie University (Administering Institution), Curtin University and the University of Western Australia (Collaborating Institutions). The Geological Survey of Western Australia is a Partner Institution and researchers from Monash University and the University of New South Wales are formally affiliated. Our strong formal international partnerships and growing networks leverage our resources across intellectual, infrastructure and funding bases.

New instrumentation operational in 2016 includes the CAMECA NanoSIMS 50L ion probe, continuing the CCFS vision of delivering new techniques and applications in spatially resolved (*in situ*) analysis. These *in situ* methodologies solve the problems of averaging relatively large volumes of minerals, including the obscuring of fine-scale variations. Resolution of compositional variations at the nano- to micro-scale levels is commonly crucial to understanding the whole range of fluid-related processes across deep mantle and crustal domains, including metasomatism and mineral deposit formation. This change in focus from bulk to nano- and micro-scale analytical datasets aligns with strong industry feedback through 2016.

A new CCFS initiative that gathered momentum in 2016 is the organisation of a national collaborative consortium for distributed experimental capabilities, linking these Australian facilities as a virtual Centre (enabled by the ARC LIEF Grant *"Australian virtual experimental laboratory: a multimode geoscience facility")*. Australia was once the leader in experimental petrology, a field that some decades ago ushered in a new era for geoscience directions, using experimental validation and prediction to better understand Earth processes. Geoscience is now on the brink of a great opportunity for a renaissance of experimental peak relevance, enabled by the huge technological advances in experimentation and in high-resolution nano- and micro-analysis, heralding a new ability to tackle first-order problems in Earth Sciences. The construction of a laser-heated diamond anvil cell system will give us access to the pressures of the Earth's core, enabling research into the lowermost mantle, core and the interiors of other planets.

The seven Flagship Programs implemented in 2014 (*p. 22*) to fulfil the Research goals of CCFS through 2018 have been successful in realigning our research strategies to deliver further transformational outcomes and leave a legacy in knowledge, new technology and methodologies.

Leading-edge research outcomes in 2016 ranged across a wide spectrum of discoveries amply demonstrating the power of CCFS' signature approach of integrating geophysical, geochemical and tectonic datasets, with stunning examples of nano- and micro-analytical and imaging outcomes leading to new insights on global events. Examples include the first recognition of an Archean microcontinent in Western Australia between the Pilbara and Yilgarn cratons by combining geophysical and geochemical interpretation; demonstration of the power of Hf Isotopic mapping and zircon geochemistry in unravelling the evolution of the Pilbara, in tracking fertile regions for copper-gold deposits, in identifying hidden Archean crust in Gondwana terranes; high-resolution imagery captures the actual formation process of some diamonds; evidence from rare minerals in corundum from N. Israel for highly-reduced mantle conditions; captivating glimpses of early-Earth conditions for life using geochemical and virtual approaches; establishing the complexity of subduction zone mantle; and illuminating how and where deep fluids move around 40 km beneath the surface. This is an eclectic selection of some of the *Research Highlights* on *pp. 39-81*.

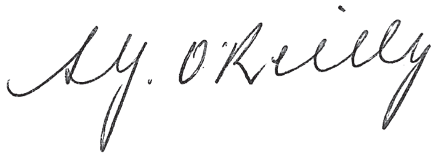
Prestigious external awards for CCFS Chief Investigators included the announcement of the award of the Australian Academy of Science (AAS) Anton Hales Medal in 2017 to Juan-Carlos Afonso. This follows two previous years of AAS awards including the 2016 Nancy Millis Medal to Elena Belousova and the 2015 Anton Hales Medal to Yingjie Yang. Four CCFS Chief investigators (Bill Griffin, Sue O'Reilly, Zheng-Xiang Li and Simon Wilde) were named as highly-cited researchers by Clarivate Analytics (previously

Thomson Reuters) in 2016. The outstanding quality of CCFS researchers, and their continuing success in gaining external leverage of resources: the most recent CCFS ARC Future Fellow, Kate Selway, will commence in 2017 - making a total of eleven Future Fellowships awarded to researchers in CCFS.

81 PhD students undertook research aligned with CCFS in 2016. CCFS postgraduates are producing world-class research with authorship of 41 publications (26 first-authored) in high-impact journals in 2016 and 78 presentations at peak international workshops and conferences. Participation of early-career researchers reached 25.

Important national initiatives relevant to the future of Geoscience were being formulated during 2016. These include the draft Decadal Plan for Earth Sciences from the Academy of Science National Committee for Earth Sciences, the setting up of the formal structure for the implementation of the UNCOVER initiative (www.uncoverminerals.org.au/purpose), the Chief Scientist's Review of national infrastructure funding, planning for the anticipated new AuScope NCRIS bid, and the 2030 draft Strategic Plan for the Australian Innovation, Science and Research System (from Innovation and Science Australia). CCFS participants contributed to all of these processes, and indeed, the 4-D Lithosphere Mapping approach, established by GEMOC and CCFS with industry partners, forms the robust conceptual basis for UNCOVER.

Alignment with such national geoscience strategies and government initiatives demonstrates the significant impact of CCFS's transformational research. CCFS is providing vital new knowledge about Australia's geological evolution, and a framework to guide smart new mineral exploration, fulfilling the CCFS vision of ***"Delivering the fundamental science needed to sustain Australia's resource base".***



Professor S.Y. O'Reilly

CCFS participants at the annual Research Meeting held on 21-22 November 2016.

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.

2016 CENTRE RESEARCH MEETING

A successful and productive CCFS Research Meeting was held on 21-22 November 2016. The meeting provided the opportunity for participants, as well as members of the CCFS Board, to hear research presentations from CCFS researchers, including postgraduates and ECRs.

The forum was a catalyst for new, exciting ideas and cemented collaboration among researchers of the Centre's nodes and partner institutions.
















L-R, T-B: Ian Gould, Crystal LaFlamme, Yingjie Yang, Laure Martin, Johannes Hammerli, Vikram Selvaraja, Martin Van Kranendonk, Sue O'Reilly, Rosanna Murphy, Ed Saunders, Yoann Gréau, Klaus Gessner, Sergei Pisarevsky, Hadi Shafaii Moghadam, Katerina Bjorkman, Matt Kilburn, Yongjun Lu and Zheng Xiang Li.

L-R, T-B: Weihua Yao, Stefano Caruso, Irena Tretiakova, Nathan Dazcko, Elena Belousova, David Barbosa da Silva, Siqi Zhang, Huaiyu Yuan, Erica Barlow, Grant Cox, Mike Etheridge, Constanza Jara Bara, Simon Wilde, Chris Kirkland, Luis Parra Avila, Amaury Porteau, Steve Reddy, Montgarri Castillo-Oliver, Jianggu Lu and Cam McCuaig.

CENTRE RESEARCH

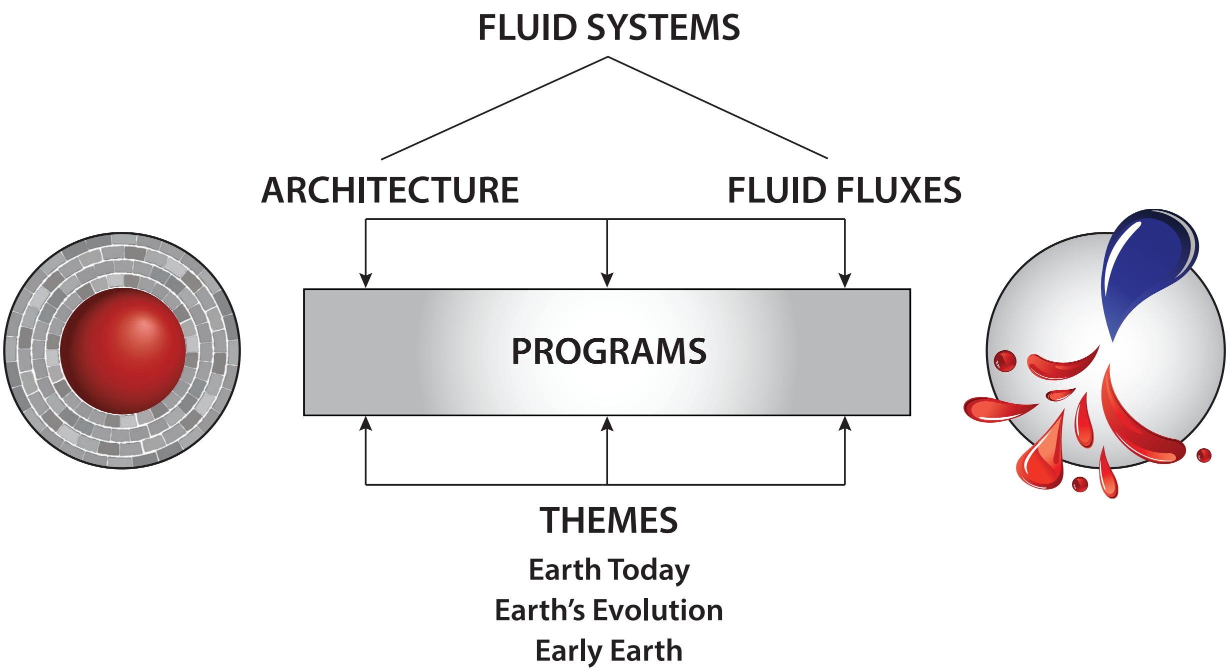
Research programs within the Centre are focused to provide maximum synergy for the scope enabled by the resource base. As it is not possible to encompass the full range of research about the Earth's fluid cycle and deep Earth dynamics, all applied and mature strategic research is carried out in parallel, 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. 22*) 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

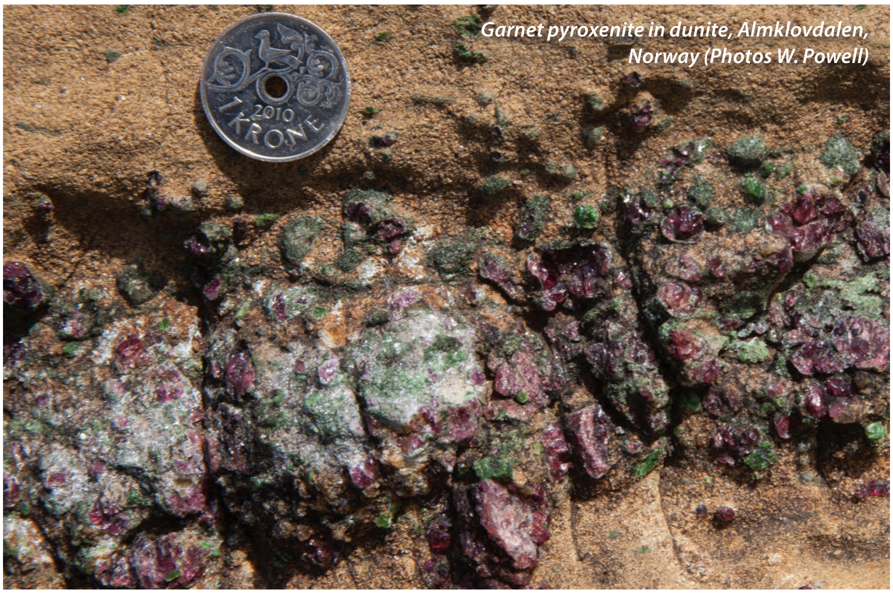
Earth's Evolution - Fluids in crustal and mantle tectonics; recycling of fluids into the deep mantle; hydrosphere, atmosphere and the deep Earth. Earth has evolved through cycles of crustal formation and destruction, punctuated by '*tipping points*', when rapid cascades of interlinked events produced 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.

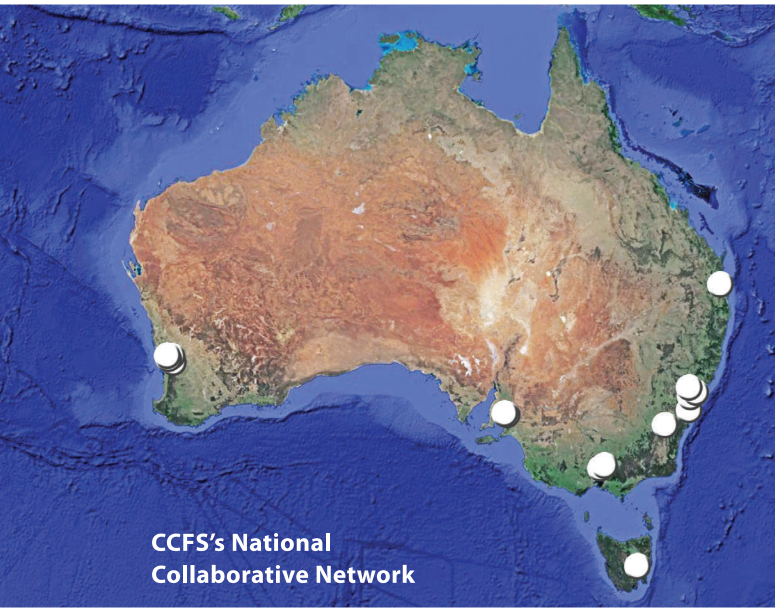
Measurement of the physical properties of potential deep Earth materials at extreme conditions will feed into petrophysical modelling of seismic data in terms of composition, temperature and anisotropy. Measurements of metal complexing at realistic conditions that mimic real ore-system fluids/melts will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



Garnet pyroxenite in dunite, Almklovdalen, Norway (Photos W. Powell)

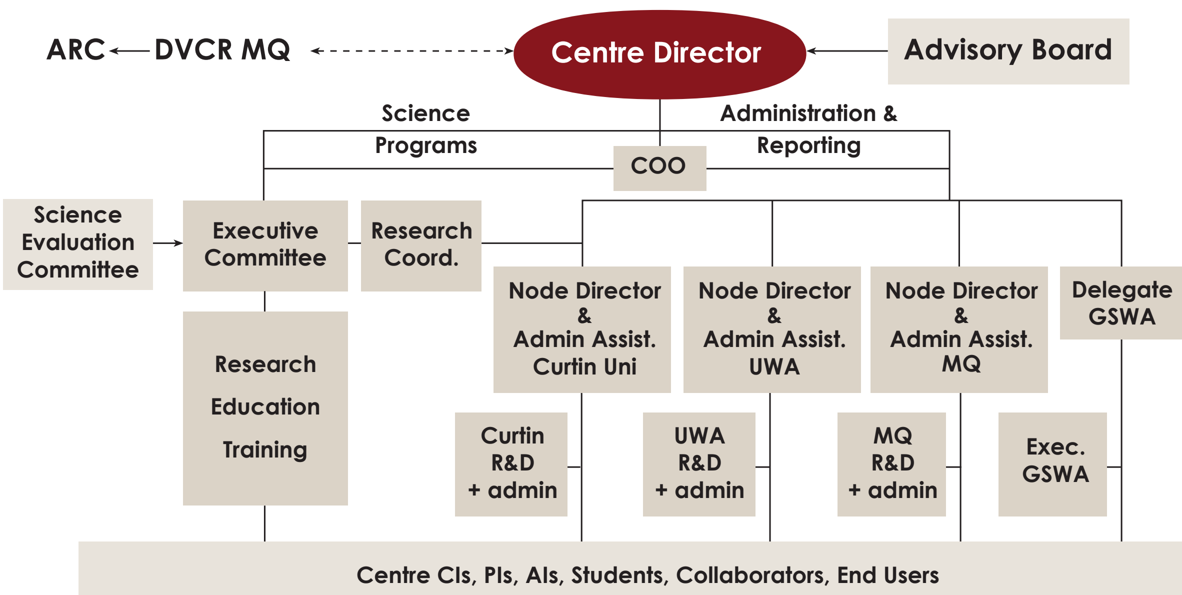
Structure

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 five additional global institutions with leading reputations in the field. CCFS also has formal Cotutelle MOU with a further fifteen global institutions (see *p. 105*). CCFS incorporates several pre-existing centres within the Administering and Collaborating Institutions: the GEMOC Key Centre (http//www.gemoc.mq.edu.au/) at Macquarie University retains its structure and is fully incorporated within CCFS; the research and strategic activities of CET (Centre for Exploration Targeting; http://www.cet.edu.au/) at the University of Western Australia lie within CCFS; and the activities of TIGeR (http://tiger.curtin.edu.au/) at Curtin University are also aligned with CCFS.

There is active national collaboration with state Geological Surveys, Geoscience Australia (GA), CSIRO, the Australian National University (RSES), University of Newcastle, the University of Sydney, the University of Wollongong, the University of Adelaide and several major industry collaborators (national and global), across a broad range of 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 (83% attendance at meetings) and extensively workshopped the new vision statement to reflect the national benefit deriving from the fundamental research in CCFS.

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

Executive Committee

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

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

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

Professor Campbell McCuaig - Node Director
Until July, 2016
School of Earth and Environment
University of Western Australia

Associate Professor Marco Fiorentini - Node Director *from August, 2016*
School of Earth and Environment
University of Western Australia

Associate Professor Matthew Kilburn
Deputy Director, Centre for Microscopy, Characterisation and Analysis
University of Western Australia

Executive Committee

(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

The CCFS Board Meeting, 23 November 2016 - Front L-R: Andy Barnicoat, Sue O'Reilly, Ian Gould. Rear L-R: Sally-Ann Hodgekiss, Zheng-Xiang Li, Steve Foley, Matt Kilburn, Cam McCuaig, Bill Griffin, Klaus Gessner, Marco Fiorentini, Roric Smith, Simon Wilde and Magdalene Wong-Borgefjord.

Participants

Organisations

Administering Organisation

Macquarie University (MQ)

Collaborating Organisations

Curtin University (CU)

University of Western Australia (UWA)

Partners

Australian Partner

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

International Partners

CNRS and Université de Montpellier, France

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

University of Maryland, USA

University of Saskatchewan, Canada

Bayreuth University, Germany

Chief Investigators

Dr Elena Belousova - MQ

Associate Professor Simon Clark - MQ

Associate Professor Marco Fiorentini, Node Leader from August 2016- UWA

Professor Stephen Foley, Research Coordinator - MQ

Professor William Griffin - MQ

Professor Matt Kilburn - UWA

Professor Zheng-Xiang Li - CU

Professor T. Campbell McCuaig, Node Leader until July 2016 - UWA

Associate Professor Alexander Nemchin - CU

Associate Professor Craig O'Neill - MQ

Professor Suzanne Y. O'Reilly, Director - MQ

Associate Professor Norman Pearson - MQ

Professor Martin Van Kranendonk - UNSW

Professor Simon Wilde, Node Leader - CU

Associate Professor Yingjie Yang - MQ

Partner Investigators

Australian Partner Investigator

Dr Klaus Gessner - GSWA

International Lead Partner Investigators

Professor Michael Brown - Maryland

Dr David Mainprice - Montpellier

Professor Catherine McCammon - Bayreuth

Professor Fuyuan Wu - CAS Beijing

Associate Investigators

Associate Professor Juan Carlos Afonso - MQ

Dr Olivier Alard - MQ

Associate Professor Christopher Clark - CU

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 Chris Kirkland - CU

Professor Jochen Kolb - GEUS

Dr Yongjun Lu - GSWA

Professor Louis-Noel Moresi - University of Melbourne

Associate Professor Sandra Piazolo - MQ

Professor Steven Reddy - CU

Associate Professor Tracy Rushmer - MQ

Dr Bruce Schaefer - MQ

Professor Paul Smith - MQ

Professor Simon Turner - MQ

Dr Michael Wingate - GSWA

Professor Shijie Zhong - University of Colorado, Boulder, USA

Early Career Researchers (ECR)

Dr Andreas Beinlich - CU

Dr Montgarri Castillo-Oliver - MQ

Dr Denis Fougerouse - CU

Dr Rongfeng Ge - CU

Dr Andrea Giuliani - MQ at UM - DECRA

Dr Christopher Gonzalez - UWA

Dr Yoann Gréau - MQ

Dr Johannes Hammerli - UWA

Dr Jin-Xiang Huang - MQ

Early Career Researchers (ECR) *cont.*

Dr Heejin Jeon - CMCA, UWA
Dr Uwe Kirscher - CU
Dr Crystal LaFlamme - UWA
Dr Erwann Lebrun - UWA
Dr Zhen Li - CU
Dr Yongjun Lu - GSWA
Dr Ross Mitchell - CU
Dr Rosanna Murphy - MQ
Dr Hugo Olierook - CU
Dr Diana Palvsa - CU
Dr Luis Parra Avila - UWA
Dr Amaury Pourteau - CU
Dr Qing Xiong - MQ
Dr Weihua Yao - CU
Dr Siqi Zhang - MQ
Dr Nan Zhang - CU

NEW STAFF

Dr Andrea Agangi has a background in igneous petrology and ore deposits geology. He received a PhD from CODES - University of Tasmania. He then moved to the University of Johannesburg, South Africa, to study Archaean gold deposition and felsic magmatism in the Barberton Greenstone Belt and the Witwatersrand basin. Andrea joined Curtin University as a Post-Doctoral Fellow to work on the Proterozoic Capricorn Orogen. His present work investigates various aspects of precious and base metal mineralisation in ancient terrains, and especially the Precambrian. This includes the use of rutile geochemistry as a tracer of Au mineralisation under cover, the use of sulfur isotopes to trace the origin of mineralising fluids in gold deposits, and the behaviour of chalcophile elements (such as copper and silver) in volcanic arc environments. His research contributes to CCFS Flagship Program 2.

Dr Nick Gardiner is a Research Fellow at CET-Curtin Node under the Timescales of Mineral Systems theme. He was awarded an undergraduate degree in geology from the University of Oxford and a MSc in geochemistry from the University of Leeds. He

then returned to Oxford to complete a DPhil in isotopic and metamorphic geochemistry. After a number of years working in the global commodities markets, he returned to Oxford (and academia) in 2013, and joined Curtin in 2015.

Nick's current research focuses on using geochemical tools to constrain magmatic-metamorphic processes in three areas: (a) petrogenetic controls on granite-hosted mineral deposits; (b) the growth and development of Earth's early continental crust; (c) Hf isotope systematics applied to crustal evolution studies. His research contributes to CCFS Flagship Programs 5 and 7. See *Research highlights pp. 44-45, 48.*

Other new staff

Ms Keng Chai Ng (Finance officer, UWA)

ECRs *(featured on pp. 12-17 of our ECR section)*

Dr Andreas Beinlich	Dr Zhen Li
Dr Montgarri Castillo-Oliver	Dr Ross Mitchell
Dr Denis Fougerouse	Dr Rosanna Murphy
Dr Rongfeng Ge	Dr Hugo Olierook
Dr Christopher Gonzalez	Dr Luis Parra Avila
Dr Johannes Hammerli	Dr Diana Plavsa
Dr Uwe Kirscher	Dr Amaury Pourteau
Dr Erwann Lebrun	Dr Nan Zhang

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

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. Ten Future Fellows, Dr Elena Belousova, Associate Professor Marco Fiorentini, Dr

Heather Handley, Professor Dorrit Jacob, Associate Professor Craig O'Neill, Associate Professor Sandra Piazolo, Associate Professor Yingjie Yang, Dr Xuan-Ce Wang, Dr David Wacey and Dr Olivier Alard have projects relevant to CCFS goals and are profiled in the "*Participants*" section of our previous reports (http://www.ccfs.mq.edu.au/AnnualReport/Index.html). An 11th CCFS Future Fellow, Dr Kate Selway, will commence her fellowship in 2017.

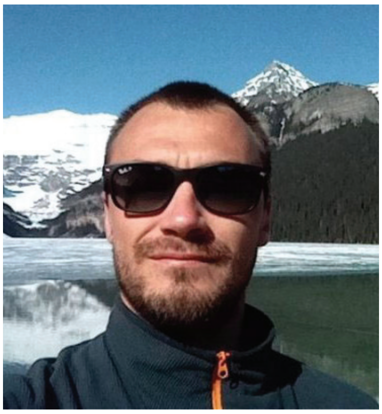
EARLY CAREER RESEARCHERS (ECR)

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

The following profiles present 2016 ECRs and summarise their expertise and research areas.

NEW 2016

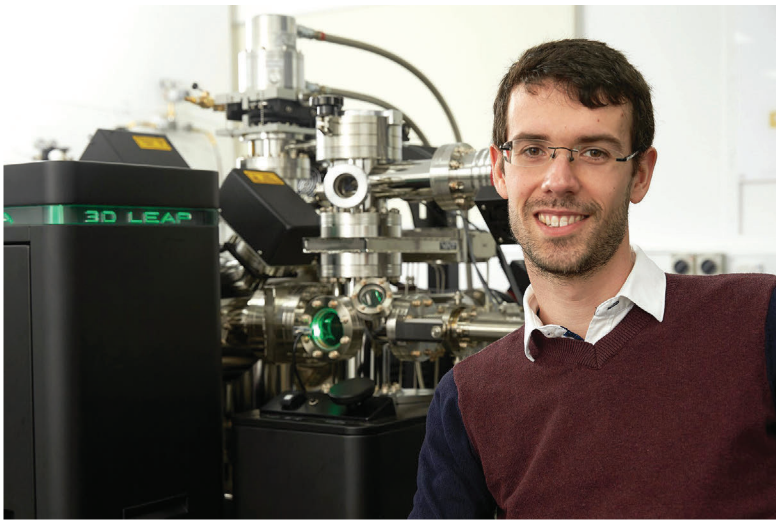
Dr Andreas Beinlich has a Diplom (~MSc) from the University of Würzburg (Germany), a Postgraduate Diploma from the University of Otago (New Zealand), and a PhD from the University of Oslo (Norway). Andreas' research is focused on the mechanisms, rates and consequences of fluid-rock interaction with application to economic and environmental challenges. During his PhD thesis research at the Norwegian Centre of Excellence Physics of Geological Processes (PGP), he investigated natural carbonation of ultramafic rocks as an analogue for geological CO_2 sequestration under conditions ranging from deep hydrothermal to surface weathering. After completing his PhD, Andreas was appointed as a Postdoctoral Researcher at The University of British Columbia (Canada) and the Mineral Deposit Research Unit (MDRU). At MDRU he coordinated the industry-collaborative research project "*Carbonate Alteration Footprints*" (CAF), which focused on the application of stable isotope analysis during exploration for carbonate hosted hydrothermal ore deposits. He joined CCFS as a Research Fellow at Curtin University and The Institute for Geoscience Research (TIGeR) in September 2015 to continue his work on hydrothermal alteration of mainly mafic and ultramafic systems. His current research focuses on alteration-related mass transport, mineral replacement reactions and their time scales through investigation of hydrothermally altered mineral deposits of Western Australia, Canada and Norway in tandem with hydrothermal experimental work. Andreas' research contributes to CCFS Flagship Program 2.



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. Montgarri's thesis focused on the characterisation of the structure and metasomatic evolution of the subcontinental lithospheric mantle in NE Angola, based on the study of mantle xenoliths and their host kimberlites. In September 2016, she graduated with a PhD from both universities.

Her current role as Research Associate in CCFS involves the textural, compositional and isotopic (C, O and Sr) characterisation of kimberlitic carbonates, using *in situ* techniques [(MC-)LA-ICPMS and SIMS]. Primary carbonates are targeted as CO_2 traps and their study could provide new insights into the composition of the parental kimberlite melt (i.e. volatile contents), as well as the role of degassing processes during eruption. Her research contributes to the TARDIS II project, and also aims to enlarge the current understanding of the deep Earth's carbon cycle in cratonic roots by studying the C isotope variation of the deep mantle with space and time. See *Research highlight p. 79-80*.

Dr Denis Fougerouse completed his BSc at the university of Saint-Etienne (France) and his MSc at the University of Nancy (France). The research focus of his MSc was the timing of mineralisation events in the West Africa Craton using Re-Os dating. He subsequently joined the University of Western Australia at the Centre for Exploration Targeting (CET) for his



PhD focused on the mineralisation processes occurring in the Giant Obuasi gold deposit. In his current position at Curtin University, Denis uses atom probe microscopy to understand the mechanisms of nanoscale trace element mobility associated with ore deposits and hydrothermal activity. 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. He is now a Research Associate at Curtin University. Rongfeng's study interests include origin and evolution of continental crust, reconstruction of Precambrian supercontinents, and tectonic evolution of orogenic belts. His study mainly focuses on the Tarim Craton, NW China, and the Central Asian Orogenic Belt. He uses multiple laboratory techniques as well as field-based work. His study has 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.

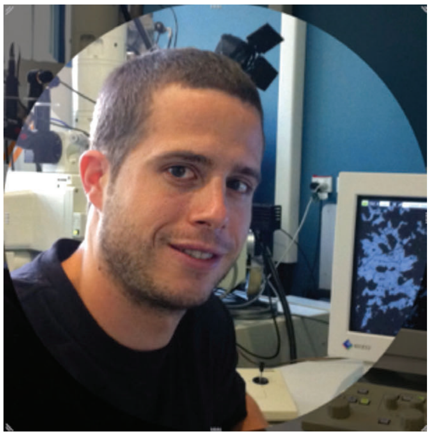
Rongfeng's current study focuses on the Hadean detrital zircons from Jack Hills. Using cutting-edge techniques, including ion imaging and atom probe, Rongfeng will revisit the isotopic and elemental distributions and compositions of these ancient and complex zircon grains. His study will provide new insights into the origin of continental crust and the geodynamic setting in the early Earth. This research contributes to CCFS Flagship Program 6.

Dr Christopher Gonzalez joined the CET and CCFS team, first as a PhD student in 2012, and now 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 the larger ARC Linkage project *"Multiscale Dynamics of Ore Body Formation"*.

His research includes numerical modeling 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 better understanding of the two most abundant recycled volatiles on Earth (H_2O and CO_2).

As a Research Associate, he has used 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'* were observed, which are thought to be a direct consequence of slab derived carbonic fluids interacting with the mantle wedge. To examine this hypothesis, the code Chris developed during his thesis was used to numerically constrain the sequence of events that led to the formation of the sulfur-rich carbonate pods. This research contributes to CCFS Flagship Program 2, Module 3 - Transient Geodynamics.

Dr Johannes Hammerli completed his MSc in Earth Sciences at the University of Bern, Switzerland, before moving to Townsville, Australia, to study for a PhD. 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. He joined the CET in late 2014 on a Swiss National Science Foundation Fellowship. During this time he has focused on studying crustal differentiation and evolution. In May 2016, Johannes joined the CCFS research group where he focuses on microanalysis of accessory minerals, in particular apatite from magmatic systems, to unravel processes which lead to the fertile systems feeding ore deposits. His research contributes to CCFS Flagship Program 2.



See *Research highlight p. 47.*

Dr Uwe Kirscher started in January 2016 as a CCFS funded Research Associate at Curtin University. He finished 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 Professor Zheng-Xiang Li's Laureate team at Curtin University.

His research interests in this group are focused on Proterozoic paleomagnetic constraints of the Australian Precambrian blocks. He aims to use several paleomagnetic approaches in order to add constraints for a better and more precise understanding of the supercontinent cycle and its geodynamic features. His research contributes to CCFS Flagship Program 5. *See Research highlight p. 63-64.*

Dr Erwann Lebrun is a structural geologist who typically uses a multidisciplinary-multiscale approach in his applied research. Erwann is currently a Research Associate at the Centre for Exploration Targeting (CET). His research interests are focused on the magmatism, tectonics and mineralisation of eastern Greenland. His experience spans 4 of the 6 continents and a wide range of geological terranes, ranging from Archean to Jurassic in age.

Erwann received his BSc in Geology from Blaise Pascal University, France in 2008, an MSc in Economic Geology from the University of Québec in Montréal (UQAM), Canada and from the Earth Sciences Institute of Orléans (ISTO), France in 2010. Subsequently, Erwann moved to Australia to start a PhD which he recently finished at CET. His PhD project focused on the 4D evolution of the orogenic gold district of Siguiri, in Guinea (West Africa). This project was funded by AngloGold Ashanti and is part of the West African eXploration Initiative (WAXI). During his PhD, Erwann used a multidisciplinary set of geological tools such as structural geology, 3D modelling, geochronology, sedimentology and geochemistry, at the micro-, deposit, district and regional scale to reconstruct the deformation and hydrothermal history of the Siguiri orogenic gold district and the tectonic evolution of the Siguiri Basin, hosting the district. This integrated study permitted the identification of the controls on gold mineralisation in the Siguiri Basin and the development of various targeting criteria for future exploration strategies. His research contributes to CCFS Flagship Program 2. See *Research highlight pp. 60-61.*

Dr Zhen Li was awarded his PhD Degree in 2011 from Nanjing University. He then joined China University of Petroleum, Beijing (CUPB) as a full-time Lecturer and was promoted to a position of Associate Professor (tenured) at CUPB in June 2014. Zhen then joined CCFS (Curtin) in 2016 as a Post-Doctoral Fellow.

One of Zhen's research interests is to unravel the tectono-magmatic evolution of Earth. Zhen uses a multidisciplinary approach (geochronology, petrology and geochemistry, and isotope geochemistry), to explore complex geodynamic processess in deep-Earth, focusing on the Asia-Pacific region and Tibet. Zhen's on-going research also includes the geological processes in sedimentary basins and geochronology of oil-gas accumulation. He leads two research projects on the Re-Os geochronology of ancient oil pools in the Tarim and Yanshan basins, supported by China's Ministry of Education and the CUPB. As lead CI, Zhen has competitive research funding from the National Science Foundation of China, the 2015 Fok Ying Tung Education Foundation College and Higher Education Fellowship (both are equivalent to DECRA). His research contibutes to CCFS Flagship Programs 2 and 4.

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 Rosanna Murphy completed her PhD with CCFS/GEMOC in 2015. Her thesis examined the 3.1 Ga Mpuluzi Batholith in South Africa/Swaziland as a case study to understand the processes involved in the creation of ancient continental crust.

In December 2015, Rosanna became the manager of the *TerraneChron®* team at CCFS. This role involves integrating *in situ* analysis of U-Pb ages, Hf-isotope, and trace element

concentrations in zircons and involves collaboration with a number of industry and geological survey partners. This methodology has provided valuable insight into geological mapping and exploration programs. In 2016, *TerraneChron®* imaged and analysed 1642 zircon grains for a total of 9 different projects from Australia, Iran and the USA. See *Research highlight pp. 44-45*.

Dr Hugo Olierook is Dutch-Australian and completed his undergraduate studies at Curtin University in 2011. He continued at Curtin with a PhD into the tectonic and stratigraphic evolution of the Western Australian margin. After completing his PhD in 2015, he moved to the University of Liverpool as a NERC postdoctoral associate examining 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 is using

his expertise in geochronology, geochemistry, tectonics and geodynamics to understand the 3 billion year history of the Capricorn Orogen and its mineral endowment. His research contributes to CCFS Flagship Program 2.

Dr Luis Parra Avila, from Caracas, Venezuela, earned his Bachelor's degree in 2007 at the University of Central Missouri, then moved to the state of Illinois to work on his Masters' degree, which he earned in 2010 at Southern Illinois University-Carbondale. His Masters' thesis involved Co-Ni enriched

Mississippi Valley-type deposits in southeast Missouri. For the project, he had the support of the *"The Doe Run Co."* This not only provided financial support, but allowed him to gain access to their mines and gain meaningful industry experience. After concluding his master degree, he continued his education at the Centre for Exploration Targeting (CET), University of Western Australia, where he earned his PhD 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. In October of 2015, Luis joined CCFS as a post-doctoral research associate. His research focuses on evaluating zircon characteristics and its link to porphyry Cu deposits. The project seeks 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. His research contributes to CCFS Flagship Program 2. See *Research highlights pp. 53, 72-73*.

Dr Amaury Pourteau graduated from the University of Rennes 1 (France) in 2007 and joined the University of Potsdam (Germany) for his doctoral thesis, completed in 2011. In this project, he studied the tectonic-metamorphic evolution of low-grade, high-pressure metamorphosed sedimentary sequences of a Neotethyan continental margin in Anatolia. As a Lecturer and then Post-doc working on Late Cretaceous to Cenozoic metamorphic domains throughout Anatolia, he applied Lu-Hf garnet geochronology to address the pace of subduction and collision-related processes.

In early 2016, he joined Curtin Earth Dynamics Research Group as a Research Fellow. He is supervising several field-based studies aimed at deciphering the tectonic evolution of the NE Australian Proterozoic inliers in order to provide new constraints on connections. Within this multidisciplinary project, he is addressing the age of prograde metamorphism in the different NE Australian inliers using mainly Lu-Hf garnet geochronology. This will shed light on the timing and mode of assembly of NE Australia and its connection with other continents during the amalgamation of the supercontinent Nuna. His research contributes to CCFS Flagship Program 5.

Dr Nan Zhang completed his BSc at Peking University, China. He pursued his MSc at University of Toronto, and PhD at University of Colorado, respectively. Before he joined Curtin University as a research fellow, he worked as postdoctoral fellow at Brown University and Woods Hole Oceanography Institution for 4 years. Currently, Nan works on the supercontinent geodynamics as part of Professor Zheng-Xiang Li's Laureate group.

His researches focuses on 1) the global geodynamics associated with the supercontinent cycles, 2) lunar and planetary sciences, especially planetary interiors, and 3) melt-rock interaction with two-phase flow modelling. He primarily uses numerical methods to tackle geological problems. His research contributes to CCFS Flagship Program 5.

CONTINUING

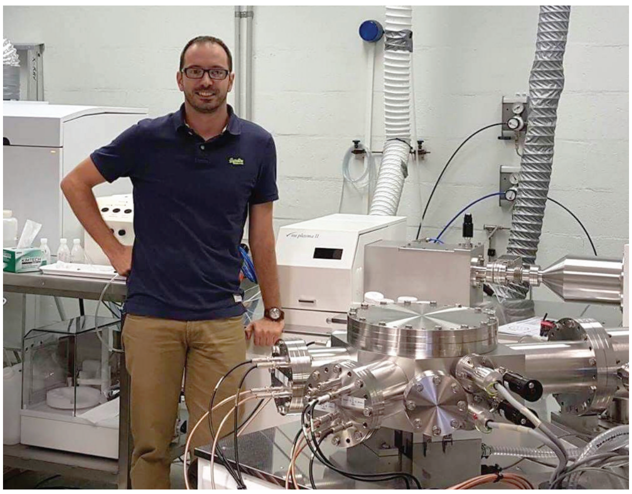
Dr Andrea Giuliani joined CCFS in June 2015 as an ARC DECRA (Discovery Early Career Research Award) Fellow. Andrea completed his PhD in mantle geochemistry at the University of Melbourne in 2013 where he then undertook a year of post-doctoral research in 2014 before becoming a lecturer in Igneous Petrology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

Andrea's research focuses on the composition and sources of deep Earth fluids and melts - including kimberlites, which are the main source of terrestrial diamonds. Specifically, 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 highlight p. 71.*

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

From 2013 to June 2015 Yoann co-managed the *TerraneChron*® team in CCFS. In July 2015, Yoann was appointed as a Research



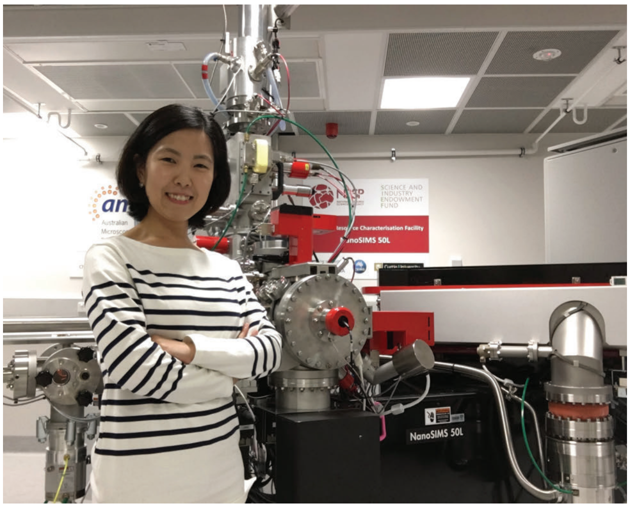
Associate within the CCFS Technology Development Program "*GAU multi-instrument development - Frontiers in integrated laser-sampled trace-element and isotopic geoanalysis*". In this role, Yoann aims to provide high-quality research related to the development of innovative methods for *in situ* analysis of trace elements, radiogenic isotopes and non-conventional stable isotope systems by laser ablation ICPMS. In particular, he will focus on promoting the advancement of geochemical methodologies and techniques involving the Femtosecond laser and the new Nu Plasma II Multi-Collector ICPMS (MC-ICPMS) installed at MQ in July 2015. His research also contributes to CCFS Flagship Program 1.

Dr Jin-Xiang Huang completed her undergraduate study at China University of Geosciences, Beijing. She received her PhD from Macquarie University in December 2011 studying the metasomatism and origins of xenolithic eclogites from the Roberts Victor kimberlite, South Africa. This provided her with experience in the clean labs, on state-of-art instruments producing precise geochemical data, and in integrating a wide range of information into a coherent model. Her research concluded that mantle metasomatism has completely changed the petrography and chemical and isotopic compositions of most eclogites; therefore, evidence from these can no longer be used to support the popular idea that they represent subducted oceanic crust. Information from the few unmetasomatised eclogites favours their origin from deep-seated magmas.

After completing her PhD, Jin-Xiang joined CCFS as a Post-doctoral Research Associate, to work on the stable isotope and water contents of mantle rocks (both eclogites and peridotites) in different mantle processes (e.g. magma crystallisation, mantle metasomatism). This will provide a better understanding of mantle processes and further constraints on geodynamics.

In 2016, she worked on the moissanite (SiC) project to unravel the relationships between alloy inclusions and the host SiC; to connect the SiC with the associated materials; to investigate the redox effects on C- and Si-isotope fractionation; to understand the formation and preservation of SiC; and to evaluate the redox state of the mantle in detail. Her research indicated that SiC was one product of the interaction of basaltic magma and mantle methane in a volcanic plumbing system in northern Israel. SiC crystallised from metallic melts that became immiscible during the reduction of the magma. Its low ^{13}C may be caused by Rayleigh fractionation under reduced conditions; the variation of Si isotopes may reflect fractionation between immiscible metallic melts and silicate magma. Her research contributes to CCFS Flagship Program 1. See *Research highlights pp. 49, 62-63, 76-77.*

Dr Heejin Jeon received her Bachelor and Master degrees at the School of Earth and Environmental Sciences, Seoul National University. She was awarded a PhD at the Research School of Earth Sciences, Australian National University (2012). Her PhD project focused on continental crust evolution and crustal recycling in southeastern Australia (Carboniferous-Permian granites across the Lachlan Fold Belt and New England Orogen).



During her time at ANU, Heejin worked extensively on zircon for U-Th-Pb dating, O and Hf isotope measurements (SHRIMP II and LA-MC-ICPMS). She then had two years of postdoc experience in the NORDSIM ion probe lab, Swedish Museum of Natural History, where she expanded her ion probe expertise with the CAMECA IMS1280 and contributed to a wide variety of collaborative projects. She also carried out a project in the Neoproterozoic Arabian Shield and studied how much this apparently juvenile crust is contaminated by older crustal materials. Heejin is now working at the Ion Probe Facility, CMCA, University of Western Australia, with CCFS participants Matt Kilburn and Laure Martin, to improve widely used isotope applications and also to develop new applications. Her research contributes to CCFS's Technology Development Program at CMCA.

Dr Crystal LaFlamme is Canadian and attended Acadia University for her BSc. She 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. She joined CCFS as a Postdoctoral Research Associate in February 2015 to study the sulfur isotope record of craton margins at the Centre for Exploration Targeting, University of Western Australia. Her research focuses on anomalous sulfur isotope signatures preserved in the Archean-Proterozoic rock record. Crystal is leading the development of a suite of reference materials for *in situ* multiple sulfur isotope analysis of magmatic and hydrothermal ore deposit sulfides. Early sulfur and lead isotope results demonstrate that sulfur and metals in certain Proterozoic ore deposits are being sourced from metal-endowed Archean cratons. This knowledge base is building to ultimately better understand the link between fluid-driving tectonic processes and ore genesis. Her research contributes to CCFS Flagship Program 2. See *Research highlight pp. 58-59*.

Dr Yongjun Lu is the Senior Geochronologist at the Geological Survey of Western Australia (GSWA), an Associate Investigator at CCFS, and an adjunct Senior Research Fellow at the Centre for Exploration Targeting (CET), UWA. Together with Dr Michael Wingate at GSWA, Yongjun is ensuring that about 80 samples from WA are dated by SHRIMP every year, contributing to a fantastic world-class geochronological dataset, the foundation for understanding Earth's evolution and mineral resources formation. He manages the isotopic program at GSWA such

as Sm-Nd (c. 100 samples per year), Lu-Hf (c. 100 samples per year) and O isotopes (c. 50 samples per year), which are used to tackle various scientific questions such as imaging the lithospheric architecture through cover and understand crustal evolution and mineral deposit formation. In addition, Yongjun is leading a project at GSWA investigating the zircon chemistry of Archean granitoids, which is aimed at unravelling the pressure, temperature, water content and redox state of Archean granitoids. He is also involved in studying the petrology, geochemistry, isotopes and tectonics of the Southwest Terrane of the Yilgarn Craton, and is investigating the detrital zircon records of the Kimberley Basin to correlate the different basins in the North Australian Craton. Through CCFS, Dr Lu has ongoing collaboration with Chinese Academy of Geological Sciences (CAGS) and China University of Geosciences in Beijing (CUGB) to investigate the porphyry copper systems in the Tibetan plateau and surrounding region. Yongjun is invited to chair the session "*Mineral Deposits in Tibet*" at SEG 2017: "*Ore Deposits of Asia: China and Beyond*". His research contributes to CCFS Flagship Program 7. See *Research highlights pp. 44-45, 53, 72-73*.

Dr Qing Xiong completed his undergraduate studies at China University of Geosciences (Wuhan), and joined CCFS in 2011 as a Cotutelle PhD candidate. He received PhD degrees from China University of Geosciences (Wuhan) in December 2014 and from Macquarie University in November 2015. Qing's PhD project focused on the origin and evolution of orogenic peridotites and ophiolites from Tibet (China), and revealed the detailed upper-mantle processes and subduction geodynamics during the assembly of the Tibetan-Himalayan Plateau in the Phanerozoic, using conventional and cutting-edge methodologies.

Qing commenced his employment as a Research Associate at CCFS, Macquarie University in June 2015. His current research focuses on the mantle rocks from the representative ophiolites in the Yarlung Zangbo Suture Zone of South Tibet as part of targets of CCFS Flagship Program 1, TARDIS II. He has systematically collected ultramafic rock samples from the Kangjinla and Dazhuka ophiolites, and is planning to carry out petrochemical and microstructural characterisation of these ophiolitic mantle sections, using petrochemical and Electron Backscattered Diffraction (EBSD) tools. He also started to work on the super-reducing mineral assemblages in the Zedang and Kangjinla ophiolites. The studies will provide new insights into 1) tectonics of the Neo-Tethyan Ocean between Eurasia and Greater India, 2) mantle recycling processes and unusual interaction between fluids/magmas and mantle rocks in subduction and collision zones, and 3) the genesis of chromitite ore deposits in ophiolites. See *Research highlights pp. 49, 62-63.*

Dr Weihua Yao completed her undergraduate study at China University of Geosciences (Wuhan), and graduated with a PhD degree from Curtin University in July 2014. She then joined CCFS as a Postdoctoral Research Associate after her graduation, working with CCFS, TIGeR, ACTER and IGCP648 at Curtin University. Her research mainly focuses 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. Two main highlights of her research suggest an Ediacaran-Cambrian collision between South China and northern India, leading to the formation of the Nanhua foreland basin and the Ordovician-Silurian Wuyi-Yunkai orogeny in South China; and Hainan Island's connection with western Laurentia during the Nuna breakup and Rodinia assembly. Weihua is also leading a China Geological Survey funded project, investigating the Ediacaran-Silurian basin on the western Yangtze margin of South China. Her research contributes to CCFS Flagship Program 5.

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

Siqi joined CCFS as a Postdoctoral Research Associate in April 2013. Since then, his research has focused on using high resolution numerical models to study planetary evolution. He is exploring the construction of an Earth mantle-flow model constrained by plate motion in the past few hundred million years to recover the mantle structure and to track its evolution over that time. He has built new features into existing mantle dynamic codes to better address early planetary body evolution, such as decaying radioactive heating, heating from large impacts, core-mantle coupling, and treatment for melt extraction. Working with Craig O'Neill, the code has been applied to early planetary evolution studies: 1) exploring the plausibility of mobile-lid tectonics on early Mars; 2) studying impact triggered tectonics on Hadean Earth; 3) modelling the lunar magma-ocean overturn and its effect on crustal evolution. In addition, he is involved in developing high performance SPH (smoothed particle hydrodynamics) code using an Intel Xeon Phi co-processor to study the process of planetary formation. His research contributes to CCFS Flagship Program 3.

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. 22*) 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 2017 workplan.**

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

2014 FLAGSHIP PROGRAMS

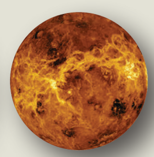
Program / Theme / Framework	Coordinator and main Centre personnel
1. Deep Earth fluids in collision zones and cratonic roots (TARDIS II) Themes 1, 2, 3 Earth's Architecture and Fluid Fluxes	**O'Reilly**, **Griffin**, Pearson, Kilburn, Martin, Alard, Shafaii Moghadam, Huang, Giuliani, Gréau, Castillo-Oliver, Xiong (ECRs) McGowan, Xu, Tilhac, Colas, Lu, Liptai, Chasse (PhDs)
2. Genesis, transfer and focus of fluids and metals Themes 2 and 3 Fluid Fluxes	**Fiorentini**, McCuaig, Foley, O'Reilly, Griffin, Reddy, Rushmer, Turner, Lu (ECR), Bagas, Gorczky, Piazolo, Kilburn, Loucks, Clarke, Lebrun (ECR) Bjorkman, Iaccheri, Stevenson, Davies, Dering, Poole, Bennett, Lampinen (PhDs), Poh (Masters)
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 (ECR), Gorczky, Smith, O'Reilly, Griffin Wasilev, Ramzan, Oliveira, Grose, Jiang (PhDs)
4. Atmospheric, environmental and biological evolution Theme 1 Earth's Architecture and Fluid Fluxes	**Van Kranendonk**, Fiorentini, Foley, Kirkland, Kilburn, Grange, Alard, LaFlamme Barlow, Baumgartner, Djokic, Selvaraja (PhDs), Gogouvitis (MSc, Germany), Tadbiri, Bannister, Blake (MPhils), Gudbrandsen, Nomchong, Soares, Steller (Hons)
5. Australia's Proterozoic record in a global context Themes 2 and 3 Earth's Architecture	**Li**, Pisarevsky, Wang, Yao (ECR), Wingate, O'Reilly, Griffin, Pearson, Belousova, McCuaig, Kirscher (ECR) 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, Grange, 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, Merdie, Wingate, Tyler, Lu Derring (PhD)
TECHNOLOGY DEVELOPMENT	
Cameca Ion microprobe development Themes 1, 2 and 3 Earth's Architecture and Fluid Fluxes	**Kilburn**, Martin, Jeon, Fiorentini, McCuaig, Wacey, 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	**Pearson**, Griffin, O'Reilly, Gréau (ECR), Kilburn, Martin, Alard, Huang (ECR) McGowan, Gao, Xiong (PhDs)

Where out of this world is CCFS?

As part of our quest to better understand the processes that led to the formation of the early Earth, CCFS has been investigating the early history of the Moon, Mars and Venus.
See *Research highlight pp. 78-79*.


Moon

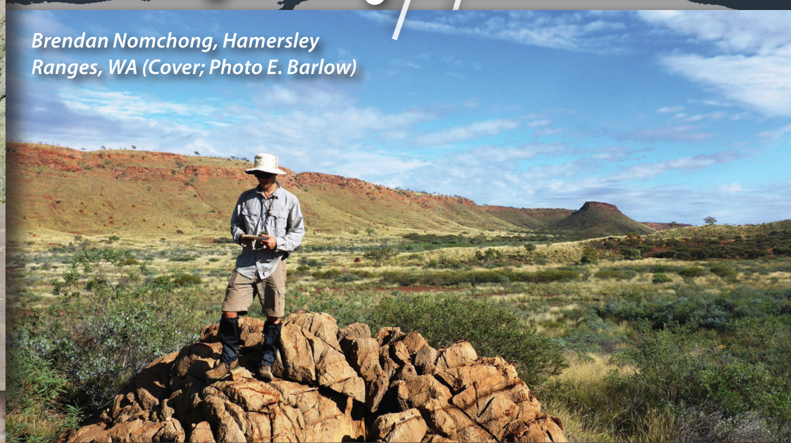

Mars


Venus

Fjords of Western Norway (Photo W. Powell)

WHERE IN THE WORLD IS CCFS?

Marco Fiorentini and guide riding to the mine site Castaño Viejo, Argentina (Photo G. Poole)



Brendan Nomchong, Hamersley Ranges, WA (Cover; Photo E. Barlow)

The Damara Orogen of Namibia - Neoproterozoic Samara Formation (Photo Z.-X. Li)

Yongjun Lu in the Kimberleys, WA

Communications 2016

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 2016 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 2016 are given in Appendix 5.

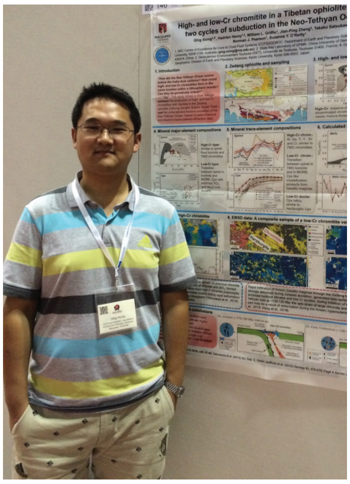
The 165 CCFS publications that were published in 2016 are dominantly in high-impact international journals (Thomson ISI); the remainder are in outlets targeted to specific stakeholders (e.g. Australian Journal of Earth Sciences, Economic Geology).

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

PARTICIPATION IN WORKSHOPS, CONFERENCES AND INTERNATIONAL MEETINGS IN 2016

CCFS Investigators, associated staff, early-career researchers and postgraduates had a high profile at 41 peak geophysical, metallogenic, geodynamic and geochemical conferences as convenors, invited speakers, or presenters, with 222 presentations including:

- Annual Meeting of The Israel Geological Society (IGS), Eilat, Israel, 19-21 January 2016
- 32nd Nordic Geological Winter Meeting, Helsinki, Finland, 13-15 January 2016
- 5th Australasian Universities Geoscience Educators Network Meeting, Canberra, Australia, 28-29 January 2016
- 24th Australian Conference on Microscopy and Microanalysis (ACMM24) Melbourne, Australia, 1-4 February 2016
- GSWA Open Day 2016, Fremantle, Australia, 26 February 2016
- NAC+ 2016, The North Atlantic Craton and Surrounding Belts: A Craton-Specific Approach to Exploration Targeting, Edinburgh, UK, 21-23 March 2016
- 47th Lunar and Planetary Science Conference, The Woodlands, Texas, USA, 21-25 March 2016
- European Geosciences Union (EGU), Vienna, Austria, 17-22 April 2016
- 17th International Seismix Symposium, Aviemore, Scotland, 15-20 May 2016
- Japan Geoscience Union Meeting 2016, Makuhari Messe, Japan, 22-26 May 2016
- Anisotropy and Dynamics of The Lithosphere-Asthenosphere System Workshop, Prague, Czech Republic, 22-25 May 2016
- SEG Munich Technical Meeting, Munich, Germany, 1 June 2016
- GAC-MAC 2016, Margins Through Time, Whitehorse, Yukon, Canada, 1-3 June 2016
- EMPG XV Fifteenth International Symposium on Experimental Mineralogy, Petrology and Geochemistry, Zurich, Switzerland, 5-8 June 2016
- International Diamond School 2016, Edmondton, Canada, 8 June 2016
- Polar Symposium, Lubin, Poland, 8-11 June 2016
- Gordon Research Conference, Geochemistry of Mineral Deposits, Les Diablerets, Switzerland, 19-24 June 2016
- AESC 2016 - Australian Earth Sciences Convention - Uncover Earth's Past to Discover Our Future, Adelaide Convention Centre, Australia, 26-30 June 2016
- 26th Goldschmidt Conference, Yokohama, Japan, 26 June - 1 July 2016



Qing Xiong with his poster at the 26th Goldschmidt Conference.

- Australian Astrobiology Meeting, Perth, Australia, 10-12 July 2016

- Workshop on the Origin and Evolution of Plate Tectonics, Monte Veritá, Locarno, Switzerland, 17-22 July 2016
- Asia Oceania Geosciences Society 13th Annual Meeting, Beijing, China, 31 July - 5 August 2016
- 7th International Dyke Conference (IDC7), Beijing, China, 18-20 August 2016
- ASEG-PESA-AIG 2016 25th International Geophysical Conference and Exhibition in Adelaide, South Australia, August 21-24, 2016
- European Microscopy Conference, Lyon, France, 28 August - 2 September 2016
- 35th IGC, International Geological Congress, Cape Town, South Africa, 27 August - 4 September 2016

Zheng-Xiang Li (second from right) and fellow delegates at the 35th IGC, Capetown.

- 13th International Nickel-Copper-PGE Symposium, Fremantle, Australia, 5-9 September 2016
- 2nd European Mineralogical Conference, EMC2016 Minerals, Fluids and Rocks: Alphabet and Words of Planet Earth, Palacongressi of Rimini, Italy, 11-15 September 2016
- GSA Annual Meeting, Denver, Colorado, USA, 25-28 September 2016
- SEG 2016 Tethyan Tectonics and Metallogeny, Çeşme, Turkey, 25-28 September 2016
- TIGeR Conference, Rock Alteration in The Upper Crust: Element Mobility and Concentration, Curtin University, Perth, Australia, 26-28 September 2016
- 16th Australian Space Research Conference, Melbourne, Australia, 26-28 September 2016
- ACTER 2016 Annual Field Symposium, Xi'an, China, 20-29 October 2016
- 2016 International Conference on The Earth's Deep Interior, Wuhan, China, 4-6 November 2016
- SSERVI Australia Workshop 2016, Perth, Australia, 9-11 November 2016
- Resources for the 21st Century Symposium, Research School of Earth Sciences (RSES), Canberra, Australia, 22-24 November 2016
- TANG3O, Thermochronology and Noble Gas Geochronology and Geochemistry Organisation, Perth, Australia, 29-30 November 2016
- CET-UWA 2016 Corporation Members Day, Perth, Australia, 7 December 2016
- Greenland Day Conference, Perth, Australia, 9 December 2016
- AGU Fall Meeting, San Francisco, USA, 12-16 December 2016
- Palaeontology Association Annual Meeting, Lyon, France, 14-17 December 2016

INVITED TALKS AT MAJOR CONFERENCES AND WORKSHOPS IN 2016

Annual Meeting of The Israel Geological Society (IGS), Eilat, Israel, 19-21 January 2016

Deep-Earth Methane, mantle dynamics and mineral exploration: insights from northern Israel, southern Tibet and Kamchatka
W.L. Griffin, **S.E.M. Gain**, **D. Adams**, V. Toledo, **N.J. Pearson** and **S.Y. O'Reilly** **Plenary**

The role of the deep lithosphere in metallogeny
S.Y. O'Reilly, **W.L. Griffin** and **N.J. Pearson** **Keynote**

INVITED TALKS *cont...*

32nd Nordic Geological Winter Meeting, Helsinki, Finland, 13-15 January 2016	From Nuna to Rodinia: Stenian-Tonian paleogeography S.A. Pisarevsky **Invited**
GSWA Open Day 2016, Fremantle, Australia, 26 February 2016	Secular change in Archean crust formation recorded in Western Australia H. Yuan **Keynote**
EGU, Vienna, Austria, 17-22 April 2016	Uncertainty quantification in complex joint inversion problems J.C. Afonso **Invited**
17th International Seismix Symposium, Aviemore, Scotland, 15-20 May 2016	Multi-observable probabilistic tomography for the physical state of the Earth's interior J.C. Afonso **Keynote**
Anisotropy and Dynamics of the Lithosphere-Asthenosphere System Workshop, Prague, Czech Republic, 22-25 May 2016	Thermochemical tomography for the physical state of the Earth's interior J.C. Afonso **Keynote**
International Diamond School 2016, Edmondton, Canada, 8 June 2016	Trace element traverses across kimberlite olivine: A new tool to decipher the evolution of kimberlite magmas **A. Giuliani**, A. Soltys, **W.L. Griffin**, **S. Foley**, D. Phillips and A. Greig **Invited**
AESC 2016 - Australian Earth Sciences Convention - Uncover Earth's Past to Discover Our Future, Adelaide Convention Centre, Australia, 26-30 June 2016	Plume and superplumes: their formation, nature and geodynamic roles Z.X. Li **Keynote** 1800-900 Ma global paleogeography: new insights S. Pisarevsky **Invited** Duration of tectonic processes constrained by Lu-Hf garnet geochronology - Insights from HP/LT oceanic rocks (Halilbağı Complex) and Barrovian-type mica-schist (Menderes Massif) A. Pourteau **Keynote** Pb isotope evolution in the Martian mantle J. Belluccci, **A. Nemchin**, M. Whitehouse and J. Snape **Invited**
26th Goldschmidt Conference, Yokohama, Japan, 26 June - 1 July 2016	Pb isotope evolution in the Martian mantle J. Belluccci, **A. Nemchin**, M. Whitehouse and J. Snape **Invited** Evolution of the early continents and localisation of Ni-Cu-Pge systems **D. Mole**, **M.L. Fiorentini**, **C. Kirkland**, S. Barnes, **C. McCuaig**, K. Cassidy, **E. Belousova**, S. Romano and M. Doublier **Invited** Early-formed chemical heterogeneity recorded by ^{142}Nd-^{143}Nd in 3.8-3.0 Ga samples from the Archean Anshan Complex, North China Craton **X.-C. Wang**, C.-F. Li, **S. Wilde**, X.-H. Li and Y.-F. Wang **Invited**
Australian Astrobiology Meeting, Perth, Australia, 10-12 July 2016	A terrestrial origin of life B. Damer, **M.J. Van Kranendonk**, **T. Djokic** and D. Deamer **Invited**
AOGS 13th Annual Meeting, Beijing, China, 31 July - 5 August 2016	Paleoproterozoic subductions and their roles in craton assembly in Western Australia **H. Yuan**, S. Johnson, M. Dentith, R. Murdie and **K. Gessner** **Invited**

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

INVITED TALKS *cont...*

7th International Dyke Conference (IDC7), Beijing, China, 18-20 August 2016	Proterozoic dyke swarms of the Siberian Craton and their geodynamic implications D.P. Gladkochub, T.V. Donskaya, R. Ernst, **S.A. Pisarevsky**, **M.T.D. Wingate** and U. Söderlund **Invited** Paleomagnetic data and dyke swarms geometries - Important tools for Precambrian paleogeographic reconstructions **S.A. Pisarevsky** **Keynote** Updated digital map of mafic dyke swarms and large igneous provinces in Western Australia **M.T.D. Wingate** and D. McB. Martin **Invited**
ASEG-PESA-AIG 2016, Adelaide, South Australia, August 21-24, 2016	Multi-observable thermochemical tomography: a new approach to an old problem **J.C. Afonso** **Keynote** 3D imaging of the Earth's lithosphere using noise from ocean waves **Y. Yang**, **J. Xie** and **K. Zhao** **Keynote**
35th IGC, Cape Town, South Africa, 27 August - 4 September 2016	Trace element variations across olivine record the evolution of kimberlite melts: Case studies from the Kimberley kimberlites (South Africa). **A. Giuliani**, A. Soltys, **W.L. Griffin**, **S. Foley**, V.S. Kamenetsky, D. Phillips, A. Greig and K. Goemann **Keynote** Global Seismic LAB measurements from full waveform tomography **H. Yuan** and B. Romanowicz **Invited**
GSA Annual Meeting, Denver, Colorado, USA, 25-28 September 2016	Assessing trace element (dis)equilibrium and the application of single element thermometers in metamorphic rocks A.M. Cruz-Uribe, M. Feinman, T. Zack, and **D.E. Jacob** **Invited**
SEG 2016, Çeşme, Turkey, 25-28 September 2016	Zircon compositions as a pathfinder for porphyry Cu ± Mo ± Au systems **Y. Lu**, **R.R. Loucks**, **M.L. Fiorentini**, **T.C. McCuaig**, N.J. Evans, Z. Yang, Z. Hou, **C.L. Kirkland**, **L.A. Parra-Avila** and A. Kobussen **Keynote**
TIGeR Conference, Perth, Australia, 26-28 September 2016	Metal and sulfur cycles in the deep continental crust: Insights from the Ni-Cu-PGE sulfide deposits of the Ivrea Zone (Italy) **M.L. Fiorentini**, M. Locmelis, **T. Rushme**r, R. Arevalo Jr., **J. Adam**, **S.W. Denyszyn**, and **C. LaFlamme** **Invited**
2016 International Conference on the Earth's Deep Interior, Wuhan, China, 4-6 November 2016	Iron spin transitions in the Earth **S. Clark** **Invited** Corundum crystallization and ultra-low fO_2 in a volcanic plumbing system: Mt Carmel area, Israel **W.L. Griffin**, **S.E.M. Gain**, **J-X. Huang**, V. Toledo, **N.J. Pearson** and **S.Y. O'Reilly** **Keynote**
Resources for the 21st Century Symposium, RSES, Canberra, Australia, 22-24 November 2016	Tracing metal and fluid sources in magmatic and hydrothermal systems **M.L. Fiorentini** **Keynote** Targeting new deposits: Margins, metasomatism and metallogeny **S.Y. O'Reilly** **Invited**
CET-UWA 2016 Corporation Members Day, Perth, Australia, 7 December 2016	Understanding the Precambrian crust in the Capricorn region - some results from recent passive source deployments **H. Yuan**, S.P. Johnson, M. Dentith, R. Murdie, **K. Gessner**, F. Korhonen and T. Bodin **Invited**
AGU Fall Meeting, San Francisco, USA, 12-16 December 2016	Pb-Pb systematics of lunar rocks: Differentiation, magmatic and impact history of the Moon **A. Nemchin**, M. Whitehouse, M.D Norman, J. Snape, J.J. Bellucci and **M. Grange** **Invited** Crustal structure of the late-Archean to Proterozoic Glenburgh Terrane in the Western Australian Craton: roles of a micro-continent in craton formation and reworking **H. Yuan**, S. Johnson, M.C. Dentith, R. Murdie, **K. Gessner**, F.J. Korhonen and T. Bodin **Invited** Lithospheric layering in major continents: results using full waveform tomography **H. Yuan**, P. Clouzet, B.A Romanowicz and L. Zhao **Invited** The Hainan Lone Plume prompted by encircling subduction zones around the South China Sea **N. Zhang** and **Z.X. Li** **Invited**

OTHER CONFERENCE ROLES

5th Australasian Universities Geoscience Educators Network Meeting, Canberra, Australia, 28-29 January 2016	*Co-Organiser:* Nathan Daczko
GAC-MAC 2016, Margins Through Time, Whitehorse, Yukon, Canada, 1-3 June 2016	*Member of Organising and Scientific Committee:* Zheng-Xiang Li - Special Session 2 (SS2): *"Northwest Laurentia's Neighbours in Proterozoic Supercontinents: Cratonic Identifications and Their Geodynamic Implications"*
AESC 2016 - Australian Earth Sciences Convention - Uncover Earth's Past to Discover Our Future, Adelaide Convention Centre, Australia, 26-30 June 2016	*Sub Theme Chair:* Kelsie Dadd - Theme: *"Earth's Environment - Past to Present"* - Sub Theme: *"Scientific Results of the International Ocean Discovery Program (IODP)"* *Sub Theme Co-Chairs:* Juan Carlos Afonso and Louis Moresi - Theme: *"Deep Earth Geodynamics"* - Sub Theme: *" Linking Plate Tectonics and Mantle Convection to Surface Processes"* *Sub Theme Chair:* Chris Kirkland - Theme: *"Tectonics of the Planet"* - Sub Theme: *"Proterozoic Orogens Welding the West, North and South Australian Cratons"* *Sub Theme Co-Convenor:* Zheng-Xiang Li - Theme: *"Tectonics of the Planet"* - Sub Theme: *"Supercontinent Cycles and Global Geodynamics"* *Sub Theme Chair:* Ross Mitchell - Theme: *"Tectonics of the Planet"* - Sub Theme: *"Supercontinent Cycles and Global Geodynamics"* *Symposium Co-Chair:* Juan Carlos Afonso - *"Early to Mid Career Researchers Symposium"*
26th Goldschmidt Conference, Yokohama, Japan, 26 June - 1 July 2016	*Session Co-Convenor:* William Griffin - Session 09a: *"Sustainable Resourcing of Ore Deposits Related to Ultramafic-Mafic Magmas"*
The 4th Conference on Earth System Science, Shanghai, China, 4-6 July 2016	*Symposium Co-Convenor:* Zheng-Xiang Li - *"Eastern Eurasian Tectonics, Evolution of the Western Pacific, and Ocean-Continent Collision Processes"*
Australian Astrobiology Meeting, Perth, Australia, 10-12 July 2016	*Organising Committee/Scientific Committee:* Martin Van Kranendonk - *"Eastern Eurasian Tectonics, Evolution of the Western Pacific, and Ocean-Continent Collision Processes"* *Session Chair:* Simon George - Session 7: *"Early Life 2"*
AOGS 13th Annual Meeting, Beijing, China, 31 July - 5 August 2016	*Primary Session Convenor:* Huaiyu Yuan - Session SE06: *"Across-scale And Multi-discipline Studying of Continental Lithosphere"*

OTHER CONFERENCE ROLES *cont...*

7th International Dyke Conference (IDC7), Beijing, China, 18-20 August 2016	*Members of Organising committee:* **Sergei Pisarevsky** **Michael Wingate**  *International Steering Committee Member, Session Convenor:* **Steven Denyszyn** - Session: *"Remote Sensing of Dykes"* *Session Chair:* **Michael Wingate** - Session 4: *"Geochronology of dyke swarms"*
35th IGC, Cape Town, South Africa, 27 August - 4 September 2016	*Symposium Co-convenor:* **Zheng-Xiang Li** - Theme: *"Supercontinent Cycles and Global Geodynamics (IGCP 648)"* *Theme Champion:* **Simon Wilde** - Theme: *"Geochronology"* *Session Convenor:* **Simon Wilde** - Session: *"Hadean and Archaean Earth"*
13th International Nickel-Copper-PGE Symposium, Fremantle, Australia, 5-9 September 2016	*Organising Committee:* **Marco Fiorentini**
AGU Fall Meeting, San Francisco, USA, 12-16 December 2016	*Session Co-Convenor and Co-Chair:* **Craig O'Neill** - Session T53C: *"Secular Change in Earth Processes: Shifting Uniformitarianism II"*

SELECTED WORKSHOP ROLES

Activity	Details & Participant/s	Date
CET Seminar Series	**Cam McCuaig**	2016
CCFS/EPS Seminar Series	**CCFS/EPS MQ**, organised by Stefan Loehr	2016
A Short Course in Numerical Geodynamic Modelling	Co-instructors **Weronica Gorczyk** and **Christopher Gonzalez**, hosted by UWA	6-8 June 2016
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 2016
Goldschmidt 2016 Workshop - Atom Probe Microscopy for Geoscientists	Workshop Co Leader **Steven Reddy**	25-26 June 2016

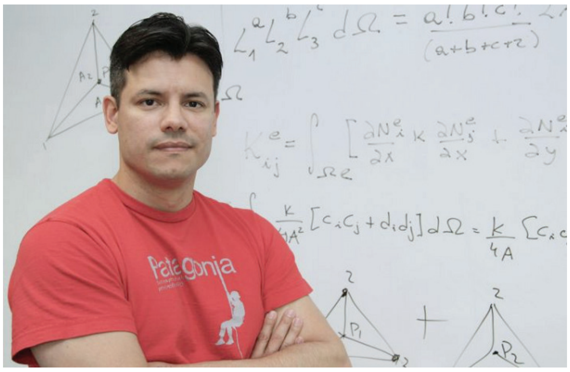
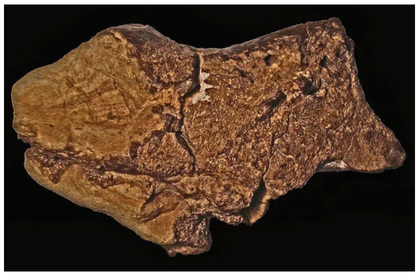
SELECTED WORKSHOP ROLES *cont...*

Gold workshop at The Ludwig Maximilians University of Munich, Germany	Speaker - **Stefano Caruso**	28 June 2016
UNCOVER Isotope geology: a window into crustal evolution, fertility and the geodynamics of Earth	Co-organiser - **Chris Kirkland**	1 July 2016
Pilbara Craton field trip - Australia Astrobiology Meeting, Perth, Australia	Organiser - **Martin Van Kranendonk**, Co-Field Trip Leaders **Martin Van Kranendonk** and **Tara Djokic**	13-17 July 2016
CCFS Short Course on Snowball Earth	Instructor - Professor Paul Hoffman (Department of Earth and Planetary Sciences at Harvard University, Cambridge, MA, USA. Organised by **Zheng-Xiang Li**, Hosted by Curtin. Lectures were live streamed and made available here: http://tectonics.curtin.edu.au/ccfs-sponsored-short-course-snowball-earth-lectures/	15 July 2016

Workshop for early and mid-career geoscientists, ASEG-PESA-AIG 2016	Convenor - **Juan Carlos Afonso**	1 August 2016
MetSoc 2016 Workshop - Microstructure and geochronology of shocked accessory minerals	Co-Converor - **Timmons Erickson**	7 August 2016
CNRS Forsterite Master Class - Structural Geology, France	Presenter - **Nicolas Thébaud**	5-7 October 2016
West African Metallogeny Workshop, Ouagadougou, Burkina Fasso	Presenter - **Nicolas Thébaud**	17-22 October 2016
ACTER 2016 Field Symposium/ Workshop - Orogenesis during Supercontinent Cycles	Event Co-organiser - **Zheng-Xiang Li**	20-29 October 2016
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**	16 November 2016
CCFS sponsored shortcourse: Raman, Luminescence Spectroscopy and Imaging in the Earth and Planetary Sciences	Instructor - Professor Lutz Nasdala (Institute of Mineralogy and Crystallography, University of Vienna, Austria). Organised by **Dorrit Jacob**, hosted by Macquarie University. See *photo p. 108*.	28 November - 1 December 2016
CET-UWA 2016 Members' Day	Presenters included - **Weronika Gorczyk, Huaiyu Yuan**	7 December 2016

ESTEEM

AWARDS

Participant	Activity
Juan Carlos Afonso	Awarded the 2017 Anton Hales Medal for being *"at the forefront of revolutionising the way that geoscientists interpret the signals they obtain from deep in the Earth by geophysical methods"* 
Bill Griffin	Recognised by Clarivate Analytics (previously Thomson Reuters) as a Highly-Cited Researcher (http://highlycited.com) 2016 Citation Milestone - Google Scholar named him as one of Australias' most highly cited researchers when his H-Index passed 100
David Wacey	Gained entry into the *"Guinness Book of World Records"* as part of the team responsible for the first discovery of a fossilised dinosaur brain (*photo - David Wacey*). The brain once belonged to an iguanodon and is 133 million-years old. 
Elena Belousova	Presented with the 2016 Nancy Millis Medal for Women in Science at the Shine Dome, ACT in May 2016 (*pictured centre*) 
Andrea Giuliani, Montgarri Castillo-Oliver	Received a European Commission, Europlanet 2020 Research Award
Robert Loucks	Awarded the A.B. Edwards Medal of Geological Society of Australia (Presented June 2016 GSA Meeting) Received the Stillwell Award of Geological Society of Australia (Presented June 2016 GSA Meeting)
Simon Wilde	Recognised by Clarivate Analytics (previously Thomson Reuters) as a Highly-Cited Researcher (http://highlycited.com) 2016

AWARDS *cont...*

Sue O'Reilly	Became a 2016 Member (AM) in the General Division of the Order of Australia for *"significant service to the Earth Sciences as an academic and researcher, to tertiary education and to scientific associations"*. The Award was presented by his Excellency General, The Honourable David Hurley AC DSC (Ret'd).  Recognised by Clarivate Analytics (previously Thomson Reuters) as a Highly-Cited Researcher (http://highlycited.com) 2016
Zheng-Xiang Li	Received the Geological Society of Australia S.W. Carey Medal, 2016 Recognised by Clarivate Analytics (previously Thomson Reuters) as a Highly-Cited Researcher (http://highlycited.com) 2016

2016 NEW APPOINTMENTS AND POSITIONS

Ian Fitzsimons	Fellow of the Geological Society, London Fellow of the Mineralogical Society Keynote Speaker for SEG 2016: Tethyan Tectonics and Metallogeny
Marco Fiorentini	Appointed Associate Editor Mineralium Deposita
Weronika Gorczyk	Appointed as committee member of Geoconferences WA
Bill Griffin	Co-Convenor for Session 09a Sustainable Resourcing of Ore Deposits Related to Ultramafic-Mafic Magmas at Goldschmidt 2016 at Yokohama, Japan Appointed Co-Editor with Sisir Mondal of a book to be published by Elsevier in 2017 titled *"Processes and ore deposits of ultramafic-mafic magmas through space and time"*
Yongjun Lu	Appointed Associate Editor for SEG 2016 Special Publication on Tethys Appointed Councillor for Society for Geology Applied to Mineral Deposits (SGA) in 2016-2019
Craig O'Neill	Member of the Australian Academy of Science National Committee for Earth Sciences
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 Elected Member of Council, Australian Academy of Science (http://www.mq.edu.au/newsroom/2014/11/14/eminent-geologist-joins-australian-academy-of-science-council/) Sue O'Reilly (with Professor Peter Koopman) set up an Equity and Diversity Reference Group at the request of the Council of the Australian Academy of Science. Sue O'Reilly is Deputy Chair of that group for 2017 Invited Convenor - Lithosphere evolution during subduction and collision session, Goldschmidt 2017 Member of the Order of Australia (2016)

EDITORIAL APPOINTMENTS	
Acta Geologica Sinica	Li
Acta Geoscientia Sinica	Li
American Journal of Science	Wilde
American Mineralogist	Piazolo
Chemical Geology	Wilde
Cogent Geosciences	O'Neill, Moresi
EGU Journal Solid Earth	Afonso, Schaefer
Exploration Geophysics	Yang
Geobiology	Wacey
Geodynamics & Tectonophysics	Pisarevsky
Geology	C. Clark
Geological Society of America Bulletin	Griffin, Li
Geosphere	Yuan
GeoResJ	George, Jacob, Schaefer
Journal of Earth Sciences	Griffin
Journal of the Geological Society, London	C. Clark, Fitzsimons
Journal of Jilin University - Earth Science	Wilde
Journal of Metamorphic Geology	Brown
Journal of Petrology	Turner
Journal of Structural Geology	Piazolo
Lithos	C. Clark, Foley, Griffin
Mineralium Deposita	Fiorentini
Nature Scientific Reports	Wacey
Ore Geology Reviews	Bagas
Physics and Chemistry of Minerals	McCammon
Precambrian Research	Barley, Pisarevsky, Van Kranendonk
Scientific Reports	Piazolo

OUTREACH

Forum	Participant/s	Date
Public lectures - **Nancy, Barcelona, Frankfurt, Brussels**	Andrea Giuliani	2016
Public lectures - **McGill University, University of New Brunswick, Memorial University of Newfoundland, Technical University of Munich, Northern Star Resources, BHPB iron ore**	Crystal LaFlamme	2016
Numerous government briefings	Chris Kirkland	2016
Feature presenter **- TV documentary "The Living Universe" ABC television**	Martin Van Kranendonk	2016
Public lecture to the **Western Australian Chinese Scientists Association (WACSA)** on *"How the Earth Engine Works - from the Crust to the Core"*	Zheng-Xiang Li	20 January 2016
Presenter - **GSWA 2016 Open Day Lectures**	Huaiyu Yuan	26 February 2016

OUTREACH *cont...*

Forum	Participant/s	Date
Public lecture - **Australian National University - RSES Seminars** *"Atoms on the move: deformation-induced trace element redistribution in zircon"*	Sandra Piazolo	10 March 2016
Talk - **Science at the Shine Dome 2016** - *"Evolution of Earth's crust through the prism of zircon crystals"*	Elena Belousova	25 May 2016
Public lecture - **University of Adelaide** - *"Seismic structure of the Paleoproterozoic Gascoyne Province: roles of a micro-continent in craton amalgamation and reworking processes"*	Huaiyu Yuan	3 June 2016
Public lecture *"Alfred Wegener and modern plate tectonics"* **Goethe Society, WA, Australia**	Uwe Kirscher	6 June 2016
Chief Scientist briefing (NRIS)	Matthew Kilburn	20 July 2016
Public lecture - **iVEC-Pawsey Supercomputing Open Day**	Gregory Dering	20 August 2016
Feature presenter - **IMAX documentary film, "Earth Story"** 	Martin Van Kranendonk	18 August - 30 September 2016
Public lecture - **CMCA Geoscience industry open house**	Matthew Kilburn	17 November 2016
Public lecture - **Geological Survey of Western Australia** annual lecture series	Gregory Dering	23 November 2016
Address - **Australian Academy of Science Decadal Plan for Earth Science - Town Hall Meeting**, ANU, 23 Nov 2016	Sue O'Reilly	23 November 2016
Talk - **Greenland Day, Perth** - *"Reconnaissance-scale geodynamic understanding of basement-cover relationships linked to mineral systems targeting in North-West Greenland"*	Crystal LaFlamme	9 December 2016
Talk to **high school students** - *"Tectonics, geodynamics, and the life of geoscience researchers"*	Zheng-Xiang Li	12 December 2016

MEDIA

Activity	Participant/s	Date, Forum	Web address
Heaven on Earth...	Bll Griffin	26/1/2016, YouTube video, Shefa Yamim	https://www.youtube.com/watch?v=_5vHjnsL0L4&feature=youtu.be
The role of the deep lithosphere in metallogeny	Sue O'Reilly	1/2/2016, YouTube video	https://www.youtube.com/watch?v=cYTzKv8PApc
Defining mineral system footprints in the Edmund Basin of the Capricorn Orogen, Western Australia	Heta Lampinen et.al.	18/2/2016, ASDInc.	http://discover.asdi.com/defining-mineral-system-footprints-in-the-edmund-basin-of-the-capricorn-orogen-western-australia
PhD student gets some help to detect mineral system footprints	Heta Lampinen et.al.	19/2/2016, CET News and Events	http://www.cet.edu.au/news-and-media/news/news-details/2016/02/19/phd-student-gets-some-help-to-detect-mineral-system-footprints
Australian university confirms Israeli rare mineral discovery	Bill Griffin	21/2/2016, J-Wire	http://www.jwire.com.au/60546-2/
Kosciuszko explained: mystery of the Snowy Mountains solved	Craig O'Neill	14/4/2016, Sydney Morning Herald	http://www.smh.com.au/environment/kosciuszko-explained-mystery-of-the-snowy-mountains-solved-20160314-gnj2zg.html
Kosciuszko explained: mystery of the Snowy Mountains solved	Craig O'Neill	14/4/2016, The Age	http://www.theage.com.au/environment/kosciuszko-explained-mystery-of-the-snowy-mountains-solved-20160314-gnj2zg
Kosciuszko explained: mystery of the Snowy Mountains solved	Craig O'Neill	14/4/2016, Canberra Times	http://www.canberratimes.com.au/environment/kosciuszko-explained-mystery-of-the-snowy-mountains-solved-20160314-gnj2zg.html
Kosciuszko explained: mystery of the Snowy Mountains solved	Craig O'Neill	14/4/2016, WA Today	http://www.watoday.com.au/environment/kosciuszko-explained-mystery-of-the-snowy-mountains-solved-20160314-gnj2zg.html
Plate tectonics just a stage in Earth's life cycle; Simulation shows crust to stop shifting in 5 billion years	Craig O'Neill	31/05/2016, Science News	https://www.sciencenews.org/article/plate-tectonics-just-stage-earth%E2%80%99s-life-cycle
Asteroids delivered bulk of the Moon's water, study finds	Craig O'Neill	1/6/2016, ABC Online	http://www.abc.net.au/news/2016-06-01/asteroids-may-have-delivered-bulk-of-the-moon's-water/7463102
Asteroids delivered bulk of the Moon's water, study finds	Craig O'Neill	1/6/2016, ABC Radio Australia	http://www.radioaustralia.net.au/international/2016-06-01/asteroids-delivered-bulk-of-the-moons-water-study-finds/1586242
Queen's Birthday Honours 2016: the full list	Sue O'Reilly	13/6/2016, Sydney Morning Herald	http://www.smh.com.au/national/queens-birthday-honours-2016-the-full-list-20160608-gpec51.html
Queen's Birthday Honours 2016: the full list	Sue O'Reilly	13/6/2016, The Age	http://www.theage.com.au/national/queens-birthday-honours-2016-the-full-list-20160608-gpec51.html
Queen's Birthday Honours List: Ros Packer tops list of Aussies awarded a Companion of the Order of Australia (AC)	Sue O'Reilly	13/6/2016, The Daily Telegraph	http://online.isentialink.com/dailytelegraph.com.au/2016/06/13/891f8388-ee50-4df8-81ac-b39267b515ef.html
Queen's Birthday Honours	Sue O'Reilly	15/6/2016, Northern District Times	Print only
Sue O'Reilly rocks!	Sue O'Reilly	20/6/2016, This Week, Macquarie University	http://www.mq.edu.au/thisweek/2016/06/20/sue-oreilly-rocks/#.WJKFWbZ97OZ
Modern-day regional mapping training in the Aussie Outback	Heta Lampinen et.al.	22/6/2016, CET News and Events	http://www.cet.edu.au/news-and-media/news/news-details/2016/06/22/modern-day-regional-mapping-training-in-the-aussie-outback
Does a planet need plate tectonics to develop life?	Craig O'Neill	29/6/2016, The Conversation	https://theconversation.com/does-a-planet-need-plate-tectonics-to-develop-life-61303
Does a planet need plate tectonics to develop life?	Craig O'Neill	29/6/2016, IFLScience	http://www.iflscience.com/environment/does-a-planet-need-plate-tectonics-to-develop-life/
Does a planet need plate tectonics to develop life?	Craig O'Neill	29/6/2016, Australasian Science	http://www.australasianscience.com.au/article/science-and-technology/does-planet-need-plate-tectonics-develop-life.html

MEDIA *cont...*

Activity	Participant/s	Date, Forum	Web address
Does a planet need plate tectonics to develop life?	Craig O'Neill	29/6/2016, Australasian Science	http://www.australasianscience.com.au/article/science-and-technology/does-planet-need-plate-tectonics-develop-life.html
Does a planet need plate tectonics to develop life?	Craig O'Neill	29/6/2016, Phys Org	http://phys.org/news/2016-06-planet-plate-tectonics-life.html
Does a planet need plate tectonics to develop life?	Craig O'Neill	4/7/2016, Cosmos	https://cosmosmagazine.com/geoscience/does-a-planet-need-plate-tectonics-to-develop-life
World's oldest gem leading us to hidden treasures	Elena Belousova	4/7/2016, Stories of Australian Science	http://stories.scienceinpublic.com.au/2016/oldestgem/
Study Says Earth's Plate Tectonics May Be Just a Phase	Craig O'Neill	8/7/2016, Smithsonian magazine	http://www.smithsonianmag.com/science-nature/study-says-earths-plate-tectonics-may-be-just-phase-180959705/
Old planets always get too hot or cold for life in the end	Craig O'Neill	27/7/2016, New Scientist	https://www.newscientist.com/article/2099139-old-planets-always-get-too-hot-or-cold-for-life-in-the-end/
Old planets always get too hot or cold for life in the end	Craig O'Neill	27/7/2016, New Sceintist	https://www.newscientist.com/article/2099139-old-planets-always-get-too-hot-or-cold-for-life-in-the-end/
Top geologist: Israel has major deposits of precious stones	Bill Griffin	1/8/2016, Globes	http://www.globes.co.il/en/article-israel-has-significant-precious-stone-and-diamond-deposits-1001143242
What 3.7-billion-year-old fossils mean for life on Mars	Craig O'Neill	1/9/2016, Cosmos Magazine	https://cosmosmagazine.com/palaeontology/what-3-7-billion-year-old-fossils-mean-for-life-on-mars
Journal of Geophysical Research - Editorial Highlight	Juan Carlos Afonso, Yingjie Yang	1/10/2016, AGU Publications	http://agupubs.onlinelibrary.wiley.com/hub/article/10.1002/2016JB013049/editor-highlight/
Professional fossil hunter discovers fossilised dinosaur brain tissue, scientists say	David Wacey	28/10/16, ABC radio	http://www.abc.net.au/am/content/2016/s4564887.htm
Macquarie Earth Sciences researcher awarded prestigious Medal	Juan Carlos Afonso	18/11/2016, Macquarie University News	http://www.mq.edu.au/newsroom/2016/11/18/macquarie-earth-sciences-researcher-awarded-prestigious-medal/
Macquarie Earth Sciences researcher awarded prestigious Medal (Macquarie University)	Juan Carlos Afonso	18/11/2016, Wn.com News	https://article.wn.com/view/2016/11/18/Macquarie_Earth_Sciences_researcher_awarded_prestigious_Meda/
Prestigious Earth Sciences medal for Macquarie researcher	Juan Carlos Afonso	21/11/2016, This Week, Macquarie University	http://www.mq.edu.au/thisweek/2016/11/21/prestigious-earth-sciences-medal-macquarie-researcher/#.WJJ-5LZ97OY
Macquarie Earth Sciences researcher awarded prestigious Medal	Juan Carlos Afonso	23/11/2016, Foreign Affairs	http://foreignaffairs.co.nz/2016/11/23/macquarie-earth-sciences-researcher-awarded-prestigious-medal/
SEG Students Head to the Kimberleys	Heta Lampinen, Constanza Jara, et.al.	29/11/2016, CET News and Events	http://www.cet.edu.au/news-and-media/news/news-details/2016/11/29/seg-students-head-to-the-kimberley-s
Australian Academy of Science 2017 Awardees - Early career honorifics - 2017 Anton Hales Medal	Juan Carlos Afonso	18/11/2016, Australian Academy of Science	https://www.science.org.au/opportunities-scientists/recognition/honorific-awards/honorific-awardees/2017-awardees#hales
Geoscience really rocks	Juan Carlos Afonso	07/12/2016, Rouse Hill Times	Print only
DMP tests earthquake recording site in Broome	Klaus Gessner, Huaiyu Yuan, Liang Zhao	22/12/2016, WA Department of Mines and Petrolium	http://www.dmp.wa.gov.au/News/DMP-tests-earthquake-recording-20715.aspx?platform=hootsuite
First discovery of a fossilised dinosaur brain	David Wacey	27/10/2016, Official Guiness Records Magazine	http://www.guinnessworldrecords.com/world-records/449184-first-discovery-of-a-fossilised-dinosaur-brain

MEDIA - FEATURED PAPERS

716. **D.E. Jacob**, **S. Piazolo**, A. Schreiber and P. Trimby 2016. Redox-freezing and nucleation of diamond via magnetite formation in the Earth's mantle. *Nature Communications*, *7*, *11891*.

Activity	Date, Forum	Web address
Ultra-thin slices of diamonds reveal geological processes	21/6/2016, EurekAlert!	https://www.eurekalert.org/pub_releases/2016-06/ggph-uso061716.php
How to build a diamond factory	22/6/2016, Cosmos	https://cosmosmagazine.com/geoscience/to-build-a-diamond-it-first-needs-sulfide-minerals
Ultra-thin slices of diamonds reveal geological processes	22/6/2016, Health Medicine Network	http://healthmedicinet.com/i/ultra-thin-slices-of-diamonds-reveal-geological-processes/
Geology: Sulphides may be a diamond's best friend	22/6/2016, Nature Asia	https://www.natureasia.com/en/life-sci/research/10742

895. Barham, M., **Kirkland, C.L.**, Reynolds, S., O'Leary, M.J., Evans, N.J., Allen, H., Haines, P.W., Hocking, R.M., McDonald, B.J. **Belousova, E.** and Goodall J. 2016. The answers are blowin' in the wind: Ultra-distal ashfall zircons, indicators of Cretaceous super-eruptions in eastern Gondwana. *Geology*, *44*, *643-646*.

Activity	Date, Forum	Web address
The answers are blowin' in the wind: Ultra-distal ashfall zircons, indicators of Cretaceous super-eruptions in eastern Gondwana	21/7/2016, ENGGtalks	https://www.enggtalks.com/news/5127/the-answers-are-blowin-in-the-wind-ultra-distal-ashfall-zircons
Curtin scientists make Earth-shattering discovery	12/8/2016, Curtin News	http://news.curtin.edu.au/media-releases/curtin-scientists-make-earth-shattering-discovery/
Volcano 'super-eruptions' blasted crystals from Australia's east coast to WA	12/8/2016, Herald Sun	http://www.heraldsun.com.au/news/volcano-supereruptions-blasted-crystals-from-australias-east-coast-to-wa/news-story/6aaf0491640ddc14419078af213f6388
Scientists make Earth-shattering discovery	14/8/2016, Geology Page	http://www.geologypage.com/2016/08/scientists-make-earth-shattering-discovery.html
Curtin scientists make Earth-shattering discovery	15/8/2016, AZO Materials	http://www.azom.com/news.aspx?newsID=46183
Giant ancient supervolcanoes threw rock right across Australia	17/8/2016, New Scientist	https://www.newscientist.com/article/2101518-giant-ancient-supervolcanoes-threw-rock-right-across-australia/
Ancient SUPERVOLCANOES blasted rock from one side of Australia to the other 100 million years ago	18/8/2016, Daily Mail	http://www.dailymail.co.uk/sciencetech/article-3746954/Ancient-SUPERVOLCANOES-blasted-rock-one-Australia-100-million-years-ago.html
Mega volcanoes once blasted debris right across Australia	18/8/2016, Sky News	http://news.sky.com/story/mega-volcanoes-once-blasted-debris-right-across-australia-10541485
Ancient supervolcanoes threw rocks right across Australia	19/8/2016, Science Alert	http://www.sciencealert.com/ancient-supervolcanoes-had-the-power-to-throw-rocks-right-across-australia
Ancient super-eruptions blasted volcanic debris all the way across Australia	22/8/2016, IFL Science	http://www.iflscience.com/environment/ancient-supereruptions-blasted-volcanic-debris-all-the-way-across-australia/
Scientists discover volcanic super eruptions in Australia	23/8/2016, National Geographic	http://www.nationalgeographic.com.au/australia/scientists-discover-super-volcanic-eruptions-in-australia.aspx

837. Nutman, A.P., Bennett, V.C., Friend, C.R.L., **Van Kranendonk, M.J.** and Chivas, A.R. 2016. Rapid emergence of life shown by discovery of 3,700-million-year-old microbial structures. *Nature*, *535-538*.

Activity	Date, Forum	Web address
World's oldest fossils unveil life 3.7 billion years ago (etc)	31/8/16 - 5/9/16, various	Featured in 231 news outlets world wide

VISITORS

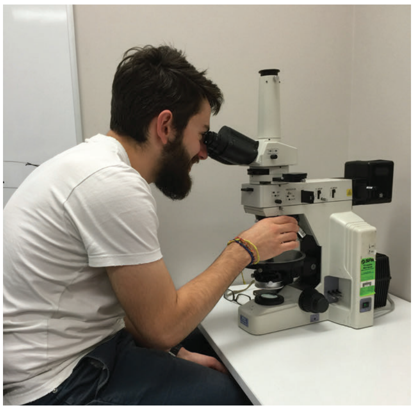
CCFS fosters links nationally and internationally through visits of collaborators to undertake defined short-term projects, or short-term visits to give lectures and seminar sessions. Formal collaborative arrangements are facilitated by partnerships in grants with reciprocal funding from international collaborators.

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

They have participated in collaborative research, technology exchange, seminars, discussions and joint publications and collaboration in postgraduate programs.

CCFS provides funds to international visitors who will add value to CCFS programs and contribute to the high visibility of research in the Centre.

Recipients of 2016 CCFS Visiting Researcher Funds were:



Mr Alexis Geisler (*pictured right*) is an intern (MSc student) from Ecole Normale Superieure, France. Alexis visited CCFS from March to July 2016 to work on samples from Heard Island and use the MQ Geochemical Analysis Unit.

Dr Maibam Bidyananda Manipur from the University of India visited CCFS from June-July 2016 to collaborate on the Indo-Myanmar Ophiolite Belt.

Miss Zakie Kazemi (*pictured below left*), is an exchange PhD student working on the "*Petrology, geochemistry and tectonic model of Late Cretaceous volcanism*" from Shahrood University of Technology, Iran. Zakie visited CCFS from August 2016 until March 2017, working with CCFS staff, using the MQ Geoanalytical facilities and treating everyone to her wonderful Iranian cooking.

Professor Paul Hoffman (*pictured above*), visited Curtin in July 2016 to present a CCFS sponsored short course on Snowball Earth. The series of seminars covered a range of aspects of the global climatic phenomenon known as snowball earth. The topics included geology, climate dynamics and geobiology (and everything in between) during two possible global glaciations. The event was extremely popular, with more than 80 delegates, along with a number of others who watched the event via a live webcast.

Professor John Wheeler from Liverpool University, UK, visited in May to collaborate on work relating to diffusion creep and grain coarsening and developing an integrated model. Professor Wheeler's expertise in diffusion creep modelling and deformation mechanisms in medium to high grade rocks made him an invaluable visitor, collaborating and interacting with Sandra Piazolo and Sandra's research group as well as the MQ geophysics group.

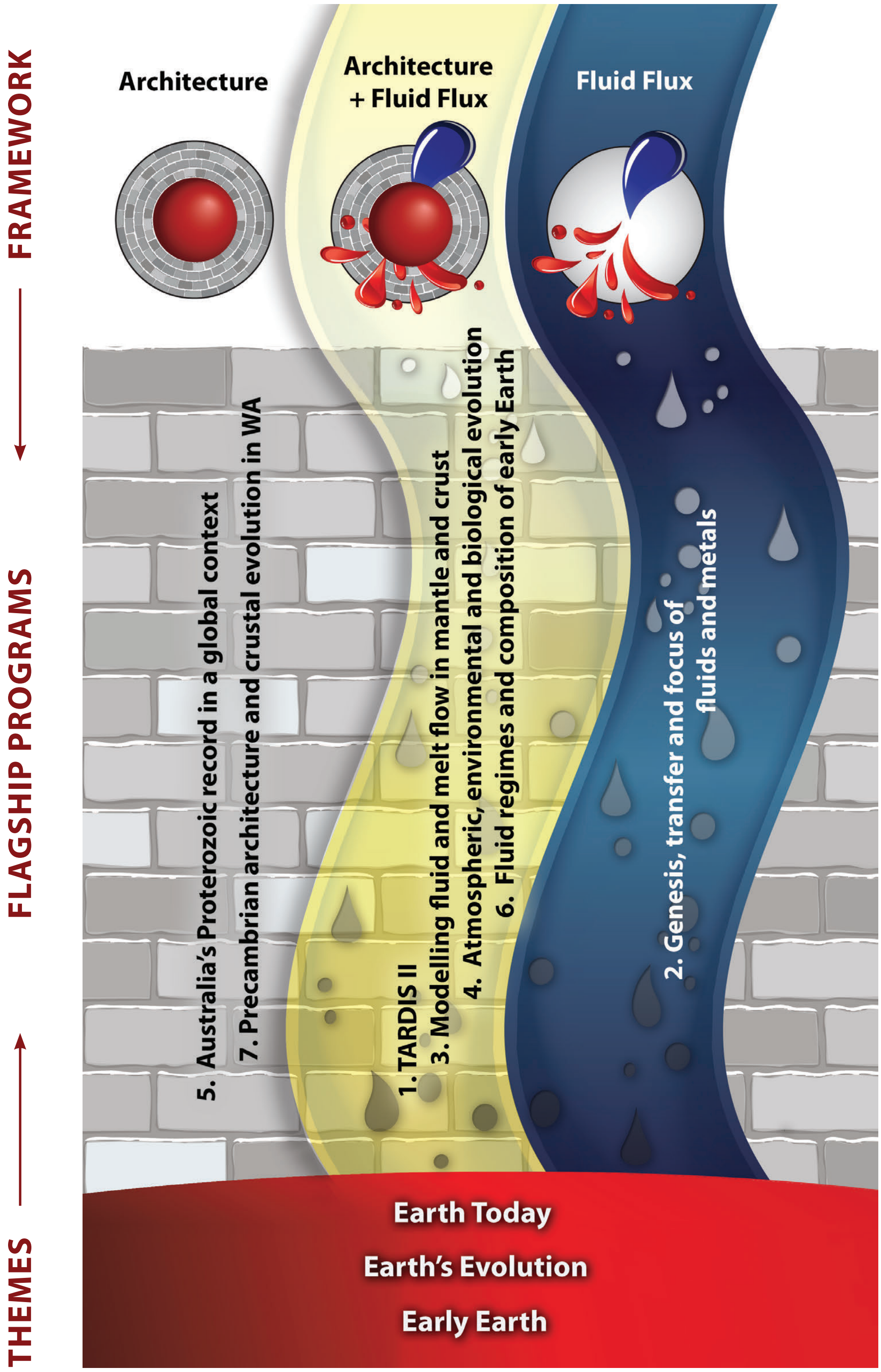
Dr Robert Loucks visited CET UWA from September to October 2016 to work on research related to CCFS Flagship Program 2 with Marco Fiorentini. During his stay he derived the thermodynamic formalism and compiled a dataset to calibrate a new zircon oxybarometer. See *Research highlight p. 81*.

Professor Richard Ernst (*pictured right*) from Carleton University, visited in August 2016 to work on research related to CCFS Flagship Program 6 and interact with Professor Zheng-Xiang Li's Earth Dynamics Research Group (http://geodynamics.curtin.edu.au). Dr Ernst's visit helped to provide constraints from the recently updated LIP record for supercontinent cycles and global Geodynamics.

Dr Stephan Wolf from the Institue for Glass and Ceramics, University of Erlangen-Nuremberg, Germany, visited CCFS MQ in September 2016, to collaborate on biomimetic materials from metastable precursors in the $CaCO_3$ system.

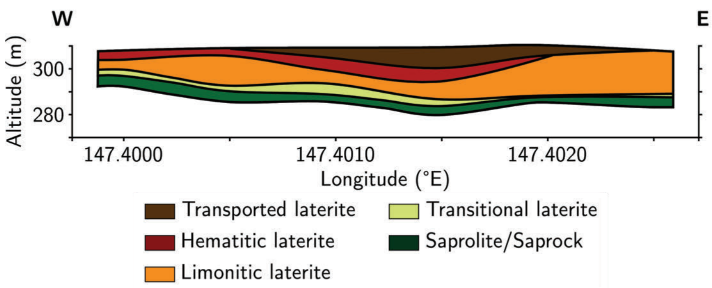
Research highlights 2016

Following the conceptual framework outlined on *page 6*, 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*.



Genesis of deposits of scandium, a promising rare metal

Rare metals play a critical role in the future of our society, through their use in the energy transition and information and communication technologies. However, this future depends on the supply of these metals. Among them, scandium is particularly interesting for a large range of applications, from medicine to electronics. The main driver for scandium demand lies in the mechanical properties and lightness this metal can add to high-performance alloys, vital to reduce carbon emissions in the transport sector. However, scandium deposits are rare and their genesis is poorly understood. Recently, promising concentrations have been found in tropical soils from Eastern Australia. In a collaborative research project with researchers from the University Pierre and Marie Curie (Paris, France) and Jervois Mining Ltd (Cheltenham, Victoria, Australia), we have determined the scandium-bearing minerals in such deposits and the nature of their association with Sc at the atomic scale. The results give a better understanding of the mechanisms of their formation, a fundamental step for exploration and exploitation of these deposits.



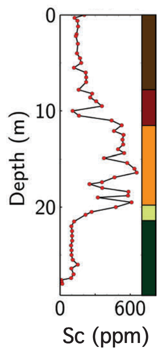


Figure 1. Diagram showing the different layers forming the lateritic cover of the deposit and evolution of the scandium concentration along these layers.

In Eastern Australia, volumes of ultramafic bedrock are frequently covered by a thick layer of residual rocks, called laterites. These formations developed during the Tertiary, under seasonally-dry humid tropical climatic conditions. These residual soils have been preserved by the geological stability of the Australian continent. Some areas are particularly enriched in scandium and constitute the richest deposits presently known for this metal. The samples studied come from the Syerston deposit, about 400 km west of Sydney. The wealth of this deposit provides a century-long resource for Sc at present levels of consumption.

The study of the parent rock, lying below the deposit, showed that it is already enriched in scandium compared to the Earth's crust. This rock is mainly composed of clinopyroxene accumulated in subvolcanic feeder conduit. The enrichment in scandium is the result of the affinity of this element for clinopyroxene, in which it is concentrated during their precipitation. The scandium concentration strongly increases in the lateritic cover, reaching outstanding levels for this element in particular, in one layer: the limonitic laterite (Fig. 1). The mineralogical study of this layer showed the absence of scandium minerals. However, scandium is dispersed and correlated with the presence of iron oxides. These samples have been studied at the SOLEIL and ESRF synchrotrons in France using X-ray fluorescence mapping and X-ray absorption spectroscopy, confirming the close association between scandium and two particular iron oxides. Most of the scandium is adsorbed at the surface of goethite (FeOOH) while a minor part is incorporated into the crystal structure of hematite (Fe_2O_3) (Fig. 2).

This study has shown that the exceptional concentration of scandium in this deposit is the result of the initial fertility of the parent rock, and of its alteration in a tropical climate, leading to the release of Sc from the primary clinopyroxenes, and its trapping by newly formed iron oxides. Long time scales of alteration in the absence of major tectonic events explain the formation of this new type of scandium deposit. This development gives us the possibility to consider the development of new technologies based on the unusual properties of this metal.

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

Contacts: Mathieu Chassé, Bill Griffin, Sue O'Reilly
Funded by: CCFS Flagship Program 1

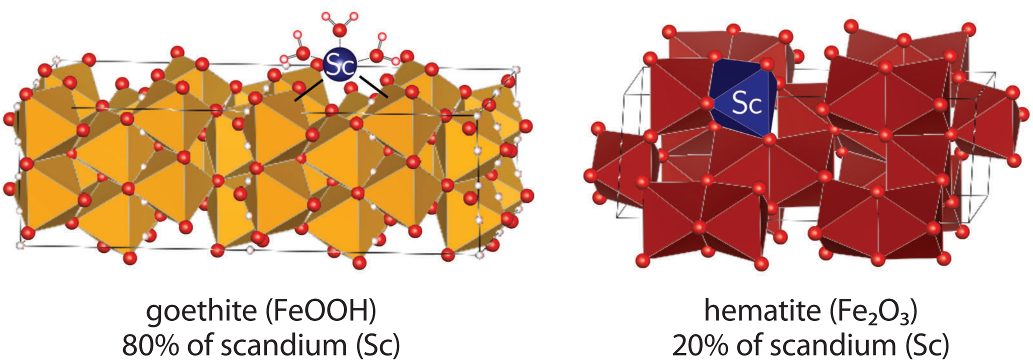


Figure 2. Proportion of scandium associated with the scandium-bearing mineral species in the deposit and diagram showing the nature of the association at the atomic scale. Scandium is adsorbed at the surface of goethite and incorporated into the crystal structure of hematite.

Oldest Evidence of life on Earth discovered

A *Nature* paper has documented the discovery of the oldest evidence of life on Earth in the form of stromatolites preserved in 3700 million-year-old carbonate rocks from Western Greenland.

The discovery was made by a team led by Prof Allen Nutman (U. Wollongong), Prof Vickie Bennett (ANU), Prof Martin Van Kranendonk (UNSW and CCFS) and others in a set of newly exposed rocks within a low-strain pocket of the famous Isua supracrustal belt. Previously, the area had been covered by permanent snow, but heavy spring rain uncovered the rocks. The new exposures revealed a series of bedded, though metamorphosed, dolomite and calc-silicate rocks that preserved primary sedimentary structures, including cross-stratification in calc-silicate rocks, units of storm-generated sedimentary breccias, and bedded carbonates with low-amplitude coniform and domical stromatolites (Fig. 1). The rocks form part of a stratigraphic succession - together with pillow basalt and banded iron-formation - that can be mapped around a fold structure.

Additional evidence in support of these structures being stromatolites and not either abiogenic primary structures or post-depositional structural features includes:

1. The composition of the rocks, which is dolomite, a mineral well known from other fossiliferous Archean sedimentary deposits. This contrasts with siderite or ankerite, Fe-bearing carbonates that are demonstrably metamorphic in origin. The dolomite has characteristic seawater-like REE+Y patterns and $\delta^{13}C$ values (+1.2-1.5‰), characteristic of microbially-precipitated carbonate.
2. The geometry of the stromatolites, which clearly show upward growth from a flat (instigation) surface, and variable topographic morphology, as seen in other Precambrian, and living, examples. This precludes the structures being derived through boudinage, which produces symmetrical pinch-and-swell structures, or representing sedimentary flame structures, which have curved bases and show variation in sediment
grain size.
3. Onlap of sediment onto the topographic highs of the stromatolites, indicating the structures formed on, and grew up above, the seafloor at the time of sediment accumulation.
4. The fact that a metamorphic foliation could be discerned that transected the bedding at a high angle, showing the bedding was a primary feature.

The sedimentary features and composition of the bedded dolomite and calc-silicate rocks suggest stromatolite growth in a shallow marine environment. This discovery pushes back the record of life on Earth by 220 million years, the equivalent to nearly half the length of the Phanerozoic. The significance is twofold. First, it shows that life on Earth began relatively early, soon after the end of the late heavy meteorite bombardment, which ceased at c. 3.9 Ga. Second, because the coniform morphology is characteristic of stromatolites formed by phototrophic organisms and occurs in a shallow marine setting, it suggests that life had evolved a complex metabolism (phototrophy) and was able to inhabit seawater by 3.7 million years ago.

See *CCFS publication #837, Nutman et al., Nature, 537, 535-538.*

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

Contact: Martin Van Kranendonk
Funded by: ARC Discovery Project

Figure 1. 3,700 million-year-old stromatolites from Western Greenland.

Does the mantle move beneath Northeast China?

Intraplate volcanism on continents is an exception to the general model of Plate Tectonics, which states that most of the world's volcanoes both in oceans and on land occur at plate boundaries. Northeast China is an ideal place to study Cenozoic intraplate volcanism. Though located more than 2000 km west of the Japan trench, Northeast China hosts widely distributed Quaternary volcanism surrounding the Songliao Basin (SLB). Some of the most prominent volcanoes in the area include the well-known Changbaishan volcano in the southeast, the Jingpohu volcano in the east, the Wudalianchi volcano in the north, and two lesser known volcanoes, Abaga and Halaha, in the west (Fig. 1a). These Quaternary volcanoes are situated hundreds of kilometres apart with the SLB at the centre, which was formed by tectonic rifting in the late Mesozoic. Although it is generally agreed that the flat stagnation of the subducting Pacific slab in the Mantle Transition Zone has played an important role in the formation of Cenozoic volcanism in NE China, there is still little consensus about the mechanism responsible for the intraplate volcanism.

In order to understand the mantle processes responsible for the widespread magmatism in NE China, we constructed a high-resolution seismic model of the crust and upper mantle beneath NE China using seismic data recorded by the newly deployed NECESSArray. Our model reveals low-velocity anomalies in the upper mantle: one strong low-velocity anomaly beneath Changbaishan volcano in the east and relatively weak low-velocity anomalies beneath the Abaga and Halaha volcanos in the Xinmeng belt, surrounding a high-velocity anomaly beneath the SLB (Figs. 1 and 2). These low-velocity anomalies in the upper mantle are closely correlated with the distribution of young volcanic fields in NE China.

The widespread low velocity zone beneath Changbaishan has been interpreted as a large volume of upwelling hot asthenospheric materials that escape upward through a gap in the Pacific slab. The slowest velocity occurs at depths of 80-160 km (~-6% to -8%) (Figs. 2a and 2b), which may suggest the depths where partial melting mainly takes place, producing the magmas that feed the Changbaishan volcano. Cenozoic potassic basalts from the Changbaishan volcano and surrounding regions are interpreted to be derived by mixing of melts from the lithospheric mantle and the asthenosphere.

The most intriguing feature is the high velocity anomaly in the uppermost mantle beneath the SLB, which extends at least to 200 km depth. The overlying crust of the SLB has undergone considerable extension during the late Mesozoic, and as a consequence, it seems unlikely to have preserved such a thick lithosphere. The S-wave receiver-function study also indicates that the lithospheric thickness beneath SLB is between 80 and 100 km. If the lithospheric thickness beneath SLB is about 100 km, then a question arises: what causes the uppermost mantle high velocity anomaly down to ~200 km beneath SLB?

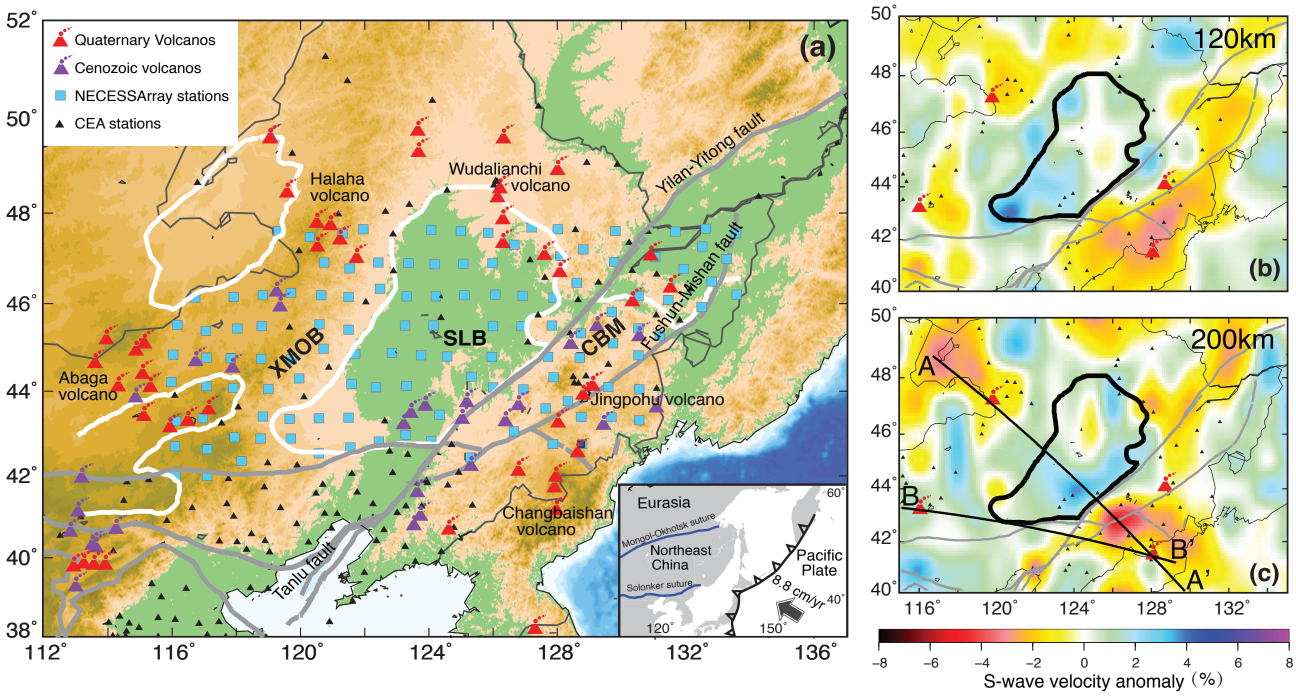


Figure 1. (a) Stations distribution and geological setting. Blue squares indicate 127 NECESSArray stations and black triangles denote 120 CEA stations. NE China is comprised of the Xing'an-Mongolia orogenic belt (XMOB), the Songliao basin (SLB) and the Changbai mountain region (CBM). Red and purple volcanic symbols are Quaternary and Cenozoic volcanoes in NE China. White lines outline major Mesozoic basins in NE China. CBV: Changbaishan volcano; JPHV: Jingpohu volcano; WDLCV: Wudalianchi volcano; HLHV: Halaha volcano; ABGV: Abaga volcano. NCC: North China Craton China, respectively. (b) and (c) S wave velocity anomaly from surface wave tomography at 120 and 200 km, respectively.

Based on our results, we propose a sub-lithosphere mantle convection model to explain both the deep upper-mantle high velocities beneath the Songliao basin, and the volcanism in the Xinmeng belt. As illustrated in the 3D cartoon (Fig. 2c), a plume-like upwelling with a large volume of hot mantle material has ascended through the upper mantle beneath Changbaishan. This mantle upwelling may also feed magma to the Quaternary Jingpohu volcano, which is located east of the SLB. If this is the case, a mantle downwelling beneath the SLB could be induced by the mantle upwelling from the mantle transition zone beneath the Changbaishan. The high velocity beneath the SLB may thus correspond to a downwelling limb of a larger upper mantle convective system. The downwelling beneath the Songliao basin would further induce secondary local convection within the asthenosphere to the west, leading to local upwelling beneath the Abaga and Halaha volcanoes (Fig. 2c), which are also imaged here as mantle low-velocity zones, but weaker and shallower than the one beneath the Changbaishan volcano (Figs. 1 and 2).

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

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Funded by: DP120102372, ARC Future Fellowship FT130101220, CCFS Flagship Program 3

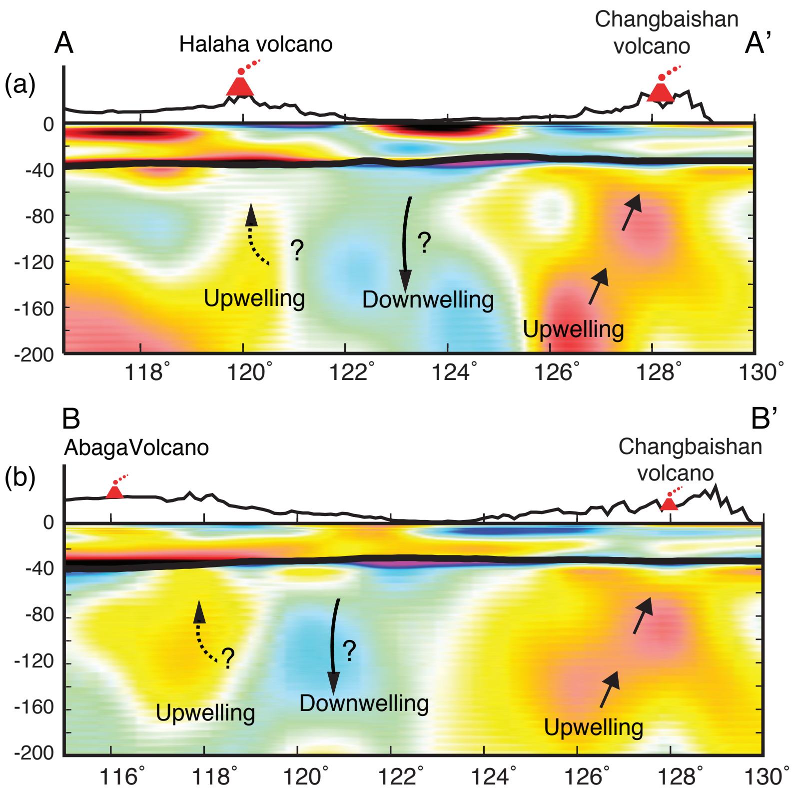
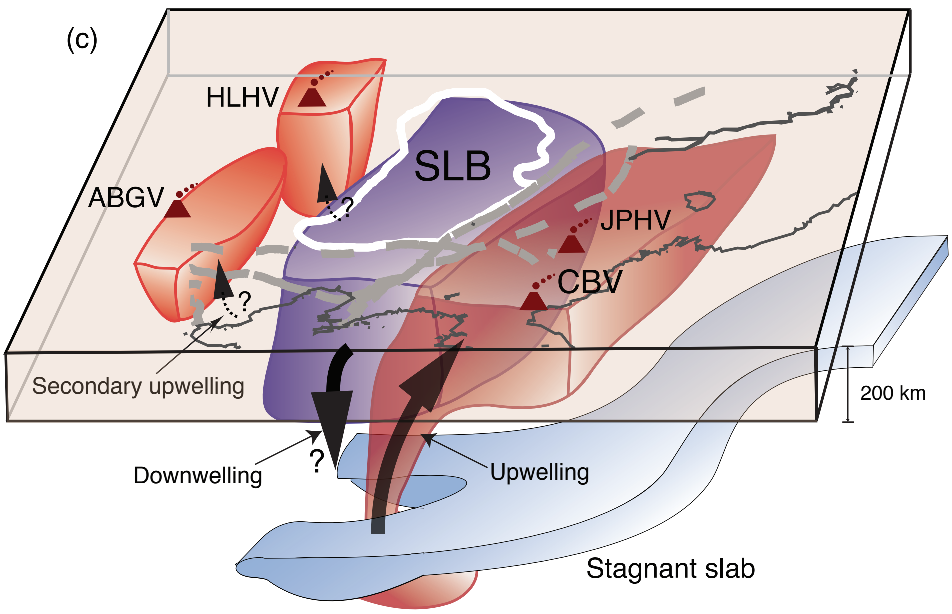


Figure 2. (a) and (b) Vertical cross-sections of S-wave velocities along A-A' and B-B'. Locations of these profiles are shown in Figure 1c. Arrows illustrate the possible upper mantle upwelling/downwelling beneath NE China. Crustal thicknesses are denoted as black bold lines. (c) Schematic model for small-scale mantle convection in NE China.



Unveiling the early history of crust in Western Australia

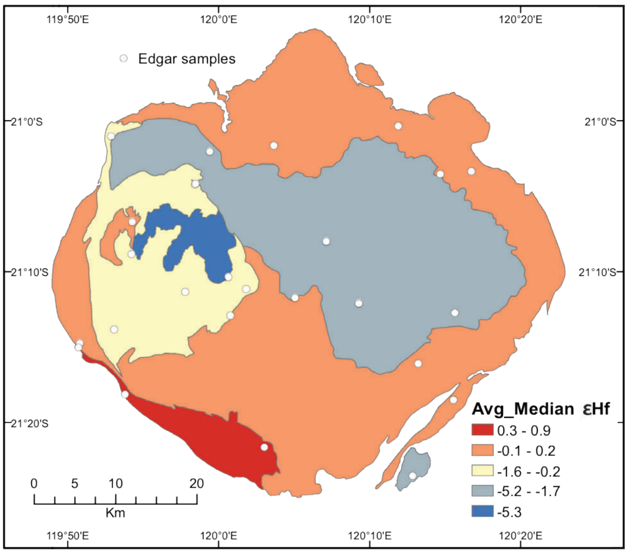


Figure 1. εHf isotopic map for the Mount Edgar Dome, East Pilbara Terrane, showing rim to core 3.5-2.8 Ga magmatism with increasingly evolved Hf signatures (From Gardiner et al. 2017, Precambrian Research, in review)

The Geological Survey of Western Australia (GSWA) in collaboration with CCFS and Curtin University has a major program for the acquisition and interpretation of Lu-Hf isotopic data, based on previously-dated zircon samples from GSWA's extensive sample holdings. The research is focused in '*greenfields*' areas where little information presently exists. More than 10,580 zircons, from 668 samples, have been analysed during the life of the project to date, including 56 samples and 1535 zircons in 2016. Zircon samples have been selected from dated material in igneous, metamorphic, and sedimentary rocks of the Pilbara Craton, the Eastern Goldfields Superterrane and Murchison Domain of the Yilgarn Craton, the Albany-Fraser Orogen, the Musgrave Province, sedimentary basins across Western Australia, the Rudall Province, the Gascoyne Complex, and basement rocks beneath the Eucla Basin. The project has addressed questions on the affinity of crustal blocks, helped map major lithospheric structures, and elucidated the timing of mantle input into the crust. The isotopic datasets produced have provided a powerful tool to understand fundamental components of mineral systems.

Recent results of note include the first major Hf-isotope dataset from the East Pilbara, with a unique focus on the magmatic evolution of a single granite dome. The East Pilbara Terrane is the archetypal granite-greenstone belt, and studies of East Pilbara have informed many ideas regarding early Earth geodynamic processes. Hf isotopes, with their sensitivity to magmatic source, have the potential to add significantly to this debate. Using this Hf dataset, important interpretations regarding: (a) the geodynamic operating model of pre-3.2 Ga Earth, (b) the existence of a ca 3.7 Ga sialic protocrust in the East Pilbara, and (c) the change in geodynamic style post-3.2 Ga can be made. Specifically, results from the East Pilbara indicate that reworking of existing tonalite-trondhjemite-granodiorite (TTG) dominated late Paleoarchean magmatism, which supports a vertical tectonic geodynamic regime for the Pilbara prior to 3.2 Ga.

Other notable outputs in 2016 include a combined oxygen- and Hf-isotope study from the Capricorn Orogen of Western Australia. This data set was used to understand the process of cratonisation in which the *in situ* chemical differentiation of continental crust produced a stable crust. Zircon Hf and O isotopes in granites from this region reflect multi-component sources and shallow crustal processes associated with magma emplacement. An increase in the Th/U ratio of magmatic zircon tracks crustal differentiation in this orogen. Cratonisation processes in the Capricorn Orogen led to shallow parts of the crust, dominated by granitic rocks, with high Th/U magmatic zircons and elevated levels of heat producing elements, becoming more susceptible to reworking.

New oxygen- and Hf-isotope data from sodic Sr-enriched magmas in the Rudall Province have proved important to understanding the crustal evolution and magmatic petrogenesis of this region. These magmas, although Proterozoic in age, are helpful to understand geochemically similar Archean magmatic rocks. Hf isotopes are sensitive to magmatic source compositions through time, and O isotopes are sensitive to the interaction of magmas with surface processes. The isotopic

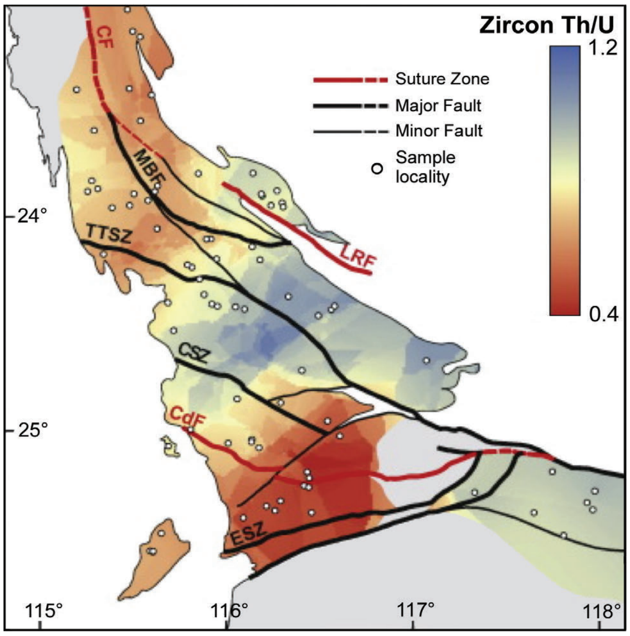


Figure 2. Gridded map of western part of the Capricorn Orogen in Western Australia showing the median Th/U ratio of magmatic zircon from U-Pb SHRIMP dated samples. Hot colours highlight areas dominated by juvenile rocks, whereas cool colours highlight magmatic rocks dominated by crustal reworking at the time of emplacement. The data highlight broad regions of crustal addition in the south and crustal differentiation and recycling in the central part (from Johnson et al., 2017; Lithos 268-271, 76-86).

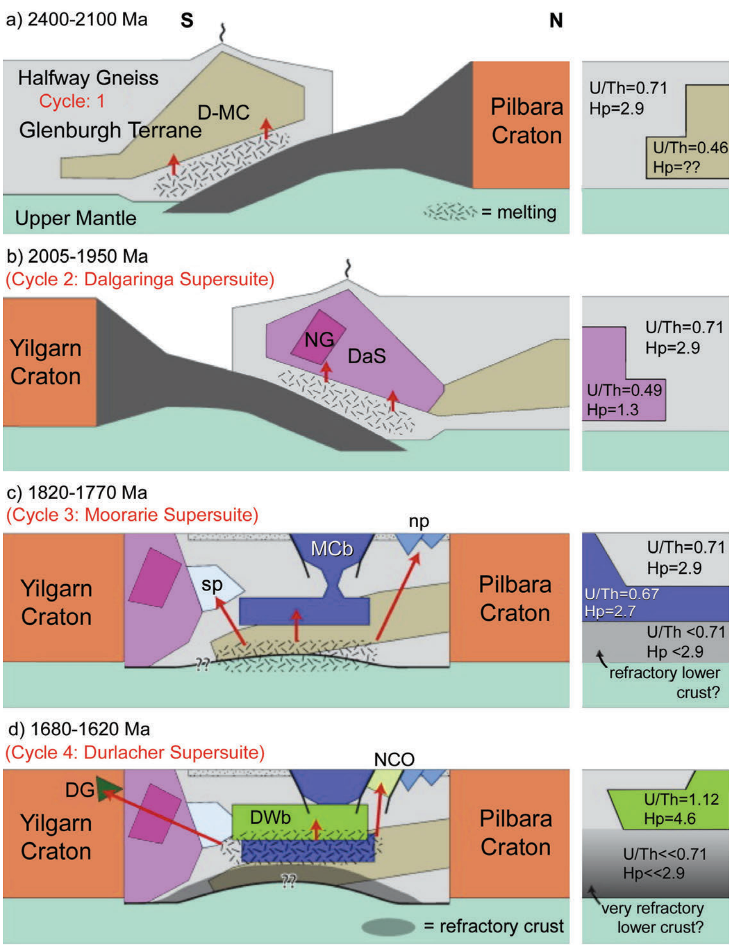


Figure 3. Schematic diagrams illustrating the tectonomagmatic evolution of the Capricorn Orogen as derived from the isotopic data. Panels on the right-hand side provide a summary of the median Th/U ratio of magmatic zircon as well as the present-day heat production (from Johnson et al., 2017; Lithos 268-271, 76-86).

results from the Rudall magmatic rocks show that, despite the TTG-like compositions, some magmas have highly-evolved Hf-isotope compositions, implying that their source was not young subducting oceanic lithosphere. Furthermore, mantle-like O-isotope compositions in these rocks suggest negligible components from a near-surface environment. This magmatic process implies the thickening of mafic source regions to generate melt that formed the crust. Given the geochemical similarity of these specialised Proterozoic melts to Archean TTG rocks, this mafic thickening and extraction of felsic melts could be a viable method to generate early Earth crust.

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

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Funded by: CCFS Flagship Program 7, GSWA

Mantle xenoliths from a young European extensional basin

The study of mantle rocks in young off-craton environments provides insights into the physico-chemical properties of the upper mantle during tectonic processes. The Pannonian Basin in Central Europe, located between the Alps, Carpathians and Dinarides, was geodynamically active throughout the Cenozoic. Its crustal structure and surface processes have been extensively studied, but we still have little knowledge about how the upper mantle there evolved.

Mantle xenoliths occur in five areas within the Carpathian-Pannonian region, hosted by late Miocene-Pleistocene alkaline basalts. The focus area of this study, the Nógrád-Gömör Volcanic Field (NGVF) is located in the northern margin of the Pannonian Basin (Fig. 1). The host basalt at this locality is calculated to have reached the surface in ~36 hours, so the entrained xenoliths are considered to closely reflect the conditions in the upper mantle beneath the area. Thus they provide an excellent base for reconstructing geochemical processes.

Two major rock series have been identified among the NGVF xenoliths: lherzolitic and wehrlitic (Fig. 1). The lherzolitic group, which is the focus of this research, has a wide range of geochemical compositions; four subgroups were distinguished based on the Mg# of olivine and LREE/HREE ratios in pyroxenes. Each of these subgroups records a different metasomatic process or processes, which overprint the chemical signature of an ancient melt extraction event with removal of between 5 and 30% melt. Modal metasomatism is reflected by the presence of amphiboles, which have trace element contents matching those of clinopyroxenes in each xenolith where they appear (Fig. 2a). Thus two types have been distinguished, a Nb-poor type with a suprasubduction origin, and a Nb-rich type (Fig. 2b) which is inferred to have formed as mafic melts percolated through the upper mantle prior to the eruption of the host basalt. Such melts were responsible for causing enrichment in LILE-LREE to different extents in a group of the lherzolitic xenoliths, and a further addition of Fe, Mn and Ti in another. This latter group represents a transition towards the wehrlitic series, which is characterised by the lack of modal orthopyroxene, and contains secondary clinopyroxene, exhibiting Fe-Mn-Ti-LREE enrichment.

Equilibrium temperatures have been calculated with different thermometers, and a discrepancy of ~50-100°C was found between values obtained by major-element based and REE-based methods (Fig. 2c, d). Since trivalent REEs have higher

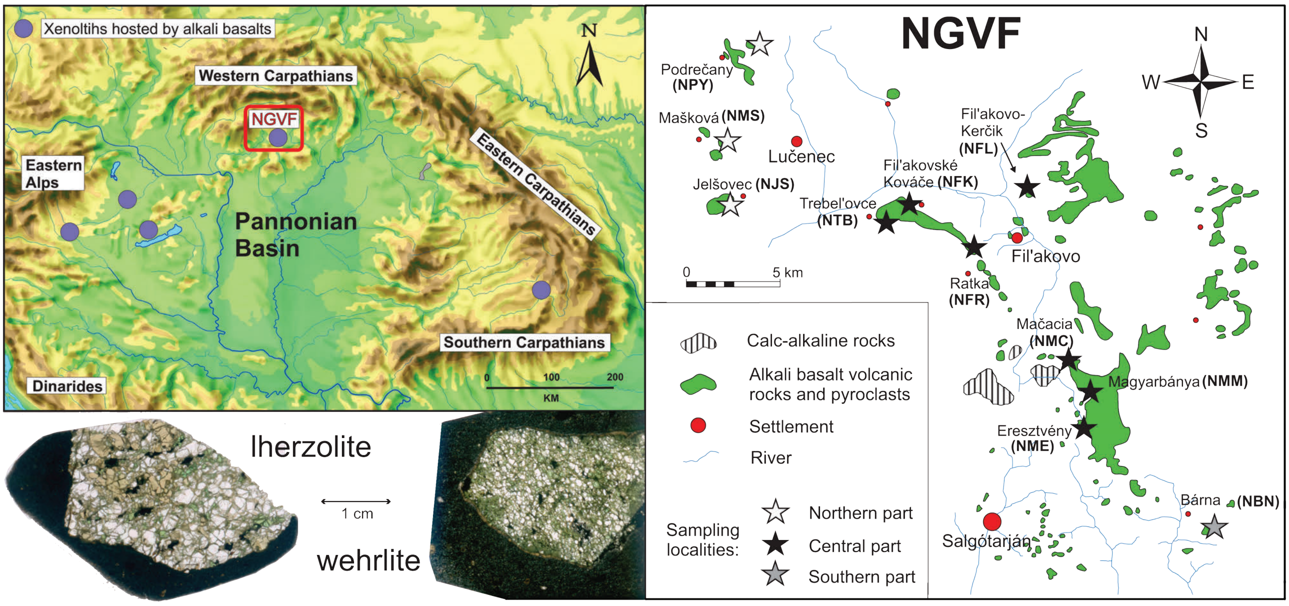

Figure 1. Top left: Alkali basalt-hosted xenolith occurrences in the Carpathian-Pannonian region. Right: Distribution of basalt outcrops and sampling localities in the NGVF. Bottom left: samples from the lherzolitic and wehrlitic series.

closing temperatures than the divalent major elements used by conventional thermometers, this difference can be explained by a major thermal event in the recent history of the NGVF mantle. It is assumed that the higher temperatures from REE-based thermometers reflect the heating by the extension and asthenospheric upwelling in the Pannonian Basin, whereas lower temperature values represent thermal relaxation and cooling following extension.

The distribution of textural types and crystal-preferred-orientation data acquired by EBSD (electron backscatter diffraction) analysis, as well as calculation of seismic properties, reveal that the three major domains of the NGVF (northern, central and southern) experienced different degrees of deformation. Xenoliths from the southern part represent a low-temperature, more equilibrated, fine-grained mantle domain, whereas the northern part is dominated by coarse-grained, high-temperature material with significant intragranular deformation. The strength of deformation and seismic anisotropy is highest in the central part, and is suspected to reflect a tectonic boundary beneath the area.

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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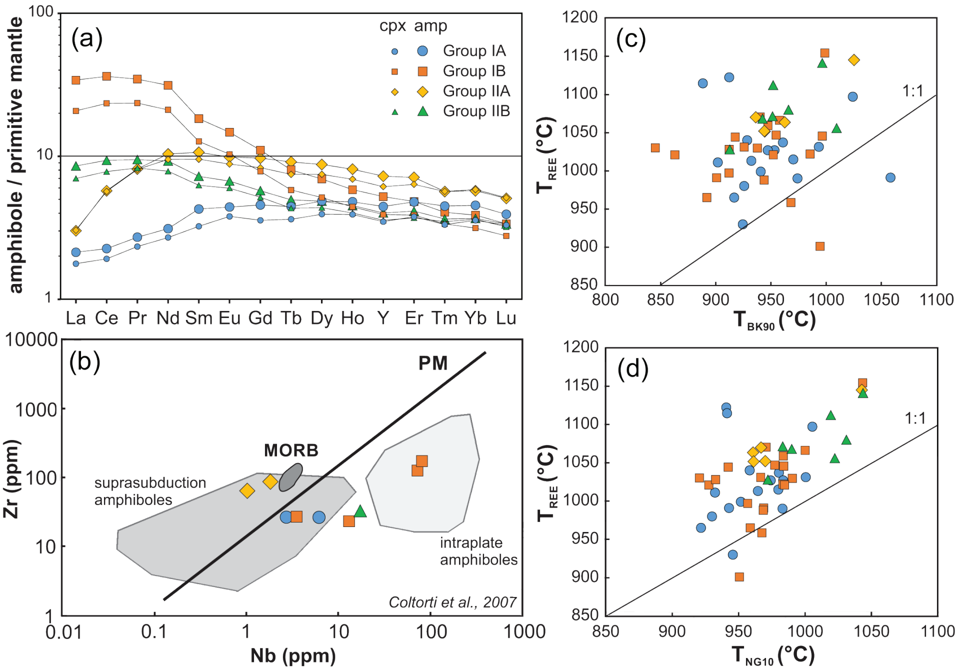


Figure 2. a) REE-distribution of clinopyroxenes and coexisting amphiboles. b) Nb-content based distinction of amphiboles from different environments. c-d) comparison of equilibrium temperatures calculated with REE-based (T_{REE}) and major element based thermometers (T_{BK90} = two-pyroxene method of Brey & Köhler, 1990; T_{NG10} = Ca-in-opx method of Nimis & Grütter, 2010).

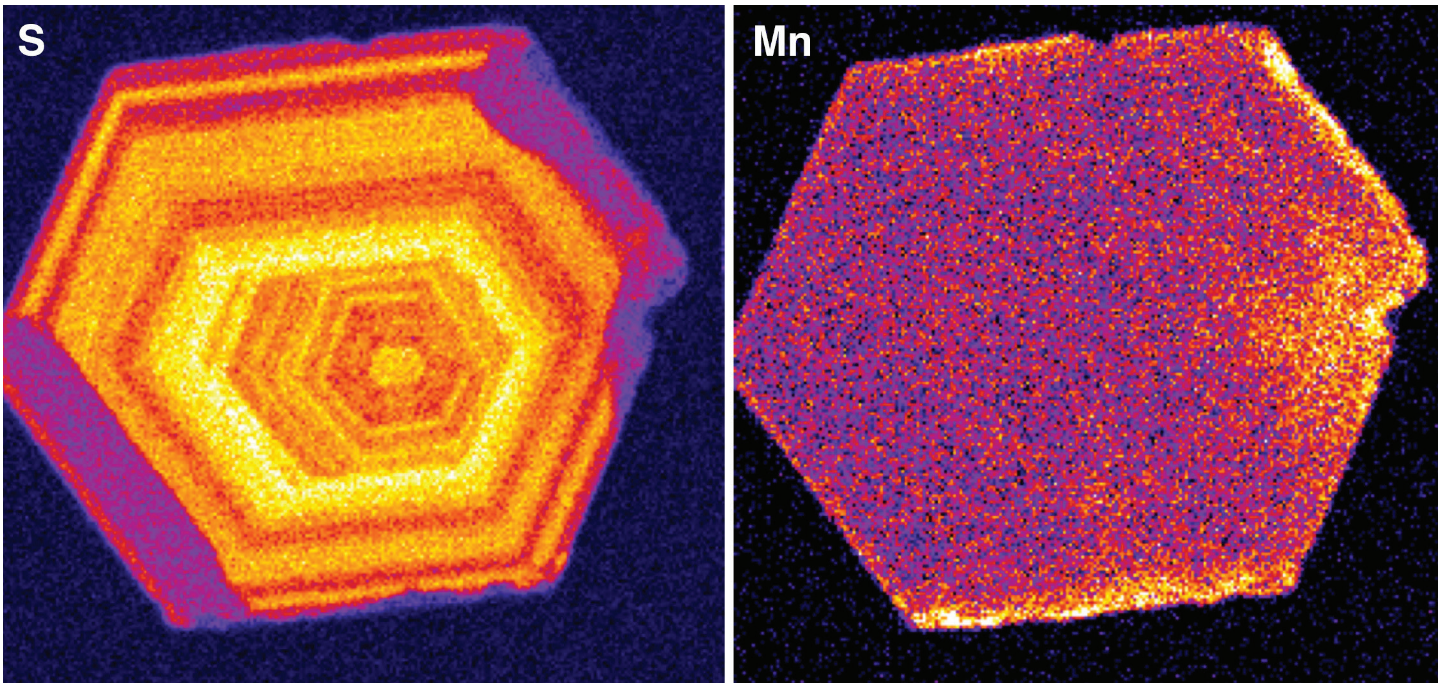
Apatite - tracer for the evolution of porphyry systems

Analysis of the evolution of porphyry systems is key to better understanding how, when, and why fertile (i.e. metal-rich) igneous-hydrothermal systems develop. Accessory minerals, and in particular apatite, can serve as archives for the evolution of such systems. Apatite is ubiquitous in granitic rocks and can potentially record fluid evolution to lower temperatures (i.e. later stages) than zircon. Apatite hosts a range of trace elements, which can be used to establish the physical-chemical conditions of the magmatic system. Of particular interest are the REE, the halogen group elements (Cl, F, Br) and S, which provide constraints on the system's oxidation state, fluid source and metal transport capabilities. Previous studies have claimed that certain trace elements can be used to distinguish between fertile (i.e. ore-forming) and barren (ore-absent) porphyry systems. However, the proposed discrimination factors, based on trace element concentrations and ratios, are not universally applicable. In this study we will investigate porphyry systems of the Macquarie Arc (NSW) where several pulses of barren and fertile magmatism have been recognised. This igneous activity is spatially and geochronologically well-constrained, so the Macquarie Arc porphyries are an ideal case-study site.
The geochemistry of apatite will be combined with whole-rock data, which include the REE and isotopic tracers such as Sm-Nd. Whole-rock analyses and *in situ* mineral geochemistry of apatite will then be used to address the following fundamental questions:

- How representative is the geochemistry of apatite of its host rock?
- Can apatite be used to identify fertile igneous (porphyry) systems?
- Can metamorphic and igneous apatite be distinguished?

Solving the last question will be essential if apatite separates, such as detrital concentrates, are to be used to trace igneous systems in the prospective regions.

Preliminary results of quantitative EPMA element mapping (Fig. 1) show that apatite from mineralised systems often is distinctly zoned in terms of S concentrations, which is not observed in apatite from barren systems. This observation might give a first indication about the importance of S as a ligand for metals and related metal-melt-unmixing processes, which may be a key to mineralisation. In order to understand the source of S, we are currently developing a method to measure S isotopes *in situ* in apatite by SIMS. Sulfur-isotope ratios from apatite can then be coupled with Sm-Nd and other tracers to gain detailed insights into the geochemical evolution of porphyry systems.



Quantitative EMPA maps of S and Mn in apatite from a mineralised porphyry system.

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

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Funded by: CCFS Flagship Program 2

Hafnium isotopes record supercontinent cycles

We interrogated a large global Hf isotope dataset (>40,000 points), using a new statistical approach to track the most juvenile part of this dataset through time, linking secular variations with the supercontinent cycle. We statistically correlated supercontinent amalgamation intervals with episodes of evolved Hf, and breakup leading to re-assembly with episodes of juvenile Hf. Further, we found that the juvenile Hf signal is more sensitive to Pangaea and Rodinia assembly, its amplitude increasing with successive cycles to a maximum with Gondwana assembly, which may reflect enhanced subduction-erosion. We demonstrated that the juvenile Hf signal carries important information on prevailing global magmatic style, and thus tectonic processes.

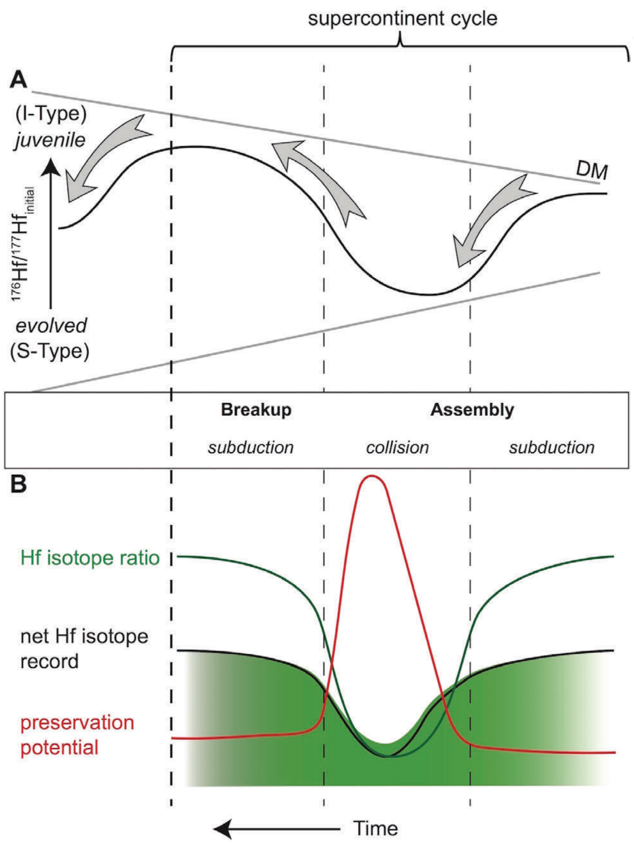


Figure 1. A. Schematic showing the conceptual evolution of initial $^{176}Hf/^{177}Hf$ ratios with respect to the stages of supercontinent assembly and breakup. B. Diagram showing the proposed effect of preservation bias on the Hf signal during a supercontinent cycle. Preservation curve and volume of generated magma retained in the geological record, and a lack of preservation will dilute global juvenile Hf signals towards a less radiogenic baseline, but will not affect the more evolved part of the record during continent collision. The net effect is to dampen but not remove the Hf isotope signal. The depth of shading reflects intensity of signal, based on number of analysis.

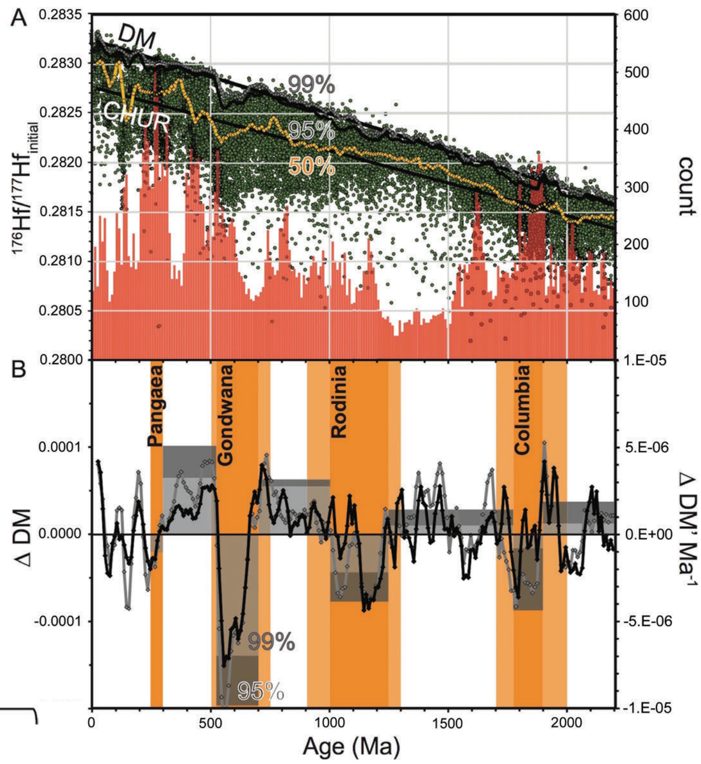


Figure 2. A. Global Hf dataset: initial $^{176}Hf/^{177}Hf$ versus U-Pb magmatic age from 0 to 2200 Ma. The 99th, 95% and median (50%) moving average time series are plotted. B. ΔDM (left scale) - a de-trended difference between DM and the Hf signal per 10 Ma; black = ΔDM95; grey = ΔDM99. A histogram of the ΔDM99 and ΔDM95 signals, the time-integrated difference for the periods within and between the indicated supercontinent assemblies (right scale). Periods of supercontinent assembly shown, with timeline A in dark orange and timeline B in lighter orange. Both from Gardiner et al. (2016), Scientific Reports 6, 38503 (CCFS publication #874).

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

Contacts: Nick Gardiner, Chris Kirkland, Martin Van Kranendonk

Funded by: CET-Curtin internal funding

Strange mineral companions

Moissanite (SiC) is a rare mineral in terrestrial rocks. It can only form in environments with extremely low oxygen fugacity (fO_2) [at least 6-8 log units below the Iron-Wüstite (IW) buffer], which are not consistent with the normal fO_2 conditions (above IW) of the Earth's lithosphere. The occurrence of SiC and other very-reduced phases (e.g. native metal) in mantle rocks of the Tibetan ophiolites (e.g. Luobusa) has caused great concern about their formation and preservation mechanism in the Neo-Tethyan oceanic lithosphere. We report new observations of intergrown grains of SiC and associated oxidised phases from the Zedang ophiolite (close to the Luobusa ophiolite) in the Yarlung-Zangbo Suture Zone (South Tibet, China), and suggest a rapid dynamic process to isolate the host lithospheric fragment from ambient mantle.

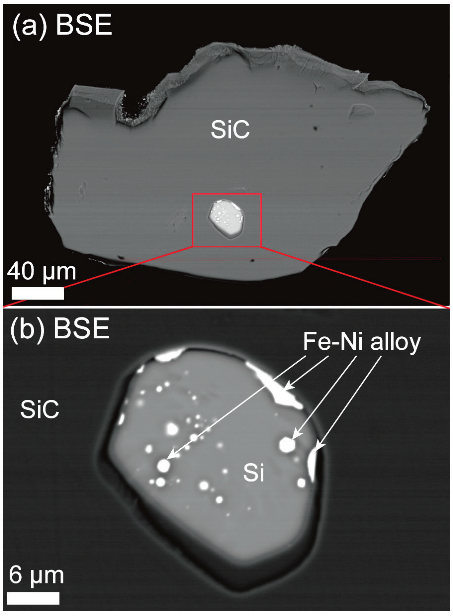


Figure 1. Back-scattered electron (BSE) images of a representative SiC grain (a) and its enclosed Si and Fe-Ni alloy (b), separated from harzburgite from the Zedang ophiolite (South Tibet).

SiC grains with diameters of ~100-500 μm have been separated from the Zedang harzburgite, chromitite and pyroxenite, all collected from the refractory harzburgite domain defined by Xiong et al. (*2016 EPSL, 438, 57-65, CCFS publication # 691*). Combined imaging (optical microscopy and scanning electronic microscropy) and qualitative analyses (energy dispersive spectroscopy and laser Raman spectroscopy) have revealed that the SiC grains (mainly 6H polytype) contain droplet-shaped inclusions of Si metal and unmixing Fe-Ni-V-Ti-Mn-Si alloy (Fig. 1), suggesting formation at very high temperatures (≥~1400-1500 ºC) and ultra-reduced conditions (fO_2≤IW-6). Interestingly, some SiC grains are irregularly surrounded by K-rich silicate glasses, which contain inclusions of crystalline zircon. One SiC grain shows gradual oxidation from SiC, through Si and Si-C-O mixtures, to amorphous SiO_2, recording a complex reaction texture suggesting quenched glasses surrounding crystallised SiC (Fig. 2).

The coexistence of SiC and oxidised glasses, as well as the quenched texture, suggest that there must be a dynamic process (i.e. quenching) rapid enough to seal the extremely un-equilibrated phases and textures. Thermodynamic simulation of diffusive equilibration of SiC in an olivine matrix (Mg#=90) suggests that a SiC grain with a diameter of 300 μm will need ~1-10 million years to be consumed under temperatures of ~600-700 ºC (*Schmidt et al., 2014, PEPS, 1:27, 1-14*). These temperatures are consistent with those calculated from olivine-spinel pairs in the Zedang peridotites and chromitites. Therefore, to preserve these SiC grains and associated oxidised phases would require a rapid cooling process from peridotite solidus temperatures to ~600-700 ºC, within several million years. This process may reflect the very rapid ascent of the recycled peridotites and chromitites (host for the super-reduced phases) from the Mantle Transition Zone or deep upper mantle to lithospheric levels (*Griffin et al. 2016, J.Petrol. 57, 655-684. CCFS publication #704*) This rapid exhumation process has suppressed the thermodynamic consumption of SiC and other super-reduced phases with the host peridotites and chromitites, and eventually preserved them in the Neo-Tethyan oceanic lithosphere.

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

Contacts: Qing Xiong, Bill Griffin, Jian-Ping Zheng (CUG Wuhan), Jin-Xiang Huang, Sarah Gain, Norman Pearson, Sue O'Reilly
Funded by: CCFS Flagship Program 1, NSFC

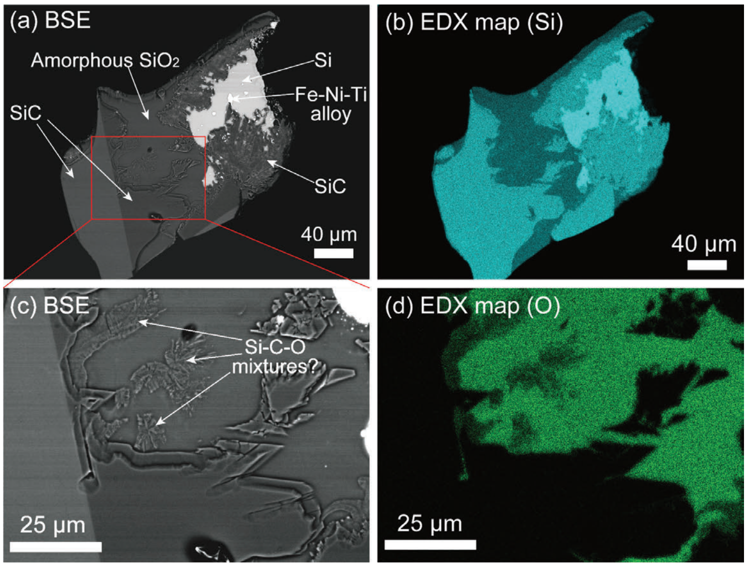


Figure 2. Back-scattered electron (BSE) images (a, c) and energy-dispersive X-ray (EDX) maps (b, Si; d, O) of a complex intergrowth grain of SiC with Si + Fe-Ni alloy (primary stage), reacted with oxygen-rich fluids/melts that formed amorphous SiO_2 and newly crystallised unknown Si-C-O mixtures (secondary products).

An Archean microcontinent lurking in the Capricorn Orogen

The Capricorn Orogen (Fig. 1a) formed during the Paleoproterozoic amalgamation of the Archean Pilbara and Yilgarn cratons to form the Western Australian Craton. Regional surveys involving geological mapping, geochemistry, and geophysics reveal a prolonged tectonic history of craton assembly and subsequent intracratonic reworking, which have significantly re-shaped the orogenic crust.

Using data from the on-going Capricorn Orogen Passive-source Array (COPA) stations and a high-density linear array embedded among the COPA stations (Fig. 1a), we conducted seismic receiver function and ambient noise studies targeting the Glenburgh Terrane, an exotic late-Archean to Paleoproterozoic crustal block previously inferred from distinct structural and isotopic characters in the core region of the terrane. The prominent Moho and intracrustal discontinuities vary across the

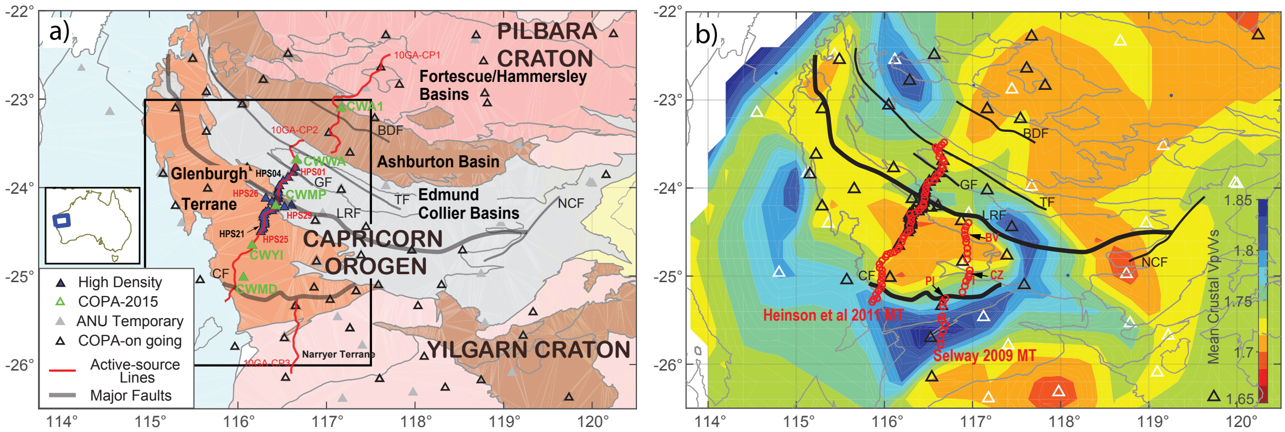


Figure 1. Crustal elements and seismic stations in the Capricorn region (a). The crustal element boundaries are simplified from the Geological map of Western Australia (2015). Red lines are the active source lines conducted by Geoscience Australia in 2010. The black and green (used in this study) triangles show the on-going Capricorn Orogen Passive-source Array (COPA). The High-density Passive Source (HPS) array is shown as the red triangles, which is partially collocated with active source line 10GA-CP2 (the middle one). Labels in a) are major faults: BDF Baring Downs Fault; TF, Talga Fault; GF, Godfrey Fault; LRF, Lyons River Fault systems; CF, Cardilya Fault; and NCF, Neds Creek Fault. (b) The seismic Vp/Vs ratio measurements which is indicative of an overall felsic composition of the Glenburgh Terrane bounded by major faults.

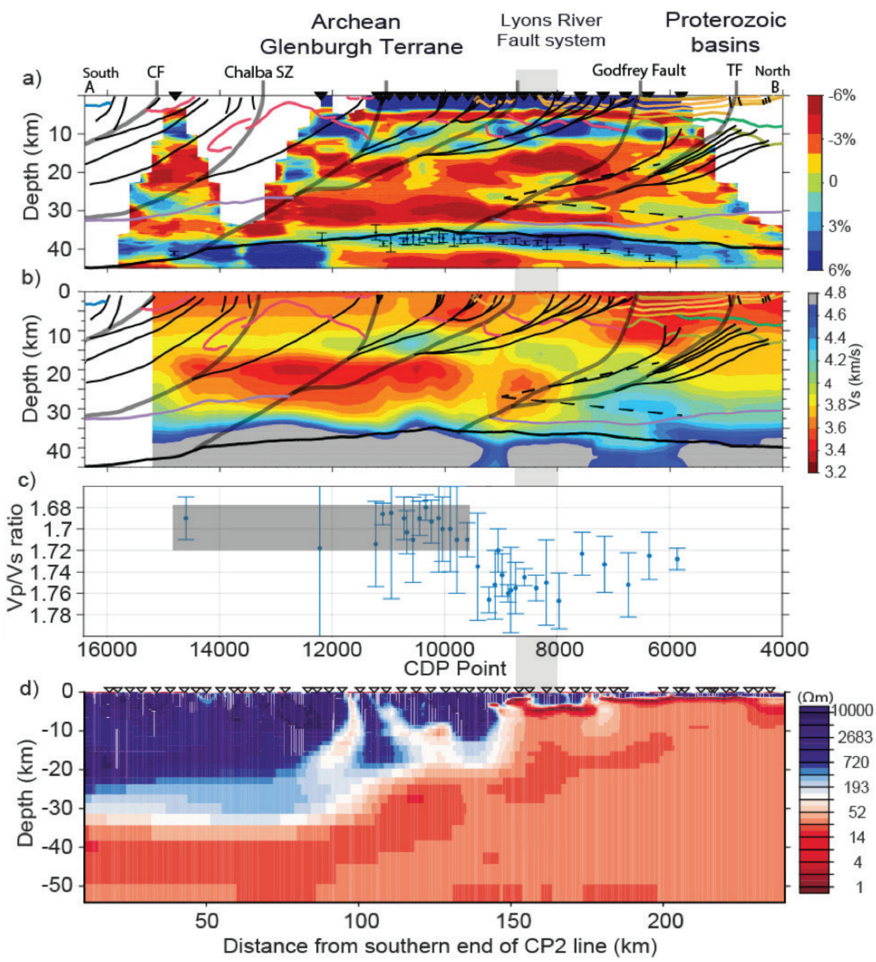


Figure 2. A compilation of available geophysical observations for the high density array, following the 10GA-CP2 line. a) Receiver function common-conversion-point stacking imaging showing the velocity gradient beneath the array. The active source interpretations are overprinted as lines. The vertical grey line shows the boundary of the Glenburgh Terrane and the Proterozoic basins. b) The shear-wave velocity model from the ambient noise inversion. Note the fast velocity shallow crustal layer which is also indicated in the receiver functions as a positive velocity gradient. c) The Vp/Vs ratio measurements. The small Vp/Vs ratios marked by the shaded region within the Glenburgh Terrane suggest a felsic bulk crustal composition, similar to that in the Archean Pilbara and Yilgarn and other global cratons. d) the 2010 magnetotelluric modeling image, showing the Glenburgh Terrane is resistive in shallow to middle crust, a common feature observed in Archean crust.

terrane boundary, showing a relatively thin crust (<40 km) with small Vp/Vs ratios (~1.70) in the Glenburgh terrane, compared with the thickened (>40 km) crust with elevated Vp/Vs ratios (>1.76) near the margins. Low Vp/Vs ratios (~1.70) are mapped terrane-wide (Fig. 1b), similar to what we have observed in the Archean Pilbara and Yilgarn cratons; they indicate a felsic bulk composition for the crust. Considering the available isotopic age data, and constraints from magnetotelluric and absolute shear wave velocity data (Fig. 2), the Glenburgh Terrane is interpreted as a microcontinent made in the Archean. A fast velocity is observed in the shallow crust (intraplating; Fig. 2), which suggests the crust was reworked during the assembly and cratonisation of the WAC and the subsequent intracratonic reworking/magmatic differentiation processes.

Our results illustrate that multi-disciplinary datasets bring complementary resolution and therefore may put tighter constraints on the tectonic processes that have affected the crust. See *CCFS Publication #649, Yuan, 2015, Nature Geoscience 8, 808-103*; *Yuan et al., 2017, Crustal structure of the Glenburgh Terrane: the role of a microcontinent in the Paleoproterozoic craton assembly in Western Australia, submitted to JGR.*

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

Contact: Huaiyu Yuan

Funded by: CCFS Flagship Program 7, SIEF Capricorn distal footprint

Magmatism lights up northern Gondwana 500-600 million years ago

Magmatism in continental arcs is often episodic, punctuated by high-volume magmatic flare-ups separated by lulls. Magmatic arcs commonly flare up every 30-70 Ma, which could be either a response to a tectonic event such as rapid slab retreat, change in dip angle and/or slab break-off; or could reflect a non-tectonic cause such as thermal runaway due to pooling of mafic magmas in the lower crust. Well-documented flare-ups are characterised by high-silica (felsic) rocks, with significant crustal inputs as indicated by high bulk-rock $^{87}Sr/^{86}Sr$, low εNd and high $\delta^{18}O$ and low εHf in zircon.

These ideas were developed for Cretaceous and younger continental arcs, where the igneous rocks are mostly exposed and include significant proportions of volcanic cover associated with plutonic rocks; these are the best places to define such magmatic episodicity and to consider its likely causes. These concepts also provide a new way to think about ancient continental arcs, where igneous rock exposures are more likely to be scattered, because most of the fossil continental arc is deeply eroded, buried by younger sediments, and disrupted by faulting. One way to explore ancient arc magmatic tempos is to complement direct sampling from scattered exposures with surveys of detrital zircons from the siliciclastic sediments derived from erosion of the nearby arcs. Recent improvements in U-Pb zircon dating and MC-ICPMS microanalysis of Hf isotopic compositions in the same grains provide powerful new tools for understanding the age of crystallisation, metamorphism and inheritance in igneous and sedimentary rocks.

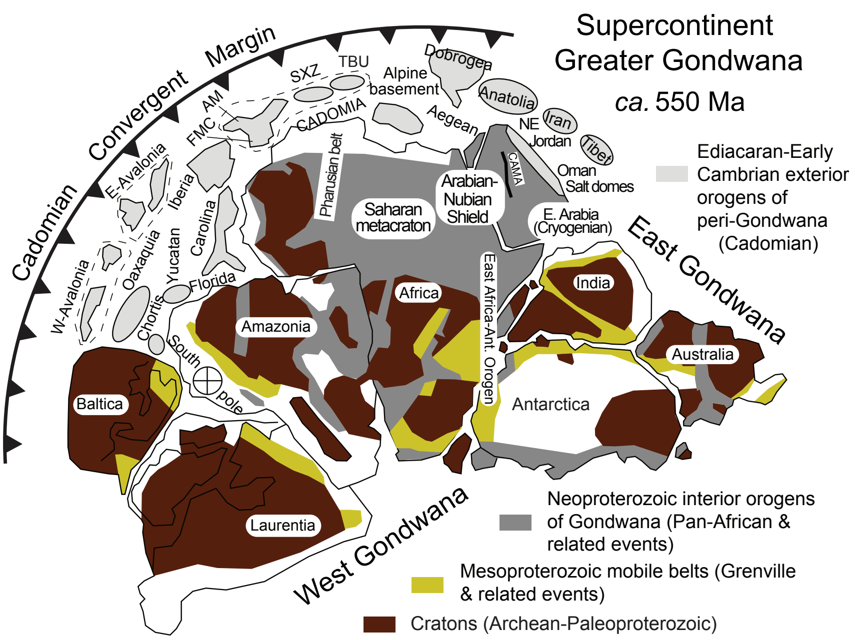


Figure 1. Paleogeography of the Cadomian - Avalonian active margin and related major peri-Gondwanan terranes at ~550 Ma. AM Armorican Massif, FMC French Massif Central, SXZ Saxo-Thuringian Zone (part of the Bohemian Massif), TBU Teplá-Barrandian Unit (part of the Bohemian Massif).

Coupled Lu-Hf and O isotopic analyses of zircons and bulk-rock Nd-isotope compositions have proven particularly powerful for distinguishing juvenile (mantle) and recycled (older continental crust) components making up igneous rocks, especially where the rocks have been well-mapped, petrographically characterised, and analysed for major and trace element geochemical data. The use of all these tools in combination provides a powerful toolkit for constraining crustal growth and investigating magmatic flare-ups.

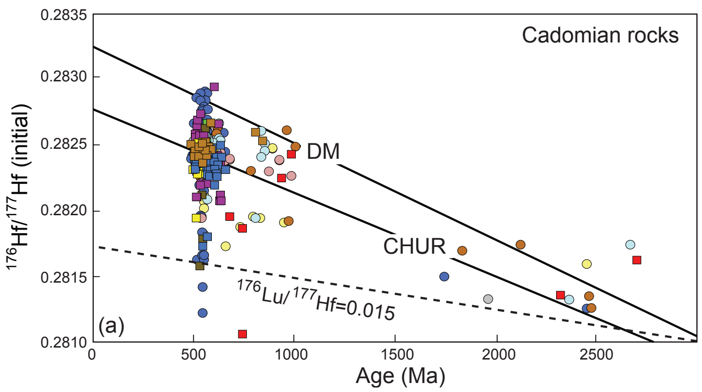
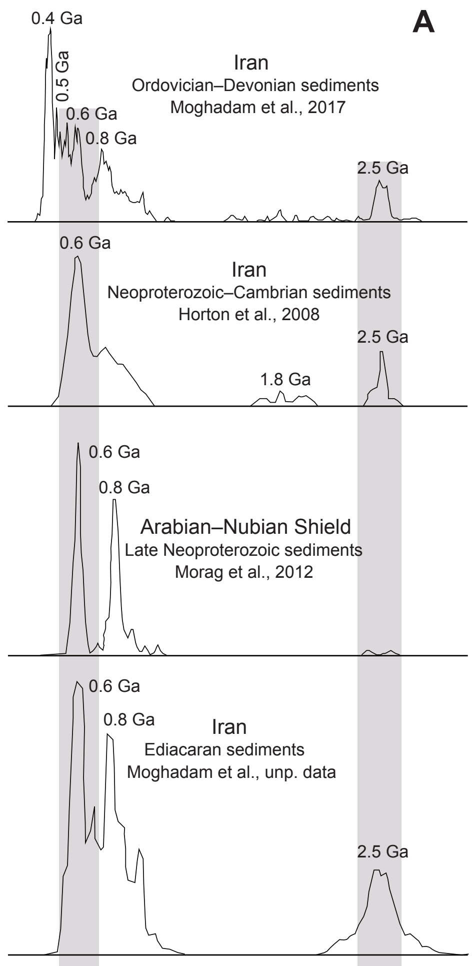


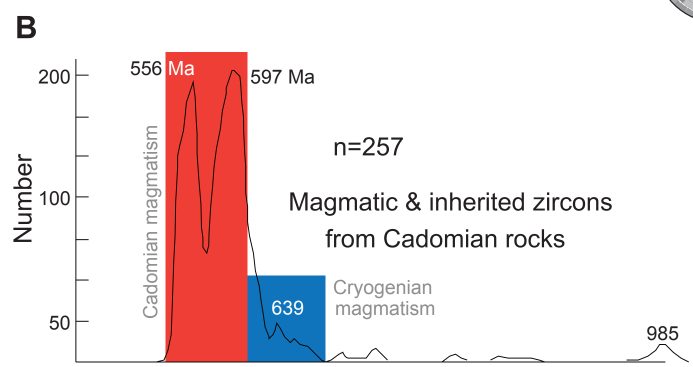
Figure 2. U-Pb age vs $^{176}Hf/^{177}Hf$ ratios for zircons from the Late Neoproterozoic-Cambrian rocks of Iran.

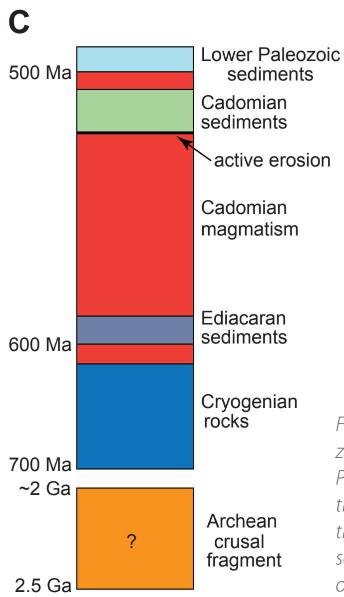
There is increasing evidence that a vigorous continental arc existed on the northern margin of the Greater Gondwana supercontinent during Late Ediacaran-Early Paleozoic time (500-600 Ma) (Fig. 1); this is referred to as the Cadomian orogen, although some segments, especially in the west, are called Avalonian. The Cadomian arc needs further study and this must use each of the outcrop areas that are now scattered across southern Europe and SW Asia. We are exploiting new zircon U-Pb-Hf-O as well as whole rock Sr-Nd isotopic data for a suite of Cadomian plutonic and volcanic rocks throughout Iran. Igneous rocks of the Cadomian arc were likely to have been dominated by development of calc-alkaline batholiths beneath thick sequences of felsic lavas, ignimbrites and arc-derived sediments, but these are rarely preserved. We are using these results to address the suitability of the magmatic flare-up model for understanding the Cadomian crust of this region and to address the thermal state of the Gondwana upper mantle and lower crust during that time span.

We have also analysed detrital zircons from a series of Late Neoproterozoic-Cambrian detrital sedimentary rocks to further unravel the role and extent of the Cadomian magmatism. Our results indicate that the Cadomian magmatism in Iran and surroundings, including Turkey, was a part of a ~100 Myr-long episode of subduction-related arc and back-arc magmatism at the northern margin of Gondwana. Zircon Hf isotope compositions (Fig. 2) show that during the Cadomian magmatic activity, juvenile arc magmas interacted with Archean crust to generate the Ediacaran-Cambrian igneous rocks. The hidden Archean crust is further evidenced by the occurrence of 2.5 Ga inherited zircons in the magmatic rocks and abundant magmatic, unrounded, Archean zircons in the sedimentary rocks (Fig. 3).

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







Contacts: Hadi Shafaii Moghadam, Bill Griffin, Sue O'Reilly
Funded by: CCFS Flagship Program 1

Figure 3. A: Probability plots for U-Pb ages of detrital zircons from Iran and Arabian-Nubian Shield. B: Probability histogram showing the age distribution of the Iran Cadomian rocks. C: A schematic geological time-scale showing the different magmatic and sedimentary events during the Cadomian evolution of Iran.

Isotopic canaries in zircon track Cu prospectivity across Southern Tibet

Porphyry deposits are the main source of copper and molybdenum worldwide and also an important source of gold and silver. Porphyry systems are found in both continental arcs and island arcs, e.g. circum-Pacific subduction zones, as well as continental collision zones, e.g. southern Tibet. Broadly, porphyry deposits are characterised by copper sulfide minerals in stockworks, disseminations and veinlets, commonly associated with porphyritic intrusions, affected by potassic, sericitic and in some cases, even argillic alteration (*Sillitoe, 2010*).

To gain new insights into the prospectivity and geologic setting of the Chongjiang (CJ), Gangjiang (GJ) and Bairong (BR) porphyry Cu prospects and the Tinggong (TG) porphyry Cu-Mo mine in the southern Lhasa terrane, southern Tibet, we use the new integrated approach published by Lu et al. (*2016*). The integrated approach includes the use of porphyry Cu fertility indicators based on traditional whole-rock geochemistry and new *in situ* zircon trace element analyses. Additional measurements included zircon U-Pb, Hf and O isotopes in order to better constrain magma sources and the petrogenetic evolution of the region.

Cu fertility indicators

Porphyry copper deposits are associated with hydrous and oxidised magmas at shallow crustal levels (*Sillitoe, 2010*). These hydrous magmas are characterised by high Sr/Y (>35), V/Sc (>10) and Al_2O_3/TiO_2 (>25) ratios. To complement the previously mentioned whole-rock indicators, Lu et al. (*2016*) took advantage of the remarkable resilience of zircon and its ability to record tectono-magmatic evolution. Under the new approach it is possible to distinguish between fertile and infertile magmatic suites and evaluate tectonic processes that are identified from whole rock geochemistry. The method includes *in situ* measurements of trace elements in zircons. The best indicators of Cu fertility based on zircon compositions are zircon Eu/Eu* (>0.3) and 10,000*(Eu/Eu*)/Y (>1), while zircon (Ce/Nd)/Y (>0.01) and Dy/Yb (<0.3) have proven to be moderately useful. In addition, the zircon O- and Hf- isotope data provide insights into the sources and petrogenetic evolution of the porphyry systems.

Southern Tibet Miocene porphyry copper deposits

The Himalayan-Tibetan orogeny is the result of the amalgamation of three distinct terranes, from north to south, the Songpan-Ganze, Qiangtang, and Lhasa terranes. The Lhasa terrane is further subdivided into three sub-terranes as shown in Figure 1 (*Hou et al., 2015*). The amalgamation of these terranes resulted from the Indo-Asian continental collision that started in the early Tertiary. The southern margin of the Lhasa terrane hosts Miocene porphyry copper deposits estimated at 18 Mt of Cu with a value of approximately 126 billion US$.

Preliminary results of the zircon U-Pb, trace element, Hf and O data indicate that the prospects CJ, BR, and GJ are fertile for Cu mineralisation and that they formed in a compression environment resulting from the continental collision of India and Asia at ca 55 Ma. The O and Hf data show that the samples are mostly of juvenile origin but after ca 55 Ma there is an increasing involvement of supra-crustal material in the magma genesis, possibly due to subduction of Indian continental sediments into the Tibetan mantle source.

See *CCFS publication # 811, Lu et.al. Society of Economic Geologists Special Publ. 19, 329-347.*

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

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Funded By: CCFS Flagship Program 2

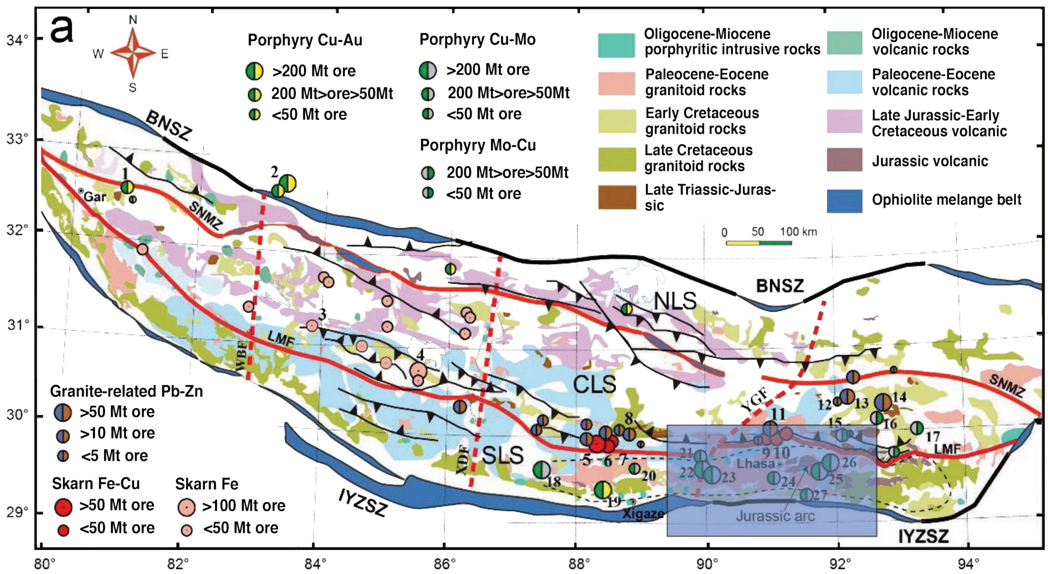

Figure 1. Simplified geological map of the Lhasa Terrane, and its sub-terranes, northern, central, and southern. Sub-terranes are cut by three Miocene normal fault systems: Wenbu, Xuru-Dangreyong, and Yadong-Gulu faults. Distribution of granitoid rocks and felsic volcanic rocks of the Lhasa terrane. Thick dashed red lines indicate N-S-trending normal fault systems. Thin dashed black line in eastern portion of the southern Lhasa sub-terrane indicates extent of a Jurassic magmatic arc (Hou et al., 2015). Blue box shows the location of the study area.

Astrobiology *'Down under'*: Visualising early life on Earth

The advent of virtual reality technologies and multi-scale 3D modelling in combination with geological mapping has allowed perspectives of geological outcrops never before explored.

Over the past 30 years the world of virtual reality has emerged, not just for games but also for education and especially industry training. In recent years virtual reality has come back into the limelight and is better and cheaper than ever. Over the past 5 years, drones or Unmanned Aviation Vehicles (UAVs) have become relatively inexpensive and easy to use, with camera quality that reaches 4K. Meanwhile, point-and-shoot digital cameras provide easy-to-use, efficient, lightweight tools for capturing high-resolution images. These technologies provide an easy, inexpensive, way to collect and display visual data. This has significant applications in science, and especially for the visually-dependent disciplines such as the geosciences.

This research capitalises on the benefits of visual data capture, focusing on building a comprehensive virtual field trip (VFT) of a site that contains evidence for some of Earth's earliest life, the *ca* 3.48 Ga Dresser Formation North Pole Dome, Pilbara Craton, Western Australia. Extensive detailed mapping, along with petrological and geochemical data from the Dresser Formation has provided a plethora of paleoenvironmental evidence showing that life was living in and around volcanic hot springs much like those found in Yellowstone National Park or the North Island of New Zealand. Rock structures built by microbes almost 3.5 billion years ago can be found in the ancient deposits (Fig. 1).

The VFT includes immersive geological outcrop visuals and photogrammetric imaging (3D models), and integrates detailed scientific observations from the macro- to the micro-scale i.e. outcrop to microscopic view, respectively (Fig. 2). Results aim to: 1. Enhance the environmental model for the Dresser Formation, developing a better understanding of why some of Earth's earliest convincing evidence of life is in a volcanic hot-spring setting and; 2. Produce an interactive and immersive learning/educational tool - by way of a VFT - that can be used in online, face-to-face teaching, and as a research tool.

The principles and practices of the VFT can be applied to other geological sites, perhaps even Mars. The VFT serves as an educational tool and as a visual aid in communicating science and early life on Earth as well as providing assessment for the use of immersive environments in education and scientific research.

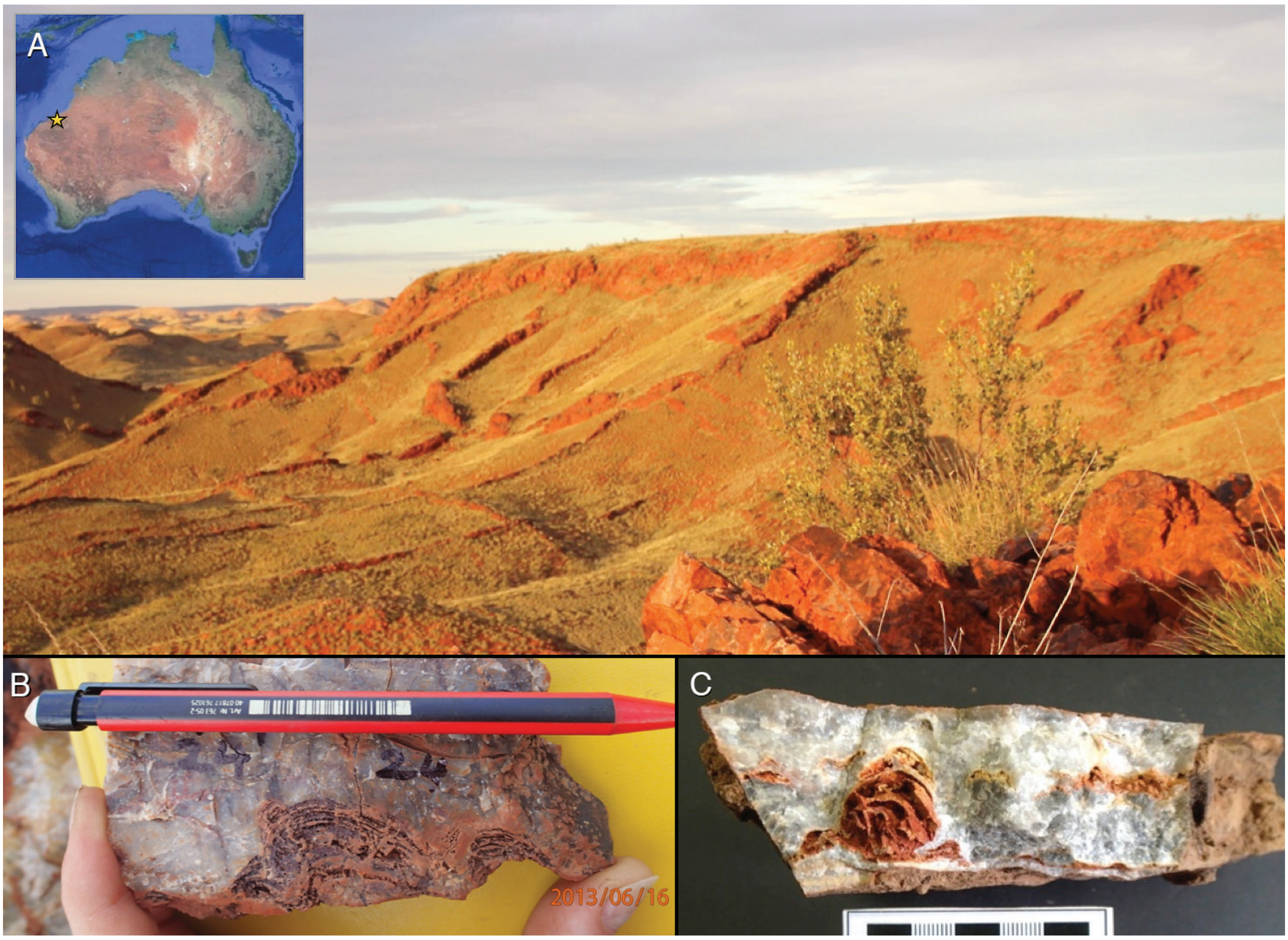

Figure 1. A. Location photo of the Dresser Formation. B-C. Signs of life: Stromatolites within the Dresser Formation - rock structures built by microbial life 3.5 billion yeas ago.

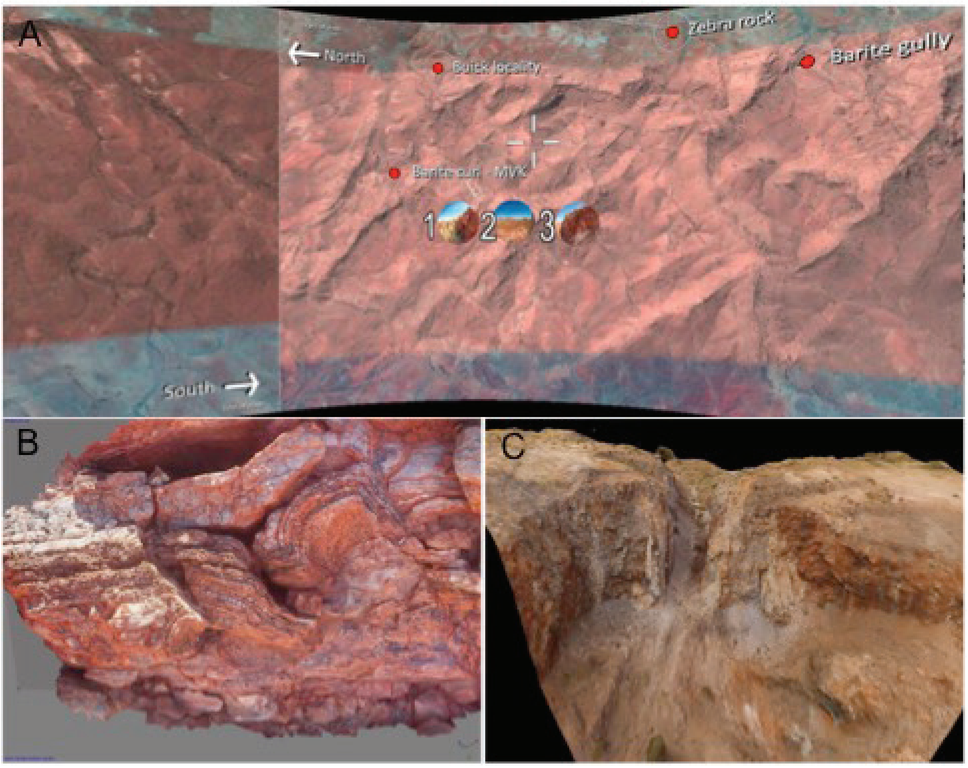

Figure 2. A. Map of the Dresser Formation within the Virtual Field Trip showing sites containing multiple 360° panoramas that contain detailed multimedia such as 3D models, photographs, micrographs and geo- chemical information. B. 3D model of stromatolites. FoV - 3 m. C. 3D model of local outcrop. FoV - 100 m.

In 2016, the Australian Centre for Astrobiology launched a pilot demonstration of the VFT at UNSW in the 3rd year astrobiology course (BEES6741: Life in the Universe). The students' task was to go through the Dresser Formation VFT and then create a table of evidence and a 3 minute video describing what they had observed and interpreted about the environment based on their experience. This has proven to be a successful and fun exercise. In 2017, we aim to develop and enhance the VFT and launch a second pilot program in this year's astrobiology course.

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

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Funded by: CCFS Flagship Program 4

Mineral gymnastics track subduction zone processes

All around the world, sections of deep Earth material are exposed in ophiolitic complexes and allow geologists to take a direct look at the deep crust, the transition zone and the underlying upper mantle. In the Moho transition zone as well as in the upper mantle, we find a characteristic layering - dunites and pyroxenites entangled with each other. The physical and chemical properties of the dunites, the most volumetrically important fraction in the upper mantle, have been extensively studied. Pyroxenites, despite being geochemically significant, have not received much attention from the mineral-physics point of view and their influence on upper-mantle rheology still remains unclear.

In north-western Spain, the Cabo Ortegal massif makes up a spectacular field occurrence of deformed interlayered

Figure 1. Typical outcrop of massive pyroxenites in the Cabo Ortegal complex. Dunites (yellowish layers) are interlayered with massive pyroxenites (green-greyish layers). Deformation markers such as boudinage can be easily observed.

pyroxenites and dunites. Such outcrops constitute a fantastic natural laboratory to investigate how deformation affects a pyroxene-rich domain.

Field and geochemical evidence has defined four different types of pyroxenites: *type-1* are olivine-bearing clinopyroxenites enclosing dunitic lenses, and are interpreted as partial replacement of the host peridotite; *type-2* are massive websterites representing either more evolved products of the melt/rock interaction that led to *type-1* pyroxenites, or crystal cumulates in dykes and veins; *type-3* are foliated amphibole-rich clinopyroxenites with evidence of significant fluid percolation; and *type-4* represent the rare orthopyroxenites. We performed a petrological and textural characterisation of the different pyroxenites by Electron Backscatter Diffraction (EBSD). Combination of the results with field evidence revealed that at least two superimposed deformation events have been recorded by the Cabo Ortegal pyroxenites.

The most ancient event is suggested by the olivine and clinopyroxene fabrics and is likely to have occurred at temperatures greater than 1000°C in a hydrated environment. Such deformation conditions are consistent with the mantle wedge setting that has been already suggested by geochemical data. The second deformation event is recorded by the amphibole and occurred at lower temperature (500 to 800°C). This event is synchronous with the development of the spectacular sheath folds observed in the field and is consistent with close proximity to a slab.

Based on this new evidence, we argue that the Cabo Ortegal pyroxenites record mantle wedge deformation during the massive delamination of the arc root where it was generated. Our results are also consistent with the exhumation of the massif by its introduction into a subduction channel. Cabo Ortegal pyroxenites are therefore an incredible opportunity to have a look at the physical state of a piece of delaminated arc root and observe the impact of pyroxenes on the local rheology.

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: Hadrien Henry, Romain Tilhac, Sue O'Reilly, Bill Griffin, Georges Ceuleneer (Géosciences Environnement Toulouse, GET, France)

Funded by: CCFS Flagship Program 1, Two iMQRES scholarships and cotutelle programs between Macquarie and Paul Sabatier University, EPS postgraduate funds, CNRS funds (G. Ceuleneer)

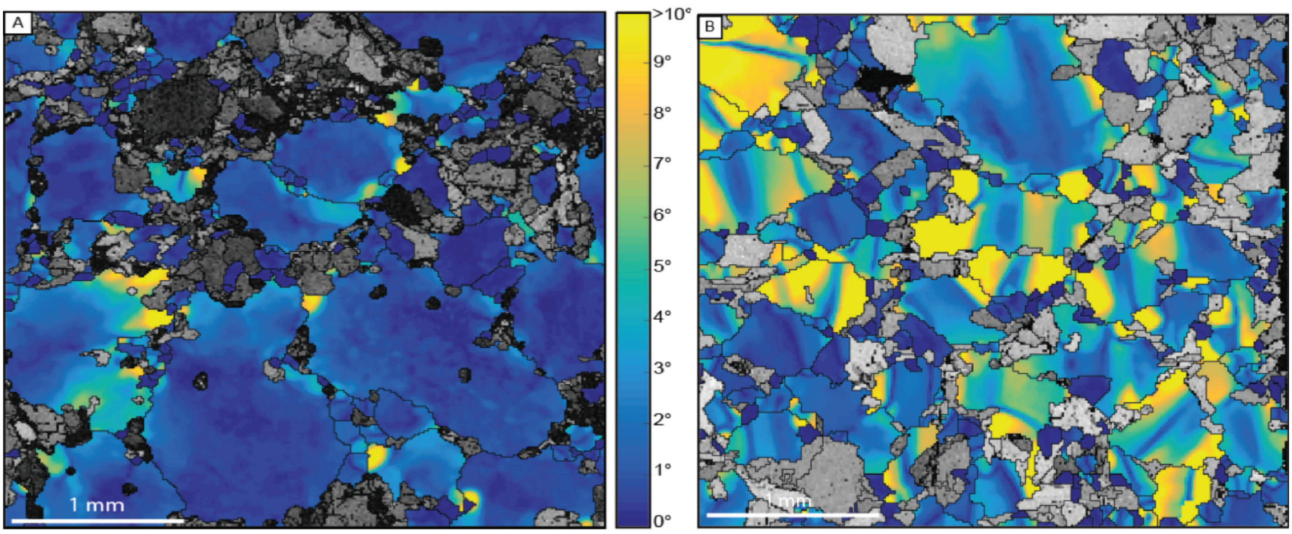


Figure 2. Microstructure of the pyroxenites plotted from EBSD data. These maps of misorientation to mean orientation indicate the angular deviation between each measurement (i.e. pixel) and the mean orientation of the grain it belongs to. A: Misorientation to mean orientation for clinopyroxenes. Misorientations are concentrated in the external part of the grain and at subgrain boundaries. B: Misorientation to mean orientation for orthopyroxenes. Misorientations are here concentrated in kink bands and form the spectacular undulose extinction one can see in thin sections.

Recognising where magma moves 40 km underground

Earth has a heterogeneous, layered crust that overlies a relatively homogeneous mantle. Every day, magma erupts from volcanoes around the world to form lava and other eruptive rock types. The geochemical signature of these volcanic rocks tells us that in most cases the source of the magma (i.e. the deep rocks that partially melted) includes both mantle and crustal components that are tens to even hundreds of kilometres deep in the Earth. Therefore, these partial melts must migrate from the deep Earth to the surface, yet geological pathways are difficult to recognise. Although some pathways are seen as dykes and shear zones, few are documented to be associated with mass transfer. Consequently, there must exist structures that are yet to be recognised as zones of substantial mass transfer.

Elongate bodies of rocks very rich in iron and magnesium, with low silica (< 45 wt%), are ubiquitous in exposures of the deep crust (exhumed from 25-50 km). Hornblendite bodies (rocks mainly comprising the mineral hornblende) of the Pembroke Valley, north of Milford Sound in New Zealand, are hosted within granulite-facies gabbroic gneiss and are typical of such occurrences. These examples have igneous grain shapes and mineral textures, in contrast with the metamorphic character of their host gneiss.

Both rock types have a common gabbroic parent; field relationships are consistent with modification to gabbroic gneiss and then into hornblendite. Although the hornblendite looks like a cumulate rock, where hornblende grains settled and concentrated in a magma chamber, the field relationships preclude this interpretation; these bodies are imposter cumulates. Instead, hornblendite formed when the host gabbroic gneiss was replaced because of channelled melt flux through the lower crust. High melt/rock ratios and disequilibrium between the migrating magma and the gabbroic gneiss induced dissolution (grain-scale magmatic assimilation) of the gneiss and crystallisation of hornblende from the migrating magma. The extent of this reaction-replacement mechanism indicates that such hornblendite bodies mark significant melt conduits. Accordingly, many of the ubiquitous elongate bodies rich in iron and magnesium of the lower crust probably map the '*missing*' mass-transfer zones.

The dissolution of plagioclase and pyroxene from the gabbroic gneiss and crystallisation of mainly hornblende marks a reactive period of melt-rock interaction. Once all the plagioclase and pyroxene of the host rock has reacted out of the channel of magma migration, it becomes an armoured channel.

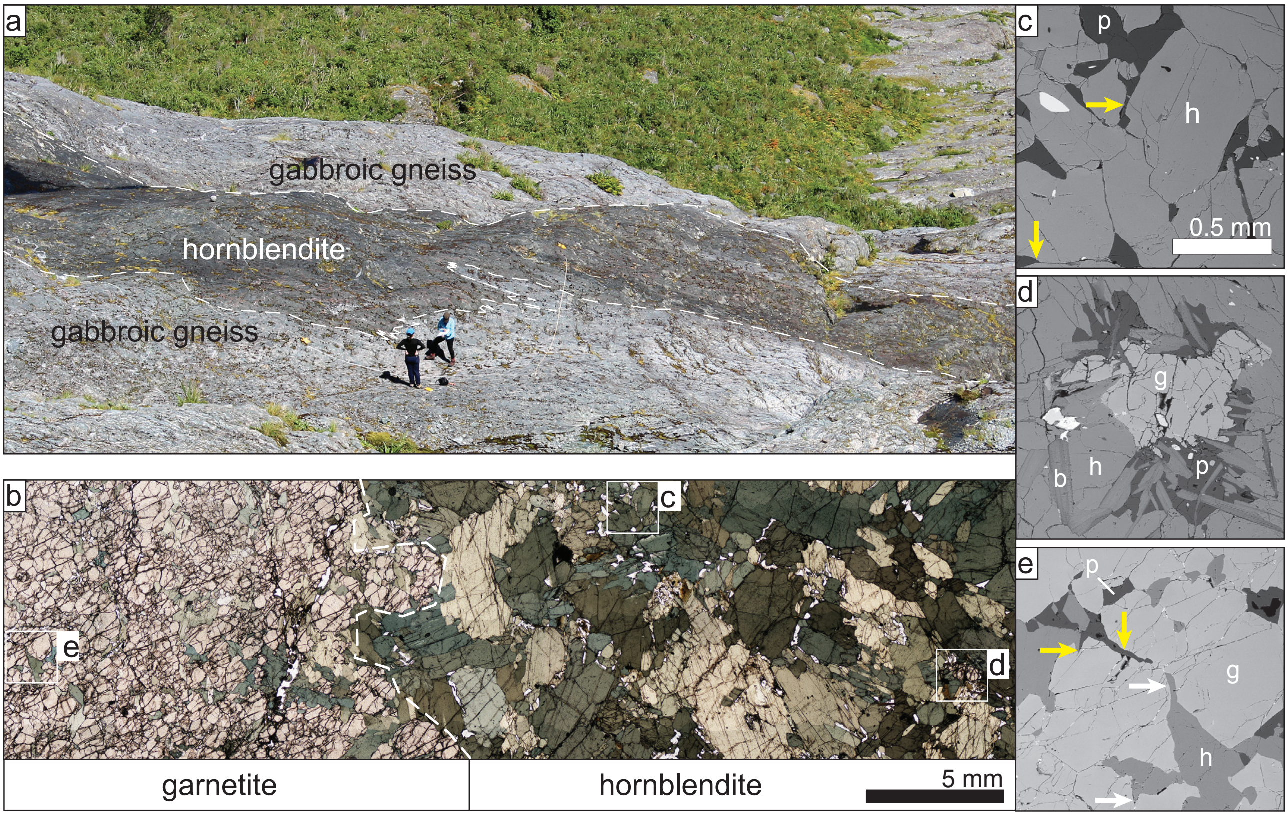


Figure 1. (a) Excellent exposure of an interpreted melt flux channel (30-40 m wide dark rock outlined by dashed lines, left to right) being mapped by Masters of Research students Uvana Meek and Victoria Elliott. (b) Photomicrograph of hornblendite (right) and garnetite stringer (left) from within the melt flux channel. (c-e) Back-scattered electron images of low dihedral angles, films along grain boundaries and small pockets representing the crystallsation of former melt, along with well-developed crystal faces at unlike mineral boundaries (e.g. plagioclase-hornblende boundaries in upper left of e). Mineral labels are plagioclase (p, yellow arrows), hornblende (h, white arrows), biotite (b) and garnet (g).

At this stage, magma can migrate through the channel without modification or chemical interaction with wall rocks. An indeterminate volume of melt could then use the channel, moving large volumes of melt through the crust.

See *CCFS Publication #832, Daczko et.al., Scientific Reports, 2016, 6, 31369.*

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

Contacts: Nathan Daczko, Sandra Piazolo
Funded by: ARC DP (SP and ND), ARC Future Fellowship (SP)

Ancient sulfur species recycled into younger igneous rocks

Cratonic margins are structurally and magmatically complex areas of the Earth's crust, and often have been affected by one or more orogenic cycles. Several studies (e.g. *Foley, 2008; Begg et al., 2010; Mole et al., 2014*) have argued that Archean lithospheric block margins exerted a first-order control on the ascent and focusing of mantle plumes that lead to the emplacement of hot magmas, host to orthomagmatic Ni-Cu-PGE deposits, and associated Au and base metal hydrothermal systems. The presence of trans-lithospheric faults along craton margins would help to focus fluids and metals, while mantle plumes provided a source of energy to drive ore-formation processes (e.g. *Mole et al., 2013*). Younger orogenic belts formed during the Proterozoic or Phanerozoic around Archean lithospheric blocks also are prospective for the presence of metal deposits (e.g. iron oxide Cu-Au, orogenic Au, porphyry Cu-Ag; *Groves et al., 2005*), suggesting that the cratonic margins continued to focus mineralisation. Therefore, it is important to elucidate the processes that drive volatiles and their associated metal cargoes into orogenic belts at the margins of reworked Archean Cratons.

Sulfur resides in the Earth's mantle, crust and hydrosphere but is locally concentrated in mineralised systems, where it acts as the primary complexing ligand in the formation of sulfide minerals. Mantle- and crustally-derived magmas have brought large quantities of economic metals from the Earth's interior to the near surface, and hydrothermal fluids have remobilised and re-precipitated these metals within the crust as different sulfides. The sulfur itself may be sourced from a variety of compositional reservoirs, each with distinct isotopic compositions. Mixing and interactions with the mantle, crustal magmas, hydrothermal fluids, country rocks, or meteoric waters imparts specific isotopic signatures, resulting in minerals with a range of isotopic compositions. Intra-grain and inter-grain chemical and isotopic variations in sulfur-rich mineralised systems record the

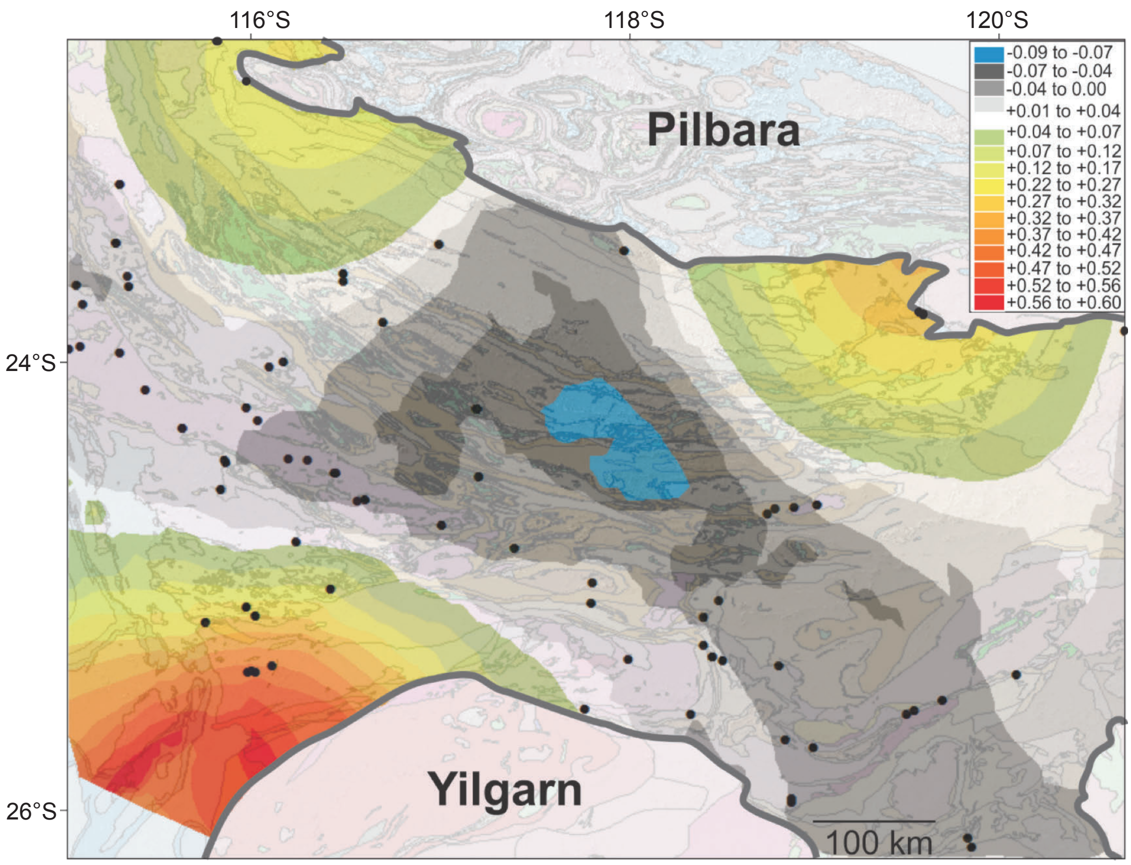


Figure 1. $\Delta^{33}S$ interpolated model of the Proterozoic Capricorn Orogen demonstrating MIF-S anomalies proximal to the Archean cratons.

interaction of these different reservoirs and offer unique insights into the complex fluid-rock interactions within mineral systems (*McCuaig et al., 2010*).

Understanding the cycling of sulfur and metals from Archean cratons into their margins can be explored using $\delta^{34}S$ - the isotopic tracer sensitive to physical processes of formation - and $\Delta^{33}S$ and $\Delta^{36}S$. The $\Delta^{33}S$ and $\Delta^{36}S$ anomalies express Mass-Independent Fractionation (MIF) - the production of sulfur isotopes by ultraviolet irradiation of a sulfur-rich atmosphere in Archean time, when Earth was not shielded by the oxygen and ozone in the atmosphere. These anomalies thus can be used as temporal tracers sensitive to the Archean-Proterozoic transition, like putting dye in watersheds to see how water travels.

The Capricorn Orogen is a natural laboratory to understand fluid, volatile and metal transfer to the margins of metal-endowed Archean cratons. The rocks making up the cratonic margins have long histories of deformation and hydrothermal fluid alteration. Results at the orogen-scale combined with detailed studies of ore deposits, help to track the mixing of geochemical reservoirs. The Proterozoic Capricorn Orogen records $\Delta^{33}S$ values that range from −0.07‰ to +0.80‰. Spatially, data from this study show that ancient sulfur, with geochemical signatures indicating formation by mass-independent fractionation, in the Capricorn Orogen occur in localised areas, especially near to the margins of Archean cratons (Fig. 1). We suggest that the spatially localised $\Delta^{33}S$ anomalies in Proterozoic samples, and the Archean $\Delta^{33}S$-$\Delta^{36}S$ array of -1 (Fig. 2) reflect a recycled MIF-Sulfur component, rather than a primary signature. This evidence indicates that MIF-Sulfur can be imparted to the Paleoproterozoic granitoid and hydrothermal record through tectonically-driven crustal formation processes.

The units hosting Archean-sourced MIF-Sulfur are dominantly magmatic (granitoids associated with collision and intraplate reworking) and hydrothermal (mineralised samples associated with faulting and veining). Other mineral deposits that preserve MIF-Sulfur anomalies occur in collisional (ca 2.0 Ga Glenburgh deposit; *Selvaraja et al. in review*) and intracontinental-reworking settings (ca 1.8 Ga Prairie Downs deposit; this study). Therefore, we propose that magmatic and hydrothermal events associated with collision and intracontinental reworking processes are responsible not only for recycling sulfur across terrain boundaries, but also for transferring metals from endowed Archean reservoirs into their younger margins.

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

Contacts: Crystal LaFlamme, Marco Fiorentini, Boswell Wing, Mark Lindsay, Vikraman Selvaraja
Funded by: MRIWA

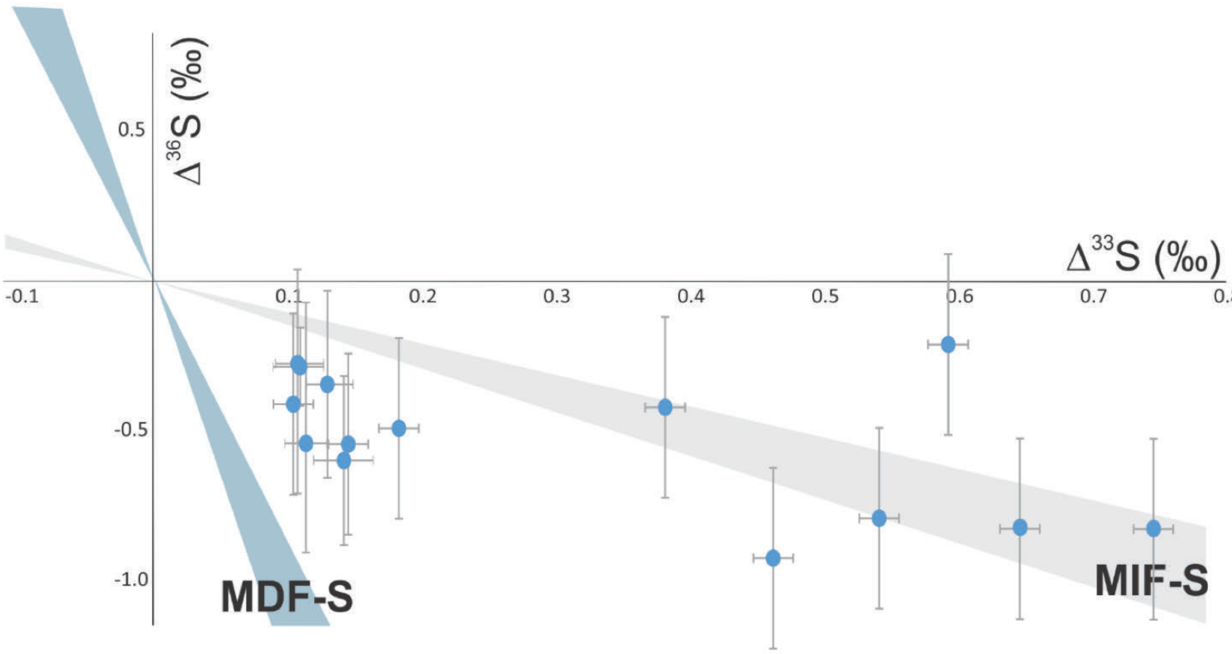


Figure 2. $\Delta^{33}S/\Delta^{36}S$ diagram for samples containing a $\Delta^{33}S$ anomaly (>0.1‰). Samples yield a $\Delta^{33}S$-$\Delta^{36}6S$ array with a slope of -1, typical of primary Archean sedimentary sulfur

Is the Ammassalik Intrusive Complex (South East Greenland) part of an ancient Ni-Cu magmatic province?

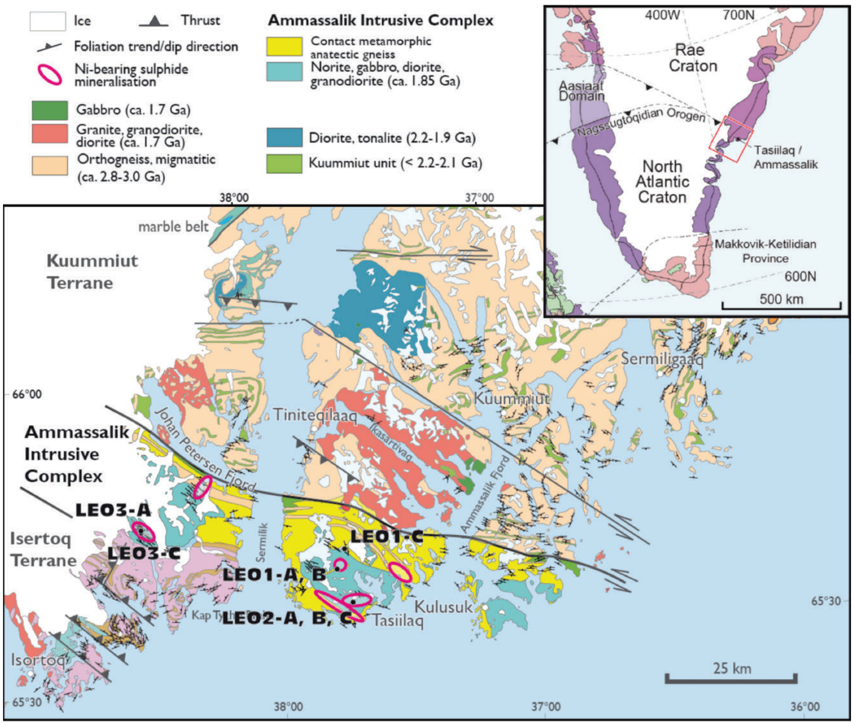


Figure 1. Detailed geology map of the Ammassalik Intrusive Complex. Geochronological samples are highlighted in black. Modified from Kolb (2014), Árting (2016) and Johannesen (2016).

The Paleoproterozoic Ammassalik Intrusive Complex formed during the Nagssugtoqidian orogeny, at the juncture of two Archean cratons, the Rae to the north, and the North Atlantic craton to the south (Fig. 1). The Ammassalik Intrusive Complex can be separated into three smaller complexes: the Johan Petersen, Tasiilaq and Kulusuk Intrusive Complexes, hosted in a ca ≤1990 Ma anatectic Bt-Gt paragneiss. The Ammassalik Intrusive Complex is interpreted to have been emplaced either as a dyke, later boudinaged, or as a series of pipes, at mid- to lower-crustal levels (granulite facies) in two successive pulses between ca 1915 and 1865 Ma.

Both the igneous rocks and the hosting Bt-Gt paragneiss show typical calc-alkaline and continental-arc signatures, including negative Ta, Nb and Ti anomalies. In addition, the fractionation of the MREE to HREE observed in the igneous samples, but not in the paragneiss, is consistent with a deep Gt-rich source. The igneous rocks of the Ammassalik Intrusive Complex can be sourced from partial melting of a Gt-lherzolite mantle, an eclogitic lithospheric mantle-wedge, or an eclogitic lower crust. However, each of these sources should have very different isotopic signatures.

Isotopic work on the igneous rocks of the Ammassalik Intrusive Complex suggests a mixture of sources. These sources represent mantle-derived magmas (from either the Gt-lherzolite mantle, or the lithospheric mantle-wedge) that assimilated and/or partially melted Paleoproterozoic to Archean supracrustal material on their way up through the mid- to lower crust. The host Bt-Gt paragneiss may have contributed to this supracrustal input and may be the source of the calc-alkaline and continental-arc geochemical signature of the igneous rocks. In detail, isotopic data (Fig. 2) show CHUR-like εHf values decreasing with time to around -10, interpreted to represent mixing of melts

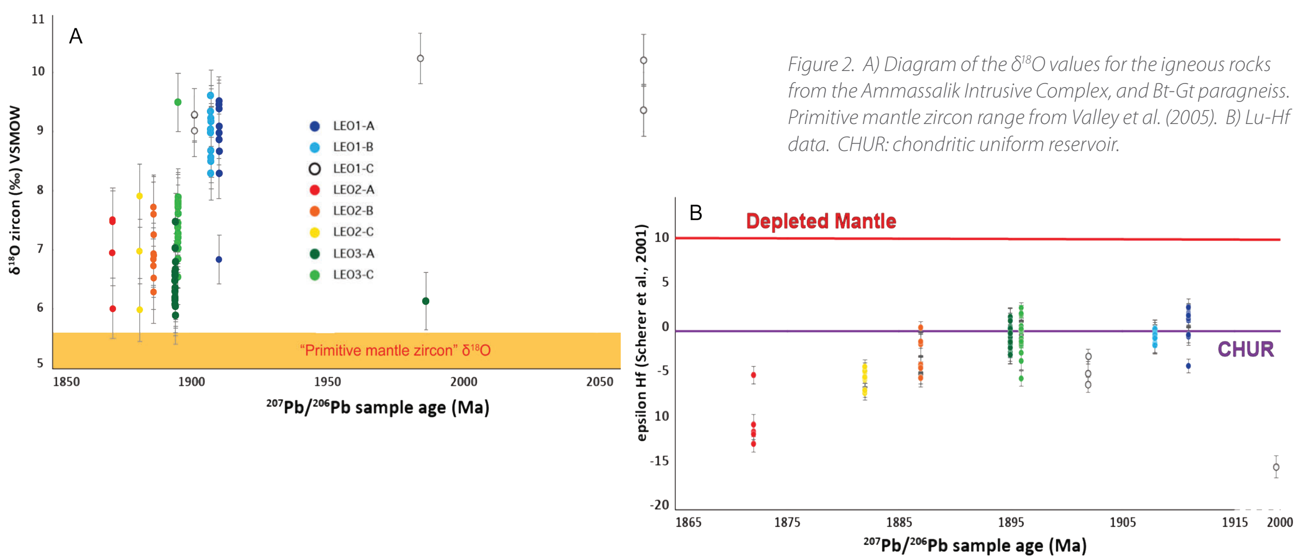
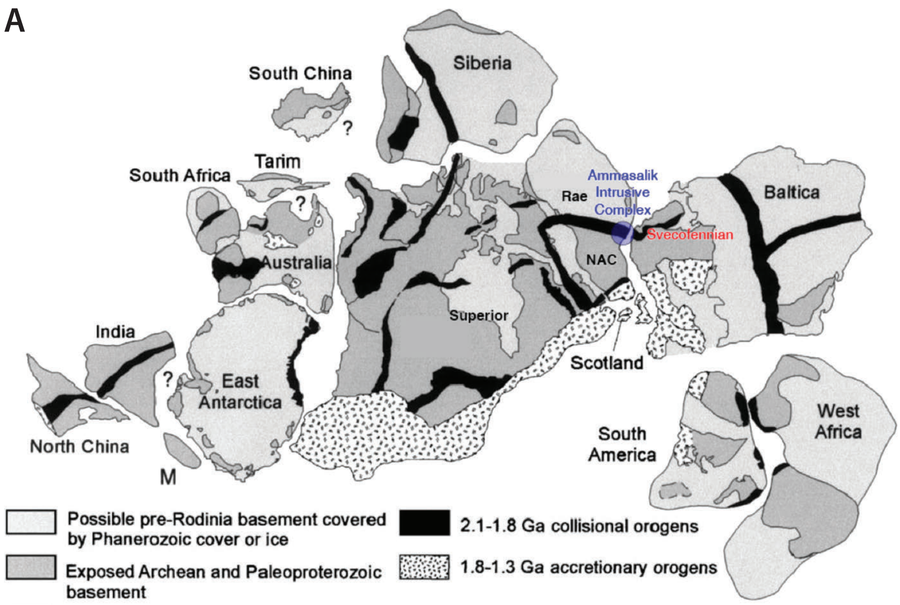


Figure 2. A) Diagram of the $\delta^{18}O$ values for the igneous rocks from the Ammassalik Intrusive Complex, and Bt-Gt paragneiss. Primitive mantle zircon range from Valley et al. (2005). B) Lu-Hf data. CHUR: chondritic uniform reservoir.



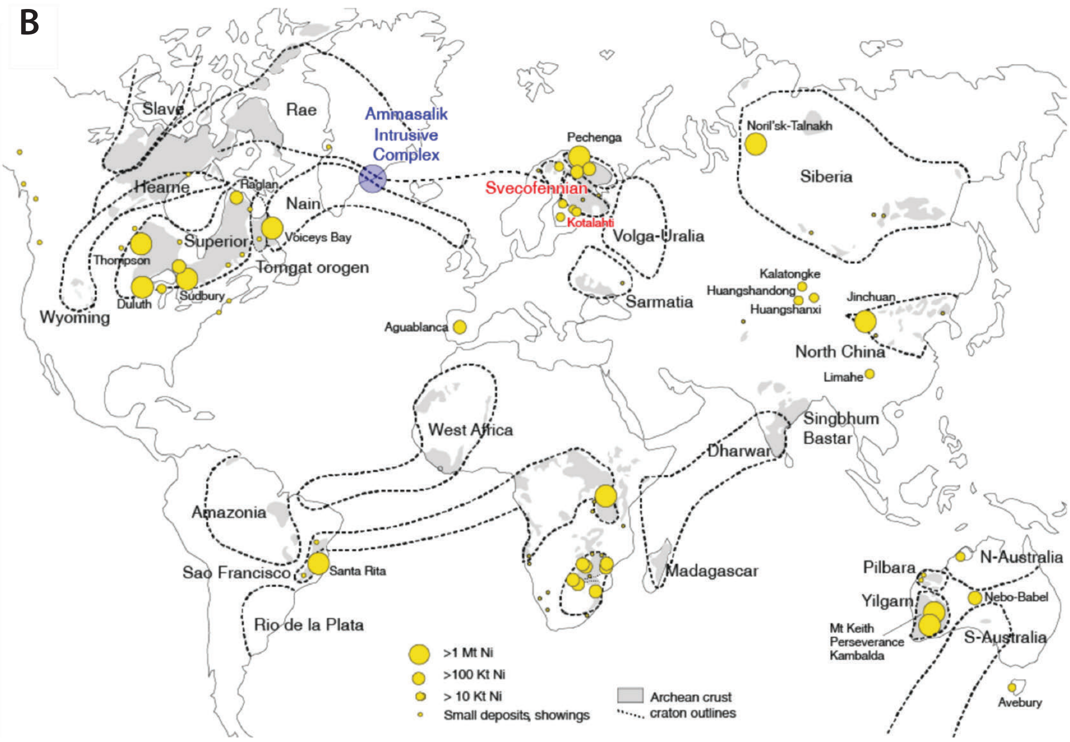


Figure 3. Reconstruction of A) the Columbia supercontinent showing the paleo-continuity between the Svecofennian Province and the Ammassalik region of south-eastern Greenland. Modified from Zhao et al. (2004). B) craton margins (modified from Bleeker, 2003) and associated Ni deposits highlighting the well-endowed Svecofennian Province and Kotalahti Ni belt and the link with south-eastern Greenland. Modified from Maier and Groves (2011).

from a deep Gt-rich mantle with increasing partial melting and/or assimilation of Precambrian to Archean supracrustal material through time (T^{C}_{DM} for igneous rocks bracketed between 2320 and 3280 Ma). This mantle-crust mixing is further supported by bimodal supracrustal $\delta^{18}O$ values around 7 and 9‰, above the *'primitive mantle zircon'* range. The bimodal distribution may indicate a change through time in the type of supracrustal material involved. The isotopic composition of anatectic zircons in the Bt-Gt paragneiss also suggest that the Bt-Gt paragneiss was part of the supracrustal contribution.

The age bracket on the magmatism, between *ca* 1915 and 1865 Ma, overlaps with that of magmatism linked to the assembly of the Columbia supercontinent. This process was marked by the formation of numerous world-class Ni-Cu deposits around the world, some intrusive-hosted. Based on the age overlap and the paleoreconstruction of the supercontinent around 1.9 Ga, we interpret the Ammasalik Intrusive Complex and the south-eastern Greenland region as a direct continuation of the Svecofennian Province and the well Ni-endowed Kotalahti belt, along a circum-Rae magmatic province (Fig. 3). This conclusion highlights the high prospectivity of the south-eastern Greenland region for world-class intrusion-hosted Ni-sulfide deposits.

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

Contacts: Erwann Lebrun, Marco Fiorentini
Funded by: CCFS Flagship Program 2

Volcanic debris from up to 60 km beneath western Victoria tracks tectonic ups and downs

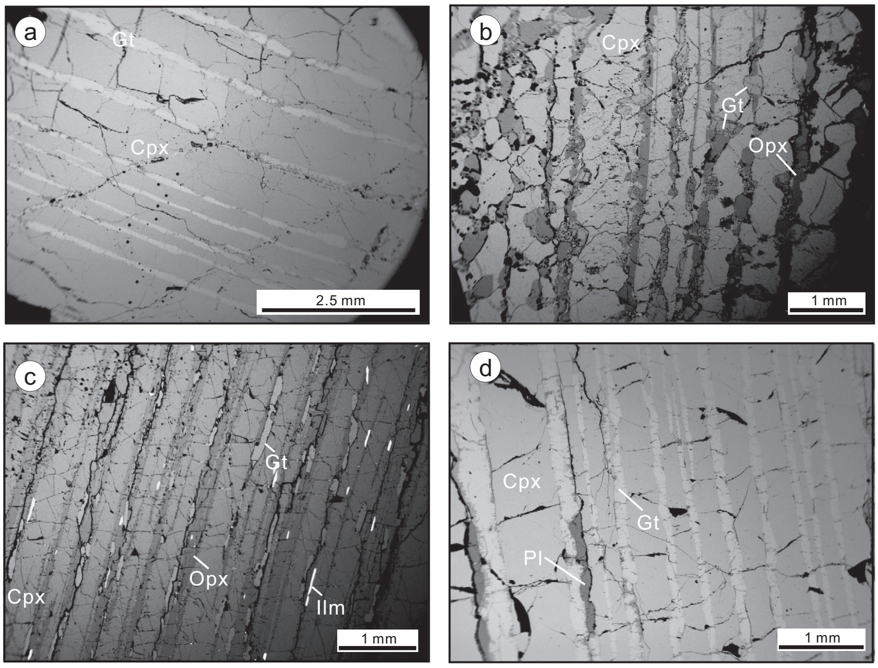


Figure 1. Backscattered electron (BSE) photomicrographs of clinopyroxene megacrysts with exsolution lamellae of garnet (Gt), orthopyroxene (Opx), ilmenite (Ilm) and plagioclase (Pl).

Subduction can draw surface, near-surface and shallow mantle materials (including volatiles) into the mantle and result in mantle/fluid interactions. The process plays a key role in cycling of volatiles and other elements and affects the composition and nature of Earth's deep interior. Pyroxenite xenoliths from ~30-60 km below the surface, provide a key tool to track these deep processes. The basanite tuffs of Bullenmerri and Gnotuk maars, southeast Australia, contain abundant garnet-bearing pyroxenite xenoliths. New petrographic, geochemical and isotopic investigations on these xenoliths reveal a picture of subduction-related magmatism at mantle depths.

Microstructural evidence of the exsolution of garnet (± orthopyroxene ± spinel ± plagioclase ± ilmenite) from complex clinopyroxene megacrysts suggest that all garnet pyroxenite xenoliths originally were clinopyroxene-dominant cumulates, modified by exsolution and recrystallisation during cooling to the ambient geotherm (Fig. 1). They can be divided into two types: Type I high-MgO garnet websterites, and Type II low-MgO garnet clinopyroxenites. The high-MgO garnet websterites have high Cr and low Al contents in both whole rock and clinopyroxene, relatively flat LREE patterns and homogeneous Sr-Nd-Hf isotopic compositions ($^{87}Sr/^{86}Sr$=0.70386-0.70657; $^{143}Nd/^{144}Nd$=0.51260-0.51283; $^{176}Hf/^{177}Hf$=0.28281-0.28305). These data suggest that they represent high-pressure cumulates from arc-related tholeiites, produced in the initial stages of partial melting of a mantle wedge due to slab dehydration. Conventional thermobarometry and thermodynamic modeling on the reconstructed clinopyroxene indicate that the primary clinopyroxenites crystallised at ~1420-1460 °C and 23-30 kb and finally equilibrated at ~982-1094°C and 14-17 kb.

Low-MgO clinopyroxenites have low Cr contents and variable REE patterns from LREE-depleted to LREE-enriched in the whole rock and clinopyroxene. They also show heterogeneous Sr-Nd-Hf isotopic compositions ($^{87}Sr/^{86}Sr$=0.70374-0.71548; $^{143}Nd/^{144}Nd$=0.51221-0.51355; $^{176}Hf/^{177}Hf$=0.28274-0.28396) in clinopyroxene but uncontaminated upper-mantle δ^{18}OV-SMOW in garnet (4.9-5.2 ‰), indicating that low-MgO pyroxenites may represent high pressure cumulates from an evolved magma derived from partial melting of hydrothermally altered oceanic crust with the addition of subducted sediments from the Paleozoic Lachlan orogenic belt. P-T calculations suggest that they crystallised at 1280-1400°C and 16-20 kb and finally equilibrated at 950-1050 °C and 12-17 kb.

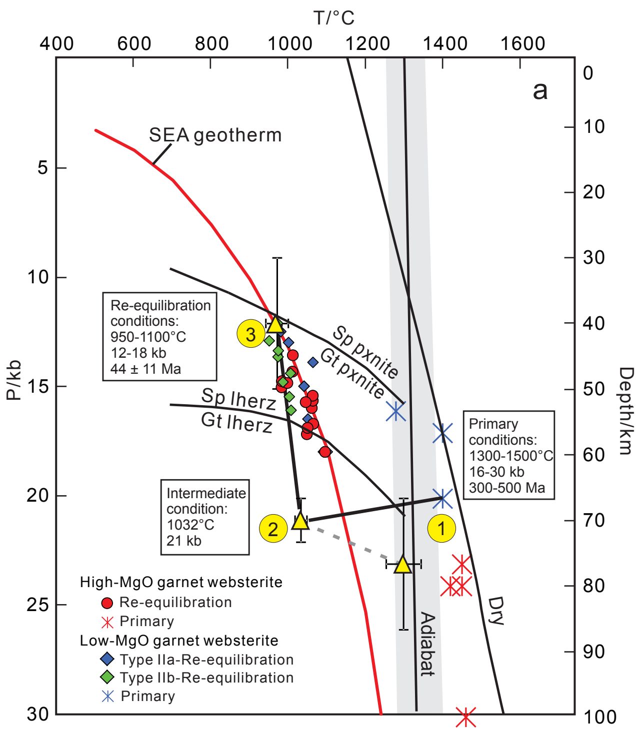


Figure 2. P-T-t path for the garnet pyroxenites from Lakes Bullenmerri and Gnotuk.

The preservation of fractionated trace-element patterns in multiple generations of garnet lamellae and their surrounding clinopyroxene indicates a decompresssional cooling path (1032 °C and 21 kb) before the xenoliths were entrained by the host basanite (Fig. 2).

These results imply that the protoliths of the garnet pyroxenite formed at a range of depths from ~50-100 km; back-calculation of the isotopic data suggests this primary crystallisation occurred about 300-500 m.y. ago. During, or shortly after cooling, they were tectonically uplifted to higher levels (~40-60 km; i.e. uplifted by at least 10~20 km) in Paleogene time (44 ± 11 Ma; Sm-Nd isochrons); this was accompanied by rifting associated with crustal inflation and thinning in southeast Australia.

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

Contacts: Jianggu Lu, Bill Griffin, Sue O'Reilly, Qing Xiong, Jin-Xiang Huang, Norman Pearson, Jianping Zheng (China University of Geosciences, Wuhan)

Funded by: CCFS Flagship Program 1, IMQRES scholarships

Earth's magnetic switch activated in the deepest mantle

Earth scientists use paleomagnetism to establish a paleogeographic framework for continental blocks through Earth's history. Rapid changes in the geomagnetic field also provide critical information about Earth's long-term evolution and dynamics. In particular, dynamic activity at the core-mantle boundary impact on the behaviour of the geomagnetic field by changing the rate and geometry of the heat flux field. For instance, the lower mantle impacts on the geomagnetic reversal rate. It has also been suggested that heterogeneity in heat flux causes specific patterns of transitional paleomagnetic poles (or virtual geomagnetic poles - VGPs) during the reversal of the geomagnetic polarity. For example, transitional poles may be arranged on the rims of the large low shear velocity provinces (LLSVPs) near the core-mantle boundary. If proven, this relationship potentially can provide important constraints on the stability of LLSVPs over time, which has a direct influence on the concept of the supercontinent cycle.

In this study we investigated a sedimentary sequence from Armenia, where the two geomagnetic field reversals bounding the youngest normal-polarity subchron (the so called Jaramillo subchron with an age between 0.988 and 1.072 Ma), prior to the current Brunhes normal-polarity chron, have been recorded. The paleomagnetic signal in the sediments is of very high quality and, because these lake deposits accumulated very rapidly (~30 cm/ka), it was possible to study the field reversals over a thickness of ~2 m. We obtained standard, 1 inch diameter, paleomagnetic samples at intervals of less than 10 cm. Based on the paleomagnetic results we calculated, at each sample level, a geomagnetic pole assuming a dipole-dominated geomagnetic field (therefore virtual geomagnetic poles). Plotting these poles allowed us to investigate the appearance of the geomagnetic field during a polarity transition (or field reversal).

The obtained virtual geomagnetic pole (VGP) path indicates an oscillatory transitional field behaviour with four abrupt transequatorial precursory jumps across the Pacific (Fig. 1). The two records are strikingly similar to another high-quality paleomagnetic record (green points in

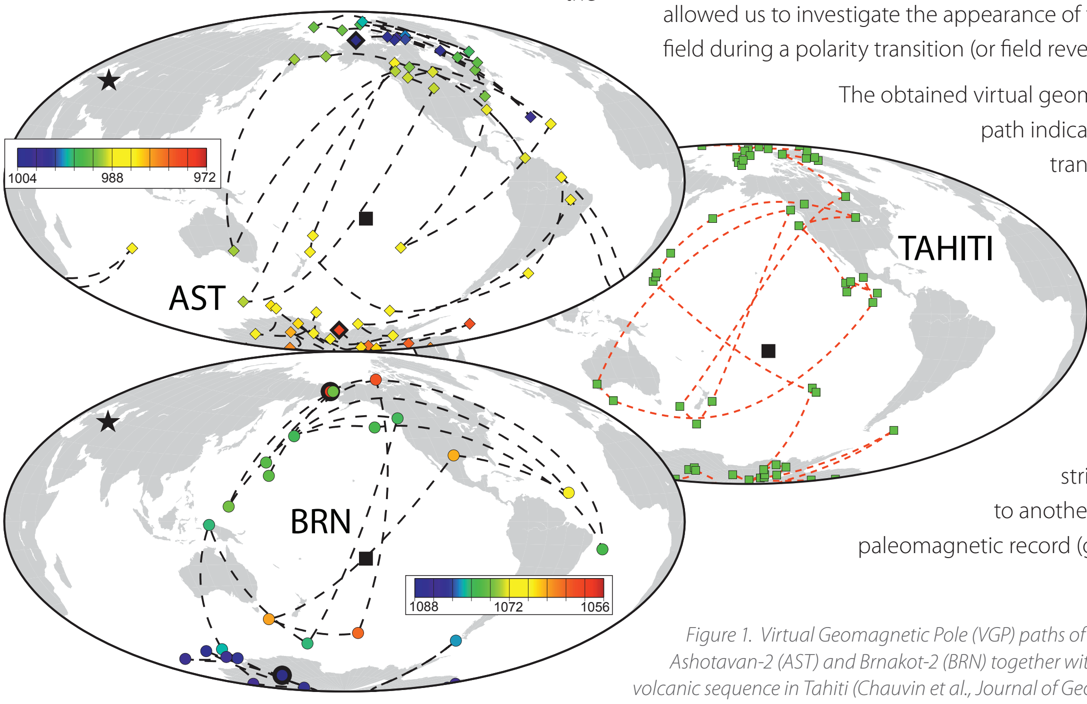


Figure 1. Virtual Geomagnetic Pole (VGP) paths of Armenian sections Ashotavan-2 (AST) and Brnakot-2 (BRN) together with the VGP path of volcanic sequence in Tahiti (Chauvin et al., Journal of Geophysical Research, 95, 1990). VGPs are colour coded with the inferred age in ka. Black star (square) indicates the location of the reversal records of this study (Tahiti).

Fig. 1), which is based on a volcanic sequence from Tahiti. The distribution of VGP positions of these three records clearly indicate regions of preferred occurrence (Fig. 2). Our results are in agreement with previously proposed bands of transitional VGP over the Americas and Australia/northwest Pacific zone, almost exclusively over the girdle of mantle downwelling between the two large provinces of low shear velocity (LLSVPs; Fig. 2).

Our observations imply a thermally stable zone within the outer core and below the LLSVPs, which persists throughout the polarity transition. This zone can generate a secondary radial dipole, which repels the transitional VGPs directly above this zone. As long as the LLSVPs are in place, all polarity transitions should look similar, as observed for the youngest polarity transitions.

Our work further demonstrates that there is an obvious link between the geometries of paleomagnetic reversals and lower-mantle structures. In future studies we may use this as a basis for investigating the temporal evolution of the lower mantle after identifying high-quality reversal records from older sequences. We show that with only three high quality records and a robust statistical analysis we can visualise an antipodal structure at the CMB. Such work will help us to evaluate how stable these features at the CMB actually are.

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

Contacts: Uwe Kirscher, Valerian Bachtadse

Funded by: CCFS Flagship Program 5, ARC Laureate Fellowship (FL150100133), DFG grant (Ba1210/14-1)

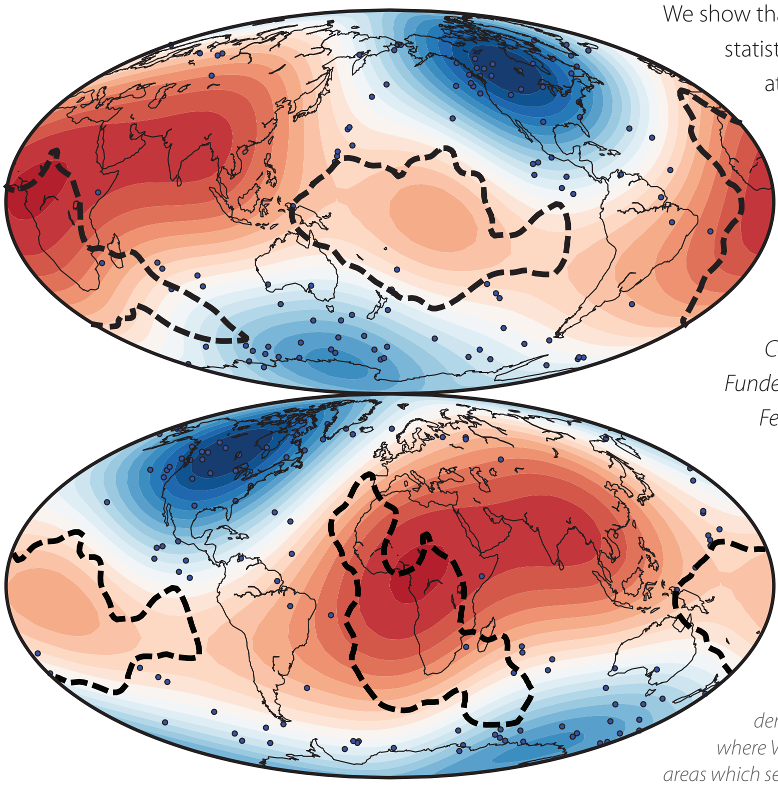


Figure 2. Stereographic projection of calculated VGPs of all studied samples (blue points) together with VGPs of a record from Tahiti (s.a.). Present day LLSVPs at the core-mantle boundary are outlines by black dotted lines. The reddish to bluish colour corresponds to a Gaussian kernel density estimate of the VGPs. Dark blue colours represent areas where VGPs are most likely to be found, while red colours represent areas which seem to be avoided by VPGs.

Sulfur isotopes reveal the evolution of mineralised Komatiites

Komatiites are ancient submarine lavas erupted over 2.5 billion years ago. Their ultramafic chemical compositions and the exceptionally high temperatures (~1600 °C) of the lavas allowed them to form spectacular channelised lava flows that find present-day analogues in the Kilauea lava fields of Hawaii. Their high temperature and low viscosity let komatiites lavas flow turbulently and to mechanically and thermally erode and assimilate crustal substrates along their path.

Komatiites are economically important because they can host massive sulfide mineralisation enriched in Ni, Cu and platinum-group elements (PGE). Indeed, komatiite-hosted Ni-Cu-PGE deposits from the Yilgarn Craton, Western Australia, account for ca 20% of global Ni-sulfide resources. Current models suggest that the assimilation of crustal sulfur-rich material by komatiite-lava erosion was necessary for sulfide supersaturation and deposition of these deposits.

This study combined mineralogical and sulfur-isotope variations to evaluate magmatic processes involved in the evolution of the ore-bearing sequence at Wannaway (Eastern Goldfields). It also provides a perspective on the potential influence of such processes on the composition of the Archean atmosphere.

The mineralised successions comprise basal sufide-rich black shales overlain by komatiite-hosted sulfides manifested by gradual transitions from massive to matrix-textured and disseminated ores (Fig. 1). We analysed the S-isotope composition of samples taken at regular distances through the mineralised sequence and then correlated sulfur mass-dependent fractionation (MDF-S) signatures with recently

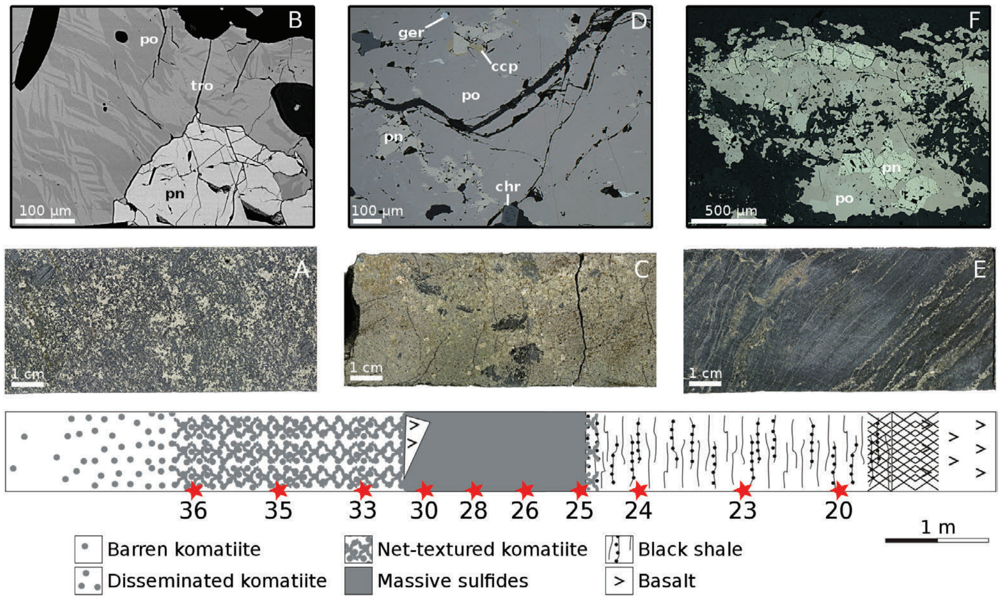


Figure 1. Scheme of the studied drillcore from the Wannaway Ni-Cu-PGE deposit, Western Australia. A) Drillcore section of net-textured komatiite; (B) BSE micro-image of net-textured sulfides; (C) Drillcore section of magmatic massive sulfides; (D) Optical reflected-light micro-image of massive sulfides; (E) Drillcore section of basal black shale; (F) Optical reflected-light micro-image of sedimentary sulfides.

discovered mass-independent fractionation (MIF-S) signatures to better constrain the effect of subsequent fractionation. The magmatic sulfides show a distinct positive MIF-S signature which indicates the assimilation of crustal material. The isotopic signatures of the sulfides are analogous to the sediments directly underlying the komatiite flows, suggesting that the assimilation occurred *in situ*. The data suggest that over 1/3 of the total sulfur in the deposit was assimilated from the country rocks.

In addition, the magmatic sulfides display a wide range in MDF-S signatures that gradually become lighter from the basal massive sulfides upwards. This isotopic drift is followed by the appearance of troilite (FeS) and a gradual decrease of pyrrhotite ($Fe_{1-x}S$) proportions. At stratigraphic levels where troilite becomes dominant, alabandite (MnS) appears; this is an unusual phase commonly related to strongly anoxic sedimentary environments and observed in meteorites. We argue that the combined upwards decrease in heavy sulfur isotopes along with the stability of troilite and alabandite is a consequence of magmatic devolatilisation and the release of SO_2-rich gasses during emplacement. The release of SO_2 would have stripped '*heavy*' sulfur from the komatiite magma, and caused local decreases in oxygen fugacity. This phenomenon, which is widely observed in present-day lava eruptions, has never been reported for Archean komatiites. This finding is particularly relevant to understanding the genesis and localisation of nickel sulfide systems with respect to the geodynamic setting of komatiite magmatism and associated sulfur degassing. A more detailed understanding of SO_2 devolatilisation processes during komatiite magmatism will shed new light on the processes that led to the oxygenation of early Earth's atmosphere.

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

Contacts: Stefano Caruso, Marco Fiorentini, Laure Martin

Funded by: GSWA, the Minerals Research Institute of Western Australia, UWA Scholarship for International Research Fees

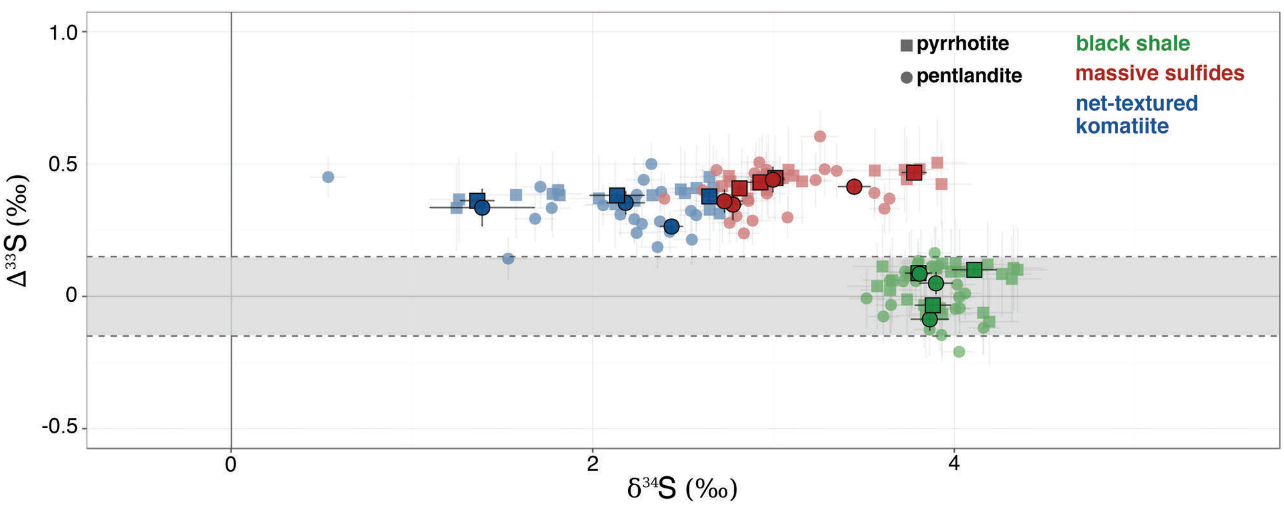


Figure 2. $\Delta^{33}S$ versus $\delta^{34}S$ data.

Ancient boron-rich, Himalayan cauldron - the soup for early life?

Figure 1. Luke Steller sampling active hot springs of the Puga Valley, India.

Darwin suggested that life may have started in "*…some warm little pond…*". What better place than hot springs, which today are known to host diverse microbial life, including not only phototrophic cyanobacteria, but also some of life's most primitive forms, chemotrophic archea. But can hot springs provide the right environments and critical elements for life to have originated there?

One of the key elements in prebiotic chemistry is Boron, which is a key catalyst in the polymerisation of organic molecules - i.e. the process that makes organic (carbon-bearing) molecules more complex. Boron is present in seawater in very dilute concentrations, but the problem with a marine environment for the origin of life is that there is no readily obvious mechanism for concentrating elements such as Boron and because many complex organic molecules cannot form just in the presence of water - they need the energy from wet-dry cycles to form. And so, hot springs!

Boron has been found in high concentrations in some hot springs, perhaps most notably from the Puga Valley of India, in the mountains of the Himalaya. Excitingly, Boron has recently been found concentrated in hot spring deposits 3.5 billion years old, intimately associated with some of the oldest evidence of life on Earth.

In July, UNSW Honours student Luke Steller, funded by CCFS Flagship Program 4, participated in a Spaceward Bound trip to the Puga Valley to collect samples of boron-bearing hot spring deposits (boratic sinter, muds and hot spring fluids) for compositional and boron isotopic analyses at the Pheasant Memorial Laboratory of Okayama University in Misasa, Japan. The aim was to compare the isotopic composition of boron in the active boratic hotspring deposits with that of 3.5 billion-year-old deposits. To our delight, the boron-isotope results from Puga Valley hot spring fluids were exactly the same as those from the ancient deposits, at -13‰, whereas muds and silicic crusts were fractionated to much more negative values.

These results support our recent observations (see *Research highlight p. 41*) that the 3.5 billion-year-old stromatolites flourished in a boron-rich hot spring environment. They also lend support to models of the origin of life in hot springs, as not only Boron, but other critical elements for prebiotic chemistry (P, C, H, Zn, O, S) have been found concentrated in these ancient rocks.

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

Contacts: Martin Van Kranendonk, Luke Steller
Funded by: CCFS Flagship Program 4

Zircon trace elements reveal oxidation signatures in ancient mantle

A major problem in understanding magmatic processes in the modern Earth and its evolution since planetary accretion is evaluation of the oxidation states of magmas and their source regions. In this study, we thermodynamically and empirically calibrate a novel method for determining magmatic oxygen fugacity (fO_2) in calc-alkalic, tholeiitic, adakitic and shoshonitic, metaluminous to moderately peraluminous and peralkaline melts as igneous zircon crystallised, to a precision of ±0.5 log unit fO_2, using only the easily measureable, redox-sensitive ratios Ce/U and U/Ti in zircon (nominally $ZrSiO_4$), without explicitly considering the ionic charge of Ce, U, or Ti, and without explicitly considering crystallisation temperature or pressure or silicate-melt composition (Fig. 1). Thermodynamic and empirical constraints indicate that our formulation is insensitive to variation of crystallisation temperature and pressure at lithospheric conditions. We use this new magmatic oxybarometer to illuminate the Hadean *'dark ages'* (4.0-4.6 Ga), for which detrital zircons are the only surviving witnesses of the period during which the Earth's proto-continental lithosphere developed.

We identify the oxidation states of magmas that produced Hadean and Eoarchean zircons in the Yilgarn, South China, Slave and Wyoming cratons (Fig. 2). Zircons in the 4375-3800 Ma age range from the Yilgarn Craton cluster in the fO_2 range of modern mid-ocean-ridge magmas, as do also most 3858-3200 Ma detrital zircons in the Wyoming Craton. More reducing conditions, about 2 log units lower fO_2, are represented by 3970-3896 Ma zircons in the Wyoming Craton and all analysed Hadean igneous zircons (4121-4002 Ma) from the Cathaysia Block of the South China Craton and from the Acasta Gneiss Complex in the Slave Craton. These data indicate that the secular evolution of the oxidation state of our planet may have not been linear and globally homogeneous. Oxidised and reduced domains co-existed in the early stages of the Earth evolution. However, the presence of early reduced suites, such as the ones from the South China and Slave cratons, imply derivation of parental mafic magmas or of re-melted mafic protoliths from sub-continental lithospheric mantle domains strongly depleted in ferric iron by prior episodes of basaltic/komatiitic melt extraction. These data indicate that by 4 Ga there may have already been a localised build up of chemically refractory, buoyant harzburgitic lithospheric mantle keels that shielded the underside of proto-continental crust from ablative loss by asthenospheric mantle convection, thus creating the conditions for the long-lived preservations of cratons.

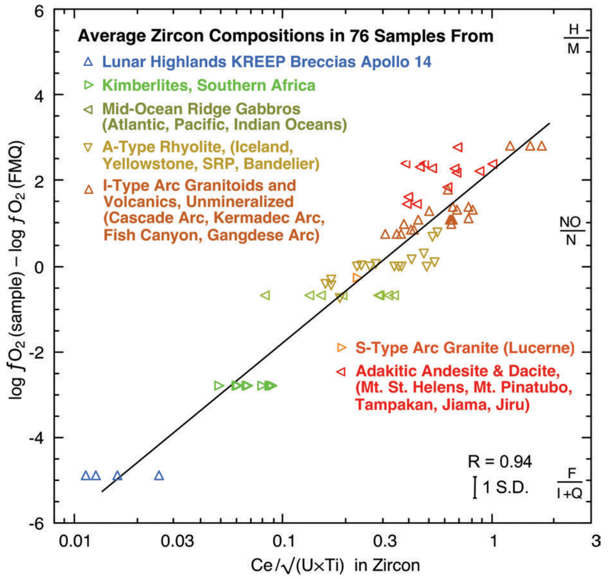


Figure 1. The average value of the parameter Ce/√(U×Ti) for the analysed zircon population in each rock sample is plotted against relative oxygen fugacity of the parent magma, as provided by independent constraints. The least-squares fit to the data (solid line) is ΔFMQ = 2.272 + 3.997 × log [Ce/√(U×Ti)], with a correlation coefficient R = 0.941 and a standard deviation of 0.495 log unit fO_2. 'SRP' denotes Snake River Plain, Idaho. Lucerne granite is in Maine, USA. Bandelier Tuff is in the Rio Grande Rift, New Mexico (USA).

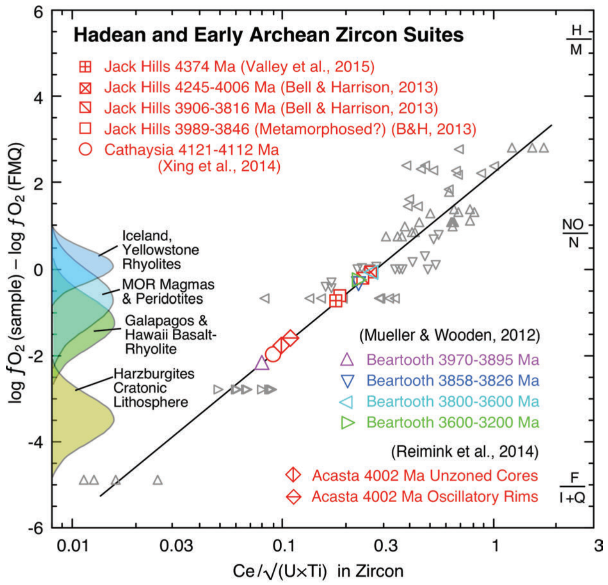


Figure 2. Average values of the parameter Ce/√(U×Ti) in suites of Hadean (4560-4000 Ma), Eoarchean (4000-3600 Ma), and Paleoarchean (3600-3200 Ma) zircons are plotted on the fO_2 calibration line and dataset from Figure 2 in order to infer oxidation states of the parental magmas. Hadean and early Archean zircons are binned by locality and by age subgroups, within which each population is relatively homogeneous. The Jack Hills locality is in the Yilgarn craton, Western Australia; the Cathaysia block is in the South China composite craton; the Acasta gneiss complex is in the Slave craton, Canada; the Beartooth Mountains are in the Wyoming craton, USA. Grey symbols are reproduced from Figure 1 for ease of reference to mid-ocean-ridge and mantle-plume-related suites. Colored curves at left represent Gaussian frequency distributions of magmatic oxidation states in various tectonic settings, based on log fO_2 data for mid-ocean ridge igneous suites and oceanic abyssal peridotites summarised from the literature.

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

Contacts: Robert Loucks, Marco Fiorentini

Funded by: CCFS Flagship Program 2

Potassium-rich magmas from a phlogopite-free source

Potassium-rich lavas are generally assumed to be produced by melting of mantle rocks that contain phlogopite, which is the source of the potassium. In the Mediterranean region, trace-element and isotopic compositions indicate that continental crustal material must be involved in the generation of many potassium-rich lavas. Melting occurs here in young lithosphere that was newly formed during the collision of small blocks and oceans, meaning that the continental crust was not stored for a long period of time in the mantle.

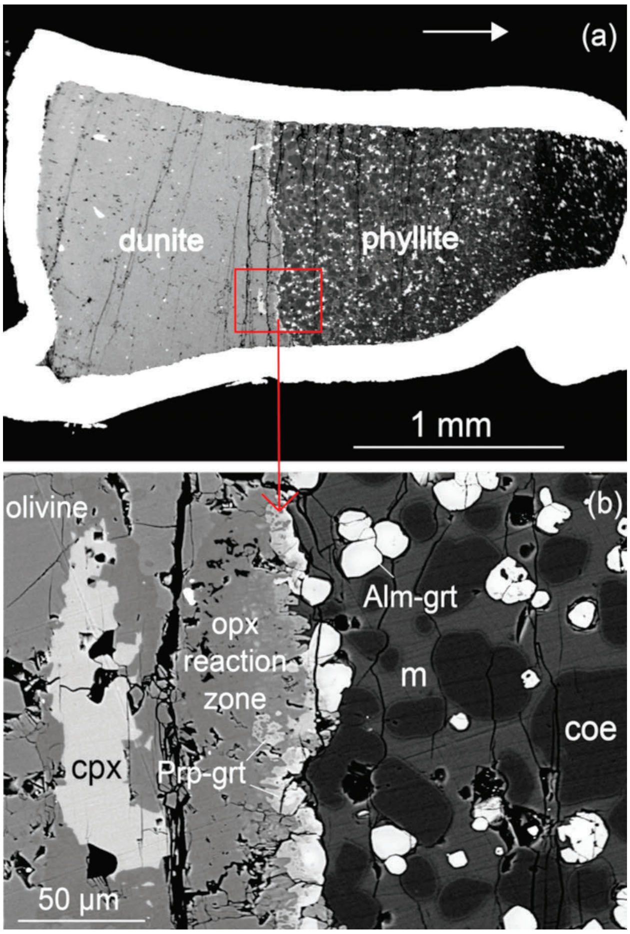


Figure 1. Representative back-scattered electron images of reaction run 139 (1000 °C, 3 GPa). Grt: garnet; Opx: orthopyroxene; Cpx: clinopyroxene; M: melt; Coe: coesite.

Few experimental studies have investigated the reaction between melts of continental crust and depleted peridotites, and so the reactions and the redistribution of trace elements during hybridisation and melting processes remains poorly constrained.

We have compared two types of experiments investigating the reaction between crust and mantle at depths of 60-100 km. In the first, continental crustal metasediment (phyllite) and depleted peridotite were juxtaposed as separate blocks, whereas in the second, the same rocks were ground together as a homogeneous powder. In the first series, a clear reaction zone dominated by orthopyroxene was formed but no hybridised melt could be analysed, whereas in the second series, analysable pools of hybridised melt were produced. Melt compositions from both experimental series show high abundances of Rb (100-220 ppm) and Ba (400-870 ppm), and consistent ratios of Nb/Ta (10-12), Zr/Hf (34-42) and Rb/Cs (28-34) similar to bulk continental crust.

The hybridisation process produces melts with $(Th/La)_N$ of ~2.5, higher than melts from the sedimentary rock alone (~1.7), accentuating the high Th/La already produced by other processes. High Th/La is a characteristic of potassium-rich lavas in these post-collisional environments. Melting of sedimentary rocks can strongly fractionate Sr from Nd, whereas hybridised melts show much less fractionation because of the diluting effect of the peridotite.

The trace-element patterns of hybridised melts produced in our experiments are remarkably similar to post-collisional K-rich volcanic rocks. Almost all trace elements exhibit almost identical arrays to the post-collisional K-rich volcanic rocks but with slightly lower concentrations, which is probably due

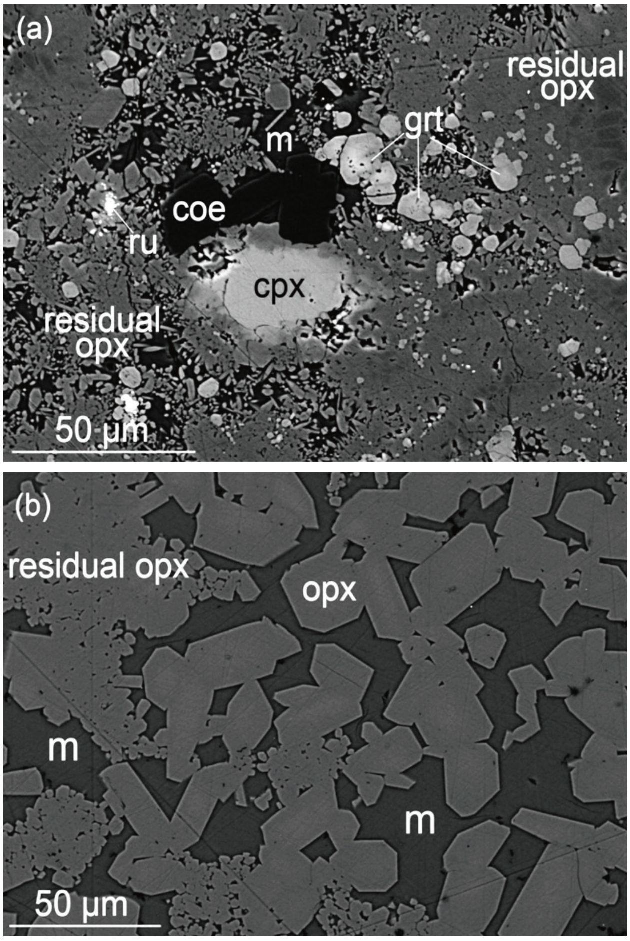


Figure 2. Representative back-scattered electron images of intimately mixed run products. Ru: rutile.

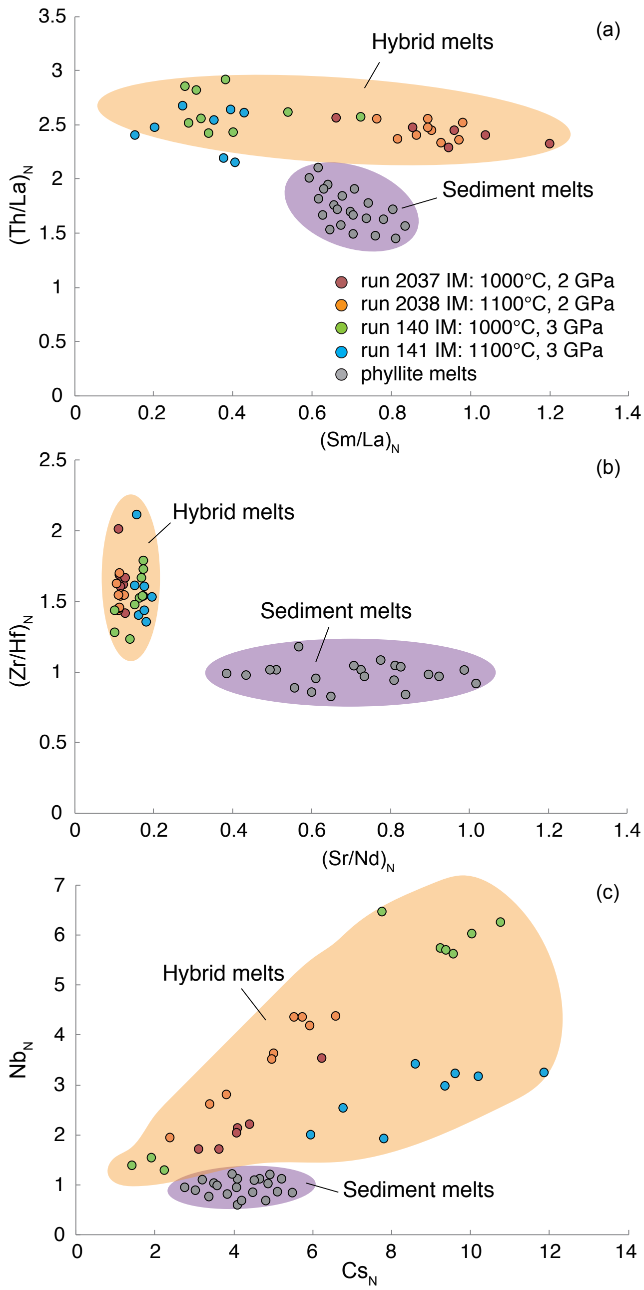


Figure 3. Variations of (a) $(Sm/La)_N$ versus $(Th/La)_N$; (b) $(Zr/Hf)_N$ versus $(Sr/Nd)_N$; (c) Cs_N (ppm) versus Nb_N (ppm) of the experimental melts. Subscript N denotes that the values have been normalised to their corresponding values in the starting materials in order to better reflect enrichment/depletion of key trace elements during melting in experimental runs. IM: intimately mixed runs.

to the higher sediment:peridotite mass ratio (1:1) used in the experiments.

A significant feature of our experimental results is the production of potassium-rich melts in the absence of residual K-rich minerals, which contrasts with most petrogenetic models that invoke phlogopite in the source of potassium-rich rocks. On the basis of previous experiments, phlogopite has been thought to form by interaction of melts with the mantle wedge due to slab-derived fluid/melt migration in the subduction zone.

Our study offers an alternative scenario that contradicts the widely held assumption that phlogopite is a required component in the source of potassium-rich magmas. Our experiments indicate that potassium may be exclusively incorporated in melts during hybridisation between sediment-derived melts and peridotite at shallow lithospheric depths. The potassium content of these melts (~4-5% K_2O) is considerably enriched relative to that in the original phyllite (1.8 wt%) due to the breakdown of phengite in the phyllite, which is the only phase capable of providing a considerable amount of potassium to the whole-rock chemical inventory.

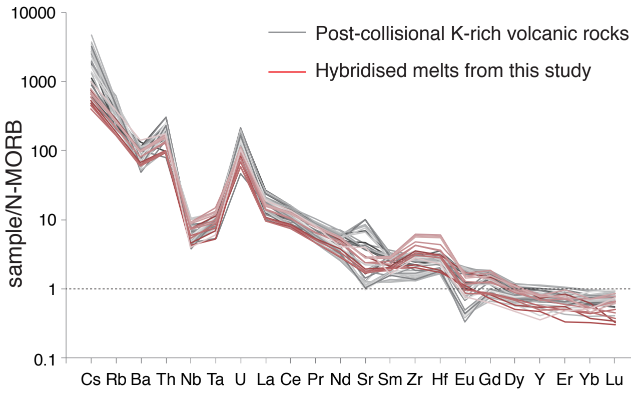


Figure 4. N-MORB normalised trace element compositions of hybridised melts in this study, compared to representative post-collisional K-rich volcanic rocks with K_2O of 3-5 wt%.

The strongly peraluminous (A/(CNK) > 1.25) composition of the hybrid melts may indicate that a phlogopite-free source is most likely for peraluminous K-rich volcanic rocks.

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: Yu Wang, Stephen Foley, Dejan Prelević
Funded by: CCFS Flagship Program 3, iMQRES scholarships, EPS postgraduate funds, Deutsche Forschungsgemeinschaft (DFG)

An increase in the complexity of life across Earth's Great Oxygenation Event

The Earth system fundamentally changed across the Archean-Proterozoic transition, not only the rate and mechanisms of crust formation, but also the composition of the atmosphere-hydrosphere. At about 2.4 Ga, the Great Oxygenation Event (or GOE), caused the irreversible oxygenation of Earth's atmosphere, producing a significant change in a variety of rock types and ore deposits. In addition, this first (but probably not last!), global pollution of the atmosphere by living organisms had a profound impact on life, resulting in the rise of eukaryotic life, with complex cell structures, and the adaptation of prokaryotic life (bacteria) to the new environmental conditions.

Perhaps the best (and only?) place to directly witness the adaptation of life across the GOE is in the Turee Creek Group of Western Australia. Here, a 350 m thick unit of stromatolitic shallow-water carbonate and microfossil-bearing deep-water black chert that was deposited in the immediate aftermath of the GOE contains a variety of evidence for a dramatic increase in the complexity of life. This includes a host of never-before described microfossils from a benthic, deep water, non-phototrophic, community. Previously documented forms are relatively large and filamentous, while the new microfossils include spherical aggregates of cells preserved in ultrafine-grained silica, and very fine filamentous forms that rim other microfossils and degraded organic material and appear to be organotrophs (organisms that harvest hydrogen or electrons from organic substrates).

In the shallow-water carbonate setting, stromatolites display a dramatic increase in morphological variation and complexity compared with any Archean example. This is the first appearance of complex branching forms, and the first occurrence of thick units of clot textured microbialites interbedded with stromatolites. This texture appears to have arisen when floating microbial communities suspended in the water column fell to the seafloor and were quickly cemented in place by coarse, radiating dolomite.

But perhaps the most exciting discovery is the small (up to 1 cm long), hollow, tube-like structures that surround finger-size columnar stromatolites in a unit 15 cm thick. The tube-like structures surround the stromatolites and are attached to them. They have thick, kerogen-rich rims, and hollow cores now filled by fine-grained silica (microquartz), carbonate, and an inner necklace of tiny framboids of highly fractionated ($\delta^{34}S = +22$ ‰) pyrite. These structures most closely resemble primitive calcareous sponges, although a eukaryotic origin has not been proven. Further work - funded by CCFS in 2017 - will investigate the kerogen in an attempt to document what may be the world's oldest eukaryote. See *CCFS Publication #697 Barlow et al., Geobiology, 4, 317-343.*

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

Contacts: Erica Barlow, Georgia Soares, Brendan Nomchong, Martin Van Kranendonk
Funded by: CCFS Flagship Program 4

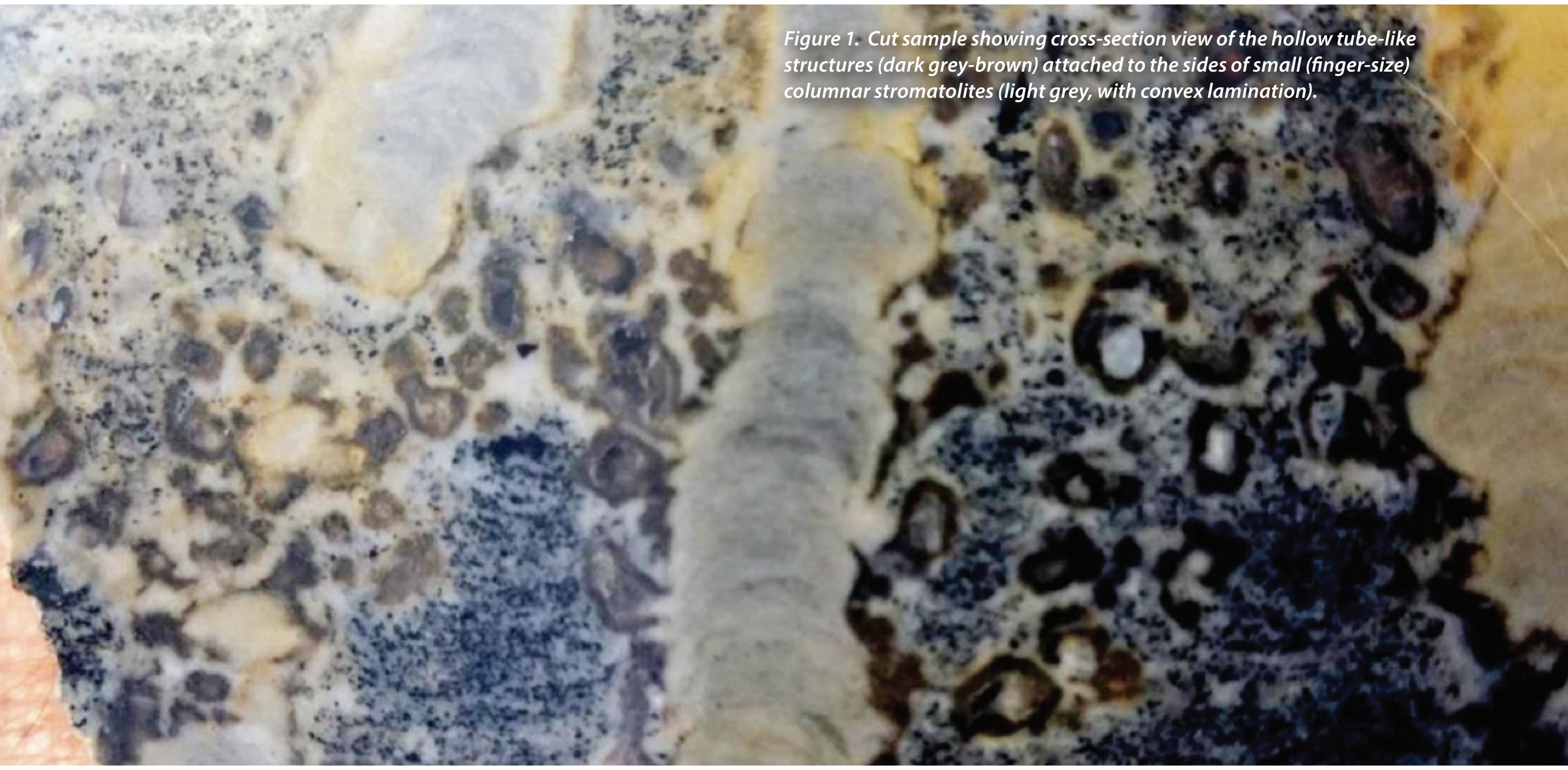


Figure 1. Cut sample showing cross-section view of the hollow tube-like structures (dark grey-brown) attached to the sides of small (finger-size) columnar stromatolites (light grey, with convex lamination).

What is the real S isotope composition of Earth's mantle?

Sulfur isotopes are a powerful geochemical tracer in high-temperature processes, but have rarely been applied to the study of the source and composition of fluids in the deep Earth. The only S-isotope data from the sub-continental lithospheric mantle (SCLM) for the mantle beneath cratons, the most ancient regions of Earth's continents, are from sulfide inclusions in diamonds. To provide new constraints on the S isotope composition of the SCLM and on the source(s) of mantle metasomatic fluids beneath the diamondiferous Kimberley region (South Africa), a research team led by ARC DECRA Fellow Andrea Giuliani and ARC Future Fellow Marco Fiorentini investigated the S isotope systematics of metasomatised (i.e. fluid-enriched) mantle xenoliths (i.e. fragments) transported to surface by the Bultfontein kimberlite (Kimberley, South Africa).

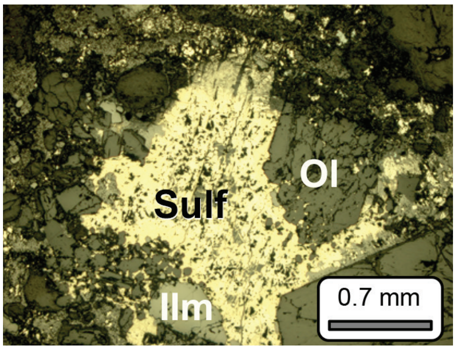


Figure 1. Photo-micrographs of sulfide aggregate in Bultfontein mantle xenolith.

Different types of sulfides (pentlandite and chalcopyrite) in these xenoliths were analysed by *in situ* secondary-ion mass spectrometry (SIMS), while bulk-rock material was analysed by gas source isotope ratio mass spectrometry techniques. Previous studies have shown that these xenoliths experienced different types of metasomatism at distinct times (~180 and ~90-80 Ma). Pentlandite grains are variably altered to heazlewoodite (Ni sulfide) + magnetite. The *in situ* S isotope analyses of pentlandite exhibit a relatively restricted range between -5.9 and -1.4‰ $\delta^{34}S$ (compared to VCDT), with no statistically meaningful differences between samples. Chalcopyrite only occurs in one sample and also shows $\delta^{34}S$ values between -5.4 and -1.0‰. The bulk-rock $S_{sulfide}$ isotope analyses vary between -3.4 and +0.8‰ $\delta^{34}S$. Importantly, the only sample hosting dominantly fresh sulfides shows a bulk-rock $\delta^{34}S$ value consistent with the mean value for the sulfides, whereas the other samples exhibit higher bulk $^{34}S/^{32}S$ ratios (i.e. higher $\delta^{34}S$ values). The differences between bulk-rock and average *in situ* $\delta^{34}S$ values are directly correlated with the degree of alteration of the sulfides. This indicates that the high $^{34}S/^{32}S$ ratios in the bulk samples are not due to the introduction of heavy S (commonly as sulfates)

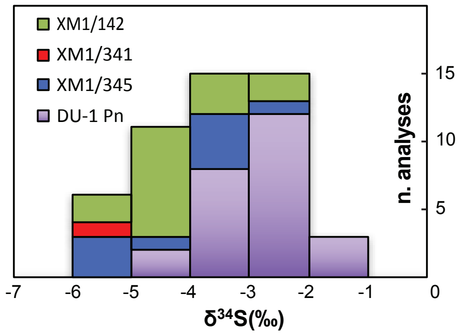


Figure 3. In situ sulfur isotope (‰ $\delta^{34}S$ relative to VCDT) analyses of pentlandite grains in Bultfontein mantle xenoliths. Different colors are used for each xenolith sample.

and are best explained by isotopic fractionation driven by the removal of light S during serpentinisation, when pentlandite is altered to S-poor mixtures of heazlewoodite and magnetite. Available bulk $S_{sulfide}$ isotopic data for SCLM peridotite xenoliths are dominated by positive $\delta^{34}S$ values, which contrasts with the negative values of the sulfides reported in this and previous studies. These results imply that the mantle S isotope values from bulk peridotite samples are commonly modified by isotopic fractionation during serpentinisation. Therefore, the S isotopic composition of the SCLM may require revision.

The limited isotopic variability shown by sulfides in the Bultfontein mantle xenoliths is probably due to intermittent tapping of fluids from a mantle source with a relatively restricted S isotope composition. While the asthenospheric mantle ($\delta^{34}S$ ≤ -1.4‰; *Labidi et al., 2013 Nature, 501, 208-211*) is one candidate, $\delta^{34}S$ values as low as -5.9‰ suggest input from recycled crustal material in the mantle. This recycled material could be represented by the sulfur reservoir with negative $\delta^{34}S$ that is missing in the >500 Ma sedimentary record (*Canfield, 2004, American Journal of Science, 304: 839-861*), which was subducted and mixed with ambient material in the Earth's deep interiors. This study highlights the importance of S isotope geochemistry to trace the source of fluids in the mantle.

See *CCFS publication # 789 Giuliani A., Fiorentini M.L., et al., Earth and Planetary Science Letters, 445, 114-124.*

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

Contacts: Andrea Giuliani, Marco Fiorentini
Funded by: ARC DECRA, ARC Future Fellowship

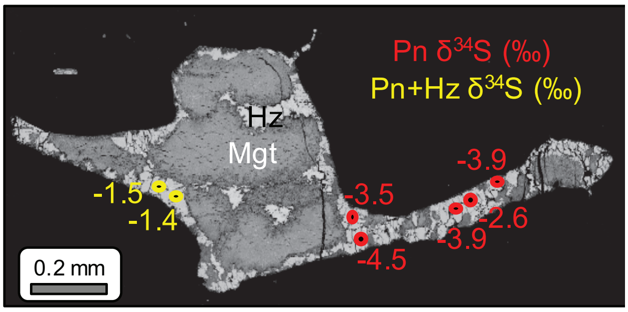


Figure 2. SEM-EDS image of sulfide grain in sample XM1/345 from Bultfontein showing $\delta^{34}S$ variations (as ‰ units) measured by SIMS. Values reported in yellow represent mixtures of pentlandite and heazlewoodite and are not considered quantitative because the instrumental fractionation factor for heazlewoodite is unknown. (Mgt: magnetite; Hz: heazlewoodite)

Zircon - a pathfinder for porphyry Cu ± Mo ± Au deposits

Porphyry Cu (±Mo ±Au) deposits supply nearly ~70% of the world's Cu, ~50% of its Mo, and ~25% of its Au. This type of mineral deposit mainly occurs in the circum-Pacific and Alpine-Himalayan mountain belts (Fig. 1). Discovery of new deposits is costly and challenging, and industry urgently needs tools for chemical fingerprinting or fertility assessment of potential exploration targets.

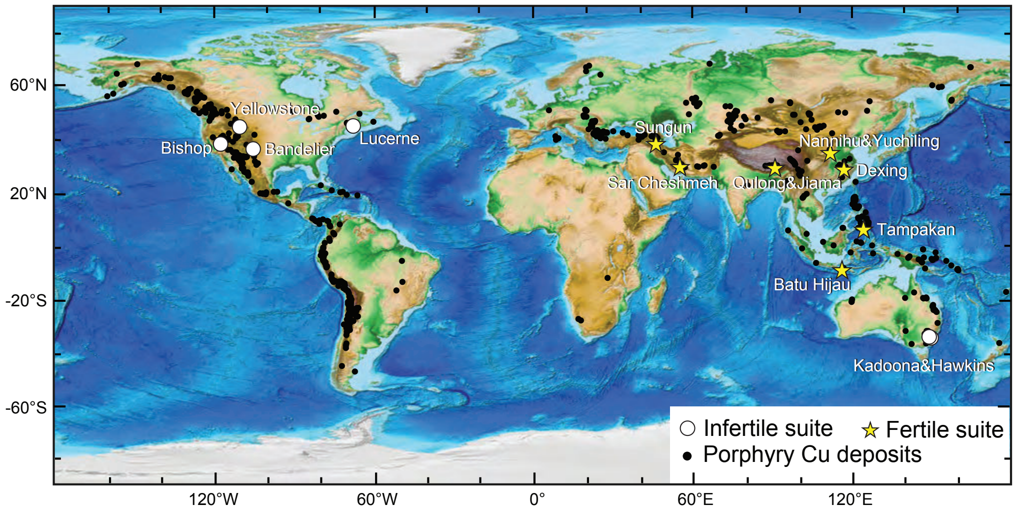


Figure 1. Map showing the worldwide distribution of porphyry Cu deposits, and the fertile and infertile magmatic suites investigated in this study.

Zircon ($ZrSiO_4$) is ubiquitous in Cu-ore-forming magmatic suites and records the compositional evolution and varying conditions of the parent melt. Zircon also survives intense hydrothermal alteration and weathering and long-distance detrital transport. It is now economically feasible to do rapid, precise characterisation of the chemistry of detrital zircons by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) to see whether a watershed contains eroding igneous rocks that might carry Cu ± Mo ± Au deposits.

We have investigated integrated LA-ICPMS U-Pb dating and trace-element analysis of zircon from infertile and fertile magmatic suites to see if there is a distinct zircon chemistry diagnostic of ore fertility of the parent magma (Fig. 1). The infertile suites are defined as magmatic rocks that have no mineralisation at any grade, whereas fertile suites refer to the intrusions related to porphyry-type ore deposits. The infertile suites are relatively reduced S- and A-type and relatively dry A- and I-type magmas, including the Yellowstone rhyolite (Wyoming), Bandelier rhyolite (New Mexico), Bishop tuff rhyolite (California), Lucerne reduced granite (Maine), and Hawkins S-type dacite and Kadoona I-type dacite (Lachlan belt, Australia). The fertile suites are more oxidised and hydrous and are selected from representative I-type intrusions related to porphyry and high-sulfidation epithermal Cu-Au deposits (Batu Hijau, Indonesia and Tampakan, Philippines), porphyry Cu-Mo-Au deposits (Sar Cheshmeh, Iran, Dexing, eastern China and Jiama, southern Tibet), porphyry Cu-Mo deposits (Sungun, Iran, and Qulong, southern Tibet), and porphyry Mo deposits (Nannihu and Yuchiling, central China).

The best fertility indicators are zircon Eu/Eu* and (Eu/Eu*)/Y ratios (Figs. 2 and 3). In particular, zircons from fertile magmatic suites have collectively higher zircon Eu/Eu* ratios (>0.3), 10,000*(Eu/Eu*)/Y (>1), and (Ce/Nd)/Y (>0.01) ratios than infertile suites. In fertile suites, zircon (Eu/Eu*)/Y ratios are positively correlated with (Ce/Nd)/Y ratios, but this correlation is absent in the infertile suites. These distinct trace element ratios are interpreted

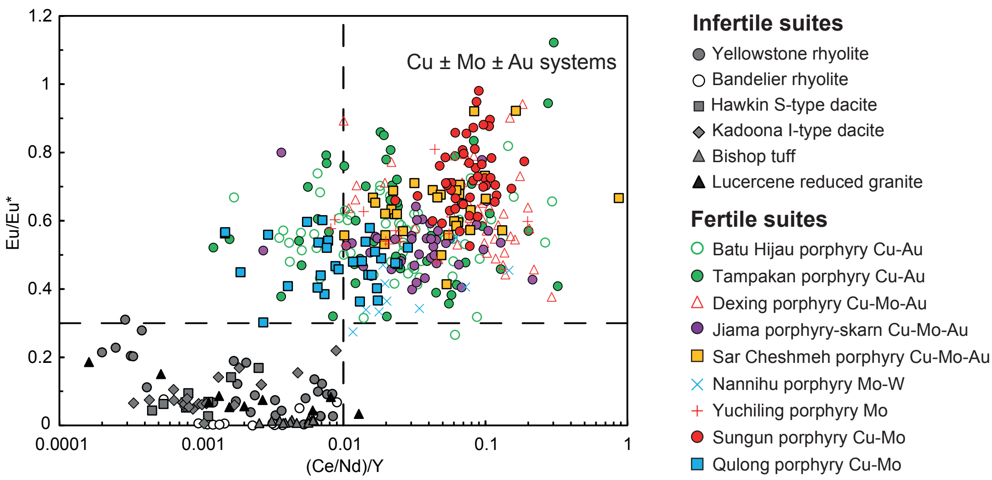


Figure 2. Zircon Eu/Eu versus (Ce/Nd)/Y plot. Eu/Eu* is europium anomaly, calculated as [Eu]/sqrt([Sm]*[Gd]) using concentrations already normalised to chondrite. Fertile suites have distinctly higher zircon Eu/Eu* values (>0.3) and (Ce/Nd)/Y ratios (>0.01) than infertile magmatic suites due to high magmatic water contents in the ore fertile suites.*

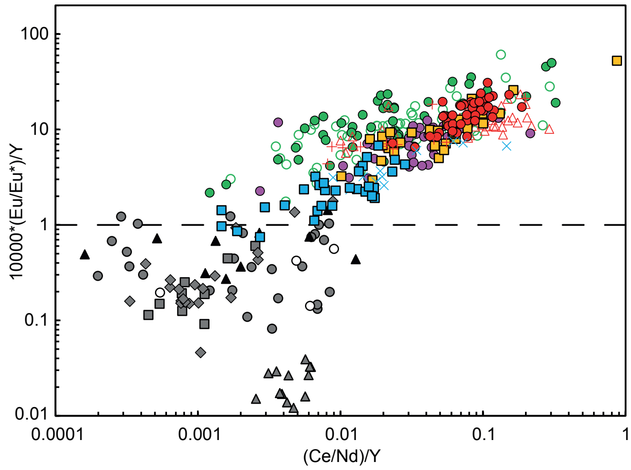


Figure 3. Zircon 10,000(Eu/Eu*)/Y versus (Ce/Nd)/Y plot. Fertile suites have distinctly higher zircon 10,000*(Eu/Eu*)/Y ratios (>1) and (Ce/Nd)/Y ratios (>0.01) than infertile magmatic suites due to high magmatic water contents in the ore fertile suites. See legend, Figure 2.*

to indicate a specific differentiation trend (suppression of plagioclase fractionation and enhanced early amphibole fractionation), the result of high magmatic water contents, which are a prerequisite for magmatic-hydrothermal (porphyry) ore formation. These zircon trace element ratios can identify magmatic suites that are potentially fertile for porphyry Cu-Au, porphyry Cu-Mo-Au, porphyry Cu-Mo, and porphyry Mo (-W) systems.

Combining all these zircon fertility indicators, it is possible to screen terranes or arc segments and distinguish those with unprospective A-, S-, and I-type granitoids from those with potentially mineralising I-type granitoids. Analysing detrital zircons from an area with little geologic information or poor outcrop could efficiently and cheaply identify drainages dominated by fertile I-type granitoids, so exploration could be focused on the most prospective areas.

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

Contacts: Yongjun Lu, Robert Loucks, Marco Fiorentini, Cam McCuaig, Chris Kirkland, Luis Parra-Avila
Funded by: CCFS Flagship Program 2; CCFS Tibet pilot project

The giant sudoku of early Earth - a new solution?

The 2.0 - 1.8 Ga time interval in Earth's history is marked by globally widespread orogeny. These events accompanied the assembly of previously dispersed microcontinents and formed large cratons such as Laurentia (the cratonic part of North America), Baltica (East Europe), Siberia, Australia and Kalahari, and the accretionary growth of others (e.g. Amazonia). Most of these and other protocontinents then collided to form the Paleo-Mesoproterozoic supercontinent Nuna. The timing of the final assembly of Nuna is still debated, but broadly considered to be between 2.0 and 1.6 Ga.

Two key members of Nuna - Laurentia and Baltica, are proven to be mainly assembled and remained together between 1700 and 1270 Ma. Paleomagnetic data clearly indicate that Fennoscandia (the northern part of Baltica) joined Laurentia at about 1775 Ma, but the details of assemblies and eventual collision of these key members is still unclear. Our new 1975 Ma paleomagnetic data from Russian Karelia, together with previously published coeval paleopoles from Superior and Slave cratons (building blocks of Laurentia) throw some new light on this story.

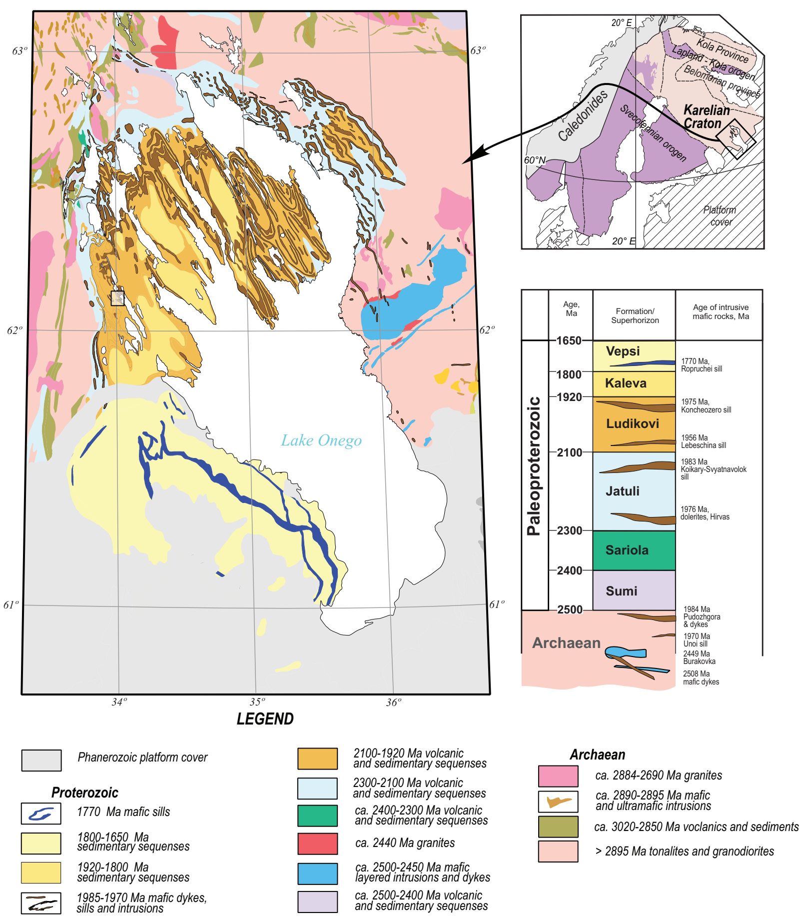


Figure 1. Geological map of the Onego Lake area.


Figure 2. 1975 Ma mafic dyke.

This study was done in collaboration with Natalia Lubnina (Moscow State University), Alexandra Stepanova and Svetoslav Sokolov (Karelian Research Center), and Svetlana Bogdanova (Lund University).

We studied well-dated 1785-1770 Ma mafic dykes and sills near the coast and on the islands of the Onego Lake in Russian Karelia (Figs. 1 and 2). Our study revealed a stable primary paleomagnetic remanence supported by several robust contact tests. Based on our new 1975 Ma Fennoscandian key paleopole and published poles from other cratons, we propose a paleomagnetically and geologically allowable 1975 Ma paleogeographic reconstruction of the Karelia (pre-Svecofennian Fennoscandia), Superior, Slave, Rae, Hearne and Amazonia cratons (Fig. 3). We conclude that at 1975 Ma all these cratons were widely separated by proto-oceans. In particular, the Karelia, Superior and Slave cratons were located at significantly different paleolatitudes, and their mutual azimuthal orientations require significant rotations before their final assembly at 1775 Ma (Fig. 3). This implies that the amalgamation of the Paleo-Mesoproterozoic supercontinent Nuna probably started after 1975 Ma.
See *CCFS publications #309, 882*.

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

Contact: Sergei Pisarevsky
Funded by: CCFS Flagship Program 5

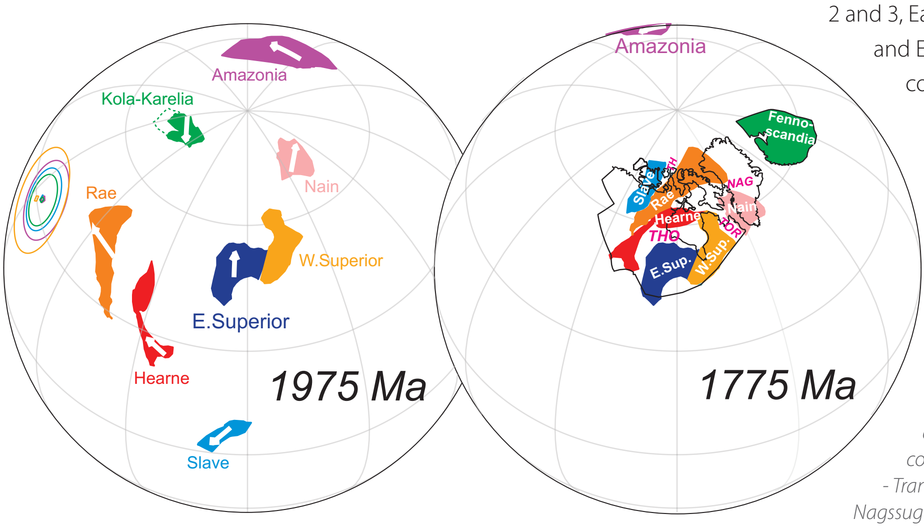


Figure 3. Paleogeographic reconstructions at 1975 Ma and 1775 Ma in Laurentian coordinates. 1.9-1.8 Ga orogens: THO - Trans-Hudson; 427 TOR - Torngat; NAG - Nagssugtoqidian; TH - Thelon.

Diamond formation caught *in flagrante delicto*

Gem-sized diamonds record a long history of growth and dissolution, resulting in complex zonation patterns that can be visualised by cathodoluminescence imaging. In contrast, polycrystalline diamonds form very rapidly, presenting snapshots of extreme conditions of diamond formation that complement our more time-integrated perspective of diamond growth derived from slowly grown gem-sized diamonds.

Polycrystalline diamonds are aggregates of diamond crystals with heterogeneous grain sizes and random orientation. They are found together with gem-sized diamonds in kimberlites in Africa and Siberia and can locally amount to *ca* 20% of the total diamond production.

The diamond aggregates can have up to 30% porosity, indicating they formed from a volatile-rich medium strongly oversaturated in carbon. Evidence from this diamond species emphasises the importance of redox gradients for the formation of diamond in the Earth's mantle. Recently we had the opportunity to study a sample from the Orapa Mine in Botswana using a novel microanalytical method called Transmission Kikuchi Diffraction. This method allows analysis of the structural and crystal orientation of mineral grains as small as some tens of nanometres (one nanometre is one billionth of a metre). It was the first time this method, developed in the material sciences, was applied to a natural rock sample.

A 150 nanometre thin foil, cut from the sample by Focused Ion Beam milling, transected one of the diamond crystals and the minerals included in that crystal (Fig.1). These inclusions were two iron sulfide crystals, one of which was rimmed by tiny grains of iron oxide (magnetite, Fig. 2). Iron oxide also occurred as larger grains in other parts of this sample, but its association with iron sulfide was only revealed in this area.

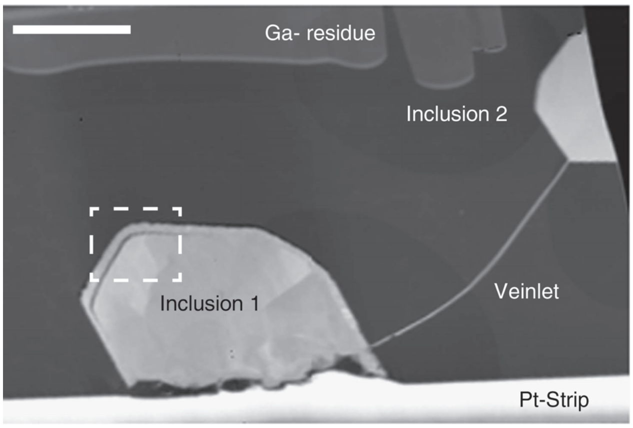


Figure 1. Overview of the iron sulfides included in diamond. A 150 nanometre thin foil cut by focused ion beam milling shows the host diamond with two iron sulfide inclusions connected by a veinlet of iron sulfide. The foil is covered by a protective Platinum strip (bottom) and displays some gallium residue from milling. Scale bar is 2µm.

Our Transmission Kikuchi Diffraction analyses showed that the crystal lattices of all three minerals, diamond host, iron oxide rim and iron sulfide grain, were systematically aligned. This phenomenon, termed epitaxy, is evidence that during their formation, each of the minerals nucleated and grew on the surface of the other. This is the first time the phenomenon has been documented in a diamond sample from the Earth's mantle and reveals that the trigger for the growth of the diamond lies in the redox (reduction-oxidation) reaction of carbonate (in a fluid) with iron sulfide to form iron oxide and diamond.

The most effective redox couple in the Earth's mantle is carbon and iron, which controls the onset of carbonate melting at depth by reduction of Fe^{3+} and oxidation of graphite or diamond. Conversely, oxidation of Fe^{2+} may lead to the freezing of mobile carbon species in the form of graphite or diamond. Iron (Fe^{2+}) sulfides in the Earth's mantle thus represent a reservoir with considerable redox potential. While sulfide is generally rare in the mantle, billions of years of subduction have created patches highly enriched in crustal material that contain abundant sulfides, carbon and volatiles and provide a very reactive environment in the Earth's mantle. One of these rarer patches seems to have been sampled by the kimberlites of the Orapa diamond mine.

Further investigation of the iron oxide grains rimming the iron sulfide could pin down the depth of this diamond-forming reaction to the base of the lithospheric root of the Kaapvaal craton (~180 km depth), because the grains preserve a *'memory'* of a phase transformation from a high-pressure modification of iron oxide.

Another important result from the use of the Transmission Kikuchi Diffraction method is that the iron sulfide grains were mechanically deformed, while the diamond hosting these inclusions was undeformed. This can only be explained if the iron sulfide grains were already crystallised and solid when the diamond included them, rather than liquid melt droplets. It appears therefore that pre-existing iron sulfide grains reacted with a carbonate-rich fluid or melt to form both a thin rim of iron oxide around the iron sulfides, and the enclosing diamond.

Unravelling the ages of diamonds relies entirely on the assumption that the inclusions in them, which are used for radiogenic isotope dating, are syngenetic to the diamond host. Our observations show that the iron sulfides predate the diamond and it is unclear how much time lies between the formation of the two minerals. This finding raises questions about some widely accepted concepts that need to be addressed in the future. See *CCFS publication #716, Jacob et al., Nature, 7, 11891, 2016.*

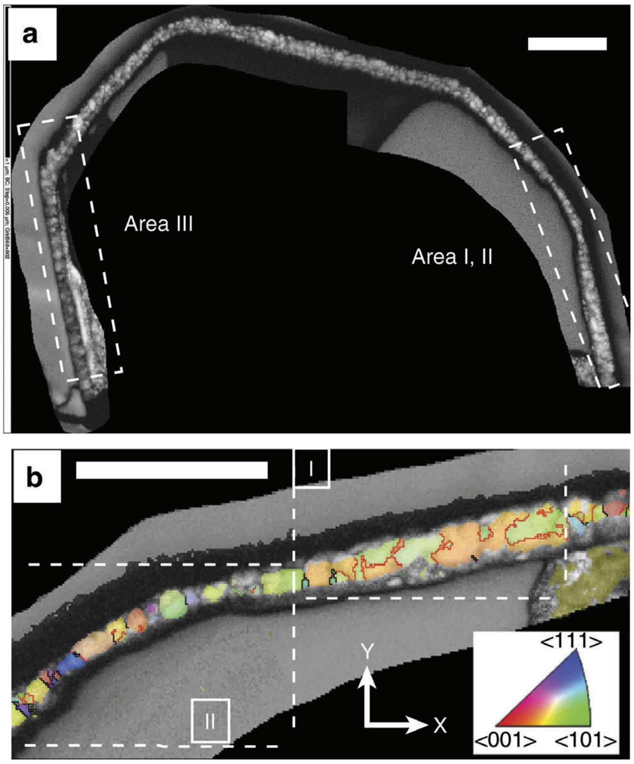


Figure 2. Crystallographic analysis of the iron oxide corona. Forescatter electron image of the iron oxide corona. Note that most of the iron sulfide was lost during re-thinning. The crystallography of areas I, II and III was further analysed. Scale bar is 0.5 µm.

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

Contact: Dorrit Jacob
Funded by: CCFS Pilot Project "Diamond growth at the nanoscale - Mantle fluids at work"

Birdshot on Mt Carmel: Immiscible metal, metal-oxide and silicate melts

Aggregates of hopper-formed corundum crystals (Carmel Sapphire) are common in Cretaceous pyroclastic ejecta exposed on Mt Carmel (Israel). Melt pockets trapped within and between corundum crystals contain mineral assemblages (SiC (moissanite), Fe-Ti-Zr silicides/phosphides, native V) that require high T and extremely low fO_2 (IW -10). Paragenetic studies suggest that the corundum and low fO_2 reflect interaction of mafic magmas with mantle-derived (CH_4+H_2) at high fluid/melt ratios, leading to progressive reduction and desilication of the magma, and ultimately to Al_2O_3-supersaturation, the rapid growth of corundum, and the deposition of abundant amorphous carbon. This evolution included several stages of liquid-liquid immiscibility.

Spherical to drop-shaped metal-rich pellets from <100 μm to several mm in diameter are common in the pyroclastics, and appear to be melts separated from basaltic magma. They comprise Fe alloys, two types of metal-oxide melts, and a Fe-K-rich silicate melt. Pellets of different types and sizes may be stuck together (Fig. 1), suggesting the collision of melt droplets. Most pellets are vesicular, and in many a large central void makes up most of the drop. These structures suggest that the initial melts contained high levels of volatiles (type unknown) that exsolved as the melts cooled, and were trapped inside the solidified outer shell. Four general types can be identified.

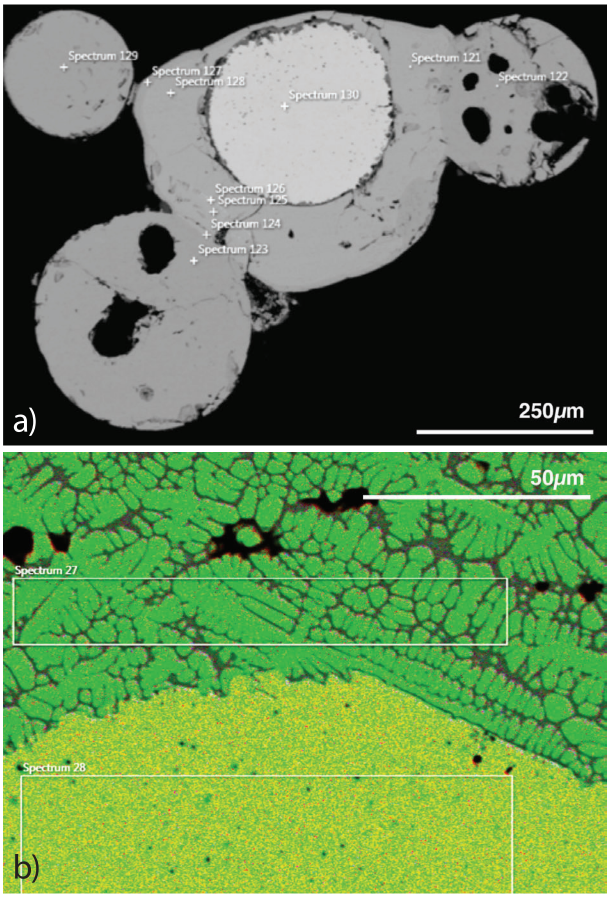


Figure 1. (a) Fe ball surrounded by shell of FeO-rich oxide melt; attached smaller balls are FeO-rich and TiO-rich melts with vesicles. (b) EDS image of Fe distribution at contact, showing dendritic crystals of FeO in a silicate-rich matrix (dark).

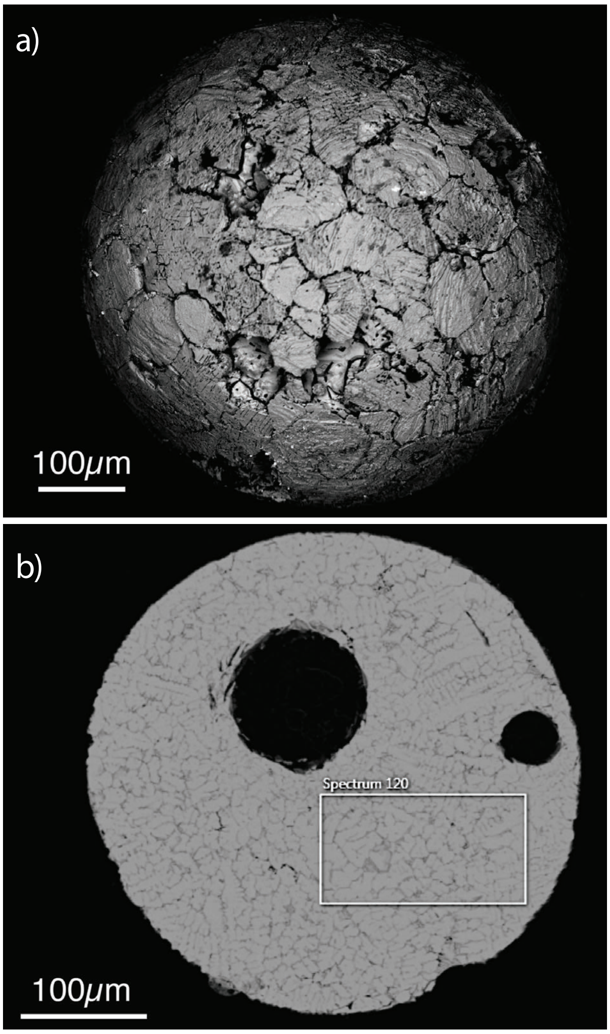


Figure 2. FeO-rich ball (a) surface showing plates made up of FeO crystals in matrix of glass richer in Si, Al, Ca; (b) polished section showing vescicles, and dendritic crystals of FeO in silicate-rich matrix.

1. Fe melts: Generally ca 90% Fe, but some contain much higher Mn, Cr and Ni. Many contain micro-inclusions of type (2) below; they are typically rimmed by types (2-4) (Fig. 1, 4).
2. Fe-oxide melts: Example: SiO_2 6%, TiO_2 2%, Al_2O_3 2%, MgO 1%, FeO 87%, CaO 1.5 %. These typically consist of skeletal crystals of stoichiometric FeO (at % Fe= 50-55%), in a matrix enriched in Si, Al, Mg and Ca, apparently glassy; they commonly have a core of type 1 (Fig. 2).

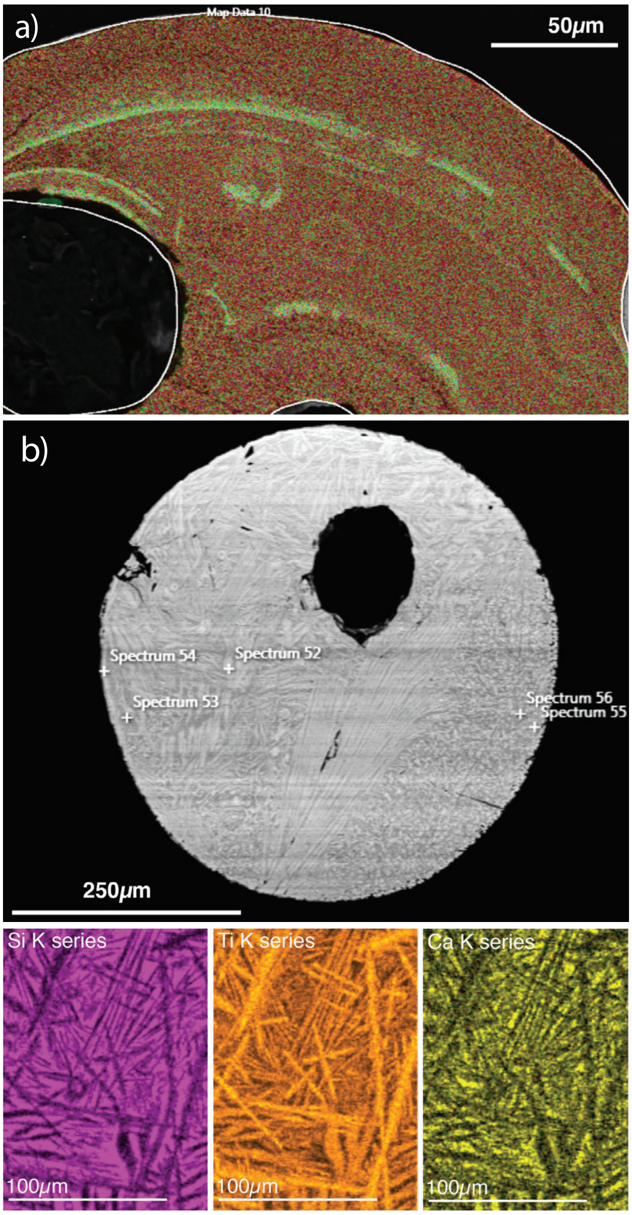


Figure 3. TiO-rich balls (a) EDS phase map of fine-grained ball, showing Liesegang-type zoning around vescicles. Light bands are rich in Ca and W. (b) TiO-rich ball with radiating crystals of $FeTi_2O_5$ (ferro-pseudobrookite) in Si-Ca-rich matrix.

3. Ti-oxide melts: Either very fine-grained, with internal bands suggestive of Liesegang rings (Fig. 3a) or quenched to long blades of $FeTi_2O_5$ in a matrix enriched in Si and Ca (Fig. 3b).
4. Iron-rich silicate glass: Extremely vesicular (Fig. 4), heterogeneous with Liesegang-ring zoning around vesicles and balls of types 1-3. Mean composition SiO_2 40%, TiO_2 1%, FeO 30%, MnO 11%, Na_2O 2%, K_2O 14%.

We suggest that these pellets were formed when fO_2 dropped to the Iron-Wustite boundary, resulting in the separation of mutually immiscible melts from the host magma. The vesicular nature of the oxide balls, coupled with the other data on the corundum system, suggests that mantle-derived methane ($\pm H_2$) provided both the reducing power, and the abundant gasses, through reactions such as 4FeO (melt) + CH_4 → 4Fe + CO_2 +$2H_2O$ and Fe_2O_3 + CH_4 → 2FeO +CO_2 +H_2O. This immiscibility played an important role in the further development of the Mt Carmel magmatic system toward final desilication and super-reduction: none of the silicate or oxide phases in the corundum aggregates contain Fe, because most of it had been removed earlier.

A similar model has been proposed by Grebnikov et al. (*2012; J. Volcanol. Seismol. 6, 211-229*) to explain Fe-cored Fe-oxide balls (our type 2) in Yakutian ignimbrites.

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, Jin-Xiang Huang, Sarah Gain
Funded by: CCFS Flagship Program 1 (TARDIS II)

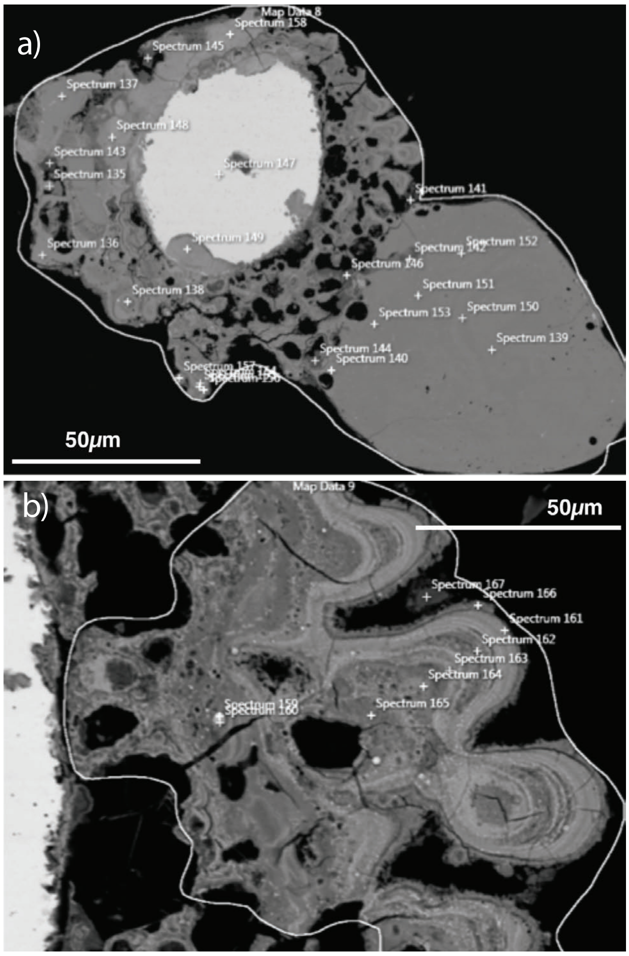


Figure 4. Silicate-metal-oxide melts. (a) BSE image, Fe ball surrounded by vesicular Fe-Mn-Si-K glass; attached ball is TiO-rich type 2. (b) Closeup of silicate glass, showing zoning around vesicles. Lighter bands are richer in Fe+Mn, lower in Si+K.

Sulfur-loving elements in meteorites from Mars probe the extra-terrestrial mantle?

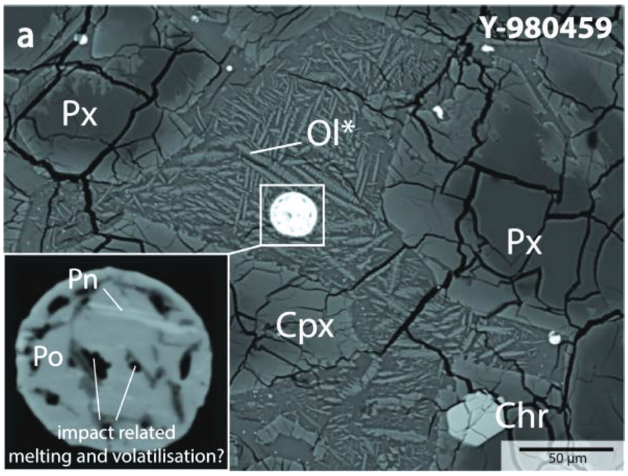


Figure 1. BSE image of a blebby (quench) sulfide assemblage in the fine-grained and plagioclase-free silicate mesostasis of Y-980459. Cpx = clinopyroxene, Chr = chromite, Ol = dendritic olivine, Po = pyrrhotite, Px = pyroxene.*

The Martian mantle is not available for direct sampling, but shergottite meteorites are thought to be derived from Mars; they can provide information on the chemical/petrological properties of Martian mantle reservoirs and igneous rocks. Whole-rock analysis of shergottites for Se and Te, as well as the highly siderophile elements (HSE) Au, Re, and PGE (Os, Ir, Ru, Rh, Pt, and Pd), led to the hypothesis that these elements were stripped from a magma ocean by Fe-Ni liquids at intermediate mantle pressures (~14 GPa).

Selenium, Te and HSE behave as chalcophile elements at redox conditions outside the stability field Fe-Ni metal. Hence, in Mars' mantle and derived magmas, sulfides may exert a major control on these elements, while PGE may also form discrete minerals (e.g. platinum group-minerals, PGM). However, the magmatic Fe-Ni-Cu sulfides contained in shergottites were not yet analysed by high-precision techniques, and no PGM were observed to date. Therefore, we acquired the first LA-ICPMS trace-element analyses on sulfides from selected high-Mg# olivine-phyric shergottites depleted in incompatible trace elements (ITE-depleted; Y-980459, DaG 476 and Dhofar 019), and one ITE-enriched, low-Mg# basaltic shergottite (Zagami).

The shergottite sulfides generally occur in spherical to ellipsoidal, and/or multiply lobed droplets usually ≤50 µm in size. Their pyrrhotite-dominated mineralogy (Fig. 1) is consistent with their *in situ* crystallisation from Ni- and Cu-poor immiscible sulfide melts, in which exsolution of Cu-sulfide and pentlandite was largely suppressed. However, magmatic characteristics have been variably masked by alteration on both Mars and Earth, as well as impact-related sulfide volatilisation during meteorite ejection. The small grain sizes and complex sulfide exsolution textures mean that individual sulfide phases cannot be resolved (Fig. 1), so the LA-ICPMS analyses represent the composition of the bulk sulfide.

The sulfide PGE-signatures mimic available whole-rock analyses, with CI-normalised patterns that increase in steepness with decreasing whole-rock Mg#, a signature of magmatic differentiation (Fig. 2a and Fig. 2b). While these variations suggest major sulfide controls, the Pt-depletions in sulfides may relate to the predominance of (nano-scale) Pt-Fe alloys in FeO-rich and reduced Martian magmas. Positive correlations exist between total Se, Te and HSE (particularly Pd) in sulfides, and whole-rock Mg# in the order Y-980459 >DAG 476 >Dhofar 019 (Fig. 3a). Notably, these trends are even preserved following recalculation to whole-rock concentrations on the basis of bulk sulfur analyses (Fig. 3b).

These results provide insights on siderophile-chalcophile element transfer in FeO-rich shergottite magmas. No whole-rock Te data exist to date, and previous whole-rock HSE concentrations have been questioned because of analytical issues (i.e., nugget effect) in the bulk-rock analyses of small

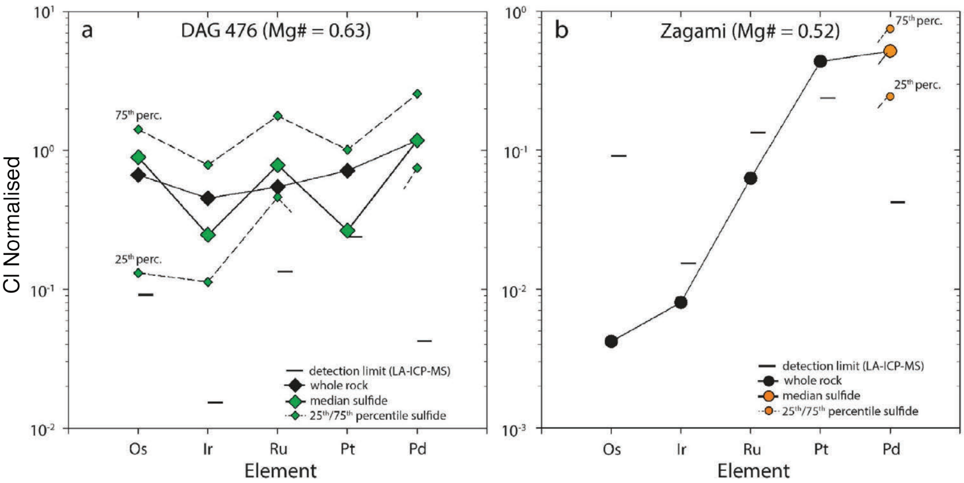


Figure 2. Chondrite-normalised concentration patterns for median PGE values in sulfides from DaG476 (a) and Zagami (b), compared to whole-rock data reported in Brandon et al. (Geochim. Cosmochim. Acta, 2012). The sulfide median and 25th/75th percentile values have been calculated from 22 and 35 single sulfide analyses from DaG 476 and Zagami. In order to improve data comparison, the whole-rock data are recalculated to the chondrite-normalised mean Pd concentrations in sulfides. The main deviations from the trends in whole-rock data are the Pt- (and Ir-?) deficiencies in sulfides, specifically in Zagami where no sulfide was found to contain Pt above detection limit.

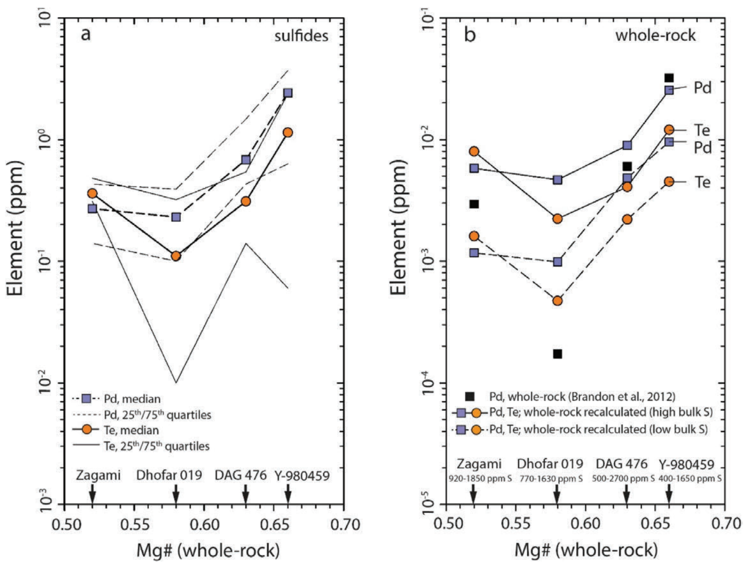


Figure 3. Concentrations of Te and Pd versus Mg# in the host rocks: a) sulfides, b) recalculated whole-rock concentrations. The latter are determined by Cwr=(Cs·Swr)/Ss, in which Cs are the median and 25th/75th percentile concentrations in sulfides, Swr is the whole-rock content of sulfur, and Ss is the sulfur content in bulk sulfides assuming troilite stoichiometry (FeS). The lower and upper whole-rock sulfur contents used for calculation are those reported/surveyed in Ding et al. (Earth Planet. Sci. Lett., 2015). Whole-rock concentrations of Pd for the analysed shergottites are taken from Brandon et al. (Geochim. Cosmochim. Acta, 2012).

sample masses. However, our data resolve distinct differences in PGE (particularly Pd) between the respective shergottites (Fig. 3b). Hence, provided that the analysed olivine-phyric shergottites relate to comparable mantle/magma sources, the positive correlations between Mg#, Se, Te and Pd may relate to sulfide immiscibility and fractionation during mantle melting, magma ascent or crystallisation.

In summary, our pilot study provides new insights into the behaviours of chalcogens and highly-siderophile elements in Martian magmas. More *in situ* analyses on sulfides from shergottite specimens may show whether the observed variations in sulfides are a general trend among (ITE-enriched and -depleted) olivine-phyric and basaltic shergottites, and if any such differences may lead to the more detailed understanding of sulfide stability and siderophile-chalcophile element transfer in igneous systems on both Mars and Earth.

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

Contacts: Raphael Baumgartner, Marco Fiorentini
Funded by: CCFS Flagship Program 2

Use and misuse of ilmenite in diamond exploration

Ilmenite is a very common phase in kimberlites and related rocks and, as a consequence, is one of the main kimberlite indicator minerals (KIM) used to locate new targets. Because of its abundance in kimberlites, ilmenite has been investigated for diamond exploration, but its use as diamond indicator mineral (DIM) has been unsuccessful to date.

Complex crystallisation and replacement processes have been previously invoked to explain the compositional and textural variety of ilmenite found in kimberlites. The research presented here was carried out as a collaboration between CCFS, University of Barcelona and the Catoca mine (Angola) and it aims to shed new light on these processes, as well as their implications for diamond exploration. Petrographic studies were combined (for the first time) with major- and trace-element analyses to characterise the ilmenite populations found in xenoliths and as xenocrysts in two Angolan kimberlites (Congo-Kasai craton).

The study of mantle xenoliths already brought to light the complexity of the processes that can be involved in ilmenite formation at depth. In these xenoliths, ilmenite has a wide compositional range. It occurs either as thin veins or as small rounded grains, and may be accompanied by the crystallisation of a variety of metasomatic minerals (i.e. apatite, kaersutite, phlogopite and rutile).

However, ilmenite mainly occurs as individual xenocrysts in the kimberlitic matrix, where it can be found either as Mg-rich ilmenite nodules or as xenocrysts of ferrian ilmenite with hematite exsolution. Likewise, different types of secondary ilmenite were identified, in most cases replacing primary ilmenite grains and/or other titanium oxides: i) symplectitic ilmenite; ii) tabular ilmenite and iii) secondary Mn-rich ilmenite.

The trace-element analysis of ilmenite revealed that populations with the highest Mg contents (i.e. symplectitic, secondary Mg enrichment in the ilmenite nodules) typically show significantly higher contents of HFSE, Cr and V at a given Nb content, and thus diverge from the general trends described for most other ilmenites. These trace-element signatures in the ilmenite nodules, coupled with the co-crystallisation of perovskite, have been interpreted as a result of an interaction with the kimberlitic magma.

A multi-stage model has been proposed to describe the evolution of ilmenite in these pipes involving: i) Crystallisation of ilmenite under different conditions, both in crustal and metasomatised mantle domains; ii) Xenolith disaggregation

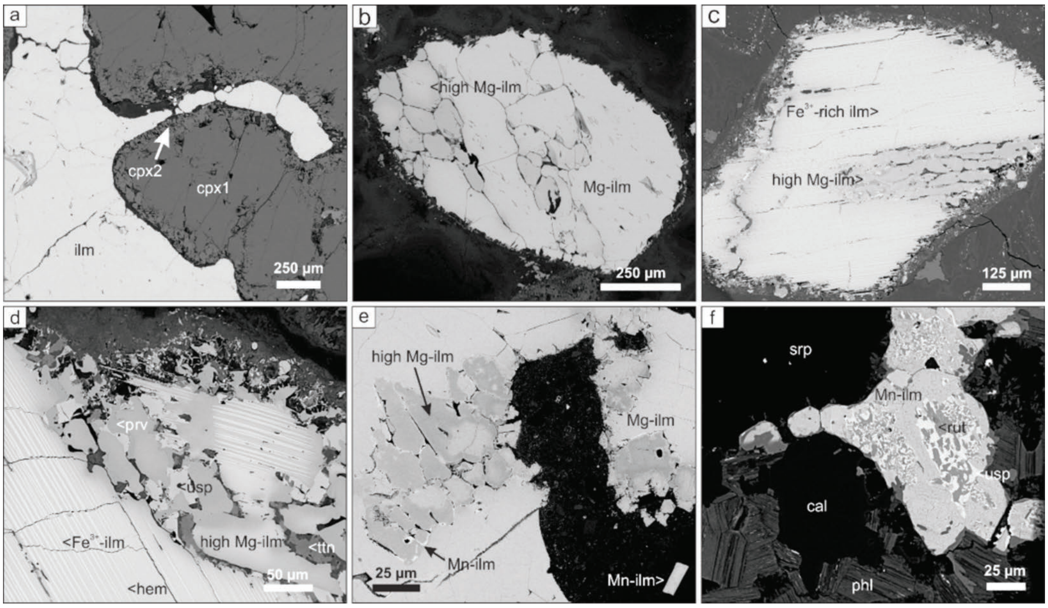


Figure 1. Textural types of ilmenite found in the Angolan kimberlites (BSE images). (a) metasomatic ilmenite in a mantle xenolith, associated with a secondary clinopyroxene (cpx2) replacing an early clinopyroxene (cpx1) and olivine; (b) ilmenite nodule showing recrystallisation and secondary enrichment in Mg set in the kimberlite matrix; (c) Fe^{3+}-ilmenite with fine hematite exsolutions replaced by symplectitic, darker Mg-rich ilmenite, which crystallises along fractures and grain boundaries. Detailed image (d) shows the complex replacement sequence of the symplectitic ilmenite: ulvöspinel (usp), perovskite (prv) and titanite (ttn); (e) nodular ilmenite replaced by Mg- and Mn-rich ilmenite along grain boundaries of the recrystallised grains, together with tabular Mn-rich ilmenite set in the kimberlite matrix; (f) late Mn-rich ilmenite, replacing previous rutile (rut) and ulvöspinel (usp), set in a matrix of serpentine (srp), calcite (cal) and phlogopite (phl).

producing at least two populations of ilmenite xenocrysts differing in composition (Fe^{3+}- and Mg-ilmenite nodules); iii) Interaction of both types with the kimberlitic magma during eruption, leading to widespread replacement by Mg-rich ilmenite along grain boundaries and fractures. These processes produced similar major-element compositions in ilmenites regardless of their primary origin, although in most cases the original enrichment in HSFE (Zr, Hf, Ta, Nb) observed in Fe^{3+}-rich crustal xenocrysts is preserved. Finally (iv) secondary Mn-ilmenite was formed by infiltration of late hydrothermal fluids, followed in some cases by subsolidus alteration in an oxidising environment.

This study has shown that ilmenite genesis is complex and may lead to misinterpretation of the diamond potential of a kimberlite during the exploration stage if textural and trace-element information is disregarded. Secondary Mg-enrichment of ilmenite xenocrysts is common and is unrelated to reducing conditions that could favour diamond formation/preservation in the mantle. Similarly, Mn-rich ilmenite should be disregarded as a diamond indicator mineral, unless textural studies can prove its primary origin.

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

Contacts: Montgarri Castillo-Oliver, Bill Griffin, Norman Pearson, Sue O'Reilly

Funded by: CCFS Flagship Program 1

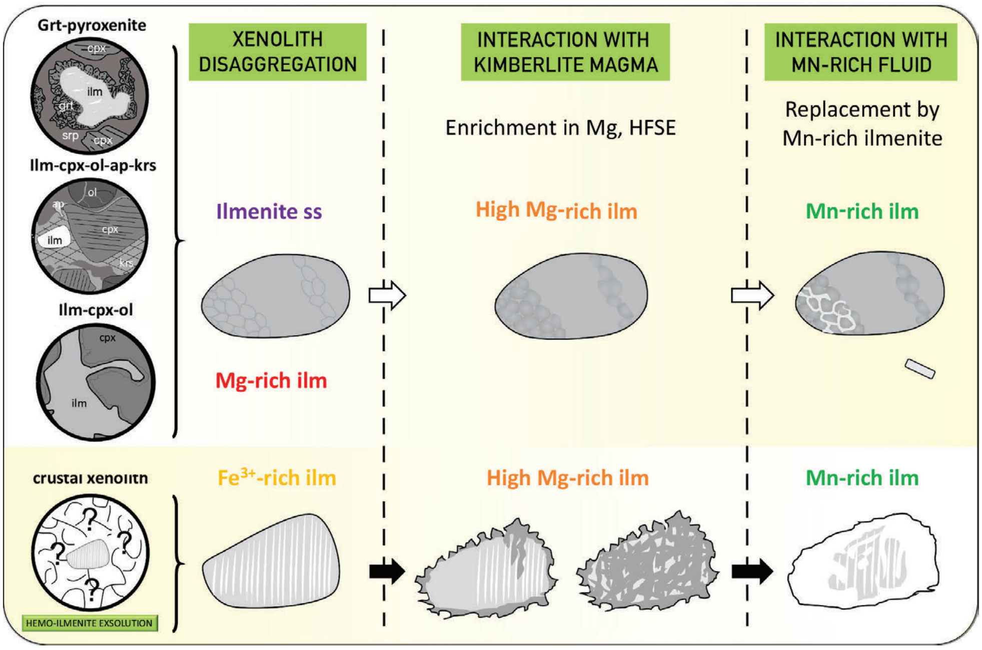


Figure 2. Schematic model of the multi-stage petrogenesis of ilmenite in the studied kimberlites, including the average composition of ilmenite at each stage. Mineral abbreviations: clinopyroxene (cpx), ilmenite (ilm), garnet (grt), serpentine (srp), apatite (ap), kaersutite (krs) and olivine (ol).

Cerium in zircon - serial tracking of mantle controls

Magmas emplaced deep in the Earth's crust cool slowly, and precipitate a sequence of mineral assemblages on the floor and walls of magma chambers. This crystallisation produces residual liquids that are depleted in many elements and enriched in others, relative to the parental silicate melt. In many cases, whether an element is sequestered in early minerals or accumulates in residual melts depends on the oxidation state of the melt, which enhances or hinders the ability of any given magma to produce ore deposits of many elements.

Oxidation/reduction couples that commonly are of petrologic and economic interest include Fe^{3+}/Fe^{2+}, $S^{6+}/S^{4+}/S^{2-}$, Eu^{3+}/Eu^{2+}, Ce^{4+}/Ce^{3+}, $U^{6+}/U^{5+}/U^{4+}$, Mo^{6+}/Mo^{4+}, Sn^{4+}/Sn^{2+}, $V^{5+}/V^{4+}/V^{3+}$, Ti^{4+}/Ti^{3+}, As^{5+}/As^{3+}, Se^{6+}/Se^{2-} and Mn^{3+}/Mn^{2+}.

Determination of the former oxidation state of a magma by chemical analysis of minerals in igneous intrusions is often hampered by subsolidus re-equilibration and/or alteration. The most sensitive and best-calibrated of the igneous mineral oxybarometers currently in use by petrologists - titanomagnetite-hemoilmenite pairs and chromite-bearing assemblages - re-equilibrate within days to weeks at near-solidus temperatures, and are reliable only when used on quickly-quenched volcanic rocks. A problem affects igneous amphibole oxybarometry and hygrometry; as magmas rise to depths <4-5 km, exsolution of H_2O from the silicate melt causes breakdown of amphibole to anhydrous minerals on timescales of days to weeks, and magmatic hornblende is not stable at shallower depths. Consequently, we need other equilibria to constrain fO_2. The potential appeal of a zircon oxybarometer is that chemical diffusion (re-equilibration) in zircon is extremely slow and zircon compositions are unaffected at granitoid magma temperatures at timescales on the order of 10^5-10^6 years.

The Ce^{4+}/Ce^{3+} ratio in zircon and the closely related Ce anomaly, which is commonly denoted Ce/Ce*, are widely used as proxies for the oxidation state of the zircon's parent silicate melt. The ratio U^{4+}/Pr^{3+} involves nearly the same ion sizes as Ce^{4+}/Ce^{3+} in zircon, so the two have similar temperature sensitivity, but opposite responses to redox variation in the parent melt. Plots of these ratio pairs in natural igneous zircon populations show strong positive correlations with slopes near unity, which invalidates their use as magmatic redox indicators (Fig. 1). We conclude that the Ce^{4+}/Ce^{3+} and Ce/Ce* ratios in zircon that are commonly referred to as oxybarometers actually vary in and among zircons chiefly in response to variations in the temperature at which zircon crystallised. Presently available zircon geothermometers are too imprecise to distinguish the small redox effect from the dominant temperature effect in most natural assemblages.

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

Contacts: Robert Loucks, Marco Fiorentini, Bruce Rohrlach (Avalon Minerals Ltd)
Funded by: CCFS Flagship Program 2

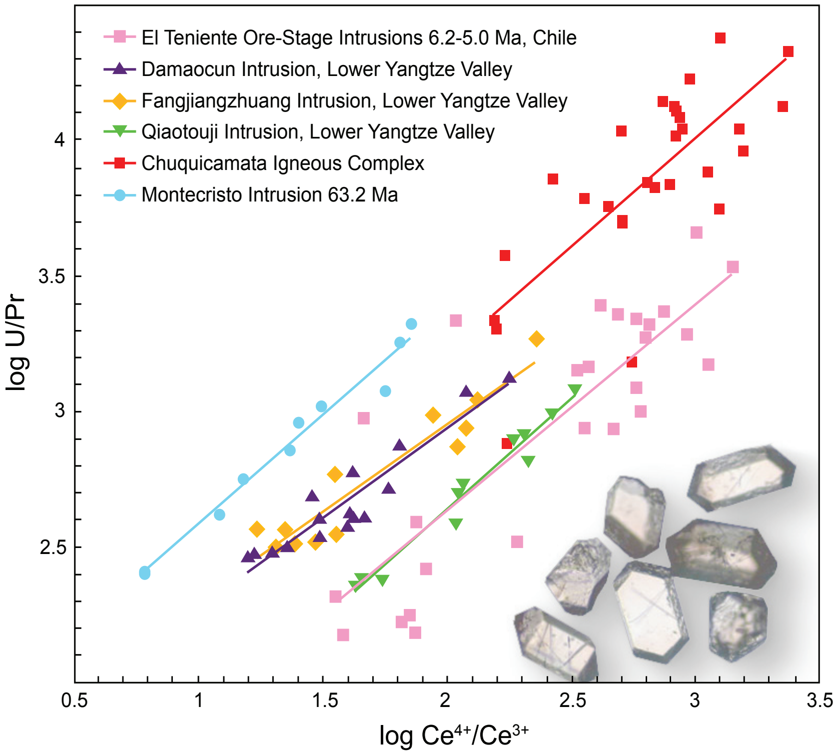


Figure 1. Zircon Ce^{4+}/Ce^{3+} values reported by authors of the source publications are plotted against the U/Pr ratios in those zircons. The zircon/melt partition coefficients of Ce and U respond oppositely to varying magmatic oxidation state, so these strong positive correlations prove that there is no resolvable component of the variation in zircon Ce^{4+}/Ce^{3+} that can be attributed to varying magmatic oxidation state.

CCFS honours & postgraduates

HONOURS

COMPLETED 2016

Wendy Dang: Implications for life on Mars at Gusev Crater and Nili Patera using a terrestrial analogue at the North Pole Dome, Western Australia (UNSW)

Alison Davis delivering her talk at the November 2016 CCFS Research Meeting.

Alison Davis: Emplacement dynamics of the La Balma Monte Capio intrusion, Ivrea Zone, NW Italy (UWA)

Chris Guldbrandsen: The role of microbial precipitation of '*buckshot pyrite*' in the 2.76 Ga Hardey Formation, Fortescue Group, Pilbara, Australia (UNSW) See *p. 114.*

Brendan Nomchong: The origin of clotty-textured (thrombolitic) microbialites at the rise of atmospheric oxygen: The c. 2.4 Ga Turee Creek Group, Western Australia (UNSW) See *Research highlight p. 70.*

Georgia Soares: The developmental significance of stromatolite complexity across the rise of atmospheric oxygen: The c. 2.4 Ga Turee Creek Group, Western Australia (UNSW) See *Research highlight p. 70.*

Eager to hit the hills - Honours students from UNSW; Georgia Soares and Brendan Nomchong (Photo E. Barlow).

Luke Steller: Boron and the origin of life: geochemical analysis of ancient tourmaline crusts, Recent boron-rich muds, and synthesised boron-rich products (UNSW) See *Research highlight p. 66.*

MASTERS OF RESEARCH, MQ

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

COMPLETED 2016

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

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

Mitchell Gerdes: Amphibole and magma evolution: Insights from composite xenoliths from Batan Island, Philippines

CONTINUING 2017

Cameron Brown: The geomechanics of granular asteroids

Harrison Jones: Geophysical and geological study of Silurian base metal occurence

Christopher Corcoran: The relationship between crystal-plastic deformation and chemical variation in peridotites

Hindol Ghatak: The role of fluids in mid crustal shear zones in Central Australia

COMMENCING 2017

Omar Elkhaligi
Michael Farmer
Anthony Finn
Lucas Gamertsfelder
Byron Gear
Tasman Gillfeather-Clark
Stephanie Kovach
Colleen McMahon
Carla Raymond
Luke Smith
Morgan Stewart
Haoming Wu

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 2012-2016. 41 papers with CCFS postgraduates as authors were published in high-profile international journals in 2016, including *Geochemical Perspectives Letters, Gondwana Research, Journal of Petrology, Scientific Reports, Precambrian Research, Earth and Planetary Science Letters, Geology, Lithos, Ore Geology Reviews* and *Chemical Geology.*
78 presentations were also given at 17 international conferences (see *Appendix 6*).

2016 HIGHLIGHTS

Cotutelle student, **Mathieu Chassé**, pictured left, represented the Faculty of Science and Engineering in the September finals of the 2016 MQ 3MT (Three minute thesis) competition with his talk entitled "*Mining our Future*".

Gregory Derring was awarded the "*Best student presentation*" at the 13th Annual International Nickel Symposium.

MRes student, **Hindol Ghatak**, won best poster at the MQ EPS 2016 Seminar Series.

The winner of this year's student poster competition at the CCFS Whole of Centre Meeting was **David Stevenson**, pictured left receiving his award from Sue O'Reilly.

Heta Lampinen won the 2016 DEETalks photo competition in the category "*Earth*". Her winning image, "*Geopaparazzi*", pictured right, was taken in Rio Tinto's Argyle Diamond Mine during the UWA SEG student chapter Kimberley fieldtrip.

CCFS PhD graduate **Chris Grose** gained the "*Seismology Laboratory Director's Postdoctoral Scholar position*", the most prestigious fellowship offered by the Seismological Lab at CalTech. Chris will work with Paul Asimow and Mike Gurnis to develop the first grain-scale non-equilibrium thermodynamic numerical simulations of diffusion, phase transformation, grain coarsening and deformation in the mantle. Eventually, the grain-scale model will be coupled to geodynamic models to produce a next-generation tool for understanding the chemistry, petrology and dynamics of the mantle.

COMPLETED

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

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

Montgarri Castillo-Oliver (PhD): Compositional evolution of indicator minerals: Application to diamond exploration (MQ 2016)

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)

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)

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


"Geopaparazzi", by Heta Lampinen.

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)

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 Fougourouse (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)

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)

Christopher Gonzalez (PhD): CO_2 devolatilisation and its influence on partial melting, subduction, and metasomatism in the mantle lithosphere (UWA 2016)

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)

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)

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

Carissa Isaac (PhD): 4D architecture of the Eastern Goldfields Superterrane in the Yilgarn Craton of Western Australia, in order to constrain the role of the lithospheric structure at 2.7 Ga in the localisation of nickel mineral systems (UWA 2015)

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

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 sulphide 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)

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)

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)

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 sulphide deposit, Western Australia (UWA 2016)

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

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)

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)

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

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

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)

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

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) *Pictured above, left.* See *Research highlight pp. 68-69.*

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

Qing Xiong (PhD): Shenglikou and Zedang peridotite massifs, Tibet (China): Upper mantle processes and geodynamic significance (MQ 2015)

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)

Yu Wang celebrating with his supervisor, Stephen Foley after Yu's Graduation ceremony, April 2016.

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

Sonia Armandola (PhD): Geochronology and geochemistry of accessory phases in basins of the Capricorn Orogen (WA); *CIPRS* (CU, commenced 2016)

Samuel Bain (PhD): Olivine: trace elements and deformation; *APA* (CU, commenced 2016)

David Barbosa da Silva (PhD): Spatial, temporal and metasomatic patterns in hydrous shear zones, Strangways Range, Central Australia (MQ, commenced 2016)

Erica Barlow (PhD): Microfossils of the Paleoproterozoic Turee Creek Group: Biological evolution resulting from atmospheric change?; *APA* (UNSW, commenced 2015) See *Research highlight p. 70.*

Bataa Baatar (MSc): Fertility of the Lock Lilly Belt for porphyry Cu-Au mineralisation - constraints from whole-rock chemistry and zircon studies (UWA, submitted 2016) See *photo p. 94.*

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

Raphael Baumgartner (PhD): Frontiers in mineral exploration: Ni-Cu-PGE sulfide mineralisation on Mars; *IPRS-A* (UWA, submitted 2016) See *Research highlight pp. 78-79.*

Jason Bennett (PhD): Microgeochemistry of cassiterite; *University Postgraduate Award* (UWA, commenced 2015)

Katarina Bjorkman (PhD): Crustal and geodynamic evolution of the Western Superior Craton, Canada using U-Pb, Lu-Hf and O isotopes in igneous zircons from the Marmion terrane; *UWA SIRF-A* (UWA, commenced 2013)

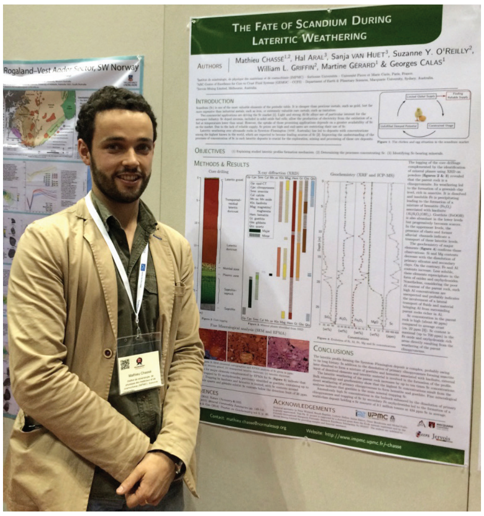
Richard Blake (MPhil): Determining recent organic contamination in ancient rocks (UNSW, commenced 2015)

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

Stefano Caruso (PhD): Geological controls on the fractionation of multiple sulfur isotopes in Archean mineral systems; *SIRF & MRIWA Postgraduate Scholarship* (UWA, commenced 2015) *See Research highlight pp. 64-65*

Julian Chard (PhD): Petrochronology of the Albany-Fraser Orogen and Eucla Basement: mineral scale pathfinders to deposits; *CIPRS* (CU, commenced 2016)

Mathieu Chassé (PhD): Behaviour of scandium from mantle to supergene contexts; *iMQRES, COT* (MQ, commenced 2015) See *photo below and Research highlight p. 40.*



Mathieu Chassé with his poster at the 26th Goldschmidt Conference, Yokohama, Japan, 26 June - 1 July 2016.

Eunjoo Choi (PhD): Alkaline magmatism as a probe into the lithospheric mantle evolution beneath the Yilgarn Craton, Western Australia; *IPRS&APA, MRIWA* (UWA, commenced 2016)

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

Daria Cyprych (PhD): Deformation behaviour of polymineralic rocks: implications for rheology and seismic properties of the middle to lower crust; *iMQRES* (MQ, submitted 2016)

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, commenced 2014)

Tara Djokic (PhD): Visualising early life on Earth: A 4D reconstruction of the Dresser Formation, Pilbara, WA; *APA* (UNSW 2016) See *Research highlight pp. 54-55.*

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

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

Timmons Erickson (PhD): Deformation microstructures in zircon and monazite: implications for shock, tectonic and geochronological studies; *CIPRS* (CU, submitted 2016) *Pictured above.*

Katherine Farrow (PhD): *In situ* melt generation and thermal origin of the Nagadarunga Granite: Implications for the geochronology and tectonic evolution of the eastern Arunta Region, Central Australia (MQ, part time, commenced 2014)

Michael Förster (PhD): Earth's Deep Nitrogen Cycle; IPRS (MQ, commenced 2016)

Robyn Gardner (PhD): Flow behaviour of the middle and lower crust: Insights from field observations and numerical modelling; *APA* (MQ, commenced 2012)

Markus Gogouvitis (MSc): Microstructural analysis of a reef complex across the rise of oxygen (UNSW/Frei Universiteit Berlin, commenced 2016)

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

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

Hadrien Henry (PhD): Mantle pyroxenites: Deformation and seismic implications; *iMQRES, COT* (MQ, commenced 2015) See *Research highlight pp. 55-56.*

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

Constanza Jara Barra (PhD): Gold pathways: in the El Indio Belt, Chile-Argentina; *Barrick Exploration* (UWA, commenced 2015)

PhD student Constanza Jara Barra looking at drillcore from the Savannah Nickel mine of Panoramic Resources during the UWA SEG student chapter Kimberley field trip.

Kim Jessop (PhD): The role of fluids in HTLP metamorphism; *APA* (MQ, commenced 2013)

Jelte Keeman (PhD): Isotope characterisation of detrital zircons across the Delamerian Orogen in South Australia; *APA* (MQ, commenced 2015)

Heta Lampinen (PhD): Defining mineral systems footprints in the Edmund Basin of the Capricorn Orogen; *SIEF* (UWA, commenced 2014)

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

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

Nora Liptai (PhD): Nature of the mantle beneath the Carpathian-Pannonian basin, Hungary - A mantle xenolith study; *iMQRES, COT* (MQ, commenced 2015) See *Research highlight pp. 45-46.*

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; *CIPRS* (CU, commenced 2016) *Pictured right.*

Yebo Liu (PhD): Paleomagnetism of Proterozoic igneous rocks in Australia and East Antarctica: implications for pre-Pangea supercontinents; *CIPRS* (CU, commenced 2015)

Jianggu Lu (PhD): Garnet pyroxenites in southeast Australia: Tracking deep lithospheric events; *iMQRES Cotutelle, China Scholarship Council,* (MQ, commenced 2014) See *Research highlight pp. 62-63.*

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 hafnium isotope arrays; *APA* (CU, commenced 2016)

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

Nicole McGowan (PhD): Messages from the mantle: Geochemical investigations of ophiolitic chromites; *APA* (MQ, submitted 2016)

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

Holly Meadows (PhD): Structure and geochemistry of shear zones in the Capricorn Orogen, Western Australia - Implications for distal footprints of giant ore deposits; *CIPRS* (CU, commenced 2014)

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

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

Stephanie Montalvo Delgado (PhD): Compositional modification in deformed zircon: Insights from Atom Probe Microscopy; *CIPRS* (CU, commenced 2016)

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

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

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

Carl Peters (PhD): Biomarkers and fluid inclusions of early Earth using samples from Australia; *iMQRES* (MQ, submitted 2016)

Zsanett Pintér (PhD): The composition of melts in the incipient melting regime; *MQRES* (MQ, commenced 2016)

Greg Poole (PhD): Permian-Triassic porphyry and epithermal mineralisation in the Cordillera Frontal, Argentina; *APA* (UWA, commenced 2015) *Pictured below.*

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

Valerie Roy (MSc): Hydrogeological and hydrogeochemical study of the Peak Hill-Horseshoe Deposit, Capricorn Orogen to identify mineral system footprints (UWA, sumbmitted 2016)

Farshad Salajegheh (PhD): 3D multivariable probabilistic inversion in spherical coordinate (MQ, part time, commenced 2014)

Sarath-Kumara Samaya-Manthri (PhD): Quantifying the effects of surface and bulk proton transport in mantle materials; *iMQRES* (MQ, commenced 2016)

Vikram Selvaraja (PhD): Multiple sulfur isotopes as a tracer of geological processes; *SIRF/UIS* (UWA, commenced 2014) See *Research highlight pp. 58-59.*

Liene Spruzeniece (PhD): Fundamental link between deformation, fluids and the rates of reactions in minerals; *iMQRES* (MQ, submitted 2016)

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

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

Jack Stirling (MSc): Geochronology of lower crustal cumulate complexes in the Kohistan Terrane, North-East Pakistan; *UPA* (UWA, submitted 2016)

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

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

Romain Tilhac (PhD): Petrology and geochemistry of pyroxenites from the Cabo Ortegal Complex, Spain; *iMQRES Cotutelle* (MQ, submitted 2016) See *Research highlight pp. 55-56.*

Mehdi Tork Qashqai (PhD): Multi-observable probabilistic inversion for the thermochemical structure of the lithosphere; *iMQRES* (MQ, submitted 2016)

Irina Tretiakova (PhD): The nature, extent and age of the lower crust and underlying subcontinental lithospheric mantle (SCLM) beneath the Siberian Craton (Russia); *iMQRES* (MQ, submitted 2016)

Rick Verberne (PhD): Fluids, metamorphism and ore deposits at the nanoscale; *CIPRS* (CU, commenced 2016)

Silvia Volante (PhD): A multi-scale structural and metamorphic study of the Georgetown Inlier, NE Queensland: Implications for the assembly of the supercontinent Nuna; *CIPRS* (CU, commenced 2016)

Alexander Walker (PhD): Sulphide sources and budgets of the Albany-Fraser Orogen and Eulca Basement; *CIPRS* (CU, commenced 2016)

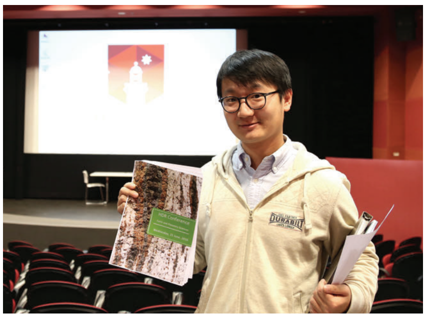
Kai Wang (PhD): Joint inversion of surface waves and body waves from ambient noise seismic interferometry; *iMQRES* (MQ, commenced 2015)

Jonathon Michael Wasiliev (PhD): Activating the lower mantle: viscosity by numerical analysis; *MQRES* (MQ, commenced 2013)

Shucheng Wu (PhD): The geodynamic setting of the Western Junggar region during the Late Paleozoic: evidence from seismic tomography; *iMQRES, Cotutelle* (MQ, commenced 2015)

Jun Xie (PhD): Verification and Applications of Surface Waves Extracted from Ambient Noise; *iMQRES Cotutelle* (MQ, submitted 2016)

Bo Xu (PhD): Ultrapotassic rocks and Xenoliths, implications for tectonics and mineralisation; *iMQRES Cotutelle CSC* (MQ, commenced 2014) *Pictured left.*



COMMENCING 2017

Jonathan Munnikhuis (PhD, MQ)

Brendan Nomchong (PhD, UNSW)

Georgia Soares (PhD, UNSW)

Luke Steller (PhD, UNSW)

Alexander Wellhauser (PhD, MQ)

Marina Veter (PhD, MQ)

Infrastructure and technology development

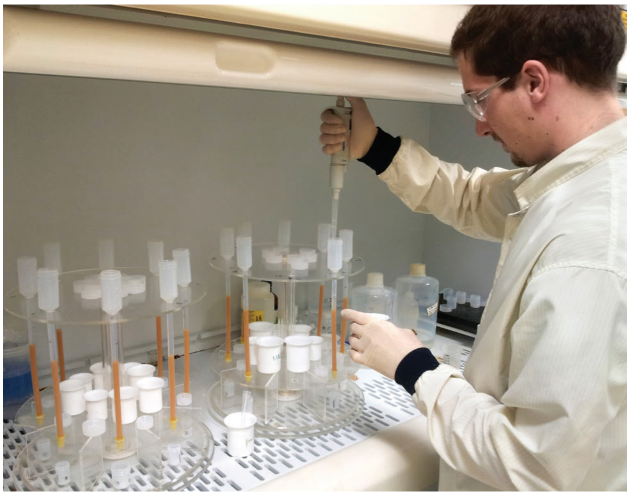
CCFS links three internationally recognised concentrations of analytical geochemistry infrastructure: GEMOC's Geochemical Analysis Unit (Macquarie University, reorganised in 2016 as MQGA) and the associated Computing Cluster, the Centre for Microscopy, Characterisation and Analysis (UWA/Curtin) and the 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 Geochemical facilities Unit 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)
- four Agilent quadrupole ICPMS (industry collaboration; two 7500cs; two 7700cx)
- two Nu Plasma multi-collector ICPMS (one decommissioned in June 2015)
- 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
- three New Wave laser microprobes (one 266 nm, two 213 nm, each fitted with large-format sample cells) for the MC-ICPMS and ICPMS laboratories (industry collaboration)
- two Photon Machines Excite Excimer laser ablation systems
- a Photon 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.



Romain Tilhac separating Sr, Nd and Hf by column chromatography for isotope analysis (Photo by Soumaya Abbassi).

Experimental petrology laboratories currently include two piston-cylinder presses (pressures to 4 GPa), hydrothermal apparatus, Griggs apparatus and a multi-anvil apparatus for pressures to 27 GPa. Additional multi-anvil and piston-cylinder presses, plus a Laser-heated Diamond Anvil Cell apparatus are currently being acquired.

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 capabilities 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.

The geochemical facilities operations at Macquarie University were reorganised by the Department of Earth and Planetary Sciences in 2016 without consulting CCFS, and input from CCFS during the subsequent GAU review process, to ensure operational security, was not taken into account. Staff changes in early 2016 resulted in a shortfall of three key positions (including the resignations of David Adams and Dr Will Powell). As a result, the functioning of some instruments (including the electron microprobe, the SEM and the LAM-ICPMS) was compromised throughout 2016. Research staff from CCFS were able to keep the SEM, LAM-ICPMS and multi-collector (MC) ICPMS in operation, producing CCFS-GEMOC's unique suite of *in situ* results key to many CCFS projects. Despite the efforts of the CCFS staff, this series of problems and lack of experienced leadership impinged on the research projects of many staff and students.

EQUIPMENT FOR HIGH-PRESSURE EXPERIMENTATION

The expansion of the high-pressure experimental facilities continued, with plans for an extension to the laboratory in a new wing extending into the yard behind building E5A. This will house two large multi-anvil presses, and a third will be installed in the current laboratory. Laser-heated diamond anvil cells and an additional piston-cylinder apparatus are being acquired through LIEF funds from the Australian Research Council. An experimental program on electrical conductivity in mantle materials has begun with the currently available multi-anvil apparatus, and experiments studying the reaction between melts of sediment and mantle peridotite are being conducted.

PROGRESS IN 2016:

1. Facility for Integrated Microanalysis

a. Electron Microprobe: As noted above, the electron microprobe laboratory did not produce results throughout 2016, due to the staffing situation and the lack of appropriate technical expertise. As a stopgap measure, CCFS PhD students and research staff were directed to other microprobe laboratories nationwide and internationally. We are grateful to our colleagues at these institutions (among others) University of Melbourne, ANU-RSES, University of Western Sydney, University of New South Wales, Mainz University and IGGCAS, Beijing (a CCFS international Partner Organisation), for their expert and enthusiastic assistance for instrument access. Sarah Gain is especially thanked for her efforts in keeping the SEM operative and available to students until the Department, late in 2016, provided a part-time student assistant to help with the SEM. The EMP is not yet operational due to lack of care during downtime which resulted in failing pumps and detectors. Dr Timothy Murphy has been appointed to oversee the electron microprobe functions, and arrives in early 2017.

CCFS has 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 Prof Damien Gore (Department of Geography). The versatility of this instrument has attracted a significant interest from most faculties across Macquarie University, including Arts.

b. Laser-ablation ICPMS microprobe (LAM): In 2016 the combination of the Photon Machines G2 laser system and Agilent 7700 ICPMS was used for *in situ* trace element analyses and U-Pb geochronology. The facility was used by 12 Macquarie PhD thesis projects, 6 international visitors, 6 Masters Research students, 15 users from other Australian institutions and several in-house funded research projects and industry collaborations. Projects included the analysis of minerals from

Archaeologist Michelle Whitford with Egyptian beads for LAM analysis.

mantle-derived peridotites, pyroxenites and chromitites, new, unusual types of ultra-reduced phases from volcanic sources and ultra-high pressures terranes, high-grade metamorphic rocks and biominerals.

More unusual materials were also analysed including Egyptian pottery and stone beads and remains of swords from the Dubai area, in collaboration with Ivan Stepanov and Prof Lloyd Weeks (UNE). Further development regarding the fingerprinting of archaeological materials is in progress and discussions are underway with the Department of Ancient History.

Following the resignation of Dr Will Powell in early 2016, U-Pb analysis of zircon was enabled through 2016 by the expertise of CCFS Research Associates Rosanna Murphy and Yoann Gréau with generous input from other CCFS researchers. Sarah Gain and Rosanna Murphy also kept the laboratory operating for the analysis of trace elements in a variety of materials. *TerraneChron®* applications http://www.gemoc.mq.edu.au/TerraneChron.html) continued. Method development and *TerraneChron®* work were restricted in 2016 due to the reorganisation, staffing shortfall, and resulting difficulties in maintaining instrument operation. A Technical Officer to provide technical expertise has been selected and is likely to arrive in May 2017.

c. MC-ICPMS: A Nu Plasma II MC-ICPMS was installed in June 2015 and followed the decommissioning of 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 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.

The *in situ* measurement of U-Pb isotopes in zircon using the combination of the femtosecond laser system and 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. The development of Mg isotope methodologies for chromite and chromite-rich ultramafic rocks as part of the TARDIS Program (Nicole McGowan PhD) in the ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS) was completed; high-precision results were obtained in wet-plasma mode on the Nu Plasma II and corroborated by replicate measurements at IGGCAS, Beijing.

At the time of the installation of the new Nu Plasma II, 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 Nu Plasma HR 034. After successful installation and commissioning had been achieved and 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. A new Future Fellow, Dr Olivier Alard (pictured above), has relevant expertise and a technical position replacement process is in progress. In addition, the ARC Centre of Excellence for Core to Crust Fluid Systems has funded a technology development program employing a Research Associate (Dr Yoann Gréau) with a high level of instrument expertise who, with Dr Alard, has been recently making good progress with the envisaged developments. A new split-stream approach is now being investigated, involving additional gas lines and mass-flow controllers to control the amount of aerosol transported into each instrument. Ultimately, this approach will assist in achieving adequate sensitivity on both sides of the system, and therefore will optimise both signal outputs for a given ablated volume. The planned first application of this new methodology will be combined U-Pb and Lu-Hf characterisation of zircons and simultaneous measurements of Pb-Pb and Re-Os in sulfides.

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). 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. Re-Os studies were undertaken on xenoliths from eastern China, Siberia, Italy and Algeria (Hoggar), and sulfide and platinum group minerals in chromitites from Tibet, Australia, Spain and Turkey. This activity was also made possible by the expertise of CCFS Research Associates Rosanna Murphy and Yoann Gréau with input from other CCFS researchers, and CCFS

Future Fellow Olivier Alard, following the resignations in early 2016. 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.

d. Laboratory development: The clean-room facility established in 2004 continued to be used primarily for isotope separations for analysis on the Triton TIMS and Nu Plasma MC-ICPMS. Routine procedures continued for Rb-Sr, Nd-Sm, Lu-Hf and Pb isotopes, as well as U-series methods (U, Th and Ra).

e. Software: GLITTER (GEMOC Laser ICPMS Total Trace Element Reduction) software is our on-line interactive program for quantitative trace element and isotopic analysis and features dynamically linked graphics and analysis tables. This package provides real-time interactive data reduction for LAM-ICPMS analysis, allowing inspection and evaluation of each result before the next analysis spot is chosen. GLITTER's capabilities include the on-line reduction of U-Pb data. Sales of GLITTER are handled by AccessMQ and GEMOC provides customer service and technical backup. During 2016 a further 16 full licences of GLITTER were sold, bringing the total number in use to more than 287 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 2016 on a consultancy basis, following his resignation and relocation to Rio Tinto (Melbourne) in early 2016. The current GLITTER release is version 4.4.4 and is currently available without charge to existing customers.

2. X-Ray Fluorescence Analysis

In November 2012 a PANalytical Axios 1 kW X-ray Fluorescence 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.

2.1. A high performance CHNS elemental analyser from Elementar (Vario El Cube) fitted with an extra IR-detector for low-level sulfur analysis has been purchased and recently installed. This facility enables us to better estimate whole-rock sulfur contents and thus sulfide abundance in order to select appropriate samples for *in situ* Re-Os isotopic analysis.

3. Whole-rock solution analysis

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

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

4. Diamond preparation and analysis

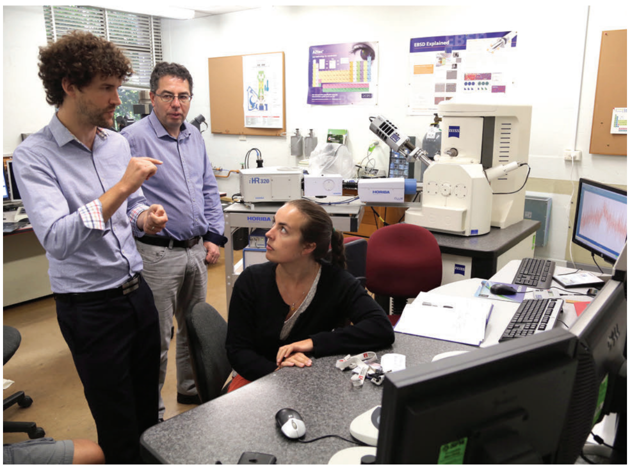
The GEMOC laser-cutting system (donated by Argyle diamonds in 2008) was used through 2015 to cut thin plates of single diamond crystals as part of the on-going research into diamond genesis. However, in 2016 the instrument has repeatedly broken down and is being decommissioned.

5. selFrag - a new approach to sample preparation

GEMOC's selFrag instrument was installed in May 2010 and was the first unit in Australia. This instrument uses high-powered electrical pulses to disaggregate rocks and other materials along the grain boundaries. It removes the need to crush rocks for mineral separation, and provides a higher proportion of unbroken grains of trace minerals such as zircon. Since its installation selFrag has been used for a range of applications including zircon separation, the analysis of grain size and shape in complex rocks, and the liberation of trace minerals from a range of mantle-derived and crustal rocks.

6. Spectroscopy

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



Sarah Gain with personnel from Horiba and Quark Photonics during the installation of the CL monochromator on the SEM.

elements are incorporated in the mineral crystal lattices (e.g. Mn in aragonite). The new instrumentation is in the process of 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).

7. Raman spectrometry

A confocal laser Raman microscope (co-funded by 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. This year the system's capabilities were extended with the purchase of two new laser wavelengths (MQSIS 2017), upgrading the Raman spectrometer to one of the most versatile and capable in the Sydney area. The instrument enjoys attention from a growing user group across the Faculty of Science and Engineering at Macquarie University with users from Chemistry, Physics, Biology and Environmental Sciences as well as continued popularity with Dr Christoph Lenz from ANSTO. Professor Lutz Nasdala (University of Vienna), one of the world-leading experts in Raman Spectrometry provided a short course on Raman spectrometry for CCFS in December 2016 (See *p. 108*).

In 2017 we plan to extend the applications of Raman Spectrometry towards forensics applications, namely ink characterisation on Egyptian papyrus (with Prof Damian Gore and Assoc Prof Malcolm Choat).

8. Computer cluster

The cluster Enki has continued to be a powerhouse for the geodynamics group, having supported multiple research projects, > 5 PhD projects, postdocs, and numerous Masters-level projects. Recent developments have included the incorporation of melt transport and crustal creation into the mantle convection code Aspect (based on the deal.II finite element libraries), led by Siqi Zhang. Other codes utilising Enki for simulation include O'Neill and Zhang's smoothed-particle hydrodynamic codes to simulate early solar-system processes (currently in review). In addition, the lithosphere/seismic cluster "*Toto*" (managed by J.C. Afonso) continues operation, while a GPU Tower (supplied by Xenon systems) acts as a development machine for GPU-capable code, including the SPH code. A Xeon-Phi server (supplied by Dell) has recently been installed, enabling the modelling group to start development and migration of their codes onto this next generation hardware.

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

CMCA TECHNOLOGY DEVELOPMENT AND INSTRUMENTATION

The University of Western Australia's Centre for Microscopy, Characterisation and Analysis (CMCA) is a $50 M 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 3 00RA+)
- 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 CAMECA NanoSIMS 50L.

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 i*n situ*, high-precision isotopic and elemental analyses, and secondary ion imaging on a wide range of samples.

UWA MSc student Bataar Bataar using the Cameca 120 ion probe for oxygen isotope Analysis.

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). In 2015, the CMCA installed a new CAMECA NanoSIMS 50L ion probe as part of the NRSP's Advanced Resources Characterisation Facility (ARCF). The ARCF provides multiscale characterisation capabilities for Geoscience research, from the scale of drill core down to atom scale. The Facility, funded through CSIRO's Science and Industry Endowment Fund (SIEF), features the Geoscience Atom Probe installed in the John de Laeter Centre at Curtin University, and the MAIA mapping facility currently under development at CSIRO. 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.

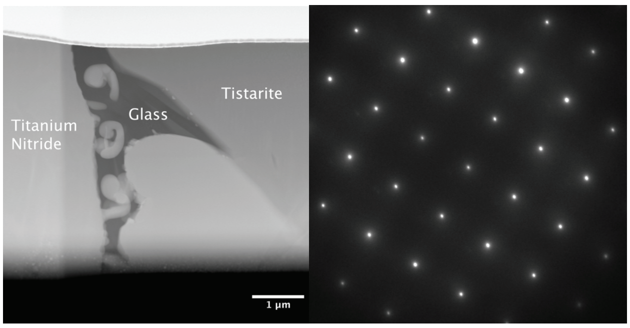
The Ion Probe Facility is a key characterisation component within the ARC Centre of Excellence for Core to Crust Fluid Systems. To ensure the highest levels of quality and throughput, CCFS has provided funding for a Research Associate position within the Ion Probe Facility, to facilitate direct scientific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

PROGRESS IN 2016:

The Ion Probe Facility has continued to contribute to various projects in the context of CCFS. The CAMECA IMS1280 clocked up more than 4300 hours, far in excess of the '*full-utilisation target*' of 1800 hours. The lab contributed to 42 individual projects, originating from CCFS partners, other Australian research institutes, and overseas. In addition, 7 new development projects were initiated to extend the lab's capabilities, including REE measurements and ion imaging. 8 journal articles were published in 2016 featuring data acquired using the IMS1280 at UWA, of which 7 were directly related to CCFS projects.

With the new CAMECA NanoSIMS 50L coming online in late 2015, the NanoSIMS lab saw a big increase in the number of projects - 47, spread across 6500 hours. Projects originated from 11 Australian institutions, with 5 projects from overseas. Several new development projects that utilise the new RF plasma oxygen ion source were initiated, focusing predominantly on isotope mapping in minerals. The NanoSIMS lab contributed to 13 publications in 2016, of which 6 were Earth science-related. One high impact paper (*Reith et al. Nature Geoscience*) featured NanoSIMS imaging of Pt to shed light on the role of microbes in the transformation of PGE minerals. The CCFS pilot project *"Making the invisible visible"* yielded its first publication, illustrating the role of fluids in simplectite formation revealed by isotope labelling (*CCFS Publication* #866, *Spruzeniece et al., J. Metamorphic Geol.*).

CCFS research has also incorporated other analytical techniques at the CMCA. In 2016, the FEI Helios DualBeam and FEI Titan TEM were used to investigate the detailed mineralogy of '*nebular*' mineral assemblages initially described in the 2015 CCFS Annual Report. In a collaboration between Bill Griffin's Macquarie group and the CMCA's Associate Prof Martin Saunders, the high resolution analytical capabilities of the Titan TEM have allowed the composition and crystal structure of these complex, fine-grained materials to be investigated, which has led to the identification of several exceedingly rare or previously unreported minerals. The first publication from the collaboration appeared in Geology and was featured as a '*Nature Research highlight*' (*CCFS Publication #830, Griffin et.al. 2016, Geology*).



High-Angle Annular Dark Field STEM image (left) and diffraction pattern from the Tistarite phase (right).

CMCA-CCFS 2016 publications were published in high profile journals such as *Earth and Planetary Science Letters, Chemical Geology, Geological Society Special Publications, Journal of Metamorphic Geology* and *Terra Nova:* CCFS Publications #797, 816, 830, 838, 847, 866, 921.

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

JOHN DE LAETER CENTRE

The John de Laeter Centre (JdLC) is a collaborative research venture involving Curtin University, the University of Western Australia, CSIRO and the Geological Survey of Western Australia.

It hosts over $28 M 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 mission of the Centre is to *"build world-class research infrastructure in Western Australia for the benefit of Earth, Environment and Materials Science research"*. The JdLC is headquartered in the Faculty of Science and Engineering at Curtin University, but has a governing board consisting of members of the joint venture partners as well as representatives from the mining, petroleum and environment sectors.

The Centre experienced rapid growth in 2015 through the merger of mass spectrometry and microscopy facilities at Curtin, the commissioning of $5,200,000 in new analytical instrumentation and the appointment of 4 new research fellows. A website has been developed to provide detailed information on the new facilities, instrumentation and research staff (http://www.jdlc.edu.au).

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 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 back scattered 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 on a wide range of length scales.

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

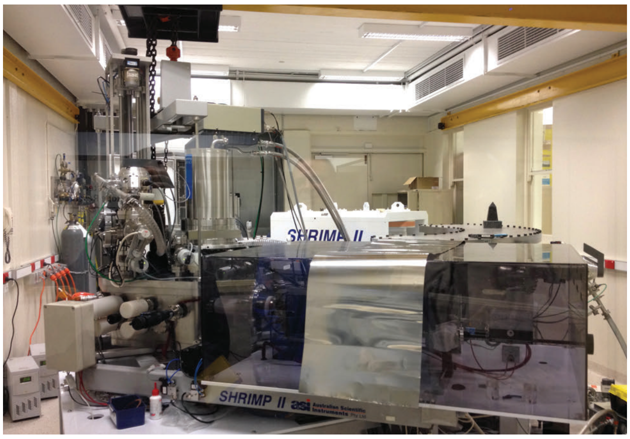
- High resolution imaging (TEM) - A new FEI Talos F200X S/TEM system will be commissioned in early 2017 to complement ongoing research at the nanoscale. The system combines high resolution S/TEM and TEM imaging with EDS and 3D chemical characterisation.

  The JEM is a transmission electron microscope (TEM) with a LaB6 filament. The TEM is equipped with an EDS detector and a scanning TEM attachment. This instrument is capable of elemental and microstructural analysis at extremely high magnifications.
- Spatially resolved elemental analysis (EDS) and Phase & orientation analysis (EBSD) - The MIRA3 is a variable pressure field emission scanning electron microscope (VP-FESEM) that features sensitive EDS and EBSD detectors and integrated software for high quality microstructural analysis of crystalline samples.
- 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. Instrumentation includes a Bruker NANOSTAR SAXS comprising a copper sealed tube X-ray source with a gas filled two dimensional photon counting detector. In 2016, LIEF funding was used to upgrade the instrumentation in the facility.

(SHRIMP) Sensitive High Resolution Ion Micro Probe Facility:
The facility at Curtin has two automated SHRIMP II ion microprobes capable of 24-hour operation, together with a preparation laboratory that was remodelled in 2014. The equipment allows *in situ* isotopic analysis of chemically complex materials with a spatial resolution of 5-20 microns. The main application of the SHRIMP instruments at Curtin is for U-Th-Pb geochronology of zircon and other U-bearing minerals, including monazite, xenotime, titanite, allanite, rutile, apatite, baddeleyite, cassiterite, perovskite and uraninite where multiple growth zones commonly require analyses with high spatial resolution. SHRIMP II (*pictured below*) is fitted with a Cs source, electron gun and 5 channel M/C. SHRIMP II A is currently being developed for stable isotope analysis of O in zircon and other silicates, and S in sulfides.



(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. 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 at Curtin incorporates a Thermo Finnegan *Triton*™ and a VG 354 multicollector mass spectrometer. The Triton is equipped with a 21-sample turret and 9 faraday cups, enabling a precision of 0.001% on isotopic ratios. As well as geological applications within the broad field of isotope geochemistry (Re/Os, U/ Pb, Pb/Pb, Sm/Nd, Rb/Sr) the TIMS instruments can be applied to a variety of isotope fingerprinting, such as forensics and the environmental impact of human activities. The TIMS instruments are also used for the calibration of isotopic standards and the calculation of isotopic abundances and atomic weights. 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 with a low-blank automated extraction system coupled with a New Wave Nd-YAG dual IR (1064 nm) and UV (216 nm) laser, an electromultiplier detector and Niers source. 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 facility also houses an Argus VI Multi-Collector Noble Gas Mass Spectrometer.

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

WESTERN AUSTRALIA PALEOMAGNETIC AND ROCK-MAGNETIC FACILITY

The Western Australia Paleomagnetic and Rock-magnetic Facility, recently upgraded and relocated to Curtin University's Bentley campus, is a national research infrastructure with the latest upgrade co-funded 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 latest upgrade includes the construction of a magnetically shielded room in mid-2015 by Dr Gary Scott's team, which provides a laboratory space with ambient magnetic fields less than 0.5% of the local geomagnetic field. Within this shielded room we now have a new 2G 755 superconducting rock magnetometer with a vertical Model 855 automated sample handler (the RAPID system) and other accessories attached to it (automated AF demagnetiser, susceptibility meter, etc.). The RAPID system, the first and only one in Australia, was installed and commissioned in February 2017. Other systems now operating inside the shielded room include an AGICO JR-6A spinner magnetometer and ASC TD-48SC and MAGNETIC MEASUREMENTS thermal demagnetisers. The day-to-day operation of the facility is overseen by the recently appointed Technical Officer, Dr Josh Beardmore. A number of key pieces of apparatus are currently being relocated from UWA to the new Curtin precinct.

The new purchases represent a major enhancement to the productivity and capabilities of the facility. Apparatus which is now available 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, and ARM system)
- a second 2G 755 cryogenic magnetometer upgraded (LE0668377) to a 4K DC SQUID system (currently returned to 2G enterprises for a minor upgrade and for 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
- a Bartington MS2 susceptibility meter with MS2W furnace
- 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, studying 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.

The 2G RAPID superconducting magnetometer system.

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 2016

- *TerraneChron*® studies (see *p. 100* 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 31,600 zircon U-Pb and Hf-isotope analyses) in the Macquarie laboratory allows unparalleled contextual information in the interpretations and reports provided to industry.
- 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.

At the Dead Sea: Bill Griffin, Sue O'Reilly, John Ward and Vered Toledo (COO, Shefa Yamim).

- The CCFS collaboration with Shefa Yamim Ltd. (Akko, Israel) continued and expanded in 2016. Bill Griffin and Sue O'Reilly visited Israel in January to give talks at the annual congress of the Israel Geological Society in Eilat. Bill gave the Plenary address entitled "*Deep-Earth methane, mantle dynamics and mineral exploration: insights from N. Israel, S. Tibet and Kamchatka*" and a session talk "*Heaven on Earth: tistarite (Ti_2O_3) and other 'nebular' phases in corundum aggregates from Mt Carmel volcanic rocks*". Sue gave a session talk on "*The role of the deep lithosphere in metallogeny*". 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.
- 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 2016 as part of the close collaborative working pattern for this project.
- A new Linkage Project "*Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia*" commenced 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.
- A collaborative project funded by Rio Tinto Limited commenced in 2014. Marco Fiorentini and Yongjun Lu (UWA) are investigating "*The mineral chemistry of zircon as a pathfinder for magmatic-hydrothermal copper and gold systems*". The project aligns with the goals of Flagship Program 2, Genesis, transfer and focus of fluids and metals.
- 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.
- A collaborative research project continued in 2016 with the GSWA as a formal CCFS Flagship Program, in which GEMOC is carrying out *in situ* Hf-isotope analyses of previously SHRIMP-dated zircon grains from across the state. This is a part of the WA Government's Exploration Incentive Scheme.
- Following Professor Bill Griffin's Noumea workshop on new approaches to exploration and minor-element exploitation in ophiolitic complexes, a collaborative project was established with Jervois Mining, involving a co-tutelle PhD student (Mathieu Chasse) jointly supervised by Professor George Callas, Pierre et Marie Curie University, Paris, France. This project continued in 2016. It has led to significant advances in understanding the speciation and mineral residence of the element Scandium (Sc) in lateritic weathering profiles developed on mafic and ultramafic rocks. It also has helped to characterise and define a world-class Sc resource in western New South Wales, and to provide indicators for further exploration.
- CET held their annual "*Corporate Members Day*" on the 7th of December 2016, 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.


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

- Industry visitors spent varying periods at Macquarie, Curtin and UWA (CET) in 2016 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 2016 (see Abstracts, *Appendix 6*).

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

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 and applied aspects of the basic research programs, and many are based on understanding the architecture of the lithosphere and the nature of Earth's geodynamic processes that have controlled the evolution of the lithosphere and its important discontinuities. Basic research strands translated to strategic applications include the use of geochemical data integrated with tectonic analyses and large-scale datasets (including geophysical) to understand the relationship between lithosphere domains and large-scale mineralisation. The use of sulfides to date mantle events, and the characterisation of crustal terrane development using U-Pb dating and Hf isotopic compositions of zircons (*TerraneChron*®) are being developed as regional isotopic mapping tools for integration with geophysical modelling.

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.
Reducing 3D geological uncertainty via improved data interpretation methods	***Linkage Project (LP140100267)*** ***Industry Collaborators: Western Mining Services Australia Pty Ltd, Geological Survey of Western Australia*** ***CIs: Jessell, Holden, Baddeley, Kovesi, Ailleres, Wedge, Lindsay, Gessner, Hronsky*** ***Summary:*** The integrity of 3D geological models heavily relies on robust and consistent data interpretation. This project proposes an innovative workflow for 3D modelling to minimise geological uncertainty. Advanced visualisation and intelligent decision support methods will be combined to assist geological interpretation. Feedback on interpretation will be provided based on data evidence and consistency with expert knowledge and previous interpretations. The process can be considered as a spelling and grammar checker for geological interpretation. The outcome of this study aims to achieve an improved workflow that reduces model uncertainty, resulting in a broad and significant impact on the management of Australian mineral, energy and water resources.

Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	***Linkage Project (LP130100413)*** ***Industry Collaborator: Geological Survey of Western Australia*** ***CIs: Tkalcic, Kennett, Spaggiari, Gessner*** ***Summary:*** The objective of this work is to achieve new, synergistic techniques for delineating the three-dimensional structure of the east Albany-Fraser Orogen in Western Australia, and the lithospheric structure below it. These methods will guide understanding of the potential for mineral resources in this region with little surface geological exposure.
Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	***Linkage Project (LP130100922)*** ***Industry Collaborator: Geological Survey of Western Australia*** ***CIs: Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate*** ***Summary:*** The application of innovative age dating techniques with field mapping and a new deep seismic survey across the Capricorn Orogen by this project will help construct a vastly improved geological framework for understanding large mineral systems. Outcomes of this project will reduce uncertainty and risk in exploration, thereby improving the discovery rate of natural resources.
The role of whole-lithosphere architecture on the genesis of giant gold systems in the El-Indio region, Chile-Argentina	***Industry Collaborator: Barrick Gold*** ***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.
The distal footprints of giant ore systems: UNCOVER Australia	***Supported by CSIRO ex Science & Industry Endowment Fund (SIEF)*** ***Industry Collaborator: 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.
Lithospheric architecture mapping in Phanerozoic orogens	***Industry Collaborator: Minerals Targeting International (PI G. Begg)*** ***CIs: Griffin, O'Reilly, Pearson, Belousova, Natapov*** ***Summary:*** The GEMOC Key Centre has developed the conceptual and technological tools required to map the architecture and evolution of the upper lithosphere (0-250 km depth) of cratons (the ancient nuclei of continents). Through two industry-funded programs we have mapped most of the world's cratons, making up ca 70% of Earth's surface. The remaining 30% consists of younger mobile belts, which hold many major ore deposits, but are much more complex and difficult to map. This pilot project is developing the additional tools required to map the mobile belts.

Multiscale dynamics of hydrothermal mineral systems	***Supported by MRIWA*** ***Industry Collaborators: Integra Mining, First Quantum Minerals, AngloGold Ashanti, SIPA Resources, GSWA, Newmont, Goldfields, Barrick Gold, OZ Minerals*** ***CIs: Ord, Gorczyk, Gessner, Hobbs, Micklethwaite*** ***Summary:*** The project aims to produce an integrated framework for the origin of giant hydrothermal deposits. The study crosses all the length scales from lithospheric down to thin section. The goal is to define measurable parameters that control the size of such systems and that can be used as mineral exploration criteria. In particular the emphasis is on: (i) criteria that distinguish a '*successful*' from a '*failed*' mineral system and (ii) vectors to mineralisation within a successful system.
Mineral footprint and 4D architecture of the Callie Gold Deposit	***Industry Collaborator: Newmont*** ***CIs: Thébaud, Occhipinti, LaFlamme, Petrella*** ***Summary:*** The aim of this project is to do an effective assessment of the controls and significance of the variations in the gold systems in the Dead Bullock Soak Mining Lease, in order to aid with Callie deposit mine development and near-mine exploration as well as regional targeting and delineation of further resources. The proposed research partnership involves a project that will do a 4D reconstruction of the gold deposits by integrating the structural, metamorphic and alteration histories of the various deposits in the Dead Bullock Soak Mining Lease. This will be integrated with new geochronology on key phases of the alteration history, structurally constrained intrusive rocks and host rock types. The aim will be to use this knowledge in a mineral systems context to aid exploration targeting, however the deposit scale studies will also potentially impact on resource and geotechnical domaining strategies.
Magmatic sulfide mineral potential in the East Kimberley	***Supported by MRIWA M459*** ***Industry Collaborators: CSIRO, MRIWA, Panoramic Resources Ltd and Kind River Copper Ltd.*** ***CIs: Barnes, Fiorentini*** ***Summary:*** Magmatic sulfide mineral potential in the East Kimberley igneous intrusions of broadly basaltic composition are the hosts for some of the world's most valuable ore deposits of Ni, Cu and PGE, and indeed some of the most valuable ore deposits of any type on the planet. Exploration for this style of deposit in Proterozoic mobile belts has recently received a major boost in Australia following the discovery of the Nova deposit in greenfields-terrane in Western Australia, and also with exciting new discoveries and deposit extensions in the Musgrave province also in WA. However, detailed camp-scale targeting and exploration for these deposits remains extremely challenging and new approaches are required. The project will investigate the prospectivity of mafic igneous intrusive rocks in the East Kimberley based on age, internal differentiation and geochemistry of parent magmas, and isotope fingerprinting of ore minerals. The centerpiece of this extension of the project will be an investigation of the relationship between multiple small intrusions in the Savannah district, including the ore-hosting Savannah intrusion itself. We will also investigate similar attributes of the neighbouring Hart Dolerite suite and its potential for PGE-enriched magmatic sulfides. Results will be applied to an assessment of potential exploration targets within the East Kimberley region and other greenfield areas in Proterozoic mobile belts elsewhere in Western Australia.

Mineral systems on the margin of cratons: Albany-Fraser Orogen/ Eucla Basement case study	***Supported by MRIWA M470*** ***Industry Collaborators: GSWA and Ponton Minerals*** ***CIs: Kirkland, Clark, Kiddie, Tyler, Spaggiari, Smithies, Wingate*** ***Summary:*** Modern exploration requires a new integrated approach, utilising a broad range of techniques, which can collectively enhance the geological knowledge of a region's mineral endowment. Craton margins host significant lithospheric discontinuities that focus fluids and heat and which, under favourable circumstances, may become mineralised corridors. Additionally, high-grade terrains are frequently viewed as less prospective for some mineralisation (e.g. gold) than lower-grade regions. However, recent discoveries in the Albany-Fraser Orogen highlight that many common models for mineral endowment are lacking and their resolution through cover limited. This program of research will focus on the partially covered terrain of the Albany-Fraser Orogen and the covered Eucla Basement of Western Australia. The project will utilise a lithosphere-scale mineral systems approach to establish the fundamentals (timing, scale, material) of mass transfer processes within the crust. The project will utilise a broad range of geochronology techniques to enhance GSWA's regional U-Pb zircon coverage and will apply crustal evolution studies via novel analytical equipment to rapidly delimit domains of enhanced mantle input.
Western Africa Exploration Initiative (WAXI)	***Industry Collaborator: AMIRA International Ltd.*** ***CIs: Jessell, McCuaig, Miller, Thébaud*** ***Summary:*** The West African Exploration Initiative (WAXI) has been a truly remarkable collaboration between a host of research institutions, government agencies from West Africa and industry. The initiative has focused essentially on two overarching themes, namely research to better understand the tectonic history and mineralisation of the West African Craton (WAC); and to assist in building capacity in the region through the assistance of the Geological Surveys and Universities and through training. The initiative is now moving to a Stage 3 which will involve extending the work to the Archean and continuing to assist with capacity building.

International links in CCFS

BACKGROUND

CCFS' International links provide leverage of intellectual and financial resources on a global scale, and an international network for postgraduate experience. International Partners provide the core of such collaborations. Other international activity includes funded projects and substantial collaborative programs with major exchange-visit programs in France, Norway, Germany, United Kingdom, New Zealand, Canada, USA, Taiwan, Italy, Spain, South Africa, South America, China, Brazil, Mexico, Japan, Thailand and Russia.

FORMAL MEMORANDA OF UNDERSTANDING (MOU)

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

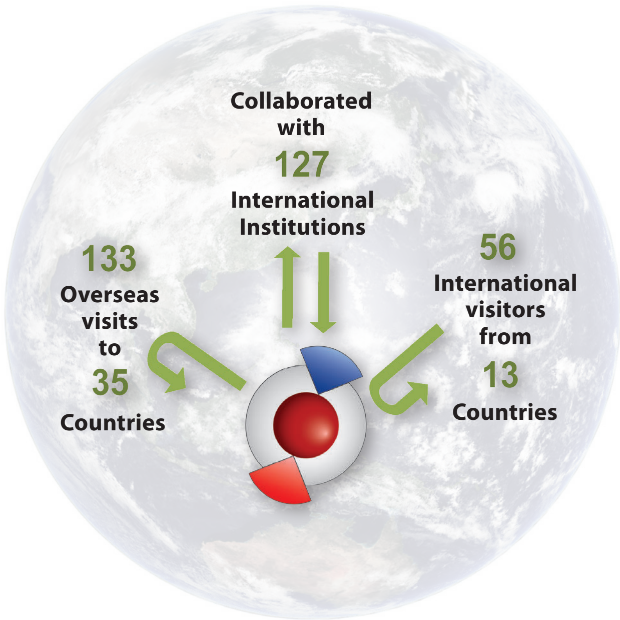
- China University of Geosciences (Wuhan) - 2011 (& Cotutelle)
- Constitution of the International University Consortium in Earth Science - 2012
- University of Science and Technology of China, Hefei - 2012 (& Cotutelle)
- Institute of Geology and Geophysics, China University of Geosciences (IGGCAS, Beijing) - 2014
- 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:

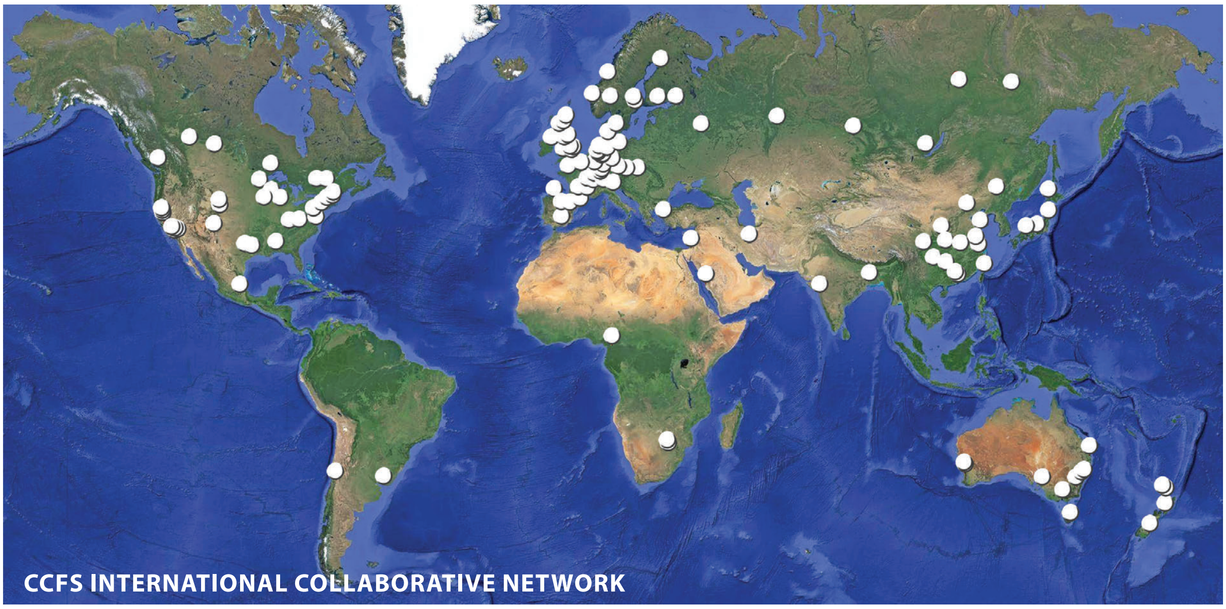
- China University of Petroleum, Beijing, China
- Durham University, United Kingdom
- Eötvös Loránd University, Hungary
- Friedrich-Alexander-University of Erlangen, Nuremberg, Germany
- Institute of Geology and Geophysics, Chinese Academy of Sciences, China
- Nanjing University, China
- Peking University,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

2016 COLLABORATIVE ACTIVITY



INTERNATIONAL LINKS - 2016 SELECTED HIGHLIGHTS

- Delegates from a range of international institutions visited CCFS in 2016 to discuss programs including the exchange of staff, joint research activities and the exchange of students. These included China University of Geosciences (Wuhan) and China University of Geosciences (Beijing).
- Dr Yongjun Lu continues collaboration with the Chinese Academy of Geological Sciences (CAGS) and China University of Geosciences in Beijing (CUGB) to investigate the porphyry copper systems in the Tibetan plateau and surrounding region.
- A collaborative project between the Institute of Geology and Geophysics, China University of Geosciences (IGGCAS, Beijing), GSWA and CCFS Macquarie, the China-Western Australia Sesmic Survey (CWAS), will install a 900 km long dense seismic profile across Western Australia from Port Hedland to the southwestern border of the Kimberly Craton. The station spacing is 10-15 km, and the whole CWAS Project will include 80 broadband seismic stations and deployed



over 18 months from April 2017 to October 2018. IGGCAS is providing seismic instruments for 60 stations. A test station was successfully installed in October 2016. See *photo p. 117*.

- A collaborative research agreement was signed between the China University of Geosciences (Wuhan) for funding by the Chinese Scholarship Council (CSC). This grant will provide a living allowance for students and visiting scholars in Australia with travel between China and Australia. 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/)

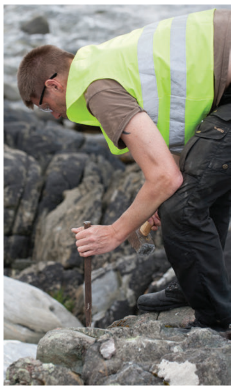
  ACTER aims to facilitate: collaborative research and research training in geotectonics and mineral and hydrocarbon resources, the exchange of staff and joint supervision of research students, shared access to analytical facilities, organisation of joint conferences and annual focused field-based workshops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

  The 2016 ACTER annual field symposium was very successful, focusing on the theme of "*Orogenesis during supercontinent cycles*". It was held in Xi'an and the adjacent Qinling orogen, China, from 20-29 October 2016. Australia will host the 2017 annual field workshop "*Tectonics of the Lachlan Fold Belt and granite petrogenesis*" on the 23-29 October 2017.
- In August GEMOC/CCFS and China University of Geoscience-Wuhan collaborated to organise a field trip to the famous UHP terrane in the Western Gneiss Region (WGR) of western Norway, led by Prof Bill Griffin. One primary aim was to study the metastable preservation of igneous and high-grade granulite parageneses as the rocks went through UHP metamorphism during crustal subduction to depths of up to 200 km. Another was to view the evidence for metasomatic

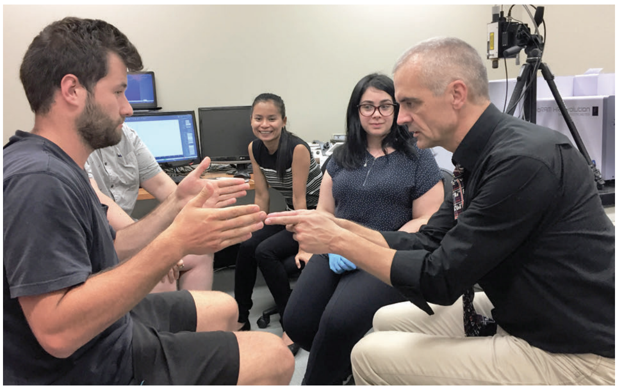
Participants in the the 2016 ACTER annual field symposium.

refertilisation of ancient depleted mantle via the intrusion of mafic melts; the third was to understand more about the ultra-high-pressure terrane in the northern part of the Western Gneiss Region, and its tectonic exhumation. A local geologist (Johannes Vik Seljebotn) volunteered to organise the logistics and to provide local knowledge all along the route. Seljebotn and Griffin prepared a guidebook with contributions by colleagues from Norway, Holland, the USA and England.

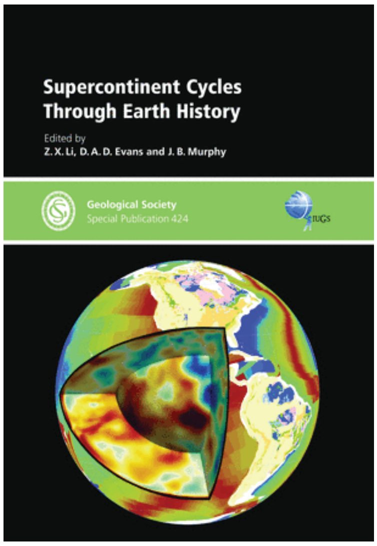
The 15 participants met in Bergen on August 14, and were joined by Prof Håkon Austrheim (University of Oslo), an expert on the problem of metastability in high-pressure rocks and the role of water in eclogite-facies metamorphism; he led the first day of the trip and rejoined it for the fourth day. Traversing north through the region, the trip visited a wide spectrum of outcrops and occurrences. An outstanding highlight was the opportunity to study the massive dunite quarries, with their associated garnet peridotites and eclogites, in the Almklov valley. This access was possible thanks to Johannes Seljebotn's close association with the operating company Sibelco. From there the group proceeded further north, where they were joined by another long-time colleague, Prof Herman von Roermund (University of Utrecht, Netherlands) who has worked for many years on the ultra-high-pressure terrane in the the northern part of the WGR. He led the fieldwork for the last two days, showing off many known and some more hidden (and slippery) outcrops. While the Chinese participants may have found western Norway's food (mainly boiled cod and potatoes) somewhat strange, it did not deter their enthusiasm, and many kilos of Norwegian eclogites and peridotites are now safely resting in Wuhan. Truly a successful international collaboration.



Scenes from the CCFS-Wuhan Field trip to the UHP terrane in the Western Gneiss Region of western Norway - Johannes Vik Seljebotn is hard to miss in the hi-vis vest and far right in the group photo below; his partner Eline brought her cello and performed Bach sonatas in a quarry that provided excellent acoustics. Above, Herman von Roermund (second from left) explains some of the samples. (photos curtesy of Johannes Vik Seljebotn and Will Powell)



- A four day shortcourse on Raman Spectrometry was held from the 28th November to December 1st 2016. The course was hosted by Macquarie University and sponsored by CCFS, Horiba Jobin Yvon and Quarkphotonics (thank you sponsors). The shortcourse was led by Professor Lutz Nasdala (University of Vienna, pictured above right), one of the leading Raman spectroscopy experts in the Earth Sciences community worldwide. Professor Nasdala was assisted by postdoctoral researcher Dr Chutimun Chanmuang (University of Vienna, *pictured above centre*). Twenty three participants from across the Faculty and CCFS attended.
- In March 2016, CCFS sponsored Dr Richard Carlson, the Mineralogical Society of America 2016 Distinguished Lecturer and Director Carnegie Institution, Washington, to give a general lecture at MQ. His talk was entitled *"A History of Earth Formation"*. After the lecture, Dr Carlson held a mentoring session with HDR students and ECRs.
- CCFS has collaborated with the ion-microprobe laboratories at IGG-CAS (Dr Li Xianhua) to develop standards for the analysis of oxygen isotopes in Cr-bearing and Ca-rich garnets; this was necessary because the SIMS technique is sensitive to matrix effects arising from compositional differences between sample and standard. Another important development was the development of a synthetic standard SiC, which now enables the *in situ* analysis of both Si isotopes (a world-first) and C isotopes in natural SiC. This development was supported by Dr Paul Savage and Dr Anita Andrews, who analysed the Si isotopes and C isotopes, respectively, of the standard material by '*conventional*' means. A survey of SiC from Russian kimberlites, Tibetan ophiolites and Israeli basalts has been completed and will be published in 2017. In a new project, IGG-CAS and CCFS are developing standards that will allow the *in situ* analysis of Ti isotopes in a variety of matrices, to investigate the isotopic fractionation of Ti as a function of oxygen fugacity.
- The UNESCO-IUGS IGCP Project 648, Supercontinent cycles and global geodynamics continued in 2016. 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. An important output in 2016 was the publication of the CCFS sponsored book: Li, Z.-X., Evans, D.A.D. and Murphy, J.B. 2016. Supercontinent Cycles Through Earth History. *Geological Society, London, Special Publications, 424, 297pp.*



- CCFS fosters many of its international links through visits by collaborators to undertake defined short-term projects, or short-term visits to give lectures and seminar sessions. CCFS sponsored exchange PhD students and visiting researchers are featured on *p. 38*.

International visitors are listed in Appendix 7.

CET/GSWA organised a geological mapping field trip with Greenland geologists - Sunset over camp in the Bryah-Padbury Basin, Capricorn Orogen. (photo: Heta Lampinen)

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:

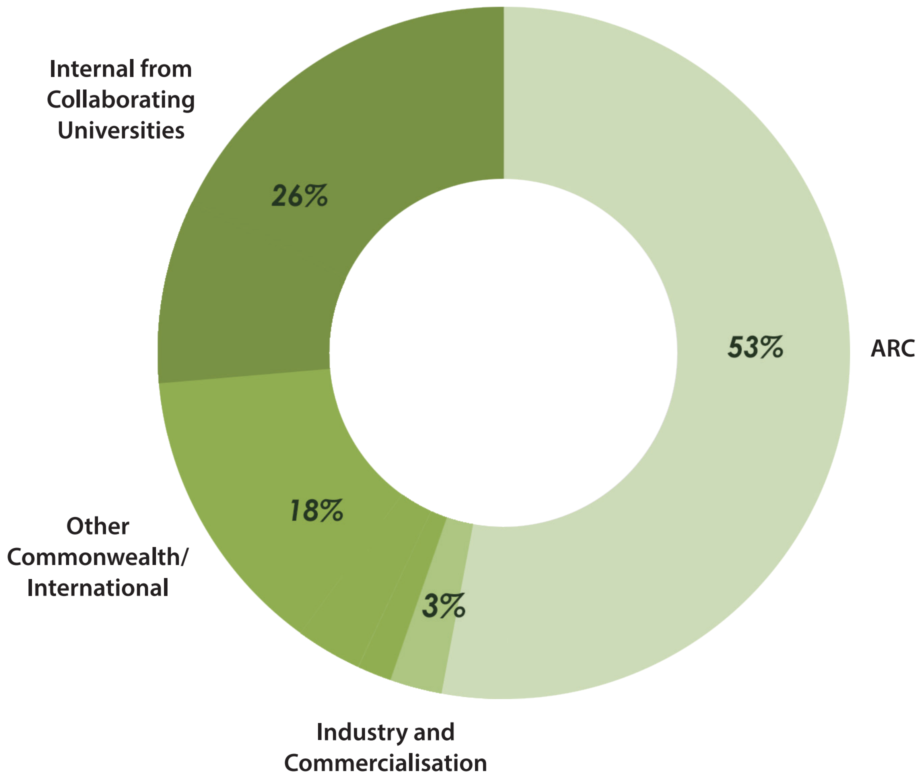
- Collaborative project building with industry partners
- Applications to funding schemes for matching funds for new infrastructure purchases and partner co-investment
- Technology development to deliver new and improved methodologies and tools for enhanced research collaboration and for the exploration 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 2011-2016 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 2011-2016

Source	2011	2012	2013	2014	2015	2016
Income						
ARC	$1,828,350	$2,004,179	$1,971,746	$2,031,333	$1,952,842	$1,986,040
MQ	$626,705	$1,032,004	$1,822,748	$1,464,360	$1,925,076	$1,621,113
UWA	$133,500	$763,500	$415,000	$415,000	$453,539	$415,000
Curtin	$727,725	$608,055	$851,244	$611,290	$523,292	$1,027,772
GSWA	$150,000	$150,000	$150,000	$150,000	$150,000	$150,000
SLF Income	$500,000					
SLF Interest	$13,744	$12,530	$5,790	$1,811	$336	$405
ECR Income from ARC	$1,250,000					
ECR Interest		$24,734	$16,118	$6,566	$1,841	
TOTAL INCOME	**$5,230,024**	**$4,595,003**	**$5,232,646**	**$4,680,360**	**$5,006,926**	**$5,200,330**
ACCUMULATED FUNDS		$3,702,071	$4,960,194	$5,181,390	$4,776,770	$4,378,094
Expenditure						
Salary	$783,390	$1,608,470	$2,263,183	$2,402,327	$2,423,825	$2,828,977
Equipment	$90,128	$220,548	$785,851	$512,413	$93,008	$86,061
Travel	$91,305	$280,795	$388,431	$404,572	$440,158	$398,178
Maintenance/Consum.	$42,433	$459,530	$487,255	$494,580	$640,889	$461,139
Scholarships	$520,697	$767,538	$1,086,730	$1,271,088	$1,807,722	$1,783,678
TOTAL EXPENDITURE	**$1,527,952**	**$3,336,880**	**$5,011,450**	**$5,084,980**	**$5,405,602**	**$5,558,034**
ACCUMULATED FUNDS	$3,702,071	$4,960,194	$5,181,390	$4,776,770	$4,378,094	$4,020,390

INCOME SOURCES 2016



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 2016

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 ultra-high pressure 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 newly recognised geodynamic collision process that may improve mineral exploration concepts for paleosubduction regimes. The recent discovery of similar exceptionally reduced mineral assemblages in ejecta from Cretaceous volcanoes in Israel suggests a previously unrecognised process of interaction between deep mantle fluids and ascending basaltic magmas. We aim to produce an experimentally testable model for the generation of such fluids in the mantle, to quantify constraints on the geochemical and tectonic processes that produce SuR-UHP assemblages, and to formulate a geodynamic model for their formation.

2016 Report

A comprehensive investigation of microstructures and mineralogy in Tibetan ophiolites has defined their evolution, including formation in ancient SCLM within a subduction zone setting, followed by transport into the upper transition zone, exhumation to the sea floor and finally emplacement by thrusting during continental collision. The Zedang ophiolite had a two-stage history, with the deeply subducted harzburgite portion being underplated by a younger lherzolitic portion before both were emplaced onto the continental crust. This model is now being tested for other ophiolitic bodies along the Yarlong-Zangbo suture. On the north side of this suture, studies of ultrapotassic rocks and mantle xenoliths are shedding new light on the lithospheric structure of the Lhasa block, and its control on Cu-porphyry mineralisation.

The team was joined by Dr Hadi Shafaii Moghadam, who is investigating the Iranian section of the Tethyan Belt, 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 as exposed in Tibet. The project has already established a geochemical and geochronological framework, and shown the existence of buried Archean-Paleoproterozoic crust.

Studies of the suite of highly reduced minerals in the ejecta from Cretaceous volcanoes in Israel (industrial collaboration with Shefa Yamim Ltd., Akko) led to the development of a model involving interaction of mantle-derived methane and hydrogen with basaltic magmas in conduits near the crust-mantle boundary. Detailed mineralogical studies included TEM analysis, in collaboration with Professor Martin Saunders (CMCA, UWA) and FE-SEM work with Professor V. Kamenetsky (UTAS). SIMS analyses of Si and C isotopes (Perth and Beijing) identified two suites of moissanite in the alluvial deposits and volcanic rocks, suggesting the presence of younger eruptions carrying similarly reduced xenolithic material. Analysis of zircons from the different Cretaceous volcanic bodies revealed an unexpectedly long history of magmatism in the mantle beneath Mount Carmel, extending back to the Permian.

Work on other mantle rocks continued, including Victorian and Cabo Ortegal pyroxenites, Au in pyroxenites, the lithosphere beneath the Pannonian Basin (Hungary-Slovakia). Studies of kimberlites and diamonds in Angola, Siberia and South Africa, included conventional (S, C, O, N) and unconventional (Mg, Fe) isotopes. Work on the deep crust and its reworking continued in China, with petrological studies of xenoliths and adakites, and magnetotelluric imaging of the Dabie UHP terrain. Mathieu Chasse's study of Sc speciation in NSW laterites (industry collaboration, Jervois Mining Ltd.) produced exciting results relevant to the exploitation of this important resource.

See *Research highlights pp. 40, 45-46, 49, 51-52, 55-56, 57-58, 62-63, 71, 74-75, 76-77, 79-80.*

Published outputs for 2016

CCFS publications: #793, 797, 799, 801, 805, 812, 816, 821, 822, 825, 826, 827, 828, 830, 831, 833, 834, 835, 841, 851, 856, 858, 862, 863, 864, 865, 867, 876, 878, 881, 924

27 Conference Abstracts

Cabo Ortegal pyroxenite, Spain.

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 environment 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.

2016 Report

In 2016, the ongoing integrated projects reached some important milestones. Projects in Module 1 (Fertility) focused on unravelling the global cycle of metals. Outcomes include the definition of a new calibrated oxybarometer that may be indirectly applied to discriminate the copper fertility of porphyry belts as well as unravel the secular oxygen fugacity evolution of the planet from the Hadean through the Eoarchean (see *Research highlights pp. 67, 81*), as well as the definition of new fertility indicators for porphyry copper mineralisation based on the trace element composition of zircon (see *Research highlights pp. 53, 72-73*). This work is integrated with ongoing porphyry studies to develop a new metallogenic model for porphyry-related and epithermal systems of the Permian-Triassic Choiyoi Group in the Cordillera Frontal, Argentina (PhD study by Greg Poole) and in the Macquarie Arc of New South Wales (postdoc project by Johannes Hammerli). Finally, recent work completed in east Greenland suggests that nickel sulfide mineralisation associated with the Ammassalik Intrusive Complex may be genetically related to the highly endowed ca. 1.9 Ga Kotalhati belt in the Svecofennian Province of Scandinavia, thus opening up the prospectivity of that region for Ni-Cu intrusion-hosted deposits (see *Research highlight p. 61*).

Projects in Module 2 (Architecture) have made significant progress in defining and imaging the key pathways that connect geochemical reservoirs, permitting the efficient multi-scale flux of energy and fluids in space and time. The PhD work of Linda Iaccheri on the North Australian Craton was successfully completed, whereas the PhD studies of Katarina Bjorkman and Eunjoo Choi, in the Superior and Yilgarn cratons, respectively, have reached significant milestones. Within Module 2, the high-precision TIMS work carried out by Jack Stirling (Masters' project) focused on the Kohistan Arc Complex of northeast Pakistan, providing a refinement of current models describing continental crust formation in island arc settings, with crucial implications for the understanding of the architecture of magma plumbing networks in the lower crust. Finally, in Module 3 (Transient Geodynamics), the seminal work of Chris Gonzalez coupled, for the first time, geodynamic modelling with the solidi for carbonated basalts and sediments at pressures and temperatures relevant to upper mantle conditions. This was accomplished by a robust thermomechanical and petrological modelling framework previously applied to decarbonation of subducting slabs and in intracratonic settings.

See *Research highlights pp. 47, 53, 57-58, 58-59, 60-61, 64-65, 67, 71, 72-73, 78-79, 81*.

Published outputs for 2016

CCFS Publications: #630, 639, 644, 646, 657, 660, 686, 682, 797, 811, 813, 846, 847, 873, 879

> 25 Conference Abstracts

Marco Fiorentini hiking through the Cu-Mo prospect 'Alcaparossa' in the province of San Juan, Argentina, as a large storm drifts across the Cordillera Frontal (photo by Greg Poole).

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.

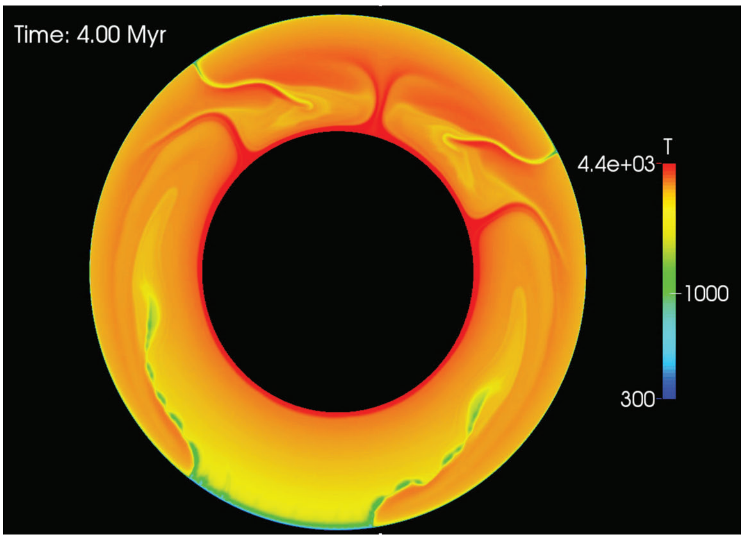
The new high-pressure experimental group at Macquarie joins this initiative to provide input on physico-chemical parameters of minerals, melts and fluids in the deep mantle, the composition of melts that infiltrate the lithosphere, and their effects on its geodynamics and stability.

2016 Report

In 2016, several features of our modified version of the code ASPECT, which has been in development over the past few years, have been improved. We revised the impact heating formulation in our model, and have applied it to the Hadean Earth to study how the Late Heavy Bombardment affects mantle and core evolution (see below). We also improved our melting treatment, which now takes into account vertical advection of heat/material during melt extraction and emplacement (known as the '*Heat Pipe*' model). This effect is crucial in early planetary body evolution and has not been treated in detail in previous global-scale models. Based on these developments, we are developing early lunar models to study the link between post-magma-ocean overturn and lunar crustal evolution.

A main aim of this program is the development of in-house computational simulation tools to model complex geochemical-geodynamic processes involving multiple-phase reactive flow in multi-component deformable media (MCMPRF). The mathematical formulation and computational implementation was copmpleted and benchmarked at the end of 2016 (*Oliveira et al. 2016; 2017*). This new MCMPRF approach is now being applied to study the evolution of trace-elements during melt generation, percolation and extraction in MOR environments and in 2017 we plan to apply it to study mantle metasomatism beneath continents as well as incorporate it into the ASPECT models developed in the global stream.

This year, we developed a method of joint tomography of body wave and surface wave, which enables us to image fine structures from the surface down to the transition zone. We applied this method to NE China to build a high-resolution crustal and upper mantle model by joint inversion of body wave travel-time and surface wave dispersion curves. The joint tomography significantly improves the resolution at shallow depths compared with the body-wave tomography, and provides seismic evidence for the origin and dynamics of Quaternary intraplate volcanoes in NE China. The new model supports the idea that mantle upwelling beneath the Changbaishan volcano originates from the mantle transition zone. The lithosphere beneath this region has been thinned to ~60 km, as revealed by the joint inversion model. Our model illustrates localised mantle upwelling beneath the Abaga and Halaha volcanoes in the Xinmeng belt, which is not directly related to the deep subduction of the Pacific slab, but more likely due to the mantle convection at shallow depths (see *Research highlights pp. 42-43).*



The evolution of Hadean Earth - Response of the early Earth to an extreme (1700 km radius) impact event. The large impact drives wholesale recycling of the proto-lithosphere.

Plans for the expansion to the high-pressure laboratory have been delayed due to the extension of the building plans to include the whole basement area of the building in which the experimental laboratory is located. A new laser-diamond anvil cell is under construction and should be ready for use in mid-2017, and an additional piston-cylinder apparatus will be acquired shortly. Experiments on electrical conductivity in mantle materials have been written up and submitted for publication, and projects on the role of blueschists in the production of volcanic melts in collisional areas (see *Research highlights*) and on the role of deep carbon under the continents are advanced.

See *Research highlights pp. 42-43, 68-69.*

Published outputs for 2016

CCFS Publications: #578, 656, 668, 675, 685, 706

13 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.

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. 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 pathways that connect geochemical reservoirs through time, linked to the changing tectonic style of the planet.

2016 Report

In 2016, we were engaged in a wide range of research activities, including the habitat of the earliest evidence for life on Earth, the adaptation of life across the Great Oxygenation Event, and global tectonics. Additional studies focused on the origin of boron in the newly discovered sinter deposits of the 3.5 Ga Dresser Formation, Western Australia, and the origin and variability of *'buckshot pyrite'* grains in a Neoarchean sedimentary-hosted gold deposit from the Pilbara region. Investigators participated in research activities in Australia, China, India, Japan and New Zealand, studied Martian meteorites, and helped guide NASA in their decision on where to land their Mars2020 rover. The UWA component focused on two main themes:
1) new constraints on the scale and rate of sulfur cycling in Proterozoic orogens and
2) new insights into the role of sulfides in the fractionation and concentration of chalcophile and siderophile elements in Martian igneous systems.

The presence of mass-independent fractionated sulfur in the Proterozoic granitoid rock record has the potential to revolutionise our understanding of secular changes in the evolution of crust formation mechanisms through time.

The discovery of the first platinum group mineral in a Martian meteorite provides new constraints on the redox state and metal budget of the Martian mantle.

FP4 research included colleagues from Australia, Europe, Japan and the USA. Fieldwork was conducted in Australia's Pilbara, Hamersley and Ashburton regions, in the Archean Barberton Greenstone Belt of South Africa, in the Ladakh region of northern India, and in the northern Cape Province of South Africa. Collaborative fieldwork activities included Dr Mark van Zuilen of the Institute de Physique du Globe de Paris (IPGP), and Prof Carsten Münker of the University of Cologne, Germany.

The Astrobiology Australasia 2016 meeting (Perth, 120 participants) was followed by a fieldtrip (25 participants) to see the ancient life of the Pilbara. CI Van Kranendonk also led a fieldtrip for a group of 50 German researchers across the southern Barberton Greenstone Belt.

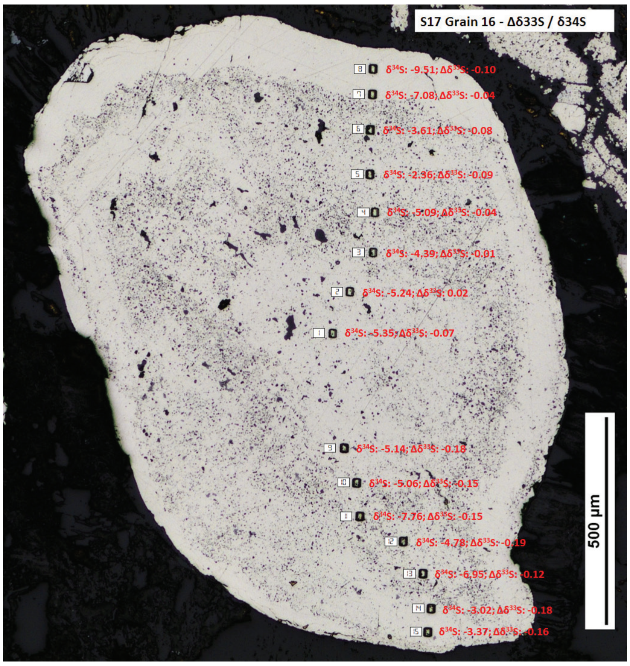
FP4 participants attended the NASA Mars Biosignatures workshop in Lake Tahoe, NV, and the 35th International Geological Congress in Cape Town, South Africa. Visiting scholars Professor Clark Johnson (U. Wisconsin at Madison) and Dr Michelle Gehringer spent time at UNSW. Filming roles on ABC TV's *"The Living Universe"* and December Media's IMAX 3-D documentary *"Earth Story"* feature CI Van Kranendonk and UNSW PhD student Tara Djokic.

See *Research highlights pp. 41, 54-55, 64-65, 66, 70.*

Published outputs for 2016

CCFS Publications: #630, 639, 644, 657, 660, 682, 683, 686, 697, 699, 791, 797, 811, 813, 829, 837, 874, 847

16 Conference Abstracts



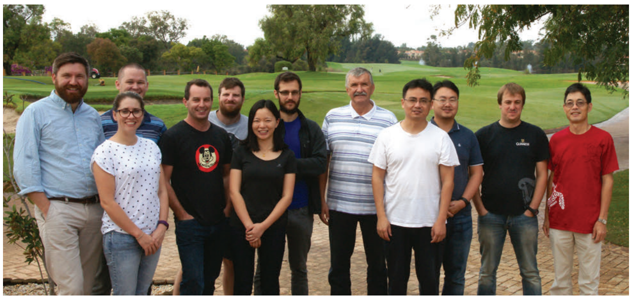
Scanning electron microscope image of a Neoarchean 'buckshot pyrite' grain from the 2.76 Ga Beatons Creek deposit, Pilbara, Western Australia. Grain shows textural and sulfur isotopic zonation, indicative of microbial precipitation from a water source with varying sulfate availability, probably a seasonally fluctuating stream. Image courtesy of Chris Guldbrandsen, UNSW.

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.



Members from Flagship Program 5.

2016 Report

In situ SHRIMP U-Pb dating of mafic dyke samples collected from SW Yilgarn during 2015 and 2016 was conducted. TIMS U-Pb analysis was undertaken in collaboration with UWA and Lund University (Sweden), confirming the presence of three previously unstudied dyke suites in SW Yilgarn Craton. Geochemical analyses were carried out for selected Yilgarn and Bunger Hills (Antarctica) dyke samples. Two additional paleomagnetic sampling trips were carried out on the Yilgarn dykes, and we are now trying to generate three new, high-quality paleomagnetic poles for Precambrian Yilgarn.

One sampling trip to the Gawler Craton targeting the Gawler Range Volcanics and the Gairdner Dolerites was conducted. Samples from 30 sites were collected and will be analysed by PhD student Yebo Liu in 2017. Pilot paleomagnetic sampling was also carried out on South Australia's Truro Volcanics (~526 Ma) and the Gairdner Dykes (~827 Ma) in a Broken Hill Mine.

Detailed basin studies have been conducted on the Ediacaran-Silurian of South China, especially on the Cathaysia and southeastern Yangtze side. Field sampling and sedimentary section logging continued, and most provenance analytical work has been completed through collaborations. Two new papers reported our results on South China's basin record during its collision with northern Gondwana (#710), and on Hainan Island's record of the supercontinents Nuna and Rodinia (#883), were published. Pilot provenance studies were also conducted on the Cambrian and Devonian sedimentary rocks in the Ord basin, Kimberley; the results will be used for testing Australia's connections to Asian continents during the Paleozoic.

A new key paleomagnetic pole and a 1975 Ma paleogeographic reconstruction of Fennoscandia were published (#882). New analysis of geological time series using a novel approach with sample weights proportional to continental surface areas established a strong correlation between the detrital-zircon and LIP age spectra (#840). We also analysed the accretional/collisional orogens and passive margins of the '*Iapetian*' parts of Rodinia during its evolution with implications for models of supercontinent cycles (#815, 888), and discovered the LIP barcode and paleomagnetic correlation of the Siberian, Congo, São Francisco and North China cratons, leading to a new model for their paleopositions in Nuna (#628). We also reported the first Ordovician paleomagnetic poles for the New Siberian Islands (Arctica) (#648).

IGCP 648, co-led by CCFS CI Li, is progressing well, including the publication of the CCFS-sponsored Geological Society of London Special Publication 424, and the compilation of global paleomagnetic and geological databases. For more achievements of IGCP 648 see http://geodynamics.curtin.edu.au/igcp-648/.

See *Research highlights pp. 44-45, 48, 58-59, 63-64, 73-74.*

Published outputs for 2016

CCFS Publications: #642, 648, 664, 687, 709, 710, 723, 789, 790, 792, 798, 802, 804, 814, 815, 840, 869, 882, 883, 888, 891, 892, 893, 894, 897, 898

19 Conference Abstracts

Uwe Kirsher camped within the Hiltaba Suite granites as part of a Paleomagnetic sampling campaign in the Gawler Ranges.

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. In this program, the geochemical signatures of zircon crystals from all known Hadean and early Archean localities will be utilised, together with geochemistry of the oldest known rocks and the application of geophysical and geochemical modelling, to establish how the first crust formed, why it was destroyed, and the role fluids played in this process. The changes that took place throughout the Archean will also be 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 will provide further constraints on the early history of the Solar System, especially the role played by fluids.

2016 Report

A major new initiative commenced on the Jack Hills detrital zircon suite from NW Australia with the aim of characterising the most pristine portions of the grains. Although there is a huge amount of published data on such crystals, it remains unclear what the true age spectra of the grains and the nature of their isotopic signature are. Solving these problems will place precise constraints on the earliest crust. Former CCFS PhD student Dr Rongfeng Ge was appointed to investigate these issues. The isotopic study of another former PhD student, Dr Qian Wang, which includes over 6,000 U-Pb zircon analyses from her traverse through the entire Jack Hills belt, has been prepared for publication. Work on the identification of CO_2 inclusions in Jack Hills' zircons, in conjunction with German colleagues, is currently in revision.

Work continued on zircons obtained from the ancient gneisses of Labrador. SHRIMP and CAMECA 1280 data have been compiled and several areas targeted for further investigation in 2017. The Nd study on TTG rocks from the Anshan area of the North China Craton, with ages between 3.8-3.0 Ga, has been completed. There are no systematic variations in ^{142}Nd with age, but several rocks do show positive Nd anomalies. Also in China, work continued in the Kuruktag area of the northern Tarim Craton. Here, a newly-identified tonalite unit records an age of 3.7 Ga making it one of the oldest rock units in China. Additional zircon U-Pb and Lu-Hf analyses were undertaken on samples from Aker Peaks in Kemp Land, Antarctica, to better characterise their age and provenance. The metallic lead nanospheres in Napier Complex zircons were further characterised using NanoSIMS and an atom probe study will commence in early 2017.

Precise dating of phosphates in breccias from the Apollo 14 landing site has revealed a 10-15 Ma difference in age, indicating two impact events; a similar feature is observed at the Apollo 17 site. Work continued developing a chronology of lunar events, with evidence for major mantle differentiation at 4370 Ma and a major basalt-producing event at 4330 Ma. Ion imaging studies have shown that all zircons < 4 µm in size have been reset by impacts at approximately 4.2 Ga. Evidence for major differentiation of the Martian mantle at 4.5 Ga has been revealed by studies of both shergottite and pyroxenite meteorites. Martian breccia sample NWA7533 has plagioclase with a very primitive Pb composition, making the host fragments the oldest known material in the solar system.

Published outputs for 2016

CCFS Publications: #703, 705, 960, 961

6 Conference Abstracts

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

Iron, Gold and Nickel deposits are of global economic significance, and the Neoarchean Yilgarn Craton and the Proterozoic orogens around its margins constitute one of Earth's greatest mineral treasure troves. Whereas the Yilgarn Craton is one of the best-studied Archean cratons, its enormous size and limited outcrop are detrimental to a deep understanding of what controls the distribution of resources and which geodynamic processes were involved in the tectonic assembly of the Australian continent. This program combines geological, geochemical and geophysical techniques to propose a 3D structural model of the lithosphere of the Yilgarn Craton and its margins. The Yilgarn Craton is a highly complex piece of Archean crust with a long history extending from 4.4-2.6 Ga: amalgamation of terranes is thought to have occurred around 2.65 Ga. The program includes the Capricorn Orogen Passive Array (COPA), a passive source experiment that studies the structure of the deep crust and shallow lithosphere using earthquake seismology. The data from this experiment will be the main source for the local ambient noise inversion, the receiver function common convection point (CCP) stacking techniques, and possibly a body-wave tomography study. Given the fact that the passive source site coverage in Western Australia is sparse and that the available permanent sites in the region provide nearly 10 years of data at isolated locations, several techniques that focus on crust and upper mantle structure beneath single stations will also be applied. This approach has the potential to provide quick access to the crustal and lithospheric structure from these representative sites.

2016 Report

Recent work by GSWA in the northwestern part of the craton has identified a long-lived, autochthonous history of crustal development there. There is a growing realisation that understanding how mineralised crustal provinces form requires structural and chemical information on the entire lithosphere. This is addressed in the CCFS-associated multi-disciplinary SIEF project *"The Distal Footprints of Giant Ore Systems: UNCOVER Australia"*, which involves collaborative research between CSIRO, UWA, Curtin and GSWA, and targets the Capricorn Orogen at the northern boundary of the Yilgarn Craton.

The Capricorn Orogen Passive-source Array (COPA) field deployment reached a critical phase in 2016. In June and July, the western half of the COPA stations were moved over to the eastern region. By the end of the year, over two thirds of the array coverage had been achieved. By November 2017 the rest of the orogen will have been covered and the array will have recorded sufficient data for processing. In 2016, the data collected from previous services were analysed with a focus on the seismic structure of the Capricorn orogen crust. Two sub-projects targeting the crust of the Glenburgh Terrane and its northern boundary were conducted and yielded very intriguing results. From the seismic perspective, the interpretation favours that in between the Archean Pilbara and Yilgarn cratons, the Glenburgh terrane represents a microcontinent with strong Archean heritage that was caught and deformed during the assembly of the Western Australian craton. The Capricorn orogen therefore also preserves a unique piece of crust that may have witnessed the transition of crust-formation processes from early Archean vertical tectonics to the modern-style subduction related plate tectonics. The results were presented at several international meetings (including keynote presentations) and are currently in preparation for publication.

See *Research highlights pp. 44-45, 50-51.*

Published outputs for 2016

CCFS Publication: #704

4 Conference Abstracts

Figure 1. Successful deployment of a trial station for the Canning Basin project near Broome, WA.

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 2016 and plans for 2017, please see pp. 93-94 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 2016 and plans for 2017, please see pp. 89-93 in Technology Development

Appendix 2: CCFS workplan 2017

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

Continued research in Tibet will focus on the complete mapping the Kangjinla chromitite bodies and mapping of lherzolite/harzburgite boundaries in other massifs. In addition, mineral separation and analysis of SiC isotopes and inclusions as well as other SuR-UHP phases will be carried out.

Work in Israel will be summarised in papers on the SiC isotopes, alloy phases and zircons. Mineral separations and analysis will be undertaken on samples from selected vents. Upstream tracking of specific phases will also be used to identify primary sources for alluvials.

Pyroxenite studies will include the publication of EBSD and petrological work on Cabo Ortegal Complex in northern Spain. A field trip is planned to sample the Trinity Ophiolite in California. Analysis of these samples will be compared with results from the Cabo Ortegal. Studies of Victorian pyroxenites will also be completed and published.

Activities planned for samples from Iran include:
1) Completing the Hf isotope analysis on detrital zircons from the Neoproterozoic sediments and publication of results, 2) Completing zircon U-Pb ages and publication of data on the Cenozoic '*flare-up*', 3) Completing and publishing EBSD and petrological work on mantle peridotites, 4) Completing and publishing data on Neoproterozoic delaminated gabbros and pyroxenites from the deep crust.

Kimberlite work will focus on completing and publishing isotopic/petrographic studies of primary carbonates.

2. GENESIS, TRANSFER AND FOCUS OF FLUIDS AND METALS

The integrated plan of action for 2017-2018 aims to take all currently ongoing studies to a successful completion. The focus on porphyry studies will continue into next year, consolidating datasets from Tibet. Bob Loucks will continue his effort to unravel the relationship between volatile endowment (and speciation) and emplacement dynamics of mineralising felsic magmas in arcs. The PhD thesis of Katarina Bjorkman will be submitted in early 2017, whereas the other studies in the Ivrea Zone and in South America will continue into 2018. Work on alkaline magmatism in the Yilgarn Craton will be accelerated in 2017, with a large campaign of isotopic and trace element data acquisition that began in late 2016. This work will strengthen collaboration among different CCFS nodes as different expertise is available at multiple institutions. In terms of modelling, we will investigate the fate of carbonated sediments during subduction and slab break-off. Three implications arise from this work: 1) these models confirm that carbon is filtered out at upper mantle conditions, suggesting a carbon increase in the upper mantle over time; 2) carbonate melting in the mantle transition zone may be an important source component for organic carbon signatures of eclogitic diamonds; and 3) the base of the subcontinental lithospheric mantle may be enriched by percolation of carbonatitic melts acting as a nucleation point for continental breakup.

3. MODELLING FLUID AND MELT FLOW IN MANTLE AND CRUST

In 2017, the matured modelling techniques will be applied to a variety of geodynamic problems in the mantle and crust. This will involve a suite of simulations exploring the dynamics of subduction over Earth's history, and its effect on fluid systems. We will also further integrate the newly developed advanced methods for multiphase/component flow with large-scale geodynamic flow models to explore the effects of realistic fluid release and migration on geodynamic model predictions. These will then be integrated with seismology constraints.

Seismology components of this project will focus on imaging the lithosphere-asthenosphere system in NE China, where the oceanic subduction in the east has profound impacts on geological features such as the destruction of NE China Craton keels, extensive intraplate volcanism and a systematic variation of topography from west to east.

Activities in the experimental laboratory will be transferred to the piston-cylinder laboratory, which will remain open whilst the multi-anvil laboratory is being renovated. Projects will include formation of early continental crust, melting of volatile-rich mantle rocks, partitioning of nitrogen between minerals and melts, and interactions between carbonate and mantle rocks. Construction of the laser-heated diamond-anvil cells will be finalised during 2016.

4. ATMOSPHERIC, ENVIRONMENTAL AND BIOLOGICAL EVOLUTION

Research will continue on established CCFS FP4 projects, including:
(1) the early life setting and composition at North Pole - Van Kranendonk (CI), Djokic (PhD), Steller (PhD), Tadbiri (MPhil), Fiorentini (CI), Baumgartner (Post-doc), Johnson (UWisc), Satkowski (UWisc), Nakamura (Okayama U);
(2) the composition of Archean seawater and organics - Reitner and Duda (Gottingen);

(3) the adaptation of life across GOE - Erica Barlow (UNSW), Soares (PhD), Nomchong (PhD), Bannister (MPhil), Blake (MPhil, with Simon George);
(4) the planetary driver of atmospheric, environmental and biological change through the Precambrian (Van Kranendonk, Kirkland); and
5) the characterisation of sulfur in the history of Mars (Fiorentini, Baumgartner).

5. AUSTRALIA'S PROTEROZOIC RECORD IN A GLOBAL CONTEXT

All the new findings from southwest Yilgarn and the Gawler craton, including the newly dated mafic dyke suites/swarms and their paleomagnetic implications in terms of supercontinent cycles, will be written up for publication as a series of high-impact papers. Final results from the detailed geochemical analyses and isotope studies of the Bunger Hills (Antarctica) dyke samples will be published. Paleomagnetic samples from the Kimberley will be analysed, and additional sampling may be carried out on a ca. 1.85 Ga ring complex and the ca. 1.8 Ga Davenport Province of the Northern Territory.

The study on the Ediacaran-Silurian of the western Yangtze will be finished in 2017, and summarised in a tectonostratigraphic history of the targeted strata, including how the detritus may have been shed from the Gondwana source regions to the Yangtze Block. The South China record will be compared with the new results from Western Australia, and we will synthesise their possible past connections at the dynamic northern margin of Gondwana.

One of the major showcases of our work will be the CCFS co-sponsored IGCP 648 event, the Rodinia 2017 conference to be held in Townsville in June 2017 (for information see http://geodynamics.curtin.edu.au/rodinia-2017/)

6. FLUID REGIMES AND THE COMPOSITION OF EARLY EARTH

Work in Australia will focus on Jack Hills. The oldest zircons from the original W74 sample will be identified and characterised for all isotopic systems in order to place the most stringent constraints yet on the nature of Earth's oldest crust. In addition, the extent of the younger events in the Jack Hills belt will be re-investigated to resolve the depositional age and any affects related to metamorphism. The Pb nanospheres in ancient zircons from the Napier Complex, Antarctica, will be investigated using the atom probe to precisely determine their distribution and isotopic composition. Work on the Kemp Land samples will be completed. Another fieldtrip to Labrador will be undertaken in mid-2017 to more closely define the distribution of the most ancient gneissic components. A fieldtrip is planned to the Kongling area in South China to sample the most ancient rocks in the South China block in order to investigate their similarity or otherwise to the ancient gneisses in the North China Craton. Work will continue on both Lunar rocks and Martian meteorite samples with the aim of constraining the precise timing of events in the early solar system.

7. PRECAMBRIAN ARCHITECTURE AND CRUSTAL EVOLUTION IN WA

The structural imaging of the seismic data will be the first main task for 2017. With now over two thirds of the study area covered, Capricorn orogen-wide images of the crustal velocity and the spatial variation of crustal discontinuities (for example the Moho) will be produced, and the results will be passed to other research groups within the SIEF Capricorn project for mineral potential analyses. Secondly, seismic velocities of the entire lithosphere of the orogen will be developed using body wave tomographic techniques. The model will provide direct input to correlate mineralised crustal provinces and lithospheric structural anomalies. Thirdly, the crust and lithosphere imaging tools developed and tested in the Capricorn region can now be used in other regions in Western Australia. High-resolution crustal velocity images will be produced following the previous and planned deployments in the western-central region and the southwestern margin of the Yilgarn Craton.

A major focus will be the development of more field projects through various collaborating efforts in Western Australia.
An initial agreement between Macquarie University, GSWA and the Institute of Geology and Geophysics, Chinese Academy of Sciences states that in the middle of 2017 a major 60 broadband seismic deployment will commence which targets the Canning Basin and the margins of the neighbouring Pilbara and Kimberley cratons. A 30-site ocean bottom seismic deployment is planned to follow later in the year, which will provide spatial coverage to offshore areas of the Canning basin. Early in 2017 collaboration between CET-UWA and GSWA has resulted in a 25-station deployment in the Perth region to target the young Perth Basin and the southwest Yilgarn craton margin.

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. 101-104.*

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.
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:*** This project is dedicated to developing a proton conduction model for the Earth's upper mantle to allow for correct interpretation of magnetotelluric data such as those currently being collected by the Australian AusLAMP initiative.

The global consequences of subduction zone congestion	**L. Moresi**, P. Betts, J. Whittaker, M. Miller: *Supported by ARC Discovery (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.
Timescales of mixing and volatile transfer leading to volcanic eruptions	**H. Handley**, **S. Turner**, M. Reagan, J. Barclay: *Supported by ARC Discovery (commenced 2015)* ***Summary:*** The short-lived lead isotope, ^{210}Pb, has the unique ability to place timescale constraints on volcanic processes, such as the input, mixing and degassing of magma. These processes are believed to be of fundamental importance in the triggering of volcanic eruptions. This project will measure ^{210}Pb isotopic compositions and elemental diffusion profiles in crystals of volcanic rocks that represent the end members of mixed magmas to constrain the volume and timescale of volatile transfer from magmatic recharge and also the time between magma mixing events and eruptions. The project aims to test the paradigm that magma recharge triggers volcanic eruptions and aims to yield significant outcomes for understanding eruption triggers at hazardous volcanoes.
Migmatites, charnockites and crustal fluid flux during orogenesis	**I. Fitzsimons**, M. Holness, **C. Clark**: *Supported by ARC Discovery (commenced 2015)* ***Summary:*** Migration of volatile fluid and molten rock controls many Earth processes including rock deformation and the formation of mineral and energy deposits. Deep crustal fluids are hard to study directly, and their characteristics are usually inferred from lower crustal rock brought to the surface by erosion. For over 30 years one such rock called charnockite has been used to argue that lower crust is dehydrated by influx of carbon dioxide-rich fluid, while other evidence supports dehydration by water extraction in silicate melt. This project aims to use the shape, distribution and chemistry of mineral grains to trace the passage of volatiles and melt through charnockite, constrain the nature of lower crustal fluids and resolve a long-standing controversy.
How the Earth works-toward building a new tectonic paradigm	**Z.X. Li**: *Supported by ARC Laureate Fellowships (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.
From Core to Ore: emplacement dynamics of deep-seated nickel sulphide systems	**M. Fiorentini**: *Supported by ARC Future Fellowship (commenced 2012)* ***Summary:*** Unlike most mineral resources, which are generally concentrated in a wide range of crustal reservoirs, nickel and platinum are concentrated either in the core or in the mantle of our planet. In punctuated events throughout Earth history, large cataclysmic magmatic events have had the capacity to transport and concentrate these metals from their deep source to upper crustal levels. This project aims to unravel the complex emplacement mechanism of these magmas and constrain the role that volatiles such as water and carbon dioxide played in the emplacement and metal endowment of these systems.

The timescales of Earth-system processes: extending the frontiers of uranium-series research	**H. Handley**: *Supported by ARC Future Fellowship and MQ (commenced 2012)* ***Summary:*** This project will advance our understanding of the timescales of Earth processes using short-lived (22 to 380,000 years) isotopes. The results will provide better constraints on the timescales of magmatic processes and frequency of large-scale eruptions for volcanic hazard mitigation and also soil production rates for landscape erosion studies.
A new approach to quantitative interpretation of paleoclimate archives	**D. Jacob**: *Supported by ARC Future Fellowship and MQ (commenced 2013)* ***Summary:*** Skeletons of marine organisms can be used to reconstruct past climates and make predictions for the future. The precondition is the knowledge of how climatic and environmental information is incorporated into the biominerals. This project will use cutting-edge nano-analytical methods to further our understanding of how organisms build their skeletons.
New insights into the origin and evolution of life on Earth	**D. Wacey**: *Supported by ARC Future Fellowship and MQ (commenced 2014)* ***Summary:*** This project aims to provide new insights into the origin of life on Earth, life's diversification through the Precambrian, and the co-evolution of life and early Earth environments. It will be discipline-leading in that it will take the study of early life to the sub-micrometre and hence sub-cellular level. This will facilitate new opportunities for identifying the types of life present during early Earth history, their metabolisms, cellular chemistry and interactions with their environment. This project aims to also provide new search engines and more robust assessment criteria for life on other planets, and help to resolve specific scientific controversies, for example, the validity of claims for cellular life from 3.5 billion-year-old rocks.
Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	**X.C. Wang**: *Supported by ARC Future Fellowship and MQ (commenced 2014)* ***Summary:*** This project aims to test a provocative and potentially ground-breaking hypothesis that fluid released from subducted oceanic slabs and stored in the mantle transition zone, may trigger or control some major intra-plate geotectonic phenomena. It aims to provide a self-consistent model that links geological processes occurring at plate boundaries with those far-field effects well away from plate boundaries via deep-Earth fluid cycling. The outcomes of this project aim to help to better understand links between plume and plate tectonic processes in the first-order dynamic system of Earth, and identify ways to improve success in future mineral exploration.
How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	**Y. Yang**: *Supported by ARC Future Fellowship (commenced 2013)* ***Summary:*** The concept of small-scale convection currents from about 100-400 km below the Earth's surface is a model proposed to explain the origins of intraplate volcanoes and mountains. However, direct evidence for the physical reality of small-scale convection cells is generally weak. This project will develop a novel seismological approach combining both ambient noise and earthquake data that can image such small-scale upper mantle convection. The outcomes of this project will help to fill the gap left in the Plate Tectonic paradigm by its inability to explain intraplate geological activity (volcanoes, earthquakes, mountains), which would be a significant step towards unifying conceptual models about how the Earth works.
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 of 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.

Measuring mantle hydrogen to map ore fluids and model plate tectonics	**K. Selway**: *Supported by ARC Future Fellowship (commenced 2015)* ***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.
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.
A new approach to revealing the composition of kimberlite melts and their deep mantle source	**A. Giuliani**: *Supported by a Marie Curie Grant (commenced 2015)* ***Summary:*** The overarching aim of this project is to provide novel constraints on the composition of the Earth's deep mantle, particularly its volatile content, by undertaking an innovative geochemical and isotopic study of the deepest formed melts on Earth: kimberlites. Kimberlite melts are derived from depths in excess of 150-200 km. They are important as the major host of diamonds because they entrain xenoliths (i.e. fragments) of upper mantle and deep crustal rocks during ascent to the surface, providing a major source of information about the geochemistry of the deep Earth. Despite their importance, the composition of primary kimberlite melts and their exact mantle source are hotly debated issues. This is due to contamination of kimberlite melts by mantle and crustal rocks during magma emplacement and near surface alteration of primary kimberlite mineralogy. To determine the composition of primary kimberlite melts, I will employ a novel approach that combines radiogenic (Sr-Nd-Pb) and stable (C-O) isotope fingerprinting of melt inclusions in kimberlitic magmatic minerals (i.e. olivine and spinel). This approach will constrain whether the carbonate-dominated melt inclusions truly represent examples of pristine kimberlite magma by quantifying processes like crustal contamination and degassing that may have altered the melt composition. I will investigate kimberlites from targeted localities from different parts of the world (South Africa, Canada, Greenland, Russia) and of variable ages (Proterozoic to Cretaceous) to assess if there are spatial and/or temporal controls to kimberlite composition. This information would provide important new constraints on the global cycle of volatiles through geological time.
IGCP project: Supercontinent cycles and global geodynamics	**Z.X. Li**, D. Evans, S. Zhong and B. Eglington and Co-Leaders, and around 170 members from around the world: *Supported by UNESCO-IUGS IGCP (commenced 2016)* ***Summary:*** In this project, we will bring together a diverse range of geoscience expertise to explore the occurrence and evolution history of supercontinents through time, in the process to construct global databases of geotectonics, mineral deposits, and the occurrences of past mantle plume events. We will further utilise all information collected to conduct better-constrained geodynamic modelling on how the Earth's engine works in the first order, and how the supercontinent cycles interacted with the mantle to produce episodic and unevenly distributed Earth resources.

Australian membership of the International Ocean Discovery Program	R.J. Arculus, E.J. Rohling, A.P. Roberts, N.F. Exon, C.J. Yeats, **S.Y. O'Reilly**, **S.C. George**, D. Muller, J.C. Aitchison, J.M. Webster, M.F. Coffin, P.M. Vasconcelos, K.J. Welsh, **T.C. McCuaig**, A.D. George, C.G. Skilbeck, A.T. Baxter, J.M. Hergt, S.J. Gallagher, C.L. Fergusson, C.R. Sloss, A.D. Heap, W.P. Schellart, J.D. Stilwell, J.D. Foden, A.P. Kershaw, W.R. Howard, M.B. Clennell, J.J. Daniell, L.B. Collins: *Supported by ARC LIEF (commenced 2014)* ***Summary:*** This project is for an Australian membership of the International Ocean Discovery Program. The Program will recover drill cores, situate observatories, and conduct down-hole experiments in all the world's oceans from lowest to highest latitudes to address fundamental questions about Earth's history and processes within four high-priority scientific themes: climate and ocean change - reading the past and informing the future; biosphere frontiers - deep life, biodiversity, and environmental forcing of ecosystems; Earth connections - deep processes and their impact on Earth's surface environment; Earth in motion - processes and hazards on a human time scale.
Australian virtual experimental laboratory: a multimode geoscience facility	**S. Foley**, J. Mavrogenes, A. Putnis, J. Brugger, **S. Clark**, H. O'Neil, A. Cruden, K. Evans: *Supported by ARC LIEF (commenced 2016)* ***Summary:*** This project aims to establish seven types of high-pressure equipment to form a multi-node experimental laboratory at four locations across Australia. Experiments conducted at the high pressures and temperatures of the internal Earth form the basis of our knowledge about the physical and chemical processes that drive geological processes such as plate tectonics, melting to form volcanoes, and the formation and movement of fluids that concentrate precious metals into valuable ore deposits. The new facility may enable major advances in fields such as mantle geodynamics and element transport in fluids, improving our understanding of internal Earth processes and ore deposit formation and location. It also includes portable systems, which can be used in synchrotron applications.
NanoMin: quantitative mineral mapping of nanoscale processes	M. Kennedy, C. Sorrell, D. Haberlah, D. Dewhurst, **S. Turner**, D. Gore, **S. O'Reilly**, **M. Van Kranendonk**, J. Foden, P. Nelson, M. Haghighi, P. Le-Clech, C. Ward, P. Koshy, N. Sherwood: *Supported by ARC LIEF (commenced 2016)* ***Summary:*** The project seeks to establish an electron microscope-based mineral mapping and analysis facility to provide rapid, quantitative and statistically reliable mineralogical, petrographic and metallurgical data unobtainable by other means in fine-grained materials. The proposed equipment can identify minerals in complex mixtures of sub-μm-grain size materials by virtue of an integrated software and hardware system called NanoMin which incorporates a spectral deconvolution engine combined with a mineral spectra database. A key limitation in understanding complex materials is sub-micron to nanometre scale spatial variability of mineralogical phases. Imaging and quantifying these phases is now possible with the NanoMin system. This promises to open up petrological, geobiological, and materials science research in complex fine-grained materials.
The Ediacaran-Silurian palaeogeography of western Yangtze Block and its tectonic linkage with the Gondwana assembly	**W. Yao**, J. Wang, X. Zhou: *Supported by the China Geological Survey and CU (commenced 2015)* ***Summary:*** This project targets the Ediacaran-Silurian sedimentary packages on the western margin of the Yangtze Block, by analysing its sedimentary facies and environments, tracking the provenances of the targeted sedimentary detritus as well as the basin fillings. Based on the sedimentary facies and provenance results, it aims at correlating the western Yangtze Ediacaran-Silurian sedimentary strata with the coeval sedimentary packages of other continents on the northern Gondwana margin (e.g. north India, western Australia etc.), and investigating the paleogeographic linkages amongst those areas. Together with the well-known paleogeographic link between the Cathaysia Block and northern Gondwana during the Ediacaran-Silurian, this project will evaluate the paleogeography of South China in the supercontinent assembly and its geodynamic significance.

Genesis of comb quartz layers: case studies from porphyry Cu deposits at Qulong, Tibet and Now Chun, Iran	Z. Yang, **Y. Lu**: *Supported by NSFC (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 the nature and variation of initial ore-forming fluids in the two deposits; (2) clarify the genesis of comb quartz layers; and (3) identify the sources of ore-forming fluids for porphyry Cu system.
China-Western Australia Seismic Survey (CWAS)	L. Zhao, **H. Yuan**: *Supported by the Institute of Geology and Geophysics, Chinese Academy of Sciences (commenced 2016)* ***Summary:*** IGGCAS, Macquarie and GWSA will install a 900 km-long dense (station spacing of 10-15 km) seismic profile across the Western Australia from Port Hedland to the southwestern border of the Kimberley Craton. The project will include 80 broadband seismic stations for 18 months from April 2017 to October 2018 with IGGCAS to provide seismic instruments for 60 stations. A test station was installed in Oct 2016.
From space to the deep Earth	**J.C. Afonso**, J. Ebbing: *Supported by Germany-Australia Joint Research Cooperation Scheme and MQ University (commenced 2016)* ***Summary:*** We will develop a novel joint analysis of satellite-derived gravity-magnetic datasets and land-based seismic data within a 3D probabilistic inversion framework. This project thus marks the beginning of a new field in integrated Earth imaging methods and provides an unprecedented opportunity to produce the first images of the thermal and mineralogical structure of the Earth's lithosphere. We will apply this method to GOCE and Swarm satellite data, as well as to global seismic data, to improve our understanding of the roles of lithospheric vs deep mantle mechanisms in controlling near-surface processes. The outcomes of the project will also provide key information for society-relevant activities such as ore and energy exploration and natural hazard assessment.
Maintaining and upgrading the Global Palaeomagnetic Database	**S.A. Pisarevsky**: *Supported by NSFC University of Oslo (commenced 2015)* ***Summary:*** Maintaining and upgrading the Global Palaeomagnetic Database (GPMDB) (*http://www.ngu.no/geodynamics/gpmdb/*), which was originally developed by McElhinny and Lock (*1996, Surv. Geophys. 17, 575*). Updated versions of the GPMDB will be delivered electronically in Microsoft Access database format twice a year (June and December). At Oslo University the updated versions will subsequently be incorporated in both the GPMAP (*Torsvik and Smethurst 1999, Computers & Geosciences 25, 395-402*) and GPlates (*www.gplates.org*) software and made available electronically online.
Defining mineral systems footprints in the Edmund Basin of the Capricorn Orogen	**H. Lampinen**, S. Occipinti: *Supported by the Australian Society for Exploration Geophysicists (commenced 2014)* ***Summary:*** The results of this project will lead to a fully integrated and ground truthed geological-geophysical map and a 3D basin architecture model containing the information and analysis of the mineral assemblages detected from the spectral signatures. In addition, the project aims to produce a detailed methodology in how to use the selected datasets as an exploration tool.

Carbon isotope evolution of the deep Earth from coupled C-O isotope SIMS measurement of carbonates In kimberlites

A. Giuliani, **M. Castillo-Oliver**: *Supported by a Europlanet 2020 Research Award (commenced 2016)*

Summary: Kimberlites are carbonate-rich volcanic rocks that represent the deepest-derived melts at Earth's surface. They have formed since at least ~2.5 Ga and represent a unique probe of the deep Earth. Understanding the C isotope evolution of kimberlites and their mantle source(s) through space and time can provide fundamental new clues on the time-integrated deep C cycle. To constrain the C-O isotope composition of kimberlites, we will examine the C-O isotope composition of kimberlite carbonates by SIMS. Selected samples include kimberlites from South Africa, Canada, Finland, Brazil and Australia emplaced at between 2.0 Ga and 50 Ma and whose petrography and geochemistry has been thoroughly investigated. SIMS analyses of the C-O isotope composition of texturally and geochemically well-characterised carbonates will permit, for the first time, determination of the magmatic signature of kimberlite carbonates, which was previously hampered by the employment of bulk analytical techniques to (partially) altered samples. This approach, coupled with other isotopic systems (e.g. S, N) that are sensitive to crustal contribution, will allow evaluation of the extent of crustal C recycling in the kimberlite source over the last 2.0 Ga. This project has implications for understanding of the temporal evolution of Earth's mantle and exosphere and potentially major implications for other terrestrial planets.

Appendix 4: Participants list

Chief Investigators

- Professor Suzanne Y. O'Reilly (Centre Director, MQ)
- Professor T. Campbell McCuaig (Node Director, UWA) *until July 2016*
- Professor Simon Wilde (Node Director, CU)
- Dr Elena Belousova (MQ)
- Associate Professor Simon Clark (MQ)
- Associate Professor Marco Fiorentini (Node Director, UWA) *from July 2016*
- 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)
- Associate Professor Norman Pearson (MQ)
- Professor Martin Van Kranendonk (UNSW)
- Associate Professor Yingjie Yang (MQ)

Associate Investigators

- Associate Professor Juan Carlos Afonso (MQ)
- Dr Olivier Alard (MQ)
- Associate Professor Christopher Clark (CU)
- 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 Christopher Kirkland (CU)
- Associate Professor Mary-Alix Kaczmarek (University Paul Sabatier Toulouse III)
- Professor Jochen Kolb (GEUS and KIT, Germany)
- Dr Yongjun Lu (GSWA at UWA)
- Dr Louis-Noel Moresi (University of Melbourne)
- Associate Professor Sandra Piazolo (MQ)
- Professor Steven Reddy (CU)
- Associate Professor Tracy Rushmer (MQ)
- Associate Professor Bruce Schaefer (MQ)
- Professor Paul Smith (MQ)
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- Professor Michael Brown (University of Maryland, USA)
- Dr Klaus Gessner (Geological Survey of Western Australia)
- Professor David Mainprice (Université de Montpellier, France)
- Professor Catherine McCammon (Bayreuth University, Germany)
- Professor Fuyuan Wu (Chinese Academy of Science, China)

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- Ms Sally-Ann Hodgekiss, Reporting & Coms. Manager (MQ)
- Ms Summer Luo, Centre Finance & Admin Officer (MQ)
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- Ms Gillian Evans, Business Manager (CET, UWA) *until June 2016*
- Ms Keng Chai Ng, Finance Officer (CET, UWA) *from July 2016*
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- Mr David Adams (MQ) *until Jan 2016*
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- Mr Steven Craven (MQ)
- Ms Sarah Gain (MQ)
- Dr Oliver Gaul (MQ)
- Mr Anthony Lanati (MQ)
- Ms Lauren Miller (MQ) *until June 2016*
- Dr William Powell (MQ) *until March 2016*
- Mr Farshad Salajegheh (MQ)
- Mr Peter Wieland (MQ)

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Dr George Amulele (MQ) *until Aug 2016*	Dr Heather Handley (MQ)	Adjunct Professor Robert Pigeon (CU)
Dr Andreas Beinlich (CU)	Dr Jin-Xiang Huang (MQ)	Dr Sergei Pisarevsky (CU)
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Dr Grant Cox (CU)	Dr Uwe Kirscher (CU)	Dr Amaury Pourteau (CU)
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Dr Rongfeng Ge (CU)	Dr Laure Martin (CMCA, UWA)	Dr Xuan-Ce Wang (CU)
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Dr Richard Glen	Dr David Leach	Mr Peter Kym Williams
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Dr Mehmet Akbulut	Professor Manel Fernandez	Dr Claudio Marchesi
Professor Tom Andersen	Dr José María Gonzaléz-Jiménez	Dr Bertrand Moine
Dr Debora Araujo	Dr Michel Grégoire	Ms Ria Mukherjee
Dr Jacques Batumike Mwandulo	Dr Bin Guo	Dr Oded Navon
Dr Graham Begg	Dr Jeff Harris	Dr Ryan Portner
Dr Christoph Beier	Dr Daniel Howell	Dr Yvette Poudjom Djomani
Dr Phillip L. Blevin	Dr Bram Janse	Dr Peter Robinson
Professor Hannes Brueckner	Dr Felix Kaminsky	Dr Giovanna Sapienza
Mr Robert Bultitude	Dr Hans-Rudolf Kuhn	Dr Takako Satsukawa
Dr Mei-Fe Chu	Dr Christoph Lenz	Dr Ed Saunders
Dr Beverly Coldwell	Ms Qian Liu	Dr Simon Shee
Professor Massimo Coltorti	Mr Qingyong Luo	Dr Thomas Stachel
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Mr Raphael Baumgartner (UWA)	Miss Maria Iaccheri (UWA)	Miss Zsanett Pintér (MQ)
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Mr Raul Brens Jr (MQ)	Mr Chengxin Jiang (MQ)	Mr Farshad Salajegheh (MQ)
Mr Stefano Caruso (UWA)	Mr Jelte Keeman (MQ)	Mr Sarath-Kumara Samaya-Manthri (MQ)
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Mr Mathieu Chassé (MQ)	Mr Shaojie Li (CU)	Ms Jutta Stark (CU)
Mr David Child (MQ)	Ms Nora Liptai (MQ)	Mr David Stevenson (UWA)
Miss Eunjoo Choi (UWA)	Mr Kai Liu (CU)	Miss Catherine Stuart (MQ)
Mr Bruno Colas (MQ)	Mr Yebo Liu (CU)	Mr Romain Tilhac (MQ)
Mr Stephen Craven (MQ)	Ms Jianggu Lu (MQ)	Mr Mehdi Tork Qashqai (MQ)
Ms Daria Cyprych (MQ)	Miss Maria Manassero (MQ)	Miss Irina Tretiakova (MQ)
Mr Gregory Dering (UWA)	Ms Erin Martin (CU)	Mr Rick Verberne (CU)
Ms Tara Djokic (UNSW)	Mr Quentin Masurel (UWA)	Ms Silvia Volante (CU)
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Ms Eileen Dunkley (MQ)	Miss Nicole McGowan (MQ)	Mr Kai Wang (MQ)
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Mr Michael Förster (MQ)	Ms Vicky Meier (CU)	Mr Shucheng Wu (MQ)
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Appendix 5: 2016 Publications

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

451. Song, Y., Jiang, S.-H., **Bagas, L.**, Li, C., Hu, J.-Z., Wang, S.-Z., Zhou, W. and Ding, H.-Y. 2016. The geology and geochemistry of Jinchangyu gold deposit, North China Craton: Implications for metallogenesis and geodynamic setting. *Ore Geology Reviews*, *73*, *313-329*.

529. Adams, C.J., Campbell, H.J., Mortimer, N. and **Griffin, W.L.** 2016. Perspectives on Cretaceous Gondwana break-up from detrital zircon provenance of southern Zealandia sandstones. *Geological Magazine*, *1-22*.

581. Kvasnytsya, V., Wirth, R. **Piazolo, S.**, **Jacob, D.** and Trimby, P. 2016. Surface morphology and the structural types of natural impact apographitic diamonds. *Diamond and Related Materials*, *38*, *71-84*.

597. **Dadd, K.** and Foley, K. 2016. A shape and compositional analysis of ice-rafted debris in core from IODP Expedition 323 in the Bering Sea. *Deep Sea Research II*, *125*, *191-201*.

618. Tunini, I., Jiménez-Munt, I., Fernandez, M., Vergés, J., Villaseñor, A., Melchiorre, M. and **Afonso, J.C.** 2016. Geophysical-petrological model of the crust and upper mantle in the India-Eurasia collision zone. *Tectonics*, *35*, *1642-1669*.

619. **Afonso, J.C.**, Moorkamp M. and Fullea, J. 2016. Imaging the lithosphere and upper mantle: Where we are at and where we are going. *Integrated Imaging of the Earth., M. Moorkamp, P. Lelievre, N. Linde and A. Khan (Eds), AGU Geophysical Monograph 218, Wiley*, *Ch 10*, *191-218*.

623. Veevers, J.J., **Belousova, E.A.** and Saeed, A. 2016. Zircons traced from the 700-500 Ma Transgondwanan Supermountains and the Gamburtsev Subglacial Mountains to the Ordovician Lachlan Orogen, Cretaceous Ceduna Delta, and modern Channel Country, central-southern Australia. *Sedimentary Geology*, *334*, *115-141*.

630. **Le Vaillant, M.**, Barnes, S., **Fiorentini, M.L.**, Santaguida, F. and Törmänen, T. 2016. Effects of hydrous alteration on the distribution of base metals and platinum group elements within the Kevitsa magmatic nickel sulphide deposit. *Ore Geology Reviews*, *72*, *128-148*.

639. Ariskin, A.A., Kislov, E.V., Danyushevsky, L.V., Nikolaev, G.S., **Fiorentini, M.**, Gilbert, S., Goemann, K., González-Jiménez, J.-M. and Malyshev, A. 2016. Cu-Ni-PGE fertility of the Yoko-Dovyren layered massif (Northern Transbaikalia, Russia): from quantified sulfide mineralogy towards thermodynamic modeling of the sulfide geochemistry in low mineralized dunites. *Mineralium Deposita*, *51*, *993-1011*.

642. Cederberg, J., Söderlund, U., Oliveira, E.P., Ernst, R.E. and **Pisarevsky, S.A.** 2016. U-Pb baddeleyite dating of the Proterozoic Pará de Minas dyke swarm in the São Francisco craton (Brazil) - implications for tectonic correlation with the Siberian, Congo and North China cratons. *GFF*, *138*, *219-240*.

644. **Parra-Avila, L.A.**, **Belousova, E.**, **Fiorentini, M.L.**, Baratoux, L., Davis, J., Miller, J. and **McCuaig, T.C.** 2016. Crustal evolution of the Paleoproterozoic Birimian terranes of the Baoulé-Mossi domain, southern West African Craton: U-Pb and Hf-isotope studies of detrital zircons. *Precambrian Research*, *274*, *25-60*.

648. Metelkin, D.M., Vernikovsky, V.A., Tolmacheva, T. Yu., Matushkin, N.Yu., Zhdanova, A.I. and **Pisarevsky, S.A.** 2016. First paleomagnetic data for the New Siberian Islands: Implications for Arctic paleogeography. *Gondwana Research*, *37*, *308-323*.

655. Malitch, K.N., Anikina, E.V., Badanina, I.Yu., **Belousova, E.A.**, Pushkarev, E.V. and Khiller, V.V. 2016. Chemical composition and osmium isotope systematics of primary and secondary platinum-group mineral assemblages from high-Mg chromitite of the Nurali lherzolite massif, South Urals, Russia. *Geology of Ore Deposits*, *58*, *1-19*.

657. **Le Vaillant, M.**, Saleem, A., Barnes, S.J., **Fiorentini, M.L.**, **Miller, J.**, Beresford, S. and Perring, C. 2016. Hydrothermal remobilisation around a deformed and remobilised komatiite-hosted Ni-Cu-(PGE) deposit, Sarah's Find, Agnew Wiluna greenstone belt, Yilgarn Craton, Western Australia. *Mineralium Deposita*, *51*, *369-388*.

658. **Gonzalez, C.**, **Gorczyk, W.** and Gerya, T.V. 2016. Decarbonation of subducting slabs: insights from petrological-thermomechanical modeling. *Gondwana Research*, *36*, *314-332*.

660. Huston, D.L., Mernagh, T.P., Hagemann, S.G., Doublier, M.P., **Fiorentini, M.**, Champion, D.C., Jaques, A.L., Czarnota, K., Cayley, R., Skirrow, R. and Bastrakov, E. 2016. Tectono-metallogenic systems - the place of mineral systems within tectonic evolution, with an emphasis on Australian examples. *Ore Geology Reviews*, *76*, *168-210*.

662. Perrouty, S., Jessell, M.W., Bourassa, Y., Miller, J., Apau, D., **Parra-Avila, L.A.**, Le Mignot, E., Velásquez, G., Ganne, J., Siebenaller, L., Baratoux, L., Aillères, L., André-Mayer, A.-S., Béziat, D. and Salvi, S. 2016. Geological setting of the Wassa Gold Deposit, SW Ghana. *Ore Geology Reviews*, *78*, *687-691*.

663. **Wacey, D.**, Saunders, M., Kong, C., Brasier, A. and Brasier, M. 2016. 3.46 Ga Apex chert '*microfossils*' reinterpreted as mineral artefacts produced during phyllosilicate exfoliation. *Gondwana Research*, *36*, *296-313*.

664. **Niu, J.**, **Li, Z.-X.** and Zhu, W. 2016. Paleomagnetism and geochronology of mid-Neoproterozoic Yanbian dykes, South China: Implications for ca. 820-800 Ma true polar wander event and the reconstruction of Rodinia. *Supercontinent Cycles Through Earth's History*, *Z.X. Li, D.A.D. Evans and J.B. Murphy (Eds)*, *424*, *191-211*.

665. **Genske, F.S.**, Beier, C., Stracke, A., **Turner, S.P.**, **Pearson, N.J.**, Hauff, F., **Schaefer, B.F.**, Haase, K.M. 2016. Comparing the nature of the western and eastern Azores mantle. *Geochimica et Cosmochimica Acta*, *172*, *6-92*.

669. **Adam, J.**, Turner, M., Hauri, E.H. and **Turner, S.** 2016. Crystal/melt partitioning of water and other volatiles during the near-solidus melting of mantle peridotite: comparisons with non-volatile incompatible elements and implications for the generation of intraplate magmatism. *American Mineralogist*, *101*, *876-888*.

670. **Abily, B.** and Python, M. 2016. Data report: Lithological diversity, mineral composition and temperature and redox conditions in ODP/IODP Hole 1256D - A study of sand and gravels recovered during IODP Expedition 335. *Proceedings of the Integrated Ocean Drilling Program*, *335*.

671. **McCuaig, T.C.**, **Fougerouse, D.**, Salvi, S., Siebenaller, L., **Parra-Avila, L.**, Seed, R., Beziat, D. and Andre-Mayer, A.-S. 2016. The Inata Deposit, Belahouro District, northern Burkina Faso. *Ore Geology Reviews*, *78*, *639-644*.

672. **Guo, Z.**, Chen, Y.J., Ning, J., **Yang, Y.**, **Afonso, J.C.** and Tang, Y. 2016. Seismic evidence of on-going sublithosphere upper mantle convection for intra-plate volcanism in Northeast China. *Earth and Planetary Science Letters*, *433*, *31-43*.

675. **Zhang, S.** and **O'Neill, C.** 2016. The early geodynamic evolution of Mars-1 type planets. *Icarus*, *265*, *187-208*.

676. Wang, C.M., Chen, L., **Bagas, L.**, Lu, Y.J., He, X.Y. and Lai, X.R. 2016. Characterization and origin of the Taishanmiao aluminous A-type granites: Implications for Early Cretaceous lithospheric thinning at the southern margin of the North China Craton. *International Journal of Earth Sciences*, *105*, *1563-1589*.

677. **Saunders, J.E.**, **Pearson, N.J.**, **O'Reilly, S.Y.** and **Griffin, W.L.** 2016. Gold in the mantle: The role of pyroxenites. *Lithos*, *244*, *205-217*.

679. Badanina, I.Yu., Malitch, K.N., Lord, R.A., **Belousova, E.A.** and Meisel, T.C. 2016. Closed-system behaviour of the Re-Os isotope system recorded in primary and secondary platinum-group mineral assemblages: Evidence from a mantle chromitite at Harold's Grave (Shetland Ophiolite Complex, Scotland). *Ore Geology Reviews*, *75*, *174-185*.

680. **Giuliani, A.**, Phillips, D., Kamenetsky, V.S. and Goemann, K. 2016. Constraints on kimberlite ascent mechanisms revealed by phlogopite compositions in kimberlites and mantle xenoliths. *Lithos*, *240-243*, *189-201*.

681. Payne, J.L., McInerney, D.J., Barovich, K.M., **Kirkland, C.L.**, **Pearson, N.J.** and Hand, M. 2016. Strengths and limitations of zircon Lu-Hf and O isotopes in modelling crustal growth. *Lithos*, *248-251*, *175-192*.

682. **Locmelis, M.**, **Fiorentini, M.L.**, **Rushmer, T.**, Arevalo Jr., R., **Adam, J.** and **Denyszyn, S.W.** 2016. Sulfur and metal fertilization of the lower continental crust. *Lithos*, *244*, *74-93*.

683. Duda, J.P., **Van Kranendonk, M.J.**, Thiel, V., Ionescu, D., Strauss, H., Schäfer, N. and Reitner, J. 2016. A rare glimpse of Paleoarchean life: Geobiology of an exceptionally preserved microbial mat facies from the 3.4 Ga Strelley Pool Formation, Western Australia. *PLoS ONE*, *11*, *e0147629*.

684. **Moghadam, H.S.**, Rossetti, F., Lucci, F., Chiaradia, M., Gerdes, A., Ghorbani, G., Nasrabady, M., Martinez, M.L. 2016. The calc-alkaline and adakitic volcanism of the Sabzevar structural zone (NE Iran): implications for the Eocene magmatic flare-up in Central Iran. *Lithos*, *248-251*, *517-535*.

685. **Oliveira, B.**, **Afonso, J.C.** and Zlotnik, S. 2016. A Lagrangian-Eulerian finite element algorithm for advection-diffusion-reaction problems with phase change. *Computer Methods in Applied Mechanics and Engineering*, *300*, *375-401*.

686. **Bagas, L.**, **Kolb, J.**, **Fiorentini, M.L.**, **Thébaud, N.**, **Owen, J.** and **Rennick, S.** 2016. On the processes that formed Archaean Ni-Cu sulfide mineralisation in the deep continental crust, Thrym Complex, southeastern Greenland. *Precambrian Research*, *277*, *68-86*.

687. Zhu, K.-Y., **Li, Z.-X.**, Xu, X.-S., **Wilde, S.A.** and Chen, H.-L. 2016. Early Mesozoic ferroan (A-type) and magnesian granitoids in eastern South China: Tracing the influence of flat-slab subduction at the western Pacific margin. *Lithos*, *240-243*, *371-381*.

688. **Piazolo, S.**, La Fontaine, A., Trimby, P., Harley, S., Yang, L., Armstrong, R. and Cairney, J.M. 2016. Deformation-induced trace element redistribution in zircon revealed using atom probe tomography. *Nature Communications*, *7*, *10490*.

689. Kaczmarek, M.A., **Reddy, S.M.**, Nutman, A.P., Friend, C.R.L. and Bennett, V.C. 2016. Earth's oldest mantle fabrics indicate Eoarchaean subduction. *Nature Communications*, *7*, *10665*.

691. **Xiong, Q.**, **Griffin, W.L.**, Zheng, J.P., **O'Reilly, S.Y.**, **Pearson, N.J.**, **Xu, B.** and **Belousova, E.A.** 2016. Southward trench migration at ~130-120 Ma caused accretion of the Neo-Tethyan forearc lithosphere in Tibetan ophiolites. *Earth and Planetary Science Letters*, *438*, *57-65*.

692. Akbulut, M. González-Jiménez, J.M., **Griffin, W.L.**, **Belousova, E.**, **O'Reilly, S.Y.**, **McGowan, N.** and **Pearson, N.J.** 2016. Tracing ancient events in the lithospheric mantle: A case study from ophiolitic chromitites of SW Turkey. *Journal of Asian Earth Sciences*, *119*, *1-19*.

695. Li, G., Chen, H., Niu, F., Guo, Z., **Yang, Y.** and Xie, J. 2016. Measurement of Rayleigh wave ellipticity and its application to the joint inversion of high-resolution S-wave velocity structure beneath northeast China. *Journal of Geophysical Research*, *121*, *864-880*.

696. **Castillo-Oliver, M.**, Galía, S., Melgarejo, J.C., **Griffin, W.L.**, **Belousova, E.**, **Pearson, N.J.**, Watanguac, M. and **O'Reilly, S.Y.** 2016. Trace-element geochemistry and U-Pb dating of perovskite in kimberlites of the Lunda Norte province (NE Angola): Petrogenetic and tectonic implications. *Chemical Geology*, *426*, *118-134*.

697. **Barlow, E.**, **Van Kranendonk, M.J.**, Yamaguchi, K.E., Kehara, M. and Lepland, A. 2016. Lithostratigraphic analysis of a new stromatolite-thrombolite reef from across the rise of atmospheric oxygen in the Paleoproterozoic Turee Creek Group, Western Australia. *Geobiology*, *4*, *317-343*.

698. Robert, A.M., Grotheer, H., Greenwood, P.F., **McCuaig, T.C.**, Bourdet, J. and Grice, K. 2016. The hydropyrolysis (HyPy) release of hydrocarbon products from a high maturity kerogen associated with an Orogenic Au deposit and their relationship to the mineral matrix. *Chemical Geology*, *425*, *127-144*.

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701. Colás, V., Padrón-Navarta, J.A., González-Jiménez, J.M., **Griffin, W.L.**, Fanlo, I., **O'Reilly, S.Y.**, Gervilla, F., Proenza, J.A., **Pearson, N.J.** and Escayola, M. 2016. Compositional effects on the solubility of minor and trace elements in oxide spinel minerals: insights from crystal-crystal partition coefficients in chromite exsolution. *American Mineralogist*, *101*, *1360-1372*.

702. Wang, K., Luo, Y. and **Yang, Y.** 2016. Correction of phase velocity bias caused by strong directional noise sources in high-frequency ambient noise tomography: a case study in Karamay, China. *Geophysical Journal International*, *205*, *715-727*.

703. Pidgeon, R.T., Merle, R., **Grange, M.**, **Nemchin, A.A.** and Whitehouse, M.J. 2016. Annealing of radiation damage in zircons from Apollo 14 impact breccia 14311: implications for the thermal history of the breccia. *Meteoritics and Planetary Science*, *51*, *155-166*.

704. **Griffin, W.L.**, **Afonso, J.C.**, **Belousova, E.A.**, **Gain, S.**, Gong, X-H., González-Jiménez, J.M., **Howell, D.**, **Huang, J-X.**, **McGowan, N.**, **Pearson, N.J.**, **Satsukawa, T.**, Shi, R., Williams, P., **Xiong, Q.**, Yang, J-S., Zhang, M. and **O'Reilly S.Y.** 2016. Mantle recycling: Transition-Zone metamorphism of Tibetan ophiolitic peridotites and its tectonic implications. *Journal of Petrology*, *57*, *655-684*.

705. Snape, J.F., **Nemchin, A.A.**, **Grange, M.L.**, Bellucci, J.J., Thiessen, F. and Whitehouse, M.J. 2016. Phosphate ages in Apollo 14 breccias: resolving multiple impact events with high precision U-Pb SIMS analyses. *Geochimica et Cosmochimica Acta*, *174*, *13-29*.

708. Ahmadi, A., Koyi, H., Juhlin, C. and **Gessner, K.** 2016. Seismic signatures of complex geological structures in the Cue-Weld Range area, Murchison domain, Yilgarn Craton, Western Australia. *Tectonophysics*, *698*, *56-66*.

709. **Pisarevsky, S.A.**, Rosenbaum, G., Shaanan, U., Hoy, D., Speranza, F. and Mochales, T. 2016. Paleomagnetic and geochronological study of Carboniferous forearc basin rocks in the southern New England Orogen (eastern Australia). *Tectonophysics*, *681*, *263-277*.

710. **Yao, W.-H.** and **Li, Z.-X.** 2016. Tectonostratigraphic history of the Ediacaran-Silurian Nanhua foreland basin in South China. *Tectonophysics*, *674*, *31-51*.

714. Czertowicz, T., Scott, J. and **Piazolo, S.** 2016. Coupled extrusion of sub-arc lithospheric mantle and lower crust during orogen collapse: a case study from Fiordland, New Zealand. *Journal of Metamorphic Geology*, *34*, *501-524*.

715. **Jiang, C.**, **Yang, Y.** and Zheng, Y. 2016. Crustal structure in the junction of Qinling Orogen, Yangtze Craton and Tibetan Plateau: implications for the formation of the Dabashan Orocline and the growth of Tibetan Plateau. *Geophysical Journal International*, *205*, *1670-1681*.

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Appendix 6: 2016 Abstract titles

A FULL LIST OF CCFS ABSTRACTS FOR CONFERENCE PRESENTATIONS IS AVAILABLE AT: http://www.ccfs.mq.edu.au/

Annual Meeting of The Israel Geological Society (IGS), Eilat, Israel, 19-21 January 2016	Deep-Earth methane, mantle dynamics and mineral exploration: Insights from northern Israel, southern Tibet and Kamchatka **W.L. Griffin**, **S.E.M. Gain**, **D. Adams**, V. Toledo, **N.J. Pearson** and **S.Y. O'Reilly** **Plenary** Heaven on Earth: tistarite (Ti_2O_3) and other "nebular" phases in corundum aggregates from Mt. Carmel volcanic rocks **W.L. Griffin**, **S.E.M. Gain**, **D. Adams**, **J.-X. Huang**, M. Saunders, V. Toledo, **N.J. Pearson** and **S.Y. O'Reilly** The role of the deep lithosphere in metallogeny **S.Y. O'Reilly**, **W.L. Griffin** and **N.J. Pearson** **Keynote**
32nd Nordic Geological Winter Meeting, Helsinki, Finland, 13-15 January 2016	From Nuna to Rodinia: Stenian-Tonian paleogeography **S.A. Pisarevsky** **Invited**
5TH Australasian Universities Geoscience Educators Network Meeting, Canberra, Australia, 28-29 January 2016	The free desktop software, Virtual Petrographic Microscope **N.R. Daczko**
24th Australian Conference on Microscopy and Microanalysis (ACMM24) Melbourne, Australia, 1-4 February 2016	Stable isotope labelling with high-resolution imaging mass spectrometry **M. Kilburn**, P. Guagliardo, H. Jiang, **L. Martin** and **H. Jeon**
GSWA Open Day 2016, Fremantle, Australia, 26 February 2016	Secular change in Archean crust formation recorded in Western Australia **H. Yuan** **Keynote**
NAC+ 2016, The North Atlantic Craton and Surrounding Belts: A Craton-Specific Approach to Exploration Targeting, Edinburgh, UK, 21-23 March 2016	Cratonic structure and regional controls on mineral systems G.C. Begg, J.M.A. Hronsky, **S.Y. O'Reilly**, **W.L. Griffin** and **L. Natapov** Metallogeny of the North Atlantic Craton, Greenland **J. Kolb,** B.M. Stensgaard and **L. Bagas**
47TH Lunar and Planetary Science Conference, The Woodlands, Texas, USA, 21-25 March 2016	Impact-driven tectonism during the Hadean **C. O'Neill**, S. Marchi, **S. Zhang** and W. Bottke
European Geosciences Union (EGU), Vienna, Austria, 17-22 April 2016	Estimating uncertainties in complex joint inverse problems **J.C. Afonso** **Invited** Erosion and assimilation of substrate by martian low-viscosity lava flows: Implications for sulfur degassing and the genesis of orthomagmatic Ni-Cu-PGE sulfide mineralisation **R. Baumgartner**, D. Baratoux, F. Gaillard and **M.L. Fiorentini**

European Geosciences Union (EGU), Vienna, Austria, 17-22 April 2016 *cont...*	Simulation of substrate erosion and sulphate assimilation by Martian low-viscosity lava flows: Implications for the genesis of precious metal-rich sulphide mineralisation on Mars **R. Baumgartner**, D. Baratoux, F. Gaillard and **M.L. Fiorentini** Velocity gradients in the Earth's upper mantle: Insights from higher mode surface waves S. Fishwick, V. Maupin and **J.C. Afonso** Lithospheric structure of the Iberian Peninsula from coupled geophysical-petrological inversion J. Fullea, A. Negredo, M. Charco, I. Palomeras, A. Villaseñor and **J.C. Afonso** Geophysical and geochemical nature of relaminated arc-derived lower crust underneath oceanic domain in southern Mongolia A. Guy, K. Schulmann, V. Janoušek, P. Štípská, R. Armstrong, **E. Belousova**, A. Dolgopolova, R. Seltmann, O. Lexa, Y. Jiang and P. Hanžl Multi-phase multi-component reactive flow in Geodynamics **B. Oliveira**, **J.C. Afonso** and S. Zlotnik Mapping reflections from the sub-crustal lithosphere of southwestern Spain I. Palomeras, P. Ayarza, R. Carbonell, S. Ehsan, **J.C. Afonso** and J. Diaz New paleomagnetic data from 1.80-1.75 Ga mafic intrusions of Fennoscandia and Sarmatia: Implications for the late Paleoproterozoic paleogeography of Baltica and Laurentia **S.A. Pisarevsky**, N.V. Lubnina, S.J. Sokolov and S.V. Bogdanova
17th International Seismix Symposium, Aviemore, Scotland, 15-20 May 2016	Multi-observable probabilistic tomography for the physical state of the Earth's interior J.C. Afonso **Keynote**
Japan Geoscience Union Meeting 2016, Makuhari Messe, Japan, 22-26 May 2016	Messengers from the deep: Fossil wadsleyite-chromite microstructures from the Mantle Transition Zone **T. Satsukawa**, **W.L. Griffin**, **S. Piazolo** and **S.Y. O'Reilly**
Anisotropy and Dynamics of The Lithosphere-Asthenosphere System Workshop, Prague, Czech Republic, 22-25 May 2016	Thermochemical tomography for the physical state of the Earth's interior J.C. Afonso **Keynote**
SEG Munich Technical Meeting, Munich, Germany, 1 June 2016	Zircon compositions as a pathfinder for porphyry Cu ± Mo ± Au deposits **Y.J. Lu, R.R. Loucks, M.L. Fiorentini**, **T.C. McCuaig**, N.J. Evans, Z.M. Yang, Z.Q. Hou, **C.L. Kirkland**, **L.A. Parra-Avila** and A. Kobussen. Atmospheric sulfur in orogenic gold deposits **V. Selvaraja**, **M.L. Fiorentini** and **C. LaFlamme**
GAC-MAC 2016, Margins Through Time, Whitehorse, Yukon, Canada, 1-3 June 2016	Can structurally controlled hot aqueous fluids produce the steep metamorphic field gradients found in HTLP regional aureoles? Evidence from Wongwibinda, NSW, Australia **K. Jessop**, **N.R. Daczko** and **S. Piazolo** Understanding Earth's 4D supercycles through IGCP 648 **Z.X. Li** Phanerozoic constraints on older plate motions and reconstructions B. Eglington, D. Evans and **Z.X. Li** Anomalous sulfur isotopes trace volatile transfer in arc magmas **V. Selvaraja**, **M.L. Fiorentini**, **C. LaFlamme**, B.A. Wing and T.H. Bui

EMPG XV 15th International Symposium on Experimental Mineralogy, Petrology and Geochemistry, Zurich, Switzerland, 5-8 June 2016	Reaction experiments of glimmerite + harzburgite at 1-2 GPa and genesis of orogenic ultrapotassic magmas **M.W. Förster**, D. Prelević, S. Buhre, H.R. Schmück, M. Veter, R. Mertz-Kraus, **S. Foley** and **D.E. Jacob** Reaction experiments of glimmerite + harzburgite at 3-5 GPa and genesis of low-SiO_2 ultrapotassic magmas **M.W. Förster**, D. Prelević, S. Buhre, H.R. Schmück, M. Veter, **S. Foley** and **D.E. Jacob** The generation of orogenic ultrapotassic magmas in newly formed lithosphere **Y. Wang**, D. Prelević, S. Buhre and **S. Foley**
International Diamond School 2016, Edmonton, Canada, 8 June 2016	Trace element traverses across kimberlite olivine: A new tool to decipher the evolution of kimberlite magmas **A. Giuliani**, A. Soltys, **W.L. Griffin**, **S. Foley**, D. Phillips and A. Greig **Invited**
Polar Symposium, Lublin, Poland, 8-11 June 2016	Petrographic description of gneisses from Saglek Block (Northern Labrador, Canada) as a basis for searching for the Archaean crust - preliminary data A. Sałacińska, **M.A. Kusiak**, M.J. Whitehouse, D.J. Dunkley and **S.A. Wilde**
Gordon Research Conference, Geochemistry of Mineral Deposits, Les Diablerets, Switzerland, 19-24 June 2016	Petrogenesis and mineralization of the Nimbus Ag-Zn-(Au) VHMS deposit, Yilgarn Craton, Western Australia: Insights from multiple sulfur isotopes and trace elements analysis **S. Caruso**, S.P. Hollis, **M.L. Fiorentini**, **C. LaFlamme**, **L. Martin** and P. Gillespie Paulsens, an Archaean sediment hosted gold deposit **V. Selvaraja**, **M.L. Fiorentini**, **C. LaFlamme**, B.A. Wing and **H. Jeon** Comparing sulfur isotope systematics in modern and ancient hydrothermal systems: Evidence for laterally dominated fluid flow **C. LaFlamme**, **M.L. Fiorentini**, S. Hollis and J. Bell
AESC 2016 - Australian Earth Sciences Convention - Uncover Earth's Past to Discover Our Future, Adelaide Convention Centre, Australia, 26-30 June 2016	Towards simulation-based inversions of multiple geoscientific data for the physical state of the Earth's interior **J.C. Afonso** Large scale reorganization within supercontinents - The Pangea Controversy K. Aubele, **U. Kirscher**, V. Bachtadse, G. Muttoni, A. Ronchi and D.V. Kent The answers are blowin' in the wind: Ultra-distal airfall zircons, evidence of Cretaceous super-eruptions in eastern Gondwana M. Barham, **C. Kirkland**, S. Reynolds, M. O'Leary, N. Evans, H. Allen, P. Haines, R. Hocking, B. McDonald, **E. Belousova** and J. Goodall Reconstructing the record of Continental Flood Basalt (CFB) and Ocean Island Basalt (OIB) geochemistry: initial results from a data mining approach **G.M. Cox** and **Z.X. Li** **Invited** Seamount volcanism at Site U1431, South China Sea, International Ocean Discovery Program Expedition 349 **K. Dadd** and A. Koppers Relating seismicity to dike emplacement, and the conundrum of dyke-parallel faulting **G. Dering**, S. Micklethwaite, A.R. Cruden, S.J. Barnes and **M.L. Fiorentini** Paleoproterozoic subduction zones and their role in craton assembly in Western Australia **K. Gessner**, **H. Yuan**, S.P. Johnson, M. Dentith and R.E. Murdie Paleoproterozoic crust in the Glenburgh Terrane and its role in craton assembly in Western Australia **K. Gessner**, **H. Yuan**, M.C. Dentith, S. Johnson and R. Murdie The birth of a Proterozoic ocean; isotopic backtracking the WAC and the SAC **C.L. Kirkland**, R.H. Smithies, C.V. Spaggiari, **M.T.D. Wingate**, **N. Gardiner** and **E. Belousova** Evolution of the Central Asian Orogenic Belt in the Paleozoic - A subduction epicentre during the formation of Pangea **U. Kirscher** and V. Bachtadse Geodynamic numerical modelling for examining tectonic scenarios of the Halls Creek Orogen F. Kohanpour, **W. Gorczyk**, M. Lindsay, S. Occhipinti and **C. McCuaig** Relationship of geochemistry and mineralogy to parent lithology and the degree of weathering in regolith **H. Lampinen**, C. Laukamp, S. Occhipinti and S. Spinks Supercontinent-superplume coupling in Earth history: Toward a new tectonic paradigm **Z.X. Li**

AESC 2016 - Australian Earth Sciences Convention - Uncover Earth's Past to Discover Our Future, Adelaide Convention Centre, Australia, 26-30 June 2016 *cont...*	Plume and superplumes: their formation, nature and geodynamic roles **Z.X. Li** **Keynote** Palaeomagnetic investigation of mafic dykes in the southwestern Yilgarn Craton, Western Australia **Y. Liu**, **Z.X. Li**, **S. Pisarevsky** and **C. Stark** Identifying a magmatic source for the Pacific-Gondwana association: Zircon Hf evidence from the Paterson Orogen, Western Australia E.L. Martin, W.J. Collins and **C.L. Kirkland** Passive seismic studies show configuration of Paleoproterozoic subduction zones and their role in craton assembly in Western Australia R. Murdie, **H. Yuan**, M. Dentith, S.P. Johnson and **K. Gessner** Translating mineral systems analyses into a sensible workflow for ground selection and targeting S. Occhipinti, M. Lindsay, A. Aitken, V. Metelka, **C. McCuaig** and **I. Tyler** 1800-900 Ma global paleogeography: new insights **S. Pisarevsky** **Invited** Trace element geochemistry of TiO_2 polymorphs in igneous rocks: an example from the igneous Moorarie Supersuite, Capricorn Orogen, Western Australia **D. Plavsa**, **S. Reddy** and **A. Agangi** Duration of tectonic processes constrained by Lu-Hf garnet geochronology - Insights from HP/LT oceanic rocks (Halilbağı Complex) and Barrovian-type mica-schist (Menderes Massif) **A. Pourteau** **Keynote** Still oceans apart - probing the Eucla basement shows what separates the Albany-Fraser Orogen and the Gawler Craton C.V. Spaggiari, H. Smithies, **C.L. Kirkland**, **M.T.D. Wingate** and R.N. England The structural evolution and kinematics of the southern Tamworth Belt of the New England Orogen at Gundy, Rouchel Block, New South Wales A. Takonis and **M. Van Kranendonk** Magnetostratigraphy of late Devonian carbonates of Western Australia: Integrating reversal history with biostratigraphic and ^{13}C records E. Tohver, T. Playton, K. Hillbun, M. Yan, **S. Pisarevsky**, J. Hansma, B. Roelofs, K. Trinajstic, J.L. Kirschvink and P. Haines A palaeoenvironmental proxy with more bite: assessing the applicability of O-isotopes in micromammal teeth M. Wallwork, M. Barham, A. Blyth, **L. Martin**, M. Joachimski, N. Evans and B. McDonald The Ediacaran-Silurian Nanhua foreland basin in South China: Response to the Gondwana assembly **W. Yao** and **Z.X. Li** Hainan Island (south China) in the Nuna breakup and Rodina assembly **W. Yao**, **Z.X. Li** and W.-X. Li The Hainan flood basalts: a deep plume origin prompted by the encircled subductions at Southeast Asia **N. Zhang** and **Z.X. Li**
26th Goldschmidt Conference, Yokohama, Japan, 26 June - 1 July 2016	Sulfur isotopic composition of the sub-continental lithosphere mantle **O. Alard**, E. Thomassot, **L. Martin**, P. Cartigny and **S.Y. O'Reilly** Low-Ni olivines in silicaundersaturated ultrapotassic igneous rocks as evidence for carbonate metasomatism in the mantle E. Ammannati, **D.E. Jacob**, R. Avanzinelli, **S.F. Foley** and S. Conticelli Pb isotope evolution in the Martian mantle J. Belluccci, **A. Nemchin**, M. Whitehouse and J. Snape **Invited** Insights into mantle geochemistry of Sc from the main carrier minerals **M. Chassé**, **S.Y. O'Reilly**, **W.L. Griffin** and G. Calas Mineralogical and geochemical mechanisms concentrating scandium in lateritic deposits **M. Chassé**, H. Aral, S. van Huet, **S.Y. O'Reilly**, **W.L. Griffin**, M. Gérard and G. Calas *In situ* isotopic analysis of sulfides in high-pressure serpentinites R. Crossley, K. Evans, **H. Jeon**, **M. Kilburn**, M. Roberts and **S. Reddy** Visualizing He distribution in zircon by laser ablation noble gas mass-spectrometry: Implications for (U-Th)/He geochronology and thermochronology M. Danišík, B.I.A. McInnes, B.J. McDonald, **C.L. Kikland**, N.J. Evans and T. Becker

26th Goldschmidt Conference, Yokohama, Japan, 26 June - 1 July 2016

A bigger tent for CAMP? Geochronology and geochemistry of mineralized lower-crustal intrusions in NW Italy
S. Denyszyn, **M.L. Fiorentini** and **A. Davis**

Monazite as a tectonic and shock deformation chronometer - Linking EBSD and U-Pb analyses
T. Erickson, N. Timms, **S. Reddy**, A. Cavosie, M. Pearce, **C. Kirkland** and E. Tohver

Invisible gold in arsenopyrite revealed by correlated atom probe microscopy, NanoSIMS and Maia Mapping
D. Fougerouse, **S. Reddy**, D. Saxey, W. Rickard, A. van Riessen and S. Micklethwaite

U-Pb dating of zircons from Paleozoic lamprophyric dykes of Western Sangilen (CAOB)
A. Gibsher, V. Malkovets, **I. Tretiakova**, **E. Belousova**, S. Rudnev, A. Gibsher, T. Tsujimori and R. Shelepaev

Decarbonation of subducting slabs: a petrological-thermomechanical modeling approach
C. Gonzalez, **W. Gorczyk** and T. Gerya

A secondary (PGE-Au) ± Ni-S-As-Sb-Pb mineralization in serpentinite shear zones from Central Chile
J.M. González-Jiménez, L.N.F. Garrido, R. Romero, E. Salazar, F. Barra, M. Reich, **T. Satsukawa** and V. Colás

Plume-lithosphere interaction through time
W. Gorczyk, D. Mole and S. Barnes

Integrated 2D and 3D geochemical modelling of the Sari Gunay epithermal gold deposit applied in complementary drilling
H.A. Haroni and O. Mahmoodi

Deep carbon: SiC in mantle- and mantle-generated rocks
J.-X. Huang, **W.L. Griffin**, **L. Martin**, V. Toledo and **S.Y. O'Reilly**

Detrital zircons record rigid continents after 2.5 Ga
L.M. Iaccheri and A.I.S. Kemp

Rapid crustal recycling in the New England Orogen, eastern Australia: Magma to mud to magma in < 20 Ma
H. Jeon, **M. Kilburn** and I. Williams

Impacts in the Lunar Highlands: Shocked zircon from Apollo 16
K. Joy, J. Snape, **A. Nemchin**, M. Whitehouse and V. Vishnyakov

Chemical variation and deformation of the upper mantle across an OCT
M.-A. Kaczmarek, **S. Reddy** and P. Vonlanthen

Stable isotope labelling as a tool to investigate mineral-fluid interaction
M. Kilburn, **M.L. Fiorentini**, **S. Piazolo**, **T. Rushmer**, **S. Reddy**, **L. Martin** and **H. Jeon**

NanoSIMS $^{207}Pb/^{206}Pb$ analysis of metallic Pb nanospheres in zircons
M. Kusiak, I. Lyon, R. Wirth, **S. Wilde**, M. Whitehouse, D. Dunkley, K. Moore and G. McMahon

Small-scale geochemical heterogeneity in the upper mantle of the Nógrád-Gömör Volcanic Field (N-Hungary - S-Slovakia)
N. Liptai, **S.Y. O'Reilly**, **W.L. Griffin**, **N.J. Pearson** and C. Szabo

Upwelling of the SE Australian lithosphere: Thermo-tectonic evolution of garnet pyroxenite xenoliths from western Victoria
J.-G. Lu, **Q. Xiong**, **W.L. Griffin**, **J.-X. Huang**, **S.Y. O'Reilly**, **T. Satsukawa**, J.-P. Zheng and **N. Pearson**

Ar-Ar dating of K-richterite from the Bab'e Leto (An-134) kimberlite pipe, East Ukukit field, Siberian craton
V.G. Malkovets, D.S. Yudin, D.I. Rezvukhin, A.A. Gibsher, **I.G. Tretiakova** and T. Tsujimori

Evolution of the early continents and localisation of Ni-Cu-PGE systems
D. Mole, **M.L. Fiorentini**, **C. Kirkland**, S. Barnes, **C. McCuaig**, K. Cassidy, **E. Belousova**, S. Romano and M. Doublier **Invited**

Targeting the timing of zircon deformation with atom probe and correlative microscopy
S.M. Reddy, D.W. Saxey, W.D.A. Rickard, **D. Fougerouse**, R.J.M. Taylor and T.E. Johnson

Messengers from the deep: Fossil wadsleyite-chromite microstructures from the mantle transition zone
T. Satsukawa, **W.L. Griffin**, **S. Piazolo** and **S.Y. O'Reilly**

Nanoscale analysis of zircon standards by atom probe microscopy
D. Saxey, **S. Reddy**, W. Rickard, **D. Fougerouse** and A. Van Riessen

High-Mg carbonatitic to water-silicic growth environments of cloudy diamonds from the Malobotuobia Kimberlite Field (Siberian Craton)
S. Skuzovatov, D. Zedgenizov, D. Howell and **W.L. Griffin**

26th Goldschmidt Conference, Yokohama, Japan, 26 June - 1 July 2016 *cont...*	The magmatic evolution of the Moon as recorded by Pb isotopes J. Snape, **A. Nemchin**, J. Bellucci, M. Whitehouse, R. Tartèse, J. Barnes, M. Anand, I. Crawford and K. Joy EIMF Sediment melt and the highest recorded $\delta^{18}O$ in sub-Moho granitoids of the Oman-UAE Ophiolite C.J. Spencer, T.D. Raub, A.J. Cavosie, J.D. Miller, H. Rollinson and **H. Jeon** *In situ* SHRIMP U-Pb geochronology and geochemistry of mafic dykes in the Yilgarn Craton, Western Australia and Bunger Hills, East Antarctica **J.C. Stark**, **X.-C. Wang**, **Z.-X. Li**, B. Rasmussen, J.-W. Zi, **C. Clark** and M. Hand Coastal hydrothermal field was hot spot for biotic diversity on the Paleoarchean Earth K. Sugitani, K. Mimura, M. Takeuchi, T. Yamaguchi, K. Suzuki, R. Senda, Y. Asahara, S. Wallis and **M.J. Van Kranendonk** Zircon breaking bad: Fingerprinting impact histories from $ZrSiO_4$ and zirconia microstructures N. Timms, A. Cavosie, **T. Erickson**, M. Pearce, **S. Reddy**, M. Schmieder, E. Tohver, M. Zanetti and A. Wittmann Mosaic zircons indicators of a long-lived mantle pathway **I. Tretiakova**, **E. Belousova**, V. Malkovets, **W. Griffin** and **N. Pearson** Tourmaline-bearing crusts in the 3.48 Ga Dresser Formation: derivation and implications for the origin of life **M.J. Van Kranendonk**, T. Ota, E. Nakamura and **T. Djokic** Depleted SSZ type mantle peridotites in Proterozoic Eastern Sayan Ophiolites in Siberia K.-L. Wang, Z. Chu, M.A. Gornova, V.A. Belyaev, K.Y Lin and **S.Y. O'Reilly** Early-formed chemical heterogeneity recorded by ^{142}Nd-^{143}Nd in 3.8-3.0 Ga samples from the Archean Anshan Complex, North China Craton **X.-C. Wang**, C.-F. Li, **S. Wilde**, X.-H. Li and Y.-F. Wang **Invited** Melting of mixed continental crust and depleted peridotite: Potassium rich magmatism from a phlogopite-free source **Y. Wang**, **S.F. Foley** and D. Prelević Two types of chromitites in a Tibetan ophiolite produced by two-stage accretion of Tethyan Arc lithosphere **Q. Xiong**, **W.L. Griffin**, J.-P. Zheng, **S.Y. O'Reilly** and **N.J. Pearson**
Australian Astrobiology Meeting, Perth, Australia, 10-12 July 2016	A ~2.4 billion year old microfossil community from the rise of atmospheric oxygen in the Turee Creek Group, Western Australia **E. Barlow** and **M.J. Van Kranendonk** Enhanced volcanogenic sulfur exhalation on Mars by the erosion and assimilation of sulfate-rich substrate during flow of lava **R. Baumgartner**, D. Baratoux, F. Gaillard and **M.L. Fiorentini** Organic contamination of 2.6Ga stromatolitic dolomites leading to false-positive biomarker results **R.P. Blake**, **M. Van Kranendonk**, **C. Peters** and **S.C. George** A terrestrial origin of life B. Damer, **M.J. Van Kranendonk**, **T. Djokic** and D. Deamer **Invited** Bringing astrobiology down to Earth: A 4D virtual field trip back in time 3.5 billion years to the oldest convincing evidence of life on Earth in the Pilbara Craton, Western Australia **T. Djokic**, **M.J. Van Kranendonk**, C. Oliver and S. Guan Oil-bearing fluid inclusions and solid bitumens: Biogeochemical repositories of information about the Archean biosphere **S.C. George**, **C.A. Peters**, **S. Piazolo**, T. Leefmann and A. Dutkiewicz Transforming a face-to-face astrobiology course to fully online C.A. Oliver, **M. Van Kranendonk** and **T. Djokic** Origin of life in terrestrial hotsprings: New evidence from the oldest life on Earth, and implications for the search for life on Mars **M.J. Van Kranendonk**, **T. Djokic** and K. Campbell
Workshop on the origin and evolution of plate tectonics, Monte Verità, Locarno, Switzerland, 17-22 July 2016	Impact-driven tectonism during the Hadean **C. O'Neill**, S. Marchi, **S. Zhang** and W. Bottke

Asia Oceania Geosciences Society 13th Annual Meeting, Beijing, China, 31 July - 5 August 2016	Towards joint tomography of broadband ambient noise data and teleseismic body waves **Y. Yang**, **K. Wang** and S.-H. Hung Paleoproterozoic subductions and their roles in craton assembly in Western Australia **H. Yuan**, S. Johnson, M. Dentith, R. Murdie and **K. Gessner** **Invited**
7th International Dyke Conference (IDC7), Beijing, China, 18-20 August 2016	An elevated perspective: Dyke-related fracture networks analysed with UAV photogrammetry **G. Dering**, S. Micklethwaite, S. Barnes, **M.L. Fiorentini**, S. Cruden and E. Tohver Age and geochemical characteristics of major mafic dyke swarms in the southern part of the Siberian Craton T.V. Donskaya, D.P. Gladkochub, R. Ernst, **S.A. Pisarevsky**, A.M. Mazukabzov, U. Söderlund, **M.T.D. Wingate**, M.A. Hamilton and E.I. Demonterova Proterozoic dyke swarms of the Siberian Craton and their geodynamic implications D.P. Gladkochub, T.V. Donskaya, R. Ernst, **S.A. Pisarevsky**, **M.T.D. Wingate** and U. Söderlund **Invited** Late Paleoproterozoic paleogeography of Baltica and Laurentia: New paleomagnetic data from 1.80-1.75 Ga mafic intrusions of Fennoscandia and Sarmatia N.V. Lubnina, **S.A. Pisarevsky**, S.V. Bogdanova and S.J. Sokolov Paleomagnetic data and dyke swarms geometries - Important tools for Precambrian paleogeographic reconstructions **S.A. Pisarevsky** **Keynote** Updated digital map of mafic dyke swarms and large igneous provinces in Western Australia **M.T.D. Wingate** and D. McB. Martin **Invited**
ASEG-PESA-AIG 2016 25th International Geophysical Conference and Exhibition in Adelaide, South Australia, August 21-24, 2016	Multi-observable thermochemical tomography: a new approach to an old problem **J.C. Afonso** **Keynote** Magnetic susceptibility of Edmund Basin, Capricorn Orogen, WA **H. Lampinen**, S. Occhipinti, M. Lindsay and C. Laukamp Numerical modelling of the Sydney Basin using temperature dependent thermal conductivity measurements **A. Lemenager**, **C. O'Neill** and **S. Zhang** Potential field studies along the 13GA-EG1 Eucla-Gawler deep crustal seismic reflection line R.E. Murdie, **H. Yuan**, M. Dentith, S.P. Johnson and **K. Gessner** Passive seismic studies show configuration of Paleoproterozoic subduction zones and their role in craton assembly in Western Australia R.E. Murdie, L. Brisbout, J. Brett, C.V. Spaggiari, **K. Gessner**, R.A. Dutch, S. Thiel, T. Wise and M.J. Pawley 3D imaging of the Earth's lithosphere using noise from ocean waves **Y. Yang**, **J. Xie** and **K. Zhao** **Keynote**
European Microscopy Conference, Lyon, France, 28 August - 2 September 2016	New insights into the Precambrian fossil record using correlative electron and ion beam microscopy **D. Wacey**, K. Eiloart, M. Saunders, P. Guagliardo and **M. Kilburn**
35th IGC - International Geological Congress, Cape Town, South Africa, 27 August - 4 September 2016	The answers are blowin' in the wind: ultra-distal airfall zircons, evidence of Cretaceous super-eruptions in eastern Gondwana M. Barham, **C. Kirkland**, S. Reynolds., M. O'Leary, N. Evans, H. Allen, P. Haines, R. Hocking, B. McDonald, **E. Belousova** and J. Goodall Diversification of early life: microfossils of the c. 2.4 Ga Turee Creek Group, Western Australia **E. Barlow** and **M.J. Van Kranendonk** Kimberlites from the Kundelungu Plateau (southeast D.R. Congo): Age determination, implications for regional tectonism and mineralization **J.M. Batumike,** R.T. Lubala, M. Chabu, L. Ferriere, K. Kaseti, **W.L. Griffin** and **E. Belousova** Stagnant-lid tectonics during the Archaean and delayed onset of plate tectonics V. Debaille, **C. O'Neill** and A.D. Brandon Visualising early life on Earth: Building a 4-Dimensional virtual field trip (VFT) of the 3.5 Ga Dresser Formation, North Pole Dome, Pilbara Craton, Western Australia. **T. Djokic**, **M.J. Van Kranendonk**, C. Oliver and S. Guan

35th IGC - International Geological Congress, Cape Town, South Africa, 27 August - 4 September 2016 *cont...*

SIMS dating of the Neoarchean to Eoarchean Saglek block, Labrador
D.J. Dunkley, **M.A. Kusiak**, M.J. Whitehouse, A. Sałacińska, **S.A. Wilde** and R. Kielman

Dating orogenic gold mineralization at the Paulsens deposit, Western Australia
I. Fielding, S. Johnson, B. Rasmussen, J. Muhling, D. Dunkley, J. Zi, **M.T.D. Wingate** and S. Sheppard

Archean magmatism and crustal evolution in the northern Tarim Craton: Insights from zircon U-Pb-Hf-O isotopes and geochemistry of ~2.7 Ga orthogneiss and amphibolite in the Korla Complex
R.F. Ge, W.B. Zhu and **S.A. Wilde**

Trace element variations across olivine record the evolution of kimberlite melts: Case studies from the Kimberley kimberlites (South Africa).
A. Giuliani, A. Soltys, **W.L. Griffin**, **S. Foley**, V.S. Kamenetsky, D. Phillips, A. Greig and K. Goemann **Keynote**

Ordovician dioritic magmatism of the Donken area, far SE Laos: Implications for Gondwana evolution in SE Asia
C.J. Gardner, I.T. Graham, **E. Belousova**, **W. Powell**, G. Booth and R. Gardiner

Textures of sulphides, and association with gold mineralisation in the Beatons
C.J. Guldbrandsen, **M.J. Van Kranendonk** and I.T. Graham

Origin and genesis of alluvial sapphires from the Orosmayo region, Sierra de Rinconada, Jujuy Province, northwest Argentina
S.H. Harris, I.T. Graham, A. Lay, **W. Powell**, **E. Belousova** and E. Zappettini

An unusual ruby-sapphire transition in megacrystic corundum, New England gem field, New South Wales, eastern Australia
S.H. Harris, I.T. Graham, F.L. Sutherland, T. Coldham, **W. Powell** and **E. Belousova**

Mineral physics and surface observational constraints on the topographic uplift of the Southern African Plateau due to the African Superswell
A.G. Jones, **J.C. Afonso** and J. Fullea

Imaging the lithosphere-asthenosphere boundary beneath continents using mineral physics and surface observational constraints
A.G. Jones and **J.C. Afonso**

Self-consistent thermo-chemical modelling of the lithosphere beneath the West African Craton
A.G. Jones, F. Le Pape and **J.C. Afonso**

The sources of magmatic rocks matter of the Arctic Ocean and the Central Atlantic Ocean from isotopic geochemical data
A.A. Kremenetsky, Yu.A. Kostitsyn, N.A. Gromalova, S.G. Skolotnev, O.G. Shulyatin and **E.A. Belousova**

Igneous protoliths of the Uivak gneiss, Saglek block, northern Labrador
M.A. Kusiak, D.J. Dunkley, A. Sałacińska, M.J. Whitehouse, **S.A Wilde** and A. Gawęda

Geochronological implications of metallic Pb nanospheres in zircon exposed to high-grade metamorphism.
M.A. Kusiak, R. Wirth, **S.A. Wilde**, M.J. Whitehouse, D.J. Dunkley and I. Lyon

The life cycles of mantle plumes and superplumes: observations, modelling, and geodynamic implications
Z.X. Li and N. Zhang

Timing of the Siberian craton kimberlite magmatism: evidences from the U-Pb dating of kimberlitic zircon
V.G. Malkovets, **E.A. Belousova,** I.G. Tretiakova, **W.L. Griffin** and **S.Y. O'Reilly**

Geodynamic reconstruction and metallogeny of the Tien Shan, Uzbekistan
R. Seltmann, A. Dolgopolova, R. Armstrong, **E. Belousova**, D. Konopelko, V. Shatov, R. Khalmatov and R. Koneev

An early multicellular holozoan from the 1 Ga Torridon Group, Scotland
P. Strother, **D. Wacey**, M. Brasier and C. Wellman

Conditioned duality of the Earth system via the supercontinent cycle
M.J. Van Kranendonk and **C.L. Kirkland**

Remarkable preservation: metamorphic processes in the 3.5 Ga North Pole Dome, Pilbara Craton, Australia
M.J. Van Kranendonk

A volcanic plateau origin of the Barberton granitoid-greenstone terrain
M.J. Van Kranendonk

Ancient continents among the accretionary complexes of the Central Asia Orogenic Belt: *In situ* Os isotope evidence
K.-L. Wang, **S.Y. O'Reilly,** M.I. Kuzmin, V. Kovach, S. D'Ril, A. Vorontrov, V. Yarmolyuk, **W.L. Griffin** and **N.J. Pearson**

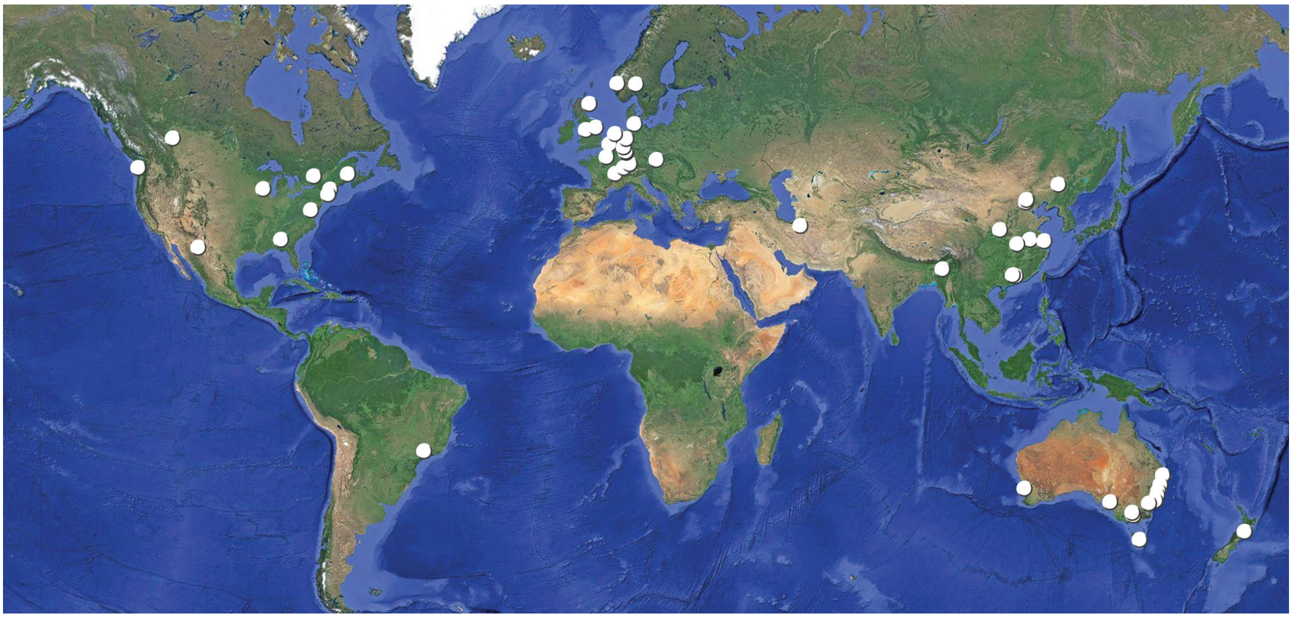
35th IGC - International Geological Congress, Cape Town, South Africa, 27 August - 4 September 2016 *cont...*	Global Seismic LAB measurements from full waveform tomography **H. Yuan** and B. Romanowicz **Invited**
13th International Nickel-Copper-PGE Symposium, Fremantle, Australia, 5-9 September 2016	The first *in situ* minor and trace element analysis of sulfides in martian magmatic rocks - unravelling the hosts of (highly) siderophile and chalcophile elements in some shergottite meteorites **R. Baumgartner**, **M.L. Fiorentini**, J-P. Lorand, D. Baratoux, F. Zaccarini, L. Ferriere, M. Prasek and K. Sener The Fisher East nickel sulphide prospects L.L. Burley, S.J. Barnes, **M.L. Fiorentini, D.R. Mole** and W. Belbin Magmatic degassing of sulfide melt in komatiite: stratigraphy-controlled mineral assemblages, mineral chemistry and isotopic signatures in the Ni-PGE ores at Wannaway deposit, Eastern Goldfields, Western Australia **S. Caruso**, M. Moroni, **M.L. Fiorentini,** S. Barnes, B. Wing and **L. Martin** Channelling magma flow in the crust to form magmatic ore deposits A.R. Cruden, S.J. Barnes, J. van Otterloo, S. Micklethwaite, **M.L. Fiorentini** and A. Slim Dyke tips and melt pathways: Insights from UAV Photogrammetry **G. Dering**, S. Barnes, S. Micklethwaite, S. Cruden, **M.L. Fiorentini** and E. Tohver Carbonatitic melt in deep seated mafic pipes physically entrains dense sulfide blebs during vertical magma flow **M.L. Fiorentini**, M. Moroni, **S. Caruso**, G. Sessa, B. Godel, M. Anenburg and J. Mavrogenes Ni-Cu-PGE ore deposition driven by metasomatic fluids and melt-rock reactions into the deep crust G. Sessa, M. Moroni, S. Tumiati, **S. Caruso** and **M.L. Fiorentini**
SHRIMP Conference, Granada, Spain, 6-10 September 2016	SHRIMP dating of zircon and monazite from the Archean Saglek block, Labrador D.J. Dunkley, **M.A. Kusiak**, A. Sałacińska, M.J. Whitehouse, **S.A. Wilde** and R. Kielman Age complexity in the composite Uivak Gneiss of the Saglek Block, Labrador A. Sałacińska, **M.A. Kusiak**, M.J. Whitehouse, D.J. Dunkley, **S.A. Wilde** and R. Kielman
2nd European Mineralogical Conference, EMC2016 *"Minerals, Fluids and Rocks: Alphabet and Words Of Planet Earth"*, Rimini, Italy, 11-15 September 2016	Geochemical evolution of PGM-bearing sulfides in low-mineralized rocks from the Yoko-Dovyren layered intrusion, Russia A. Ariskin, L. Danyushevsky, G. Nikolaev, S. Gilbert, **M.L. Fiorentini**, E. Kislov and G. Barmina The effect of composition on minor and trace elements in spinels: Insights from exsolved chromite V. Colás, C.S. Tassara, J.A. Padrón Navarta, J.M. González Jiménez, **W.L. Griffin**, I. Isabel Fanlo, **S.Y. O'Reilly**, F. Gervilla, J.A. Proenza, N.J. Pearson, A. Camprubí and M.P. Escayola The curious case of the impostor amphibole cumulates - identifying zones of significant mass transfer through the lower crust **N. Daczko**, **S. Piazolo**, **U. Meek**, **C.A. Stuart** and V. Heath Redistribution of trace elements in reactive abyssal mantle: A LA-ICPMS study of ODP Site 1274 peridotites (15° 20 FZ, Mid-Atlantic Ridge) M. Godard, **O. Alard** and **Y. Gréau** Hot aqueous fluids: Are they the key to HTLP regional aureoles? **K. Jessop**, **N. Daczko** and **S. Piazolo** Geochemical evolution of the upper mantle beneath the Nógrád-Gömör Volcanic Field (N-Hungary - S-Slovakia) as reconstructed from spinel peridotite xenoliths **N. Liptai**, L. Patkó, I.J. Kovács, K. Hidas, **S.Y. O'Reilly**, **W.L. Griffin**, **N.J. Pearson** and C. Szabó Atoms on the move: Deformation-induced trace element redistribution in zircon revealed using atom probe tomography **S. Piazolo**, A. La Fontaine, P. Trimby, S. Harley, L. Yang, R. Armstrong and J.M. Cairney NH-bearing nanoinclusions in milky diamonds from Juina area Mato Grosso, Brazil J. Rudloff-Grund, F.E. Brenker, K. Marquardt, D. Howell, **S.Y. O'Reilly** and F.V. Kaminsky Amphibole as a proxy of the secular variations in primitive magmas G. Sessa, M. Tiepolo, M. Moroni, **M.L. Fiorentini**, A. Langone, G. Giazzi, L. Krotz, E. Ferrari and **R.R. Loucks**

2nd European Mineralogical Conference, EMC2016 Minerals, Fluids and Rocks: Alphabet and Words Of Planet Earth, Rimini, Italy, 11-15 September 2016 *cont...*	Intracontinental orogeny, central Australia: shear zone patterns and the role of fluids in lithospheric weakening **D. Silva**, **N. Daczko**, **S. Piazolo**, R. Raimondo and A. Putnis Symplectite formation in the presence of a reactive fluid: Insights from hydrothermal experiments **L. Spruzeniece**, **S. Piazolo**, A. Putnis, **N. Daczko** and **M.R. Kilburn**
GSA Annual Meeting, Denver, Colorado, USA, 25-28 September 2016	Assessing trace element (dis)equilibrium and the application of single element thermometers in metamorphic rocks A.M. Cruz-Uribe, M. Feinman, T. Zack and **D.E. Jacob** **Invited** ID-TIMS U-Pb geochronology of lower crustal cumulate complexes in the Kohistan Terrane, NE Pakistan: Implications for island arc formation J. Stirling, **S. Denyszyn**, **M.L. Fiorentini** and **R. Loucks**
SEG 2016 Tethyan Tectonics and Metallogeny, ÇeşMe, Turkey, 25-28 September 2016	Zircon compositions as a pathfinder for porphyry Cu ± Mo ± Au systems **Y. Lu**, **R.R. Loucks**, **M.L. Fiorentini**, **T.C. McCuaig**, N.J. Evans, Z. Yang, Z. Hou, **C.L. Kirkland**, **L.A. Parra-Avila** and A. Kobussen **Keynote**
TIGeR Conference, Rock Alteration in The Upper Crust: Element Mobility and Concentration, Curtin University, Perth, Australia, 26-28 September 2016	Metal and sulfur cycles in the deep continental crust: Insights from the Ni-Cu-PGE sulfide deposits of the Ivrea Zone (Italy) **M.L. Fiorentini**, M. Locmelis, **T. Rushmer**, R. Arevalo Jr., **J. Adam**, **S.W. Denyszyn** and **C. LaFlamme** **Invited** Anomalous sulfur isotope signatures preserved in the Proterozoic Capricorn Orogen: Linking fluid-driving tectonic processes and ore genesis at craton margins **C. LaFlamme**, **M.L. Fiorentini**, M. Lindsay, B. Wing, **V. Selvaraja**, T.H. Bui, S. Occhipinti and S. Johnson Chemical and thermal evolution of subduction zones: Insights from trace-element distribution and Lu-Hf geochronology in HP oceanic rocks, Halilbağı Complex (Central Anatolia) **A. Pourteau**, L. Ebert, A. Schmidt, E.E. Scherer and R. Bast
16th Australian Space Research Conference Melbourne, Australia, 26-28 September 2016	How does prolonged magma-ocean solidification affect lunar evolution **S. Zhang** and **C. O'Neill**
ACTER 2016 Annual Field Symposium, Xi'an, China, 20-29 October 2016	Proterozoic tectonics of Hainan Island in supercontinent cycles W. Yao, **Z.X. Li**, W.-X. Li and X.-H. Li
2016 International Conference on The Earth's Deep Interior, Wuhan, China, 4-6 November 2016	Iron spin transitions in the Earth **S. Clark** **Invited** Corundum crystallization and ultra-low fO_2 in a volcanic plumbing system: Mt Carmel area, Israel **W.L. Griffin**, **S.E.M. Gain**, **J-X. Huang**, V. Toledo, **N.J. Pearson** and **S.Y. O'Reilly** **Keynote** Extremely un-equilibrated intergrowth of SiC and oxidized phases in a Tibetan ophiolite preserved by rapid cooling **Q. Xiong**, **W.L. Griffin**, J.-P. Zheng, **J.-X. Huang**, **S.E.M. Gain**, **S.Y. O'Reilly** and **N.J. Pearson**
SSERVI Australia Workshop 2016, Perth, Australia, 9-11 November 2016	Global-scale evolving simulations of the post-magma ocean Earth through the Hadean **C. O'Neill** Activating the lower mantle: Viscosity by numerical analysis **J. Wasiliev**, **C. O'Neill** and **S. Zhang** Lunar post-magma-ocean overturn and crustal evolution **S. Zhang** and **C. O'Neill**

Resources for the 21st Century Symposium, Research School of Earth Sciences (RSES), Canberra, Australia, 22-24 November 2016	Tracing metal and fluid sources in magmatic and hydrothermal systems **M.L. Fiorentini** **Keynote** Targeting new deposits: Margins, metasomatism and metallogeny **S.Y. O'Reilly** **Invited**
TANG3O, Thermochronology and Noble Gas Geochronology and Geochemistry Organisation, Perth, Australia, 29-30 November 2016	The Hf isotope paradox applied to crustal evolution of the Early Earth **N.J. Gardiner,** T. Johnson, **C. Kirkland**, A. Hickman, H. Smithies and **E. Belousova** Cutting-edge SIMS capabilities at UWA's Ion Probe Facility **M. Kilburn**, **L. Martin**, **H. Jeon** and M. Roberts
CET-UWA 2016 Corporate Members Day, Perth, Australia, 7 December 2016	Understanding the Precambrian crust in the Capricorn region - some results from recent passive source deployments **H. Yuan**, S.P. Johnson, M. Dentith, R. Murdie, **K. Gessner**, F. Korhonen and T. Bodin **Invited**
Greenland Day Conference, Perth, Australia, 9 December 2016	Timing and genesis of magmatism and Ni mineralisation in the Ammassalik Intrusive Complex (SE Greenland) **E. Lebrun**, **J. Kolb**, **M. Fiorentini**, T. Arting, T. Kokfelt, A. Johannesen, **N. Thébaud**, **C. LaFlamme**, R. Doutre, **L. Martin** and **R. Murphy** Gold mineralization in the Nuuk goldfields - first impressions **N. Thébaud**
AGU Fall Meeting, San Francisco, USA, 12-16 December 2016	Thermo-chemical structure of the North China Craton from multi-observable probabilistic inversion: extent and causes of cratonic lithosphere modification **J.C. Afonso**, **Z. Guo**, **M. Qashqai**, **Y. Yang** and J. Chen A high resolution magnetostratigraphic profile across the Permian-Triassic boundary in the Southern Sydney Basin, eastern Australia M.E. Belica, E. Tohver, R. Nicoll, **S.W Denyszyn**, **S. Pisarevsky** and A.D. George Sanukitoids record the onset of widespread Neoarchean supracrustal recycling **K. Bjorkman**, T. Kemp, **Y. Lu**, **T.C. McCuaig** and P. Hollings Melting mud in Earth's mantle, evidence from sub-Moho S-type granites with extreme oxygen isotope signatures A.J. Cavosie, C.J. Spencer, T.D. Raub, J.D. Miller, H. Rollinson and **H. Jeon** Isotopic analysis of individual refractory metal nuggets using atom probe tomography L. Daly, P. Bland, **B.F. Schaefer**, D.W Saxey, **S. Reddy**, **D. Fougerouse**, R.D.A. William, L.V. Forman, P. Trimby, A. La Fontaine, L. Yang, J. Cairney and S. Ringer Relating seismicity to dike emplacement, and the conundrum of dyke-parallel faulting **G. Dering**, S. Micklethwaite, S. Barnes, **M. Fiorentini** and S. Cruden Microstrain and short-range ordering of Ca and Mg cations in pyrope-grossular garnet system W. Du, **S.M. Clark** and D. Walker A 2D petrological-thermomechanical study of a carbonate metasomatized subcontinental lithospheric mantle with variable tectothermal ages **C.M. Gonzalez**, **W. Gorczyk** and T. Gerya Chemical disequilibria in the source of oceanic basalts: Insights from grain-scale models **C.J. Grose**, P.D. Asimow, M. Gurnis and **J.C. Afonso** Crustal radial anisotropy in Northeast China and its implication for the regional tectonic extension **Z. Guo**, **Y. Yang** and Y.J. Chen Layered crustal anisotropy in the NE Tibetan Plateau inferred from ambient noise tomography **C. Jiang**, **Y. Yang** and Y. Zheng

AGU Fall Meeting, San Francisco, USA, 12-16 December 2016 *cont...*	Measurement of Rayleigh wave ellipticity and its application to the joint inversion of high-resolution S wave velocity structure beneath northeast China G. Li, H. Chen, F. Niu, **Z. Guo**, **Y. Yang** and **J. Xie** High resolution crustal and upper mantle velocity model of northern Ordos block from surface wave tomography: evidence for the on-going craton reactivation S. Li, **Z. Guo**, Y.J. Chen and **Y. Yang** Revisit the lunar mantle overturn with the Ilmenite rheology H. Li and **N. Zhang** Pb-Pb systematics of lunar rocks: differentiation, magmatic and impact history of the Moon **A. Nemchin**, M. Whitehouse, M.D Norman, J. Snape, J.J. Bellucci and **M. Grange** **Invited** Studying the sub-crustal reflectors in SW-Spain I. Palomeras, P. Ayarza, R. Carbonell, S. Akhtar Ehsan, **J.C. Afonso** and J. Diaz Continental growth along the Proto-Pacific margin of East Gondwana in Australia: Insights from seismic tomography N. Rawlinson, S. Pilia, M. Salmon, **Y. Yang** and M.K. Young Magma interaction in the root of an arc batholith V. Robbins, T. Chapman, G.L. Clarke, **N.R. Daczko** and **S. Piazolo** The formation of micro-diamonds in micro-cracks controlled by the C:O:H ratio of NAMS H. Sommer, **D.E. Jacob**, K. Regenauer-Lieb and B. Gasharova Geochronology of lower crustal cumulate ccomplexes in the Kohistan Terrane, North-East Pakistan: Implications for island arc formation? J.E. Stirling, **S.W. Denyszyn**, **R.R. Loucks** and **M.L. Fiorentini** Correction of phase velocity bias caused by strong directional noise sources in high-frequency ambient noise tomography: a case study in Karamay, China **K. Wang**, Y. Luo and **Y. Yang** Plate motion changes drive Eastern Indian Ocean microcontinent formation J.M. Whittaker, S. Williams, J. Halpin, T. Wild, J. Stilwell, F. Jourdan and **N.R. Daczko** On the accuracy of long-period Rayleigh waves extracted from ambient noise **Y. Yang**, **J. Xie** and S. Ni Crustal structure of the late-Archean to Proterozoic Glenburgh Terrane in the Western Australian Craton: roles of a micro-continent in craton formation and reworking **H. Yuan,** S. Johnson, M.C. Dentith, R. Murdie, **K. Gessner**, F.J. Korhonen and T. Bodin **Invited** Lithospheric layering in major continents: results using full waveform tomography **H. Yuan**, P. Clouzet, B.A. Romanowicz and L. Zhao **Invited** The Hainan Lone Plume prompted by encircling subduction zones around the South China Sea **N. Zhang** and **Z.X. Li** **Invited** Formation of mantle '*Lone*' Plume in a global downwelling zone **N. Zhang** and **Z.X. Li**
Palaeontology Association Annual Meeting, Lyon, France, 14-17 December 2016	A closer look at a possible stem group holozoan from the 1 Ga Torridon Group of northwest Scotland **D. Wacey**, P. Strother, M. Brasier and C. Wellman

Appendix 7: CCFS visitors



CCFS VISITORS 2016 (Excluding participants in conferences and workshops)

VISITOR	ORGANISATION	COUNTRY
Dr Chris Adams	Lower Hutt	New Zealand
Mr Patrick Ball	University of Cambridge	USA
Ms Emily Barthgate	University of Technology, Sydney	Australia
Dr Charlotte Bary	Geological Survey of New South Wales	Australia
Dr Graham Begg	Minerals Targeting International	Australia
Dr Ivan Belousova	University of Tasmania	Australia
Professor Peter Betts	Monash University	Australia
Dr Maibam Bidyananda	Manipur University, Imphal	India
Dr Alex Brasier	University of Aberdeen	UK
Professor Richard Carlson	The Carnegie Institute of Washington	USA
Dr Chutimun Chanmuang	University of Vienna	Austria
Mr Chunfei Chen	Chinese University of Geosciences, Wuhan	China
Miss Ying Chen	Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS)	China
Dr Peter Downes	Geological Survey of New South Wales	Australia
Professor Jörg Ebbing	Kiel University	Germany
Dr Richard Ernst	Carleton University	Canada
Ms Vanessa Fichtner	University of Münster	Germany
Dr Ria Fisher	Zürich, ZH	Switzerland
Professor Carmen Gaina	Department of Geosciences, University of Oslo	Norway
Dr Michelle Gehringer	University of Kaiserslautern	Germany
Mr Alexis Geisler	Ecole Normale Superieure, Paris	France
Professor Thorsten Geisler-Wierwille	University of Bonn	Germany
Dr Wenyan He	China University of Geosciences, Beijing	China

VISITOR	ORGANISATION	COUNTRY
Professor Marco Herwegh	University of Bern	Switzerland
Professor Paul Hoffman	University of Victoria	Canada
Mr Daniel Howlett	The University of Adelaide	Australia
Mr Zong-ying Huang	Guangzhou Institute of Geochemistry, Chinese Academy of Sciences	China
Professor Herbert Huppert	Institute of Theoretical Geophysics & Department of Applied Mathematics and Theoretical Physics, University of Cambridge	USA
Dr Andrew Jane	Manager, Spectroscopy Applications and Service Support, Quark Photonics	Australia
Professor Clark Johnson	University of Wisconsin at Madison	USA
Miss Zakie Kazemi	Shahrood University of Technology, Semnan	Iran
Professor Brian Kennett	Australian National University	Australia
Dr Christoph Lenz	Institut für Mineralogie and Kristallographie, Universität Wien	Austria
Mr Shilin Li	Beijing University	China
Dr Yanguang Li	Xi'an Centre, China Geological Survey	China
Mr Kai Liu	Peking University	China
Mr Ben Maher	University Melbourne	Australia
Ms Erin Martin	University of Newcastle	Australia
Dr Luke Milan	University of New England	Australia
Professor Lutz Nasdala	University of Vienna	Austria
Mr Florian Nehmé	Export Area Sales Manager chez HORIBA Scientific	France
Professor James Ni	New Mexico State University	USA
Professor Allen Nutman	School of Earth & Environmental Sciences, University of Wollongong	Australia
Professor Elson Oliveira	University of Campinas, Sao Paulo	Brazil
Dr Feng Pan	Xi'an Centre, China Geological Survey	China
Professor Graham Pearson	University of Alberta	Canada
Professor Zhigang Peng	Georgia Institute of Technology	USA
Dr Ryan Portner	Brown University	USA
Associate Professor Daniel Price	Monash University	Australia
Ms Nadia Priyatkina	University of Newcastle	Australia
Professor Andrew Putnis	Curtin University	Australia
Dr Anthony Quinn	Director, Quark Photonics	Australia
Dr Tom Raimondo	University of South Australia	Australia
Professor John Reijmer	University of Amsterdam	Netherlands
Dr Mike Rogerson	University of Hull	UK
Professor Stephane Rondenay	Department of Earth Sciences, University of Bergen	Norway
Mr Yilun Shao	Jilin University	China
Ms Georgia Soares	University of New South Wales	Australia
Dr Christopher Spencer	Curtin University	Australia
Dr John Spray	University of New Brunswick	Canada
Mr Ivan Stepanov	University of New England	Australia
Professor Benoit Tauzin	Lyon University	France
Dr Svetlana Tessalina	Curtin University	Australia
Professor Laixi Tong	Chinese Academy of Sciences	China

VISITOR	ORGANISATION	COUNTRY
Professor Ying Tong	Chinese Academy of Geological Sciences	China
Mr Pang Wang	China University of Geosciences (Wuhan)	China
Dr Shuangshuang Wang	Xi'an Centre, China Geological Survey	China
Mr Tao Wang	China University of Geosceinces (Wuhan)	China
Professor John Wheeler	University of Liverpool	UK
Mr Ian Withnall	Geological Survey of Queensland	Australia
Dr Stephan E. Wolf	Institute for Glass and Ceramics, Erlangen	Germany
Mr Sebastian Wong	University of Newcastle	Australia
Mr Wolfgang Wzwilius	University of Kiel	Germany
Mr Xiaobing Xu	Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS)	China
Miss Anqi Zhang	China University of Geosciences (Wuhan)	China
Professor Haijiang Zhang	University of Science and Technology of China	China
Mr Kaifeng Zhao	China University of Geosciences (Wuhan)	China
Professor Liang Zhao	Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS)	China
Professor Huaiyang Zhou	Tongji Univesity	China
Mr Xiang Zhou	China University of Geosciences (Wuhan)	China
Ms Irina Zhukova	University of Tasmania	Australia

Appendix 8: Research funding

GRANTS AND OTHER INCOME FOR 2016

Investigators	2016 Funding Source	Project Title	Amount
O'Reilly	ARC Centre of Excellence (CE1101017)	Core to Crust Fluid Systems	$1,986,040
Wilde	ARC CoE (CU contribution)	Core to Crust Fluid Systems	$280,000
GSWA	ARC CoE (GSWA)	Core to Crust Fluid Systems	$150,000
O'Reilly	ARC CoE (MQ contribution)	Core to Crust Fluid Systems	$550,000
O'Reilly	ARC CoE (MQ FSE contribution)	Core to Crust Fluid Systems	$110,000
McCuaig	ARC CoE (UWA contribution)	Core to Crust Fluid Systems	$415,000
Handley, Turner, Reagan, Barclay	ARC Discovery Project (DP150100328)	Timescales of mixing and volatile transfer leading to volcanic eruptions	$109,215
Fitzsimons, Holness, Clark	ARC Discovery Project (DP150102773)	Migmatites, charnockites and crustal fluid flux during orogenesis	$52,700
Moresi, Betts, Whittaker, Miller	ARC Discovery Project (DP150102887)	The global consequences of subduction zone congestion	$172,600
Jacob, Eggins, Wirth	ARC Discovery Project (DP160102081)	Mechanisms of proxy uptake in biominerals	$103,521
Putnis, Raimondo, Daczko	ARC Discovery Project (DP160103449)	Just add water: a recipe for the deformation of continental interiors	$103,654
Putnis, Raimondo, Daczko	ARC Discovery Project (MQ contribution)	Just add water: a recipe for the deformation of continental interiors	$24,215
Clark, Afonso, Jones	ARC Discovery Project (DP160103502)	To develop a geophysically relevant proton conduction model for the Earth's upper mantle	$96,767
Hand, Clark, Hasterok, Rushmer, Reddy, Hacker	ARC Discovery Project (DP160104637)	Rehydration of the lower crust, fluid sources and geophysical expression	$115,000
Li	ARC Australian Laureate Fellowship (FL150100133)	How the Earth works - toward building a new tectonic paradigm	$618,147
Li	ARC Australian Laureate Fellowship (CU contribution)	How the Earth works - toward building a new tectonic paradigm	$323,685
Fiorentini	ARC Future Fellowship (FT110100241)	From core to ore: emplacement dynamics of deep-seated nickel sulphide systems	$94,847
Handley	ARC Future Fellowship (FT120100440)	The timescales of Earth-system processes: extending the frontiers of uranium-series research	$83,821
Jacob	ARC Future Fellowship (FT120100462)	A new approach to quantitative interpretation of paleoclimate archives	$118,235
Yang	ARC Future Fellowship (FT130101220)	How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	$190,986

Investigators	2016 Funding Source	Project Title	Amount
Wacey	ARC Future Fellowship (FT140100321)	New insights into the origin and evolution of life on Earth	$198,716
Wang	ARC Future Fellowship (FT140100826)	Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	$198,716
Wang	ARC Future Fellowship (CU contribution)	Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	$126,813
Alard	ARC Future Fellowship (FT150100115)	Earth's origin and evolution: a sulphurous approach	$303,247
Selway	ARC Future Fellowship (FT150100541)	Measuring mantle hydrogen to map ore fluids and model plate tectonics	$241,154
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
Foley, Mavrogenes, Putnis, Brugger, Clark, Simon, O'Neill, Cruden, Evans	ARC LIEF (LE160100103)	Australian virtual experimental laboratory: a multimode geoscience facility	$547,000
Foley, Mavrogenes, Putnis, Brugger, Clark, Simon, O'Neill, Cruden, Evans	ARC LIEF (MQ contribution)	Australian virtual experimental laboratory: a multimode geoscience facility	$157,333
Foley, Mavrogenes, Putnis, Brugger, Clark, Simon, O'Neill, Cruden, Evans	ARC LIEF (partner universities contribution)	Australian virtual experimental laboratory: a multimode geoscience facility	$207,500
Kennedy, Sorrell, Haberlah, Dewhurst, Turner, Gore, O'Reilly, Van Kranendonk, Foden, Nelson, Haghighi, Le-Clech, Ward, Koshy, Sherwood	ARC LIEF (LE160100155)	NanoMin: quantitative mineral mapping of nanoscale processes	$1,058,000
Tkalcic, Kennett, Spaggiari, Gessner	ARC Linkage Project (LP130100413)	Craton modification and growth: the east Albany-Fraser Orogen in three-dimensions	$50,000
Rasmussen, Dunkley, Muhling, Johnson, Thorne, Korhonen, Kirkland, Wingate	ARC Linkage Project (LP130100922)	Chronostratigraphic and tectonothermal history of the northern Capricorn Orogen: constructing a geological framework for understanding mineral systems	$85,000
Jessell, Holden, Baddeley, Kovesi, Ailleres, Wedge, Lindsay, Gessner, Hronsky	ARC Linkage Project (LP140100267)	Reducing 3D geological uncertainty via Improved data interpretation methods	$96,650
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	$79,000 ($37,208 to MQ)
Giuliani	ARC DECRA (DE150100510)	A new approach to revealing melting processes in the hidden deep Earth	$128,367
Giuliani	Marie Curie Grant	A new approach to revealing the composition of kimberlite melts and their deep mantle source	$244,581 (€177,589)
Hough, McCuaig, Reddy, Clark, Fiorentini, Gray, Miller	SIEF/MRIWA M436	Distal footprints of giant ore systems	$314,421

Investigators	2016 Funding Source	Project Title	Amount
Hough, Reddy, McCuaig	SIEF RP	The distal footprints of giant ore systems: UNCOVER Australia	$346,146
Kirkland, Clark, Kiddie, Tyler, Spaggiari, Smithies, Wingate	MRIWA M470	Mineral systems on the margin of cratons: Albany-Fraser Orogen/Eucla Basement case study	$66,700
Ord, Gorczyk, Hobbs, Micklethwaite	MRIWA M424	Multiscale dynamics of hydrothermal mineral systems	$145,900
Barnes, Fiorentini	MRIWA M459	Magmatic sulphide mineral potential in the East Kimberley	$31,000
O'Reilly	NCRIS AuScope	AuScope Project Plan 3.53 - Earth composition and evolution	$222,410
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	$350,000
Piazolo	MQSIS	Precision lapping machine	$147,800
Jacob et al.	MQRIBG	A state-of-the-art solid material preparation system for microbeam applications	$46,591
Pearson	MQRIBG	Probe for EPMA software	$61,405
Kirkland	Ministry of Mineral Resources (Greenland)	Geochronology for the Greenland Ministry of Mineral Resources	$94,850
Kirkland	Department of Mines and Petroleum	Crustal evolution project Geological Survey of Western Australia	$44,173
Martin	UWA staff grant	Fay-Gale Fellowship	$7,800
Piazolo, Schaefer, Turner	Bragg Institute/ANSTO	Hydration of the early solar system	$75,000
Daczko, Piazolo	Australian Synchrotron - Access Program	Tracing melt transfer zones in the lower crust: A microchemical perspective	$2,933
Jacob	Australian Synchrotron - Access Program	H_2O and CO_2 distribution along grain boundaries	$534
Xu	Australian Synchrotron - Access Program	Oxidation state of iron in phlogopite from lamprophyre, implication for gold porphyry mineralisation	$972
McCuaig, Fiorentini	Barrick Gold	The role of whole-lithosphere architecture on the genesis of giant gold systems in the El-Indio region, Chile-Argentina	$215,034
Thébaud, Occhipinti, LaFlamme, Petrella	Newmont	Mineral Footprint and 4D Architecture of the Callie Gold Deposit	$82,500
Jessell, McCuaig, Miller, Thébaud	AMIRA	Western Africa Exploration Initiative (WAXI)	$394,825
Yang, Lu	National Science Foundation, China	Genesis of comb quartz layers: case studies from porphyry Cu deposits at Qulong, Tibet and Now Chun, Iran	$50,000
Lampinen	TerraSpec Student in Mining Instrument Programme	Sponsored equipment	$78,095 ($60,000 USD)
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (Minerals Targeting International Pty Ltd)	Lithospheric architecture mapping in Phanerozoic orogens	$60,000

Investigators	2016 Funding Source	Project Title	Amount
Li, Evans, Zhong, Eglington	UNESCO-IUGS IGCP Project	IGCP project #648: Supercontinent cycles and global geodynamics	$21,414
Yao, Wang, Zhou	China Geological Survey	The Ediacaran-Silurian palaeogeography of western Yangtze Block and its tectonic linkage with the Gondwana assembly	$30,000
Lampinen, Occhipinti	Australian Society for Exploration Geophysicists	Defining mineral systems footprints in the Edmund Basin of the Capricorn Orogen	$6,000
Zhao, Yuan	Institute of Geology and Geophysics, Chinese Academy of Sciences	China-Western Australia Seismic Survey (CWAS)	$100,000
Afonso, Ebbing	Germany-Australia Joint Research Cooperation Scheme	From space to the deep Earth	$12,000
Afonso, Ebbing	Germany-Australia Joint Research Cooperation Scheme (MQ contribution)	From space to the deep Earth	$17,200
Pisarevsky	University of Oslo	Maintaining and upgrading the Global Palaeomagnetic Database	$10,000
Giuliani, Castillo-Oliver	Europlanet 2020 Research Award	Carbon isotope evolution of the deep Earth from coupled C-O Isotope SIMS measurement of carbonates in kimberlites	$14,074 (€10,000)
Daczko	Uni of Tasmania ADD subcontract agreement	Reconstructing East Antarctica in Gondwana: ground-truthing a new tectonic model	$4,400
Daczko	ANZIC Ocean Discovery Program	Reconstructing East Antarctica in Gondwana: ground-truthing a new tectonic model	$19,180
Clark	MQ Enterprise Partnership Scheme	Pilot Research Grant - Sydney Water	$100,000
Clark	MQ Enterprise Partnership Scheme	Pilot Research Grant - MQ contribution	$50,000
Caruso	MRIWA Scholarship	Geological controls on the fractionation of multiple sulfur isotopes in Archean mineral systems	$30,000
Choi	MRIWA Scholarship	Alkaline magmatism as a probe into the lithospheric mantle evolution beneath the Yilgarn Craton, WA	$30,000
Stirling	MRIWA Scholarship	Geochronology of Lower Crustal Cumulate Complexes in the Kohistan Terrane, North-East Pakistan	$29,000
O'Neill	CO_2 CRC Student Scholarship	CO_2 CRC	$30,000
Clark	ANSTO	Scholarship	$13,676
Colas	ANSTO Scholarship	Why is the San Andreas Fault so Weak?	$24,653
CCFS Postgraduates	MQ, CU Scholarships	Scholarships	$1,708,884
Oliveira	MQPGRF	Multicomponent and multiphase reactive flows in the Earth's mantle	$5,500
O'Reilly	Access MQ	Core to Crust Fluid Systems	$15,754
O'Reilly	GLITTER software	Core to Crust Fluid Systems	$47,499
O'Reilly	Interest	SLF interest	$4,882

GRANTS AND OTHER INDICATIVE INCOME FOR 2017

Investigators	2017 Funding Source	Project Title	Amount
O'Reilly	ARC Centre of Excellence (CE1101017)	Core to Crust Fluid Systems	$2,015,831
Wilde	ARC CoE (CU contribution)	Core to Crust Fluid Systems	$280,000
GSWA	ARC CoE (GSWA)	Core to Crust Fluid Systems	$150,000
O'Reilly	ARC CoE (MQ contribution)	Core to Crust Fluid Systems	$550,000
O'Reilly	ARC CoE (MQ FSE contribution)	Core to Crust Fluid Systems	$110,000
McCuaig	ARC CoE (UWA contribution)	Core to Crust Fluid Systems	$415,000
Handley, Turner, Reagan, Barclay	ARC Discovery Project (DP150100328)	Timescales of mixing and volatile transfer leading to volcanic eruptions	$110,000
Fitzsimons, Holness, Clark	ARC Discovery Project (DP150102773)	Migmatites, charnockites and crustal fluid flux during orogenesis	$65,000
Moresi, Betts, Whittaker, Miller	ARC Discovery Project (DP150102887)	The global consequences of subduction zone congestion	$180,000
Jacob, Eggins, Wirth	ARC Discovery Project (DP160102081)	Mechanisms of proxy uptake in biominerals	$105,300
Clark, Afonso, Jones	ARC Discovery Project (DP160103502)	To develop a geophysically relevant proton conduction model for the Earth's upper mantle	$96,400
Putnis, Raimondo, Daczko	ARC Discovery Project (DP160103449)	Just add water: a recipe for the deformation of continental interiors	$105,300
Hand, Clark, Hasterok, Rushmer, Reddy, Hacker	ARC Discovery Project (DP160104637)	Rehydration of the lower crust, fluid sources and geophysical expression	$137,600
Rushmer, Reddy, Hacker, Armand, George, Belt, Heraud, Bowler, Beardall	ARC Discovery Project (DP170100557)	Understand seasonal Antarctic sea-ice extent using molecular, geochemical, elemental and genomic characteristics of specific marine phytoplankton (diatoms)	$180,500
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
Li	ARC Australian Laureate Fellowship (FL150100133)	How the Earth works - toward building a new tectonic paradigm	$630,510
Li	ARC Australian Laureate Fellowship (CU contribution)	How the Earth works - toward building a new tectonic paradigm	$493,899
Yang	ARC Future Fellowship (FT130101220)	How the Earth moves: Developing a novel seismological approach to map the small-scale dynamics of the upper mantle	$87,515
Wacey	ARC Future Fellowship (FT140100321)	New insights into the origin and evolution of life on Earth	$201,969
Wang	ARC Future Fellowship (FT140100826)	Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	$129,753
Wang	ARC Future Fellowship (CU contribution)	Roles of deep-Earth fluid cycling in the generation of intra-continental magmatism	$126,813

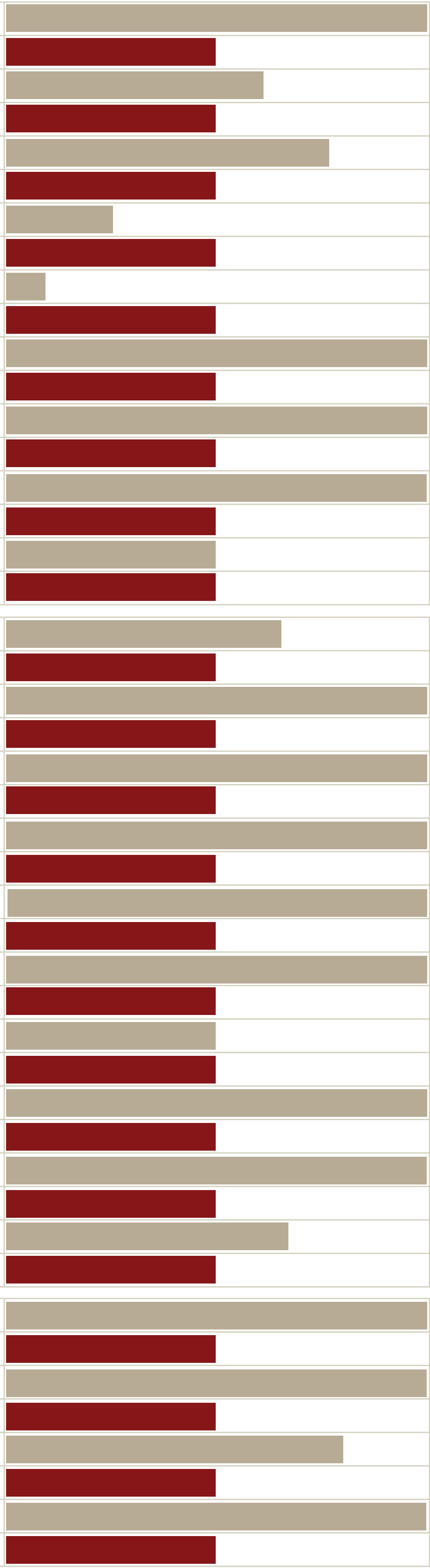
Investigators	2017 Funding Source	Project Title	Amount
Alard	ARC Future Fellowship (FT150100115)	Earth's origin and evolution: a sulphurous approach	$197,740
Selway	ARC Future Fellowship (FT150100541)	Measuring mantle hydrogen to map ore fluids and model plate tectonics	$173,088
Arculus, Cohen, Gallagher, 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
Jessell, Holden, Baddeley, Kovesi, Ailleres, Wedge, Lindsay, Gessner, Hronsky	ARC Linkage Project (LP140100267)	Reducing 3D geological uncertainty via improved data interpretation methods	$43,300
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	$164,000 ($36,000 to MQ)
Giuliani	ARC DECRA (DE150100510)	A new approach to revealing melting processes in the hidden deep Earth	$124,000
Hough, McCuaig, Reddy, Clark, Fiorentini, Gray, Miller	SIEF/MRIWA M436	Distal footprints of giant ore systems	$352,155
Hough, Reddy, McCuaig	SIEF RP	The distal footprints of giant ore systems: UNCOVER Australia	$254,806
Barnes, Fiorentini	MRIWA M459	Magmatic sulphide mineral potential in the East Kimberley	$35,000
Kirkland, Clark, Kiddie, Tyler, Spaggiari, Smithies, Wingate	MRIWA M470	Mineral systems on the margin of cratons: Albany-Fraser Orogen/Eucla Basement case study	$150,000
Jacob	MQSIS	Ramen Laser Extension Kit	$114,348
Fiorentini	GSWA	Mapping sulfur sources in selected Precambrian terranes of Western Australia to enhance predictive targeting for gold and base metal mineralisation	$15,000
Kirkland	Ministry of Mineral Resources (Greenland)	Geochronology for the Greenland Ministry of Mineral Resources	$76,138
Kirkland	Department of Mines and Petroleum	Crustal evolution project Geological Survey of Western Australia	$44,173
Zhao, Yuan	Institute of Geology and Geophysics, Chinese Academy of Sciences	China-Western Australia Seismic Survey	$100,000
McCuaig, Fiorentini	Barrick Gold	The role of whole-lithosphere architecture on the genesis of giant gold systems in the El-Indio region, Chile-Argentina	$215,000
Thébaud, Hagemann	Anglogold Ashanti	Structural history and controls on gold mineralisation in Madras prospect, Plumridge Terrain	$16,965
Thébaud, Masurel, Jessell, Meriaud	Perseus Mining	4D reconstruction of the Yaouré gold mineral camp (Cote d'Ivoire)	$26,535
Yang, Lu	National Science Foundation, China	Genesis of comb quartz layers: case studies from porphyry Cu deposits at Qulong, Tibet and Now Chun, Iran	$50,000

Investigators	2017 Funding Source	Project Title	Amount
Griffin, O'Reilly, Pearson, Belousova	MQ Enterprise Partnership Pilot Research Grant (Minerals Targeting International Pty Ltd)	Lithospheric architecture mapping in Phanerozoic orogens	$60,000
Lampinen, Occhipinti	Australian Society for Exploration Geophysicists Research Grant	Defining mineral systems footprints in the Edmund Basin of the Capricorn Orogen	$3,000
Pisarevsky	University of Oslo	Maintaining and upgrading the Global Palaeomagnetic Database	$10,000
Yao, Wang, Zhou	China Geological Survey	The Ediacaran-Silurian palaeogeography of western Yangtze Block and its tectonic linkage with the Gondwana assembly	$10,000
Huang	ANZIC	Mg-isotope composition of altered oceanic crust	$20,000
Caruso	MRIWA Scholarship	Geological controls on the fractionation of multiple sulfur isotopes in Archean mineral systems	$30,000
Choi	MRIWA Scholarship	Alkaline magmatism as a probe into the lithospheric mantle evolution beneath the Yilgarn Craton, Western Australia	$30,000
Meek	MQPGRF	Melt metasomatism within the Lower Crust	$2,523

Appendix 9: Standard performance indicators

All values maximised at double target

RESEARCH	Number & quality of outputs	R1	Research outputs	Actual	165
				Target	40
		R2(a)	Journals with Impact Factor >2.5	Actual	86%
				Target	70%
		R2(b)	Journals with impact Factor >3 Note: (11%>6)	Actual	77%
				Target	50%
		R2(c)	Journals with specific target audiences	Actual	11%
				Target	20%
		R2(d)	Book chapters / international conference proceedings	Actual	3%
				Target	10%
		R3(a)	Number of presentations / talks / papers / lectures given at major international meetings	Actual	212
				Target	40
		R3(b)	Number of invited or keynotes given at major international meetings	Actual	35
				Target	10
		R4	Number & nature of commentaries on Centre's achievements in general/specialist publications	Actual	>100
				Target	8
		R5	Citation data for publications: at least 4 CI's 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	13
				Target	10
		R7	Number of Centre attendees at all professional training courses	Actual	61
				Target	20
		R8	Number of new postgraduates working on core Centre research, supervised by CoE staff (PhD, Mast.)	Actual	24
				Target	8
		R9	Number of new postdoctoral researchers recruited to the CoE working on core Centre research	Actual	18
				Target	4
		R10	Number of new Honours/MRes students working on core Centre research & supervised by CoE staff	Actual	12
				Target	6
		R11(a)	Number of postgraduate completions working on core Centre research and supervised by CoE staff	Actual	23
				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	25
				Target	6
		R13	Number of students mentored	Actual	107
				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	56
				Target	20
		R16	Number of national and international workshops held / organised by Centre	Actual	8
				Target	3
		R17	Number of visits to overseas laboratories and facilities	Actual	31
				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*	8
		Target	6
R20	*Number and nature of public awareness programs*	*Actual*	6
		Target	5
R21	*Currency of information on the Centre's website*	*Actual*	9
		Target	4
R22	*Number of website hits*	*Actual*	14,203
		Target	10,000
R23	*Number of public talks given by centre staff*	*Actual*	13
		Target	6

ORG SUPPORT — **Generate cash & in-kind contributions from partners & other sources & build collab. & infrastrucutre support**

O1	*Annual new and existing cash contributions from collaborating organisations*	*Actual*	3,213,884
		Target	1,790,000
O2	*Annual in-kind contributions from collaborating organisations*	*Actual*	15,037,698
		Target	12,418,100
O3	*Annual cash contributions from partner organisations*	*Actual*	150,000
		Target	150,000
O4	*Annual in-kind contributions from partner organisations*	*Actual*	1,924,153
		Target	1,229,300
O5	*Other research income secured by Centre staff*	*Actual*	11,342,129
		Target	140,000
O6	*Number of new organisations collaborating with, or involved in, the Centre*	*Actual*	13
		Target	6
O7	*Level and quality of infrastructure provided to the Centre*	Documented *pp. 89-97*	

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 *pp. 9-10*), and was endorsed by the Mid-term Review Panel.
G2	*Frequency, attendance and value added by Advisory Committee meetings*	A very productive Advisory Board meeting was held in November 2016. Attendance at the meeting was over 83%. Frequency of Board meetings exceeded target. Board input has been invaluable, including providing a different perspective of Centre activities, and has been very engaged in workshopping key aspects of Centre business, 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 *Appendix 5 and p. 76*)
G6	*Capacity building of the Centre through scale and outcomes*	Recruitment of staff: 19 (see *pp. 12-17*) Recruitment of postgraduate students: 36 (see *pp. 82-88*) International Linkages: 56 visitors (see *pp. 105-108*)

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		17
		N2	*Postgraduate units established by end year 3*	*Actual*	6
				Target	2
			Number of honours and Postgraduate students		107

CCFS KPI	Outcomes	C1	*Linkage of geochemical / petrologic / geological data with geophysical datasets / modelling* *2014 - Convene international conference on integration of geophysics / geology*	*Actual*	Complete
				Target	Complete
		C2	*Technology & method development related to NCRIS infrastructure* *2013 -1st results submitted for publication / conference presentation*	*Actual*	Complete
				Target	Complete
	Training	C3	*Establishment of formal postgraduate units & training within host and collaborating university frameworks*	*Actual*	Complete
				Target	Complete
	End-user	C4	*Establishment of linkages and collaborative projects with end-users relevant to external core business of the Centre* *2013 - proceed with projects*	*Actual*	Complete
				Target	Complete

Appendix 10: CCFS postgraduate opportunities

POSTGRADUATE OPPORTUNITIES

CCFS has a flourishing postgraduate research environment with postgraduate students from many countries (currently including France, Germany, China, Russia, USA, Canada and Australia). Scholarships funding tuition fees and a living allowance are available for students with an excellent academic record or equivalent experience.
These include:

- **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. 23* 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
APA	Australian Postgraduate Award
ARC	Australian Research Council
BSE	Backscattered Electrons
(ICG) CAS	(Institute of Geology and Geophysics) Chinese Academy of Sciences
CAGS	Chinese Academy of Geological Sciences
CCFS	Core to Crust Fluid Systems
CET	Centre for Exploration Targeting
CMCA	Centre for Microscopy, Characterisation and Analysis (UWA)
CNRS	French National Research Foundation
CoE	Centre of Excellence
COO	Chief Operating Officer
CSIRO	Commonwealth Scientific Industrial Research Organisation
CU	Curtin University
DECRA	Discovery Early Career Researcher Award
DEST	Department of Education, Science and Training
DIATREEM	Consulting company within Access MQ Limited
DP	Discovery Project
EBSD	Electron Backscatter Diffraction
ECR	Early Career Researcher
(D)EPS	(Department of) Earth and Planetary Sciences
EMP	Electron Microprobe
FIM	Facility for Integrated Microanalysis
FSE	Faculty of Science and Engineering (MQ)
FTIR	Fourier Transfer Infrared Spectroscopy
GA	Geoscience Australia (formerly AGSO)
GAC-MAC	Geological Association of Canada-Mineralogical Association of Canada
GAU	Geochemical Analysis Unit (DEPS, Macquarie University)
GEMOC	Geochemical Evolution and Metallogeny of Continents
GEUS	Geological Survey of Denmark and Greenland
GIS	Geographic Information System
GLAM	Global Lithospheric Architecture Mapping
GLITTER	GEMOC Laser ICPMS Total Trace Element Reduction software
GSWA	Geological Survey of Western Australia
ICPMS	Inductively Coupled Plasma Mass Spectrometer
IPRS	International Postgraduate Research Scholarship
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
MRIWA	Minerals Research Institute of Western Australia
(i)MQRES	(International) Macquarie University Research Excellence Scholarships
MQSIS	Macquarie University Strategic Infrastructure Scheme
MOU	Memoranda of Understanding
NASA	National Aeronautics and Space Administration
NCRIS	National Collaborative Research Infrastructure Scheme
PGE	Platinum Group Element
RIBG	Research Infrastructure Block Grant
SAC	Science Advisory Committee
SEM	Scanning Electron Microscope
SIRF	UWA Scholarship for International Research Fees
TIGeR	The Institute for Geoscience Research
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

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